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GROUND WATER FLOW AND WATER BUDGET FOR THARTHAR LAKE

*Dr. Thair Sharif Khayyun[1], Mustafa Majeed AbdulAaimma [2], Ahlam Sajir Mohamad [3]

1) Lecturer, Building and Construction Engineering Department., University of Technology, Baghdad, Iraq.
2) Assist lect., Building and Construction Engineering Department, University of Technology, Baghdad, Iraq.
3) Assist lect., Building and Construction Engineering Department, University of Technology, Baghdad, Iraq.

Abstract: Ground water inflow to Tharthar lake and leakage from it, in time and space were evaluated using hydrologic data and simulation model (Processing Modflow Pro) of the ground water system adjacent to the lake. The temporal parameters include the time unit, stress period, time steps and transport steps. The spatial parameters include the initial hydraulic head, horizontal and vertical hydraulic conductivities and the effective porosity. The simulation model indicates that ground water inflow to the lake and leakage from the lake to the ground water system are the dominant components in the total inflow (precipitation, surface water inflow and ground water inflow) and total outflow (evaporation, surface water outflow and leakage) budgets of Tharthar lake. Simulated ground water inflow and leakage were approximately (5) and (10) times larger than precipitation plus surface water inflow to the lake and evaporative losses plus surface water outflow respectively, during years 1992-1996. Exchange of water between Tharthar lake and the ground water system was larger than atmospheric lake exchange. A consistent pattern of ground water inflow was also evident throughout the study period. The residence time for ground water that discharge at Tharthar lake was estimated to be within a range of (4) to (11) years. Flow- path evaluations indicated that the Lower Fars formation probably has negligible influence on the ground water inflow to Tharthar lake. The water budget and flow-path evaluation provide critical information for developing the budgets for Tharthar lake, and for improving the understanding of the relative importance of various processes that regulate the movement of water for lakes in Iraq.

Keywords: *Tharthar lake, Ground water flow simulation, Precipitation, Evaporation.*

جريان المياه الجوفية والموازنة المائية لبحيرة الثرثار

خلاصة: جريان المياه الجوفية الى بحيرة الثرثار والتسرب من البحيرة في الزمان والمكان المعينين تم تقييمه باستعمال البيانات الهيدرولوجية ونموذج المحاكات لمنظومة المياه الجوفية المجاور للبحيرة. ان المتغيرات الزمنية تتضمن وحدة الوقت،فترة الاجهاد،الخطوات الزمنية،الخطوات الانتقالية،اما المتغيرات المكانية فتتضمن الشحنة الهيدروليكية الابتدائية، الموصلية الهيدروليكية الافقية والعمودية والمسامية الفعلية. يشير نموذج المحاكات بان جريان المياه الجوفية الى البحيرة والتسرب من البحيرة الى منظومة المياه الجوفية يمثلان المكونات المسيطرة في موازنات الجريان الكلي الداخل(المطر، الماء السطحي الداخل وجريان المياه الجوفية) والجريان الكلي الخارج (التبخر،الماء السطحي الخارج والتسرب) لبحيرة الثرثار. ان جريان المياه الجوفية الداخل للبحيرة والتسرب منها (المحسوب بواسطة نموذج المحاكات) يمثلان تقريبا (5) و (10) مرات اكبر من (المطر زائدا المياه السطحية الداخلة للبحيرة) و (فواقد التبخر زائدا المياه السطحية الخارجة من البحيرة) على التوالي وخلال الفترة الزمنية من 1992-1996 . ان تبادل الماء بين بحيرة الثرثار ومنظومة المياه الجوفية كان اكبر من تبادل الماء بين البحيرة والمحيط الجوي . ان نمط جريان المياه الجوفية الداخلة للبحيرة كان واضحا وثابتا خلال فترة الدراسة . ان الوقت المستغرق للمياه من لحظة تغذيتها للمياه الجوفية الى لحظة تصريفها الى البحيرة كان بحدود من (4) الى (11) سنة . اشارت تقييمات مسار التدفق بان التشكيل الجيولوجى (الفارس الاوطأ) له تاثير مهمل على جريان المياه الجوفية الداخلة

*thshkhma@yahoo.com

الى بحيرة الثرثار . ان الموازنة المائية وتقييم مسار التدفق تزودنا بمعلومات حرجة لتطوير الموازنات لبحيرة الثرثار وتحسين فهم الاهمية النسبية للعمليات المختلفة التي تنظم حركة المياه للبحيرات في العراق .

1. Introduction

Water resources of the extensive Euphrates and Tigris river basins are very important for people living on its watershed and for its ecosystems. Euphrates and Tigris river basins are extensively used for irrigation and other types for water consumption. So the analysis of hydrological regime of these basins is very important, specially the variability of water level for large reservoirs and lakes like Tharthar lake, Fig.(1). Ground water use in Iraq is small in proportion to surface water, but is more important in rural areas. It may be the only practical source of water in large areas of the country as in [1].

Sustainable water management requires the existence of a certain level of data and information. This is especially true for ground water management (quantity and quality), as ground water flow systems and recharge mechanisms are often not obvious to the affected people. Hydrologic budgets that describe the sources and losses of water to lakes are essential to many lake –management decisions (to adopt the best management practices and evaluate lake-restoration project).

However, many available hydrologic budgets lack the necessary accuracy to define cause and effect clearly when lake levels begin to change. The lack of adequate information on the hydrologic-budget component make it difficult to distinguish the effects of evaporation, lake leakage and ground water withdrawals on lake level declines. Previous budget studies that focused on ground water fluxes generally are based on of three approaches.

The most common approaches treats net ground water inflow and leakage (negative seepage) as the sole unknown term in the hydrologic- budget equation, as in [2].Several articles and reports which describe various aspects of the studies of Tharthar lake and other lakes have been published.

The Ministry of Development as in [3] ,illustrated that the storage coefficient for wadi-Al Tharthar varies between 0.05-0.10. The recharge is about $52*10^6$ m^3/year for a drainage area of 41000 km^2 at Jazira desert and $9*10^6$ m^3/year for a drainage area of 9700 km^2 . The safe yield for Baiji-Samarra is about $6*10^6$ m^3/year/1km of the river and for Jazira desert is $55.5*10^6$ m3/year for 22300 km^2 of drainage area.

For simulation models of the ground water flow systems, hydraulic and storage properties of the aquifers must be known. Recharge to the unconfined aquifer have been estimated on an annual basis using ground water chemistry and water balance method as in [4].

He estimated recharge as 30 percent of rainfall by comparing chloride concentration measured in ground water and atmospheric deposition. The specific yield (Sy) of a soil or rock as the ratio of the volume of water that after saturation can be drained by gravity to its own volume.

Representative specific yields for various geologic materials vary between 6-44%. A storage coefficient is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of an aquifer per unit change in the head normal to that surface. In most confined aquifer values fall in the range ($0.00005<S<0.005$).

The porosities range from near zero to more than 50% and the effective porosity is equal to (0.65-0.95) of the porosity. The horizontal hydraulic conductivity values are 10^{-3}_10^{-5}, 10^{-4}_10^{-6}, 10^{-5}_10^{-8} and 10^{-7}_10^{-10} m/sec for gravel, sands, silts and clay respectively. The horizontal hydraulic conductivity is 1-100 times larger than the vertical hydraulic conductivity (anisotropy ratio), as in [5]

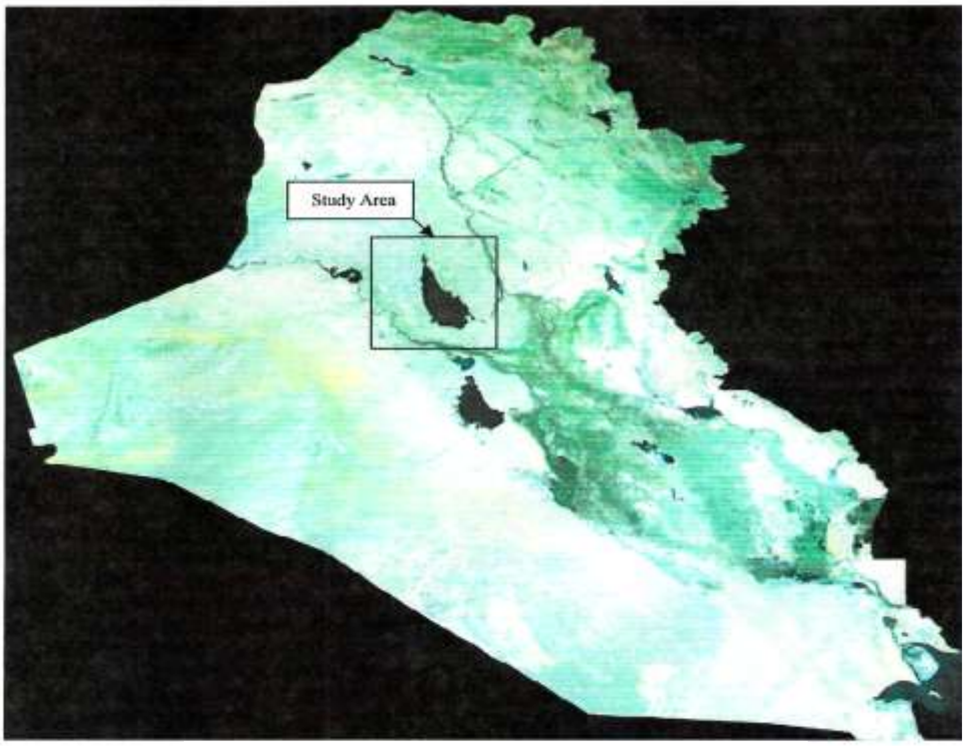

Fig. (1): Tharthar Lake Study Area

2. The Objective of The Study

This study describes:

1. the hydrology of the ground water flow system near lake Tharthar (the exchange of water between lake and surrounding aquifer).
2. the development and calibration of simulation models of the ground water flow system near lake Tharhtar
3. the hydrologic budget of lake Tharthar as determined from model simulation results data collected during (1992-1996).

