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Using computer systems to predict the changes in groundwater elevations due to recharge from rainwater harvesting

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Abstract From the 19th century, the Bashiqa Region of Iraq has depended on groundwater for irrigation and domestic uses. Since 1980, many deep wells of small diameter have been drilled. This excessive water consumption caused a notable decline in groundwater level, which now lies more than 15 m below the ground surface. In consequence, nearly all the shallow large diameter wells have dried up. This present study introduces recharging aquifers using rain water harvesting techniques as a solution for this problem. A raster-based GIS was employed in conjunction with a surface runoff model that used a watershed modelling system (WMS) and a groundwater numerical model that used a finite-difference flow code (MODFLOW). The calibrated groundwater model suggested that four check dams should be employed to store rainwater at selected places where the infiltration ratio is very high. Model results indicate that after one year the check dams may raise groundwater elevations by more than 4.5 m at particular locations and generally by more than 0.2 m for the study area as a whole. Prediction of the expected elevations after five years suggested a continuing very positive effect on groundwater levels.

Key words GMS; groundwater; modelling; MODFLOW; Mosul; recharge; runoff; WMS

INTRODUCTION AND BACKGROUND INFORMATION

Many regions in the world depend mainly on the use of underground water for irrigation, domestic and industrial purposes. This is especially so in the arid and semiarid areas where groundwater resources are used greatly.

Excess use of groundwater for thousands of years has unpredicted consequences for one of the most important sources of water in nature and represents a depletion process leading to disorder in the natural system. Decreasing groundwater levels is a problem in many regions of the world, especially in small basins, such as in the present study area of the Bashiqa Plain, Iraq, where there has been a continuous decline in recent years (Hasan, 1999), reflecting excessive use of groundwater and the drilling of a large number of deep water wells without restrictions. This has caused the depletion of water storage leading to a great decrease in water levels in the region and the drying of many of the shallow wells with wide diameters, which were dug earlier and have been a traditional source of water supply (Bashiqa Agriculture Office, 2002).

In order to solve the problem of continuously decreasing groundwater levels in the study area, the method of artificial recharge of groundwater was used. Basically, the groundwater is fed from surface water in many ways including drilling wells into which water is poured or digging trenches which are filled with water that is left to filter into the ground, or by filling low areas with water from any source such as rivers, or by making barriers or small dams to trap water in a suitable area to feed the groundwater in that region (Fox & Rushton, 1976; Lehr, 1982).

The last method was chosen for the purposes of this research because all the factors are suitable to make such dams at the outlets of valleys that are present at high elevations in the study area, and are regarded as important sources for recharging groundwater.

The process of modelling the artificial recharge of groundwater in the study area can be divided into two parts. The first consisted of constructing a computer model to calculate the quantity of surface flow at the outlets of mountain valleys due to rainfall, while the second comprised a computer simulation of the infiltration of the calculated surface runoff into groundwater following trapping.

RESEARCH AREA AND FIELD WORK

The Bashiqa research area is located to the northeast of Mosul City in the north of Iraq and has an area of 49.5 km^2 of which 11.5 km^2 is mountainous and the remainder is a plain. The field work included topographic surveying and the determination of the areas where the artificial recharge process would be concentrated, as well as collecting information about the location, depth and water level of the active wells (Fig. 1), 16 of which are distributed within the study area (Water Wells Company & Nineveh Irrigation Office, 2002). Rain data were also available from the Mosul Station, which is in the vicinity of the study area.

Geological reports provided information about the formations containing groundwater, which helped in preparing suitable hypotheses for the conceptual model as well as proposing soil permeability values for the modelling work.

AQUIFER FORMATIONS IN THE STUDY AREA

The geology of the Bashiqa area includes the Pilaspi, Fat'ha and Injana Formations. The Pilaspi Formation consists of stratigraphic sequences of dolomitic limestone, marly limestone, limestone and clastic dolomitic limestone. This formation is characterized by cracks and fissures which make it a good groundwater aquifer. The Fat'ha Formation is composed of sedimentary cycles of marl, limestone and gypsum, and its outcrop occurs in a belt between the major anticlinal (Bashiqa anticline) and synclinal (Bashiqa plain) structures of the study area. The Injana Formation forms a stratigraphic succession of sandstone rocks of gradational sizes, siltstone and mudstone. Significant storage of water occurs in the silt layers (Al-Dabagh & AL-Naqib, 1989).

