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# FUTURE VISIONS FOR THE INTEGRATED WATER RESOURCES MANAGEMENT FOR OLD CULTIVATED AREAS OF SIWA OASIS, WESTERN DESERT, EGYPT.

# " الرؤى المستقبلية للإدارة المتكاملة لمصادر المياه للأراضي الزراعية القديمة بواحة سيوة ، الصحراء الغربية ، مصر"

**MOHAMED I. M. GAD*** **TAREK A. SAAFAN****

*Head of Modeling Unit, Hydrology Dept., Desert Research Center. Cairo, Egypt
e-mail : drmohamedgad @ yahoo.com
** Associate Prof., Irrigation and Hydraulics Dep., Fac. of Engineering – El-Mansoura Univ.

## خلاصة

تعاني واحة سيوة من مشكلة غدق أراضيها نتيجة الحفر العشوائي للآبار الارتوازية بمعدل أكبر بكثير من الاحتياجات الفعلية للأغراض الزراعية . ويُجري حالياً استصلاح ١٠,٠٠٠ فدان بمنطقة السهل الرملي المرتفع جنوب منطقة الأراضي الزراعية القديمة التي تم علاج مشكلة غدق أراضيها. وبناءً على ذلك تم في هذه الدراسة استخدام نموذج رياضي مناسب لدراسة تأثير النشاط الزراعي بمنطقة الاستصلاح المذكورة على الأراضي الزراعية القديمة التي تقع شمالها. وتم تقدير الميزان المائي الحالي لمنطقة وسط سيوة التي تحتوي على الأراضي الزراعية القديمة والميزان المائي المتوقع لها بعد حوالي ٣ سنوات بطريقة تفصيلية و دقيقة - وقد أجريت معايرة النموذج الرياضي في حالة الاتزان بدقة وصلت إلى ٩,٣x ١٠$^{-٥}$ م$^{٣}$ / ثانية. ووضعت ثلاث سيناريوهات للدراسة. يعتمد السيناريو الأول على تقييم الوضع الحالى باستخدام معدلات التصرف من العيون الطبيعية و الآبار ، وأوضحت وجود فائض من المياه يعادل ٢٩,٦ مليون متر مكعب سنوياً . أما السيناريو الثاني فيعتمد على تخفيض كمية المياه المستخرجة من قطاع التربة بمعدل ٢٩ %. أما السيناريو الثالث فيعتمد على زيادة التغذية من الحدود الجنوبية للنموذج بنسبة ١٠% وهو ما يعادل كمية المياه اللازمة لزراعة ١٠,٠٠٠ فدان حسب التركيب المحصولي للواحة . فكانت النتيجة أن معدل ما يستقبله قطاع التربة بمنطقة الدراسة من الحدود الجنوبية سيصل إلى ٢٢٣٢ م٣/يوم وهو أكثر مما تم التخلص منه بالتحكم في الآبار مما يدل على التدهور الشديد للمنطقة.

وعليه تم التوصية بمنع حفر أى آبار جديدة ومواصلة عملية التحكم فى الآبار فى قطاعات مختلفة من الواحة كما تم التوصية بإعادة استخدام مياه الصرف فى أى مشاريع استصلاح مستقبلية للحفاظ على أراضى الواحة من التدهور.

## ABSTRACT

The present paper predicts the deterioration and water logging in the old cultivated area due to the random future reclamation projects in the south. This prediction is based on applying mathematical model for planning and managing this locality (Aquifer Simulation Model–ASM-in groundwater flow and solute-

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transport in two spatial dimensions). The solution of the flow equation is based on the finite difference method.

The input data to the model includes basic and field items. Basic data comprises the dimensions, boundaries and hydraulic properties (permeability and storativity) of the water bearing sediments. Field data include surface and groundwater levels, boundary fluxes and pumping operations. The model was calibrated in steady-state condition with nil factor between the input and output items of the water balance in the modeled area (the difference input /output was in the order of $9.3\text{x}10^{-5}$ $m^3$/sec).

Among several scenarios, three water management scenarios were predicted after about 3 years with different conditions. The first scenario keeps the present discharge from the natural springs and flowing wells with no change (620 springs and wells with total discharge of 7634 $m^3$/h). The results showed an increase in soil water with 0.94 $m^3$/sec, which means rising in soil water table and more deterioration. The second proposed scenario was ambitious by decreasing the total discharge by 29 % via controlling 120 flowing wells. The results showed a decrease in soil water with 2.8 $m^3$/sec during 1000 day, which confirms with the field investigation. The third scenario was the predicted case due to reclamation activities of 10000 Fed. with new wells of total discharge 1.49 $m^3$/sec. The model showed that the old cultivated area will receive an excess water of 0.62 $m^3$/sec causing a rise in soil water level. The study recommended that any reclamation activities must depend on the reuse of drainage water. The digging of any new wells must not be allowed, especially in the southern parts.

## INTRODUCTION

Geographically, Siwa oasis lies between longitudes 25° 16′ and 26° 12′ E and latitudes 29° 06′ and 29° 24′ N. The area that lying below the zero contour level elevation is usually considered as Siwa depression. It lies at 330 km southwest of the Mediterranean shoreline and at 65 km east of the Libyan borders, Fig.(1). It attains about 75 km length and a variable width of range 5 to 25 km. The ground surface elevation ranges from 10 to 20 m below mean sea level. The total surface area inside the zero contour line reaches 1088 $km^2$. Siwa oasis is characterized by desert climate. The average temperature ranges between 6 °C in January and 38 °C in July. The precipitation is scarce and does not exceed 11 mm/year.

Geomorphologically, Siwa oasis occupies a large depression opening from the border of the Tamir and Libyan plateaus to the large desert sandy area of the great sea of sand in correspondence of which it altitude sinks by some meters below sea level. Proceeding from north, the plateau is fragmented into numerous small isolated relieves (outlier hills), representative of erosion remnants of the depression escarpment. These relieves with more or less steep concave slopes reach the bottom of the basin which is occupied by large water stretches and by emerged zones, gradually moving towards south to the vast extensions of the dunes of the desert. Within the oasis some geomorphological features may be identified and grouped as follows, Fig.(2):

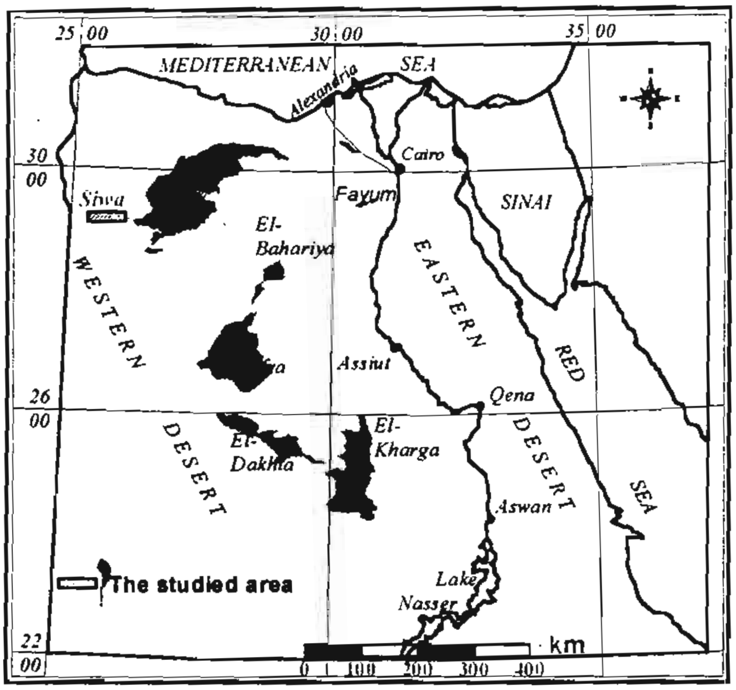


Fig.1. Location map of Siwa oasis.

