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Simulation and Prediction of Water Allocation Using Artificial Neural Networks and a Spatially Distributed Hydrological Model

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Abstract

Lake Koronia is located in the North part of Greece and is protected by the Ramsar Convention of wetlands. A deficit in the water balance has been presented at the last twenty years due to the excessive water consumption for agricultural uses. This research is an attempt to simulate water flow with MIKE SHE model in order to observe how the water is allocated in the study area. The results of water flow module used for the estimation of Lake's water balance for 4 hydrological years (2008-2012). Furthermore the Artificial Neural Networks (ANNs) was used for the prediction of water flow in two sub-catchments. The coefficient correlation (R) was found for Bogdanas (0.9) and Kolxikos (0.86). The Root Mean Square Error (RMSE) and the Mean Absolute Percentages Error (MAPE) were also calculated in order to evaluate the quality of the ANNs results.

Key words

ANNs, MIKE SHE, water allocation, water balance, wetlands, Lake Koronia.

Introduction

Wetlands are important natural environmental systems providing many benefits for e.g. natural habitat for wildlife, water filtration and supply, microclimate modification etc. They also contribute to socio-economic benefits in human's life with direct and indirect benefits as tourism, aesthetic values, domestics need, agricultural uses, fisheries, hunting etc (Alexander and McInnes, 2012). During the past decades many of these ecosystems experienced ecological stress due mostly to human activities and high demand of water consumption (Alexander and McInnes, 2012; Singh et al, 2010).

Wetlands are unique ecosystems that need specific approaches in order to assess the ecological balance (Zalidis et al., 2004). The distribution of water amount is highly affected by the climatic conditions (Nazarifar et al., 2012). The MIKE SHE model is developed from Danish Hydraulic Institute (DHI) and is a physically-based spatial distributed hydrological model that incorporates many environmental parameters and physicals processes of hydrological cycle (Thompson et al., 2004, Wang et al., 2012). The application of the model covers a wide range under different case studies in water management with efficient results. Some of these applications with consistent results are related to groundwater management (Demetriou, Punthakey, 1999), simulation of overland flow in a flashy mountainous stream (Sahoo et al., 2006) and impacts of land use changes (Im et al., 2009). Simulation of the water balance with MIKE SHE is able to be done in wetlands presenting an integrated fully-distributed approach (Thompson et al., 2004; Rahim et al., 2012). Estimations of water balance using future climatic scenarios were developed with MIKE SHE; from the results they concluded that the estimation of current and potential future climate conditions could be useful tool in wetland management (Singh et al., 2011).