Most of the water wells in the Bashiqa area have been drilled in the Injana Formation, although some have been drilled in the Pilaspi Formation in the northern part of the study area.

In general, anticlinal structures are regarded as recharging groundwater, whereas the fold axes of synclinal structures in northern Iraq determine groundwater movement. Figure 2 illustrates a cross-section of the three geological formations which outcrop in the study area.

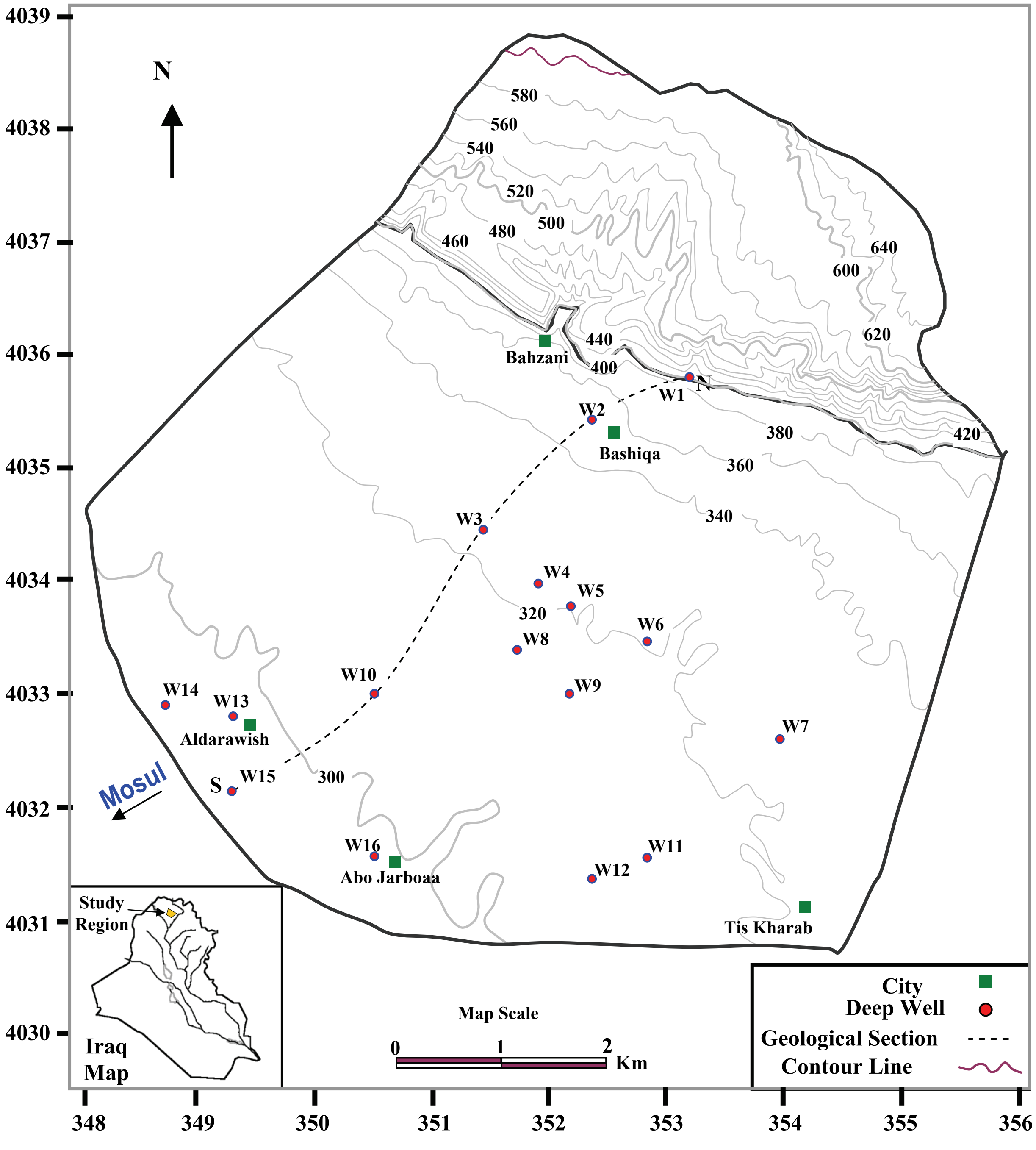

Fig. 1 Study area topography and location of the deep wells.

