  Journal of Water Supply: Research and Technology—AQUA | 50.6 | 2001

An evaluation of planning distribution in water resources management

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ABSTRACT

With the recent radical changes imposed on the Egyptian water system by the Southern Valley Development there is a clear need for better water resources management. The entire project water planning relies on discounting the old Nile valley and delta water requirements. A package of five computer models was established in 1993 to be integrated within the improved water resources planning enterprise in Egypt. The core of this task is the high level simulation Operation and Planning Distribution Model (OPDM).

The model is shown as a reliable water management tool. The model is successfully used to simulate the water distribution mechanism within a highly dendritic scheme in the Nile delta. The model is utilised to perform some useful analysis on the relative significance of the various parameters involved in the water distribution practice. Issues including night-time irrigation, free cropping pattern, water shortages, and reduction of rice areas can be studied. The technique enables both factual and hypothetical policies to be addressed within the course of water planning. Optimal strategies can be defined thereof.

Key words | irrigation systems, water balance, water demands, water distribution, water management, water supply

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INTRODUCTION

Egypt's water resources base could be considered essentially simple. There is one river, one major reservoir whose inflow is confined to one point, one major irrigation system, and outflows from the total system are readily discernible. Precipitation is minimal and considered negligible for most analyses (Elarabawy *et al*. 1998). The entire system (3.2 million ha) is divided into 26 irrigation and drainage directorates (administrative authorities).

With increased population and urbanisation, the limitation of water resources has become a planning consideration. Water use in all sectors, other than agriculture, is expanding at the expense of the agricultural water base. Horizontal expansion of agriculture has begun with the rationale that one possible source for the needed water will be from improved management in irrigation (USAID 1995; Elarabawy 1998).

The basic problem with the Egyptian water system is the lack of data available regarding the movement of water through the system. The gravity-fed delivery system to most farms is in canals lying below the land surface. The same is true of many minor and major canals. The terminal level of the conveyance system is the mesqa (field canals fed by tertiary canals and used by farmers to irrigate their farmlands) system where the farmers manage the water. Since there are no control gates on the mesqas, the farmers are mutually concerned with management of the water among adjacent mesqas on the branch canals. This added dimension complicates the water use pattern among farmers as well as the organisational arrangements required (PSM 1993).

Under the current free cropping pattern policy (Elarabawy *et al*. 2000), water deliveries to each Irrigation Directorate are based on needs estimated from the expected cropping pattern (crop types and areas) and consumptive use values (crop water intake for evapotranspiration or crop basic water duties for plant growth, with no field or conveyance losses) based on formulae and experience. Other water demands (such as domestic, industrial, navigation, recreation, etc.) are programmed according to values based on previous experience (PSM 1995).

On the other hand, the inefficiency in water distribution policies extends beyond the agriculture sector since the same river and canals serve municipal and industrial users. Egypt lies at the end of the Nile and the reliability of the limited supplies for different competitive sectors takes on an international dimension.

The irrigation system is designed to provide an abundant supply of water to each farm as evidenced by the fact that farmers seldom find it necessary to irrigate at night. The conveyance system acts as a long reservoir where water is stored providing the farmer with some flexibility regarding the timing of irrigation since the water is temporarily held in canal/drainage storage (PSM 1993; USAID 1995).

On-farm and off-farm water management are inseparable. This is because farms are small, water is delivered below grade, there are no control gates on the mesqa channels, water tables are unusually high and a significant amount of crop use is directly from the water table (WT), pumping is permitted from drains, there is considerable irrigation surface run-off and reuse, and minor canals are essentially unregulated (USAID 1995).

Traditional methods of system operation and irrigation management have led to pronounced problems, gradually becoming built into the system. Adoption of water levels as the principal indicators for the water distribution process, without translating them into discharges at key locations, causes allocation restrictions and inequitable, unreliable delivery of irrigation water (PSM 1993; USAID 1995).

The OPDM work was completed in stages: model design (1993), model development (1993 through 1995), data collection (1993 through 1996), and model applications and modification (1994 through 1997). Although the exercise summarised here aimed at model correction and modification, it demonstrates the model capabilities and its potential applicability. Because the heuristic management approach (system management through experience) considers only a limited number of parameters and produces few indicators, the OPDM modules were used to produce detailed information based on heuristic approach inputs in order to illustrate the model functionality.

STUDY AREA

Located in the eastern delta region, Sharkia Irrigation Directorate was selected for the model application as it fulfils all of the requirements concerning diversity, variation and complexity, in addition to the data availability. The area confined within the region is approximately 210,000 ha. It includes many branching levels, various soil types, different cropping patterns, numerous water uses and all the categories of water sources (USAID 1995). The selected study area shares borders with four other directorates, with intensive interaction that should be regarded in water distribution plans.

Data required to run the OPDM model were collected from various sources by the PSM (Planning Studies and Models Project) staff and analysed and processed. The system layout was finalised to reflect the most consistent configuration. Figure 1 shows the location of the study area within the Nile delta. Figure 2 shows the study area system layout built in the OPDM (Helwa 1995).

DATA COLLECTION

Since the amount of data required to apply the OPDM for an entire irrigation directorate was huge, it was not feasible to procure the whole set of data through office work and personal contacts. Field data collection was therefore necessary to fill gaps and also to check the accuracy of the existing information (MPWWR 1995).

A field data collection programme was initiated in 1993. The following sections describe the various data collected for the OPDM model application to the Sharkia Irrigation Directorate.

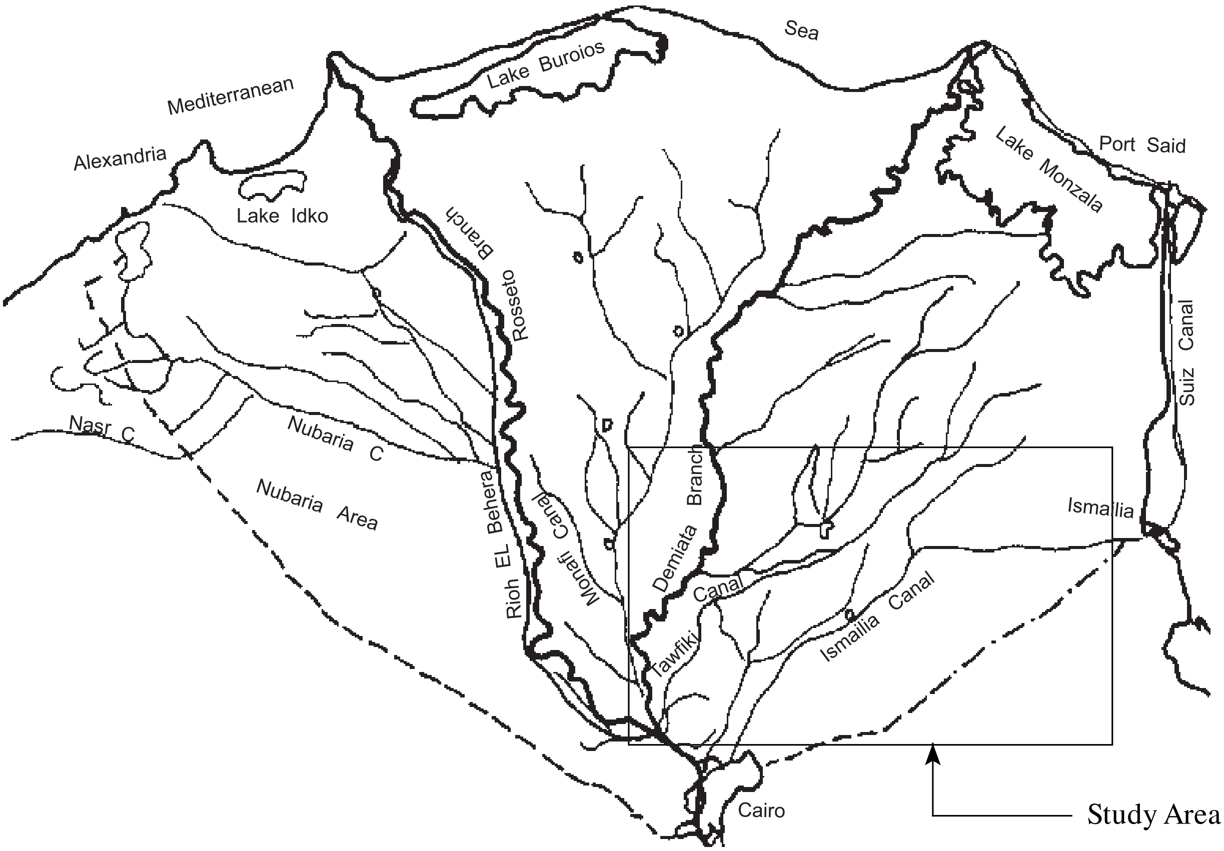

Figure 1 | Location of the Sharkia Directorate within the Nile Delta in Egypt.