-The outlier hills and the slopes connecting to the plateau (158 hills, from 30 to 100 m.a.s.l).
-The areas of sabkha (humid and with karshif with total area 355.86 km$^2$).
-The sand sheet.
-The dunes (zero to 30 m.a.s.l).
-The cultivated areas (old and new with area 10000 Fed.).
-The water sheets (lakes with surface area 61.748 km$^2$).
-The rock outcrops microreliefs (limestones and calcareous sandstones, 100 to 150 m.a.s.l).
-The alluvial fan and the colluvial deposits.

Geologically, sedimentary rocks belonging to Middle Miocene and Quaternary (Pleistocene-Holocene) occupy the surface in Siwa oasis. The Middle Miocene section is composed of chalky limestone, marl, shale and dolomite having a thickness of about 94m. The Quaternary section is differentiated into aeolian sand, alluvial and lagoonal deposits of variable thickness. In the subsurface, the stratigraphic section attains a thickness of about 3527 m and rests directly on the basement. This section belongs, from top to base, to Miocene (250m), Eocene (350-400m) Cretaceous (600m), Carboniferous (765m), Devonian (1038m), Silurian (470m) and Carbo-Ordovician (320m).

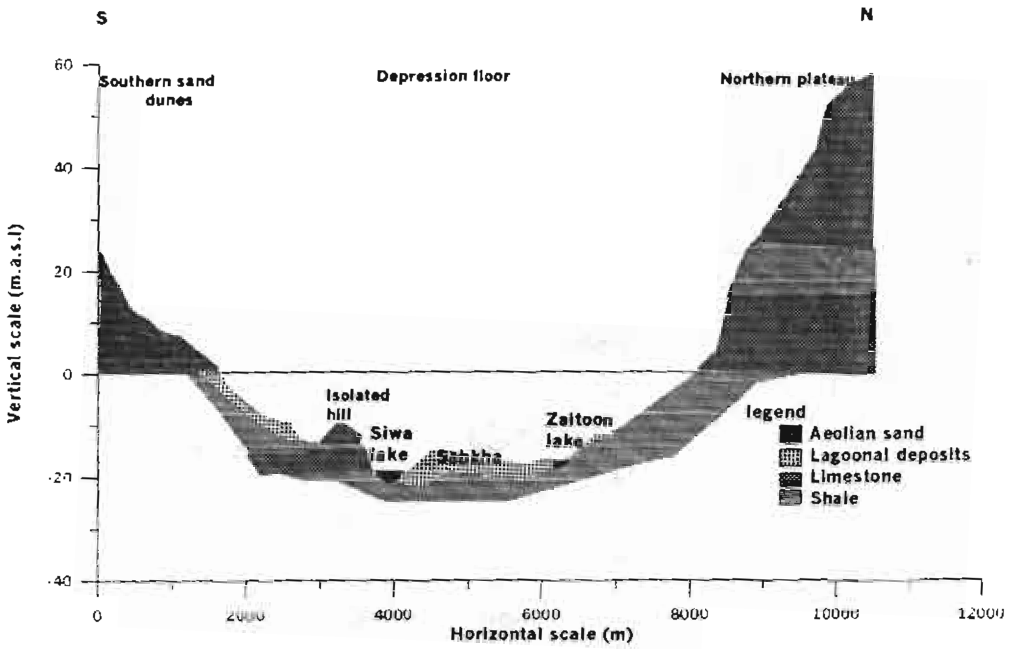


Fig. 2. Geomorphologic cross-section in Siwa oasis.

Hydrogeologically, The groundwater system that underlies Siwa oasis consists of two productive aquifers; the Lower Cretaceous Nubia sandstone and the Middle Miocene fractured limestone besides the Quaternary sand and clay water bearing. The former represents the only sustainable fresh groundwater source in the whole western desert. Its thickness decreases generally from south to north till it reaches about 200m at Siwa oasis. The groundwater flow takes SW to NE direction. The hydraulic pressure differs from 5.5 to 11 atm. and increases towards south and east. The permeability coefficient of the saturated zone ranges between 0.93 and 24.6 m/day. The extracted water from this aquifer for irrigation purposes reaches 15x $10^6$ $m^3$/year [8].

In Siwa oasis, the salinity of this aquifer increases downward from less than 400ppm to more than 55000 ppm [10]. Its groundwater occurs under artesian condition. On the other hand, high fractured zones acting as water conduits characterize the Middle Miocene limestone aquifer. Its thickness ranges between 400 m and 700 m. Two salinity zones were distinguished in this aquifer, one to a depth of about 200 m with salinity ranging between 1500 ppm to 7000 ppm and the second separated from the upper one by a thin clay layer with salinity of the order 12000 ppm.

## DESCRIPTION OF THE PROBLEM

The water logging sediments of the old cultivated land (3000 Fed.), which have a variable thickness increasing from north to south and southeast, are underlain by an impervious stratum allowing no leakage. The old cultivated land was suffered from excess groundwater discharge (620 springs and flowing wells with different discharges, Figs (3 & 4).

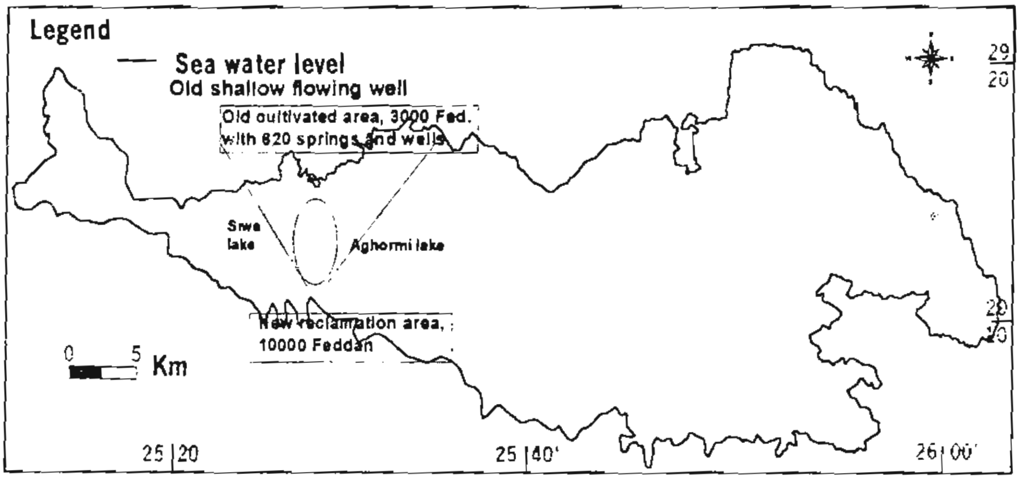


Fig. 3. Location of the different flowing wells .