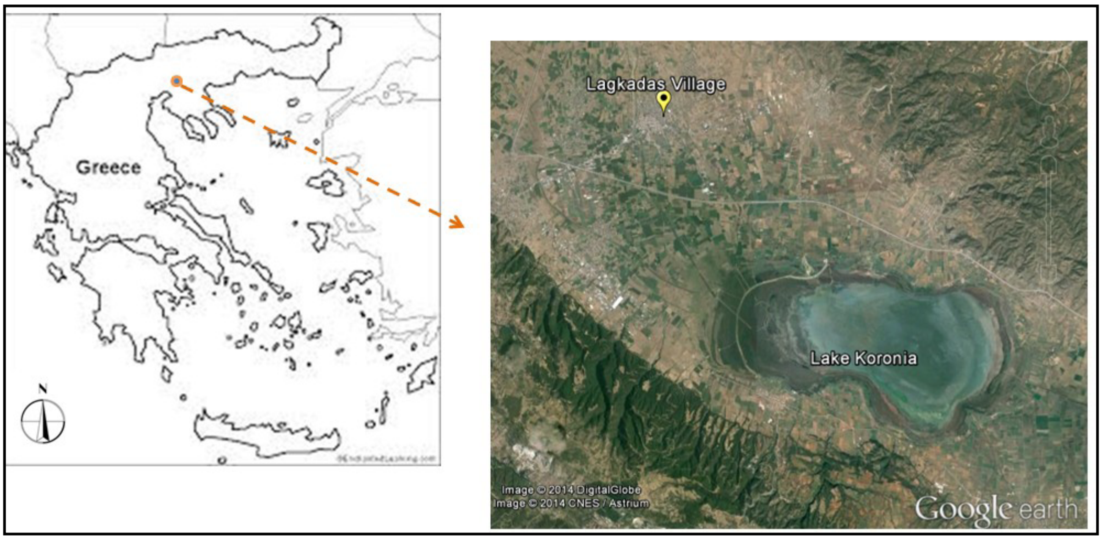
Artificial neural networks (ANNs) are mathematical models, and the main structure of neural networks is based approximately on the human's brain which is filled by neurons and synapses (Parsinejada et al., 2013). ANNs can "learn" through training processes, following the pattern of a procedure developing a functional relationship between the data and produce solutions to problems (Parsinejada et al., 2013; Mishra and Singh, 2013; Gallo et al., 2014). Myronidis et al. (2012) proposed a method to predict trends of droughts with a combination of ARIMA/ANN using the parameters of precipitation and lake's water level. Chattopadhyay and Rangarajan (2014) due to the excessive groundwater irrigation especially for agriculture uses developed a non-linear model with ANN to predict water level in shallow aquifer. They concluded that ANNs can efficiently demonstrate the seasonal variability forecast and also proposed this method as monitoring tool of groundwater sustainability. Gallo et al. (2014) used the ANNs in order to forecast future amounts of pollutant emission under different scenarios. The neural networks in their assignment were able to predict efficiently future amounts of air pollution in a short term. They concluded that the air pollution influenced by the meteorological conditions.

The aim of this study is to develop a simulation process with the MIKE SHE model in order to observe how the water is allocated in the catchment of Lake Koronia. We also used the water balance tool of MIKE SHE model to estimate the water balance for the hydrological years 2008-2012. The results of MIKE SHE water flow were used for the training of ANNs in order to predict the values of water flow. This method could be used to forecast the amounts of water flow and future amounts of water budget. For the training of ANNs we used the mean monthly rainfall data as input value and monthly water flow of Bogdanas and Kolxikos sub-catchments as output for the period of 1/6/2008-30/6/2013. The back propagation method was used for the training of the network and the sigmoid function as the activation function of each neuron. The known water flow data of MIKE SHE model will be used for the evaluation of output results of ANNs with a test facility after the training process. The development of these methods could be valuable tools in the ecological restoration of the Lake Koronia through the better understanding of the conditions that affects it.

Materials and methods

Lake Koronia belongs to the Mygdonia basin and is located in North Greece in the Region of Central Macedonia (N 40˚ 41', E 23˚ 09'). The catchment of Lake Koronia occupies an area of ~ 782 km² and is protected by the Ramsar Convention of wetlands (Figure 1). The last few years a deficit in water balance is present due mostly to the excessive irrigation for agricultural uses. Until 1985 the area of the lake was 45- 49 km² with an average depth of 5 m. In 1995, the lake surface area was 30 km² and the maximum depth 1 m. In the summer of 2002, the lake dried up completely. The restoration of Lake Koronia is considered a great challenge (Mylopoulos et al., 2007; Michaloudi et al., 2009).

In this study we used the MIKE SHE model in order to estimate the water balance for 4 hydrological years (2008-2012) in a shallow lake with semi-arid climate conditions. The model domain grid cell size selected at 250 x 250 m². For the elevation relief in the study area we used contours of 20 m digitized in ArcGIS. The hydrological network was provided from the Management Agency of Lakes Koronia-Volvis. The study area was separated into 10 sub-catchments according to the main streams flow and the topographic elevation. Meteorological data



Source: The figure of Greece obtained from EnchantedLearning.com and Lake‘s Koronia from Google earth

Figure 1: The study area, Lake Koronia.

