LAKE KARLA AQUIFER'S RESPONSE TO CLIMATE VARIABILITY AND CHANGE AND HUMAN INTERVENTION

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EXTENDED ABSTRACT

Climate change will affect the hydrology of a region through changes in the timing, amount, and form of precipitation, evaporation and transpiration rates, and soil moisture, which in turn affect also the surface water and groundwater resources in a region. The aim of this study is to assess the impact of climate variability, and change and human intervention in the Lake Karla aquifer, located on the eastern part of Thessaly in Greece. The monthly UTHBAL water balance model was selected for the assessment of the surface runoff and the evaluation of hydrological cycle components and MODFLOW code is adopted for aquifer’s simulation. Input data are monthly values of precipitation and temperature for the 42 hydrologic years starting from October 1960 to September 2002. Data from Karla’s hydrometric station were used in order to calibrate and verify the hydrological model and data from observation wells for groundwater model calibration and subsequent simulation. A hybrid statistical downscaling method which combines multiple regression (MLR) models and timeseries models for the regression residuals has been applied to downscale the outputs of the second version of the Canadian Centre for Climate Models (CGCMa2) from the Global Circulation Model grid to the watershed level. This two-part method is able to discriminate the effect of climate change as well as the effect of climate variability on the study meteorological variable (i.e. precipitation). Climate change impacts are estimated from the MLR models and the natural variability of the climate is estimated by the application of stochastic timeseries models and the generation of 100 synthetic timeseries of the MLR residuals. The downscaling method developed and validated in the period 1960-2009 and then applied to estimate future changes on precipitation and temperature for the future period 2009-2058 using two climate emissions scenarios A2 and B2 (SRES) of the CGCMa2 model. The UTHBAL model was applied in a semi-distributed mode in Lake Karla watershed and produced 100 time series of recharge data for present and future periods and scenarios. These data were imported to groundwater model forcing it to run in a stochastic mode producing 100 realizations of aquifer with hydraulic head maps. The methodology was applied for two operational simulations: a) to natural aquifer without human intervention and b) to the real aquifer, as it is today, with the human intervention. The difference between these two situations is the existence of extraction wells and the applied water policies at the study area. Evaluating the results of the study, climate change does not affect the natural aquifer of Lake Karla in contrast to human exploitation which is quite intense and requires immediate reassessment of water demands, before the situation becomes irreversible.

Keywords: Climate change and variability, human intervention, statistical downscaling, water balance, water resources management.

1. INTRODUCTION

Rainfall varies considerably over space and time. Agricultural and water resources systems have evolved in response to this variability, but in most regions of the world,
rainfall variability continues to be a major source of risks that water resources managers face. Research is being conducted to better understand climate variability, its impacts on agricultural and water resources systems, and how to reduce those risks through decisions and policies that consider climate variability. Nowadays anthropogenic climate change and its socioeconomic impacts are major concerns of mankind. Global surface temperature has been increased significantly during the last century and will continue to rise unless greenhouse gas emissions are drastically reduced (IPCC, 2007). Climate change effects are manifold and vary regionally, even locally, regarding their intensity, duration and areal extent. However, immediate damages to humans and their properties are not obviously caused by gradual changes in temperature or precipitation. The effect of climate variability on the water resources of a region could be analysed with the use of long historical data series which are unavailable in many parts of the world. Coupled atmosphere-ocean circulation models could be used to simulate the water balance. These models are able to generate long timeseries that can be used for water resources management as well as for adopting water policies to prevent the possible adverse effects of climate change on the water resources.

Lake Karla watershed is located in the east part of Thessaly, covering an area of 1171 km², with a perimeter of 228 km (Loukas et al., 2008). The intense cultivated plain covers more than 600 km² while the rest area is dominated by the mountains of Ossa, Mavrovouni and Kalkodonio (Figure 1). Elevation ranges from 40 m to more than 2000 m, and the mean elevation of the region is about 230 m. The climate of the area is typical continental with cold and wet winters and hot and dry summers. Mean annual precipitation in Lake Karla watershed is about 560 mm and it is distributed unevenly in space and time. Mean annual potential evapotranspiration is about 775 mm and the mean annual temperature is 14.3 °C (Vasiliades et al., 2009). Impermeable geological formations, located on parts of the surrounding mountains, cover 30.6% of the total area. Karstic structures cover a 14.5% and are located on the Mavrovouni Mountain at the north-east part of Lake Karla watershed. Finally, permeable structures, which appear mainly in the plain, cover a 54.9%, consisting of recent grains of various sizes originating from Lake Karla deposits (Sidiropoulos et al., 2013). The background rocks consist of impermeable marbles and schist as presented by Costandinidis (1978). The drainage of former Lake Karla in 1962, the intense cultivation of water demanding crops and the uncontrolled drilling of illegal irrigation wells in the 70s and 80s have led to an over-exploitation of the lake's sedimentary aquifer (Sidiropoulos et al. 2013) which has an extent of 500 km² (Figure 1). Nowadays, even the groundwater cannot cover the irrigation needs of the cultivate areas, while the drawdown of aquifer’s water table reaches up to the 80 meters (Goumas, 2006). In order to reverse the severe water deficit problem and create a wetland with rich fauna and flora, a partial restoration of the lake was performed. The project, which is the greatest environmental project in the Balkans during the last decade, involved the reconstruction of the new Lake Karla, the construction of ditches for the area's flood protection as well as the irrigation and water supply network. The reconstructed lake occupies the lowest part of the former Lake Karla and has a surface of 38 km², almost three times smaller than the former one.

