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Methods of groundwater recharge estimation in eastern Mediterranean—a water balance model application in Greece, Cyprus and Jordan

E. Zagana,[1]* Ch. Kuells,[2] P. Udluft[3] and C. Constantinou[4]

[1] *Hellenic Centre for Marine Research (HCMR), Institute of Oceanography, 46, 7 Km Athens—Sounio Ave., P.O. Box 712, 190 13, Anavissos, Attica, Greece*
[2] *Institute of Hydrology, University of Freiburg, Germany*
[3] *Institute of Geology, Department of Environment and Hydrogeology, University of Wuerzburg, Germany*
[4] *Geological Survey of Cyprus, Ministry of Agriculture and Environment, Nicosia, Cyprus*

Abstract:

Groundwater recharge studies in semi-arid areas are fundamental because groundwater is often the only water resource of importance. This paper describes the water balance method of groundwater recharge estimation in three different hydro-climatic environments in eastern Mediterranean, in northwest Greece (Aliakmonas basin/Koromilia basin), in Cyprus (Kouris basin and Larnaka area) and in Jordan (northern part of Jordan). For the Aliakmonas basin, groundwater recharge was calculated for different sub-catchments. For the Upper Aliakmonas basin (Koromilia basin), a watershed-distributed model was developed and recharge maps were generated on a daily basis. The mean annual recharge varied between 50 and 75 mm/year (mean annual rainfall 800 mm/year). In Cyprus, the mean groundwater recharge estimates yielded 70 mm/year in the Kouris basin. In the Larnaka area, groundwater recharge ranged from 30 mm/year (lowland) to 200 mm/year (mountains). In Jordan, the results indicated recharge rates ranging from 80 mm/year for very permeable karstified surfaces in the upper part of the Salt basin, where rainfall reaches 500 mm/year to less than 10 mm/year and to only about 1 mm/year in the southernmost part of the basin. For the north part of Jordan, a watershed-distributed model was developed and recharge maps were generated. This water balance model was used for groundwater recharge estimations in many regions with different climatic conditions and has provided reliable results. It has turned out to be an important tool for the management of the limited natural water resources, which require a detailed understanding of regional hydro(geo)logical processes.

KEY WORDS groundwater recharge; water balance modeling; Greece; Jordan; Cyprus

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INTRODUCTION

Groundwater recharge estimations are essential in any groundwater system analysis and could provide accurate information for sustainable use of groundwater resources. During the last 20 years, there has been an increasing number of recharge studies reported in scientific literature. The active support by international agencies/NGOs and many publications from international meetings (Simmers, 1988; Sharma, 1989; Lerner *et al*., 1990; Bredenkamp *et al*., 1995) show the growing need for reliable recharge estimation (Simmers, 1997).

Different methods for groundwater recharge estimation have been developed; these methods (direct measurement, water balance methods, Darcian approaches, tracer techniques and empirical methods) and many of the problems encountered with each are described by Gee and Hillel (1988); Lerner *et al*. (1990); Allison *et al*. (1994); Stephens (1994) and Simmers (1997), among others. In the water balance method, recharge forms one of the components of the water balance. In humid areas, the uncertainties in the water balance calculation are small because of the magnitude of the recharge component. In contrast, in (semi-) arid regions, the recharge estimations from the regional water balance studies is often of low quality because of the limited recharge component. Not only climate but also geology, morphology, soil condition and land use have to be involved in the recharge estimations. The variability of recharge in time and space also has to be included in the recharge estimation techniques. In this study, which was carried out in the framework of the joint European Research Project (INCO—DC18CT97-0413) GREM (Groundwater Recharge in the Eastern Mediterranean), a physical water–soil balance approach was used to quantify groundwater recharge in different hydro-climatic environments in the eastern Mediterranean. An updated version of the water balance model MODBIL (Udluft, 1992; Udluft and Zagana, 1994; Zagana, 2001) was used to simulate the hydrological processes, as well as a distributed model version, which was developed during the project (Kuells *et al*., 2000; Udluft

* Correspondence to: E. Zagana, Hellenic Centre for Marine Research (HCMR), Institute of Oceanography, 46, 7 Km Athens—Sounio Ave., P.O. Box 712, 190 13, Anavissos, Attica, Greece.
E-mail: eleza@ath.hcmr.gr

and Kuells, 2000). MODBIL was developed in 1988 at the Department of Hydrogeology and Environment (University of Wuerzburg/Germany) and was further improved within the frame of several projects that were carried out predominantly in semi-arid and arid areas like Greece, Cyprus, Israel, Jordan, Namibia, Brazil and Lower Franconia (Germany) (see Udluft and Zagana, 1994; Kuells *et al*., 2000; Udluft and Kuells, 2000; Duenkeloh *et al*., 2003; Udluft *et al*., 2003). A major advantage of this method is that the dynamics of runoff generation and of groundwater recharge can be studied under changing environmental and climatic conditions for hypothetical land use scenarios. MODBIL provides a straightforward technique to assess the regional water balance dynamics based on a physical, process-oriented and distributed model (Duenkeloh and Udluft, 2004).

STUDY AREAS

Aliakmonas basin (Greece)

The Aliakmonas basin (Figure 1) is located in the north-western part of Greece and practically covers the whole area of western Macedonia. The basin has a central hilly part, and its margins (especially the western ones) are mountainous, with altitudes up to 2520 m.

