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Water Balance Model of Vulnerability Assessment of Dojran Lake Basin

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ABSTRACT: Water resources, especially those of fresh water are the most important part of the ecosystem in the Republic of Macedonia. Natural lakes are the largest reservoirs of fresh water and their ecosystems are highly impacted by the climate and human activities. This paper presents the vulnerability assessment on climate change and human activity for Dojran Lake Basin. Dojran Lake is located in south-eastern part of the Balkan is shared by Macedonia and Greece. Hydrological analyses are obtained on basic parameters such as water level, precipitations, air temperature and evapotranspiration. Analysis used historical record for Dojran Lake Basin for the period 1951-2010 from the hydro meteorological station at Nov Dojran on the Macedonian side. By Digital Terrain Model (DTM) are obtained the basic characteristics of the entire Dojran Lake watershed. The water balance model was developed to compute the water balance components on the basis of annual, monthly and daily data. The identification of the causes and the vulnerably assessment of the present state of the aquatic ecosystems can be carried out through hydrological analysis and water balance modelling. The results are shown as comparison between the observed water levels and the computed ones.

KEYWORDS: hydrometeorology, water balance, Dojran Lake, precipitation

I. INTRODUCTION

Dojran Lake is the smallest natural freshwater lake located in South Eastern part of Balkan is shared by Macedonia and Greece.Dojran Lake and there watershed is characterized as a hydrological vulnerable system.

Dojran Lake Basin is a closed hydrological system with natural inflow of water to the lake, but no natural outflow. Filling the lake is mainly from precipitation, from direct surface inflow and from underground inflow. Consumption of water from the lake is present as a direct evaporation and usage of water from the Lake and its watershed for irrigation and water supply.

The cause of ecological catastrophe is the water level decrease in the last decade of the past century (1988-2002).

The controlled outflow of the water from the lake by the artificial canal on the Greek side imposed a regime of oscillations of the water level in the lake at a limited level (max. 147.34 m a.s.l. and min.146.14 m a.s.l.). In 1988, the lake's water level was at an altitude of 145.82 m a.s.l.,(0.32 cm under the minimum) the water surface area was 37.87 km^2 and the water volume was 220 mil. m^3. In the next period, the water level in the lake was rapidly decreased. In 2002, the water level was at an altitude of 141.33 m a.s.l.(4.51 m under the minimum altitude), the water surface area was 26.01 km^2 and the water volume dropped to only 54 mil. m^3.

In 2002, the Republic of Macedonia was finished a project to build a system for bringing water from Gjavato walls near Vardar River with capacity of 1m^3/s. The next period water level increases and in 2010 the lake level was on the altitude 144.07 m a.s.l.(2.07 m under the minimum).

The cause for the decrease of the water level in the lake is not clearly identified. These are located in the unfavourable hydrological conditions expressed through a longer dry period or uncontrolled usage of the water from the lake. The predominant factor influencing the conditions of the lake has still not been defined.

II. DOJRAN LAKE BASIN WATERSHED

A. *Hydrographical characteristic*

Dojran Lake is a trans-boundary natural lake which is located between 41'11^{0}and 41'25^{0}N and 22'41^{0}and 22'53^{0}E. The basic characteristics of Dojran Lake watershed are obtained by the Digital Terrain Model (DTM) with 30x30 m

ISSN: 2350-0328
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Vol. 3, Issue 4 , April 2016

resolution, and by GIS tool for spatial analysis, the geometry of the Lake and the watershed delineation by main rivers with its watershed were defined.

The watershed area is 271.8 km^2 out of which 32 % (86.976km^2) belongs to Macedonia, and 68 % (184.824 km^2) to Greece. The watershed length on the Macedonian side is 33.5 km and on the Greek side, it is 46.3 km. The highest altitude of the watershed is on the Greek side (Belasitsa Mountain, 1880 m a.s.l.). The lowest part is on the south part (bottom of Karadag Mountain, 153 m a.s.l.).

The water surface area of the Lake at normal elevation is 42.2 km^2 out of which 63.6% belongs to Macedonia. The volume curve and water surface area curve of the Lake based on the bathymetric survey carried out in 1991 by the Water Development Institute of the Republic of Macedonia. The shape of the lake is rather regular with a maximum length of 8.9 km and a maximum width of 7.1 km. The volume of the lake at normal water level is 262 million m^3. The average depth is 6.5 m and the maximum one is 10.4 m.

The hydrographical development of the watershed is good on the Greek side and rather poor on the Macedonian side. Small water courses on the Macedonian side are: Derven Rama, CrnPotok, Suva Reka, PazarliDere, PojataDere, and Toplik. On the Greek side, three main rivers inflow the Lake: Kavkalaris, Hanzija and Dojrani. Dry rivers are: SretenovskiPoroj, DeribaskiPotok, EleonoraPoroj, and KarakajDere. Most of the dry rivers on both sides do not reach the Lake due to sediment deposition and agricultural activities. The watershed delineation by main rivers is obtained by GIS tool for spatial analysis.