Cropping pattern data

Raw data for the cropping pattern on the district level for five years (1990–1995) were obtained from the Ministry of Agriculture and Land Reclamation (Owais 1995). Summer and winter cropping patterns for the year 1995/1996 were also collected on the village level from the Zagazig Agriculture office.

Soil data

Raw soil data have been collected for the Bahr Mashtoul pilot area as well as the entire Sharkia Directorate. The soil data necessary to run the OPDM were obtained in the form of 1:100,000 maps, and tables of soil properties. Soil types were located on the different districts of the Sharkia, and converted into OPDM format based on command areas (areas with well defined input and output controls, relatively homogeneous properties, that can be considered as units during model simulations) included in the Sharkia system layout (Owais 1995).

System configuration and layout

In order to model a system, it is necessary to delineate the system boundaries and determine its dimensions. The general arrangement of the Bahr Mashtoul Area as well as the Sharkia Directorate were obtained from maps and schematics. Survey maps required for the Sharkia Directorate were obtained from the Egyptian Survey Authority. A GIS (geographic information system) database was constructed. Various other surveys were conducted resulting in 1:25,000 maps showing the locations of agricultural districts, crops and control structures.

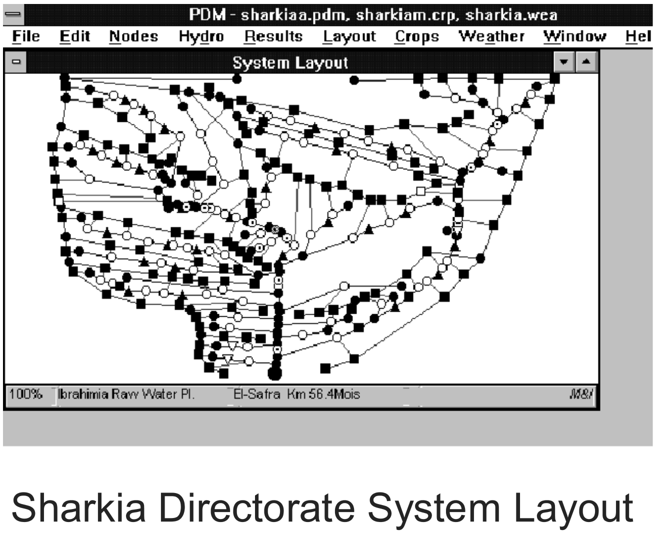

Figure 2 | OPDM system layout built for the Sharkia area.

The GPS (global positioning system) technique was used to identify the unknown elevations of some points by referencing them to existing triangulation points.

Weather data

To calculate the agricultural water demands weather data must be fed into the model for calculating potential evapotranspiration and determining agricultural water requirements. Weather data were obtained from the PSM weather station installed in the Bahr Mashtoul pilot area. Daily weather data were collected at the weather station location in the study area and processed to obtain actual daily weather parameters (MPWWR 1995). Weather data collected by the DRI (Drainage Research Institute) hydrometeorological station were used to verify the collected data and to establish long-term trends.

Agronomic data

Since agriculture consumes the bulk (75–85%) of water requirements (Elarabawy *et al*. 1998), any successful trial for modelling a system should include an accurate determination of the crop water requirements. Calculating the crop water needs depends on three main inputs. These are the cropping pattern, the water duty for each crop and the losses. The cropping pattern for the Sharkia Directorate was obtained from the agricultural office according to the MALR (Ministry of Agriculture and Land Reclamation) list for the years 1987–1996 for both summer and winter seasons. Crop staggers (different planting dates adopted at various farms to suit their crop rotation, fallow conditions or marketing constraints) were determined from field-experienced local personnel. Each crop was assumed to have five different growing stages (establishment, vegetative, flowering, yield formation, ripening) according to the FAO standards. Crops were then categorised to summer, winter, Nili and perennial crops. Water consumption values were obtained from the Water Distribution Institute of the WRC (Water Research Centre) and from the Irrigation Sector (OPDM 1997).

Operational data

Comparing actual operational values with those calculated by the mathematical models is the approach used during the field verification activities. The total water requirements of the main canals within the Sharkia Directorate were collected from the Sharkia personnel and the irrigation sector and were compared with those predicted by the OPDM. Winter and summer irrigation water rotation systems were obtained from the Sharkia Directorate and fed into the OPDM model. In order to get up-to-date water levels and discharges, seven mobile MSM (Main System Management) gauging stations were installed at the main locations of Bahr Mashtoul and its main branches (MPWWR 1995). Data from fixed MSM telemetry stations (Elarabawy *et al*. 2000) throughout the Sharkia region were obtained, categorised and used for model application.

Channel measurements and calibration

An intensive programme was set to field calibrate the main sites within the Sharkia Directorate. At least three readings were taken for each location in which water levels, discharges and gate openings were recorded at various levels of flow. Regression analysis was used to establish a reliable rating curve from which discharge could be determined based on water level and gate setting. Calibration coefficients were determined and used in the hydraulic models, STEADY and CANALS (MPWWR 1992). Channel volumetric capacities and flow rates were calculated and entered into the distribution models (Command Area Model, Water Management Model, Water Course Area Model and Command Area Model) (MPWWR 1992). Summary tables for flow characteristics were then prepared. Rating curves for major hydraulic structures of the Sharkia Directorate were prepared. Three different sets of readings were required for each structure corresponding to each flow case: free, submerged and constrained flow conditions (MPWWR 1995).

MODEL DESCRIPTION

The use of planning distribution in water management was conceived in Egypt in the 1970s. Most of the first developments were numerical models based on optimisation techniques. The OPDM represents a new concept based on simulation that enables the planner to study numerous scenarios and planning alternatives with their immediate as well as long-term implications. The model consists of a large number of small routines tackling various aspects of water distribution, integrated together to produce the overall impact on the system (OPDM 1997).

The model contains three main modules. The configuration module includes the geometric and hydraulic calculations. The crop module includes crop phenology (basic crop characteristics such as root depth, crop coefficients, threshold for salinity and water shortage, and yield decline rate), patterns (areas or percentage of the net command area planted with each crop) and staggers (particular dates and areas for which a given crop type is planted in a Command Area, to simulate the planting of a given crop type over a period of time). The weather module includes the daily and long-term basic meteorological data and the synthetic agronomic trend building facility (long-term monthly means and standard deviations of eight weather parameters are used to generate daily values according to statistical distributions, and to estimate daily potential evapotranspiration (ETp) if no other daily weather data exist). The modules are combined to estimate the various water demands. The local demands are collected additively to predict the regional demands, which are routed to the source node. The cumulative demands and available supply hydrographs are then compared to judge the surplus or deficit. Water and salt balances are also examined at root zone, crop, command area, nodes, reaches and branches levels (OPDM 1997).

The root zone is delineated according to crop type and root depth (for various development stages). These values define the extent of the root zone for the different stages. They are used during calculations to determine the maximum available soil water according to the water holding capacity. Input from surface water (canal or drain supply), groundwater (wells or water table), and lateral inflow from adjacent areas are compared to outflows to crop water use, drainage, return flows to canals, deep percolation (DP) to groundwater (GW), and flows to adjacent soils. Crop yield reduction due to soil water salinity is determined according to a linear relationship between relative yield and salinity. An outset, or threshold, value gives the soil water salinity, in dS m^{-1}, at which crop yield reduction begins. Most crops are adversely affected by waterlogging, but one notable exception is rice. The percentage of the maximum available soil water at which crop yield will be reduced due to water deficit is used to determine the reduction due to insufficient water supply. Upflux is the contribution to crop water use by groundwater, created by the capillary rise from groundwater table water into the root zone. It ranges between 0.0 when the soil water is at the wilting point to nearly 100% when the water table coincides with the ground surface. Gross revenue is used as economic indicator, allowing the financial return from different policies to be compared. It is the summation of the farm-gate price (including crop residuals) of the crops produced during the simulation (Elarabawy *et al*. 2000).

The model represents the system as a network of nodes including system source node at the upstream end of the supply system, inflow nodes of bulk inflow of water to the supply and/or drainage systems at any location downstream of the system source, municipal and industrial nodes, supply and drain return flow nodes, terminus nodes (tail escape or end nodes), bifurcation nodes, reuse nodes, and command area nodes. The command area is the model calculation unit and should have uniform land elevation, latitude, longitude, aquifer characteristics and climatological conditions. It should be sufficiently confined so that its water input, output, inflow, return flows and seepage are readily countable. Control structures and quadratic canals are typical guides for selection of command areas. The latitude is used to calculate extraterrestrial solar radiation for calculation of ETp (maximum crop evapotranspiration, which is the crop water use under ideal growing conditions, i.e. unlimited supply).