ESTIMATION OF SURFACE RUNOFF

Often, the use of computer models has been used to study unknown water basins and to substitute for field study and experiments which may be economically expensive, difficult to achieve or time consuming. For these reasons and because the surface

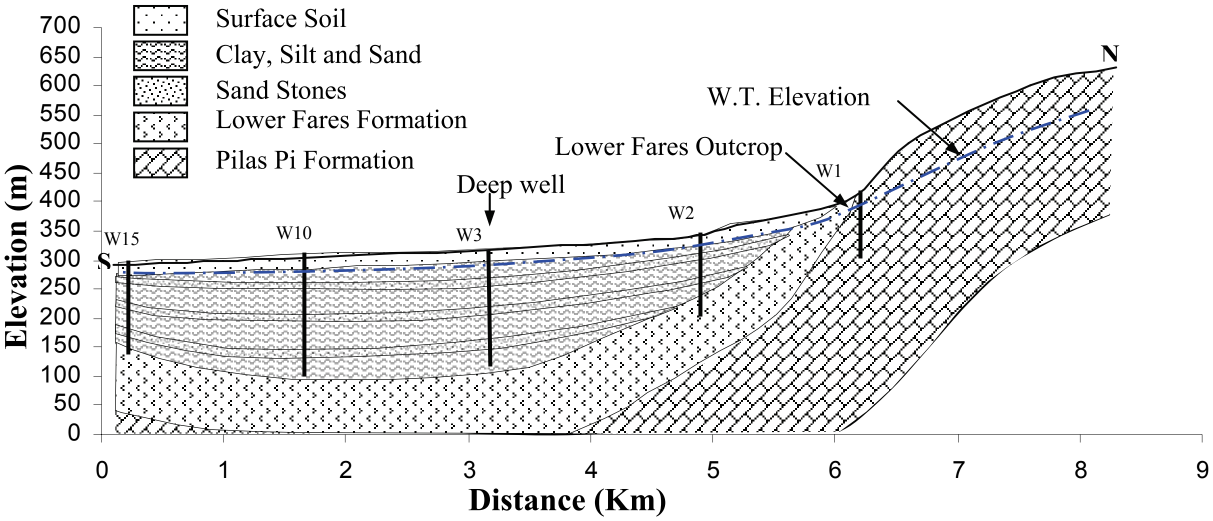

Fig. 2 Geological section (**N**–**S**) of the study region derived from well logs.

runoff is related to the geographic and geomorphological characteristics of the study basin, a Geographic Information System (GIS) was used to convert the topographic map into a digital map to be used, in turn, with other software applications. Maps describing the soils and land use of the area and land use were also converted into digital form. The main stream dimensions were determined from contour maps and aerial photographs and satellite imagery.

The information information held in the GIS was used as inputs to a watershed modelling system (WMS) (WMS 5.0, 1997) that simulated surface runoff volume based on the American soil conservation system. The model determines the boundaries of sub-basins in the study area on the basis of an irregular triangular network (TIN Model) and resulted in the definition of eight valleys (Fig. 3) with a dendritic flow network (Fig. 4). The model also defines a number of morphological properties including, area, slope, perimeter, shape, elevation and length, as well as surface runoff for each sub-basin. Table 1 lists the area and runoff generated for each sub-basin by the model.

THE GROUNDWATER MOVEMENT MODEL

Groundwater levels

Modelling the process of the groundwater movement is a difficult and complicated compared with predicting surface runoff for many reasons, including the number of input variables involved and problems of collecting data for verification. Previous studies based on numerical computer models suggested a continuing annual decline in groundwater levels of 0.7–0.85 m due to excess withdrawal from underground storage.