The crop consumption per Fed. ranges from 3.8 and 28.3 m$^3$/day [8] & [9]. So, the crop consumption of the old cultivated lands ranges from 475 and 3537.5 m$^3$/h, which is always less than the half of the total discharge (Fig.5). To solve this problem, the control of 120 flowing wells by the end of 2000 was carried out. The waterlogging problem begins to decrease. The uncontrolled reclamation activities of 10000 Fed. south of these old cultivated lands, including the digging of more flowing wells, will cause a continuous seepage to these traditionally cultivated area due to the difference in topographic level (10m). So, the simulation of this problem by a suitable mathematical model is of great importance.

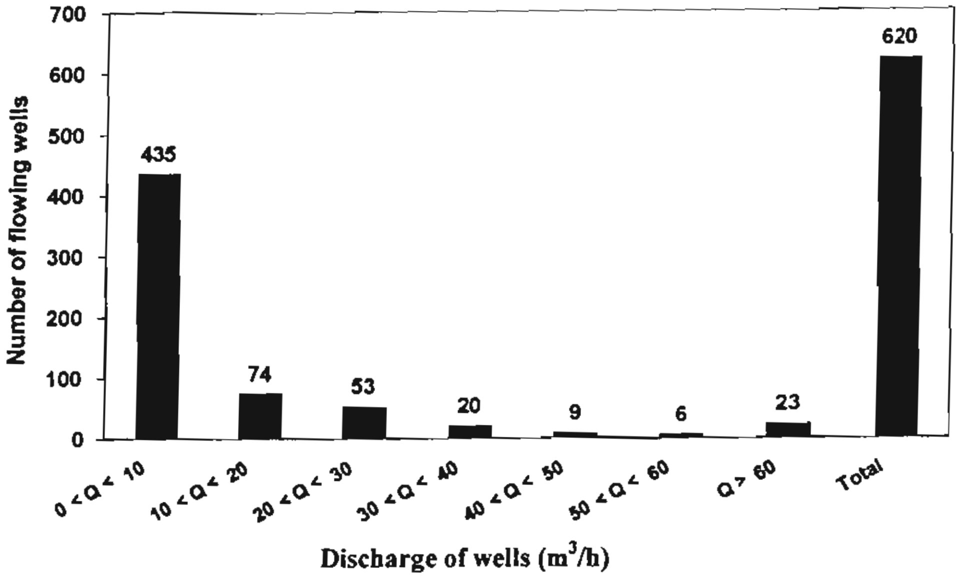


Fig.4. Discharges of the present wells in the old cultivated land ($m^3/h$) .

## AQUIFER SIMULATION MODEL (ASM)

The two spatial dimensional groundwater flow and solute-transport model (*ASM* [12] version 3.1) was applied with available climatologic , geologic and hydrologic data to characterize the present soil-water conditions of the modeled area and to predict changes in the potential surfaces of utilized aquifer under different pumping scenarios.

The equation describing the transient two-dimensional areal flow of groundwater in the heterogeneous anisotropic aquifer is expressed as by Bear [1] as :

$$\frac{\partial}{\partial x}[T_{xx}\frac{\partial H}{\partial x}]+\frac{\partial}{\partial y}[T_{yy}\frac{\partial H}{\partial y}]=S\frac{\partial H}{\partial t}+W+\sum_{k=1}^{m}[\delta(x-x_k).\delta(y-y_k).Q_k]$$

where $T_{xx}$ = Transmissivity in the $x$ direction ( $L^2/T$); $T_{yy}$= Transmissivity in the $y$ direction ( $L^2/T$); $H$ = Potentiometric head (L); $S$ = Storage coefficient (dimensionless); $W$ = Distributed volumetric water flux per unit area, positive sign for discharge and negative sign for recharge (L/ T); $Q_k$= Volumetric water flux at point (source/sink) located at $(x_k, y_k)$, positive sign for withdrawal and negative sign for injection ($L^3/T$); $\delta (x - \xi)$ = Dirac delta function; t = Time (T); x , y = Cartesian coordinates in the principal direction of transmissivity (L); and m = Number of nodal points.