A crop coefficient (Kc) and potential evapotranspiration from a reference crop (Etp) are used to determine values of actual Crop ET. Hargreaves, Jensen-Haise, Penman-Monteith equations or the Pan Evaporation Method are used. The model has many delivery modes, allocation criteria and inclusion options. Water volumes and salinities (in dS m^{-1}) are considered in the balance. Water flows from waterways to adjacent lower groundwater tables or vice versa are a loss or gain, respectively.

The model produces numerous outputs. Tables, curves, pie and bar graphs, file and printed reports, and volume balance reports are examples. The main parameters are (Tables 1, 2, 4, 6):

- the relative yield (the actual crop yield referenced to maximum crop yield) per crop, per command area, and for the whole simulation;
- water use expressed as actual and potential evapotranspiration;
- salinity profiles as curves of soil salinity versus time for each command area;
- planted area curve and table giving the physical area occupied by crops at each time step;
- command area (CA) inflow as the collective water inflow to a command area by canals, drains, rainfall, groundwater, soil moisture or the source;
- command area (CA) outflow to crop ET, deep percolation (DP) to groundwater and to drains, runoff, domestic and industrial uses or spills;
- system inflow sources and ratios;
- system outflow to various destinations;
- plant condition indicating the percentage surviving and the percentage died and the reason for deterioration that can be traced on a daily basis;
- crop yield factors indicating the percentage of nominal crop production and the deficit (if any) and the factors of reduction;
- the efficiency of the policy tested is assessed through management indices giving the amount of water actually delivered to the command area over that required to just meet the various demands;
- the supply versus demand curve at the system source that not only indicates the match between water supply and demand for each time increment but is also indicative of source and reach capacity fulfilment.

Other outputs include (Tables 3 and 5):

- water used at the system source node;
- surface water inflow to the system from adjacent system;
- groundwater abstraction during simulation;
- total water inflow to the system from various sources;
- water used for evapotranspiration;
- volume of water delivered to municipal and industrial nodes;
- return flow from municipal and industrial nodes;
- water discharges from the drainage system (outside the system);
- drainage overtopping caused by exceeding the drainage system capacity;
- outflow from canals at points beyond possible reuse;
- supply overtopping caused by exceeding the canal system capacity;
- increase of soil moisture content at the end of the season;
- total water outflow from the entire system;
- system water use efficiency (total water used/total water withdrawn);
- application efficiency (total water used/total water delivered);

- amount of drainage water reused with the command areas;
- volume of groundwater used to satisfy part of the command area requirements;
- water flows to groundwater table and drains through deep percolation.

MODEL APPLICATIONS

Test scenarios, employing different cases and conditions, were built to encompass a range of water distribution alternatives under a wide variety of conditions to verify model performance (Helwa 1995; Owais 1995). The three factors affecting crop growth and hence making crop production deviate from nominal (maximum yield per unit area per season) are salinity, water deficit and waterlogging (rice is an exception). The threshold to deficit depends on the growing stage (except perennials).

Initial runs

The model was tested with no groundwater inclusion, no drainage water reuse and no salinity effects on crop yield. Imposing a hydrograph at the source node (Bahr Ewais primary canal, from Nile Tawfiki Rayah) that contains a set of historical data allows the comparison between simulation results and actual information. The overall model performance was assessed through the numerical as well as qualitative comparison between the output results of the model and actual data. Various criteria and indicators were compared for both model results and the heuristic management approach as shown in Table 1. It is evident that the model performance has greatly enhanced water management and the errors and inefficiencies encountered by manual operation are avoided.

Unlike the old methods, the OPDM model logically distributes the deficit among all command areas, weighting the deficit and associating a reduction factor with each command area. Water use efficiency (water used/water diverted) has been increased, the soil water budget is inclusive and thus soil moisture is used as a supplementary source, higher crop yields were obtained due to the equity imposed in the water allocation. Management indices (volume of water delivered/volume of water actually required, on command area basis) show that equity has been nearly achieved. They range between 0.0 and 8.59 for the systematic approach, and 0.6 and 1.06 for the model. Plant conditions show that the proper allocation has led to a significant increase in crop survival. Comparison of the soil water and soil salinity curves generated shows that the salinity calculation was tackled consistently by the model (Fahim 1997).

Functionality test

For this test, one data file for the Sharkia Directorate was selected and used for several runs under various operational and managerial conditions to test the ability of the model to produce meaningful results. The model was applied for one year with the inclusion of all yield options (deficit, salinity and logging); setting delivery modes to automatic (unconstrained supply); consideration of the gain and loss in the reaches (the effect of losses (negative values) and gains (positive values) for each canal or drain reach); and prioritising system canal water supply over groundwater and drainage reuse.

Relative yield (actual/potential crop yields) tends to be maximal under these conditions as the model is allowed to take as much water as is needed from all unlimited resources. Some yield reduction, however, occurred due to local insufficient leaching (salts accumulation in the soil). Gross revenue (economic return of crop production) for this proposed policy was found to be US$ 580 million. Soil water content was almost 100% during the one-year simulation period. This is consistent with reality in that under relatively unlimited source capacity with automatic delivery mode, there should be no shortage exercised by the different users. The salinity profile was steady and conformity of both soil water and soil salinity curves was evident. Salinity was almost constant throughout the simulation interval; it goes up slightly during the high requirements period due to the additional salts brought into the soil by the irrigation water (Fahim 1997). Figure 3 shows the water duties and areas calculated by the OPDM for major crops.

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Table 1 | OPDM model results for initial runs, actual source node hydrograph with no groundwater or drainage reuse inclusion

Criteria	Traditional solution	OPDM model output	Remarks
Relative crop yield	Overall = 72% Range = 40–100%	Overall = 94% Range = 49–100%	Deficit is well distributed by the OPDM model
Crop water use	ETa = 1.58 billion m^3 ETp = 1.99 billion m^3	Eta = 1.84 billion m^3 Etp = 1.90 billion m^3	Water use efficiency is increased (ETa . ETp)
Soil salinity profile	No trend	Follows sensible trend	Performance indicator
Planted area curve	Max. 183,000 ha, not real	Max. 210,000 ha, real	Planted area is given
Command area inflow	100% of the system surface water supply	97% from supply and 3% from soil moisture/rainfall	Soil water budget is inclusive
Command area outflow	70% to ET, 24% to DP-drains, 2% WT-drains, 4% runoff	94% to ET, 1.8% to DP-drains, 4.2% runoff	Crop water use becomes almost optimal
System water inflow	100% from the source node surface water supply	97% from supply and 3% from soil moisture/rainfall	Soil water is used beside source supply
System water outflow	61% ET, 1% M & I, 21% drainspill, 5% supply spill, 11% drain overtopping	83% ET, 2% M & I, 16% drainspill	Water losses are kept to minimum by the OPDM
Plant condition	79% survived, 21% died	100% of the crops survived	Higher crop yield and better distribution equity
Crop yield factor	58% nominal, 42% deficit	73% nominal, 27% deficit	Optimum water utilisation
Management indices	Max. 8.59, Min. 0.0	Max. 1.06, Min. 0.6	Equity achieved
Supply curve (system source hydrograph)	Max. source supply value 12.0 million m^3	Max. source supply value 12.0 million m^3	Respect current reach capacity

Actual crop ET is equal to maximum crop ET because of the water availability for the agricultural sector. Area occupied by crops at each day is produced as model output; this information is essential for planners and directors for operational purposes. The model forecasts the rainfall based on the input long-term hydrometeorological data in addition to the ability to use actual or synthetic daily weather data, to calculate crop ET. The model accounts for actual or predicted rainfall by cutting the supply value at those days with the same amount of rain. This is illustrated in the source node supply and demand hydrograph shown in Figure 4 by the two abrupt decreases in the supply on 26 December and 23 January corresponding to the amount of rain received on the study area (Fahim 1997).

Testing and evaluation

A data set for the Sharkia region was fed into the model using a flow capacity at the source of 140 $m^3\ s^{-1}$ with the effect of seepage loss/gain (influent and effluent flows) for both the supply and the drainage reaches included. The results of both the model and the real system are summarised in Table 2 with comments. No upflux was taken into account. The behaviour of the traditional techniques compared with that of the model shows that the model performance has significantly improved the quality of the decision making (Fahim 1997).