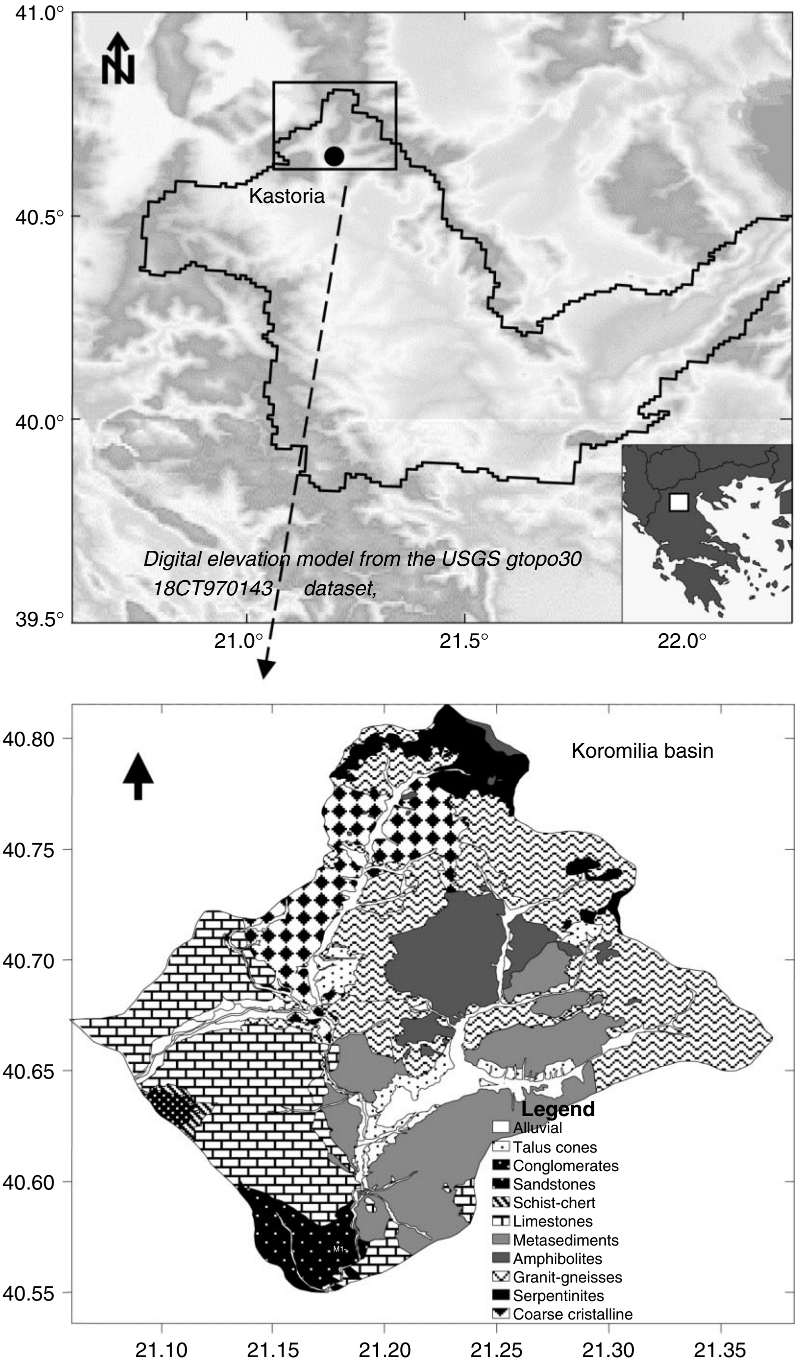

Figure 1. Aliakmonas River basin and geological map of the study area

Its relief is rough, and the mean dip of the land is very steep. The vegetation is very dense in the central, north and especially the western part, while it is very limited towards the east. It belongs climatically to western Macedonia and is characterized by the change of Mediterranean to continental climates of the Balkans (Livadas, 1976). Precipitation is present throughout the year, reaching one maximum in October through January and another one in April, May. Rainfall ranges between 1000–1200 mm/year in the north-west down to 600–700 mm/year in the east. The central part of the basin is mainly covered by molasse sediments (marls, conglomerates, sandstones) of the Oligocene-Miocene age, which compose the so-called 'Meso-Hellenic Trough' (Mountrakis, 1985; Jacobshagen, 1986). The eastern part, which belongs to Pelagonian zone, consists of metamorphic rocks (the crystalline substratum), Triassic-Jurassic marbles and ophiolites. The western part (sub-Pelagonian zone) is covered with ophiolites, limestones (Jurassic-Upper Cretaceous), flysch and molasse sediments (Mountrakis, 1985; Jacobshagen, 1986). The basin has neither rich aquifer beds nor very important springs. The spring discharges range from 0·002 to 0·045 m^3/sec (Vafiadis, 1983). The Koromilia karst spring, near Kastoria city in the northern part of the study area, is the only one with discharge rates approximately 2 m^3/sec. The Koromila basin (the upper part of Aliakmonas basin) (Figure 1), which is located upstream to the Koromilia gauging station, covers approximately 650 km^2. The western past of Koromila basin is mainly covered with carbonated rocks, while the eastern part is covered with granit-gneisses, amphibolites and serpentinites (Figure 1). This area was chosen for the development of the distributed water balance modelling.

Cyprus

Within the frame of the GREM project, two clusters of study basins were selected in Cyprus for groundwater recharge estimations using the water balance method: one in the Troodos area (Kouris Valley) and one in the Larnaka area (Figure 2). The Troodos is the central mountain complex of Cyprus—a reservoir of water and wood that has guaranteed these essential resources since the beginning of copper production despite strong exploitation (Kuells *et al*., 2000). The altitude ranges from 250 m asl (above sea level) up to 1953 m (Mt. Olympus). The total area of the Kouris Valley is about 340 km^2 and the direction of the valley is north to south. It is divided