This study is based on hydrologic and lithologic data that were collected from 1992-1996. Simulated ground water flow paths and residence times are presented in this study.

3. Ground water flow simulation

Ground water flow in the Tharthar lake study area was simulated using the Processing Modflow Pro model. It was designed to simulate three dimensional ground water flow through a porous medium as in [6]. This model divided into many processes (packages). Each process deals with specific equation. The ground water flow process (GWF) deals with the ground water flow equation.

The observation process (OBS) calculate simulated values that are to be compared to measurements, calculates sensitivity equation for hydraulic heads throughout the grid and the parameter- estimation (PES) process solves the modified Gauss-Newton equation to minimize an objective function to find optimal parameter values.

Processing Modflow Pro uses a semi-analytical particle- tracking scheme as in [7], to calculate the ground water paths and travel times. Modflow was used to represent flow conditions during a (60) month period from 1992-1996. the flow models were calibrated to measure water level and ground water exchange rates based on lake-water budget. Ground water flow models included steady- state simulation and transient state simulations. Steady state simulation provided initial conditions for the transient-state simulation and were used to depict flow paths and travel times of lake leakage to the aquifer. Transient-state simulation wear used to estimate aquifer properties with a set of monthly recharge rate.

4. Description of Study Area

Tharthar lake is located in an area characterized by a layer of sediments(Plateau deposits and Bakhtiari formation respectively) varying in thickness and rich in gravel as in [8] .

Upper Fars and Lower Fars formation underlie these rather permeable sediment. The Bakhtiari formation consists of gravel,sand,silt and clay with thickness of 3-10 ft. Upper Fars consist of mostly of fine to medium-grained(sands, silts and silty clay) with a thickness up to 200 ft. Lower Fars formation consists of silts, clay, limestone and gypsum up to 2000 ft. Land surface altitudes ranges from 70 to 200 m above sea level, Fig.(2), as in [9].

Tharthar lake is relatively deep, the altitude of the bottom was approximately (-2m) below sea level. The maximum and minimum record levels were (65m) and (43.45m) respectively. The average monthly water level was (56m). the surface area of the lake ranges from (1740) to (2710) km^2. lake volume ranges from $48.1*10^9$ m^3 to $85.6*10^9$ m^3. The climate of the study area is subtropical /continental with an annual average temperature ranging from (9.6 C°) in January to (47 C°) in July.

Mean-annual precipitation is approximately (150 mm) with the wettest months of (December) through (March) and dry period occurs through June and Septemper. The mean annual lake evaporation is approximately (2250 mm) as in [10].

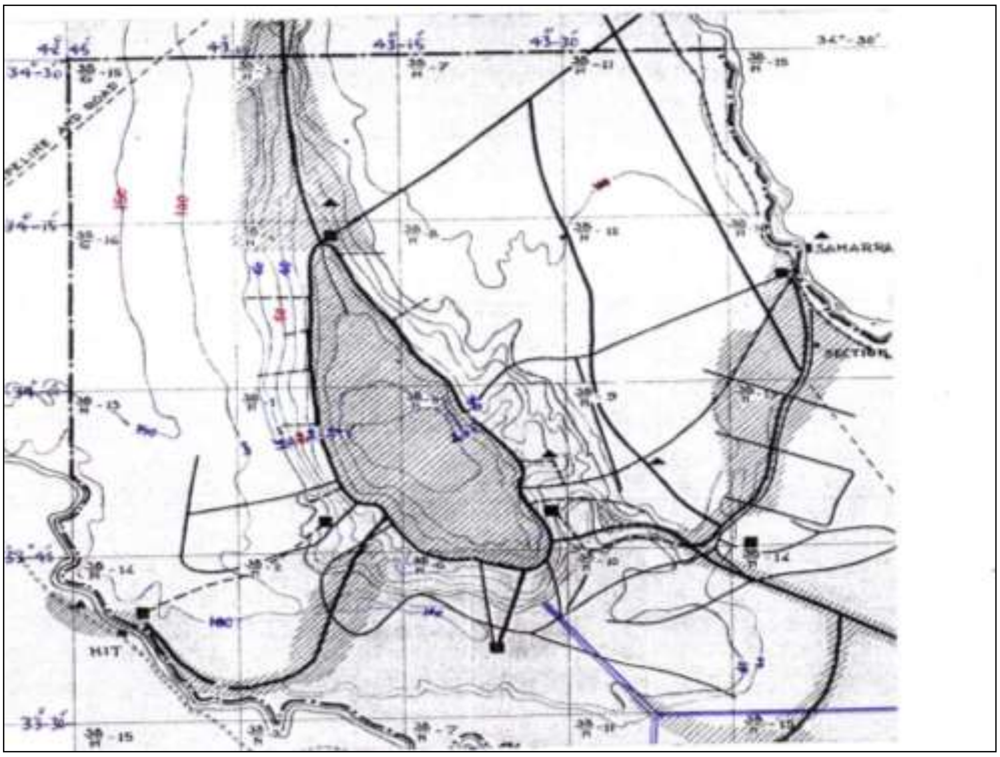

Fig.(2) :Topography of the Tharthar Lake Study Area.

5. Ground Water Flow System

A water level monitoring network was established at the study site to measure water level of the ground water system adjacent to Tharthar lake. The network consisted of (10) monitoring wells finished at various depths and locations in the Upper and Lower Fars aquifers and (11) pumping wells, Fig.(3) , as in [11].

A description of each well (monitoring and pumping) is given in Table (1). Water level (head) data from the wells were used to describe temporal variation in the head distribution near lake Tharthar, evaluate patterns of ground water inflow and leakage and infer hydraulic characteristics.

6. Hydro-geologic setting

The hydrogeologic setting of the study area has been previously discussed as in [3]. They identified (four) hydrogeologic units that influence the hydrology of Tharthar lake (surficial aquifer)(Plateau deposits and Bakhtiari), intermediate unconfined aquifer (Upper Fars) and unconfined-confined aquifer (Lower Fars). A hydrologic section A-B is shown in Fig. (4).

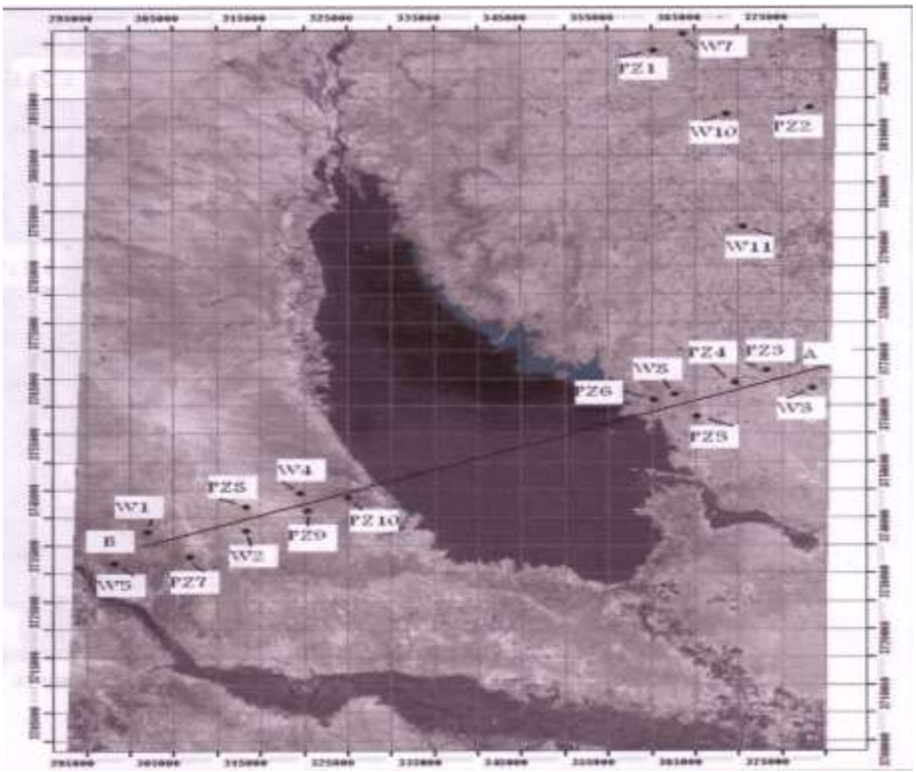

Fig.(3): Location of Data-collection Sites in The Tharthar Lake Study Area.

Table (1) :The Description of Monitoring Wells in The Tharthar Lake
(LFA:Lower Fars Aquifer; UFA: Upper Fars Aquifer).