This decline appears to take place even in years when rainfall receipt exceeds the annual average.

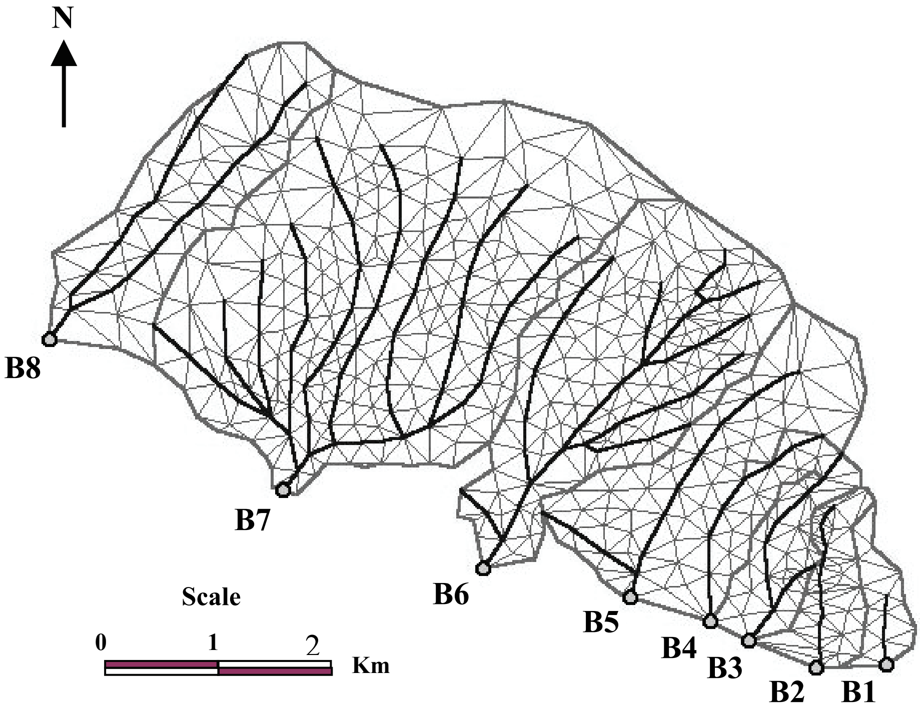

Fig. 3 Sub-basins and their triangular irregular network (TIN) in the study area.

