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GIS Modeling of the Effects of Climatic Changes on the Groundwater Recharge in the Central Western Parts of Jordan

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ABSTRACT

Groundwater recharge in arid and semi-arid areas used to be calculated as a percentage of the amount of precipitation. This approach does not seem to be suitable for these areas, because soils serve as reservoirs for evaporation water that results from precipitation water and is being retained in the soil.

Taking the water retained in the soil during and immediately after the rainy season into consideration and considering that it is the only water available for evaporation is a more logical approach.

Accordingly, groundwater recharge in the central western parts of Jordan was calculated, and scenarios of eventual climatic changes of increasing temperatures and decreasing precipitation on the groundwater recharge were evaluated.

It was found that climatic changes resulting in temperature rises by 1ºC and 2ºC will result in decreases in groundwater recharge of 11.3% and 23.2%, respectively. A decrease in precipitation by 10% and 20% will cause a reduction in groundwater recharge of 24.06% and 48.34% compared to the prevailing average conditions.

KEYWORDS: Groundwater recharge, Soil retention, Climatic changes, Temperature rise, Precipitation decrease.

INTRODUCTION

Precipitation is the main factor in the water cycle that could be recognized as the major source of all water resources on earth.

Jordan is one of the four poorest world countries in what concerns water resources. At present, the limited surface water resources and the decreasing precipitation are the main environmental issues facing the country.

During the past 5 decades, a general decrease in the precipitation amounts was recorded.

Due to decreasing precipitation, other water resources and water cycle elements, such as flood flow, soil moisture and groundwater recharge are also expected to be directly affected.

In areas such as Jordan which depends mainly on rain water to cover its water demand, changes in the available resources result in the retreat of many economic activities and therefore the predictable outcomes of any investments will be negatively affected. The returns of the economy of the country will be reduced.

Climatic changes are also expected to affect the water cycle. These effects and the impacts of reduction of rainfall on surface and groundwater resources will be discussed in this article.

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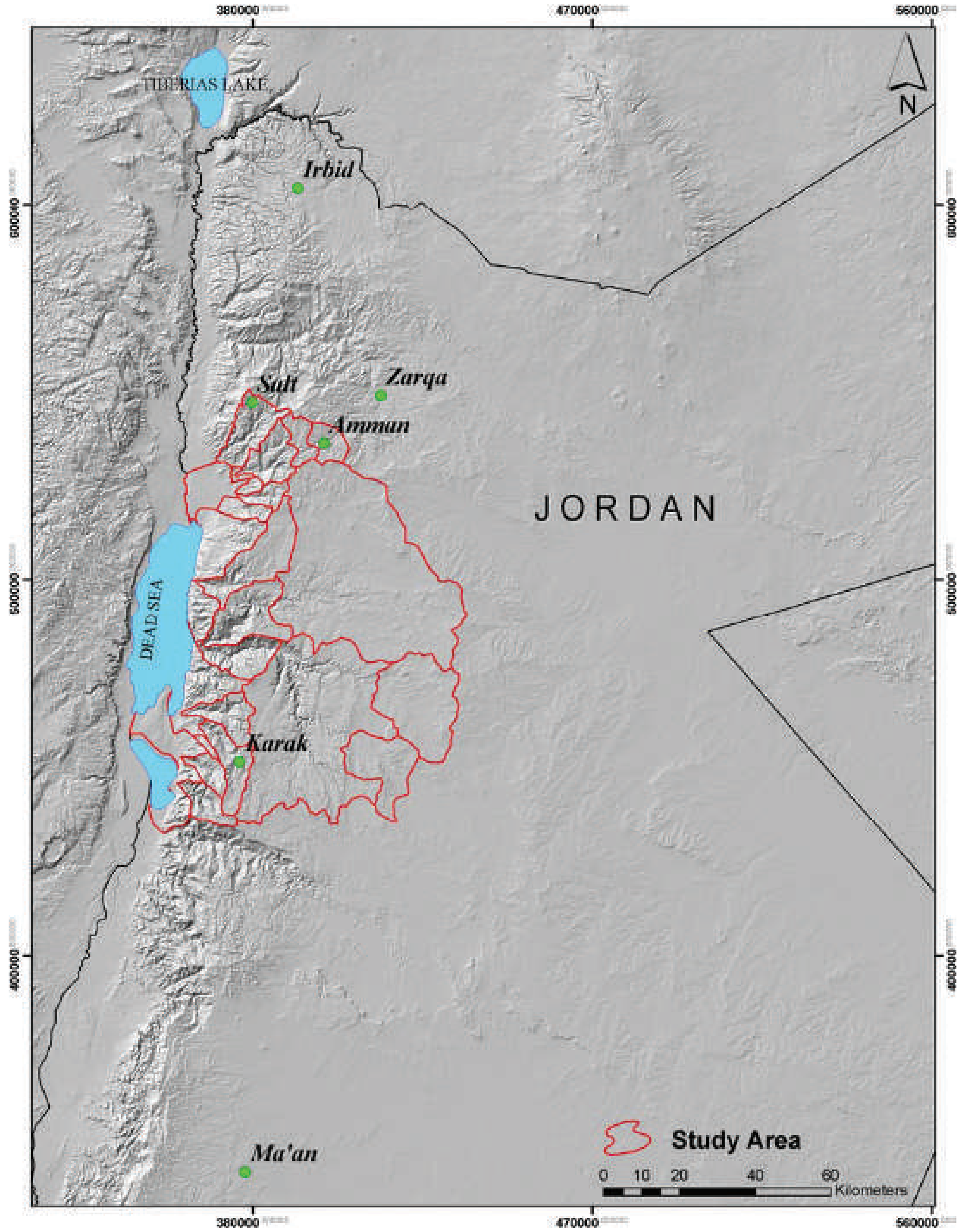

Figure (1): Location Map of the Study Area (Coordinates System is JTM).

STUDY AREA

The present study is concerned with impacts of climatic changes on the western parts of central Jordan and the escarpment to the Dead Sea with a total area of 6630 km^2 (Figure 1).

The main aquifer unit in the area is the Upper Cretaceous B2A7 aquifer complex which crops out along 53% of the area and represents one of the most important aquifer systems in Jordan due to its high potentiality.

The two elements of the water cycle; namely evaporation and infiltration to the groundwater (Recharge) are generally difficult to calculate or to measure. Approaches used until the present time calculate evaporation during the whole year although soil moisture available for evaporation is not found during the summer months in arid, semi arid and Mediterranean climatic zones.

Table (1): Long-term Averages of Climatic Data Used in the Study.

Station	East	North	Temp.	RH	Avg. W.S.	PPT
Amman Airport	403939.9	538068.4	10.8	70.4	2.7	275.0
Ghor Safi	353657.4	434160.4	18.6	59.9	0.5	125.0
Madaba	386305.5	510527.5	10.4	70.2	3.2	275.0
Qatranah	417899.9	458504.7	10.6	65.3	2.5	75.0
Rabbah	380998.1	460689.8	10.1	70.4	1.8	275.0
Salt	380397.1	545709.5	10.6	68.9	2.4	525.0
Wala	386487.6	494096.6	12.6	61.2	2.3	175.0

Recharge to groundwater in dry and semidry climatic zones is generally considered to be a few percentages of the amount of precipitation and evaporation is considered to take very high percentages of precipitation (70-100%). A small error in the estimation of evaporation will strongly reflect on the groundwater recharge amounts.

In this paper, a new approach will be adapted to calculate actual evaporation rates. By using precipitation, flood flow measurements and evaporation recharge rates to the ground water will be calculated.

METHODOLOGY

The water cycle factors of precipitation, evaporation, runoff and recharge to groundwater were considered separately. Precipitation and runoff were taken from existing measurements, evaporation was calculated by a new approach (as detailed in the section of evaporation) and groundwater recharge was calculated as the difference between precipitation and the sum of evaporation and runoff.