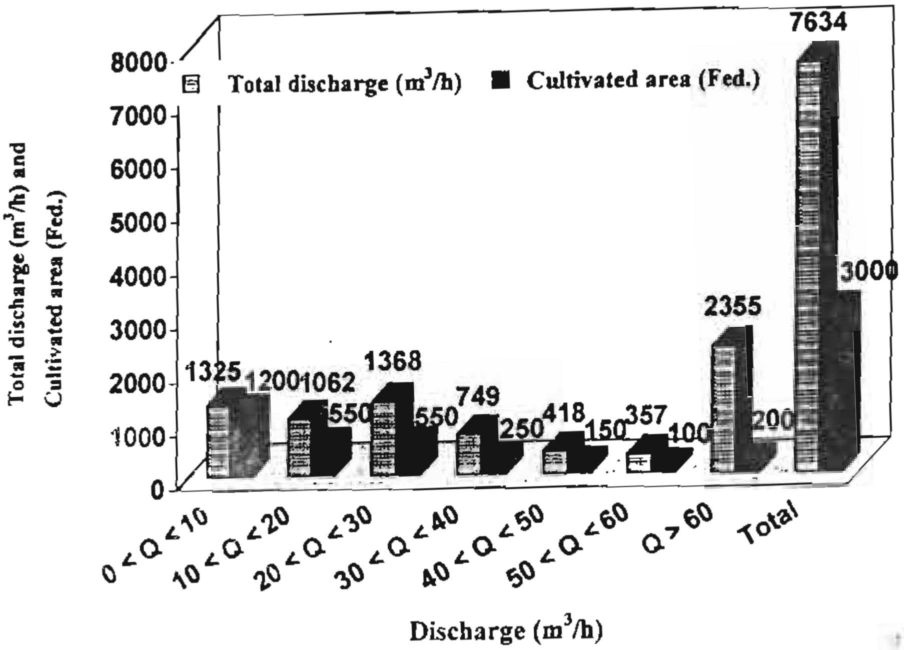


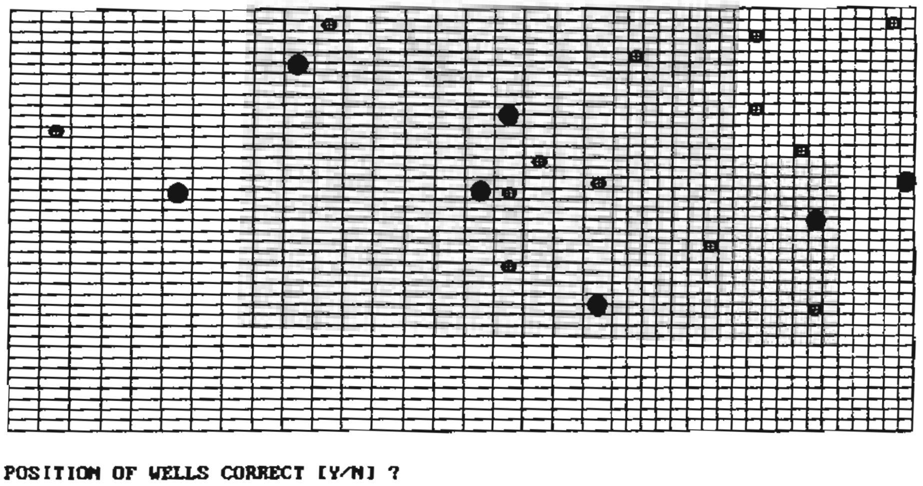
Fig. 5. Comparison between the cultivated area and the total discharge of its flowing wells.

This equation was solved using the Galerkin method and the finite difference technique [15]. In finite difference methods, an aquifer can be subdivided into many small, rectangular cells with a node at the center of each cell, forming a block- centered grid [13]. The properties of the aquifer are assumed to be uniform within each cell. Representative values of parameters within each cell are assigned to each node, creating matrices for initial heads, transmissivities, saturated thickness, and withdrawal or recharge rates. For ***n*** nodes, there are ***n*** finite-difference equations and ***n*** unknown hydraulic heads. The unknown values are found by solving the resulting system of equations with one of the matrix-solution techniques.

The matrix-solution technique is performed by both Iterative Alternating Direction Implicit method (*IADI*) and Conjugated Gradients method (*CG*) for steady state and transient state. *CG*-method has advantage that acceleration parameters, which may be hard to obtain, are not needed . If soil properties vary, the matrix coefficients have to be established on each grid separately. This is complicated task and introduces extra scale problems and the transfer of boundary conditions between the grids may cause large artificial flows where such conditions do not exactly fit with *IADI*-method in case of unsteady state [11].

## APPLICATION OF THE MODEL ON THE STUDY AREA

The simulation procedure was started by dividing the aquifer in the modeled area into a suitable grid pattern on which all the input items were performed via input menus. The total surface area of the modeled area reaches ***3000*** Feddans. The computational grid for the aquifer in the modeled area was divided into ***40*** columns x ***40*** rows = ***1600*** nodes, Fig.(6). The dimension of the cell nodes ranged between ***250m*** and ***500m*** for the old cultivated areas and ***1000m*** for the eastern Aghormi lake and Sabkha and the western Siwa lake. The grid pattern was condensed in the zone occupied by the irrigation and drainage systems to obtain a finer resolution of head distribution around them. It is worth mentioning that for the ten input items , more than ***16000*** data points have to be computed, confirmed, registered and then applied to the ***1600***-nodes model grid. This may give an idea about the capacity of work done and formidable task, which in turn, reflected on the degree of accuracy of the output schemes.



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POSITION OF WELLS CORRECT [Y/N] ?
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⊕ Spring ●Well

Fig.6. Location of the simulated wells in the finite difference grid for the modeled area.

The aquifer is shallow and phreatic. Vertical homogeneity was assumed adequate to allow treatment as a single layer. In one hand, the western boundary (Siwa Lake) and the eastern boundary (Aghormi Lake) are discharging prescribed piezometric head boundaries (equipotential boundary [2]) since the aquifer is in direct hydraulic contact with these lakes in which the water level is known. The water column ranges between ***2.5m*** and ***4.5m*** above datum on the eastern and the western sides respectively [8]. On the other hand, the natural springs through which groundwater emerges to the ground surface are also considered as a fixed piezometric head boundary. The specified heads of these springs are given by the water level in the lakes as they drain into these lakes. The aquifer boundary on the north allows no flow due to the presence of El-Diffa plateau (an impeOrvious or water-divide boundary).The aquifer receives spatially uniform areal recharge from precipitation and excess irrigation water. A system of drainage transverses the modeled area from east to west and towards the eastern and western lakes, Fig.(7).

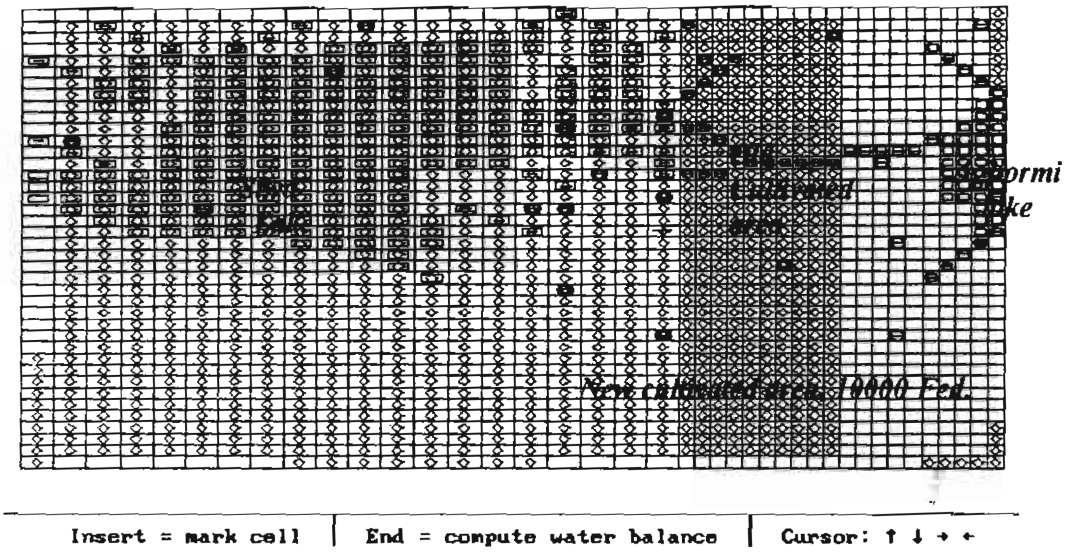


Fig. 7. Drainage system of the modeled area in the old cultivated lands.