Well Identifier	*Latitude- longitude*	*Elevation (m)*	*Well depth (m)*	*Static water level(m)*	Hydrogeo- -logic unit
W1	33° 45´ 00´´N-42º50´00´´E	110	80		LFA
W2	33° 45´ 00´´N-42º57´00´´E	110	150	15.0	LFA
W3	34° 00´ 00´´N-43º44´00´´E	83	30	5.8	UFA
W4	33° 50´ 00´´N-43º02´00´´E	98	230	50.0	LFA
W5	33° 41´ 00´´N-42º48´00´´E	100	100	21.2	LFA
W6	33° 38´ 30´´N-43º28´30´´E	70	42.5	8.7	UFA
W7	34° 38´ 15´´N-43º32´50´´E	120	100	25.0	UFA
W8	33° 59´ 00´´N-43º31´00´´E	70	100	9.0	UFA
W9	34° 36´ 40´´N-43º02´45´´E	75	40	2.5	UFA
W10	34° 26´ 30´´N-43º36´30´´E	140	85	31	UFA
W11	34° 16´ 05´´N-43º37´20´´E	88	72	23	UFA
Pz1	34° 34´ 55´´N-43º30´60´´E	115	120	11.2	UFA
Pz2	34° 27´ 00´´N-43º44´00´´E	95	70	18.4	UFA
Pz3	34° 02´ 00´´N-43º40´00´´E	74	70	5.3	UFA
Pz4	34° 00´ 30´´N-43º36´00´´E	70	70	6.5	UFA
Pz5	33° 57´ 15´´N-43º32´00´´E	67	70	7.3	UFA
Pz6	33° 58´15´´N-43º30´45´´E	66	70	9.8	UFA
Pz7	33° 42´ 15´´N-42º54´00´´E	114	70	10.2	LFA
Pz8	33° 48´ 30´´N-42º57´00´´E	120	96	23.2	LFA
Pz9	33° 48´ 00´´N-43º02´15´´E	100	100	20.3	LFA
Pz10	33° 50´ 00´´N-43º05´30´´E	65	100	9.1	LFA

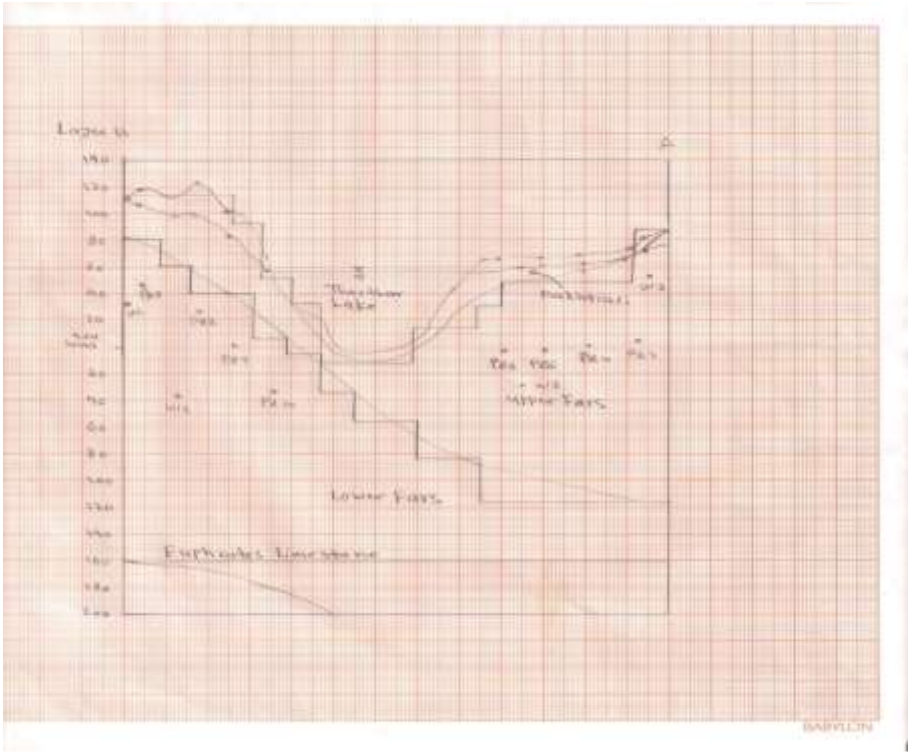

Fig.(4) :Hydrologic Section A-B, Showing the Observation of Wells Used to Construct the Section .

The first layer is Bakhtiari which consist of (gravel, sand and silt). This layer extends from land surface (30-88) m above sea level. The horizontal hydraulic conductivity ranges from (10 to 80) m/d. The ratio of horizontal to vertical hydraulic conductivity (anisotropy) was assumed within a range of (1) to (20). The porosity of the layer is within a range of (25) to (45), specific yield within a range of (10) to (30)% and specific storage of the layer is within a range of (0.005 to 0.010) m^{-1}, as in [12].

The second layer is (Upper Fars) which consist of (sand, silt and silty clay). The top and bottom of this layer occur at altitude of (88-120)m above sea level and (70m) above sea level to 117m below sea level respectively.

The vertical hydraulic conductivity was assumed to be within the range of 0.1 to 4 m/d and the horizontal hydraulic conductivity is within the rang of 5 to 60 m/d. The anisotropy of this layer was assumed to be within 10 to 50. The porosity was assumed to be in the range of 25 to 50 and specific storage was assumed to be in the range of 10^{-3} to 10^{-5} m^{-1} . The thickness of this layer may be varying between 50-200 m. The specific yield was in the range of 2-10%.

The third layer is Lower Fars which consists of (silt, clay, gypsum). The top of this layer is at depth of 70 to 117 m above and below sea level respectively. The bottom of this layer is at depths of 118-200 m below sea level. This aquifer has a thickness of approximately 300 m. The horizontal hydraulic conductivity is within the range of 2.0 to 10^{-3} m/d. The anisotropy of this layer was assumed to be in the range of 20-300.

7. Head Distribution and Ground Water Flow

Head fluctuations during the study period were generally consistent with the typical seasonal pattern of precipitation in the study area (wet conditions during the winter and dryer condition during summer season of 1992 and 1996). Heads rose during the wet winter season of 1992 -1996 and fell during dry periods during the summer months of 1992 and 1996, Fig. (5). Water table altitudes were consistently higher than the stage of Tharthar lake and water-table altitudes increased with distance from the lake.

Higher water table altitudes were observed in the south – west of the study area and decreased to the North-East. The head data also indicated no potential for downward leakage from Tharthar Lake to the layer below it.

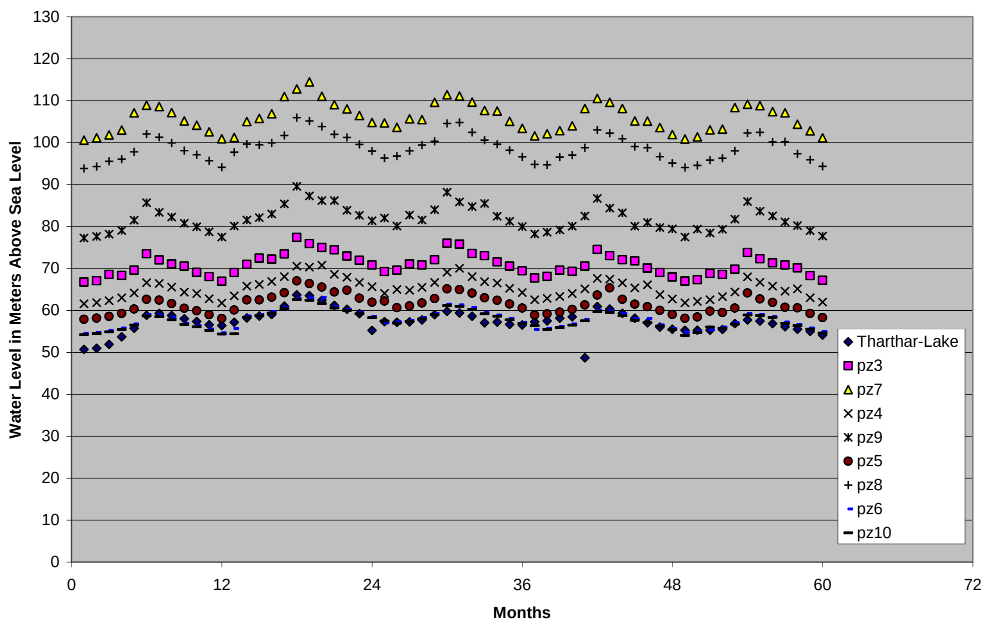

Fig.(5): water levels of tharthar lake and selected groundwater monitoring piezometers,1992-1996.

8. Boundary condition

Three boundaries were used to characterize the groundwater flow system near tharthar lake, (1) a lateral no-flow boundary, (2) an upper free- surface boundary defined by the water table and the water surface of Tharthar Lake and (3) a lateral specified –head boundary. A lateral no-flow boundary was used to define the perimeter of the shallow groundwater system. The existence and location of no-flow and specified-head boundary was inferred from water – table and topographic maps. The location of upper boundary is partially determined by the flux of water across this boundary (recharge rates for the water-table and net-precipitation rates for the lake surface).

Values of recharge over the water-table boundary were estimated from the previous estimates of recharge for similar areas in Iraq and the area of this study. The recharge rates were generally in the range of 10^{-8} to $5*10^{-11}$ m/sec. These values were (5-25%) of the precipitation for 1992 to 1996.

9. Lake-water budgets

Monthly water budgets were computed for tharthar lake during the five year periods (Jan. 1992-Dec. 1996) using the following equation , as in [13]):

$$\Delta S = P - E + A + S_i - S_o + G_i - G_o \qquad \text{.........................(1)}$$

Where: ΔS is the change in lake volume for a given time period; P is the precipitation; E is evaporation; A is total lake augmentation; S_i is surface water inflow; S_o is surface –water outflow or direct pumping from the lake; G_i is groundwater inflow; and G_o is ground-water outflow (or lake leakage).

All of the terms in Eq. (1), can be measured or estimated directly with the exception of the ground-water flow terms. The net ground water flow, G_{net} , was computed by rearranging Eq. (2) as:

$$G_{net} = G_i - G_o = \Delta S - P + E - A - S_i + S_o \qquad \text{...................(2)}$$

Because G_{net} is computed as a residual to the rest of the budget, it incorporates all of the errors or uncertainties in the other water-budget terms.

Estimates of lake volume change were assumed to have a coefficient of variation of 5% , as in [14]. Monthly precipitation estimates and lake evaporates estimates were assumed to have a coefficient of variation of 15% and 14% respectively. The standard deviation of the error associated with the net groundwater flow estimate σϵ, Q_{net} was computed as follows , as in [15]:

$$\sigma\varepsilon, Q_{net} = \sqrt{\left((p * cv_p)^2 + (E * cv_E)^2 + (\Delta s * cv_{\Delta s})^2\right)} \qquad \text{............(3)}$$

where : Cv is the coefficient of variation

The results of the monthly net ground water flow computations to Tharthar lake during (1992-1996) and associated errors are listed in Table (2) and are shown in Fig.(6). The computed monthly net ground water flow peaked during the winter wet season (6 months) in 1993-1995, Fig.(6). The large positive peak for the winter 1993 resulted from historically high precipitation during this period and due to the water surface inflow.