The aim of this study is to assess the impact of climate variability and human intervention on the lake's aquifer. A management tool for the optimal use of groundwater resources, taking into account the operation timetable of the reservoir as well as the closing down of the irrigation wells will be proposed. The objective of this management tool is to estimate the effect of climate change on the aquifer’s restoration through the rehabilitation of its water table to a desirable natural level.
2. METHODOLOGY

The combination of the hydrological model (UTHBAL) and the groundwater model (MODFLOW) was performed in order to assess the impact of climate variability, as well as the change and human intervention in the Lake Karla aquifer, under transient conditions. The calculated recharge from UTHBAL is the data that connects the two models. The climate variability and change forcing on precipitation and temperature has been evaluated using the output of the Canadian Centre for Climate Model Analysis General Circulation Model (CGCMa2) and a hybrid downscaling method. This combines a multiple regression (MLR) model and a timeseries model for the regression residuals (Vasiliades et al. 2009). The climate change and human intervention of the aquifer has been assessed for the SRESA2 and SRESB2 socioeconomic emissions scenarios for simulation period 1960-2058.

2.1 Climate variability and change

The CGCMa2 is a spectral model with 10 atmospheric levels and has a resolution equivalent to 3.75° of latitude by 3.75° of longitude. The ocean component is based on the Geophysical Fluid Dynamics Laboratory MOM1.1 model and has a resolution of roughly 1.8° of latitude by 1.8° of longitude and 29 vertical levels. SRES A2 scenario assumes a strong, but regionally oriented economic growth and fragmented technological change with an emphasis on human wealth. It represents a high emissions scenario. The second scenario is the SRES B2 scenario which emphasizes the protection of the environment and social equity, but also relies on local solutions to economic, social, and environmental sustainability and represents a low emission scenario. These scenarios represent a world in which the differences between developed and developing countries remain strong. The two socio-economic scenarios used have been widely adopted as standard scenarios for use in climate change impact studies (IPCC, 2007).

Figure 1. Lake Karla watershed and aquifer modeling characteristics.
In this study, a hybrid statistical downscaling method which combines a multiple regression (MLR) model and a timeseries model has been applied to downscale the CGCMa2 outputs from the GCM grid to the watershed level. In the development phase of the MLR models, the historical observed monthly precipitation and temperature are linearly regressed with large scale output parameters of GCM for the historical period. In the application phase of MLR models, the future monthly precipitation and temperature are estimated using the large scale output parameters of GCM for that period. The estimated meteorological variable (i.e. precipitation and temperature) from MLR model was combined with the residual values of the regression to preserve the variability of the observed series. The residuals time series of precipitation and temperature were simulated by stochastic time series model (PAR4 and PAR2, respectively for precipitation and temperature) and 100 synthetic residual timeseries were generated. The major assumption is that the residual time series remain unchained in the future periods. The future time series were generated by adding the estimated by the MLR models precipitation and temperature and the respective residuals of precipitation and temperature simulated by the time series models. More information and details about the downscaling method could be found in Vasiliades et al., (2009).

2.2 Hydrological Model
The monthly conceptual hydrological model (UTHBAL) has been used (Loukas et al., 2007) for the assessment of the surface runoff. The water balance model uses as input monthly areal time series of precipitation (estimated from 12 precipitation stations), mean temperature (estimated from 26 meteorological stations) and potential evapotranspiration (estimated by the Thornthwaite method). The model divides the total precipitation into rainfall and snowfall, since this is essential for accurate runoff simulation for snow-covered mountain watersheds. The water balance model uses a soil moisture mechanism to allocate the watershed runoff into three components namely, the surface runoff, the medium runoff and the baseflow runoff. Its outputs are actual evapotranspiration, surface runoff, soil moisture, and the groundwater recharge, which is the input data to the groundwater model. The UTHBAL model was calibrated using the limited observed monthly values of Lake Karla’s basin streamflow to Pagasitikos Gulf for the period October 1960 to September 2002 and was used to produce synthetic time series of runoff and groundwater recharge data for the Lake Karla watershed for the period 2009 to 2058 for the socioeconomic emissions scenarios SRESA2 and SRESB2. The watershed of Lake Karla was divided in two zones according to elevation. Only the recharge of the low zone comes to the aquifer and for that reason the UTHBAL was run in a semi-distributed mode. The model efficiency (Nash and Sutcliffe, 1970) of the UTHBAL semi-distributed application for model optimization and estimation of model parameters was 0.65 (Loukas et al., 2008).