## Data Input

The input data needed for use of the model include aquifer parameters (hydraulic conductivity, Fig.8, and storage coefficients), aquifer geometry (vertical and areal extent of the aquifer, Fig. 9), boundary conditions ( hydraulic conditions at the limits of the aquifer, Fig.10) and aquifer stresses ( recharge from rainfall, $3.31x10^{-10}\ m^3/sec/m^2$ , and discharge from flowing wells and springs, ***620*** water points with total discharge of $7634\ m^3/h$). Due to the limitation of the model program by only ***30 wells***, the springs and flowing wells of the modeled old cultivated land were classified into ***20*** sets of wells. The very closed wells were represented by a set with discharge equals the sum of the discharges of the individual springs and wells (*7* black color groups in Figure (6)). Applying Darcy's law on each node forming each of the four boundaries, the boundary fluxes can be estimated. The results show that the eastern and western boundaries are discharging boundaries, while the southern and southeastern and southwestern corners are recharging boundaries. On the contrary the northern boundary is considered as a hydraulic barrier as a result of the impermeable limestone hard rock of El-Diffa plateau.

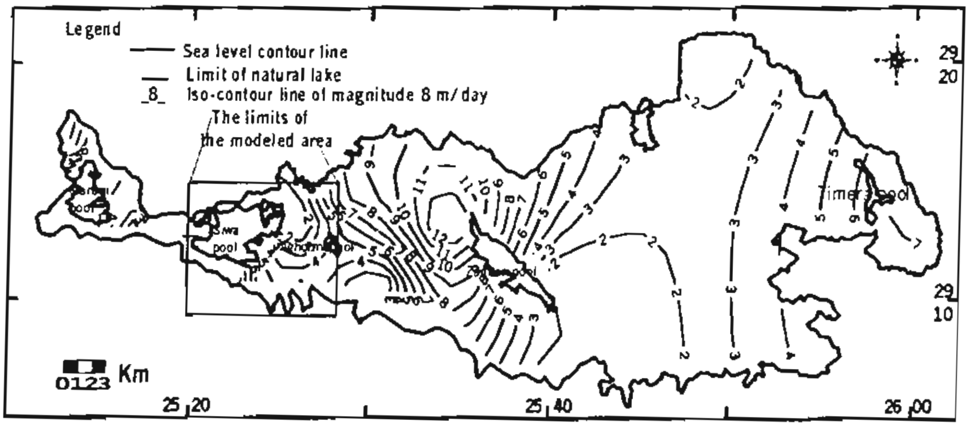


Fig.8. Hydraulic conductivity distribution contour map (m/day) in the modeled area.

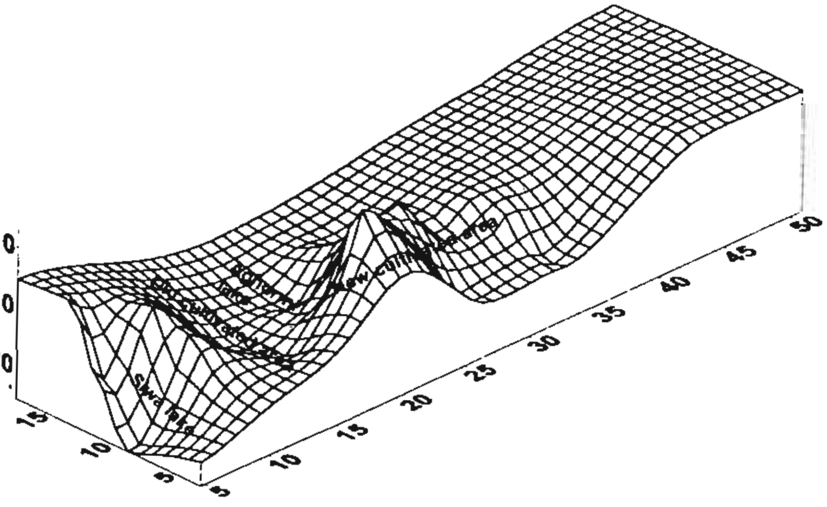


Fig. 9. 3-D diagram showing the geometry of the modeled area.

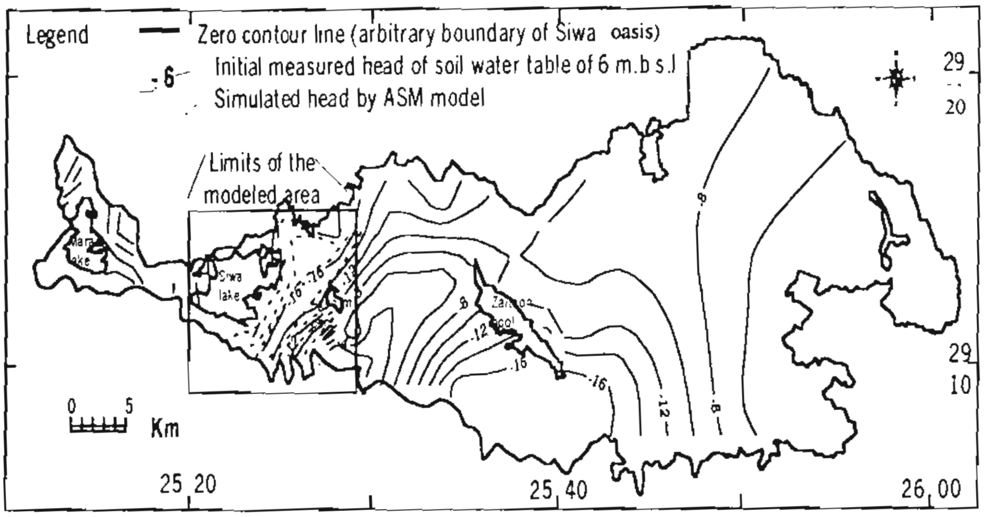


Fig. 10. Initial measured and simulated hydraulic head distribution map of the modeled area.

## CALIBRATION OF GROUNDWATER FLOW MODEL

Before the model can perform its tasks in predicting the response of the system to any future activities, it must be calibrated. Calibration of a flow model refers to a demonstration that the model was capable of producing field-measured presented heads and flows, which are the calibration values. The model was calibrated against the available average annual groundwater heads, Fig.(10). The calibration of the model was based on the steady state conditions, under which, the sum of all in/outputs had to be ***zero***. The deviation from ***zero*** was a measure for the accuracy of computation. Under time-varying conditions (transient state), the sum represents the change in water storage. The calibration process has been carried out through several iterative methods [4,5,6]. The trial and error required for adjusting aquifer thickness until the model was balanced [3]. Results were found to be comparable with maximum error $7.6\text{x}10^{-6}$ ***m/node,*** accordingly the water balance for the modeled aquifer was obtained, Fig.(11).

This figure is a graphical representation for the water balance of the total modeled area in the form of a bar chart under which the numerical values were printed. The water balance parameters showed that the difference between the in/outflows ($Q_{total}$) was in the order of $1.1\text{x}10^{-7}$ $m^3/sec$ (very near to the nil value). This obtained result may give a good reliability in both measured and calculated parameters, which extended to the response of the developed model.