Accordingly, recharge equals the sum of all water losses subtracted from precipitation. The water losses are evaporation, runoff (flood flow) and water retained in the soil to evaporate during the dry season:

$$R = PPt - (E + FF + SR)$$

R: Recharge in mm;
PPt: Precipitation in mm;
E: Evaporation in mm;
FF: Flood flow in mm;
SR: Soil retention in mm.

Precipitation

Monthly rainfall data were obtained for different weather stations in the study area operated by the Department of Meteorology (DOM) for a period of 24 years (from 1985 to 2009).

Isohyetal maps were produced in the GIS environment using Kriging method to build up the raster maps for the long-term average rainfall (Figure 2).

Rainfall scenarios of cases of 40%, 50%, 80%, 90%, 120% and 150% of the long-term average of precipitation were prepared for the study area in order to study the effects of reduction or increase of rainfall on groundwater recharge.

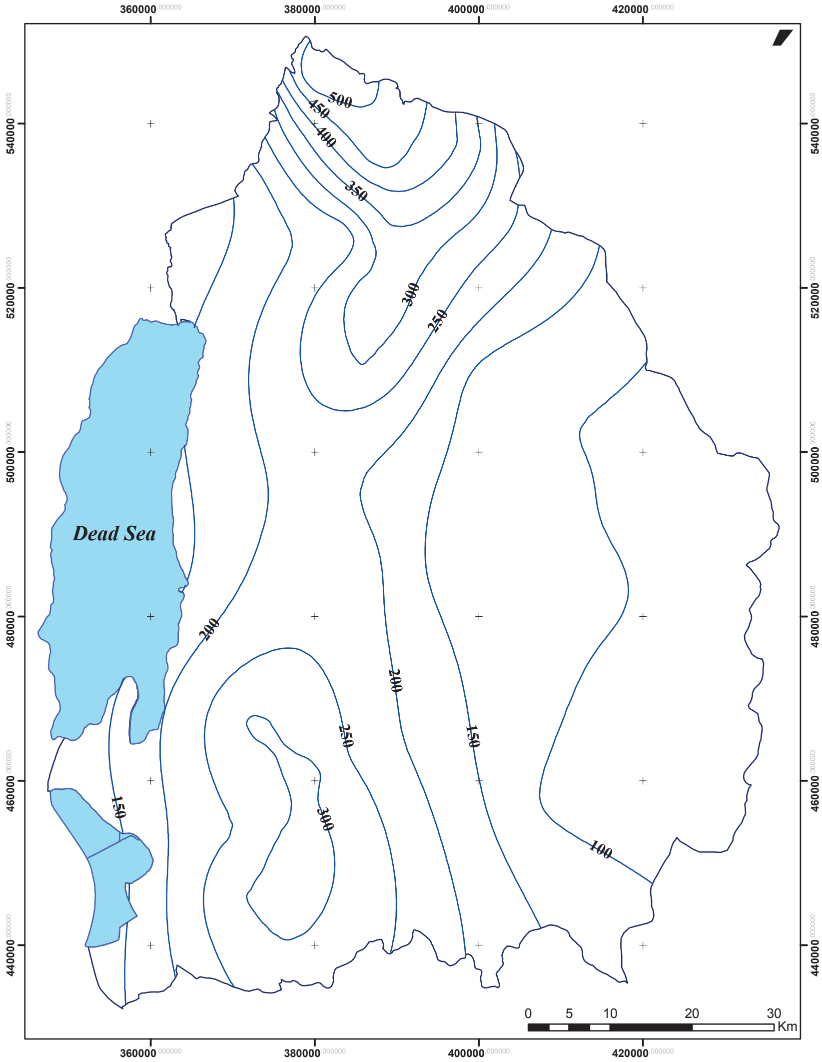

Figure (2): Rainfall Rates in an Average Year (mm/yr).

Flood Flow

MWI and GTZ (1977) calculated the runoff coefficients for the majority of catchment areas in Jordan based on estimation and measurements of actual flood flow events along wadis.

These flood flow ratios were drawn in maps and rasterized. The raster maps were multiplied by the rainfall raster maps to build up the flood flow maps that determine losses from precipitation due to flood runoff (Figure 3). This process was done for runoff coefficients for wet, normal and dry years taking the variation of runoff coefficients due to variation in rainfall into consideration.

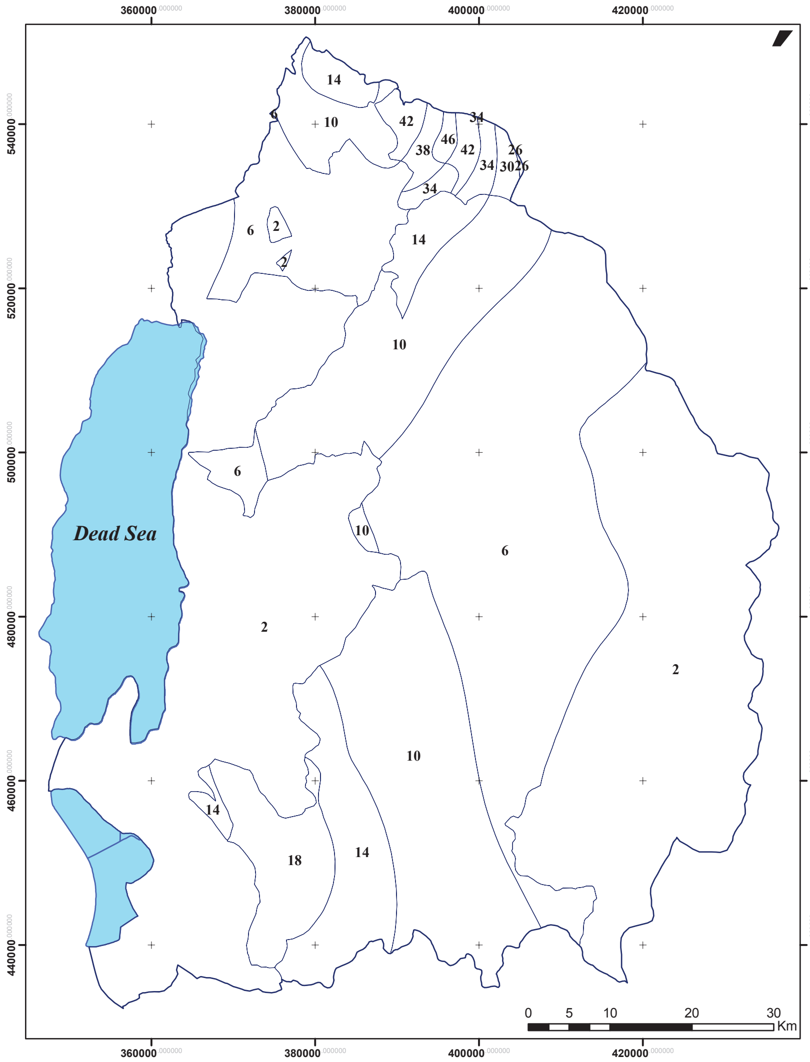

Figure (3): Runoff Rates for an Average Rainfall Year (mm).

Evaporation

Evaporation represents the main water loss in semi-arid, arid and Mediterranean types of climate.

Salameh (2009) adapted a new procedure for the calculation of evaporation based on the fact that evaporation takes place only during the wet period when moisture is available in the soil for evaporation. For Jordan, this period extends from November to the end of March. In April, soil moisture or water retained in the soil is also added to evaporation.

Linsely equation (1979) was used in this study to determine evaporation from the study area. This equation is:

*E = 0.097*Wind speed (m/s)*Saturation pressure* Saturation deficit/100)*

where:

E: Evaporation.

Wind speed (m/s) = Wind speed knots * 1.85 (km/hr).

The saturation vapor pressure was calculated from saturated water pressure curve of thermodynamics.

Saturation deficit: 100 – relative humidity (RH).