The negative values of net ground water flow indicate that leakage exceeded ground water inflow. Volumetric estimates of precipitation and evaporation were computed from the volume per unit area estimates by multiplying the total precipitation or evaporation by lake area. Lake volume changes and lake area were estimated using lake-stage measurements. The total area above the zero line (Q_{net}=0) of Fig.(6), represents the sum of all months with positive values of net ground water flow, and the total area below the zero line represents the sum of all months with negative values of net ground water flow.

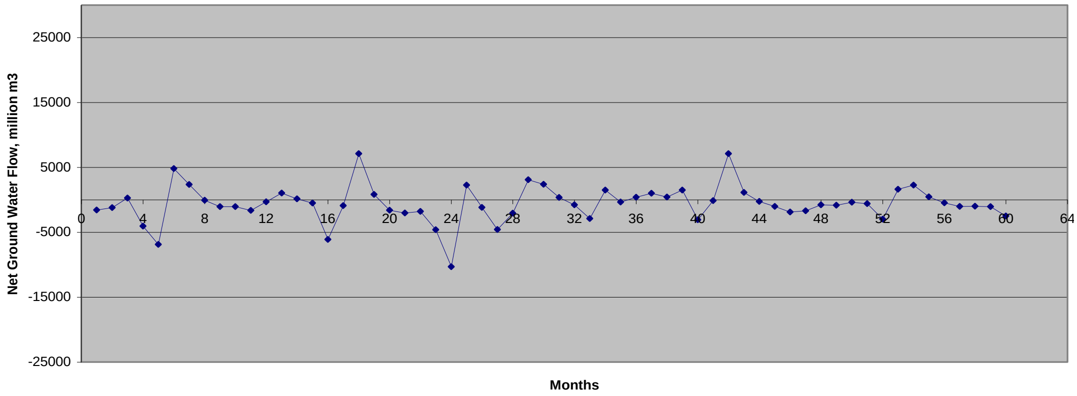

Fig.(6): computed monthly net ground water flow to lake tharthar during 1992-1996.

During the wet year of (1994), the area above and below the line are approximately equal which indicates that the groundwater inflow was approximately equal to leakage during(1994).However, the shaded area above the zero line was much smaller than

Table(2):Monthly Net Groundwater Flow to Tharthar Lake,(1992-1996).

Month	Average lake Volume m3*10^9	Change in lake volume m3*10^6	Precipita-tion m3*10^6	Evapora-tion m3*10^6	Surface water inflow m3 *10^6	Surface water out flow m3*10^6	Net ground-water flow m3*10^6	Standard deviation of error	error in percent of net gr-wat-fl.
				1992					
Jan.	57.47781	322.11	46.22003	115.9974	1944	0	-1552.11	23.89936	1
Feb.	58.0639	586.0929	48.61249	159.5692	1892.16	0	-1195.11	37.56322	3
Mar.	59.96318	1899.281	24.29257	297.1722	1892.16	0	280.001	103.7418	37
Apr.	63.6611	3697.916	4.219673	548.5575	8294.4	0	-4052.15	200.2119	4
May	68.03644	4375.336	7.780754	687.5669	11923.2	0	-6868.08	239.0108	3
June	74.9947	6958.26	0.870271	1022.942	3162.24	0	4818.091	376.2354	7
July	76.12516	1130.462	0	1229.485	0	0	2359.947	181.1708	7
Aug.	74.94873	-1176.43	0	1115.473	0	0	-60.9527	166.8768	273
Sept.	73.167	-1781.73	0	734.3587	0	0	-1047.37	136.0381	12
Oct.	71.63097	-1536.03	0	502.8958	0	0	-1033.13	104.1892	10
Nov.	69.93327	-1697.7	149.4477	216.5587	0	0	-1630.59	92.88252	5
Dec.	69.53413	-399.142	38.92906	121.3328	0	0	-316.738	26.85011	8
				1993					
Jan.	71.24948	1715.346	153.5036	174.5657	699.84	0	1036.568	92.1058	8
Feb.	73.57629	2326.813	57.48385	225.5324	2332.8	0	162.0618	120.8571	74
Mar.	74.58152	1005.233	5.444406	409.5678	1892.16	0	-482.804	76.25429	15
Apr.	75.4551	873.5774	252.8337	519.1653	7257.6	0	-6117.69	92.89237	1
May	80.0882	4633.105	32.10369	721.8068	6220.8	0	-897.992	252.7826	28
June	86.60126	6513.055	0	1108.556	518.4	0	7103.211	360.7438	5
July	86.13296	-468.295	0	1283.295	0	0	815	181.1806	22
Aug.	83.44647	-2686.49	0	1091.356	0	0	-1595.13	203.44	12
Sept.	80.61142	-2835.06	0	800.7828	0	0	-2034.28	180.7276	8
Oct.	78.36416	-2247.25	32.66716	497.2381	0	0	-1782.68	132.2702	7
Nov.	75.9169	-2447.27	16.83532	282.1801	2423.52	0	-4605.44	128.6072	2
Dec.	66.98893	-8927.97	24.28043	142.8593	1503.36	0	-10312.7	446.8611	4

				1994					
Jan.	71.6085	4619.573	65.72824	118.5498	2410.56	0	2261.835	231.784	10
Feb.	71.22707	-381.434	29.50285	244.1123	984.96	0	-1151.78	39.38648	3
Mar.	71.47376	246.6955	23.98215	384.3109	5184	0	-4576.98	55.31643	1
Apr.	72.50996	1036.198	70.78216	618.9212	3628.8	0	-2044.46	101.5137	4
May	75.33987	2829.908	1.497788	812.3001	557.28	0	3083.431	181.5315	5
June	77.1707	1830.83	0	1168.322	596.16	0	2402.992	187.439	7
July	76.35689	-813.807	0	1181.568	0	0	367.7611	170.3506	46
Aug.	74.5586	-1798.29	0	1024.639	0	0	-773.651	169.2997	21
Sept.	70.9137	-3644.9	0.474069	766.2137	0	0	-2879.16	211.4713	7
Oct.	71.31673	403.0258	76.33714	457.0701	0	725.76	1509.519	68.05796	4
Nov.	70.0888	-1227.93	170.7346	172.2601	0	894.24	-332.161	70.76011	21
Dec.	69.84448	-244.322	64.93261	136.183	0	557.28	384.2083	24.64947	6
				1995					
Jan.	71.45132	1606.841	25.5264	129.4212	725.76	38.88	1023.856	82.4488	8
Feb.	71.9459	494.5776	137.504	216.2148	259.2	103.68	417.7684	44.19513	10
Mar.	73.46249	1516.589	84.52373	361.058	544.32	259.2	1508.003	92.01068	6
Apr.	74.23807	775.5876	94.4078	458.4817	4665.6	453.6	-3072.34	76.3178	2
May	74.55442	316.3433	9.895835	930.2085	2125.44	751.68	-137.104	131.1946	4
June	79.89836	5343.948	0.393907	1073.134	349.92	1036.8	7103.568	306.539	4
July	78.48166	-1416.71	0	1325.703	0	1218.24	1127.235	198.6565	17
Aug.	76.102	-2379.65	0	1190.008	0	946.08	-243.564	204.7262	84
Sept.	73.41699	-2685.02	0	730.8892	0	933.12	-1021.01	168.8004	16
Oct.	70.9137	-2503.29	0.355552	640.2299	0	0	-1863.41	153.9482	8
Nov.	68.71721	-2196.49	2.88479	521.57	0	0	-1677.8	131.8843	7
Dec.	67.599	-1118.21	19.68747	356.4228	0	0	-781.477	74.99766	9
				1996					
Jan.	67.09767	-501.331	110.5991	162.0536	370.656	0	-820.532	37.66002	4
Feb.	67.09767	0	21.37344	229.1142	567.648	0	-359.907	32.23582	8
Mar.	67.09767	0	87.52933	377.3713	857.952	0	-568.11	54.43895	9
Apr.	67.48986	392.189	11.81909	485.3781	3846.528	0	-2980.78	70.74797	2
May	70.57871	3088.848	10.15148	673.0669	2128.032	0	1623.731	180.9253	11
June	72.48736	1908.65	0	790.2306	432.864	0	2266.016	146.1056	6
July	71.90086	-586.491	0	1046.918	0	0	460.4271	149.4733	32
Aug.	70.5118	-1389.06	0	934.1267	0	0	-454.936	148.0762	32
Sept.	68.91548	-1596.32	0.001157	584.6151	0	0	-1011.7	114.3213	11
Oct.	67.5335	-1381.98	0.228551	405.9346	0	0	-976.273	89.46739	9
Nov.	66.12213	-1411.37	10.94648	390.7224	0	0	-1031.6	89.30206	8
Dec.	64.59728	-1524.85	53.23106	204.2714	1117.152	0	-2490.97	81.82024	3

than the area below the line during the dryer year of(1992 and 1996) .This indicates that leakage from Tharthar lake greatly exceeded groundwater inflow (leakage to inflow ratio is 2:1).

The significance of groundwater inflow and leakage to the water budget of tharthar lake is illustrated by a plot of cumulative changes in lake volume over time in Fig.(7). If Tharthar lake were completely isolated from the groundwater system and one assumes that surface runoff is negligible and that errors in estimating atmospheric fluxes and lake volume changes are reasonably small and unbiased , then graphs of cumulative net precipitation and water surface input and cumulative changes in lake volume should be approximately coincident .

However, during the wet and dry seasons , the volume of lake increased and decreased much faster than predicted by atmospheric fluxes alone. These observations indicate that groundwater inflow and leakage are significant components of the water budget of Tharthar lake.

The monthly net groundwater flow values indicate that monthly inflow and leakage rates of at least ($7.1*10^9$) and ($6.9*10^9$) m^3 respectively, occurred during the study period, Table (2).