Another run was made using a flow capacity of 140 $m^3\ s^{-1}$ for the source with automatic delivery mode

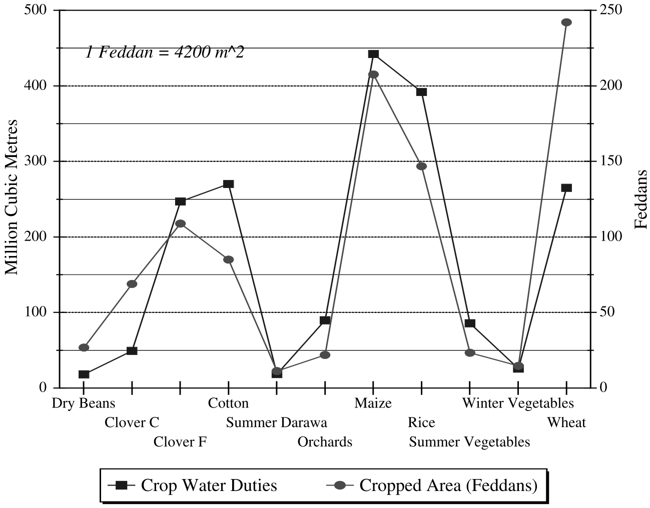

Figure 3 | Crop areas and water duties calculated by the OPDM for the Sharkia Directorate.

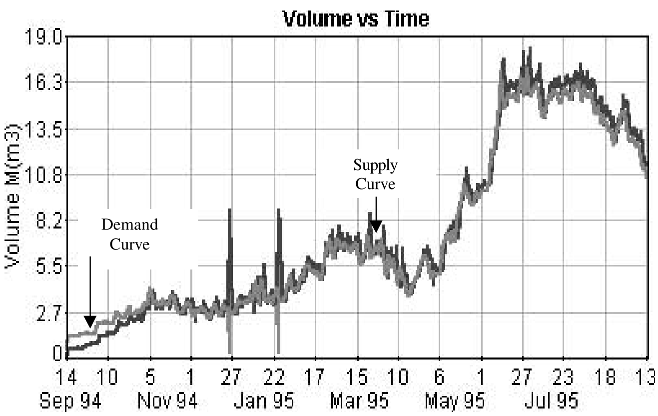

Figure 4 | Cumulative water supply versus demand hydrograph at the source node.

where the effect of seepage loss/gain for the reaches, salinity and logging yield reduction are not considered, i.e. water deficit is the main concern. Table 3 presents the model output for this case. The model role in water planning is illustrated by its good performance.

Model calibration

This was done for the Sharkia region by gradually adjusting the values assigned to the controlling parameters (within their physical bounds) to end up with the most appropriate values for the study case. After the adjustment of the calibration parameters, a model run was made to check the calibrated version performance. This run includes a flow capacity for the source node of 120 $m^3\ s^{-1}$ with automatic delivery mode; the model is allowed to supply as much water as is needed according to the cumulative requirements calculated; and neglecting the effect of reach seepage loss/gain and yield reduction caused by salinity and logging (Fahim 1997).

Results were generally satisfactory as shown in Table 4. The results show that water use is lower for the model (for all sources) while the requirements satisfied for both M & I (municipal and industrial water needs) and command areas are greater, indicating better planning. Soil salinity is better for the model results and represents the near reality status.

Two additional runs were conducted. All governing factors were fixed and different data files were adopted to test the model capability at this stage. The first file was prepared using the flow capacity for the source as 120 $m^3\ s^{-1}$ with automatic delivery mode for source, inflow and drainage reuse. Groundwater sources are considered and the effect of seepage loss/gain for the reaches neglected. A modified basic crop file in which the land preparation stage (pre-cultivation irrigation for a few weeks) for most crops except cotton, wheat, winter vegetables and potatoes was dropped reflects the true situation indicated by the field surveys. Results are shown in Table 5.

The second run was designed to overcome the problem of the resulting deficit that always appeared in model runs at some nodes and reaches. This was attributed to limited reach flow capacity. A run was made by increasing the local reach capacity and using the flow capacity for the source as 120 $m^3\ s^{-1}$ as above with the modified crop file. The maximum flow for some reaches, i.e. El Kasabi canal tail reach, was considerably increased. Model output results for both files were satisfactory (Fahim 1997).

Sensitivity analysis

This was accomplished by changing the values assigned to the main variables and observing the model behaviour to ensure that the model responded correctly, based on descriptive as well as mathematical indicators. Three model runs were performed with the inclusion of drainage

Table 2 | Sample model performance evaluation run with 140 $m^3 s^{-1}$ source capacity

Criteria	Systematic approach	The model	Remarks
Relative crop yield	Overall = 88% deficit Range = 52% deficit–99% Logging	Overall = 94% salinity Range = 55–99%	Deficit is distributed by the model and the effect of salinity on the crop yield reduction is evaluated
Crop water use	ETa = 1.85 billion m^3 ETm = 1.99 billion m^3	ETa = 1.86 billion m^3 ETm = 1.90 billion m^3	Crop water use efficiency is increased and the land preparation is treated as establishment period
Soil salinity profile	Some CAs have salinities that go up to 65 dS m^{-1} and then go down to zero. There is no compatibility with the soil water curve	Follows sensible trend Correct method for salinity calculation, Max. value 5.3 dS m^{-1}	The salinity and water curves for all command areas can be compared
Planted area curve	Max. 183,000 ha, not realistic planted area	Max. 210,000 ha, Realistic planted area	More accurate values
Command area inflow	97% from supply system 3% from GW wells	97% from supply system 1% from soil moisture 2% from GW wells	Soil water budget is inclusive
Command area outflow	70% to ET 24% DP to drains 2% DP to WT	82% to ET 14% DP to drains 4% DP to WT	Crop water use becomes almost optimum
System water inflow	83% from source 15% from sup. inflow 2% from GW wells	89% from source 10% from sup. inflow 2% from GW wells	Soil water and source surface water supply are used conjunctively
System water outflow	53% to ET 1% to M & I 21% drain spill 9% drain overtopping 5% supply overtopping 11% seepage losses	63% to ET 2% to M & I 14% drain spill 21% seepage losses	Water losses are kept to minimum. Also, the seepage calculation is accurate, highlighting policy weaknesses
Plant condition	98% survived 2% died	100% survived	Higher crop yield and more equity
Crop yield factor	82% nominal 17% deficit 1% waterlogging	75% nominal 10% deficit 13% salinity 2% waterlogging	Optimum water utilisation and the effect of salinity on the crop yield reduction was not accounted for correctly in the conventional approach
Management indices	Max. value = 12.3 Min. value < 0.20	Max. value = 1.44 Min. value = 0.75	Equity achieved and the graph results show low range of diversity

reuse (reusing drain water in irrigation by direct pumping or mixing with fresh water), seepage (water movement into or from system soils by differential head), and canal and drain inflows (water added to the system budget when a canal or a drain flows to a waterway downstream of the source), allowing the upper limit of the groundwater abstraction, represented by the maximum yield of shallow aquifer, to be 300×10^3, 600×10^3 and 900×10^3 m^3 per

Table 3 | Model testing and evaluation run without reach gain/loss, including only water deficit for yield options

Assessment criteria	Systematic approach	OPDM model
System source cumulative flow	2,430 million m^3	2,111 million m^3
Supply inflow cumulative water	429.2 million m^3	227.40 million m^3
Groundwater contribution	55.25 million m^3	46.41 million m^3
Total inflow volume	2,945 million m^3	2,426 million m^3
Crop evapotranspiration	1,823 million m^3	1,894 million m^3
Water use by M & I nodes	33.67 million m^3	51.090 million m^3
Water for M & I spills	6.765 million m^3	6.765 million m^3
Drain system water spills	701.9 million m^3	457.90 million m^3
Drain system overtopping	295.9 million m^3	0 million m^3
Supply system spills	0 million m^3	0 million m^3
Supply system overtopping	159.2 million m^3	5.653 million m^3
Soil moisture increase (– ve = decrease)	– 74.91 million m^3	– 1.047 million m^3
Total water outflow	3,019 million m^3	2,415 million m^3
Overall system efficiency	Not available	80.2%
Overall application efficiency	Not available	80.9%
Drainage reuse onto Cas	0 million m^3	0 million m^3
Groundwater flows into CAs	59.25 million m^3	46.41 million m^3
Deep percolation from CAs	749.1 million m^3	429.0 million m^3

day in the study region (Fahim 1997). Table 6 shows sample model output.