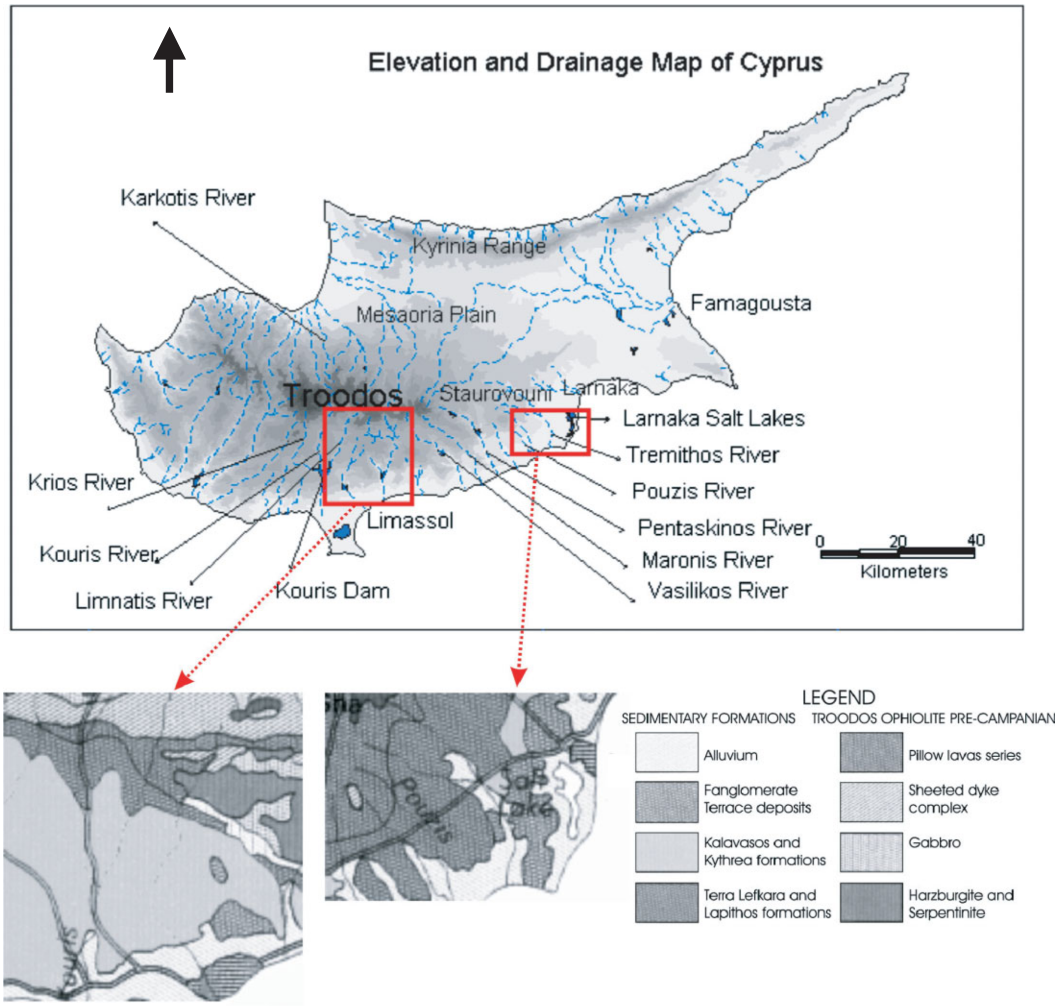

Figure 2. Location and geology of study areas in Cyprus

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into three sub-valleys, the Kouris, Limnatis and the Krios (Figure 2). The biggest dam of Cyprus has been constructed downstream to the Kouris River. The Kouris sub-catchment area is about 96 km^2 and its gauging station is located upstream to the Kouris Dam. The water–soil balance model was applied for the Kouris sub-catchment area. The Kouris River's mean annual flow is 15·4 million m^3 (1965–1993).

The second study area is defined by the coastline to the south, by the Larnaka to the east, by the Staurovouni Mountain to the north and by the Limassol to the west. The altitude ranges from sea level up to 600 m asl (Staurovouni area). There are five small rivers in the Larnaka area, which are shown in Figure 2. Three dams have been constructed in this area: the Dipotamos, the Lefkara and the Kalavasos Dam. The climate in these areas is Mediterranean with hot, dry summers and cool, wet winters. Temperatures on the mountains fall below zero in winter but in the plains may rise above 40 °C in summer. The rainfall is confined to the months from October to April, varying from 300 mm in the south to 1100 mm on the Troodos Massif. The rocks of the Plutonic Complex in the Troodos area are faulted, highly fractured, and in places brecciated. Jointing is very well developed and extends to depth (Wilson, 1959). Joints and faults are fairly open and appear to be the major pathways for infiltration. Most of the major springs in this complex are fault controlled. Although the Sheeted Dyke Complex is highly fractured and faulted in places, there is lower infiltration in comparison to the Plutonic Complex (Constantinou, 1994; Constantinou *et al.*, 1995). Six different aquifers exist in the second study area between Limassol and Larnaka: the Ophiolite Aquifer, the Lefkara Chalk Aquifer, the Pakhna Sandstone Aquifer, the Kalavasos-Maroni Gypsum Aquifer, the Coastal Plain Aquifer and the River Deposit Aquifer (Constantinou, 1994; Constantinou *et al.*, 1995). The Larnaka area was chosen for the development of the distributed water balance modelling.

Jordan

In general, Jordan can be sub-divided topographically and physiographically into the following regions (Quennell, 1958; Bender, 1974):