Estimates of minimum annual groundwater inflow and leakage during the study period can be made by summing months with positive net groundwater flow values and assigning these to groundwater inflow and by summing months with negative net groundwater flow values and assigning these to groundwater outflow (leakage).

This procedure results in estimates of minimum annual groundwater inflow of (20, 28, 42, 55, and31%) of the total inflow (precipitation plus ground water inflow) for 1992 to 1996 respectively. Minimum annual leakage was estimated to be (73 , 79, 56, 39, and 63%) of total outflow for 1992 to 1996 respectively .

11. Simulation of groundwater flow

A computer program (Processing Modflow Pro) was used to estimate groundwater flow within the layer (1) to layer(7).Three dimensional models were developed to represent the Tharthar lake groundwater system under steady- state and transient conditions . The horizontal grid and boundary conditions used in the steady-state and models are shown in Fig.(8).

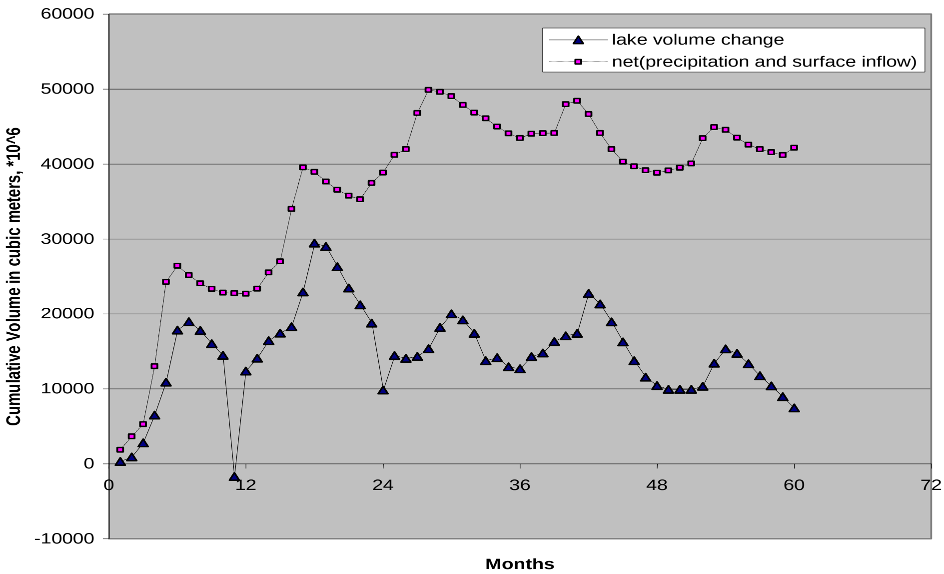

Fig.(7): cumulative monthly net-precipitation and surface inflow and cumulative monthly lake-volume changes for tharthar lake, 1992-1996.

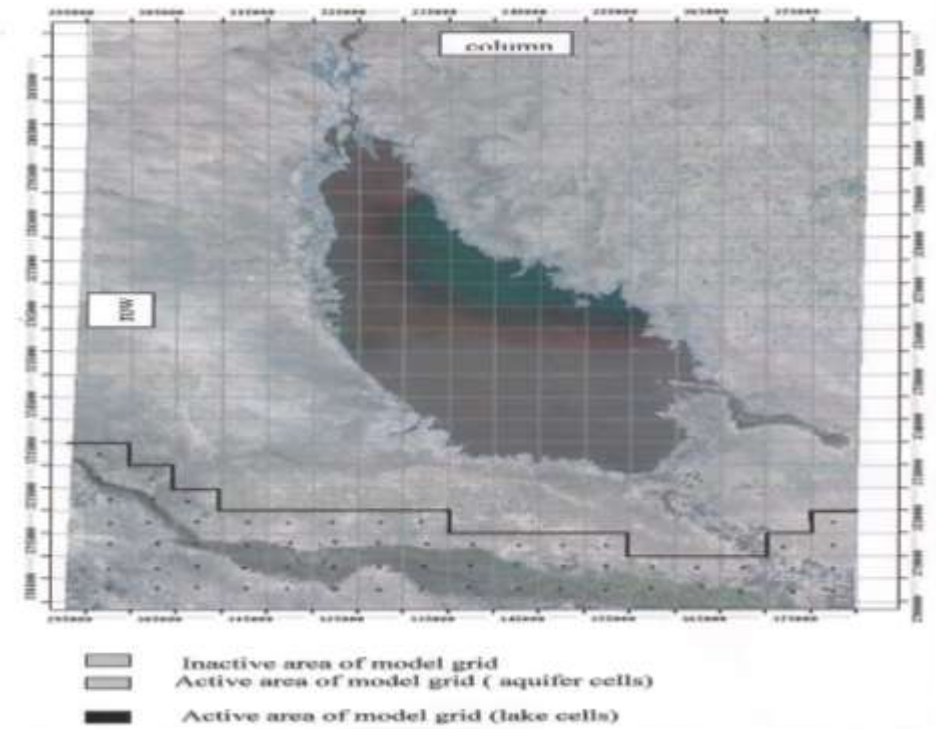

Fig.(8): area discretization and boundary condition for simulation models of groundwater flow near tharthar lake.

The modeled area covers (10800) km^2 . The horizontal grid is composed of (23) rows and (17) columns (support models with up to 1000 stress periods, 200 layers and 250000 cells in each model layer). All rows and columns in the grid have a constant width of 5 km. In vertical section the numerical models are discretized into (seven) horizontal layers of varying thickness, Fig.(9).

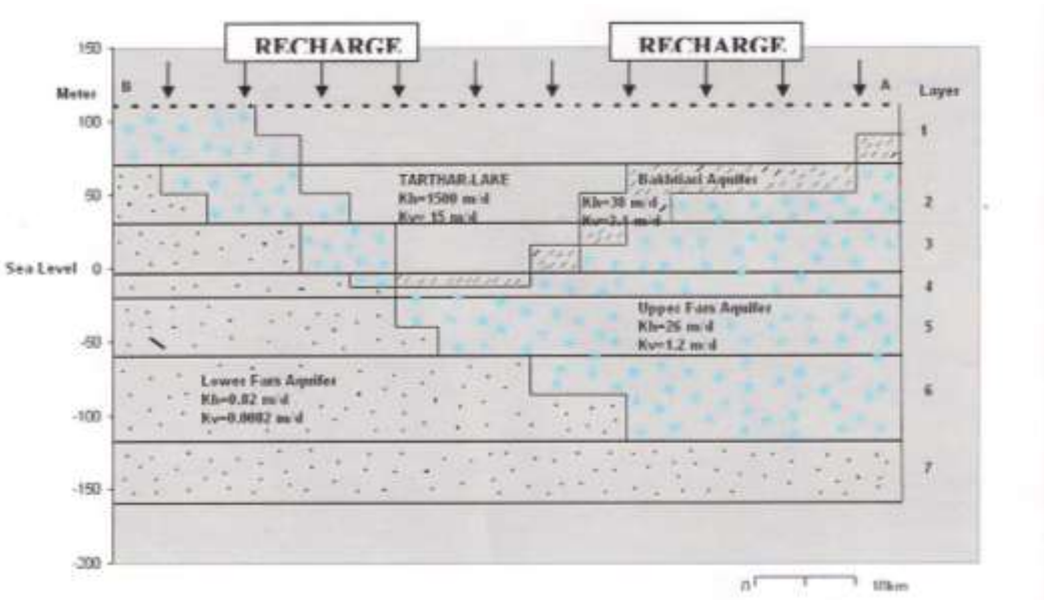

Fig.(9): vertical discretization, boundary condition, and calibrated hydraulic conductivity for simulation model of the groundwater flow system near tharthar lake, cross-section AB location is shown in Fig.(3).

Layer 1 was simulated as a water table layer and layer 7 was treated as a specified head boundary. Several parameter zones were used to represent hydraulic property variations within the model layers. The top of the layer 7 which defines the lower boundary of the simulation model, is a set at a constant altitude of (161) m below sea level.

Tharthar lake is represented in the model by a zone of highly conductive material in the layers (1-3), Fig. (9). For transient simulations, the storage properties of this zone are identical to those of water.

Within layer variations in horizontal hydraulic conductivity are accounted for by using equivalent hydraulic conductivity values, as in [16]. The transmissivity of cells in the transition zone was computed as follows:

$$T = LK_{h,eq} = L\left(\frac{K_{h,layer1}}{2} + \frac{K_{h,layer2}}{2}\right) \qquad \text{………………………(4)}$$

Where :T is transmissivity, L is the layer thickness, $K_{h,layer}$ is the horizontal hydraulic conductivity of the layer. Vertical flow between model layers is simulated using the leakance parameter (vertical hydraulic conductivity divided by flow path distance). Values of recharge, net precipitation and layer (7) head are constant in space and time for steady-state model, and constant in space, variable with time for the transient model. Layer (7) is active because it can vary with time and act as a source or sink of water for the overlying active layers.

12. Calibration of steady –state models

Four steady -state models were calibrated to hydrologic conditions observed on four different dates: Jan.(1992), May (1993), Nov.(1994), and Aug.(1995). These models were developed to satisfy one or more of the following objectives:

1- prior estimates of hydraulic properties and their special distribution .
2- provide initial conditions for transient simulations .
3- provide flow fields necessary for evaluation of flow paths and residence times of ground water that discharges to Tharthar lake (ground water inflow).

The model calibrated to Jan.1992 conditions was developed with objectives (1) and (2) in mind. The Aug.1995, steady-state model was developed to provide initial conditions for transient simulation of the latter part of the study period (Aug.1995-Dec.1996). Finally, steady-state models of May1993 and Nov.1994 were developed to evaluate ground water flow paths and residence times for low water levels and high water levels conditions respectively.

The steady-state models were calibrated by comparing simulated and observed heads and by comparing the simulated leakage from lake with the minimum estimate of leakage from the preceding section describing net ground water inflow to lake.