Results show that the overall yield changed significantly when the available groundwater was increased and consequently the plants' condition and crop yield factor were changed. The system inflow includes 3%, 5% and 7% in one run and 2%, 4% and 6% in another run, as groundwater contribution. A saving in surface water was noticed with slight enhancement of the deep percolation. In the light of these results, it is shown that the model can deal with any change in the system inflow positively.

The model has the capability to ignore or to consider any or all of the factors that affect crop yield; to verify this feature three different scenarios were examined. For each scenario, the model was found to consider the effect of each factor on the yield. To study the effects of the water supply salinity on the crop production three different runs have been executed with different water supply salinities. The surface water salinity at the source varies from 0.25 dS m^{-1} to 0.50 dS m^{-1}. The effect of other factors such as groundwater, drainage reuse, seepage and inflow were neutralised.

Table 4 | OPDM model calibration: sample run

Compared criteria	Systematic approach	OPDM model	Remarks
Relative crop yield	Overall = 85% (deficit) Range = 53–100%	Overall = 98% (deficit) Range = 71–100%	Deficit is well distributed among CAs by the OPDM
Crop water use	ETa = 1.82 billion m^3 ETp = 1.99 billion m^3	ETa = 1.89 billion m^3 ETp = 1.90 billion m^3	Crop water use efficiency is increased and the land preparation is treated as a establishment period
Soil salinity profile	Soil salinity curves had dropped from 65 dS m^{-1} down to negligible values. Compatibility with the soil water curve is lacking	Follows sensible trend. Reliable salinity calculation. Max. value of 10.7 dS m^{-1}, The max. value was 3.5 dS m^{-1} for most CAs	Salinity and water curves for command areas can be compared with evident correlation, allowing both water and salt balances
Planted area curve	Max. 183,000 ha, not real planted area	Max. 210,000 ha, real planted area	Realistic values
Command area inflow	98% from supply system 2% from GW wells	98% from supply system 2% from GW wells	Soil water budget is inclusive and optimal
Command area outflow	70% to crop ET 28% DP to drains 2% WT to drains	82% to crop ET 14% DP to drains 4% DP to WT	Crop water use becomes almost optimum
System water inflow	82% from source 16% from supply inflow 2% from GW wells	88% from source 10% from supply inflow 2% from GW wells	Less water inflow is used, surface water supply at the source is fully utilised
System water outflow	61% to crop ET 1% to M & I 24% drain spill 9% drain overtopping 5% supply overtopping	80% to crop ET 2% to M & I 18% drain spill	Water losses are kept to minimum, more crop and M & I requirements are satisfied
Plant condition	97% survived 3% died	100% survived	Higher crop yield and equity for the model
Crop yield factor	81% nominal 19% deficit	93% nominal 7% deficit	Higher crop productivity
Management indices	Max. value = 15.4 Min. value $<$ 0.20	Max. value = 1.44 Min. value = 1.00	Equity achieved and the graph results show oscillation around unity

The model output shows that the model is very sensitive to any change in the water salinity, in line with the effect of soil salinity on crop production. The model results for various ET methods, yield factors, delivery modes, and combinations of controlling parameters were consistent. Table 7 shows a typical model output and summary of results.

OPDM ROLE IN WATER MANAGEMENT

The supply and demand hydrographs

One of the core elements of the OPDM output results is the supply versus demand hydrograph, as depicted in Figure 4. This chart is the core of the OPDM model

Table 5 | OPDM model verification sample results, with 120 $m^3 s^{-1}$ source flow capacity and modified crop file

Criteria	Systematic approach	OPDM model output
System source cumulative flow	2,136 million m^3	2,104 million m^3
Supply inflow cumulative water	410.9 million m^3	162 million m^3
Groundwater contribution	51.78 million m^3	39.590 million m^3
Total inflow volume	2,625 million m^3	2,347 million m^3
Crop evapotranspiration	1,711 million m^3	1,855 million m^3
Water use by M & I nodes	33.64 million m^3	51.090 million m^3
Water for M & I spills	6.765 million m^3	6.765 million m^3
Drain system water spills	658.8 million m^3	420.600 million m^3
Drain system overtopping	201.9 million m^3	0 million m^3
Supply system spills	0 million m^3	0 million m^3
Supply system overtopping	172.5 million m^3	5.653 million m^3
Soil moisture increase (– ve = depletion)	Not available	0 million m^3
Total water outflow	2,784 million m^3	2,339 million m^3
Overall system efficiency	Not available	81.2%
Overall application efficiency	Not available	81.3%
Drainage reuse onto CAs	0 million m^3	0 million m^3
Groundwater flows into CAs	51.78 million m^3	39.59 million m^3
Deep percolation from CAs	609.3 million m^3	410.2 million m^3

functionality as it allows the user to compare the calculated accumulated demands at the source node with the total supply available, to check the possibility of satisfying the demands in full, and to determine the periods in which deficit or surplus will be experienced and thus make the reserve plans or actions necessary to cope with, or avoid, them (MPWWR 1992).

Command area water balance

This gives the water used from different sources (surface water supply, groundwater, drainage reuse, water gain through canal or drain inflow, soil moisture) and the water consumed by various components (crop evapotranspiration, deep percolation to drains, seepage to water table, surface runoff, municipal and industrial) and is a key element in the assessment of the soil water budget and therefore the water application efficiency (MPWWR 1992).

Salinity profiles

These express the water and soil salinity changes within the root zone for each command area along the simulation

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Table 6 | Sample OPDM model run of sensitivity analysis

Criteria	G.W=300,000 m^3/day	G.W=600,000 m^3/day	G.W=900,000 m^3/day
Relative crop yield	Overall = 84% (salinity) Min.–Max. = 54–99%	Overall = 86% (salinity) Min.–Max. = 54–99%	Overall = 87% (salinity) Min.–Max. = 54–99%
Crop water use	ETa = 1.75 billion m^3 ETp = 1.90 billion m^3	ETa = 1.78 billion m^3 ETp = 1.90 billion m^3	ETa = 1.79 billion m^3 ETp = 1.90 billion m^3
Command area inflow	92% of the supply, 3% of GW wells, 5% of soil moisture	90% from supply and 5% of GW wells, 5% of soil moisture	88% of the supply, 7% of GW wells, 4% of soil moisture
Command area outflow	82% to ET, 11% to DP-drains, 2% WT-drains, 5% runoff	81% to ET, 12% to DP-drains, 3% WT-drains, 4% runoff	80% to ET, 12% to DP-drains, 3% WT-drains, 4% runoff
System water inflow	80% from the source, 14% from supply 2% of wells, 4% soil moisture	78% from the source, 14% from supply 4% of wells, 4% soil moisture	77% from the source, 14% from supply 6% of wells, 3% soil moisture
System water outflow	61% ET, 2% M & I, 22% seepage, 15% drain spill,	61% ET, 2% M & I, 22% seepage, 15% drain spill,	61% ET, 2% M & I, 22% seepage, 15% drain spill
Plant condition	95% survived, 5% died	96% survived, 4% died	97% survived, 3% died
Crop yield factor	61% nominal, 17% deficit, 1% logging, 21% salinity	62% nominal, 16% deficit, 1% logging, 21% salinity	63% nominal, 15% deficit, 1% logging, 21% salinity
Management indices	Max. = 1.5, Min. = 0.75	Max. = 1.5, Min. = 0.75	Max. = 1.5, Min. = 0.75
Supply curve (source hydrograph)	Max. source surface water supply value 12 million m^3	Max. source surface water supply value 12 million m^3	Max. source surface water supply value 12 million m^3

period. The soil salinity development is an important factor for soil resources conservation and the setting of cropping patterns as well as sorting different policies and plans according to soil deterioration and crop yields reduction expected.

Water use

This parameter is used to determine system efficiency by comparing actual crop consumption with the maximum consumptive use. For a system with unlimited diversity and interacting elements, OPDM can trace the various aspects of water use, perform allocation, and produce water use information.

The water losses throughout the system and therefore the water use efficiency can be obtained by *system inflow and outflow balance* components. The percentages of water from each supply source, of water used by crops, municipal and industrial nodes, drainage, supply spills or overtopping are provided by the OPDM (MPWWR 1992).

Management indices

This is an expressive parameter that shows equity and efficiency of water use. The OPDM gives the delivered/required volume of water for each command area, for each canal command and for each crop (Figure 5) which is an excellent indicator on how optimal the water use is (MPWWR 1992).