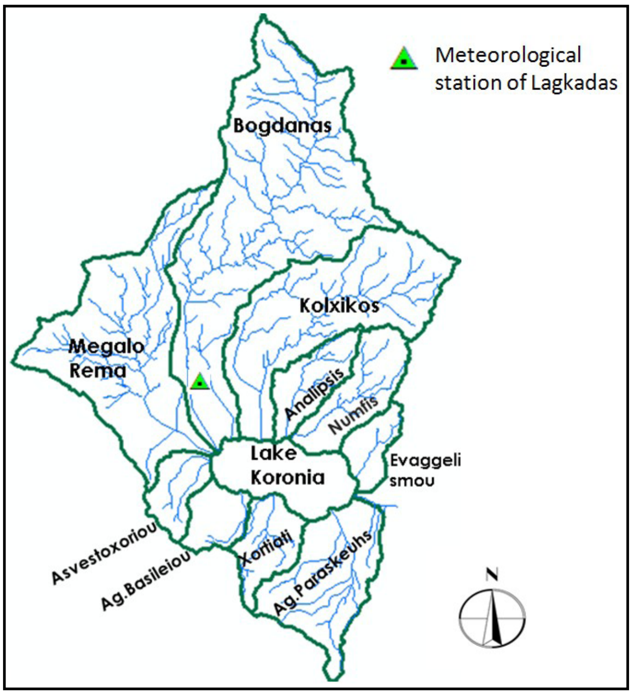
with long time series are unavailable due to the lack of data within the study catchment (Mylopoulos et al., 2007). In the past many meteorological stations were operated for small periods (5-8 years). Today meteorological stations are located outside the study catchment and only one is active inside the catchment of Koronia. The station is located in Lagkada village, at an elevation of 87 m and supervised by the National Observatory of Athens and the Municipality of Lagkadas (Figure 2). We used the monthly rainfall data (mm) in time series related for the period from 1/6/2008 to 30/6/2013.

For vegetation and land use cover we used the Corine 2000 maps. In order to estimate the actual evapotranspiration (ET) we calculated the reference evapotranspiration (ET_o) in monthly rate (mm) with a modified method of Hargreaves–Samani (HS) proposed from Droogers and Allen (2002). The equation of ET_o is described as:

$$ET_o = 0.0013 \cdot 0.408Ra \cdot (T_{avg} + 17.0) \cdot (TD - 0.0123 \cdot P)^{0.76} \quad (1)$$

Where: T_{avg} is the mean temperature (℃), TD is the Tmax-Tmin temperature (℃), P is monthly precipitation amount (mm), Ra is the extraterrestrial radiation given from the table in FAO (Food and Agriculture Organization) in unit of MJ m^{-2} day^{-1}. Ra is multiplied by 0.408 in order to convert to ET (mm). The constant numbers (0.0013, 17, 0.0123 and 0.76) was valued and estimated according to the IWMI (International Water Management Institute) Climate Atlas with efficient correlation results compared with the method of Penman–Monteith (Droogers, Allen, 2002).

For the project of Koronia Lake the calculation of overland flow developed with the method of finite difference. The estimated value of manning number for overland flow according the existing land cover conditions in the area with short vegetation is estimated at 30 $m^{1/3}/s$ (DeBarry, 2004, DHI, 2012). The Unsaturated Zone (UZ) was calculated with the 2-layer Water Balance as the more indicated method for the shallow groundwater table (Dai et al., 2010). Soil data was obtained from HWSD (Harmonized World Soil Database) and used in the model as polygon file. According to HWSD five are the main types of soils the area (Calcaric Fluvisols, Calcaric Regosols, Chromic Luvisol, Dystric Cambisol, Eutric Cambisol).



Source: own processing. The data from the meteorological station of Lagkadas were used to run MIKE SHE model and ANNs.

Figure 2: The hydrological network and the sub-catchments of Lake Koronia Catchment.

These types present different soil texture according to USDA (United States Department of Agriculture) classification covered by loam, clay, sandy and mixture of them. We categorize the soils according to their texture and the estimation of properties for each soil type was defined from the literature presented in Table 1.