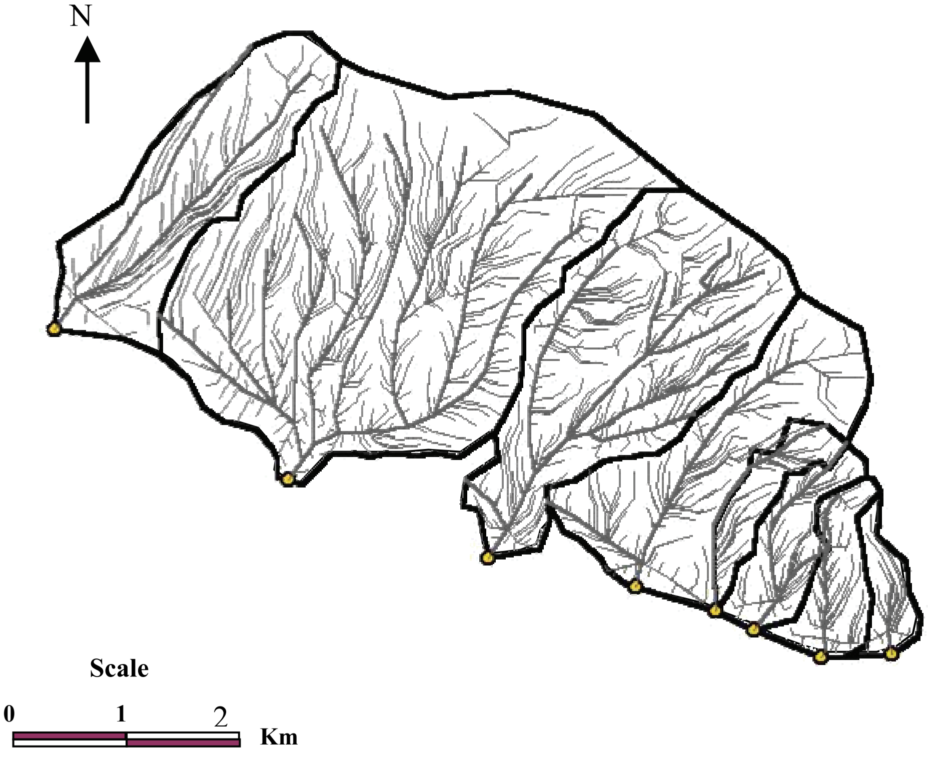

Fig. 4 Runoff flow paths and tree distribution to every sub basin in the catchment's area.

Table 1 Modelled area and runoff of each sub-basin in the study area.

Basin	Area (km^2)	Runoff (m^3)
B1	0.18	21600
B2	0.33	39600
B3	0.37	44400
B4	0.25	30000
B5	1.22	146400
B6	1.95	234000
B7	4.16	499200
B8	1.17	140400

Groundwater recharge

The present study investigates the potential effectiveness of building small dams at selected locations in the study area as a means to halt the decline in groundwater levels. These dams would create small lakes with an area and depth depending on the local topography, and sites at the outlet of small valleys were selected as being suitable because of their topographical and geological characteristics which favour impoundment and infiltration to the groundwater.

The location of the four sites selected to establish small dams is illustrated in Fig. 5. Site 1, after some earthworks, would trap water at the end of three valleys (B3, B4, B5), while sites 2, 3 and 4 are located at the end of valleys B6, B7 and B8, respectively. The maximum extension of the lakes behind the dams was calculated from the maximum discharge for each, while the maximum volume of each lake can be calculated from the hydraulic design.

Modelling groundwater movement

A conceptual model was constructed as a preliminary stage in using the groundwater modelling system (GMS) (GMS 4.0, 2003). The conditions at the outer boundaries of the study area were determined in addition to the groundwater recharge areas and their characteristics, and the location of wells and water levels. In deriving a numerical computer model, the study area was divided into small cells on the basis of longitudes and latitudes, and information in the GIS was used to define the physical properties of these units. The MODFLOW program (Harbaugh & McDonald, 1996) was employed to determine the groundwater levels in the area, and simulations were undertaken to predict water levels in the area after the passage of several years. Figure 5 portrays the simulated groundwater levels before the proposed recharge.

In the present study, it was possible to update and improve this model for calculating groundwater levels in case another source for groundwater recharge is utilized. This was achieved by adding polygons to represent the small lakes formed behind small dams and refining the calculation of infiltration rate based on previous studies (Hantush, 1967; Rao & Srma, 1980; Prabhata & Chandra Shkhar, 1997). Calculation of infiltration was based on the assumption that the new lakes are formed on areas of gypsum in the underlying Fat'ha (Lower Fris).