Area by yield factors

This is an output that presents the crop yield status. The percentage of the crops that have nominal (maximum)

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Table 7 | Model results for water allocation with automatic delivery mode (output screen)

Operational and Planning Distribution Model
Simulation Interval: 16-Sep-94 to 16-Sep-95
Overall Crop Yield: 100% (no yield reduction)
I. Relative Yield by Command Area and Stagger
1. C. Mowais 1 L.: 99% Logging

Crop	Stagger 1	Stagger 2	Stagger 3	Averages
Beans, Dry	100% Nominal	– n/a	– n/a	100% Nominal
Clover C	100% Nominal	– n/a	– n/a	100% Nominal
Clover F	100% Nominal	– n/a	– n/a	100% Nominal
Cotton	100% Nominal	100% Nominal	– n/a	100% Nominal
Darawa S	100% Nominal	– n/a	– n/a	100% Nominal
Gardens	99% Logging	– n/a	– n/a	99% Logging
Maize S	100% Nominal	100% Nominal	100% Nominal	100% Nominal

Operational and Planning Distribution Model
Simulation Interval: 16-Sep-94 to 16-Sep-95

I. Overall Water Balance		
Total Inflow	2,675,000,000 m^3	
Total Outflow	2,649,000,000 m^3	
Total Net Inflow	26,160,000 m^3	
II. Cumulative Volumes of Water		
1. System Inflow		
System Source	2,416,000,000 m^3	90.3%
Supply Inflow Nodes	174,100,000 m^3	6.5%
Drains Inflow Nodes	0 m^3	0.0%
Groundwater	44,080,000 m^3	1.6%
Groundwater (hydrograph)	0 m^3	0.0%
Seepage Gain	9,487,000 m^3	0.4%
Rain	16,810,000 m^3	0.6%
Soil Moisture Deficit	1,600,000 m^3	0.1%
Reach Storage Deficit	12,960,000 m^3	0.5%
2. System Outflow		
Evapotranspiration	1,854,000,000 m^3	70.0%
M & I Nodes	51,090,000 m^3	1.9%
M & I Spills	6,765,000 m^3	0.3%
Seepage Loss	0 m^3	0.0%
Drain System Spills	731,100,000 m^3	27.6%
Drain System OverTop	0 m^3	0.0%
Supply System Spills	0 m^3	0.0%
Supply System OverTop	5,653,000 m^3	0.2%
Command Area Spills	0 m^3	0.0%
Water Table Spills	0 m^3	0.0%
System Efficiency		71.2%
3. Command Area Inflow		
Total CA Inflow	2,609,000,000 m^3	
Canals	2,547,000,000 m^3	97.6%
Drain Reuse	0 m^3	0.0%
Groundwater	44,080,000 m^3	1.7%
Canals (hydrograph)	0 m^3	0.0%
Drain Reuse (hydrograph)	0 m^3	0.0%
Groundwater (hydrograph)	0 m^3	0.0%
Shallow GW Upflux	0 m^3	0.0%
Effective Rainfall	16,810,000 m^3	0.6%
Soil Moisture Deficit	1,600,000 m^3	0.1%
4. Command Area Outflow		
Total CA Outflow	2,593,000,000 m^3	
Evapotranspiration	1,854,000,000 m^3	71.5%
Total Deep Percolation	503,700,000 m^3	19.4%
DP To Drains	402,900,000 m^3	80.0%
DP To WT	100,700,000 m^3	20.0%
DP To Sink (no drain)	0 m^3	0.0%
Total Surface Runoff	234,800,000 m^3	9.1%
SR To Drains	234,800,000 m^3	100.0%
SR To Sink (no drain)	0 m^3	0.0%
Application Efficiency		71.1%

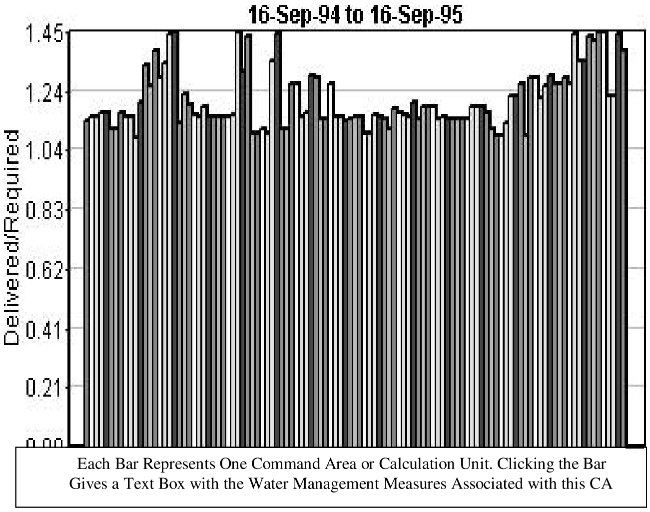

Figure 5 | Ratio of the volume of water actually delivered to the volume required for all uses, per command area.

yield is obtained in addition to the percentage that suffer yield reduction with the reason for the cut. This is useful in comparing different policies and also to make trial adjustments of the scenarios prescribed until the maximum benefits are reached and the minimum loss in crop production is obtained (MPWWR 1992).

System inflow and outflow pie charts

These give the percentage of the water use for each sector of demand. This allows the user to set various priorities for different sectors and observe the impact of each alternative in a few minutes. Knowing the water consumed by every sector of the demand side is an important indicator in the water-planning course. The OPDM model is also capable of producing information about system inflow, command area inflow and command area outflow. This information makes the user aware of every detail of the system behaviour (contribution of water supply from different sources and diversions in applied use terms) and allows study of the impact of a large number of policies and options.

Relative yield by command area and by crop type

This is used to determine the areas and crops that suffer subnormal or above normal conditions and, hence, allow the user to change cropping pattern or operational parameters to enhance the water allocation and thus the productivity throughout the entire system (MPWWR 1992).

The *planted area curve* gives information on the area cultivated on a daily basis and can only be obtained by a mathematical model such as the OPDM. The planted area information is necessary to combine with other management criteria in order to gain important decision support information (MPWWR 1992). Allocation of irrigation water can therefore be more realistic.

Plant condition and crop yield factor

These are two important criteria that are usually sought by management personnel for their policy success evaluation. The OPDM traces crop development stage by stage to determine the percentage of the crop that survives to the end of the season, the percentage of the cropping pattern that will have nominal yield, and the percentage that will suffer yield reduction and the reason for the reduction. This is not only vital for comparing different policies but also for introducing necessary measures for maximum outputs as well.

Relative crop yield

This is calculated for the entire area under the specified conditions. Since numerous factors affect crop production and the process of estimating the expected crop yield is complex and indirect, the use of a model is of clear advantage.

Other information that is considered vital is the volume of water required at each control structure for each day of the simulation period. Figure 6 provides the volume of water required versus time. This volume will encompass all of the basic water demands plus the conveyance as well as application losses; lag time is incorporated. These volumetric requirements at all control nodes are determined by the OPDM. Coupled with existing rating curves for the individual structures, these volumes can be transformed into stage hydrographs and then, using either

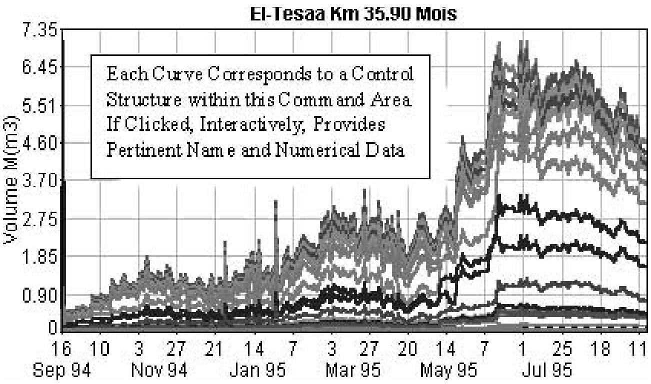

Figure 6 | Demand flow hydrographs for control regulators and diversion weirs within a command area.

simple hydraulic calculations or a steady/unsteady hydraulic routing model, into gate settings and head over weirs. Thus operational parameters can be directly or indirectly obtained (MPWWR 1992).

One of the major criticisms of the model is its huge data requirements. The scope, intervals and precision of the current data collection programmes will need modernisation before the model can be fully promoted. This will, however, lead to more understanding of the system behaviour, better evaluation of the different processes and improvements in water distribution practices. A summary of some of the OPDM model key results of different but comparable runs is shown in Tables 8 and 9 in order to help build the perception of model functionality. Comparing the outputs demonstrates that the model is responding appropriately and can be a reliable tool.

DISCUSSION

Comparison of simulated and actual data for the complex irrigation and drainage scheme of the Sharkia region demonstrates that the OPDM is a powerful planning tool that can be used as the core of the Egyptian decision making process as indicated in Figure 7. The model not only allows testing of various policies and alternative plans, but also provides technical information and economic measures that were impossible to quantify through the heuristic methods which depend mainly on past experience (MPWWR 1996).