The Saturated Zone (SZ) was calculated with the method of linear reservoir as a more appropriate due to the lack of data in the area but also because it is a useful tool for shallow lakes (Wang et al., 2012, DHI, 2012). Lake Koronia consists of a shallow aquifer with a depth of 40-60 m and a deeper at 450 m (Mylopoulos et al., 2007). Although the depths of reservoirs have a conceptual meaning we estimate the depths according to the volume of water (formation thickness x specific yield). We used the same values for the initial depth and as threshold of interflow and base flow reservoirs (Table 2). Furthermore the parameters of the time constant cannot be physically observed and they are mainly used as calibration values. A fair estimation of these parameters could be obtained from the hydro-geologic conditions and the literature review from previous studies (DHI, 2012).

In order to have more consistent results we used the utility of the hot start period for the first two years (1/6/2008-30/6/2010) as a "warm-up period" in order to provide the initial conditions and hydrological properties for the main simulation (Signh et al, 1999). The final simulation period was 1/6/2008-30/6/2013 using the hot start period of the first two years.

Precipitation is one of the main parameters, which contributes to the enrichment of aquifers. In our study we tried to combine the results of simulation water flow from MIKE SHE model with the precipitation amount in a monthly time step. The aim of this process is to train an ANN in order to predict future values of water flow in two sub-catchments (Bogdanas and Kolxikos) using the monthly amount of precipitation. We used the Neural Works Predict tool with a set of rainfall data for the period 1/6/2008-30/6/2013 as the input

	Clay loam	Clay to clay loam	Loam to Loamy sand	Loamy sand	Clay Loam to loam
Water content at saturation (cm^3) (Rawls et al., 1982; Chan, Knight, 1999)	0.43	0.45	0.42	0.41	0.42
Water content at field capacity (m^3) (Hignett, Evett, 2008)	0.34	0.35	0.15	0.14	0.26
Water content at wilting point (m^{-3}) (Hignett, Evett, 2008)	0.15	0.17	0.10	0.06	0.11
Hydraulic conductivity (m/s) (Mylopoulos et al., 2007, Batu, 1998)	1,00E-07	1,00E-09	1.3e-007	1.3e-006	2.8e-007

Source: own processing

Table 1: The soil properties for the different type of soils in the study Catchment of Lake Koronia.

	Interflow Reservoirs	Base flow Reservoir 1	Base flow Reservoir 2
Specific Yield (Mylopoulos et al., 2007)	0.08	0.08	0.08
Initial Depth (m)	4.8	18	36
Bottom Depth (m)	60 x 0.08 = 4.8	225 x 0.08 = 18	450 x 0.08 = 36
Time Constant (days) (Wang et al., 2012, Thompson et al., 2014)	40	120	250
Threshold Depth (m)	4.8	18	36
Percolation Time constant (only interflow) (Wang et al., 2012, Thompson et al., 2014)	5 days	-	-
Dead storage fraction (only base flow) (Mylopoulos et al., 2007)	-	0.3	0.33

Source: own processing

Table 2: The parameters of interflow and base flow in linear reservoir method.

value and monthly water flow for the same period as the output. The topology used for the prediction was Multi-Layer Perceptron (MLP). We used a network consisting of 2 input neurons, 24 hidden neurons in one layer and 1 output neuron. Each input neuron was connected with all the neurons in the hidden layer.

The method of gradient back propagation was used for the training of MLP network. In this method an objective function is specified which is a measure of how closely the outputs of the network match the target outputs in the training set of data. The improvement of the objective function achieved through the weights modification of each individual processing elements. The Kalman filter also was used in order to train the network due to the effectiveness for noisy behavioral problems and its inherent ability to suppress noise. Kalman filters are based on linear dynamic systems which is applicable to regression type problems in which the number of inputs is not too large (Ioannou et al., 2010). The sigmoid function (Equation 2) was used as the activation function of each neuron.

$$f(x) = \frac{1}{1+e^{-x}} \tag{2}$$

The learning rate was set to 0.1, the network was trained for 1000 epochs, and the max error was set as > 0.01. The AI topology remained stable through training epochs. The known water flow data will be used for the evaluation of output results after the training of ANNs. The correlation coefficient (R) is a statistical analysis that presents the level of matching. The Root Mean Square Error (RMSE) and the Mean Absolute Percentages Error (MAPE) are also calculated in order to evaluate the quality of the ANNs results (Ioannou et al., 2010, Mishra, Singh, 2013).

