Managing Groundwater Levels in an Agricultural Area with Peat Soils

Nir Naveh, M.ASCE,[1] and Uri Shamir, F.ASCE[2]

Abstract: The Hula Decision Support System (HDSS) is designed to aid Hula site operators in managing groundwater levels in the Hula Lake region of Israel. Groundwater levels are managed by controlling water levels by using adjustable dams in a grid of drainage canals and by the timing and intensity of irrigation. Water levels in the canals are controlled by a set of hydraulic structures. Groundwater levels are to be maintained within a specified range to minimize decomposition and subsidence of the peat soils, ensure year-round green cover of the area, and avoid saturation conditions in the crop root zone, thereby allowing farmers to continue cultivation of their fields. The management module for the HDSS performs optimization with the following two objectives: (1) minimize deviation from the specified groundwater target level, and (2) minimize supply of water from the Jordan River to the Hula drainage canals (water quantity is limited). The second objective is achieved indirectly in the HDSS by determining the dam settings and irrigation quantity and timing over a period of eight weeks and then solving again whenever conditions change. The results are checked by simulation using MODFLOW within the GMS modeling package. The procedure is demonstrated and analyzed.

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Introduction

Drainage of the Hula Lake and its surrounding swamps (Figs. 1 and 2) by the Jewish National Fund (JNF) in the late 1950s was considered a peak of success for the young state of Israel. A long-standing national dream had been accomplished: the malaria rampant in the area was eradicated, and the settlers of the Galilee gained thousands of acres for agricultural use. At the same time, measures were taken to preserve some of the natural and environmental amenities of the area (Shaham 1995). With time, a serious gap was discovered between the original expectations and the actual results. The drained peat soils subsided dramatically, igniting spontaneously as the organic matter oxidized and converted to infertile ash. Dust storms caused crop damage, and rodents multiplied in burrows in the peat soil and caused severe damage to crops. The unique natural amenities of the area were largely lost: species of plant and animal life disappeared, and the number of water birds diminished. Water quality in the Sea of Galilee was affected by an increased discharge of nitrogen compounds from the Hula region’s peat soils.

Planning of the Hula restoration project began in the late 1980s. The first step was to determine the objectives of area users and the area resources as guiding principles for the restoration plan (Shaham et al. 1988; Harpaz 1988). There was consensus on two objectives: preservation of the land value for future generations, and prevention of water pollution by the Hula peat soils. There was controversy regarding restoration of natural values, on the one hand, and on the other, allowing the farming communities who cultivate the land in the Hula valley to establish some rural tourism facilities to make up for the income from agriculture that would be lost due to the new project.

Engineering schemes were developed to improve the productivity of the agricultural land. The main objective of the restoration plan was to raise and maintain a relatively high water table in the Hula project area, using water from the Jordan River on the west side and spring water from the Golan foothills on the east side while controlling internal drainage. This was to be accomplished by a grid of drainage canals and by careful cropping and irrigation. In addition, a small lake, called the Agmon, was formed as a nature reserve and bird refuge. Water levels in the canals are controlled by a set of hydraulic structures. Controlling the groundwater levels is designed to minimize the decomposition and subsidence of the peat soils, ensure year-round green cover of the area, and, by avoiding the saturation condition of the crop root zone, allow farmers to continue cultivation of their fields (Shaham 1995).

To support the design of the new system, a research and development (R&D) program was initiated by the JNF, including a geographic information system (GIS) database that stores the soil, groundwater, water quality, and engineering infrastructure data of the project. One of the four aims defined in the R&D program is ‘‘closing the information and knowledge gap of the local water resources: groundwater and the artificial lake’’ (Shaham 1995). As part of the research program, work began on a decision support system for the Hula project (Ostfeld et al., personal communication, 1997; De Hoog et al. 1982; Sudicky 1989; Ostfeld et al. 1999).

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[1] Faculty of Civil Engineering, Technion-Israel Institute of Technology.

[2] Professor, Faculty of Civil Engineering, Technion-Israel Institute of Technology.

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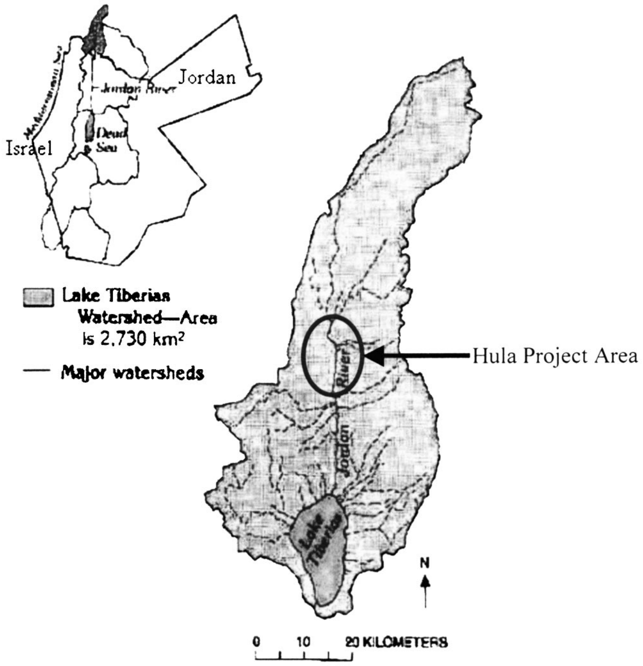


Fig. 1. Location map

Decision Support System

The Hula Decision Support System (HDSS) is designed to aid Hula site operators in controlling groundwater levels in the Hula region so as to minimize the decomposition and subsidence of the peat soils, ensure year-round green cover of the area, and improve agricultural production, thereby contributing to the stability of the land, preserving its value, and reducing the increased discharge of nitrogen compounds from the Hula region peat soils to the Jordan River, and with it to the Sea of Galilee. This is accomplished by management of the amount of water that flows into and out of the area and controlling water levels in a grid of drainage canals, and by the timing and quantity of irrigation. Water levels in the canals are controlled by a set of hydraulic structures. By controlling the operation of the Hula project area, the operators can make the best use of the water available locally and thereby reduce the amount of water that needs to be imported from the outside. The source from which water can be imported to the project area is the Jordan River, whose waters flow to the Sea of Galilee. Reducing importation of water to the project area thus increases the amount available for water supply. The components of the HDSS appear in Fig. 3.

Data Collection

The hydraulic conductivity (k) and porosity (n) of the soil are important parameters in development of the HDSS. These values are difficult to determine due to the highly variable conditions in the field. The parameters were obtained from a study by Dasberg and Neuman (1977) and supplemented by field tests carried out during this study. These tests were conducted at four sites, with three repetitions at each site, using the following procedure. A 12-in. pipe was inserted vertically to a depth of 3.5 m, leaving 1 m of pipe above the ground level. Slug tests were then used to calculate k. Porosity was also measured at the same sites using the following procedure: undisturbed soil samples were obtained from a depth of 1 to 1.2 m using 6-in. PVC pipe, and porosity was then determined by saturating the dried samples. The results are given in Table 1, together with the average for each site (over the three repetitions). Table 2 gives the averages, standard deviations, and relative variations (the latter are considered valuable even though the number of samples is small). The results are also compared to those of Dasberg and Neuman (1977).

The average values obtained in the field experiment are quite similar to those in Dasberg and Neuman (1977). The somewhat lower values of n may be due to additional subsidence that has occurred since 1977. Table 2 shows a substantial difference in the variability of the results. Dasberg and Neuman (1977) performed their tests in many different areas throughout the Hula project area, while in the present study tests were performed in a smaller part. Accordingly, the results seem more uniform. Therefore, the values used in this work are the values obtained by Dasberg and Neuman (1977).

Data on canal water levels, groundwater levels, precipitation, irrigation, and evapotranspiration were recorded weekly. For this purpose, four observation wells made of perforated stainless steel tubes were inserted into the ground to a depth of 4 m at the same four sites where soil parameters were measured. Canal water levels were measured at 18 hydraulic structures and eight nodes of the canals. The meteorology station of the Hula project records precipitation and evaporation data and then transpiration is calculated. These data are gathered and analyzed for the farmers by the North Galilee Laboratory (MIGAL) and provided to the Hula project operators. Using the evapotranspiration data, the farmers determine the irrigation amounts required.