The head calibration criteria were set at ± 0.3m. Simulated leakage from lake was also required to be greater than ($0.23*10^9$) m^3/d for an acceptable calibration.

Calibration of the steady-state models was achieved by use of horizontal hydraulic conductivity (K_h=26 and 0.164 m/d) in the Upper Fars and Lower Fars respectively, and anisotropy (K_h:K_v=20:1) within each unit.

The root mean square error of the head differences was within the calibration criteria at this point, but the simulated heads were low for the lake (-0.36 m) and high in the Lower Fars unit wells (pz.9) and (pz.10) (approximately 0.55m). Some improvement was achieved by increasing K_h in the Lower Fars unit from 0.164 m/d to 0.80 m/d. Recharge was then increased to (0.42 m/yr) to increase heads in the Upper Fars and lake.

The final model configuration was obtained by increasing the anisotropy of Bakhtiari aquifer by a factor of 5 to reduce the leakance between the Upper Fars and Lower Fars. The calibrated values of hydraulic conductivity are shown in Fig.(9).

The head RMSE for the final configuration of the Jan.1992 model was 0.13m and simulated heads for this configuration were within -0.16 to 0.28m of the observed heads for all wells and piezometers. For this final model configuration, simulated leakage from Tharthar lake to the ground water system was ($0.40*10^9$ m^3/d) which was greater than the estimated lower limit of ($0.23*10^9$ m^3/d). Simulated ground water inflow to Tharthar lake was ($0.24*10^9$ m^3/d).

Calibration of the other steady-state models (May1993, Oct.1994 and Aug.1995) were achieved by adjusting the recharge and net precipitation rates only. For model (May1993), recharge and net precipitation were set at (0.320) and (-4.14) m/yr respectively. The head RMSE for this match was 0.21 m and simulated heads were within -0.24 to 0.16 m of observed heads for all wells and piezometers.

For the model (Nov.1994), recharge and net precipitation were set at (0.047) and (-0.012) m/yr, respectively. The head RMSE for this match was 0.25 and simulated heads were within 0.20 to +0.29 m of observed heads for all wells and piezometers.

For the simulation of the Aug. 1995, values of recharge and net precipitation were (0.003) and (-7.14) m/yr respectively. The head RMSE for this match was 0.24 m and simulated heads were within -0.46 to +0.25m of observed heads for all wells and piezometers. For the simulation of Dec. 1996, values of recharge and net precipitation were identical to those used in the simulation of conditions on Jan. 1992. The head RMSE for this match was 0.26 m and simulated heads were within -0.32 to +0.22 m of observed heads for all wells and piezometers .The simulated water table for conditions observed on May. 1993, is represented by the contour map shown in Fig. (10) .

The sensitivity of the steady-state models to changes in models inputs was examined by varying model input variables such as recharge and hydraulic conductivity and comparing the model output to that of the calibrated models for conditions on Jan. 1992. The head response of the steady-state models was most sensitive to changes in recharge, horizontal hydraulic conductivity and anisotropy of the Upper Fars formation, and horizontal hydraulic conductivity of the Lower Fars formation.

The head response of the steady –state models was only partially sensitive to changes in the anisotropy of the Lower Fars formation and insensitive to changes in the leakance, Fig. (11) and Fig. (12).

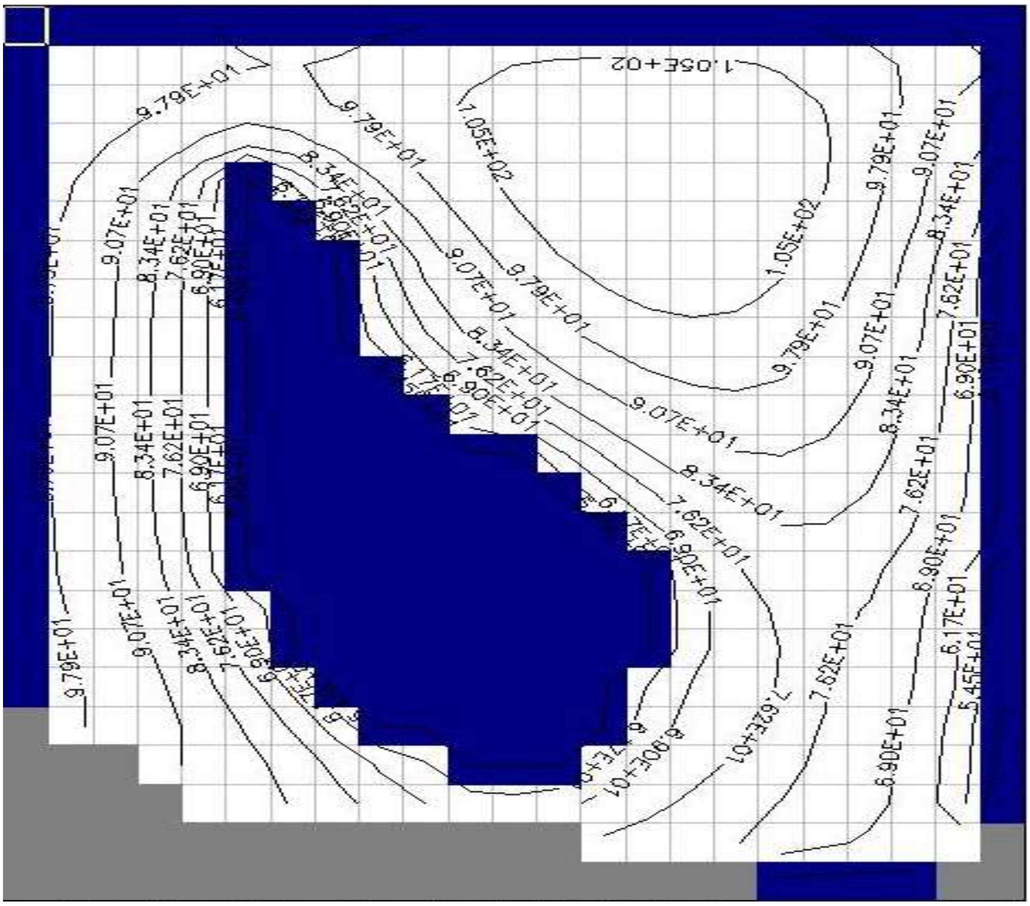

Fig.(10): Contour Map of the Simulated Heads, May 1993.

13. Calibration of transient model

Calibration of the transient model consisted of determining values of storage properties .The hydraulic conductivity distributions in the transient model were identical to those in the calibrated steady-state models. Calibration of the transient model began with a storage property calibration in which values of specific yield in layer (1) and specific storage in layers(2-7) were systematically adjusted in an effort

to simulate the slope of well hydrographs during period (Aug.(1995)-Dec.(1996)). The specific yield for lake cells in layer (1) was fixed at a value of (1) and the specific storage of lake cells in layers(2-3) was fixed at a value of ($4.5*10^{-6}$ m^{-1}),which is equal to the product of the compressibility of water and the specific weight of water .

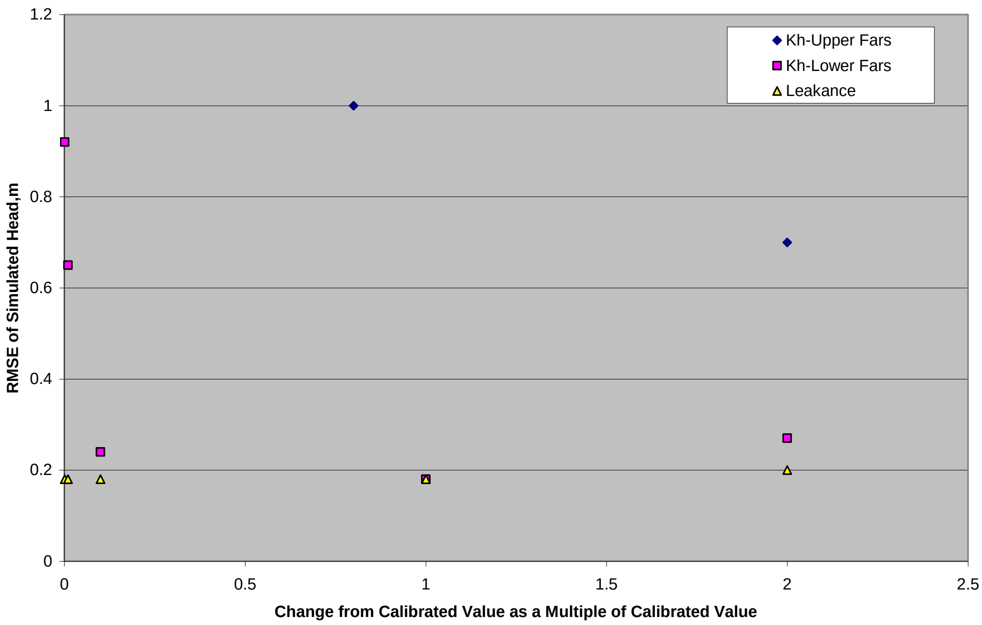

Fig.(11): Sensitivity of steady-state models of groundwater flow system to change in Kh and Leakance.