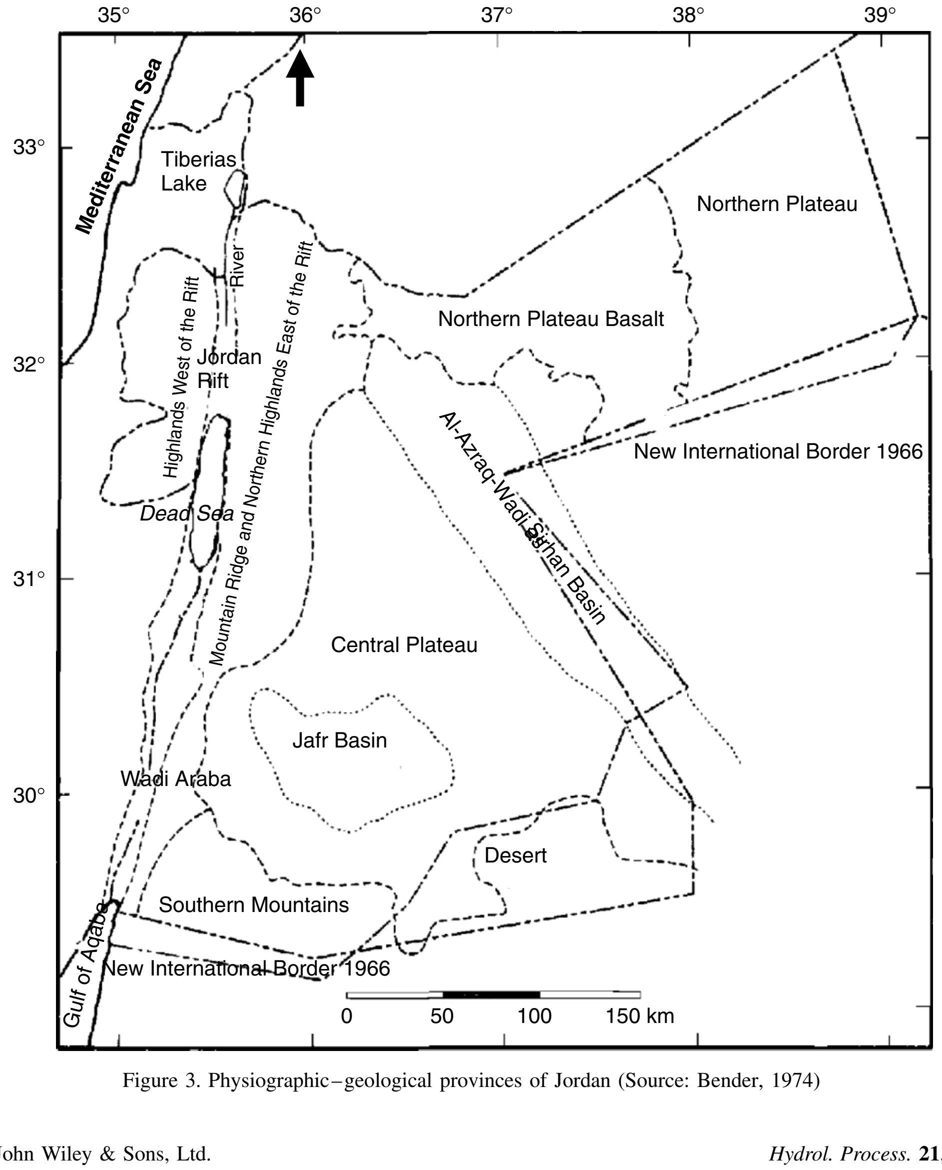

Figure 3. Physiographic–geological provinces of Jordan (Source: Bender, 1974)

1. The Jordan Rift Valley, which is the lowest land depression of the earth, and comprises the Jordan Valley and Wadi Araba (Figure 3). The Jordan Valley shows a gradual descend from approximately 220 m bsl (below sea level) in the north to about 412 m bsl at the shore of the Dead Sea. Wadi Araba has different topographical features. South of the Dead Sea, the valley floor rises gently over a distance of about 130 km from 412 m bsl to an elevation of 240 m asl, and declines again to zero in Aqaba. 2. The Eastern Highlands, which consist of the western part of the trans-Jordan plateau and descend westward to the Rift Valley and gradually slope eastward into the Eastern Desert (Mountain Ridge and Northern Highlands East of the Rift, Figure 3). 3. The Steppe Region, towards the east, the relief of East Jordan Plateau becomes undulating to flat with the absence of mountainous relief (Northern Plateau Basalt, Figure 3). 4. The Central Plateau. 5. The Eastern and Southern Deserts, which cover most of east Jordan.

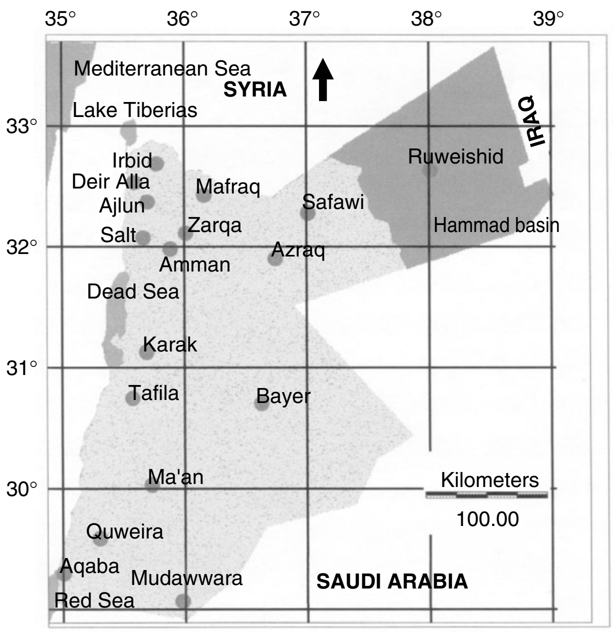

Figure 4. Location map of the stations

The study area in Jordan extends from Deir Alla (Figure 4) near the Jordan River at an elevation of 235 m bsl and with an average precipitation of 250 mm/year through Salt at an elevation of 1000 m asl with an average precipitation of 500 mm/year through Al Zarqa/Mafraq at an elevation of 600–700 m asl and an average precipitation of 180–220 mm/year respectively to Safawi in the east at an elevation of 700 m asl with precipitation as low as 100 mm/year (Obeidat, 2001). These stations are shown in Figure 4. Deir Alla is located in the Jordan valley, where Lisan marls and alluvial deposits (flood deposits) form the sediments of the valley. Salt and Al Zarqa are located in the northern highlands east of the rift. Al Mafraq is located in a transition zone with basaltic bedrock, while Safawi belongs to the realm of desert soils.

METHODOLOGY

The hydrological processes and the groundwater recharge of the study areas have been simulated with the help of the water balance model MODBIL. It uses meteorological variables, topographic, soil and vegetation parameters for the prediction of fluxes within the soil and into the aquifer. Input data consists of daily values of precipitation I_N; potential evaporation I_{vpot} is derived from temperature and relative humidity or can be entered directly (if data on pan evaporation is available). Topographic parameters are elevation and slope. The main soil parameters are effective field capacity nFK and the infiltration capacity of the soil that is a maximum infiltration rate Q_{INF}. The effective field capacity represents the capacity of the soil to hold water against gravity that can be used by plants. Surface runoff Q_{Ob} is produced if the intensity of rainfall events exceeds this threshold. The movement within the soil is controlled by evapotranspiration (upward movement) and percolation. Percolation is a function of the soil moisture states that is linked to percolation rates by the relationship θ-$K\psi$, where θ is the soil water content and $K\psi$ represents hydraulic conductivity K as a function of suction head ψ (Udluft and Zagana, 1994; Kuells *et al.*, 2000; Udluft and Kuells, 2000).