Results and discussion

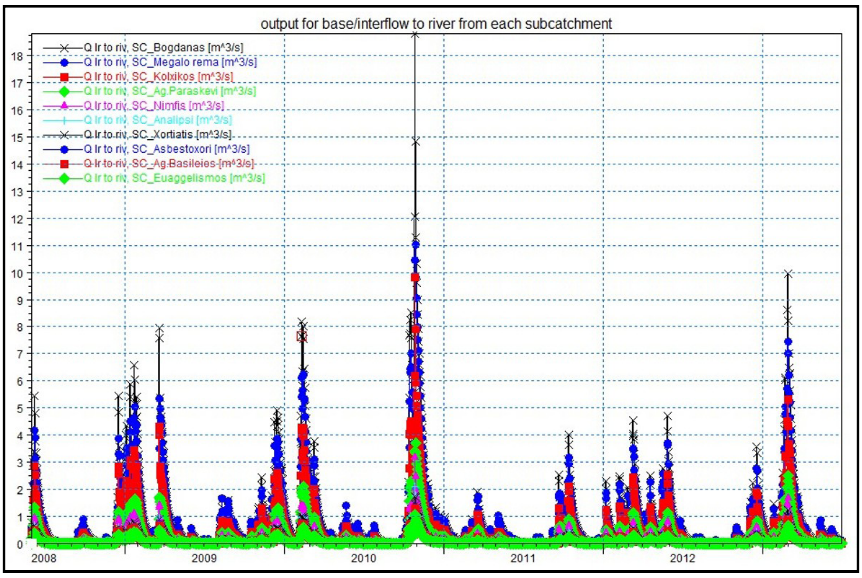
The simulation results present different values depending on the season and the hydrological conditions. In general in summer the actual ET amount is higher in contrast in winter months the ET amount is lower. The higher amounts presented in the northern part of the study area which are covered mostly from agriculture land and the lower amounts in the area around the lake where is covered with short perennial vegetation. The actual amount of ET presents a high range of values throughout the year and the components of precipitation and vegetation play an important role in the total amount of ET. Furthermore the water exchange between the UZ and SZ zone during the summer is relatively low due to the lower amount of precipitation and the higher amounts of ET. The type of soil also affects the exchange between zones. Loamy sand soils have higher amounts of infiltration followed by loam to loamy sand soils. The higher amounts of infiltration are in the area around the lake where the water creates ponds. The higher amount of infiltration and recharge of SZ appears in days with intense rainfall.

The hydrological network is divided into 10 sub-catchments according to the main streams and the water flow was calculated for each sub-catchments. From the results Bogdanas stream presents the highest amount of water recharge followed by Megalo Rema and Kolxikos (Figure 3). The maximum amount of water flow is presented in the winter months and in days with high amount of precipitation. In summer days with no amounts of precipitation, water flow values are close to zero.

Precipitation and stream flow are the main parameters of Lake Koronia's recharging process. The largest amount of water withdrawal presented in areas around the lake and also in the northern part of the Lake where Bogdanas and Kolxikos streams are flowing to the Lake. The water that flows from the northern part of the Lake the last few years has decreased because of the excessive irrigation from the main streams of the Lake and as a result we have the reduction of Lake's water level. Monitoring methods and registration of legal and illegal wells are ways that could offer important information for efficient implementation of water management. The improvement of irrigation systems especially in summer months is essential for the Lake's restoration.