Wind speed, temperature and relative humidity data were obtained from the DOM open files for the past 24 years (Table 1).

Figure (4) shows the calculated evaporation rates over the study area.

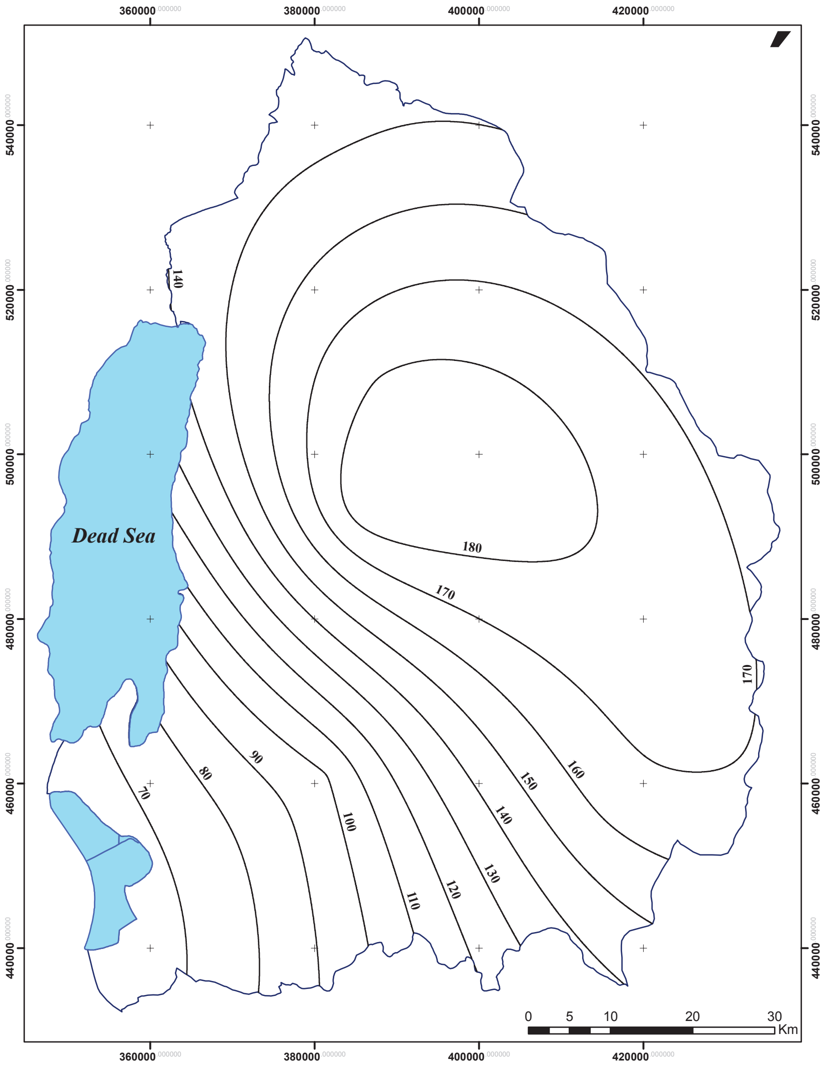

Figure (4): Evaporation Rates in an Average Rainfall Year (mm).

Determination of Soil Retention

The water retained in the soil after runoff has taken place and the gravity has pulled what it can from the soil in a downward direction is considered as retained water. Soil retention is an important water loss which can only be removed from soil by evaporation.

To determine the amount of retained undisturbed soil samples were collected in cylinders with 4.5 cm radius and 10 cm height. The samples were saturated with water by merging the cylinders in water to allow water to percolate through them from the bottom to the top for 12 hours. After that, the samples were sealed from the top to prevent evaporation and allowed to drain by gravity for 4 hours, after which no more water drops developed at the bottoms of the samples, meaning no more gravitational water can flow out of the samples.

The samples were weighted and then dried in the oven at 35º C for 5 days to calculate the amount of soil water, in this case consisting of retained and hygroscopic water.

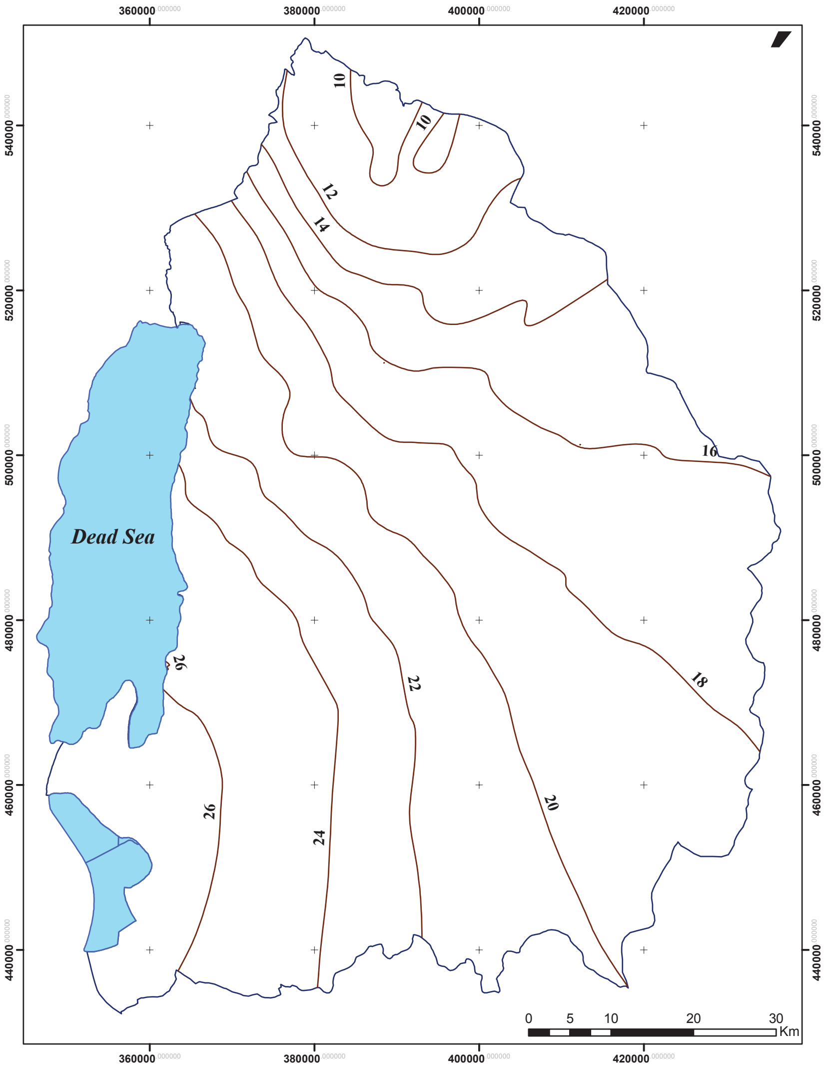

Figure (5): Soil Retention Rates (mm).

The difference between the moisture content after drying the samples at 35ºC and at 105 ºC is the amount of retained water that will be held in the soil and can only be lost by evaporation.

If the water moisture exceeds that amount, then it will percolate down by gravity to recharge the groundwater (Salameh, 2009).

Soil thickness was taken into consideration in the soil retention calculations. It ranged from zero or no soil cover and hence no retention water for evaporation and 74cm with soil moisture retention values varying according to soil types.

Loamy, marly and clayey soils show the highest water retention values, whereas silty and sandy soils have the lowest values.

The resulting thematic layer of soil retention is given in Figure (5).

Table (2): The Principle of Recharge Calculation for Different Stations Based on Measurements of the Department of Meteorology and Water Authority of Jordan.