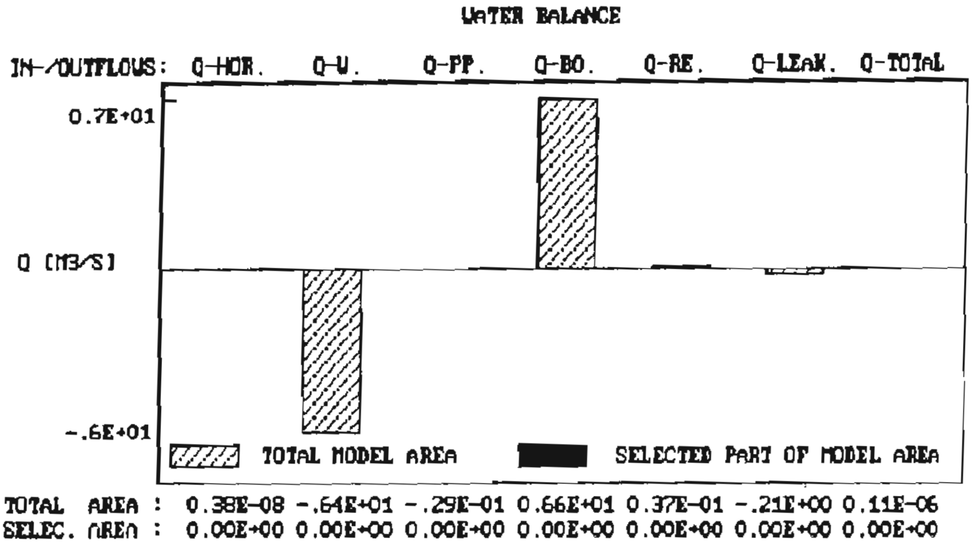


Fig. 11. Water balance of the modeled area (Steady state condition).

## TESTING OF DEVELOPMENT SCENARIOS

The solution of water logging problems depends on the social and economical conditions of the farmers. The lining of the canals and improvement of the irrigation practices are considered long- term solution. While the control of the flowing wells was the short-term solution for both irrigation and drainage. Three management scenarios were considered using different discharge rates before and after controlling ***120*** flowing wells.

### The first development scenario:

The first scenario keeps the actual discharging rates (***620*** water points with total discharge of ***7634*** $m^3/h$ at March 1999) without changes, thereby evaluating the present practices after one hydrologic year. The water balance resulting from applying one hydrologic year is presented in Fig.(12).

The difference between the in/outflows ($Q_{TOTAL}$) indicated that an increase in soil water storage equals ***0.94*** $m^3/sec$ ***(29.644*** $Mm^3/year$***)***, which might be closed enough to the annual mean storage [8]. This indicated that the modeled area was influenced by continuous deterioration conditions. The surface water inflow item ($Q_{pp}$) was increased from ***0.029*** to ***0.23*** $m^3/sec$, which compensated the increase of discharge from springs and wells. This item includes the total surface water flow through the eastern-modeled drains towards Siwa lake. Under the present outflow rate conditions from the modeled area, ($Q_w$) decreased from ***6.4 to 5*** $m^3/sec$ as a result of decreasing infiltration rate due to water logging case.

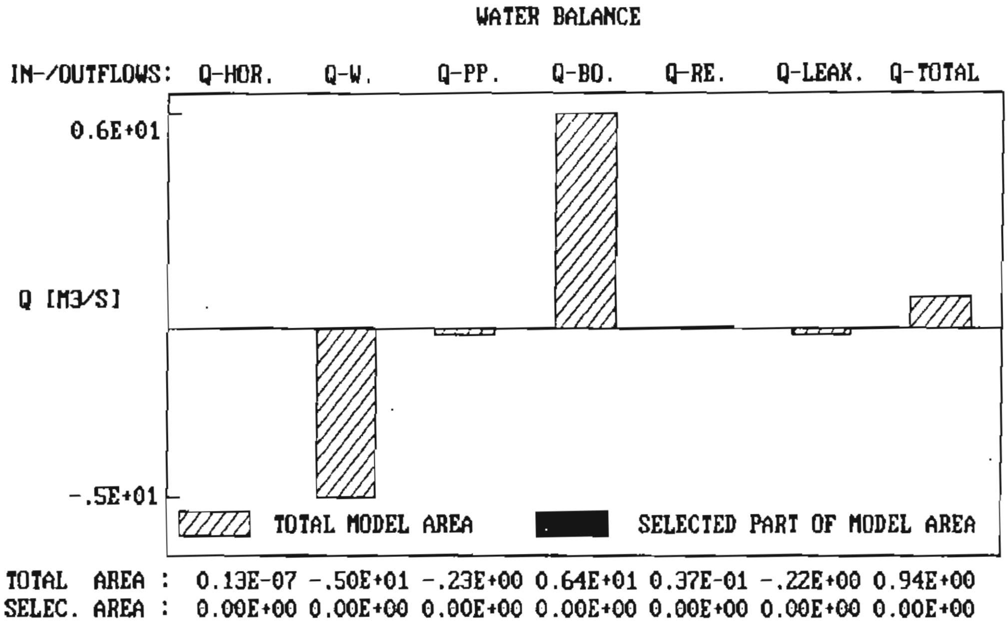


Fig. 12. Predicted water balance for the total modeled area after one hydrologic year under the current conditions

**The second development scenario:**

The second development scenario was the short-term solution of the water logging problem, i.e., the control of ***120*** flowing wells with total discharge ***2222*** $m^3/h$ [14] carried out by RIGW. This means that the total discharge from the flowing wells decreases by *29* %. Under this condition, the predicted water balance components for the old cultivated-modeled area is given in Figure (13).

The surface water inflow item ($Q_{pp}$) was increased from ***0.029*** to ***4.2*** $m^3/sec$, which compensates the increase of discharge from soil water in the southern relatively elevated areas to the adjacent low laying old cultivated areas. Also, the subsurface flow from these controlled wells may cause this large quantity.($Q_w$), which represents the sum of withdrawals through wells was decreased from ***6.4 to 2.6*** $m^3/sec$ . The predicted difference in ($Q_{TOTAL}$) indicated a decrease in soil water storage of about ***0.0021*** $m^3/sec$.

The predicted water balance after about ***3 years*** for this scenario is shown in Figure (14). The predicted surface water inflow item after this period decreased by ***33.30 %*** ($Q_{PP}$) decreased from *4.2* to ***2.8*** $m^3/sec$ and this was expected since there was no excess water due to the control process. The third predicted recharging component of the water balance after about *3* years is the recharge from the boundary fluxes ($Q_{BO}$) which was decreased from ***6.8*** to ***6.4*** $m^3/sec$. This decrease reached ***3%***, which reflects more or less balance between the adjacent neighboring hydrologic units. This reflects that the new reclamation activities may disturb this balance. The predicted leakage from surface watercourses and return flow after irrigation ($Q_{LEAK}$.) was decreased; (from ***0.066*** to ***0.045 m³/sec***) which reflected the decrease of return flow after irrigation as a result of control process.