System Equations

There are two possible ways to construct the equations that describe the system. One is to use field data and find experimental functional relationships between the independent and dependent variables. The independent variables are the external data and control variables (for example, precipitation, evaporation, transpiration, and water levels in the canals, and irrigation amounts) while the dependent variables are the groundwater levels in the plots. This approach would alleviate the need to determine the soil parameters, which are highly variable. The other approach is to use the continuity equation for each plot and insert the values of parameters (that is, geometry and soil properties). The first approach failed, since the measurements of groundwater levels throughout the Hula Valley are not sufficiently dense in space and time and are sometimes inconsistent. Therefore, due to problems in the field data, it was not possible to obtain a consistent set of system equations based on data, and we had to resort to the continuity approach. The HDSS is therefore based on the second approach.

A network of canals that surround the agricultural plots, as shown schematically in Fig. 4, divides the project area. The control scheme uses the groundwater level at the center of each plot as the control variable, based on the assumption that this would result in an adequate level throughout the entire plot. The center of the plot is the farthest point from the canals and therefore least affected by canal water levels, but is the most affected by irrigation, which turned out to be the dominant factor in controlling groundwater levels. The results of the optimization were tested by simulation (Fig. 3), and the results verified the validity of the assumption. When a plot is surrounded from only three sides, the representative point is in the middle of the side without a canal, as

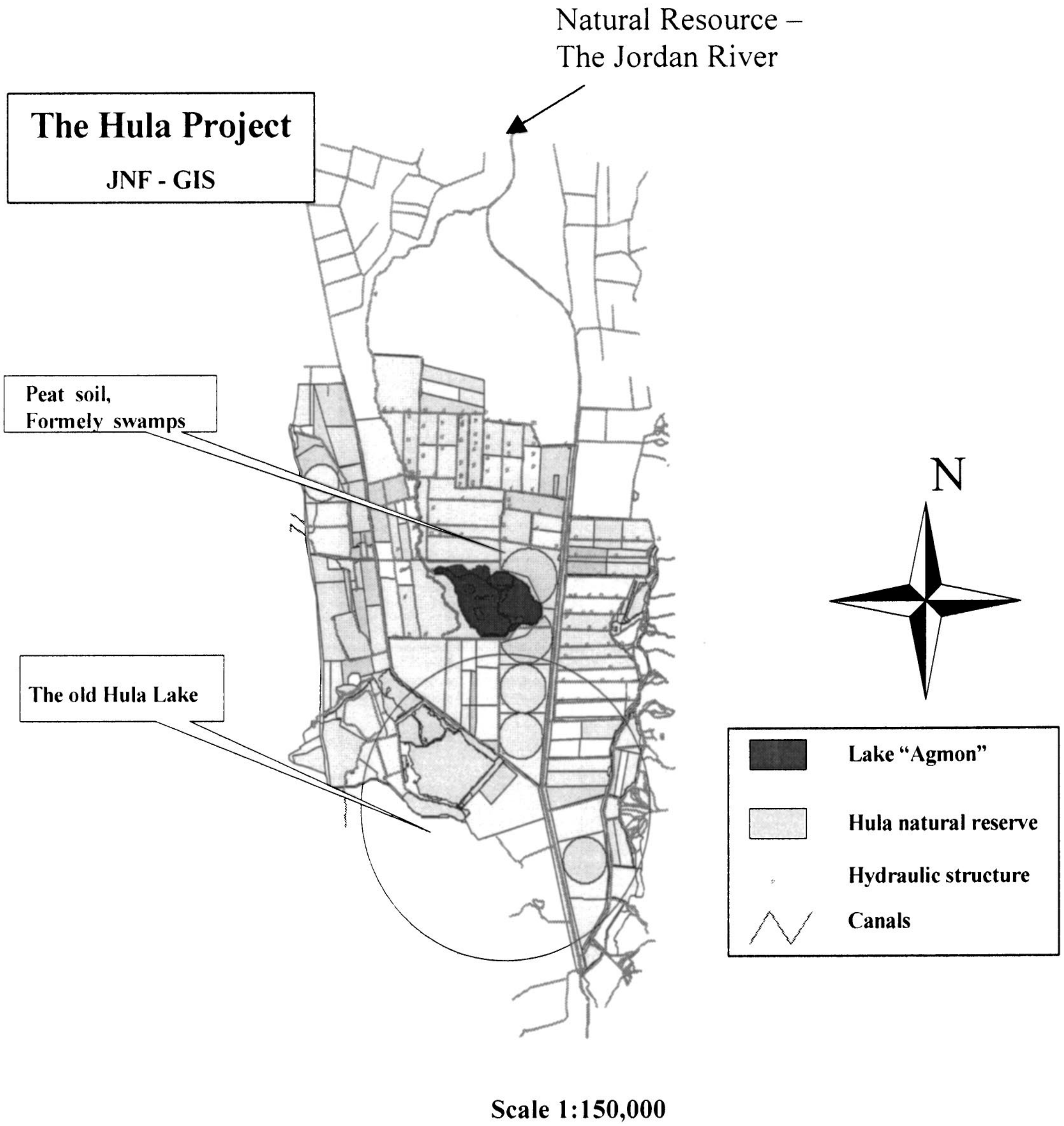


Fig. 2. The Hula project map

this is the point farthest from all three canals. (See plots B, D, and F in Fig. 4, where the west side of the plot has no hydraulic connection to the West-Jordan canal.) The canals constitute a hydraulic divide between adjacent plots, and it is therefore possible to calculate the groundwater level in a plot independent of the other plots. The water levels in the canals are controlled by dams and constitute a boundary condition for the plot's continuity equation.

The continuity equation for a plot over a specified time period is developed using the cross section shown in Fig. 5. The cross section shows the (linearized) groundwater level in the plot at times $t1$ and $t2$ and the factors that determine it: vertical components—rain (P), irrigation (R), and evapotranspiration (d)—and horizontal contributions from the canals. The latter are determined by the hydraulic conditions: distance from a canal to the center of the plot (L), water level in the canal (H_c), water level at the center of the plot (HM), hydraulic conductivity of the soil (k), and the cross section of the flow from the canal into the plot (for 1 m width it is $ac = 1 \times H_c$). The distance between the ground level and groundwater level (X) is the state variable.

Fig. 5 has a distorted vertical scale. To appreciate the relative importance of the various components in the continuity equation,

Table 1. Field Test Results

Site number	Site description	Porosity (n) (%)				Hydraulic conductivity (k) (m/day)			
		$\bar{n}$	n_1	n_2	n_3	$\bar{k}$	k_1	k_2	k_3
1	Center of plot A	**69.3**	68	74	66	**0.133**	0.12	0.13	0.15
2	Northern side of plot C	**71.6**	73	67	75	**0.127**	0.10	0.15	0.13
3	Center of plot C	**71.6**	76	75	64	**0.123**	0.11	0.13	0.13
4	Southern side of plot C	**72.3**	75	69	73	**0.153**	0.15	0.15	0.16

Table 2. Analysis of Field Test Results

Site number	Site description	Porosity (n) (%) $\overline{n}$	S_n	$\nu = S_n/\overline{n}$(%)	Hydraulic conductivity (k) (m/day) $\overline{k}$	S_k	$\nu = S_k/\overline{k}$(%)
1	Center of plot A	69.3	4.16	6.0	0.1330	0.0153	11.50
2	Northern side of plot C	71.6	4.16	5.8	0.1270	0.0252	20.00
3	Center of plot C	71.6	6.66	9.3	0.1230	0.0115	9.40
4	Southern side of plot C	72.3	3.06	4.2	0.1530	0.0058	3.80
5	All	72.2	4.18	5.9	0.1342	0.0183	13.65
6	Dasberg and Neuman (1977)	76.0	9.31	12.3	0.1260	0.2260	55.80

observe Fig. 6, which has the same vertical and horizontal scales; the ratio of depth to length is about 1:100. It becomes obvious that the side flows actually are small compared to the vertical components, which will be seen when we present the results. This also justifies the assumption of a linear water table since the curvature cannot be more than a few centimeters over a distance of hundreds of meters.