Station	PPT mm	SR mm	E mm	FF mm	Losses mm	Recahrge mm
Amman Airport	275.0	10.8	151.0	30.3	192.0	83.0
Ghor Safi	125.0	26.4	63.4	0.6	90.4	34.6
Madaba	275.0	16.9	178.1	9.9	204.8	70.2
Qatranah	75.0	19.0	166.4	3.8	189.2	0.0
Rabbah	275.0	24.3	98.4	13.8	136.4	138.6
Salt	525.0	10.6	141.4	13.1	165.1	359.9
Wala	175.0	20.1	188.7	7.4	216.1	0.0

Data Processing

Water losses whether as flood flows or evaporation were combined in the GIS environment and subtracted from the rainfall amount. An example of the calculations is given in Table (2) which illustrates the procedure under which interpolation and processing was done in the GIS environment.

The resulting values represent the groundwater recharge map according to the general water balance equation (Figure 6).

Salt station as an example of calculations:

PPT = 525 mm.

SR = 10.6 mm.

E = 141.4 mm.

FF = 13.1 mm.

R = 525 – (10.6 + 141.4 + 13.1) = 359.9 mm.

Climatic Changes Scenarios

1st Scenario: Temperature Variation

As temperature increases as a result of the global warming, the soil moisture will decrease and saturation deficit of the atmosphere will increase, hence evaporation rates will increase and therefore the recharge to groundwater will decrease.

Groundwater recharge was calculated under two climatic change scenarios by increasing temperature by 1ºC and 2ºC. Accordingly, it is noticed that groundwater recharge will reduce significantly (Figure 7, a and b). In salt station recharge will decrease from 359.9 mm in the normal year to 340 mm by a temperature increase of 1ºC.

2nd Scenario: Rainfall Variation

Due to climatic change and cyclicity in rainfall, changes in groundwater recharge are expected. In order to figure out the rainfall-recharge relation, rainfall scenarios of 40%, 50%, 80%, 90%, 120% and 150% of the long-term average year were modeled in the GIS environment in the form of raster thematic layers.

Figures (8a to 8f) illustrate the spatial distribution of recharge over the study area under the above-mentioned scenarios of increasing and decreasing precipitation amounts between 40% and 150% of the long-term average.

RESULTS

Groundwater recharge as a function of rainfall was calculated through the conversion of recharge depth maps in mm to volumetric maps by spatial zoning of recharge distribution. Areas were calculated in the GIS environment and the total recharge was calculated for the different scenarios.

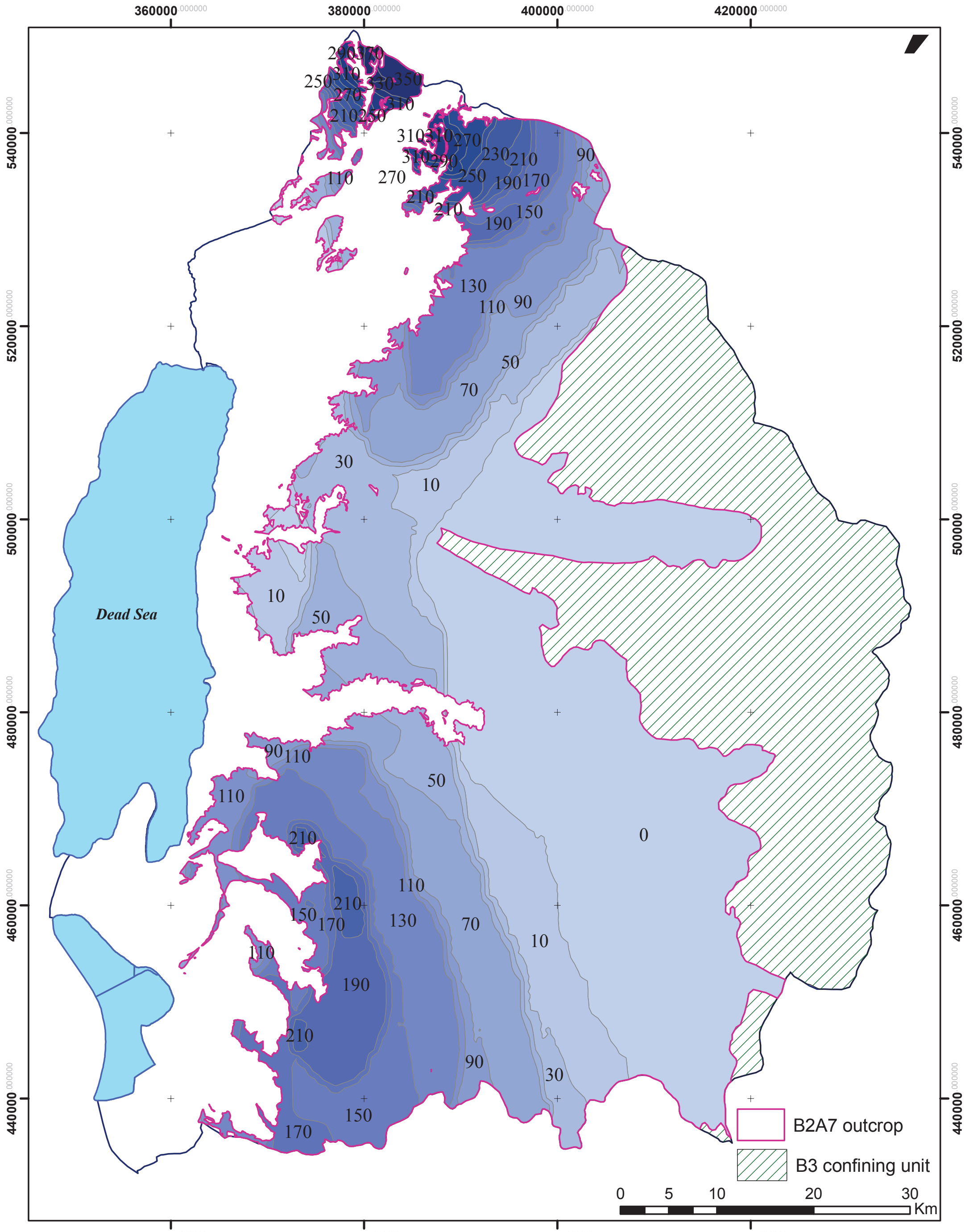

Figure (6): Calculated Groundwater Recharge for a Normal Year (mm).