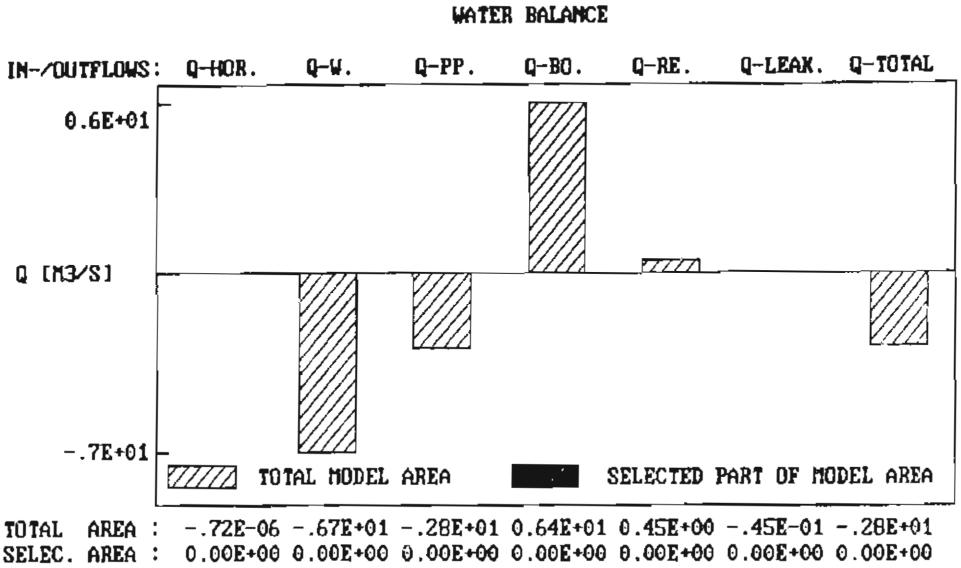


Fig. 13. Water balance of the old cultivated areas (3000 Fed.) after the control of 29% of the total discharge (Steady state condition).

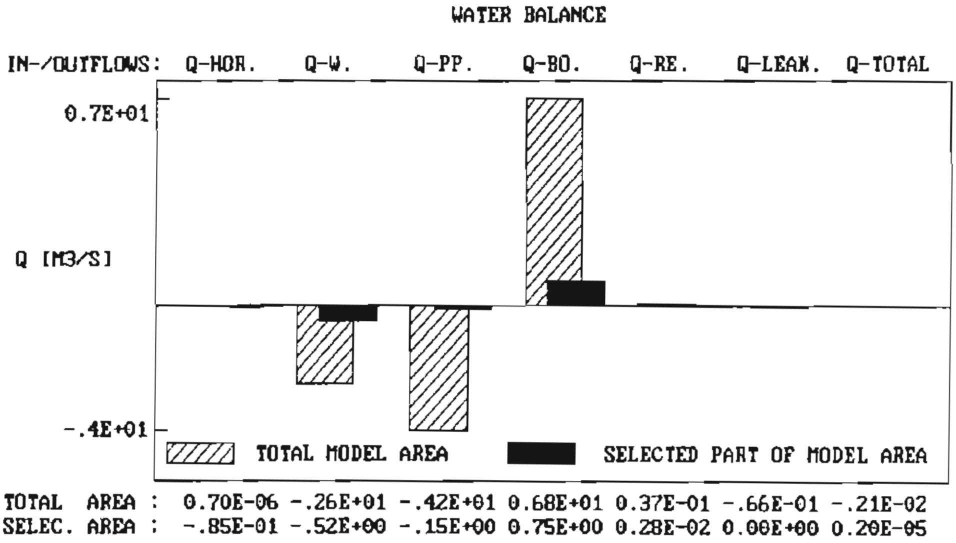


Fig. 14. Predicted water balance of the old cultivated area after about 3 years.

The predicted fluctuation in hydraulic head with time intervals in the observation well located in node (39, 34), Figure (7), in the old cultivated area between Siwa lake and Aghormi lake, Fig. (15), shows a decrease in the soil water level in the order of ***4.8 m*** during the tested period. The slight slope of the curve during the long period (about 3 years) reflects a harmony decrease due to the balance between the other parameters. So the disturbance in the water balance may be attributed essentially to the discharge from the springs and evaporation parameters.

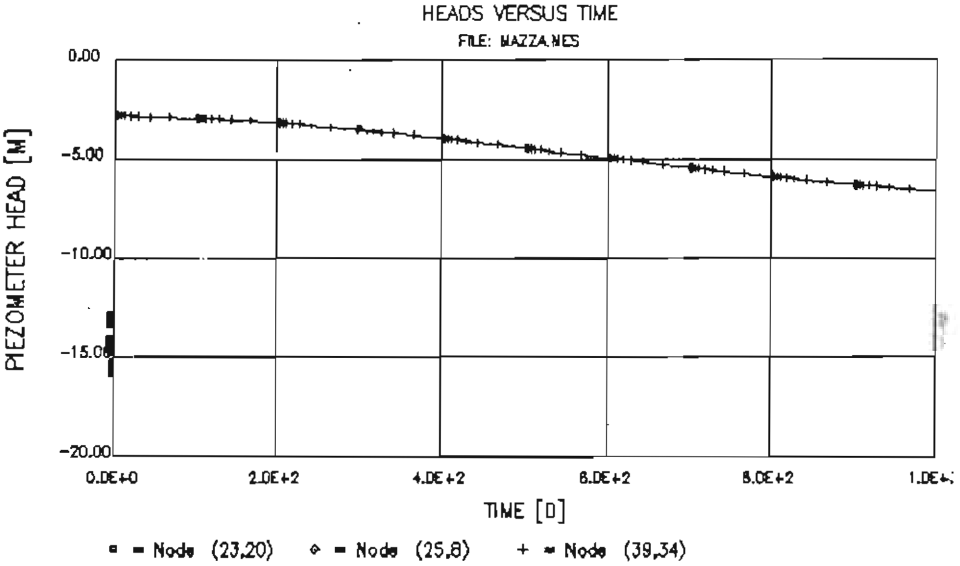


Fig. 15. The head-time relation map in the old cultivated area
( the second scenario).

**The third development scenario:**

This scenario assumes an additional quantity of water to the modeled area equals ***1.49*** $m^3/sec$, which equals the mean water requirements for crop unit of the reclaimed ***10000*** Fed. The predicted water table map for this plan is shown in Figure (16).