Management Objectives

The optimization has the following two objectives: (1) minimize the deviation from groundwater target levels in the agricultural plots, and (2) minimize supply of water from the Jordan River to the Hula canals. The target level is the level that, on the one hand, minimizes the decomposition and subsidence of the peat soils,

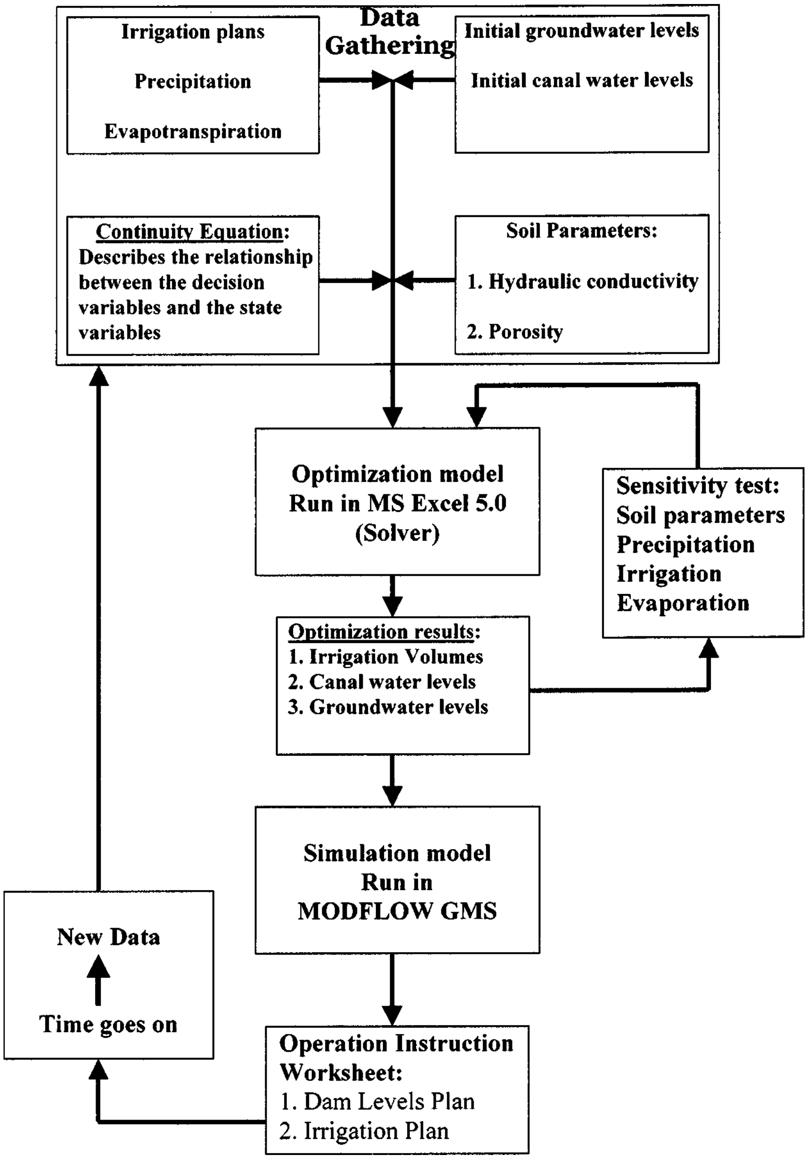


Fig. 3. Block diagram of decision support system

Fig. 4. Pilot project map

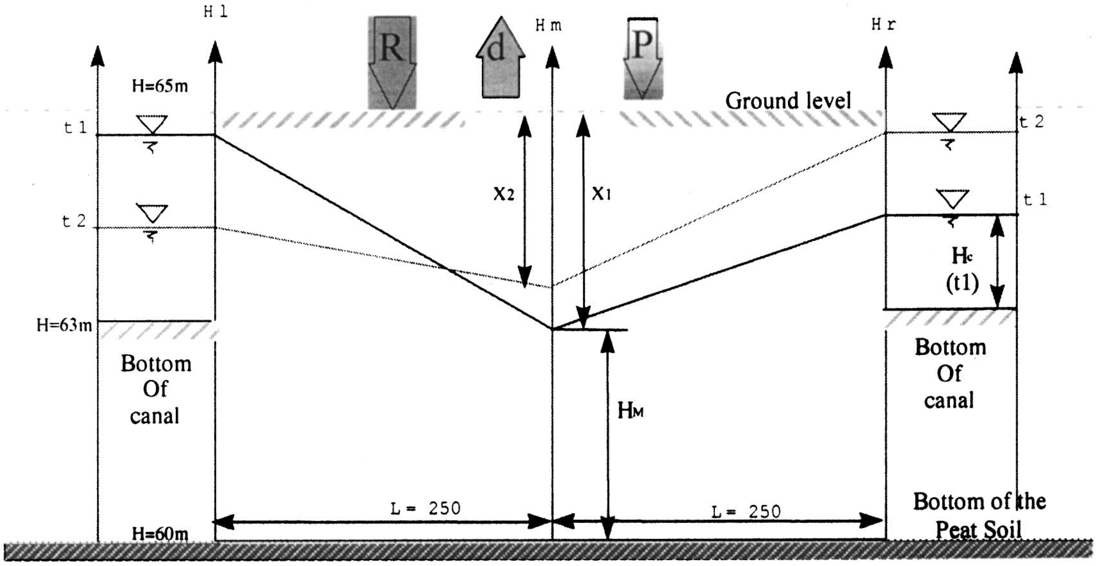


Fig. 5. Cross section of typical plot (distorted scale)

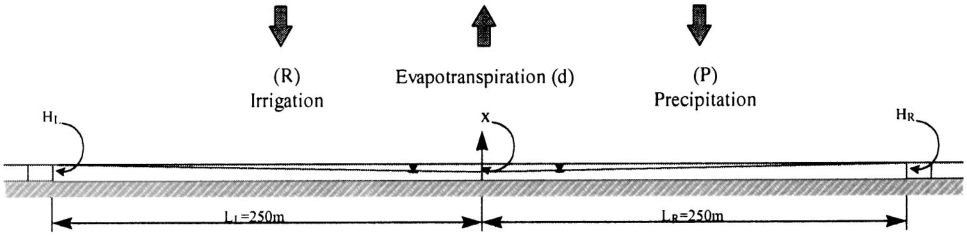


Fig. 6. Cross section of typical plot (same horizontal and vertical scale)

and on the other hand, allows farmers to continue cultivation of their fields. Minimizing water import to the area from the Jordan is in recognition of the scarcity of water in that region, particularly in summer. The second objective is designed to ensure that the project will import the least amount of water, since water quantity in this area is limited.

Constraints: Continuity Equations

The continuity equations are formulated for a 1-m wide strip across the plot between the canal on the left (denoted by the index L) and the one on the right (denoted by R) for a time period Δt, from t^1 to t^2.

The change in water volume between the beginning (superscript 1) and end (superscript 2) of the period is

$$\Delta V=\left\{\frac{L_L}{2}[(H_L^2+H_M^2)-(H_L^1+H_M^1)]+\frac{L_R}{2}[(H_R^2+H_M^2)-(H_R^1+H_M^1)]\right\}\cdot n \qquad (1)$$

where ΔV=change in water volume between beginning and end of period; L_R=distance between right canal and center of plot; L_L=distance between left canal and center of plot; H_R=water level in right canal; H_L=water level in left canal; H_M=groundwater level at center of plot; and n=soil porosity.

$$Q_{\text{Volume}}=\frac{\Delta V}{\Delta t} \qquad (2)$$

where Q_{volume}=discharge to plot calculated from change in volume; ΔV=change in water volume between beginning and end of period; and Δt=time between beginning and end of period.

$$\Delta t=t^2-t^1 \qquad (3)$$

where Δt=time between beginning and end of period; t^1=time at beginning of period; and t^2=time end of period.