In the model, two different layers S_1 and S_2 are implemented—for each of them a saturated hydraulic conductivity can be entered. The model provides the possibility to calculate the seepage through sediments and a bedrock of variable thickness; for the latter case, leakage through an aquitard can be simulated as Darcy flow Q_{LECK}. For the simulation of spring flow Q_{QUELLE}, the

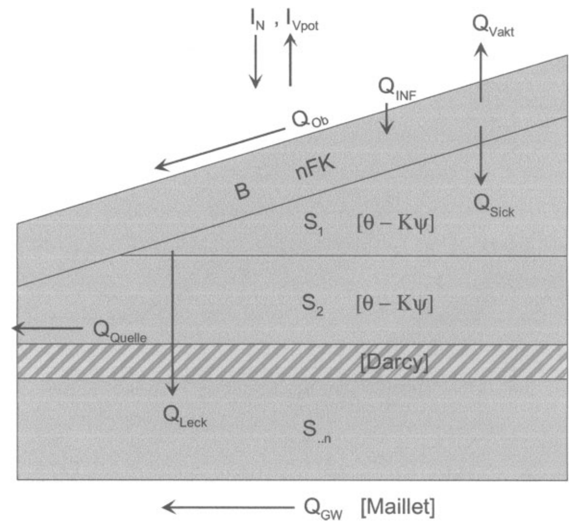

Figure 5. Flow chart representing the water balance model. (I_N: precipitation, I_{Vpot}: potential evaporation, nFK: effective field capacity, Q_{INF}: maximum infiltration rate, Q_{Ob}: surface runoff, Q_{Vakt}: actual evapotranspiration, Q_{Sick}: percolation, θ: soil water content, $K\psi$: hydraulic conductivity K as a function of suction head ψ, Q_{LECK}: leakage through an aquitard, Q_{QUELLE}: spring flow, Q_{GW}: groundwater recharge, S: different layers)

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percolating water can be routed through a Maillet-type reservoir. Figure 5 shows a flow chart representing the water balance model. The recharge leaving the soil zone can be routed through deeper geological layers (sediments or hard rock). As a result, runoff and recharge data are available. The model also provides the possibility of calculating river discharge. River discharge is modelled as a combination of direct and fast surface runoff and of baseflow from aquifer outflow. Model calibration was done by comparing the sum of the accumulated direct runoff and baseflow with the observed discharge time series. Within the frame of the GREM project, for the study basins in Greece, Cyprus and Jordan, a model database of meteorological and hydrological time series was established. Data for the soil conditions and land use were also collected. Model runs were performed for all study basins (Aliakmonas basin—Koromila basin/Greece, Kouris basin and Larnaka area/Cyprus and for several test sites and basins in Jordan/Salt basin, Deir Alla, Al Mafraq, Safawi).

This paper presents the results of the Koromila basin in Greece and the Larnaka area in Cyprus and north Jordan for which a distributed water–soil balance model was developed. For these basins, digital elevation models were created to derive the topographic parameters (elevation, slope) for each grid cell. Digital maps of meteorological data as well as data for soil and land use conditions were also produced for each grid cell.

RESULTS

Greece

For the Koromilia basin in the upper part of the Aliakmonas basin, a daily water balance model was prepared. As a result, daily maps of groundwater recharge were obtained. These maps were aggregated to maps of mean annual recharge.

In Figure 6, the groundwater recharge map for the Koromilia basin is presented. Mean annual recharge varies between 50 mm/year and 75 mm/year. The map shows that recharge is highest in the karst area in the western part of the basin with recharge rates reaching 300 mm/year. Along the river valleys, where alluvial sediments are found, recharge ranges between 100 mm/year and 200 mm/year. In the central and east part of the basin, where granit-geisses, amphibolites and serpentinites are dominated, recharge varies from more than 0 mm/year to 100 mm/year. An analysis of the temporal variability of recharge has highlighted the importance of snowmelt for the replenishment of aquifers in this area.

Cyprus

On the basis of the parameter estimates, the time series of the mean annual recharge in the area between Larnaka and Limassol was produced. In this case, spatial averages over the whole study area were produced. Figure 7 shows the precipitation map, calculated for each grid cell, and the groundwater recharge including the interflow in the area between Limassol and Larnaka. In the southern part of the basin (lowland), where the calculated precipitation reaches 300 mm/year, groundwater recharge ranges between 30 mm/year and 80 mm/year. In the mountainous area, where the calculated precipitation ranges from 400 mm/year to 650 mm/year, recharge varies between 100 mm/year and 200 mm/year.

Jordan

For the stations Deir Alla, Al Mafraq, Safawi and Salt, daily hydro-meteorological data and runoff data