By keeping the automatic option of the delivery modes for all sources and applying some limitation on the system (restricted capacity for some reaches and nodes), the relative yield has not been affected and the gross revenue remains unchanged; most of the water has been taken from the source, i.e. it was sufficient. If not, the model determines the location of bottlenecks. The reason for inadequate supply can be thus eliminated or alternatively, the demand pattern can be modified.

Imposing some constraints on the supply by specifying a supply hydrograph at the source node representing the actual flow rates recorded at the Sharkia Directorate entrance for the same simulation period, some yield reduction appears (overall crop yield was 74%) with a gross revenue of US$ 416 million. Crop actual ET is 86% of the maximum ET on one hand; on the other hand, 18% of the crops died. However, when the geometric restrictions were removed, crop yield increased to 98% with 100% crop survival (Fahim 1997). Constraints on water allocation can thus be identified and dealt with.

The slight yield decrease (2%) was mainly due to salinity that builds up in the soil during the last third of the simulation period. This is shown in Figures 8 and 9. Management indices are oscillating around unity meaning optimum water distribution as depicted in Figure 5. System efficiency as a whole was 81.2%. Leaching fraction was set to 20% and the historical hydrograph was kept as supply at the source. This implies that more water will be used for salt leaching out of the soil (Fahim 1997). Various combinations can be tested and best policies can therefore be achieved.

Using automatic delivery option at the source or imposing a hydrograph at the source produced some salinity in the soil preventing the nominal crop yield. The first case is restricted by the physical system capacity which leads to a constrained demand pattern while the latter case is limited by the fixed water supply available at the source node. Supply versus demand hydrographs for both cases had some deficit. The closure period appears as

Table 8 | OPDM testing and evaluation runs under various managerial circumstances

Criteria	With salinity effects	No drainage reuse	With ground water supply
Relative crop yield	Overall = 92% salinity Range = 72–96%	Overall = 96% salinity Range = 89–99%	Overall = 86% salinity Range = 54–99%
Crop water use	ETa = 1.87 billion m^3 ETp = 1.90 billion m^3	ETa = 1.90 billion m^3 ETp = 1.90 billion m^3	ETa = 1.78 billion m^3 ETp = 1.90 billion m^3
Soil salinity profile	Max 8.5, 4.0 dS m^{-1} on average	Follows sensible trend, conforming with soil water content	Very high at few CAs (i.e. 65 dS m^{-1} for Bahr El Hagr), moderate for most CAs
Planted area curve	Max. 210,000 ha	Max. 210,000 ha	Max. 210,000 ha
Command area inflow	94% from supply and 5% of wells, 1% soil moisture	80% from supply and 20% from GW wells	90% from supply and 5% from GW wells, 5% from soil moisture
Command area outflow	93% to ET, 3% to DP-drains, 4% as runoff	73% to ET, 17% to DP-drains, 4% WT drains, 4% as runoff	81% to ET, 12% to DP-drains, 3% to DP to WT, 4% as runoff
System water inflow	94% from supply and 5% of wells, 1% soil moisture	80% from supply and 20% of wells	78% surface supply and 4% wells, 4% soil moisture, 14% inflow
System water outflow	82% ET, 2% M & I, 16% drain spill	73% ET, 2% M & I, 25% drain spill	61% ET, 2% M & I, 16% drain spill, 22% seepage
Plant condition	100% survived	100% survived	56% survived, 4% died
Crop yield factors	49% nominal, 18% deficit, 31% salinity, 2% logging	63% nominal, 36% salinity, 2% logging	62% nominal, 16% deficit, 21% salinity, 1% logging
Management indices	Max. 1.32, Min. 0.8	Max. 1.5, Min. 1.2	Max. 1.5, Min. 0.75
Supply curve (source node hydrograph)	Max. source supply value 12 million m^3	Max. Source Supply Value 12 million m^3	Max. source supply value 12 million m^3

the period of no supply to the system. Geometric and hydraulic constraints can thereby be determined and effectively omitted.

The OPDM is working on daily basis, which means that the model works under the continuous flow principle. This leads to the appearance of cumulative demands at the source for the closure period which coincides with an off-rotation period preceded and succeeded by two general irrigation incidents when water is plentiful for irrigating the existing agriculture. Under these conditions, 87% of the total demand was served by surface water at the source node, 4% is groundwater contribution, and 10% inflow. This demonstrates the model performance as it correctly reflects the changes made within the system.

Using the model capability to allocate water according to its automatic delivery mode, the yield rose to 100% as indicated in Table 7, and the gross revenue was increased to approximately US$ 588 million. All M & I demand was satisfied in full, overall system efficiency was 71.1% due to the increase in drainage water that is spilled with no reuse. Soil water was optimal during the whole simulation period with moderate soil salinity. Various water plans can be

Table 9 | Comparison of water distribution scenarios with the calibrated OPDM for the Sharkia

Criteria	Max. source node capacity=120 $m^3\ s^{-1}$	No reach gain/loss from water seepage	No upflux contribution to crop water
System source intake	2,055 million m^3	2,111 million m^3	2,592 million m^3
Supply inflow DS of the source	227.4 million m^3	227.400 million m^3	278.3 million m^3
Groundwater abstraction	46.46 million m^3	46.41 million m^3	50.24 million m^3
Total inflow (canal + drain inflows)	2,376 million m^3	2,426 million m^3	2,991 million m^3
Crop evapotranspiration	1,887 million m^3	1,894 million m^3	1,860 million m^3
Water use by M & I nodes	51.090 million m^3	51.090 million m^3	51.090 million m^3
Water spills from M & I (return flows)	6.765 million m^3	6.765 million m^3	6.765 million m^3
Drainage system spills	420 million m^3	457.900 million m^3	422.800 million m^3
Drainage system overtopping	0 million m^3	0 million m^3	0 million m^3
Supply system spills (tail reaches)	0 million m^3	0 million m^3	0 million m^3
Supply system overtopping	5.653 million m^3	5.653 million m^3	5.653 million m^3
Soil moisture increase (– ve = decrease)	– 4.839 million m^3	– 1.047 million m^3	– 28.52 million m^3
Total system water outflow	2,371 million m^3	2,415 million m^3	2,987 million m^3
Overall system efficiency	81.6%	80.2%	63.9%
Field application efficiency	81.9%	80.9%	81.8%
Drainage reuse onto CAs	0 million m^3	0 million m^3	0 million m^3
Groundwater pumping into CAs	46.46 million m^3	46.41 million m^3	50.24 million m^3
Deep percolation from CAs.	400.9 million m^3	429.0 million m^3	397.1 million m^3

formulated based on expected demands and foreseen supply levels.

SUMMARY AND CONCLUSIONS

Water resources management is a complex task. Pertaining elements are interactive and difficult to quantify. The challenge is acute for Egypt. A methodology that integrates all the micro processes involved and determines the macro behaviour of the system under a wide variety of conditions is urgently needed. The OPDM represents a reliable approach. Model simulations for the Sharkia Irrigation Directorate were selected to reflect the OPDM potential model use and future aspects of water distribution improvements within the Egyptian Irrigation System.

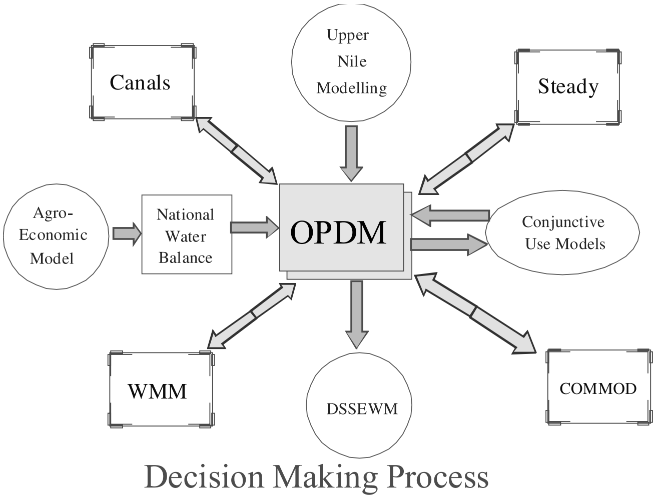

Figure 7 | The OPDM interrelationship with other models of the water management system.