The module of water balance was used for the estimation of water budget for the period of 1/10/2008 – 30/9/2012. Figure 4 presents the results of water balance simulation. An acceptable value of error simulation is equal or lower of 1% of the total precipitation. In our study the calculated error of the water balance simulation has an acceptable value of 0, 05%. The greater loss of the water balance is from the amount of ET with a percentage of 63, 8% of the total precipitation.

Furthermore the annual estimation of the water balance is calculated from the total amount of each component divided by the years



Source: own processing

Figure 3: The daily water flow for each sub-catchment (6/2008-6/2013) produced by the MIKE SHE model.

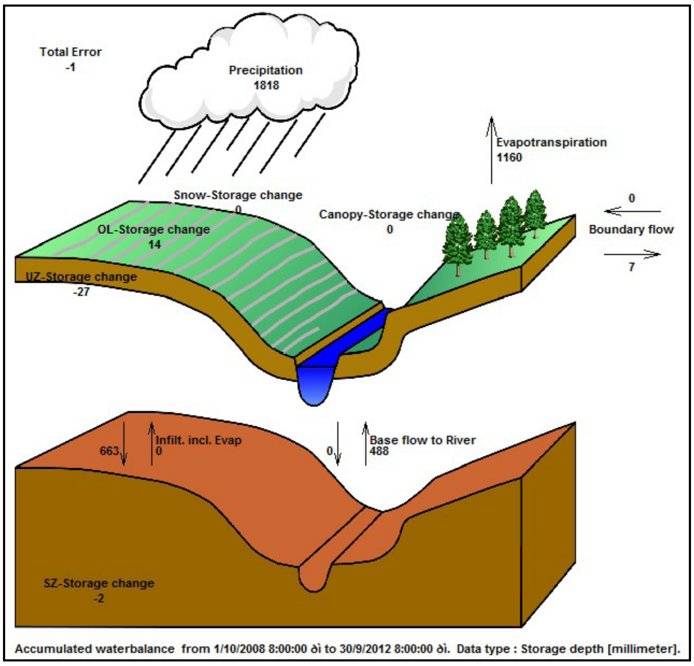


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Figure 4: The estimation of total water balance (1/10/2008-30/9/2012), the numbers on the chart are in units of millimeters (mm) produced by the MIKE SHE model.

of the simulation. The annual actual ET is calculated at 290 mm and the annual precipitation at 454,5 mm. The amount of annual precipitation (~ 450 mm) presents a reduction (~ 500 mm) and the annual amount of actual ET (290 mm) presents also a reduction (~ 460 mm) for the years 2008-2012 compared with previous study conducted in the area (Mylopoulos et al., 2007). For the decreasing amounts of precipitation and ET we provide two possible assumptions.

The results may present a hydrological change compared to the past years with a reduction of the precipitation amount or the results could be underestimated due to the unavailability of detailed data. The use of the combined Penman–Monteith method may contribute in a more efficient calculation of reference ET if the required data are available. In order to calculate the annual water budget of Lake Koronia we used an equation to convert the total water balance for each component (mm) into m^3/year is:

$$N = \frac{\frac{n}{1000} * A}{t} \tag{3}$$

Where N is the converted values (mm to m^3/year), n is the number in (mm), A is the modeled area (m²) =>782.000.000 m² and t is the simulation period length (4 years). In Table 3 we present the converted values and the total values for each components.

	Values in mm	Values in x10^6 m^3/year
Precipitation	1818	355.42
Evapotranspiration	1160	226.78
Overland storage	14	2.74
Infiltration	663	129.62
UZ storage	-27	-5.28
SZ storage	-2	-0.39
Base flow to river	488	95.40
Boundary flow	7	1.37

Source: own processing

Table 3: The converted values of the water balance from millimeters to m^3/year.

After the conversion we calculated the annual water budget (Table 4). Agriculture needs are the main factor of water consumption followed by industries and municipal needs. According to the annual consumption in order to cover these needs was estimated approximately at 100 x 10^6 m^3/year (Mouzouri et al., 2002). The results of the water budget underline the need to reduce or control the aggravating factors of irrigation. Physical ecosystems have the ability of self-preservation, if we mitigate the degradation factors. The water management plan needs to take into account a self-sustainable system at the catchment level in order to succeed the aforementioned.