The flow entering/exiting from/to the left canal is

$$Q_L=\left[\frac{1}{2}(H_L^1+H_L^2-H_M^1-H_M^2)\right]\cdot\frac{1}{L_L}\cdot a_L\cdot k=\Delta H_L\cdot\frac{1}{L_L}\cdot a_L\cdot k \qquad (4)$$

where Q_L=discharge to plot from left canal; H_L=water level in left canal; H_M=groundwater level at center of plot; L_L=distance between left canal and center of plot; a_L=area through which flow occurs; and k=hydraulic conductivity. The area through which the flow occurs is

$$a_L=H_L\times 1m \qquad (5)$$

where H_L=water level in left canal; and a_L=area through which flow occurs. Similarly, flow from/to right canal is

$$Q_R=\left[\frac{1}{2}(H_R^1+H_R^2-H_M^1-H_M^2)\right]\cdot\frac{1}{L_L}\cdot a_R\cdot k=\Delta H_R\cdot\frac{1}{L_R}\cdot a_R\cdot k \qquad (6)$$

where Q_R=discharge to plot from right canal; H_R=water level in right canal; H_M=groundwater level at center of plot; L_R=distance between right canal and center of plot; a_R=area through which flow occurs; and k=hydraulic conductivity.

$$a_R=H_R\times 1m \qquad (7)$$

where H_R=water level in right canal; and a_R=area through which flow occurs.

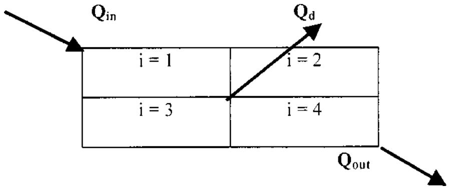


Fig. 7. Area of four adjacent plots

The total net inflow from above is

$$Q_t=(\Delta R+\Delta P-\Delta d)\cdot A \qquad (8)$$

where ΔP=rate of recharge from precipitation (depth of precipitation divided by time interval); ΔR=rate of recharge from irrigation; Δd=rate of evapotranspiration; and $A=(L_L+L_R)\times 1$ surface area of strip.

The total net inflow during the time interval is

$$Q_{\text{flow}}=Q_L+Q_R+Q_I \qquad (9)$$

where Q_{flow}=total net inflow during time interval; Q_L=discharge to plot from left canal; Q_R=discharge to plot from right canal; and Q_i=total net inflow from above.

The change in the water volume in the ground is equated to the influx calculated by the flow equation. The continuity equation for plot i is

$$Q_F^i=\sum_c Q_c^i+Q_I^i \qquad (10)$$

where Q_F=total flow to plot I; $\Sigma_c Q_c$=sum of flow from all of canal to plot I; and Q_i=total net inflow from above to plot i.

$$\Delta S_t^i=Q_F^i \qquad (11)$$

where ΔS_i=change in water storage plot I; and Q_{Fi}=total flow to plot i.

$$h_G^i-h_{t-1}^i+\Delta h_t^i=x_t^i \qquad (12)$$

where h_G^i=ground level in plot I; h_t^i=groundwater level in plot i during time period t; h_{t-1}^i=groundwater level in plot i during time period $t-1$; and x_t^i=groundwater depth at center of plot i during time period t.

In an area covering four adjacent plots, as shown in Fig. 7:

$$Q_{\text{in}}-Q_{\text{out}}-Q_d=\sum_{i=1}^{4} q_F^i=\sum_{i=1}^{4}\left(\sum_c q_c^i+q_I^i\right)=\frac{ds}{dt} \qquad (13)$$

where Q_{in}=total inflow to plot I; Q_{out}=total outflow from plot I; and Q_d=total evapotranspiration from plot i.

$$Q_d=d_t\cdot(A_i+Ac) \qquad (14)$$

where Q_d=total evapotranspiration from plot I; d_t=depth of evapotranspiration at time period t; A_i=area of plot I; and A_c=area of canals around plot i.

The water balance is calculated as successive steady states. As the gradients between groundwater level in the area and water level in the canals are not large, there will not be a large error in ignoring the transition stage (Fig. 6). The requirements are to control the groundwater level at a depth of 80 to 150 cm below the surface, which provides the necessary conditions for agricultural crops. The calculation is performed for several time periods in which the boundary conditions of the plots (the canal water level) change, as do the irrigation volumes.

Management Module

The operational plan can be developed for the entire length of a single growing season, which is typically up to 4 months, with weekly time intervals. In fact, since conditions change quite rapidly, and to maintain model simplicity for practical use, the model is developed for a period of 8 weeks and is run on a rolling window. This means that the model is rerun every time there is a change in conditions, typically once every 2 to 3 weeks, with a time horizon of 8 weeks ahead. The weekly time interval is compatible with the operational schedule in the field, as well as with the rate of change in canal and groundwater levels.

For demonstration, the model was developed for a part of the overall area that can be considered separate and independent of the neighboring areas. The division into such subareas is based on analysis of the groundwater level maps obtained with a GIS system that uses field observations.

From a visual analysis of groundwater maps using a GIS for the Hula project, one can identify four or five subareas in the project according to groundwater level behavior. In each subarea, the groundwater level is relatively uniform, while there is a relatively large difference between the subareas. Based on this information, it seems best to divide the entire project area into subareas, allowing each subarea to have its own management module with its geographic/geometric data and its specific ground parameters. The modules for the subareas are run in parallel. The boundaries of the subareas are clear landmarks (the old channel of the Jordan River, Lake Agmon, topographic differences) that separate the subareas in terms of their hydrological behavior (Fig. 2).

The first objective of the optimization is to minimize deviation of the groundwater level from the target level over all time periods. The target level is the desired groundwater level at any point in time. In setting the target level one must take into account the age of a crop and the depth of its roots. The groundwater should be as close as possible to the surface and yet leave the necessary distance for plant growth between the roots and the water. The Hula restoration plan defines the desired level as between 80 and 150 cm from the surface—80 cm in the summer and 150 cm at the beginning of winter. The second objective—minimizing the total quantity of water supplied to the area under consideration—is achieved indirectly by the first objective function. The demand for minimum deviation from the target levels leads to supply of water from the Jordan River only when there is a deficit in the area (levels are below the target values) during the first weeks in order to reach the desired target level as quickly as possible. The water demand for the rest of the time period is minimal. If the second objective is not achieved simultaneously with the first, it is possible to use a multiobjective optimization approach. The objective function is minimization of the sum of squares of the deviations from the target levels, subject to several types of constraints:

$$\underset{h_i^c, R_i \forall i,c}{\text{Min}} \sum_{i=1}^{N} \beta_i \cdot (X_i - X_{\text{target}})^2 \tag{15}$$

subject to $80\,\text{cm} \leqslant X_i \leqslant 150\,\text{cm}$; $H_{\text{up\_stream}} \geqslant H_{\text{down\_stream}}$; $(h^{\text{ground}} - 2.5) \leqslant h_i^c \leqslant h^{\text{ground}}$; H_c at canal junction equal in all directions; $0 \leqslant R_i$; and $0 \leqslant \beta_i \leqslant 1$; where X_i=groundwater depth at center of plot I; X_{target}=target for groundwater depth; β_i=importance factor of plot I; R_i=water input to plot I from above; $H_{\text{up\_stream}}$=water level in upstream canal in junction; $H_{\text{down\_stream}}$=water level in a downstream canal in a junction; h^{ground}=ground level above sea level; and h_i^c=canal water level above sea level.

The objective function is nonlinear. Since β_i is the importance factor of plot i in the subarea, at the calibration stage the importance of all plots is assumed equal, and so $\beta_i = 1$ for all the plots. When calibrating the module for each subarea, it is possible to set the β coefficient for each plot so as to reflect the weight/importance of each plot.