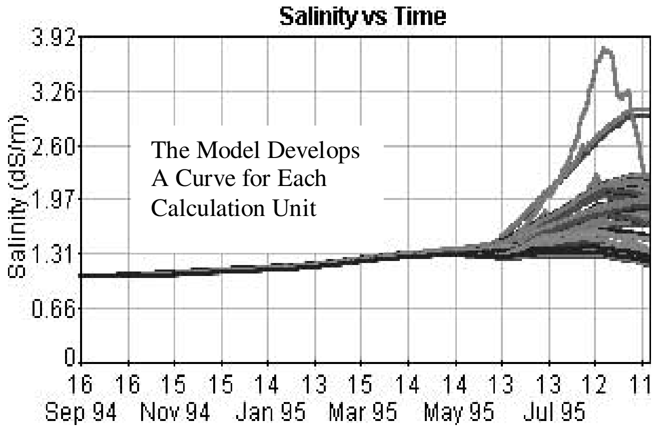

Figure 9 | Soil salinity profiles for various command areas during the simulation period.

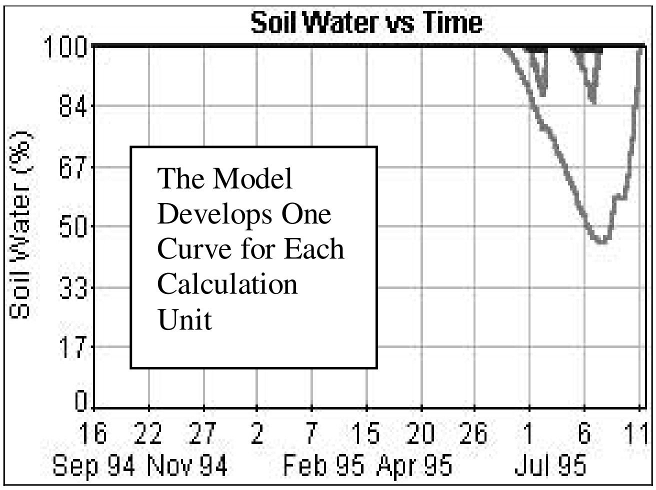

Figure 8 | Soil water content for a command area, expressed in percentage throughout the simulation period.

A system-wide adaptation of the model can significantly help in the decision-making and water resources planning and management in Egypt. It is a high-level simulation model that can cope with all degrees of system interactions and accommodate all the complex features of the system to be modelled. It manipulates system irregularities and specific characteristics in a way that produces the most appropriate results.

The OPDM model gives relative yield on all system levels (per crop, per command area, per canal, etc.), crop progress, gross revenues, crop water use, M & I demands, soil water and salt, aquifer extraction, crop yield factors, crop survival, ET by crop and by command area, management indices, cumulative volumes, crop progress, node data, reach data, branch data, and volume balance reports. The operational performance at all levels of water management from the mesqa level to the main Nile offtakes (turnouts) can be investigated using the OPDM.

In case of water shortage, the model can provide different water allocation policies such as fixed percentage options (a constant or a variable supply cut uniformly or unevenly shared by all users), priority options (satisfying specific areas in full, or supply export crops then distribute any shortage among other users), on demand options (specifying time of full supply), and other alternatives to allow the decision-maker to select the most convenient policy. The model has the ability to make efficient use of all available water resources, taking into consideration the local supplementary resources available for individual command areas.

The model includes a feature to dedicate groundwater for M & I needs. This means that the model satisfies the part of the total demand of the M & I node (specified to be served by groundwater) in the first rank and then the rest of the available groundwater goes to satisfy agricultural requirements. This is typical in the Nile delta region. Data and information are the keys for successful modelling activities. Lag time is considered in water travel through the system, water allocation, water balance, or the other procedures of the model causing a realistic shift of the demand hydrograph at the source node. Groundwater table is presented within the output of the model, to enable full utilisation with conservation of this resource. Shortage factor (total requirements – total supply), used in agricultural water allocation, is calculated after extracting the amount of M & I requirements that will be satisfied from the groundwater. This results in more equity in the water distribution.

The source and measurement hydrographs (at system control structures or locations) data are presented in the model outputs in tabular form or as text files. The root zone should equal the factual value of the root depth according to the growth stage. Command area should be subdivided into fields of various root zones corresponding to their crops' root depths. Although this option will create some lateral seepage from thin (higher) root depths to thick (lower) root depths, it conforms with reality.

Field application of the OPDM led to several powerful ideas for improving operation of the canal system in the Sharkia Directorate; therefore, extending them to other command areas in Egypt is recommended. The OPDM software can streamline data analysis and archiving; scheduling and data stream from the field can be enhanced by MSM telemetry for the key control points in the system. Coupling the OPDM to the MSM system will provide directorate managers with real time monitoring, verification and decision-making capabilities. The OPDM can help significantly in demand forecasting, allocating water to irrigation use and water distribution.

Since the strategies eventually employed for improving water management and their supporting technologies should be cost-effective, the OPDM can be used to refine water delivery schedules in such a manner as to increase agricultural production and the efficiency with which water is distributed and used.

The model can be used at the directorate level in order to evaluate demand hydrographs over a period ranging from a week to a season taking into consideration the effects of cropping pattern changes as well as variations in local climate. This is crucial for the free cropping pattern environment adopted in Egypt (Elarabawy *et al*. 2000); many revisions are necessary to account for individual choices and update the pre-season assumed cropping patterns. It can assist the authorities in preparing a much more comprehensive water distribution schedule. The model can produce water level tables on the control structures, which can be connected with weather forecasting data to increase or decrease the flow according to the weather parameters. Mutual influences between adjacent irrigation directorates can be fully accounted for and consequently considered in the operation.

It is useful to employ the model in testing the capacity of the existing canal and drain reaches to check the suitability for the horizontal expansion projects and estimate any required increase in capacity. The model can be used to study the water movement in the drains and calculate the available drainage water for reuse to assist in allocation of drainage reuse pumps. The model can be used to study the effects of implementation of irrigation improvement projects on the available drainage water and the effects of this on the water policies. Unresolved issues such as the mutual influences between adjacent directorates, drainage reuse, irrigation improvement and rice area restrictions can be clarified. The model can be used to estimate the minimum rice area needed to conserve the salt balance in the Nile Delta and avoid seawater intrusion (Elarabawy *et al*. 1998, 2000).

ACKNOWLEDGEMENTS

The ideas and issues discussed in this paper solely reflect the author's view, and may be or may not be those of the MWRI. This work was carried out under the PSM component of the IMS project, funded by the MPWWR-USAID. The OPDM model was developed by USU. Dr Bayoumi Attia was the project director. The model testing, evaluation and adaptation was performed by engineers Fatouh A. Lotfi, Mohamed E. Elshamy, Mohamed H. Abdel Latif and the author. Dr Hatim Fahim supervised the model refinement tasks. Field data were collected by Dr Mohamed Helwa, Cairo University, and

Dr Tallat Owais, Zagazig University. Thanks are due to Dr Paul Tosswell, Civil and Environmental Engineering Department of the University of Southampton, for his critical revision and valuable suggestions during the course of preparation of this manuscript.

ABBREVIATIONS

CANALS	Unsteady Hydraulic Routing Model
COMMOD	Command Area Model
DRI	Drainage Research Institute of the National Water Research Centre
GWRI	Groundwater Research Institute of the National Water Research Centre
ICMs	Irrigation Command Models
MALR	Ministry of Agriculture and Land Reclamation
MPWWR	Ministry of Public Works and Water Resources
MSM	Main System Management Project
MWRI	Ministry of Water Resources and Irrigation
OPDM	Operation and Planning Distribution Model
PS	Planning Sector of the MPWWR
PSM	Planning Studies and Models Project of the Irrigation Management Systems Project
STEAD	Steady State Flow Routing Model
USAID	United States Agency for International Development
USU	Utah State University
WCM	Water Course Model
WMM	Water Management Model

In the tables and figures:

CAs	command areas (model calculation units)
deficit	percentage of the crops that had reduced production due to water shortage
DP	deep percolation from agricultural lands (to deep groundwater or to drains)
drain spills	water flowing unused at the drains tail reaches to principal drains
DS	downstream
ETa	actual crop evapotranspiration
ETp	potential crop evapotranspiration
GW	groundwater contribution to crop water budget, from groundwater pumping
M & I	municipal and industrial water use
management indices	water actually delivered (on command area, crop, reach, etc. basis) compared to water required to meet demands
nominal	percentage of the crops that had maximum yield (no reduction)
overtopping	water overflowing banks of canals or drains due to insufficient capacities
salinity	percentage of the crops that had reduced production due to soil salinity
supply spills	water flowing at the canals tail reaches to drains through tail escapes
waterlogging	percentage of the crops that had reduced production due to waterlogging
WT	shallow groundwater table (surface of the groundwater aquifer)

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