The water distribution is highly affected by the amount of precipitation. Artificial Neural Networks were used to predict the values of water flow for Bogdanas and Kolxikos sub-catchment using time series of monthly mean precipitation amount and water flow. A first evaluation of the results accuracy may be observed when the training set and test set of training outputs are similar. Table 5 presents the results of the training and the test process for Bogdanas sub-catchment. We used 42 records for the training process with 61 test records. The R measure is the correlation between the real world target output and model output. In Bogdanas sub-catchment the R was found 0.9 for training and 0.8 for test presenting a good correlation between the observed and training output data.

Figure 5 presents the comparison diagram of the ANN training results and the observed data from the simulated water flow for the period of 6/2008-6/2013.

From the simulation results of Bogdanas River the highest amount of water flow was presented at October 2010 where the amount of precipitation in that month exceeded 200 mm. The ANNs also estimate the highest amount of water flow in that month.

	Inflow (x10^6 m^3/year)	Outflow (x10^6 m^3/ year)
Precipitation	355.42	
Evapo-transpiration		226.78
Boundary flow		1.37
Changes in storage (infiltration – base flow to river)		129.62 - 95.4 = 34.22
Water consumption		100
Water budget	Inflow - Outflow = - 6. 95 x 106 m^3/year	

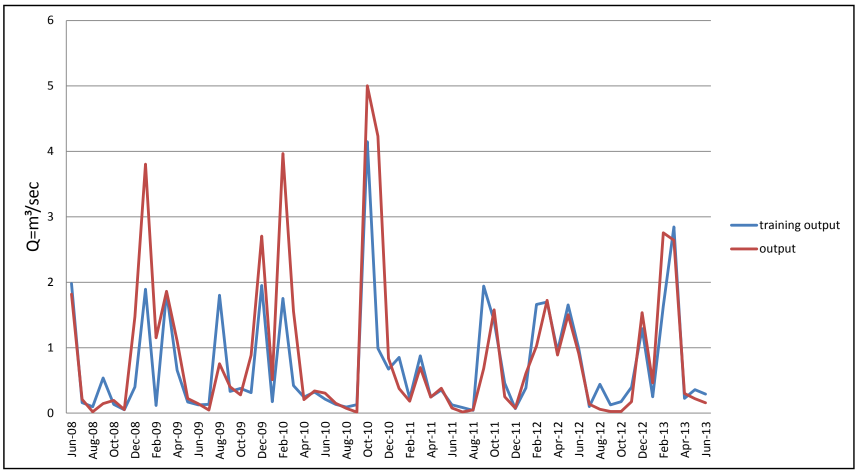
Source: own processing

Table 4: Calculation of water budget of Lake's Koronia Catchment for the period 1/10/2008-30/9/2012 in m^3/year .

OUT_1	R	Net-R	Avg. Abs.	Max. Abs.	RMS	Accuracy (20%)	Conf. Interval (95%)	Records
Train	0.900	0.773	0.277	2.213	0.551	0.905	1.110	42
Test	0.804	0.721	0.375	3.242	0.701	0.852	1.396	61

Source: own processing

Table 5: The training set and the test set of the actual and training water flow values for Bogdanas sub-catchment after the training of ANNs.