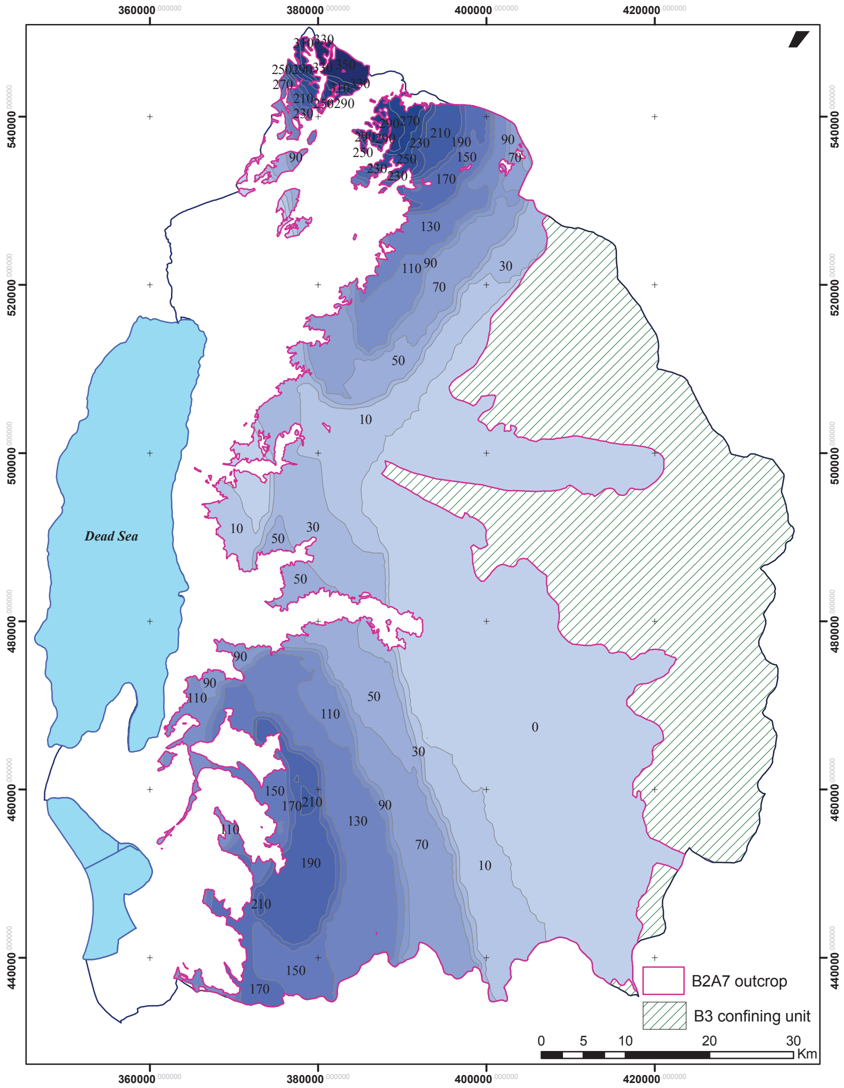

Figure (7, a): Recharge Rates by an Increase in Temperature of 1ºC (mm) (Normal Rainfall Year).

Figure (9) shows the rainfall-recharge relation. It becomes clear from this relation that a decrease in rainfall by 20% will result in 48.3 % decrease in the groundwater recharge. The relation of groundwater recharge with rainfall is in fact not linear. The expected scenario zero recharge limit was calculated to be when the rainfall in a year reaches around 38 % of the long-term average.

On the other hand, 20% and 50% increase in rainfall rates will result in 46% and 129% increase in the recharge compared to an average rainfall year (Table 3).

The effects of temperature changes on the groundwater recharge are shown in Figure (10). It was simulated that 1ºC temperature increase will lead to 11.3 % decrease in the recharge volume, while 2ºC increase will reduce the recharge by 23.2 %.

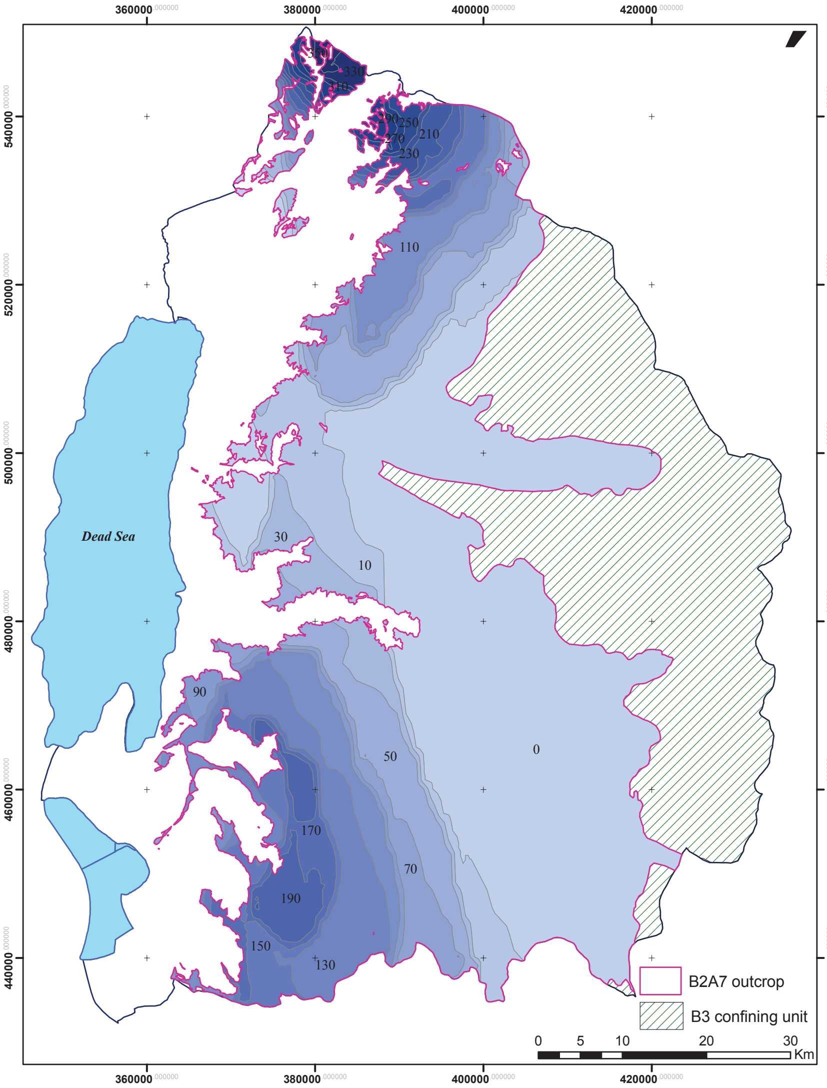

Figure (7,b): Recharge Rates by an Increase in Temperature of 2 ºC (mm) (Normal Rainfall Year).

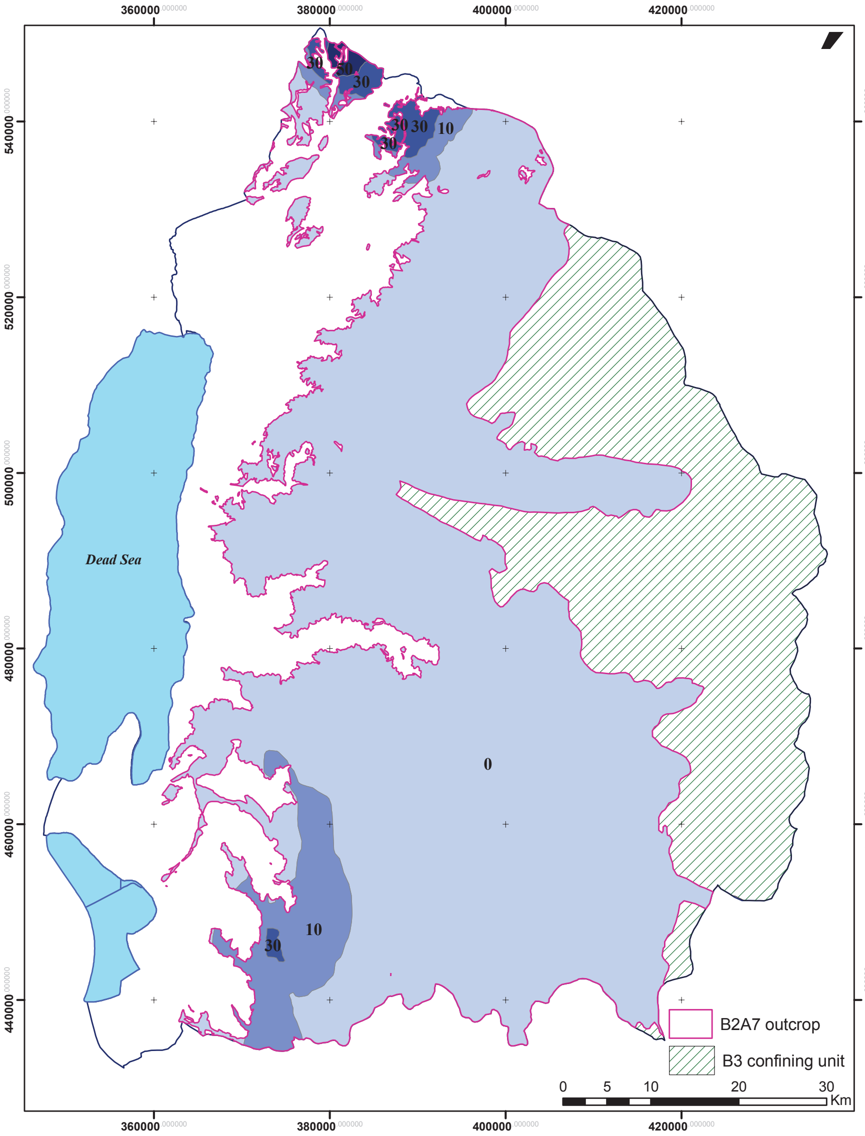

Figure (8, a): Recharge Rates Scenario for Rainfall Decrease to 40% of Its Long-term Average (mm) (No Temperature Change).