Pilot Project

The management module in this work is for one subarea in the Hula project, as shown in Fig. 4. It is called the pilot project since the first operational experiments were performed here in 1994. The data collected in those early experiments, and further data collected for the present study, were used herein. The subarea contains the following six plots: A, B, C, D, E, and F. Canal segments between operational dams in the canals surrounding the plots were numbered 1 to 18. The boundary on the west, along the West-Jordan canal, is impervious and is not connected hydraulically to the pilot project area. To the east of the pilot project area is the old Jordan River, which is used as the main canal to convey water to the entire Hula area. It also supplies water to the pilot project through canal number 1. The pilot project is drained to the south, through canal 18 to a reservoir.

Optimization

MS-Excel is used to perform the optimization. This is a simple and well-known software package that facilitates the use of the DSS by the Hula project operators. The algorithm used by Solver is the Generalized Reduced Gradient (GRG2) nonlinear optimization code developed by Leon Lasdon, University of Texas at Austin, and Allan Waren, Cleveland State University. Linear and integer problems use the simplex method with bounds on the variables, and the branch-and-bound method, implemented by John Watson and Dan Fylstra, Frontline Systems, Inc. (Visual Basic User's Guide, Microsoft Excel, Microsoft Corp.).

The setup of the optimization is according to the objective function in Eq. (15). The Pilot Project Model has 23 control variables and 6 dependent variables.

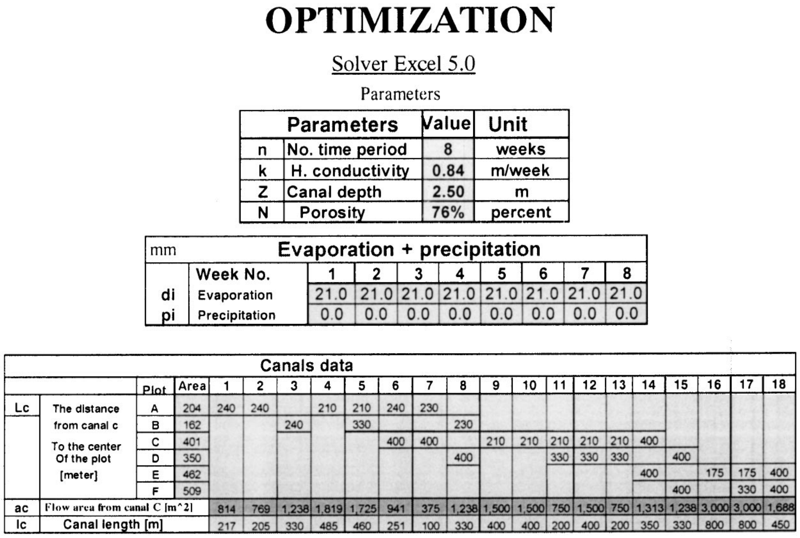
The Excel file contains the following five worksheets:

1. Input worksheet (Fig. 8) used to update input data:
    - Soil parameters (for each plot),
    - Number of time periods,
    - Forecast evapotranspiration,
    - Forecast precipitation, and
    - Canal geometry data.

The Hula site operators collect the data used in the worksheet from a meteorological station.

2. Scenario worksheet (Fig. 9) contains the decision variables for which the Excel solver performs the optimization and also the initial conditions and input data:
    - Canal water levels at all time periods,
    - Irrigation volumes for each plot and time period,
    - Initial groundwater levels in center of each plot, and
    - Groundwater target levels for each plot.

The Hula site operators collect the data from the farmers and the canals and groundwater levels from field measurements. They also determine the target levels (the 80 to 150 cm mentioned



OPTIMIZATION

Solver Excel 5.0

Parameters

	Parameters	Value	Unit
n	No. time period	8	weeks
k	H. conductivity	0.84	m/week
Z	Canal depth	2.50	m
N	Porosity	76%	percent

mm	Evaporation + precipitation								
	Week No.	1	2	3	4	5	6	7	8
di	Evaporation	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
pi	Precipitation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

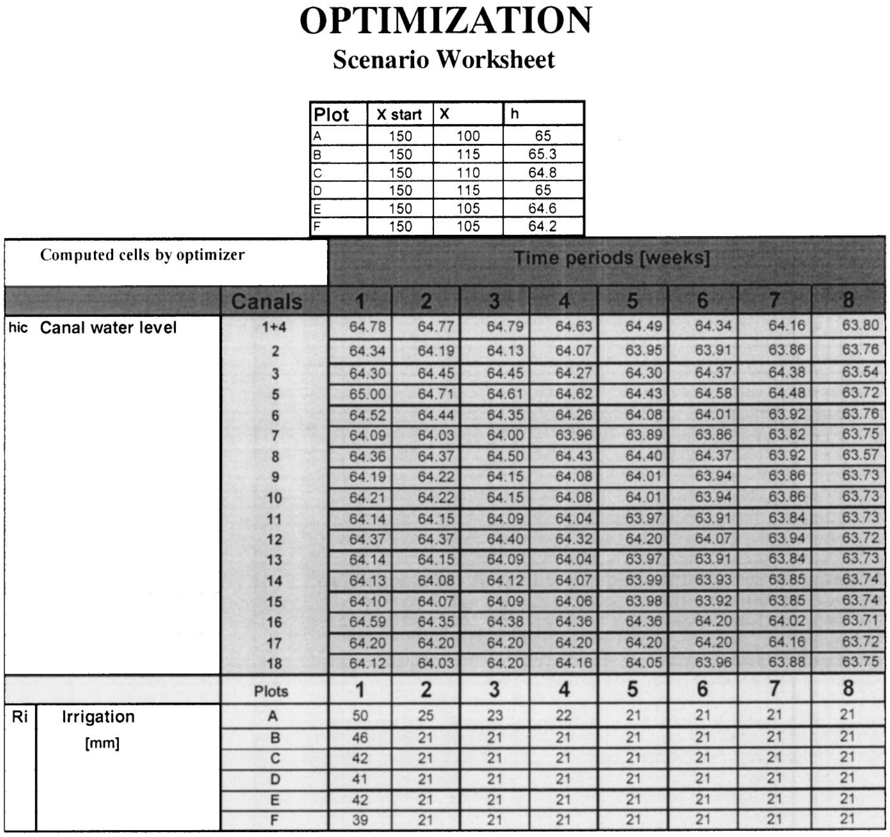
Canals data

		Plot	Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Lc	The distance from canal c To the center Of the plot [meter]	A	204	240	240		210	210	240	230											
		B	162			240		330			230										
		C	401						400	400		210	210	210	210	210	400				
		D	350								400			330	330	330		400			
		E	462														400		175	175	400
		F	509															400		330	400
ac	Flow area from canal C [m^2]			814	769	1,238	1,819	1,725	941	375	1,238	1,500	1,500	750	1,500	750	1,313	1,238	3,000	3,000	1,688
lc	Canal length [m]			217	205	330	485	460	251	100	330	400	400	200	400	200	350	330	800	800	450

Fig. 8. Input worksheet

above), based on agrotechnological experience.

3. Results worksheet (Fig. 10) shows the results of the optimization:
   - Groundwater depth in each plot center at end of every time period, and
   - Contribution to objective function of every plot at each time period.
4. Plot report worksheet (Fig. 11) contains a full report for each plot and each time step:
   - Groundwater level at center of plot,
   - Groundwater depth at center of plot,
   - Canal water levels around plot,
   - Volume of water contributed to plot from every canal,
   - Volume of water contributed to plot from all canals,
   - Volume of water contributed to plot from irrigation, and
   - Values that plot contributed to objective function.
5. Graphs worksheet contains the results of the scenario shown as graphs (Fig. 12). The graphs shown include