2.3 Groundwater Model
The two operational simulations of phreatic aquifer of Lake Karla watershed were simulated by the MODFLOW model (Harbaugh and McDonald, 2000), discretized into an orthogonal grid of 12,500 cells, with a grid spacing of 200 m x 200 m (Figure 1) and as a one layer aquifer (Loukas et al., 2008). These two simulations are: i) the natural one without human intervention with simulation period 1960-2058 and ii) the real one which reflects the today status with the irrigation wells installation the last decades and their decrease in the future according to the timetable (Table 1) of Lake Karla’s reconstruction project (Figure 1) with simulation period 1987-2058 (Greek Ministry of Environment, Regional Planning and Public Works, 2004). Regarding the model’s construction, there is a weak hydraulic contact with the adjacent aquifer to the west, while the eastern boundary is a no flow boundary, due to the presence of a schist layer. The impermeable bottom varies and consists of non rusty marbles and schists. Recharge data was obtained by the UTHBAL model for the two simulations as described below: i) for the
natural simulation, 100 stochastic recharge time series only of SRESA2 scenario were imported to groundwater model and ii) for the simulation with human intervention 100 recharge timeseries of SRESA2 scenario were selected and in order to estimate the water demand for irrigation of the second simulation, data regarding irrigated agricultural areas per crop and municipality were provided by the Greek Ministry of Agriculture. Based on these data, the study area was divided into 7 irrigation zones as shown in Figure 1 and Table 1, according to the agricultural activity in the basin. The study area was also divided in 3 zones according to the dropdown of water table using historical hydraulic head data. The simulations were conducted for both the two different periods in transient flow conditions with outputs being in a monthly time step. Data from 24 observation wells were used both for the initial head distribution as well as for the model calibration on the 01/01/1987. Hydraulic conductivity was the parameter for which MODFLOW was calibrated and was the only hydrogeologic parameter that was spatially distributed, whilst the others had the same value throughout the entire area. The calibration is achieved by the use o pilot points approach of PEST model finding the optimum model semivariogram. The high value of coefficient of determination ($R^2 = 0.98$) reveals the success of calibration. Simple Kriging was used for spatial distribution of the 15 scatter data of hydraulic conductivity (Mylopoulos and Sidiropoulos, 2009). After the calibration of the MODFLOW for the existing conditions (with pumping wells), the model was run extracting the pumping wells for the period 1960-2058. This simulation represents the hypothetical simulation of the natural aquifer without human intervention.

Table 1. Mean annual groundwater water extraction (in hm$^3$) at the irrigation zones of the study area for the period 1960-2012 and 2012-2058

<table>
<thead>
<tr>
<th>Zones</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual groundwater volume extracted for historical period 1967-2009 (hm$^3$)</td>
<td>Irrigation</td>
<td>22.0</td>
<td>3.6</td>
<td>5.9</td>
<td>2.3</td>
<td>1.2</td>
<td>38.5</td>
</tr>
<tr>
<td>Water supply</td>
<td>2.4</td>
<td>0</td>
<td>0.2</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>24.4</strong></td>
<td><strong>3.6</strong></td>
<td><strong>5.9</strong></td>
<td><strong>2.5</strong></td>
<td><strong>1.5</strong></td>
<td><strong>38.5</strong></td>
<td><strong>55.7</strong></td>
</tr>
<tr>
<td>Mean annual groundwater volume extracted for future period 2009-2058 (hm$^3$)</td>
<td>Irrigation</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0.4</td>
<td>19.95</td>
</tr>
<tr>
<td>Water supply</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15</strong></td>
<td><strong>3</strong></td>
<td><strong>1</strong></td>
<td><strong>2.2</strong></td>
<td><strong>0.7</strong></td>
<td><strong>19.95</strong></td>
<td><strong>32</strong></td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION
Climate variability and change effects on precipitation and temperature were estimated for the SRESA2 and SRESB2 socioeconomic emissions scenarios both for historical period (1960-2009) and for future one (2009-2058) with the statistical downscaling procedure. Application of the statistical downscaling method showed that in general a slight decrease is observed in the statistical properties of monthly precipitation for both SRES scenarios. Figure 2 presents using box-plots the statistical properties (average and standard deviation) of the 100 generated timeseries of monthly precipitation for the A2 scenario and the future period. In the same figure the average values of the historical period is also shown. A closer inspection of Figure 2 shows that the mean monthly precipitation for the future period is marginally decreased (Figure 2a) and the distribution of monthly precipitation is remain unchanged but the pattern is not uniform and has smaller and larger variability in winter and summer months, respectively (Figure 2b).
Box-whisker plot and Average of stochastic simulation results for mean monthly precipitation of period 2009-2058 (A2 scenario)