It is obvious that the surface water inflow item ($Q_{pp}$) increased from ***-0.029*** to ***+0.62*** $m^3/sec$, which means that the modeled old cultivated area changed under this condition from recharge area to discharge area. The amount of the recharge to the modeled area from the southern locality approaches ***2232*** $m^3$/day, which is greater than the discharge of the controlled wells (***2222*** $m^3$/day). This means that the old cultivated area will return to the first case of water logging before the control of artesian wells.

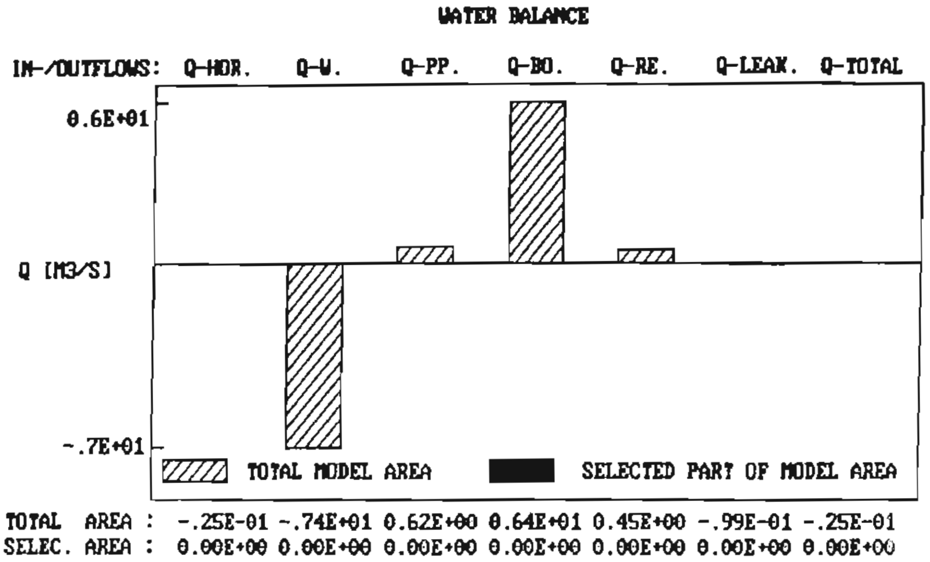
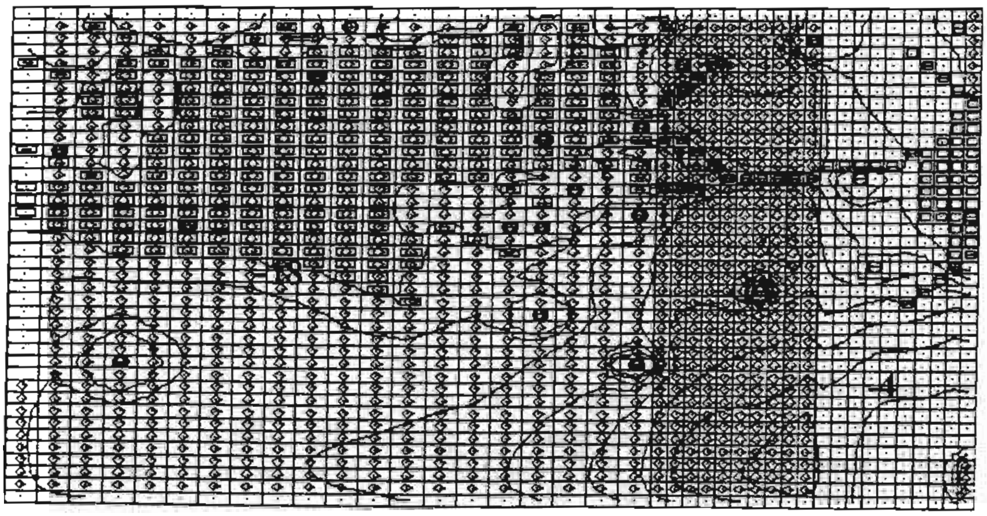


Fig.16. The predicted water balance after the reclamation projects of 10000 Fed. south of the modeled area.



**PIEZOMETER HEADS AT TIME T=1000 D**
**H-MIN = -18 M, H-MAX = -4 M , DELTA-H = 2 M**

Fig.17. Predicted hydraulic heads of the old cultivated area after the reclamation of 10000 Fed. (the third scenario).

The resulting changes of the hydraulic head due to the reclamation of ***10000*** Fed. After about 3 years are shown, Fig. (17). The ***–18*** contour line was running almost parallel to the drainage network and cultivated areas and shows an increase in the surface of Siwa lake as a result of increase the subsurface flow from the southern reclaimed area. While the maximum increase in the head (***- 4 m***) was observed in the center of the reclaimed area in the south which reflected a relatively high hydraulic gradient ($4.7\text{x}10^{-3}$). The crowded contour lines in the SE corner reflects the mound case of soil water, which assured the source of deterioration of the studied modeled area.

## CONCLUSIONS

The present paper focuses on managing the water resources of the old cultivated land in the central part of Siwa oasis (3000 Fed.), which considered the most deteriorated and water logged area. Under the recent reclamation projects of 10000 Fed. in the southern elevated sandy plain, more deterioration will be expected due to the difference in topographic level between the two localities (10m). Numerical simulations were carried out using an adequate mathematical model (Aquifer Simulation Model –ASM - in groundwater flow and solute-transport in two spatial dimensions). The model was calibrated first for steady state conditions with the present extraction rates (620 springs and wells with total discharge of 7634 $m^3/h$). Numerical simulation showed a decrease in soil water with 2.8 $m^3/sec$ via controlling 120 flowing wells (29 % of the total discharge). This means an annual decreasing of soil-water storage of about 66225.6 cubic meters per year, and a decrease of soil water level by 4.8m through about 3 years, which represented a short-term solution for water logging problem. On the other hand, the model showed that the old cultivated area will receive an excess water of 0.62 $m^3/sec$ causing a rise in soil water level as a result of digging more wells required for the mentioned new reclamation projects. So, it is recommended to continue the control of old artesian wells and prevent the digging of any new wells especially in the southern parts. Also, it is recommended that any reclamation activities must depend on the reuse of drainage water. This assures that, the reuse of the drainage water considers the long-term solution of water logging problem in Siwa oasis.

## Nomenclature

$T_{xx}$ = Transmissivity in the $x$ direction ( $L^2/T$);
$T_{yy}$= Transmissivity in the $y$ direction ( $L^2/T$);
$H$ = Potentiometric head (L);
$S$ = Storage coefficient (dimensionless);
$W$ = Distributed volumetric water flux per unit area, positive sign for discharge and negative sign for recharge (L/ T);

$Q_k$ = Volumetric water flux at point (source/sink) located at $(x_k, y_k)$, positive sign for withdrawal and negative sign for injection ($L^3/T$);

$\delta (x - \xi)$ = Dirac delta function; t = Time (T);

x , y = Cartesian coordinates in the principal directions of transmissivity (L); and m = Number of nodal points.

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