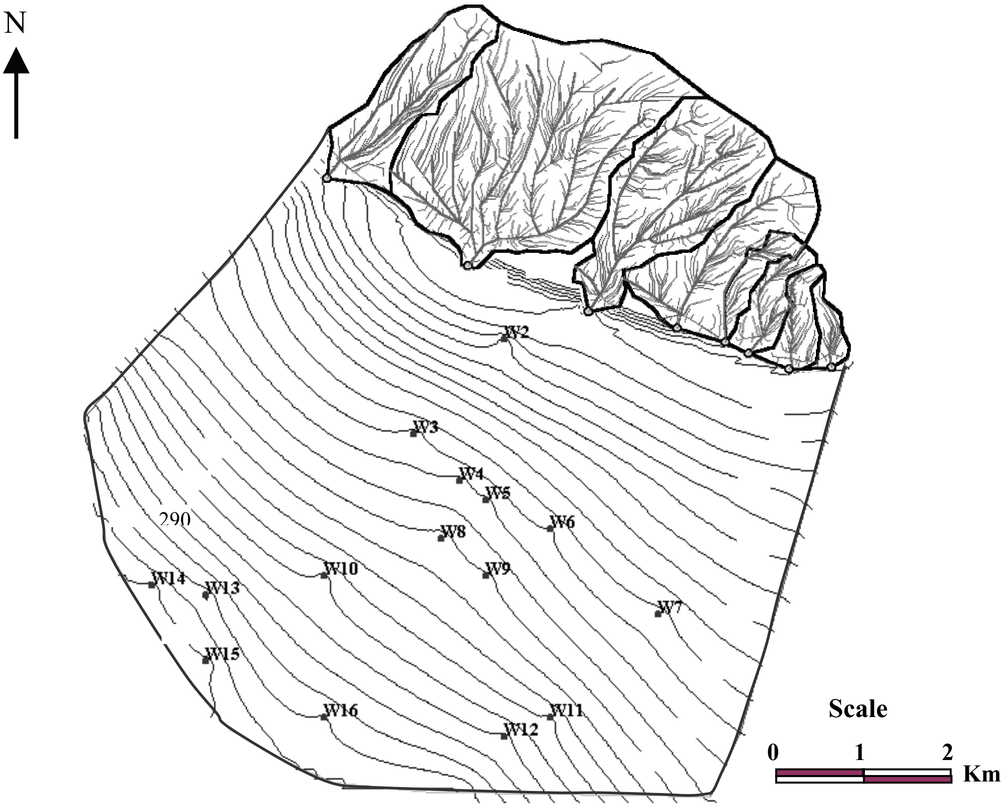

Fig. 5 Simulated groundwater elevations before the proposed recharge.

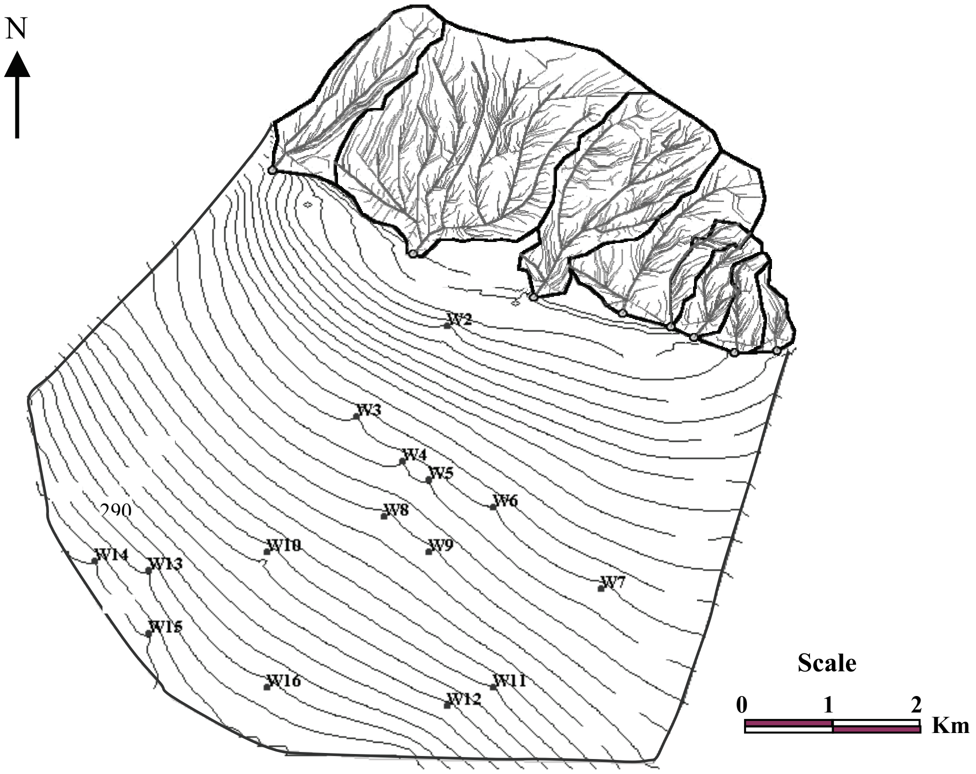

Fig. 6 Groundwater elevations contour lines after the proposed recharge.