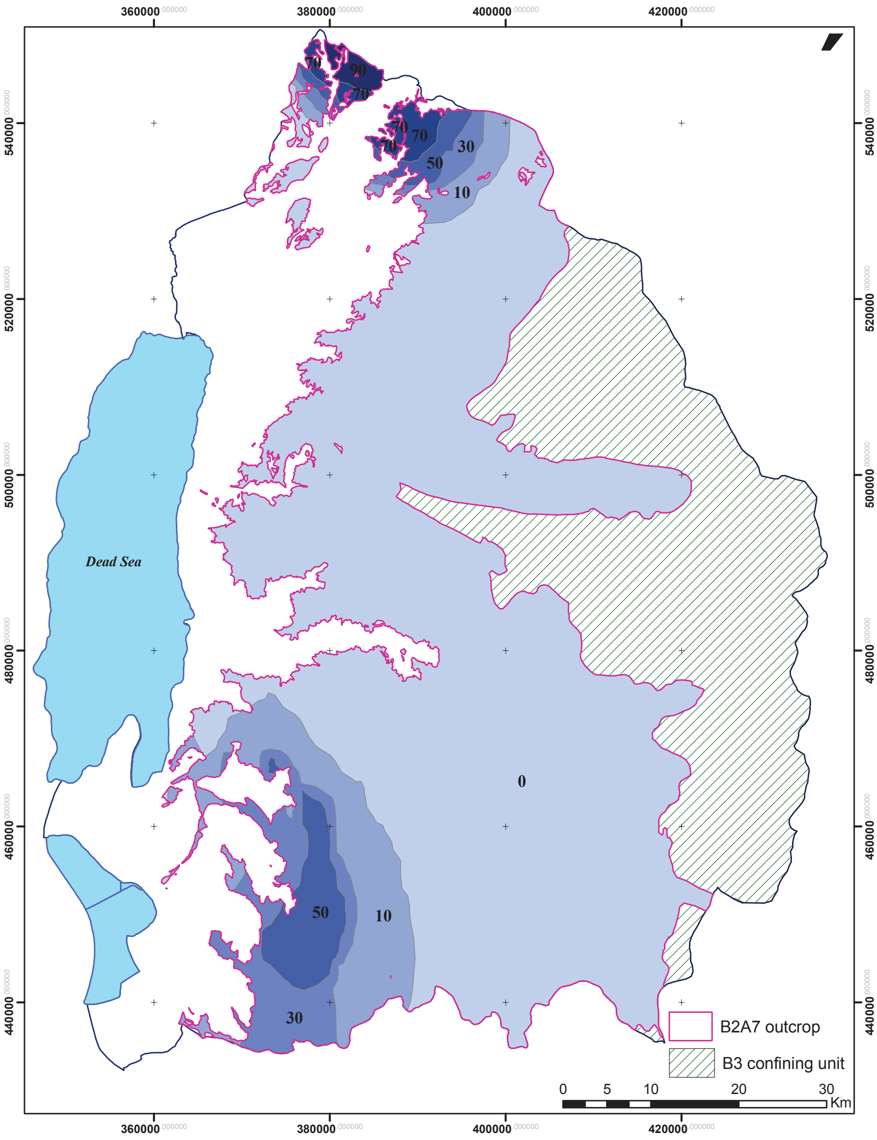

Figure (8, b): Recharge Rates Scenario for Rainfall Decrease to 50% of Its Long-term Average (mm) (No Temperature Change).

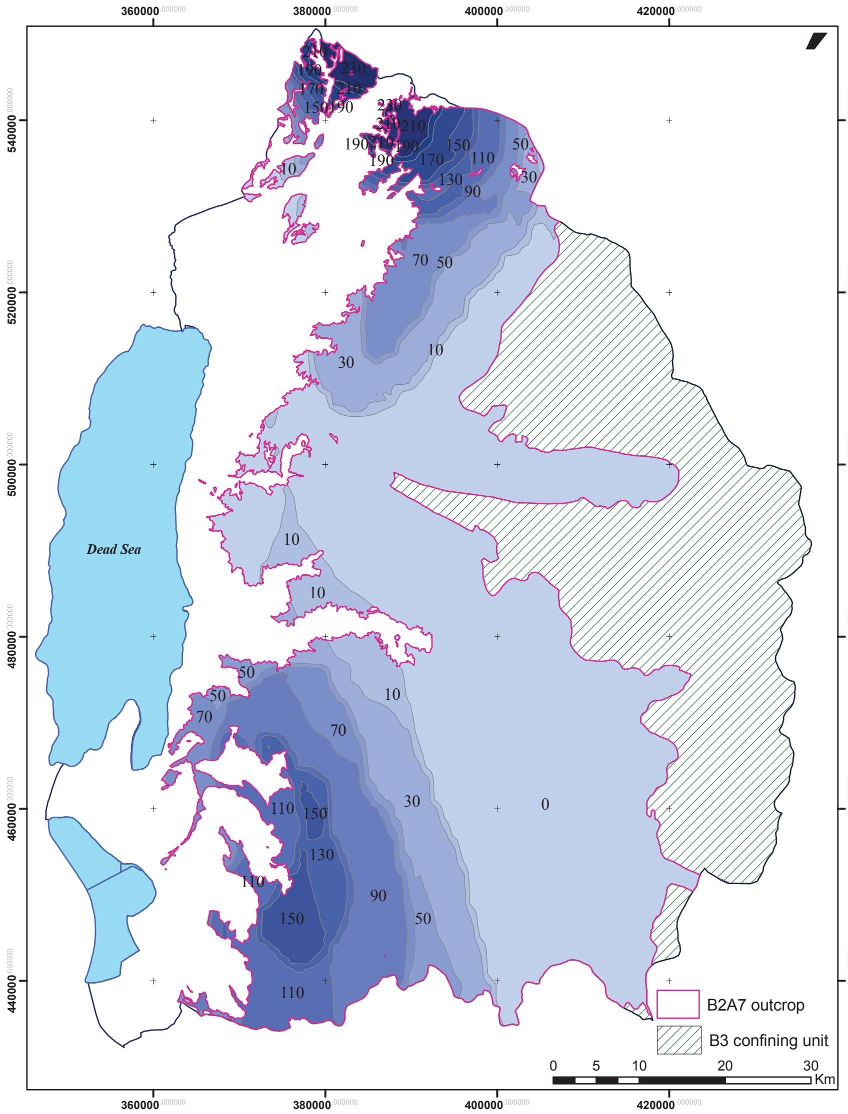

Figure (8, c): Recharge Rates Scenario for Rainfall Decrease to 80% of Its Long-term Average (mm) (No Temperature Change).