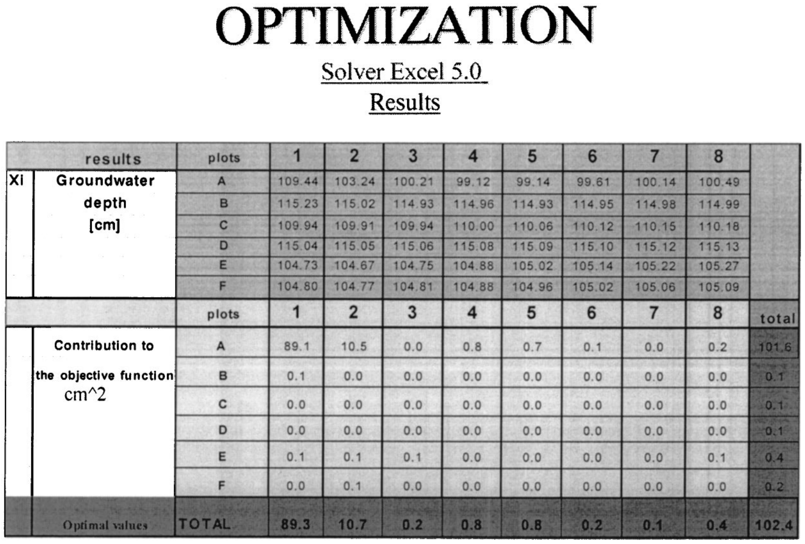
OPTIMIZATION

Scenario Worksheet

Plot	X start	X	h
A	150	100	65
B	150	115	65.3
C	150	110	64.8
D	150	115	65
E	150	105	64.6
F	150	105	64.2

Computed cells by optimizer		Time periods [weeks]							
	Canals	1	2	3	4	5	6	7	8
hic Canal water level	1+4	64.78	64.77	64.79	64.63	64.49	64.34	64.16	63.80
	2	64.34	64.19	64.13	64.07	63.95	63.91	63.86	63.76
	3	64.30	64.45	64.45	64.27	64.30	64.37	64.38	63.54
	5	65.00	64.71	64.61	64.62	64.43	64.58	64.48	63.72
	6	64.52	64.44	64.35	64.26	64.08	64.01	63.92	63.76
	7	64.09	64.03	64.00	63.96	63.89	63.86	63.82	63.75
	8	64.36	64.37	64.50	64.43	64.40	64.37	63.92	63.57
	9	64.19	64.22	64.15	64.08	64.01	63.94	63.86	63.73
	10	64.21	64.22	64.15	64.08	64.01	63.94	63.86	63.73
	11	64.14	64.15	64.09	64.04	63.97	63.91	63.84	63.73
	12	64.37	64.37	64.40	64.32	64.20	64.07	63.94	63.72
	13	64.14	64.15	64.09	64.04	63.97	63.91	63.84	63.73
	14	64.13	64.08	64.12	64.07	63.99	63.93	63.85	63.74
	15	64.10	64.07	64.09	64.06	63.98	63.92	63.85	63.74
	16	64.59	64.35	64.38	64.36	64.36	64.20	64.02	63.71
	17	64.20	64.20	64.20	64.20	64.20	64.20	64.16	63.72
	18	64.12	64.03	64.20	64.16	64.05	63.96	63.88	63.75
	Plots	1	2	3	4	5	6	7	8
Ri Irrigation [mm]	A	50	25	23	22	21	21	21	21
	B	46	21	21	21	21	21	21	21
	C	42	21	21	21	21	21	21	21
	D	41	21	21	21	21	21	21	21
	E	42	21	21	21	21	21	21	21
	F	39	21	21	21	21	21	21	21

Fig. 9. Scenario worksheet



OPTIMIZATION

Solver Excel 5.0

Results

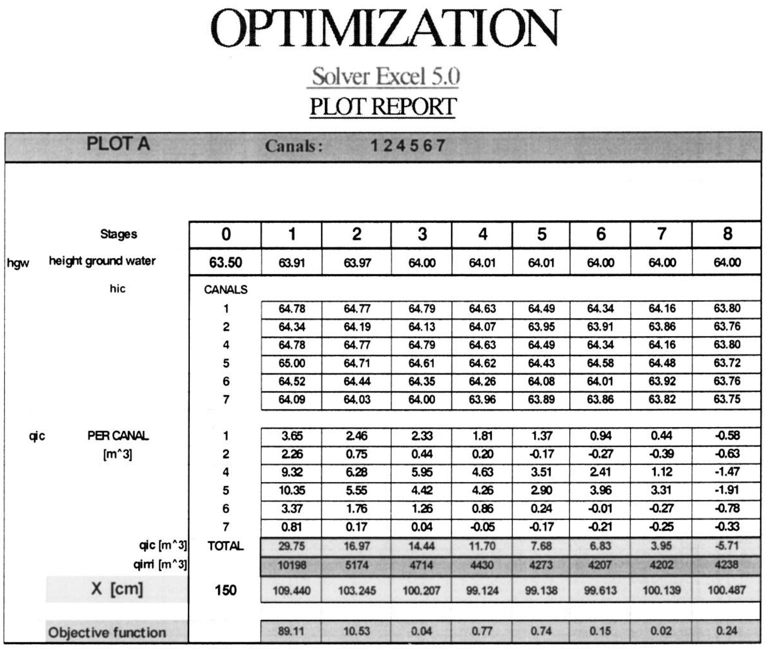
results		plots	1	2	3	4	5	6	7	8	
Xi	Groundwater depth [cm]	A	109.44	103.24	100.21	99.12	99.14	99.61	100.14	100.49	
		B	115.23	115.02	114.93	114.96	114.93	114.95	114.98	114.99	
		C	109.94	109.91	109.94	110.00	110.06	110.12	110.15	110.18	
		D	115.04	115.05	115.06	115.08	115.09	115.10	115.12	115.13	
		E	104.73	104.67	104.75	104.88	105.02	105.14	105.22	105.27	
		F	104.80	104.77	104.81	104.88	104.96	105.02	105.06	105.09	
		plots	1	2	3	4	5	6	7	8	total
	Contribution to the objective function cm^2	A	89.1	10.5	0.0	0.8	0.7	0.1	0.0	0.2	101.6
		B	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
		C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
		D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
		E	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.4
		F	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2
	Optimal values	TOTAL	89.3	10.7	0.2	0.8	0.8	0.2	0.1	0.4	102.4

Fig. 10. Results worksheet

- Groundwater depth in each plot for all time periods,
- Canal water levels around plot A for all time periods, and
- . Volume of water contributed to plot from irrigation.

Numerical Simulation

The results of the optimization are checked by simulation with MODFLOW GMS (groundwater modeling system), a groundwater pre- and postprocessing modeling environment developed at Engineering Computer Graphics Laboratories (ECGL) at Brigham Young University in partnership with the U.S. Army Engineers Waterways Experiment Station. The GMS consists of a graphical user interface that is linked to a number of groundwater simulation codes (for example, MODFLOW, MT3D, MODPATH, FEMWATER) and is capable of importing basic GIS data (for example, geometry of the feature objects by importing Arc View shape files). Several tools are provided within the GMS for site characterization, model conceptualization, calibration, mesh and grid generation, and geostatistics. The GMS was run with MODFLOW on a large number of simulation scenarios in which the boundary conditions, hydrological data, and recharge and evapotranspiration components were modified. The data provided to the simulation (for example, canal water level during each time period, irrigation during each time period, evapotranspiration) were based on the basic data and the results of the optimization,



OPTIMIZATION

Solver Excel 5.0

PLOT REPORT

PLOT A Canals: 1 2 4 5 6 7

	Stages	0	1	2	3	4	5	6	7	8
hgw	height ground water	63.50	63.91	63.97	64.00	64.01	64.01	64.00	64.00	64.00
	hic	CANALS								
		1	64.78	64.77	64.79	64.63	64.49	64.34	64.16	63.80
		2	64.34	64.19	64.13	64.07	63.95	63.91	63.86	63.76
		4	64.78	64.77	64.79	64.63	64.49	64.34	64.16	63.80
		5	65.00	64.71	64.61	64.62	64.43	64.58	64.48	63.72
		6	64.52	64.44	64.35	64.26	64.08	64.01	63.92	63.76
		7	64.09	64.03	64.00	63.96	63.89	63.86	63.82	63.75
qic	PER CANAL [m^3]	1	3.65	2.46	2.33	1.81	1.37	0.94	0.44	-0.58
		2	2.26	0.75	0.44	0.20	-0.17	-0.27	-0.39	-0.63
		4	9.32	6.28	5.95	4.63	3.51	2.41	1.12	-1.47
		5	10.35	5.55	4.42	4.26	2.90	3.96	3.31	-1.91
		6	3.37	1.76	1.26	0.86	0.24	-0.01	-0.27	-0.78
		7	0.81	0.17	0.04	-0.05	-0.17	-0.21	-0.25	-0.33
	qic [m^3]	TOTAL	29.75	16.97	14.44	11.70	7.68	6.83	3.95	-5.71
	qirri [m^3]		10198	5174	4714	4430	4273	4207	4202	4238
	X [cm]	150	109.440	103.245	100.207	99.124	99.138	99.613	100.139	100.487
	Objective function		89.11	10.53	0.04	0.77	0.74	0.15	0.02	0.24