Figure 2. Box-plots of the statistical properties of precipitation for SRES A2 future period 2009-2058 a) average monthly precipitation and b) standard deviation of monthly precipitation

The produced 100 historical and future stochastic time series of precipitation and temperature were imported to UTHBAL, which created additional 100 timeseries for recharge. Figure 3a shows the comparison of mean monthly values of recharge between scenarios SRESA2 and SRESB2 resulted from the application of the UTHBAL model at Lake Karla watershed. As shown in Figure 3a, there is no significant difference, with the SRESA2 scenario to give slightly a more intense variability than SRESB2, as it was expected, because it depends mainly on the slightly decrease of precipitation for the future period. For this reason, only the SRESA2 100 stochastic recharge series were imported to groundwater model of “natural” aquifer (near equilibrium conditions, without human intervention) for the future period 2009-2058. Figure 3b shows the box-whisker plots of the 100 monthly recharge timeseries.

Figure 2. a) Comparison of mean monthly values of recharge between SREA2 and SREB2 for 1960-2058 and b) Box and Whisker chart of mean monthly values of recharge of SREA2 scenario for future period 2009-2058.

The produced recharge time series were imported to Modflow only for the “natural” simulation which does not include any wells and human exploitation of the groundwater resources and created additional 100 hydraulic head timeseries and maps of aquifer for the two study scenarios. In the actual simulation which is the exploitation of groundwater resources with human intervention, only the extreme SRESA2 scenario was examined and 100 timeseries of recharge and subsequent hydraulic head map were produced. The results are presented for two time slots the historical 1960-2009 and the future period 2009-2058. Furthermore, 2 cells (points S1 and S3 on Figure 1) of the groundwater model were selected to show the differences of climate change and human intervention. These points are selected to represent hydraulic head data results and the differences which are caused due to climate change and human intervention. Point S1 is located at the northern part of the aquifer and belongs to the zone with the lowest water table drawdown whereas point S3 is located to the southern part of aquifer and belongs to the...
zone with the highest water table drawdown (Figure 1). Furthermore, it should be noted that the choice of point S3 was also done to demonstrate the effect of human exploitation on the groundwater resources because it belongs to irrigation zone 1, where all the irrigation wells are scheduled to be shut down. Figures 4 and 5 show the water stage of aquifer for points S1 and S3, respectively, for the simulation period 1960-2058. In the simulation without human intervention (climate change and natural conditions) the water stage is slowly rising reaching its equilibrium stage whereas in the actual simulation (climate change and exploitation of the groundwater) hydraulic heads are rapidly decreasing (Figures 4 and 5). However, for point S3 because of the shutting down of the pumping wells the water stage is rising up to a value of 20m. However, the difference on hydraulic heads between the natural and real simulations is more than 55 meters at the end of the simulation time.

**Figure 4.** Absolute hydraulic head values of aquifer at cell S1 for both “actual” and “natural” simulation.

**Figure 5.** Absolute hydraulic head values of aquifer at cell S3 for both “actual” and “natural” simulation.
4. CONCLUSIONS
A methodology is presented to assess the impact of climate variability, and change and human intervention in the Lake Karla aquifer, located on the eastern part of Thessaly in Greece. The impact of climate change in the temperature and precipitation was evaluated by a statistical downscaling method. The subsequent impact of climate change on water resources was evaluated with the use of a monthly hydrological model and a groundwater model. The methodology was applied for two simulations: the first as a natural aquifer (without human intervention) and the other simulation is the real operational conditions of aquifer, as it is today, with the human intervention. The difference between these two situations is the existence of extraction wells. Application of the statistical downscaling method showed that climate change will have insignificant impact on climate and water resources for the future period 2009–2058 at the study area. Furthermore, the simulation of the aquifer under natural conditions showed that the system is in equilibrium status which will be the ideal situation without human exploitation on the groundwater resources. However, the simulation for the actual situation which is the human intervention showed that dramatic decrease of the groundwater table. Evaluating the results of the study, climate change does not affect the natural aquifer of Lake Karla in contrast to human exploitation which is quite intense and requires immediate reassessment of water demands, before the situation becomes irreversible. Hence, water resources management policies are required in the study area if first priority is the restoration of the aquifer in its natural conditions.

REFERENCES