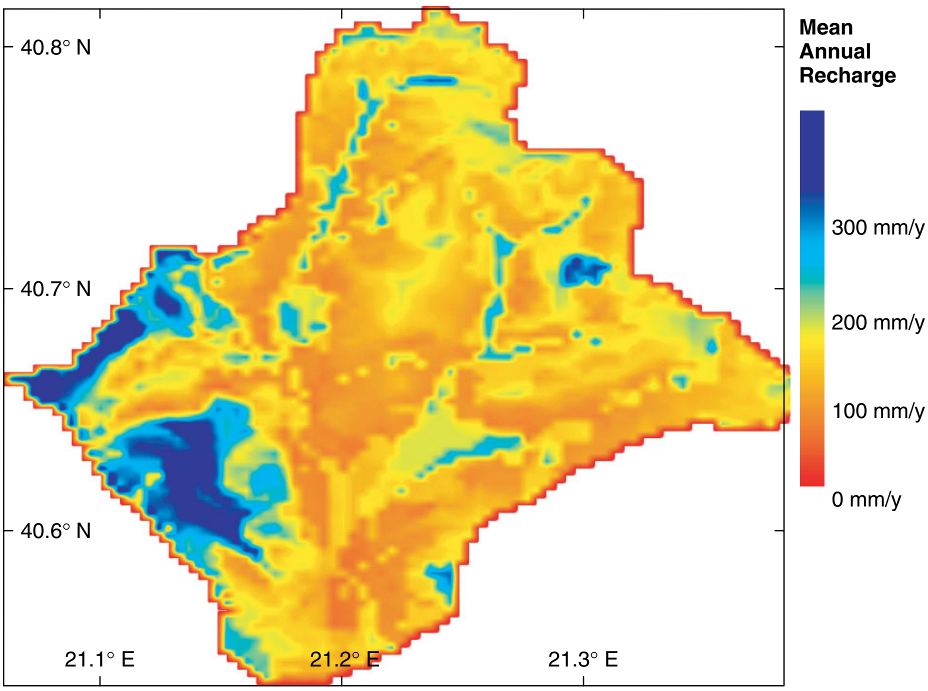

Figure 6. Mean annual groundwater recharge for Koromilia sub-catchment

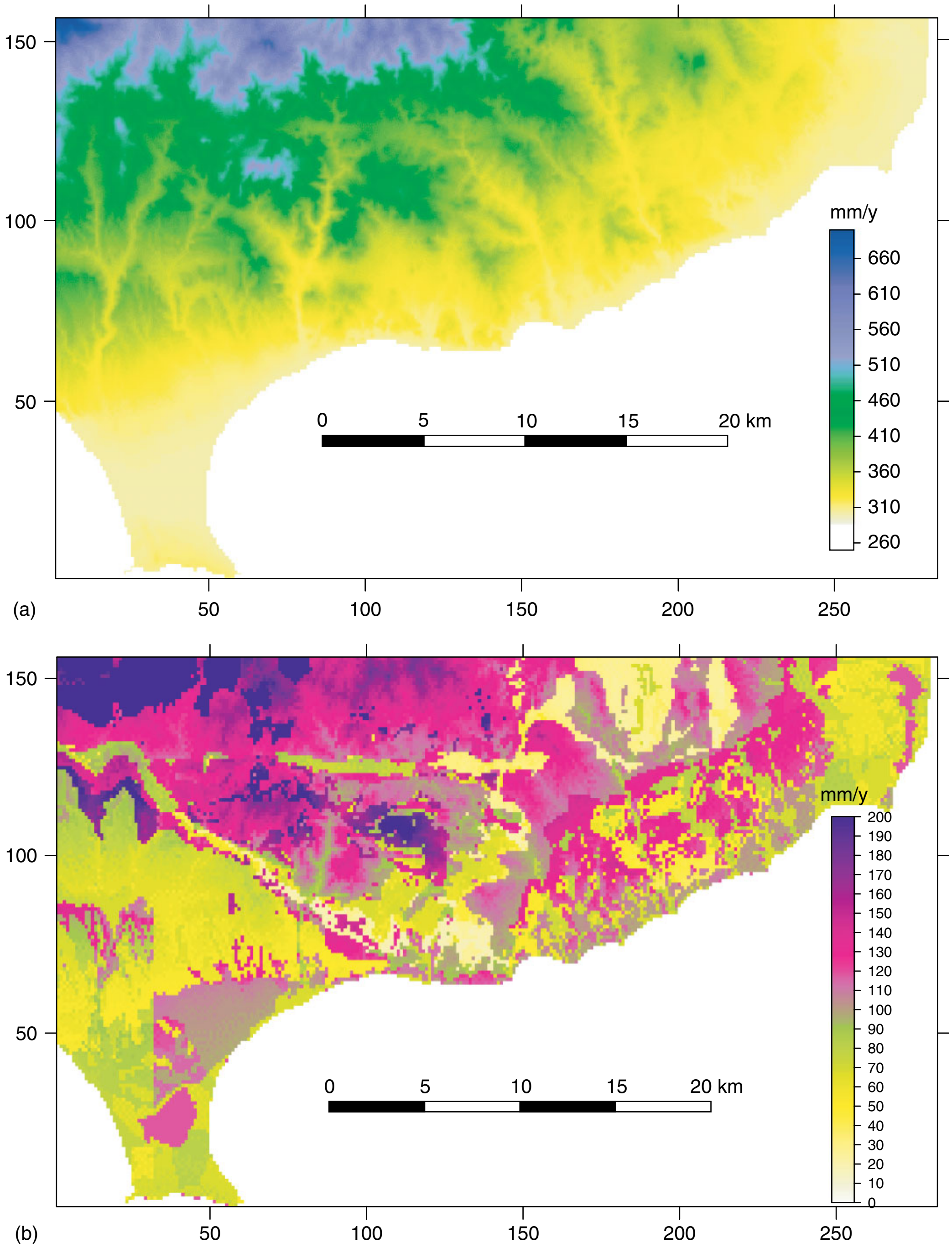

Figure 7. (a) Mean annual calculated precipitation. (b) Mean annual calculated groundwater recharge in the area between Larnaca and Limassol

were collected and the daily water balance model was calibrated for each station. As an example, the results for the Salt basin (Salt station) on the eastern side of the Jordan valley, the stations Al Mafraq and Safawi are presented.