Fig. 11. Plot report worksheet

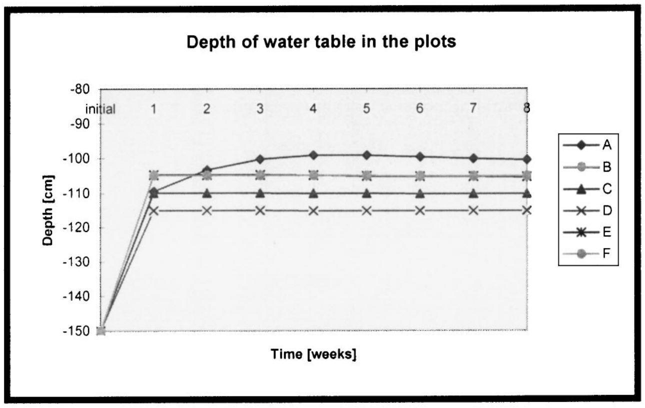
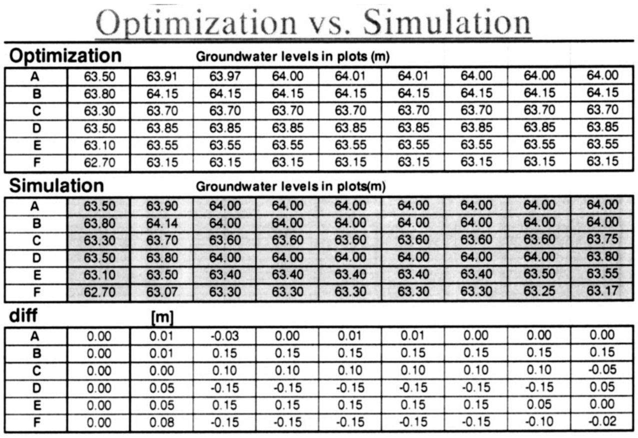


Fig. 12. Graphical results



Optimization vs. Simulation

Optimization Groundwater levels in plots (m)

A	63.50	63.91	63.97	64.00	64.01	64.01	64.00	64.00	64.00
B	63.80	64.15	64.15	64.15	64.15	64.15	64.15	64.15	64.15
C	63.30	63.70	63.70	63.70	63.70	63.70	63.70	63.70	63.70
D	63.50	63.85	63.85	63.85	63.85	63.85	63.85	63.85	63.85
E	63.10	63.55	63.55	63.55	63.55	63.55	63.55	63.55	63.55
F	62.70	63.15	63.15	63.15	63.15	63.15	63.15	63.15	63.15

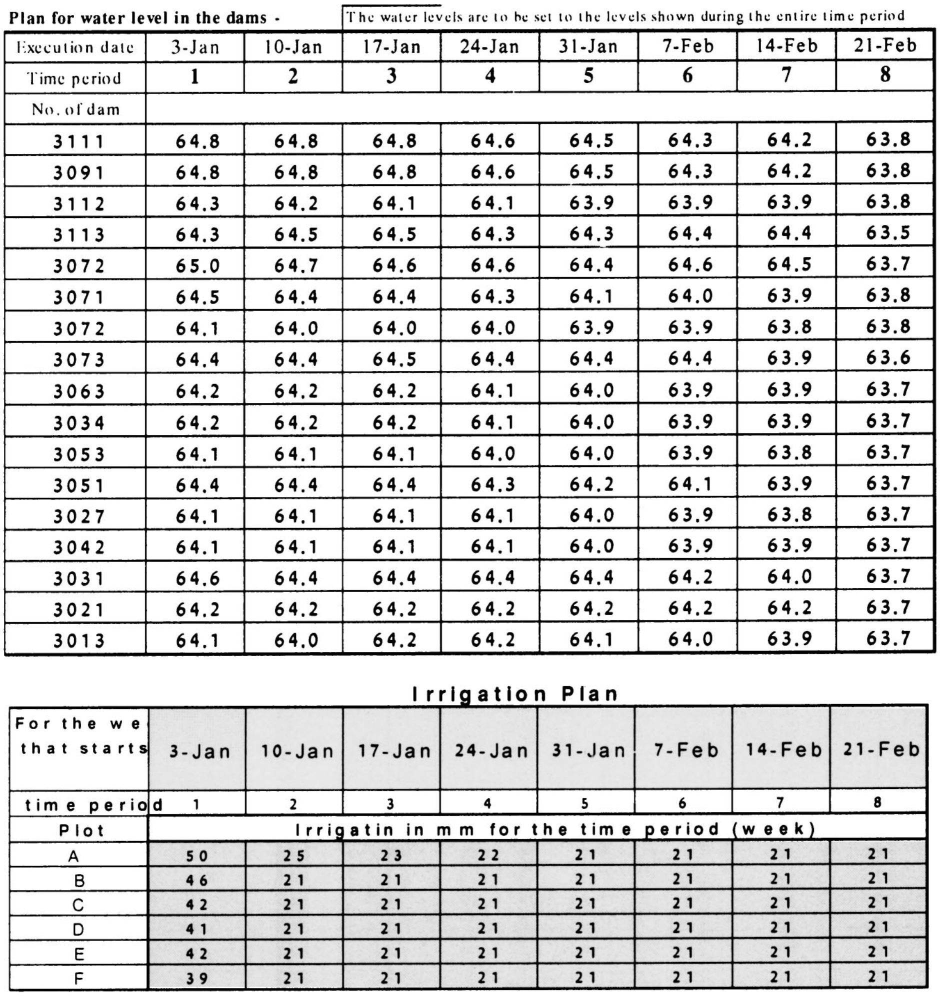
Simulation Groundwater levels in plots(m)

A	63.50	63.90	64.00	64.00	64.00	64.00	64.00	64.00	64.00
B	63.80	64.14	64.00	64.00	64.00	64.00	64.00	64.00	64.00
C	63.30	63.70	63.60	63.60	63.60	63.60	63.60	63.60	63.75
D	63.50	63.80	64.00	64.00	64.00	64.00	64.00	64.00	63.80
E	63.10	63.50	63.40	63.40	63.40	63.40	63.40	63.50	63.55
F	62.70	63.07	63.30	63.30	63.30	63.30	63.30	63.25	63.17

diff [m]

A	0.00	0.01	-0.03	0.00	0.01	0.01	0.00	0.00	0.00
B	0.00	0.01	0.15	0.15	0.15	0.15	0.15	0.15	0.15
C	0.00	0.00	0.10	0.10	0.10	0.10	0.10	0.10	-0.05
D	0.00	0.05	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15	0.05
E	0.00	0.05	0.15	0.15	0.15	0.15	0.15	0.05	0.00
F	0.00	0.08	-0.15	-0.15	-0.15	-0.15	-0.15	-0.10	-0.02

Fig. 13. Results comparison



Plan for water level in the dams - The water levels are to be set to the levels shown during the entire time period