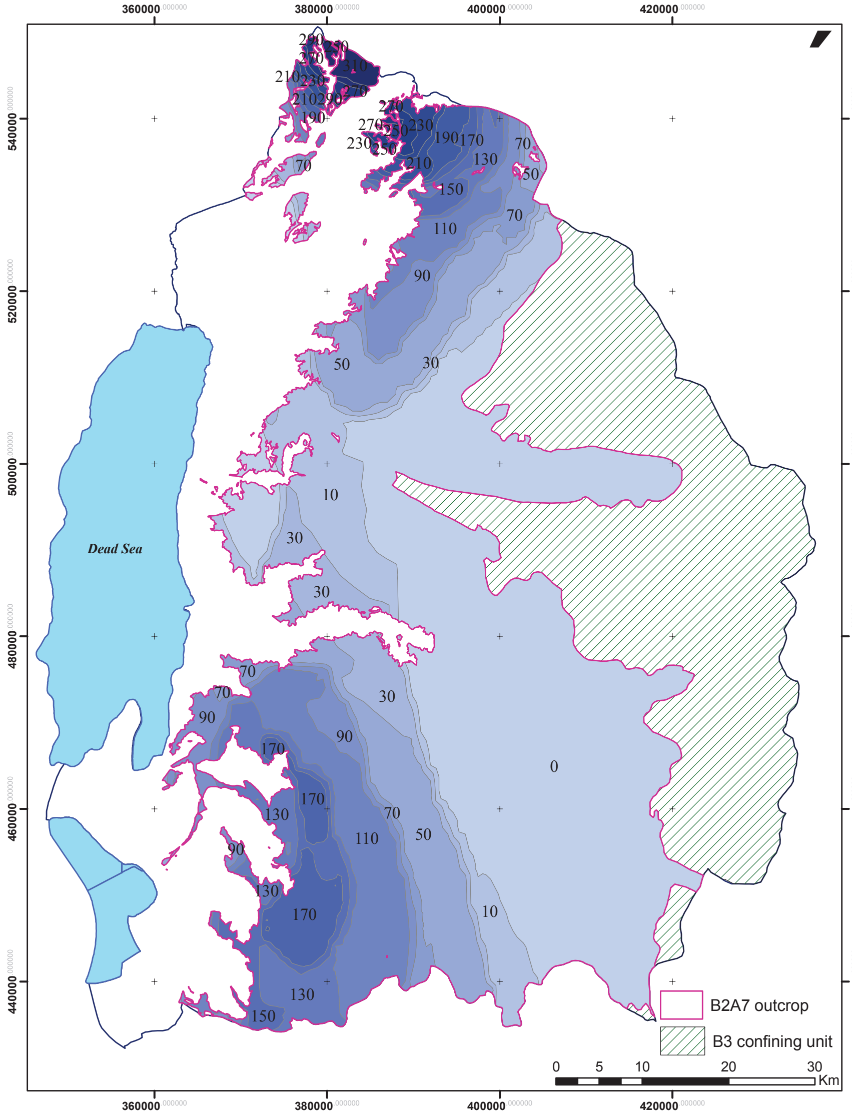

Figure (8, d): Recharge Rates Scenario for Rainfall Decrease to 90% of Its Long-term Average (mm) (No Temperature Change).

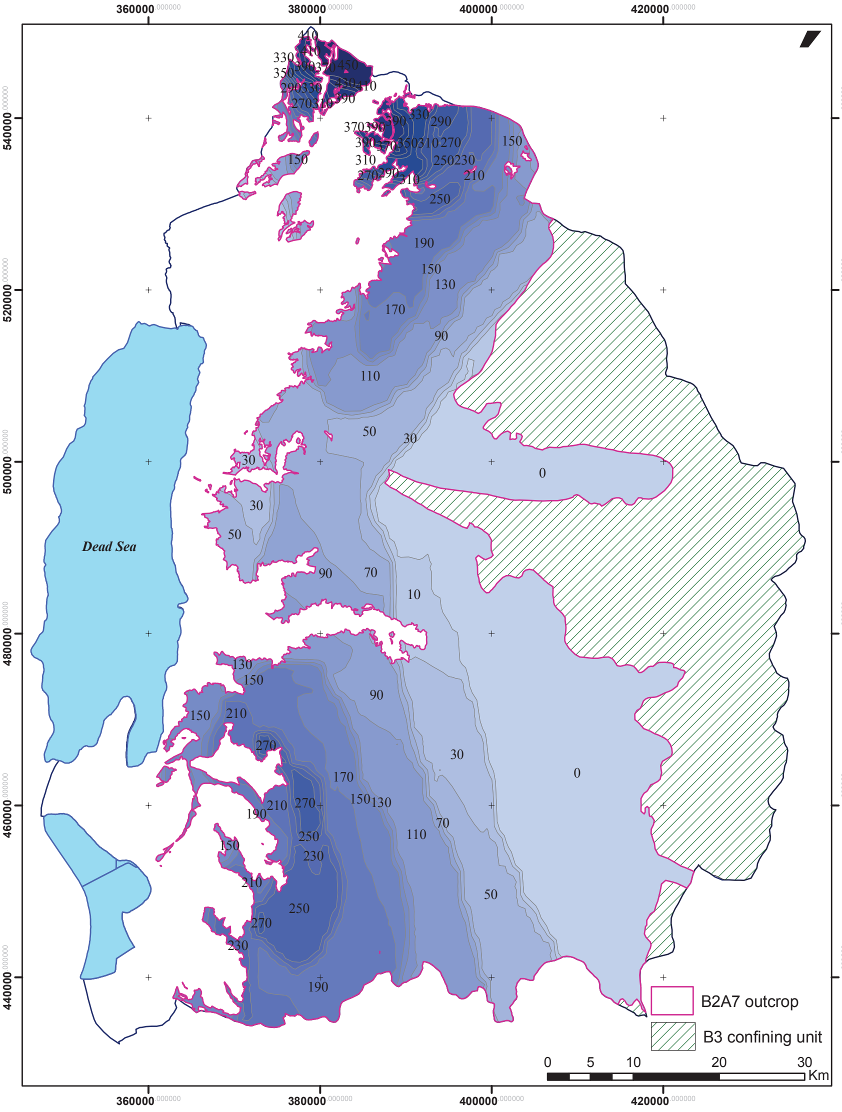

Figure (8, e): Recharge Rates Scenario for Rainfall Increase to 120% of Its Long-term Average (mm) (No Temperature Change).

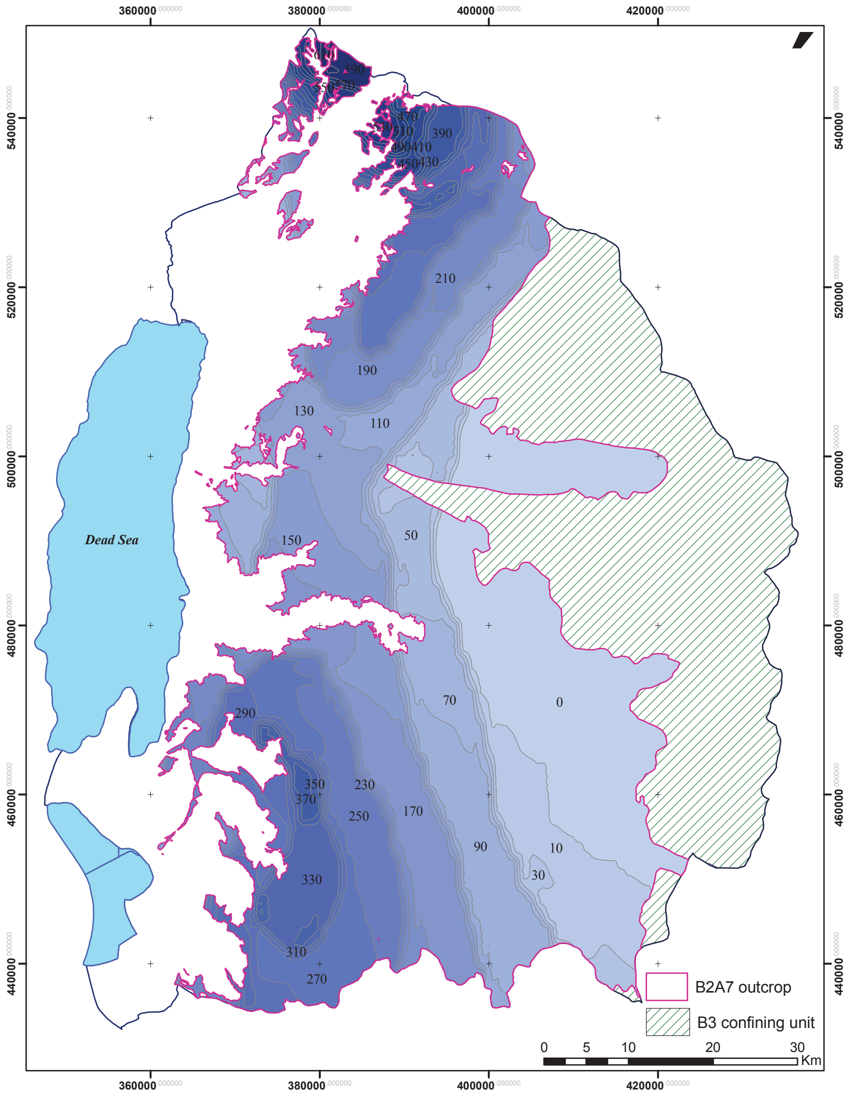

Figure (8, f): Recharge Rates Scenario for Rainfall Increase to 150% of Its Long-term Average (mm) (No Temperature Change).