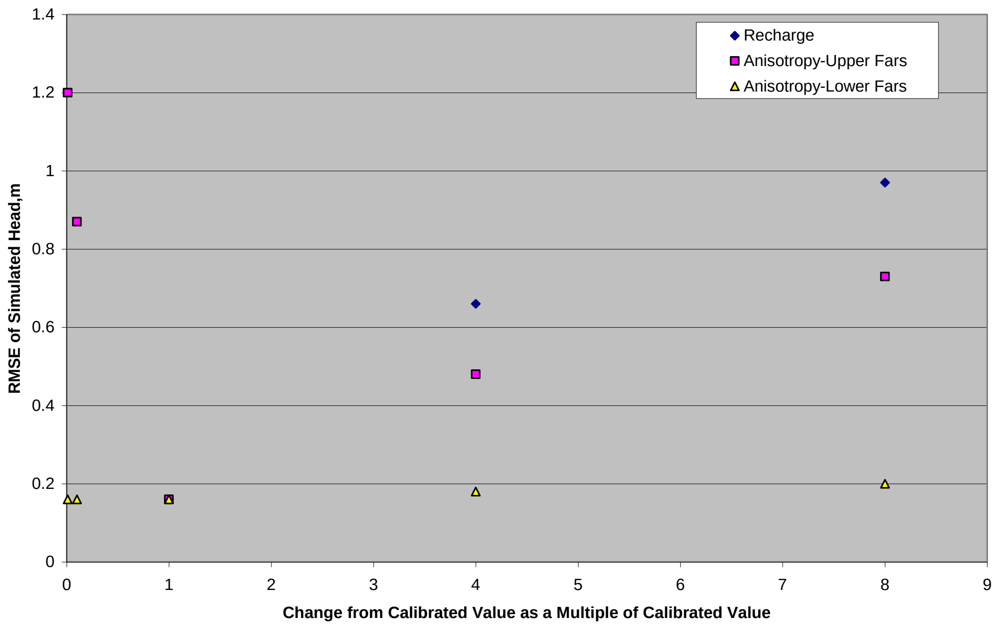

Fig.(12): Sensitivity of steady-state models of groundwater flow system to changes in recharge and anisotropy.

The calibrated head distribution from the steady- state simulation of (Aug.(1995)) was used as the initial conditions for the (Aug.(1995) to Dec.(1996) simulation period .

A suitable match to the (Aug.(1995) to Dec.(1996)) hydrograph was obtained by using a constant value of specific yield of(0.17) for aquifer cells in layer (1) and a constant specific storage value of($7*10^{-5}m^{-1}$) for aquifer cells in layers (2-7) .

Storativity values for individual model layers (2-7) were then calculated by multiplying layer thickness by the calibrated specific storage value of ($7*10^{-5}m^{-1}$).

Specific yield was determined by initially setting specific storage to ($7*10^{-5}m^{-1}$) and evaluating the correspondence between simulated and measured head declines for specific yield values of (10% to 30%).

The calibration process for specific yield and specific storage is illustrated in Fig.(13).It indicates that model was much more sensitive to changes in specific yield than to changes in specific storage .

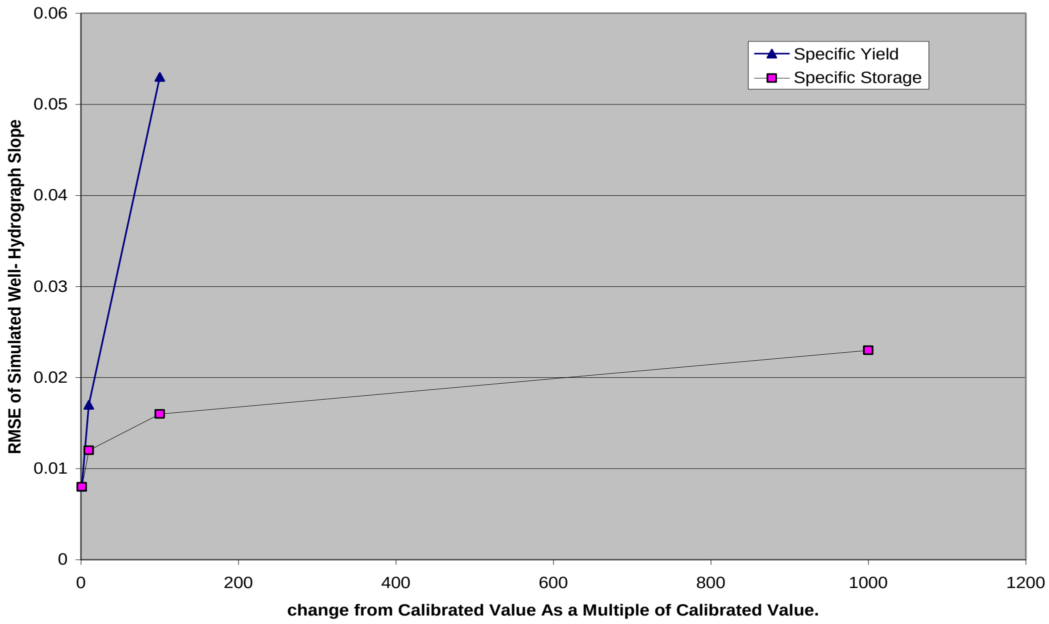

Fig.(13): Sensitivity of transient model of the properties groundwater flow to changes in aquifer storage.

Simulated and measured heads for Tharthar lake and selected piezometers are shown in Table (3). Simulated heads were generally within 0.30m of observed heads during the study period.

Simulated and computed net ground-water flow to Tharthar lake is shown in Fig.(14). Simulated net ground-water flow values within the 99% confidence intervals of the computed values. Differences between simulated and computed monthly net ground-water flow were within -16.20 and + 17.1 % of total inflow or total outflow for all months in 1992-1996.

Table (3): Simulated and Observed Heads for Tharthar Lake and Adjacent Ground- Water System (1992-1996).

Year	month	PZ7	PZ9	PZ4	Tharthar-Lake

		Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
1992	J	100.58	100.43	77.23	77.25	61.53	61.44	50.68	50.55
	F	101.10	100.91	77.63	77.51	61.85	61.73	50.97	50.74
	M	101.83	101.60	78.19	78.01	62.29	62.34	51.90	51.81
	A	102.97	102.70	79.06	78.89	62.99	62.82	53.67	53.48
	M	107.10	106.83	81.49	81.30	64.14	64.00	55.70	55.80
	J	108.89	108.74	85.67	85.60	66.61	66.42	58.80	58.67
	J	108.57	108.61	83.37	83.30	66.42	66.37	59.29	59.35
	A	107.12	107.03	82.25	82.30	65.53	65.50	58.78	58.67
	S	105.15	105.05	80.74	80.65	64.33	64.27	58.00	58.14
	O	104.11	104.15	79.94	79.85	64.00	63.96	57.32	57.25
	N	102.55	102.51	78.74	78.81	62.74	62.80	56.56	56.55
	D	100.89	100.96	77.47	77.51	61.72	61.65	56.38	56.40
1993	J	101.21	101.04	80.12	80.05	63.43	63.33	57.15	57.00
	F	105.00	104.78	81.53	81.40	65.75	65.60	58.18	58.10
	M	105.73	105.61	82.09	81.82	66.19	66.04	58.62	58.43
	A	106.87	106.70	82.96	82.83	66.89	66.65	59.00	58.87
	M	111.00	110.76	85.39	85.20	68.04	68.00	60.98	60.90
	J	112.79	112.73	89.57	89.43	70.51	70.42	63.67	63.70
	J	114.47	114.40	87.27	87.30	70.32	70.38	63.48	63.32
	A	111.02	111.10	86.15	86.14	70.75	70.85	62.38	62.20
	S	109.05	109.12	86.15	86.05	68.60	68.55	61.20	61.30
	O	108.01	108.00	83.84	83.85	67.90	67.99	60.25	60.20
	N	106.45	106.40	82.64	82.65	66.64	66.54	59.20	59.11
	D	104.79	104.66	81.37	81.30	65.62	65.43	55.22	55.08
1994	J	104.70	104.53	82.00	81.90	64.03	64.16	57.31	57.20
	F	103.60	103.43	80.13	80.00	65.00	64.76	57.14	57.00
	M	105.64	105.48	82.68	82.50	64.79	64.58	57.25	57.04
	A	105.47	105.49	81.56	81.35	65.49	65.36	57.71	57.58
	M	109.60	109.52	83.99	83.95	66.64	66.78	58.95	58.82
	J	111.39	11.30	88.17	88.00	69.11	69.01	59.74	59.65
	J	111.07	111.00	85.87	85.87	70.00	69.83	59.39	59.45
	A	109.62	109.67	84.75	84.85	68.03	68.00	58.61	58.66
	S	107.65	107.58	85.50	85.40	66.83	66.95	57.00	57.00
	O	107.50	107.37	82.44	82.40	66.50	66.39	57.18	57.03
	N	105.05	105.14	81.24	81.20	65.24	65.11	56.63	56.44
	D	103.39	103.22	79.97	79.90	64.22	64.07	56.52	56.34
1995	J	101.58	101.43	78.23	78.30	62.53	62.56	57.24	57.10
	F	102.10	102.00	78.63	78.43	62.85	62.80	57.46	57.34
	M	102.83	102.63	79.19	79.02	63.29	63.10	58.13	57.90
	A	103.97	103.85	80.06	79.90	63.99	63.85	58.47	58.30
	M	108.10	108.00	82.49	82.28	65.14	65.00	48.70	48.49
	J	110.53	110.59	86.67	86.60	67.61	67.57	60.90	60.85
	J	109.57	109.50	84.37	84.22	67.42	67.36	60.30	60.39
	A	108.12	108.20	83.25	83.26	66.53	66.50	59.28	59.20
	S	105.14	105.02	80.06	80.00	65.33	65.46	58.11	58.24
	O	105.11	105.23	80.94	80.97	66.10	66.00	57.00	57.10
	N	103.55	103.50	79.74	79.70	63.74	63.60	56.01	56.00
	D	101.89	101.84	79.43	79.33	62.72	62.78	55.50	55.49
1996	J	100.83	100.94	77.48	77.31	61.78	61.77	55.27	55.10