Execution date	3-Jan	10-Jan	17-Jan	24-Jan	31-Jan	7-Feb	14-Feb	21-Feb
Time period	1	2	3	4	5	6	7	8
No. of dam								
3111	64.8	64.8	64.8	64.6	64.5	64.3	64.2	63.8
3091	64.8	64.8	64.8	64.6	64.5	64.3	64.2	63.8
3112	64.3	64.2	64.1	64.1	63.9	63.9	63.9	63.8
3113	64.3	64.5	64.5	64.3	64.3	64.4	64.4	63.5
3072	65.0	64.7	64.6	64.6	64.4	64.6	64.5	63.7
3071	64.5	64.4	64.4	64.3	64.1	64.0	63.9	63.8
3072	64.1	64.0	64.0	64.0	63.9	63.9	63.8	63.8
3073	64.4	64.4	64.5	64.4	64.4	64.4	63.9	63.6
3063	64.2	64.2	64.2	64.1	64.0	63.9	63.9	63.7
3034	64.2	64.2	64.2	64.1	64.0	63.9	63.9	63.7
3053	64.1	64.1	64.1	64.0	64.0	63.9	63.8	63.7
3051	64.4	64.4	64.4	64.3	64.2	64.1	63.9	63.7
3027	64.1	64.1	64.1	64.1	64.0	63.9	63.8	63.7
3042	64.1	64.1	64.1	64.1	64.0	63.9	63.9	63.7
3031	64.6	64.4	64.4	64.4	64.4	64.2	64.0	63.7
3021	64.2	64.2	64.2	64.2	64.2	64.2	64.2	63.7
3013	64.1	64.0	64.2	64.2	64.1	64.0	63.9	63.7

Irrigation Plan

For the we that starts	3-Jan	10-Jan	17-Jan	24-Jan	31-Jan	7-Feb	14-Feb	21-Feb
time period	1	2	3	4	5	6	7	8
Plot	Irrigatin in mm for the time period (week)							
A	50	25	23	22	21	21	21	21
B	46	21	21	21	21	21	21	21
C	42	21	21	21	21	21	21	21
D	41	21	21	21	21	21	21	21
E	42	21	21	21	21	21	21	21
F	39	21	21	21	21	21	21	21

Fig. 14. Operation instruction worksheet

which are arranged in a specific data file format for the GMS optimization results. The saturated zone is modeled with a cell size of 40×120 m and a depth of 6 m, equal to the peat soil layer depth.

Management Module

The module provides a comparison between the simulation and optimization results and preparation of an operation instruction worksheet. At the end of the simulation, the GMS output file is converted to an EXCEL file for comparison with the results of the optimization (Fig. 13). If the differences are within a specified tolerance (±5%), the optimization results are used to construct the operation instruction worksheet (Fig. 14). When the differences are significant, it is necessary to check the input data to the simulation or use the sensitivity test to refine the data and rerun the model.

Operation Instruction Worksheet

After confirmation of the results, the user of the HDSS produces a worksheet to instruct the Hula site operators how to control canal water levels by managing the dams and the irrigation schedule during the planning period. An example to the two-part worksheet is shown in Fig. 14.

Computational Results and Analysis

Three main variables that affect the results are (1) initial groundwater levels in the plots; (2) target levels for the groundwater in the plots; and (3) evapotranspiration. These variables are evaluated under two extreme scenarios: (1) a filling scenario, which starts with low groundwater levels (that is, 2.00 m below the surface) and ends with high groundwater levels (that is, 0.60 to 1.00 m); and (2) emptying scenario, which starts with high groundwater levels (that is, 0.60 to 1.00 m) and ends with low groundwater levels that match the requirement for minimum levels to be 1.50 m below the surface. As explained earlier, the water balance is calculated for a series of (quasi) steady states. Each scenario is run for three conditions of evapotranspiration: (1) high (28 to 30 mm/week); (2) low (7 to 10 mm/week); and (3) highly variable during the planning period (varying between 15 and 30 mm/week). In all cases the maximum irrigation allowed was 50 mm/week.

Analysis

1. For the filling scenarios, when the evapotranspiration is high, the process of filling to target groundwater level requires 3 to 4 weeks in most of the plots. When evapotranspiration is low, the filling process takes only 1 to 2 weeks, and when the evapotranspiration varies during the planning period, the filling process extends over 2 weeks. In all the filling scenarios, after reaching the target level, the irrigation quantity equals evapotranspiration in most of the plots. In some plots, different boundary conditions (for example, the number of surrounding canals) and/or the topographic conditions of the plot (for example, the upstream canals contribute water to the upper and lower plots as well) affects the length of time required for filling the plot area.
2. For the emptying scenarios, the emptying process is controlled largely by the amount and rate of drainage from the plot to the canals. This is a long process due to the long drainage path. For the scenario with low evapotranspiration, the results indicate that the drainage requires about 5 weeks with no irrigation, and after reaching the target level the irrigation equals evapotranspiration. For a scenario with high evapotranspiration, irrigation is required in smaller quantities than is evapotranspiration. The emptying process is unlikely to occur in periods with high evapotranspiration; usually it occurs before the winter, when preparations are made in the Hula Valley for the rainy season.

Conclusions

The optimizer seeks a solution where groundwater reaches its target level as rapidly as possible and then maintains the target close to this level until the end of the planning period. This solution always leads to minimum release of water downstream from the project area, and therefore to minimum water consumption in the project area (this is the second objective). The optimization model developed in this work provides reasonable results that are compatible with the accumulated experience of the Hula project operators.

The accuracy of the model matches the operational precision of the dams in the canal network and the irrigation system. In plots where this is not the case, it is possible to run a more precise simulation with GMS to obtain more detailed results.

Prior to the analysis described here, both operators and researchers believed that most of the water needed to control the groundwater levels is provided laterally to the plots from the canals. For this reason, there has been a major investment in the canal network and its controls. The present study has shown that most of the water needed to raise groundwater levels is actually supplied to the plots from irrigation, and the canals are important mostly as boundary conditions to prevent the levels from dropping. This becomes quite evident when examining the cross section of the plot in true scale (Fig. 6) rather than the abstract diagram shown in Fig. 3.

As a result of this study, the operators are investing more attention and time in planning the irrigation program jointly with the farmers in a way that will meet the needs of the crops while keeping the groundwater levels within the desired range. The model is also used to understand why certain plots become overly dry or wet under certain conditions. It also helps to identify underground preferential flow paths and to calculate the water balance in plots and in the entire project more accurately.

Notation

The following symbols was used in this paper:

A = $(L_L+L_R)*1$ surface area of strip (m^2);
A_c = area of canals around plot i (m^2);
A_i = area of plot i (m^2);
a_L = area through which left flow occurs (m^2);
a_R = area through which right flow occurs (m^2);
d_t = depth of evapotranspiration at time period t (mm);
$H_{\mathrm{down\_stream}}$ = water level in downstream canal in junction (m);
H_L = water level in left canal (m);

H_M = groundwater level at center of plot (m);
H_R = water level in right canal (m);
$H_{\text{up\_stream}}$ = water level in upstream canal in junction (m);
h^{ground} = ground level above sea level (m);
h_i^c = canal water level above sea level (m);
h_G^i = ground level in plot i (m);
h_t^i = groundwater level in plot i during time period t (m);
h_{t-1}^i = groundwater level in plot i during time period $t-1$ (m);
k = hydraulic conductivity (m/h);
L_L = distance between left canal and center of plot (m);
L_R = distance between right canal and center of plot (m);
n = soil porosity (%);
Q_d = total evapotranspiration from plot (m^3/h);
Q_{Fi} = total flow to plot i (m^3/h);
Q_{flow} = total net inflow during time interval (m^3/h);
Q_i = total net inflow from above (m^3/h);
Q_{in} = total inflow to plot i (m^3/h);
Q_L = discharge to plot from left canal (m^3/h);
Q_{out} = total outflow from plot i (m^3/h);
Q_R = discharge to plot from right canal (m^3/h);
Q_{volume} = discharge to plot calculated from change in volume (m^3/h);
R_i = water input to plot I from above (mm);
X_i = groundwater depth at center of plot i (m);
X_{target} = target for groundwater depth (m);
x_t^i = groundwater depth at center of plot i during time period t (m);
β_i = importance factor of plot i;
Δd = rate of evapotranspiration (mm/h);
ΔP = rate of recharge from precipitation (mm/h);
ΔR = rate of recharge from irrigation (mm/h);
ΔS_i = change in water storage plot i (m^3);
Δt = time between beginning and end of period (h);
ΔV = change in water volume between beginning and end of period (m^3); and
$\Sigma_c Q_c$ = sum of flow from all canal to plot i (m^3/h).

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