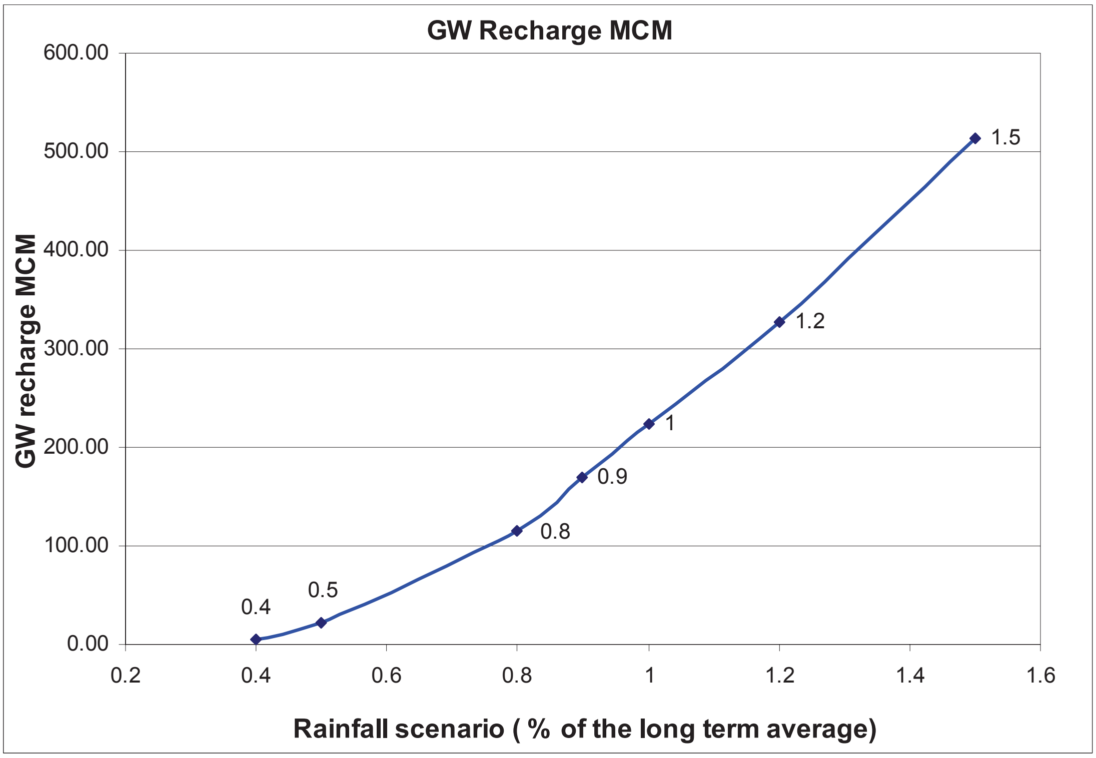

Figure (9): Rainfall-Recharge Relation.

Table (3): Rainfall Scenarios and the Expected Variation in Recharge .

Rainfall scenario %of average rainfall year	GW Recharge MCM	% of normal recharge
40%	4.50	2.01
50%	21.83	9.76
80%	115.47	51.66
90%	169.74	75.94
100%	223.53	100.00
120%	327.90	146.69
150%	512.91	229.46

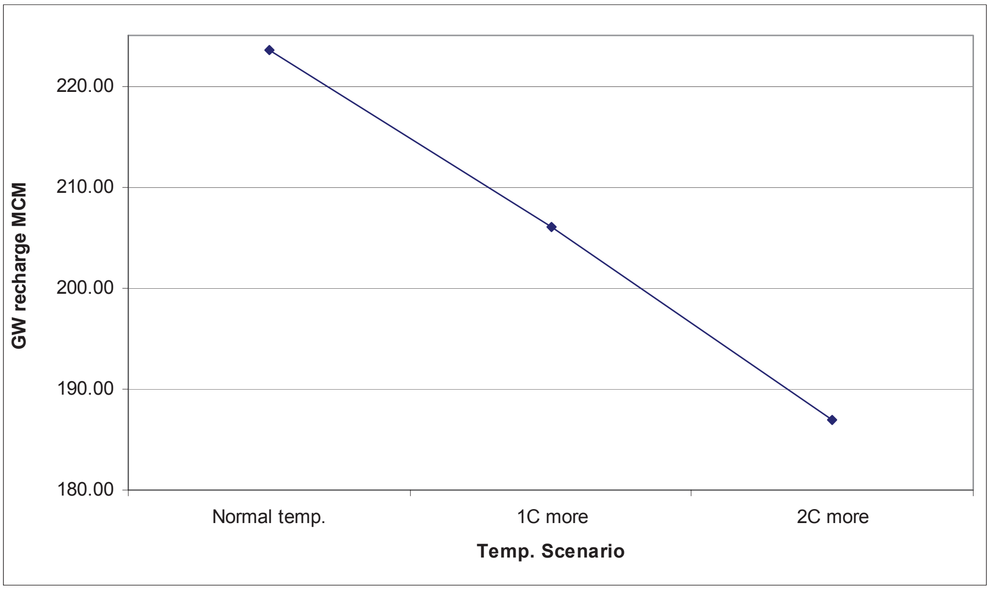

Figure (10): Temperature-Recharge Relation.

CONCLUSIONS

Climatic changes resulting in temperature rise by 1ºC and 2ºC will result in a decrease in the groundwater recharge of 11.3% and 23.2%, respectively. A decrease in precipitation by 10% and 20% will cause a reduction of groundwater recharge of 24.06% and 48.34%.

This is a result of the fact that evaporation has a water reservoir which is the soil. The retained water in the soil during and immediately after the wet season is lost by evaporation. This means that flood runoff as a certain percentage of precipitation takes its share of precipitation water.

Evaporation does the same and releases to the groundwater only what exceeds the field capacity of the soil.

Groundwater recharge takes only what remains after runoff and evaporation take whatever they can from precipitation water.

Decreasing precipitation and increasing temperature will rigorously affect groundwater recharge in a very negative way. The relationship of groundwater recharge to precipitation is not linear but exponential.

What applies to climatic changes applies also to the annual fluctuations of precipitation and temperatures. As an example, a precipitation amount in a certain year 50% less than an average year will cause a decline in groundwater recharge by 90.24%. A precipitation amount in another year with 50% more than an average year will result in an increase of groundwater recharge of 129.46%.

REFERENCES

DOM: Department of Meteorology/ Jordan (Open files).

Linsley, F. 1979. Water Resources Engineering, Third Edition. McGraw-Hill.

NWMP: National Water Master Plan of Jordan. 1977). Surface Water Resources, Natural Resources Authority/Jordan and Bundesanstalt fuer Geowissenschaften und Rohstoffe/Germany.

Salameh, E. 2009. Effects of Climatic Changes on Surface and Groundwater Resources in the Northwestern Parts of Jordan (SMART-Project Final Report, University of Karlsruhe/ Germany).

WAJ: Water Authority of Jordan (Open Files).