F	101.35	101.21	79.36	79.24	62.10	61.98	55.27	55.03
M	103.00	102.80	78.44	78.30	62.54	62.41	55.27	55.20
A	103.22	103.10	79.31	79.17	63.24	63.04	55.45	55.32
M	108.35	108.30	81.74	81.50	64.39	64.22	56.85	56.96
J	109.14	109.04	85.92	85.90	68.00	67.82	57.70	57.84
J	108.82	108.97	83.62	83.55	66.67	66.85	57.44	57.57
A	107.37	107.31	82.50	82.65	65.78	65.79	56.82	56.76
S	107.10	107.17	81.06	81.15	64.58	64.41	56.10	56.00
O	104.36	104.25	80.19	80.15	65.10	65.00	55.47	55.32
N	102.80	102.69	78.99	78.95	62.99	62.95	55.00	54.87
D	101.14	101.18	77.72	77.70	61.97	61.80	54.11	53.95

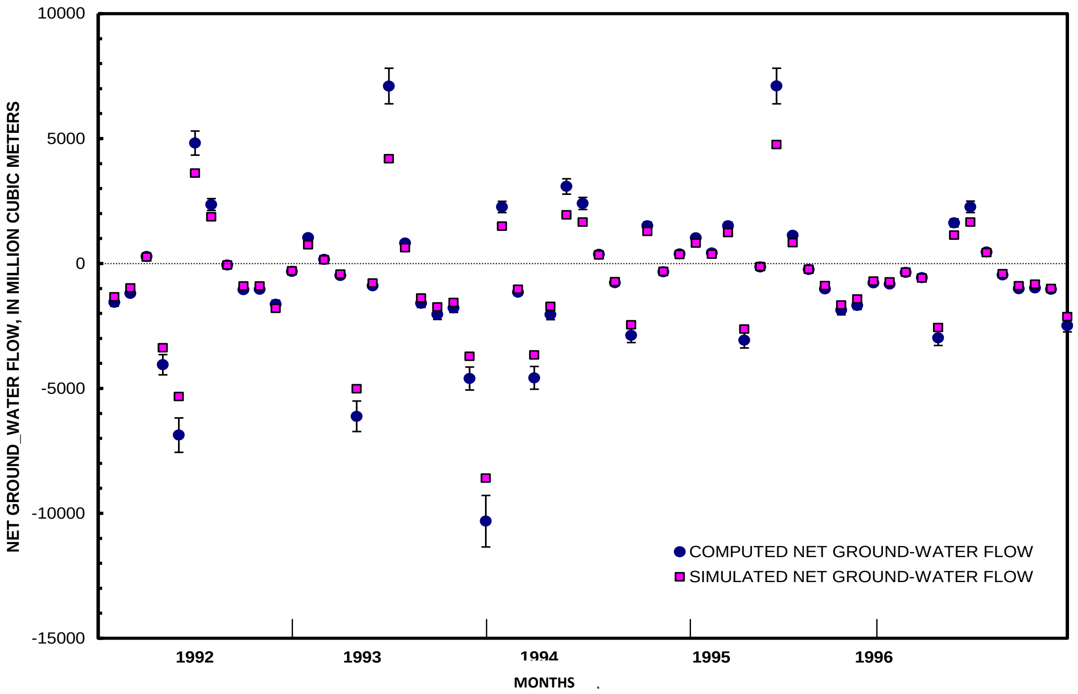

Fig.(14): Simulated and computed monthly net ground-water flow to tharthar lake (1992-1996).

During the 1992-1996 study period, simulated ground water inflow was estimated to be approximately (400.8*10^9)m^3 which is approximately (5) times larger than estimated precipitation and surface water inflow inputs (85.4*$10^9$$m^3$) for this period . The simulation results also indicate that the leakage from Tharthar lake was estimated to be approximately (436.67*$10^9$$m^3$), which approximately (10) times larger than estimated evaporation losses and surface water outflow (43.23*10^9)m^3 for this period. The lake volume increased by 6.3*$10^9$$m^3$ or (8.8%) for this period.

14. Flow- path simulations

A particle tracking program (Pmpath) was used to evaluate ground water flow paths and residence times (time from recharge at the water table to discharge at the lake). Flow path simulations were conducted using the head distributions from (Jan. (1992), May (1993), Oct. (1994), and Aug. (1995)) steady –state simulations. A range of residence times was calculated by conducting a series of flow path simulations in which porosity values were varied within the ranges (25%-45%) for Upper Fars and (35%-55%) for Lower Fars . Results of a flow path are shown in Fig. (15). Mean residence time was estimated to be within a range (4 to 11) years. The simulation flow paths indicate that almost all of the ground-water flow near Tharthar lake occurs within the Bakhtiari aquifer and Upper Fars aquifer, Fig.(16).

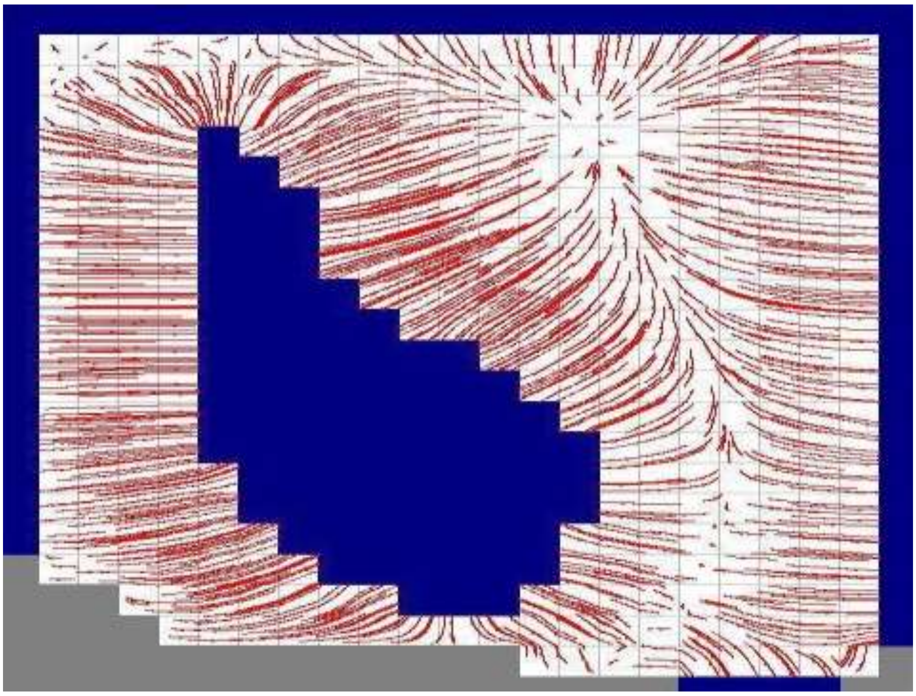

Fig.(15)Flow Paths of Ground Water That Discharge to Tharthar Lake.

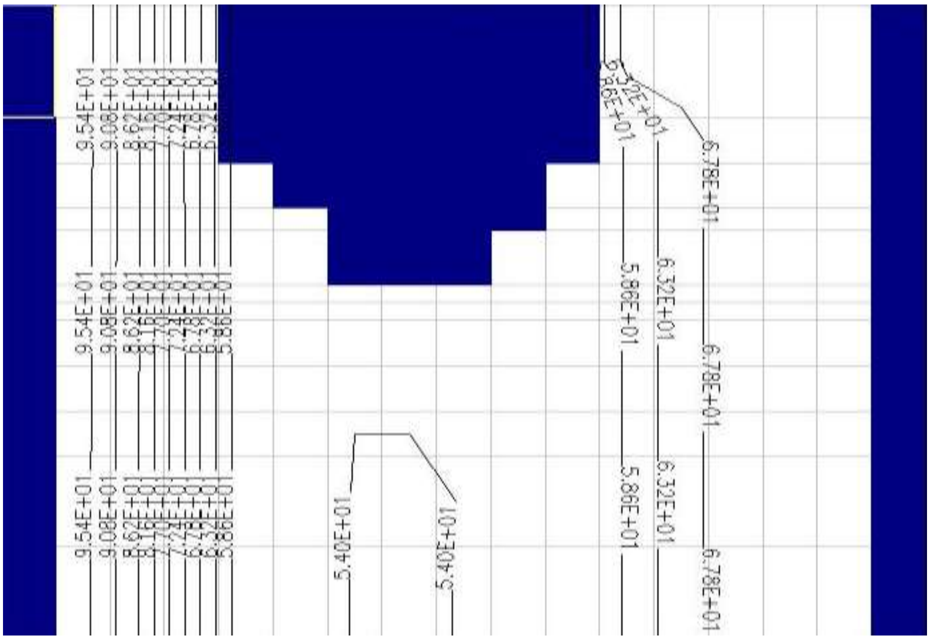

Fig.(16) Particle Traces Projected onto Section A-B, Tharthar Lake.

15. Conclusions

The study of groundwater flow and water budget for Tharthar lake may permit to draw the following conclusions:

1. Lake volume, precipitation and evaporation data indicated that:
   - Ground water inflow to Tharthar lake and leakage from lake to groundwater system are significant components in the water budget of the lake.
   - The groundwater inflow and leakage represent at least (38%) and (56%) of the total inflow and outflow water budgets of the lake respectively.
2. Simulation model of the groundwater flow system near Tharthar lake indicates that:
   - Groundwater inflow and leakage are dominant components in the inflow and outflow budget of the lake.
   - The groundwater inflow and leakage are larger than the minimum estimates (precipitation and evaporation) given by the net groundwater flow analysis.
   - Groundwater inflow and leakage were estimated to be $(400.8*10^9)m^3$ and $(436.67*10^9)m^3$ respectively during (1992-1996).
   - Groundwater inflow is approximately 5 times larger than estimated precipitation inputs. Leakage from Tharthar lake is approximately 10 times larger than estimated evaporation losses.
   - The lake volume increased by $(6.3*10^9)m^3$ or (8.8%) .
3. By using the particle tracking program the residence time of groundwater discharging to Tharthar lake was estimated between (4 to 11) years.
4. The simulation flow paths of ground water indicate that almost all of the ground-water flow near Tharthar lake occurs within the Bakhtiari aquifer and Upper Fars aquifer. The lower Fars formation has a negligible influence on groundwater discharge at the lake .

16. References

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