In the upper part of the Salt basin, rainfall still reaches 500 mm/year, while in the lower part of the basin, the annual rainfall drops to less than 200 mm/year. This basin therefore demonstrates the hydrological changes that occur along a hydro-climatic gradient from sub-humid to semi-arid and finally arid conditions. The water balance model showed that in the upper part of the basin the mean annual recharge can locally reach up to 80 mm/year. This corresponds to a relatively high percentage of mean annual precipitation and results from very permeable karstified surfaces in this area. The lower parts of the basin, especially the valley floors that are filled with sediments of low permeability, contribute only small amounts of recharge to the balance of the whole catchment. Recharge drops to less than 10 mm/year and to only about 1 mm/year in the southernmost part. In Al Mafraq (700 m asl, 220 mm/year precipitation), the hydrological processes, especially recharge, become erratic, reflecting the arid conditions in this part of Jordan. The mean annual recharge was estimated to amount to only around 1 mm/year. This rate increases with

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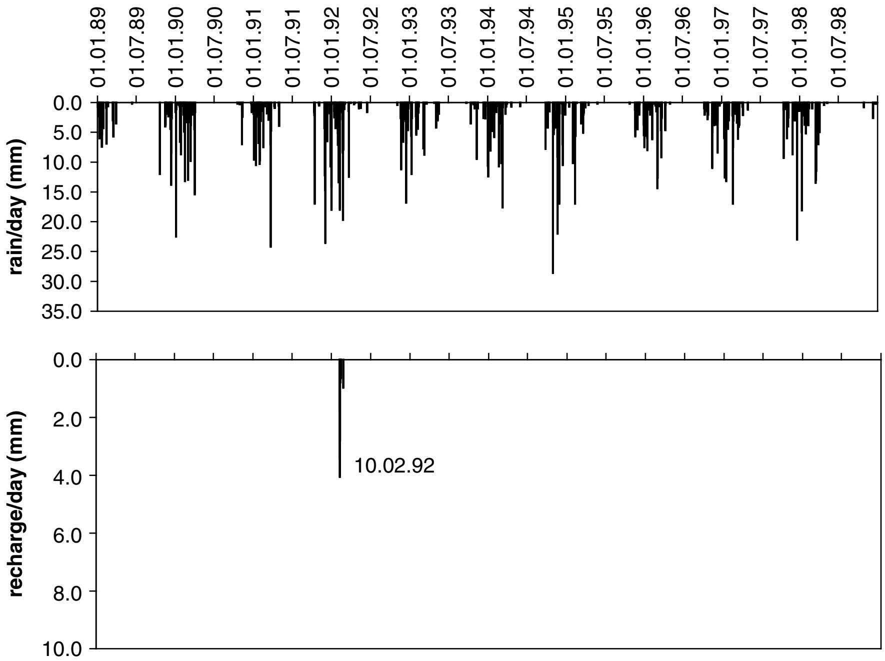