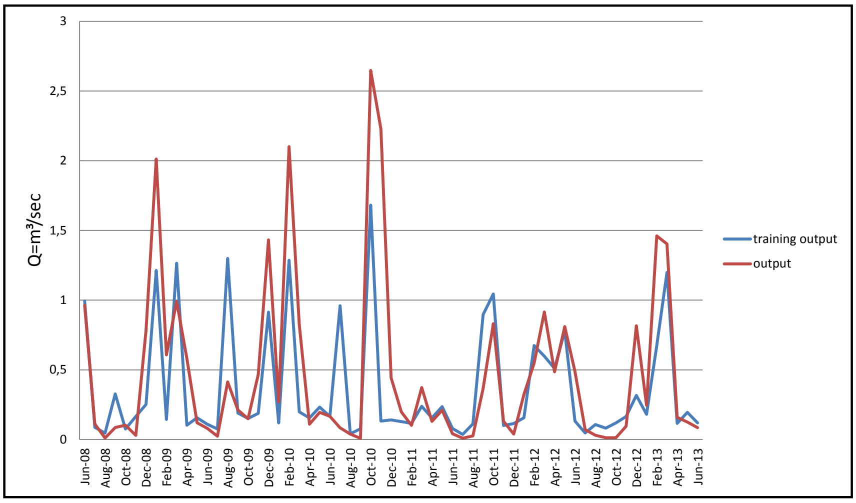
Source: own processing

Figure 5: The ANNs comparison diagram of the actual and training water flow for Bogdanas sub--catchment.

OUT_1	R	Net-R	Avg. Abs.	Max. Abs.	RMS	Accuracy (20%)	Conf. Interval (95%)	Records
Train	0.865	0.791	0.209	0.965	0.333	0.9047	0.670	42
Test	0.7129	0.660	0.249	2.095	0.434	0.836	0.865	61

Source: own processing

Table 6: The training set and the test set of the actual and training water flow values for Kolxikos sub-catchment after the training of ANNs.



Source: own processing

Figure 6: The ANNs comparison diagram of the actual and training water flow for Kolxikos sub-catchment.

Table 6 presents the results of the test facility in Kolxikos sub-catchment and Figure 6 the comparison diagram of the training output and observed data for the period 1/6/2008-30/6/2013. Also the R presents a good correlation between the observed and training output data with values of 0.865 for the training and 0.7129 for the test.

In the comparison diagram (Figure 6) the higher amount of water flow appears also at October 2010. In general the summer presents very low amount of water flow and in winter the largest amounts of water flow.

We also calculate the Root Mean Square Error (RMSE) and the Mean Absolute Percentages Error (MAPE). The RMSE is the root calculated from the difference between the actual from the predicted value and the calculated average squared error. The MAPE is usually presented as a percentage and is expressed as the ratio of actual values minus the predicted divided by the actual values. The result is divided by the number of the values and multiplied by 100 in order to calculate the average error as a percentage. In Bogdanas sub-catchment the RMSE was found ~ 0.701 and the MAPE 93.64 %. In Kolxikos sub-catchment the RMSE is ~ 0.43 and the MAPE 126.78 %. The results of the ANNs show that a fair estimation and prediction of water flow is able when the values of precipitation amount and water flow are known.

Conclusions

Wetlands processes are interlinked with the environmental conditions of precipitation, groundwater, overland flow and evapotranspiration. The adoption of new technologies can provide efficient tools with many applications in the field of water management. In this study we used MIKE SHE model in order to simulate the water flow and water balance tool to estimate the water balance for 4 hydrological years (2008-2012) in the catchment of Lake Koronia. The last twenty years Lake Koronia presents a negative water budget due mostly to excessive irrigation uses. Agriculture needs are the main factor of water consumption followed by industries and municipal needs. The adjustment of the water management to the existing hydrological conditions and the consideration of the stakeholders needs are necessary procedures for the restoration of Lake Koronia. Climatic parameters also affect the water allocation where in the months of summer presented the major deficits of water balance. Improvement of irrigation systems especially in summer is essential for lake's restoration. Although the MIKE SHE model is highly complex and high demanding of input data a fair estimation with the minimum requiring data was developed for the hydrological conditions in the catchment of Lake Koronia.

The results of the water flow from the MIKE SHE model were also used for the training of the ANNs as output values and a set of rainfall data was used as input value for the period 1/6/2008-30/6/2013. An efficient correlation (R) was found after the training of ANNs for Bogdanas (0.9) and Kolxikos (0.86) sub-catchment. The results of ANNs show that a fairly accurate estimation and prediction of water flow is able when the values of precipitation amount and water flow are known.

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