Figure 6 portrays the expected groundwater levels after one year following application of the proposed artificial recharge method. Further simulation was carried out to predict groundwater levels in the wells over the next 5 years, and results (Table 2, Fig. 7) show an increase of water levels for all wells and especially those near the proposed recharge areas. The change in water levels after one year of the proposed scheme is depicted in Fig. 8, and shows rises of 6 m in some northern areas close to the recharge sites but a small increase of 0.2 m in the southern part of the study area.

Table 2 Predicted groundwater elevations following implementation of the proposed recharge scheme.

Label	X–axis (m)	Y–axis (m)	Z–axis (m)	Discharge (m^3 day^{-1})	Water Elevation (m)					
					2003	2004	2005	2006	2007	2008
W1	352900	4035900	385	–700	330	336.8	338.4	339.3	340	340.4
W2	352000	4035500	345	–750	326	332.5	334	335	335.9	336.5
W3	351000	4034500	330	–650	308	312.4	313.6	314.5	315.2	315.8
W4	351500	4034000	3 28	–600	306	310.3	312.1	313.3	314.2	314.8
W5	351800	4033800	322	–750	306	310	311.9	313.2	314.1	314.7
W6	352500	4033500	323	–850	308	311.4	313.3	314.3	315.1	315.7
W7	353700	4032600	324	–800	308	309.8	310.6	311.2	311.8	312.3
W8	351300	4033400	318	–750	302	305.6	307	308	308.8	309.5
W9	351800	4033000	317	–750	302	305.1	306.6	307.8	308.7	309.5
W10	350000	4033000	307	–700	294	296.4	297.7	298.8	299.7	300.4
W11	352500	4031500	305	–700	296	297.2	298.2	299.1	299.9	300.5
W12	352000	4031300	304	–650	290	291	292	292.9	293.7	294.3
W13	348700	4032800	299	–650	286	287	288	289.1	290.2	291.2
W14	348100	4032900	295	–700	282	282.3	282.9	283.6	284.2	284.7
W15	348700	4032100	295	–600	282	282.4	283	283.6	284.1	284.6
W16	350000	4031500	298	–600	286	286.6	287.5	288.5	289.5	290.4

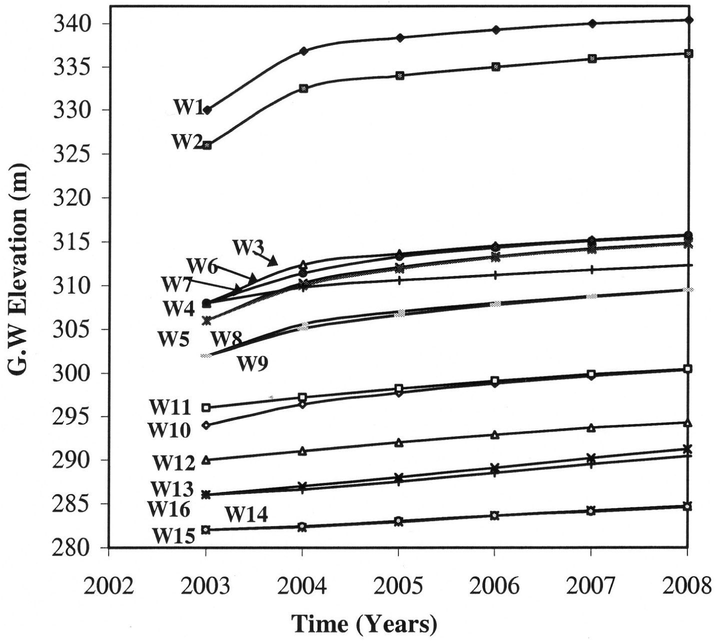

Fig. 7 Predicted changes in groundwater elevations in wells following the implementation of the proposed recharge scheme.