Figure 8. Time series of rainfall and recharge (daily) for the station Al Mafraq

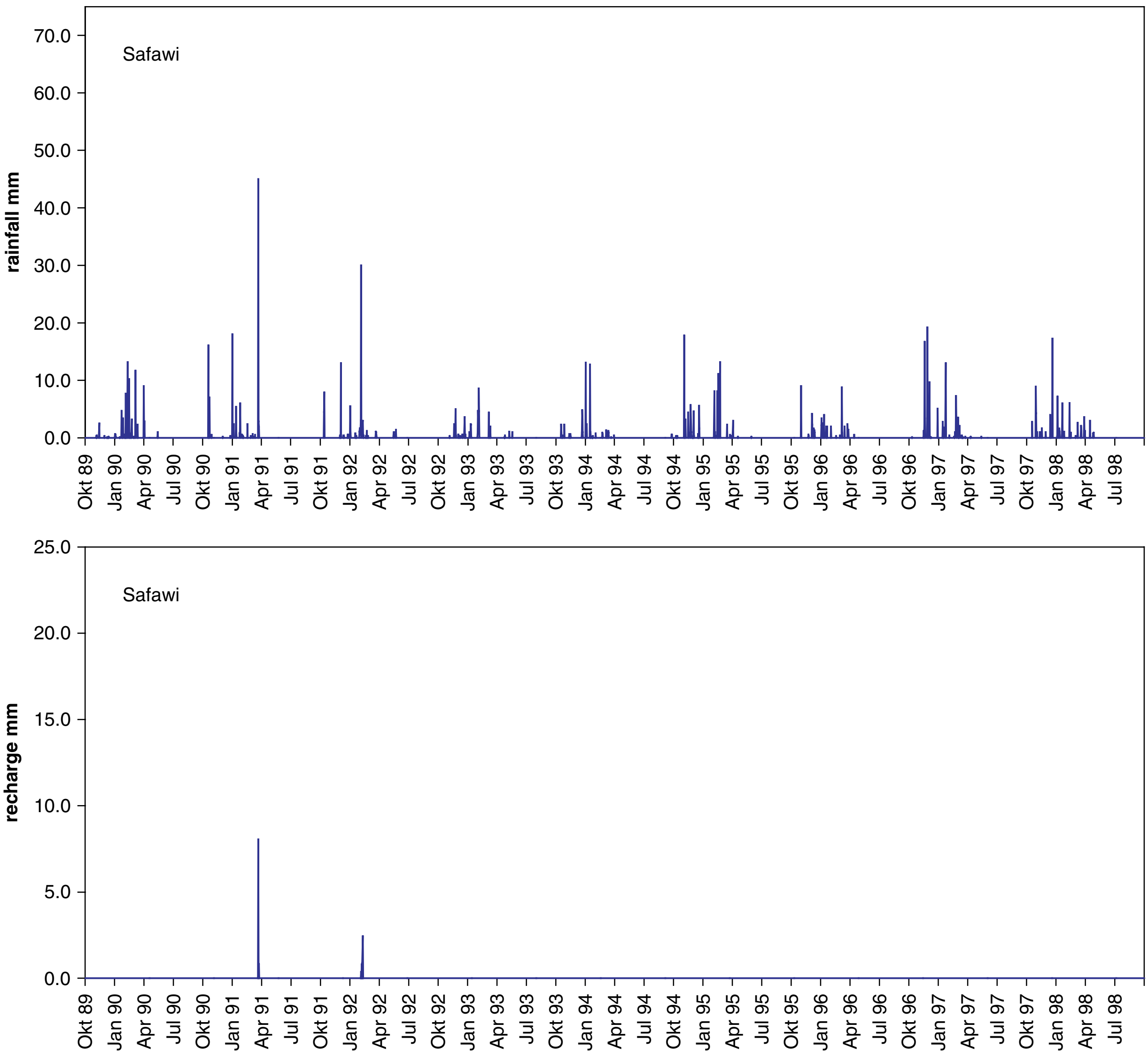

Figure 9. Time series of rainfall and recharge (daily) for the station Safawi

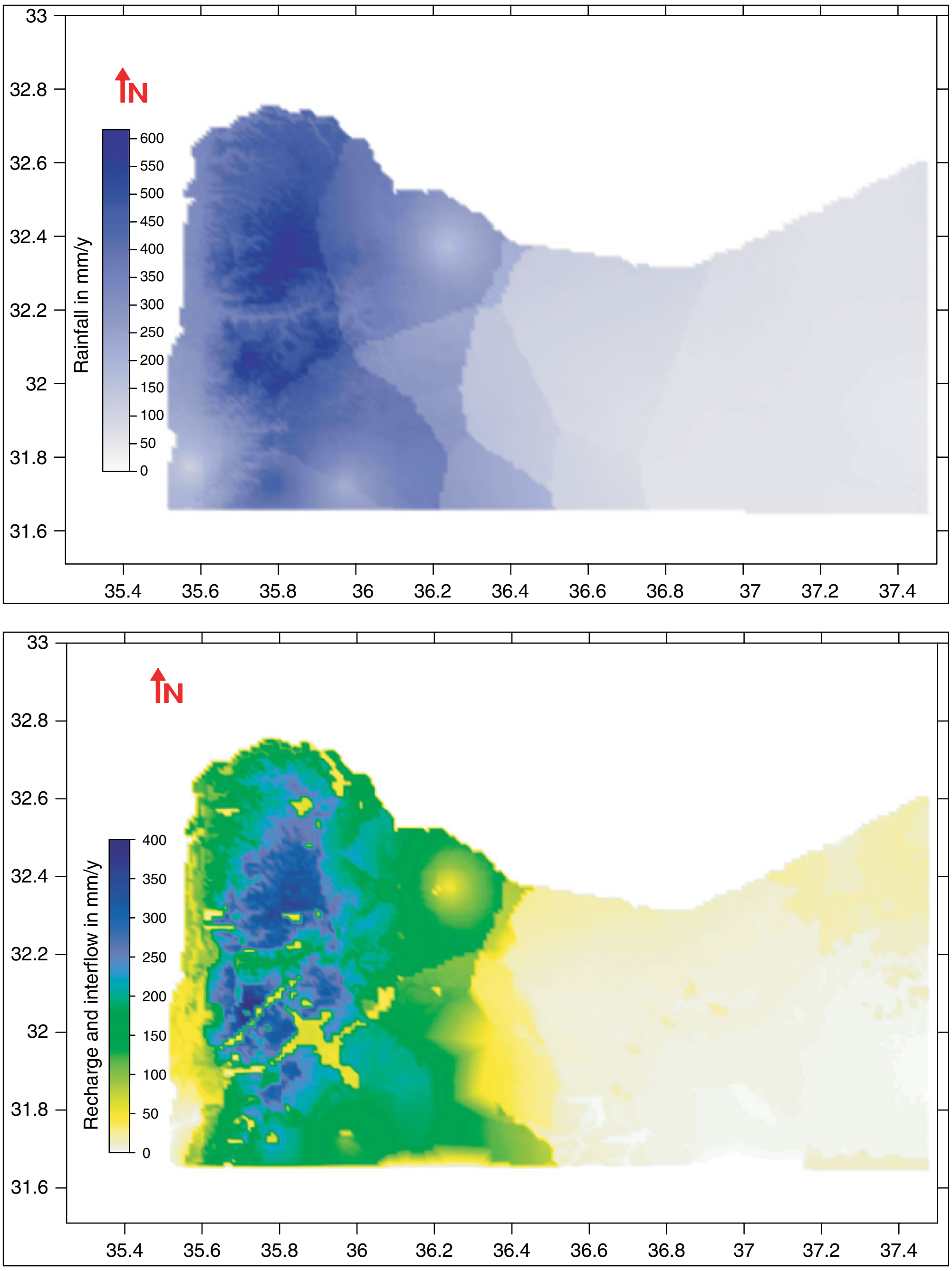

Figure 10. (a) Mean annual calculated precipitation and (b) mean annual groundwater recharge and interflow map of the northern part of Jordan (1961–1990)

shallower or stony soils—it drops with steeper slopes and infiltration capacities of the soil surface of less than 5 mm/event. As shown in Figure 8, between 01/01/1989 and 31/12/1998, only one recharge event was obtained as a result of the soil–water balance modeling. This event occurred around 10/02/1992 and accounted for all the recharge during the observation and modelling period. At Safawi in east Jordan, an area where the mean annual rainfall amounts 100 mm/year, the estimated recharge rate amounts of 1·6 mm/year. As shown in Figure 9, only two recharge events were obtained as a result of the water balance modelling. Figure 10 presents the results of the model simulation for the northern part of Jordan. As shown in the figure, in the eastern part of Jordan, groundwater recharge ranges between 0 mm/year and 50 mm/year. In the mountain ridge and highlands east of the rift (see Figure 3), groundwater recharge ranges from 200 to 350 mm/year.

CONCLUSIONS

Within this study, groundwater recharge was estimated in different hydro-climatic areas in eastern Mediterranean using the water–soil balance method. A raster distributed modelling software was developed, which allows generating recharge maps on a daily input data basis.

This approach has improved the understanding of spatial variability of groundwater resources in all study areas. While hydrological models exist that calculate runoff, this module is an innovative tool supporting sustainability studies and groundwater modelling work significantly. The comparison of the computed discharge with measured data represents an important reference for the calibration and validation of the data. In this study, it is shown that, in (semi-) arid regions, for the groundwater recharge estimations from the regional water balance studies not only climate but also geology, morphology, soil condition and land use have to be involved in the recharge estimations. The variability of recharge in time and space has been included in the recharge estimation in all study areas. The maps of recharge distribution allow an assessment of the groundwater potential of these areas.

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