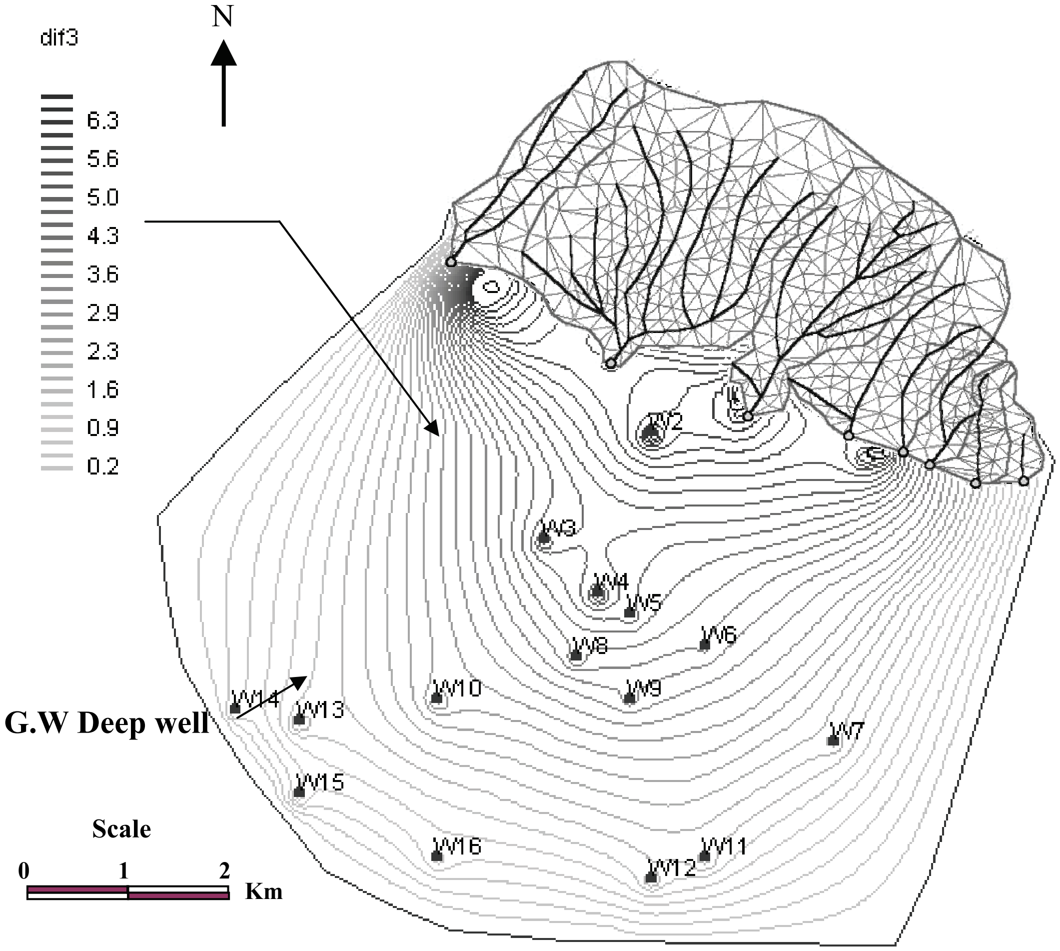

Fig. 8 Predicted increases in groundwater level after one year following implementation of the proposed recharge scheme.

CONCLUSIONS AND RECOMMENDATIONS

The present, as well as previous, studies have emphasized the excessive use of groundwater in the region, which has caused a sharp decline in groundwater levels and the drying up of all surface wells. The possibility of using surface runoff (which currently accumulates in the plains and evaporates) to reverse the decline in groundwater levels has been demonstrated through the use of computer models. Predictions suggest that artificial recharge, based on damming of small valleys, could increase groundwater levels over the next 5 years.

Although this method of artificial recharge is not new, it is considered to be particularly appropriate in the study area where outcrops of highly permeable gypsum occur. The use of modelling in this study has obviated the need for extensive fieldwork or pre-existing hydrometric records. Further hydraulic studies will be needed to determine the exact location of the small dams and their shape and dimensions, but this method of artificial recharge has the potential to improve agriculture in the region.

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