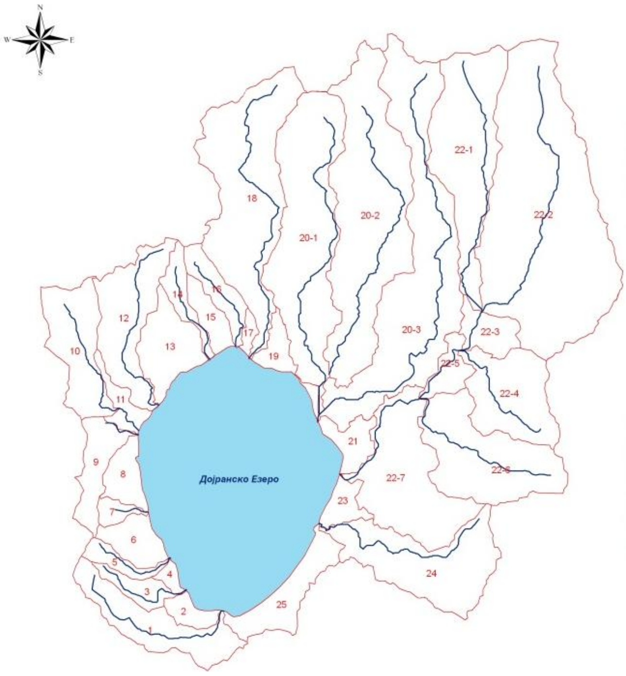

Figure 1:Dojran Lake Basin Watershed

B. *Land use*

Land cover and land use characteristics are obtained by CORINE Land Cover (CLC). CLC2000 was used and data have been worked out by GIS tools. Classification has been done on three levels: Level 1 with 7 classes, Level 2 with 17 classes and Level 3 with more than 44 classes of land use. By forest and semi-natural areas is covered about 64% or 126.61km^2 (38.20 km^2 on Macedonian side and 88.41 km^2 on Greek side of watershed). Agricultural areas account for 34 % (18.27 km^2 on Macedonian side and 73.4 km^2 on Greek side) and urban, commercial and industrial zones, mines and landfills cover less than 2 % or 4.6 km^2(1.62 km^2 and 2.98 km^2 on Macedonian side and Greek side).

ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

Vol. 3, Issue 4 , April 2016

C. ***Groundwater***

Dojran Lake is a tectonic depression filled with Neogene Quaternary sediments. The sediments of the Lake Watershed are composed of mineral-rich ancient alluvial and limestone sediments. Permeable geological structures can be classified as: incoherent.

Quaternary sediments with the coefficient of hydraulic permeability (K) varied from 10-4 cm/s to 10-2 cm/s, coherent rocks but rather fractured stones of thickness 20-25 m with hydraulic permeability between 10-4 cm/s and 10-1 cm/s and carbonate rocks. Incoherent sediments are on the north and north-west part of the Lake and there is a connection between the Lake's water and groundwater. Coherent are found as surface layers on the north and north-west part of the watershed. Springs with yields ($Q < 0.5$ l/s) are detected there. Permeable carbonate rocks are ranged on the west part of the lake in the direction north-south.

D. ***Monitoring***

Meteorological data (precipitation, air temperature, radiation, wind speed, relative humidity) are being recorded in a few meteorological stations in Greece (Muries, Ahmatovo, Evzoni, Policastro, Kukush, Sterna) and at one meteorological station in Macedonia (Nov Dojran). Unfortunately, data from Greece were not available. This paper presents analyses of Dojran Lake using hydrological (water level) and meteorological (precipitation, air temperature, radiation, wind speed, relative humidity) data from the Macedonian side only.

Precipitation data from station at Nov Dojran were used to estimate the upstream runoff inflow, to make the comparatives analysis with historical record data of water levels and also an input into the water balance model.

Air temperature, wind speed, relative humidity and radiation data were used to estimate the evaporation from the water lake surface and its watershed.

The precipitation regime in the watershed is analysed by the data from the hydro meteorological station at Nov Dojran for the period 1951÷2010, Figure 2. The location and elevation at 180 m a.s.l. of this station are not representative for the entire watershed of the Lake, but are suitable for obtaining the precipitation quantity over the Lake. It is very probable that there is an increasing precipitation gradient as the altitude rises, which cannot be neglected as well as the snowfalls that are feeding the Lake with water. It is very important to establish rainfall and snow measurements on higher altitudes in the watershed that will enable more reliable rainfall-runoff modelling. The time data series of registered annual sums of precipitation for Nov Dojran for the 1951÷2010 showed fluctuation from year to year as part of the regional climate dynamics.The lowest and the highest historical annual sums of precipitation was recorded in 2000 (392.2 mm) and 2002 (1,041.5 mm), respectively. The average annual sum of precipitation is 653.7 mm.

The air temperature are analysed by the time series of registered annual air temperature at Nov Dojran for the 1951÷2010, Figure 3. The average annual air temperature is 14.48^{o}C. The minimum average annual air temperature of 13.15 ^{o}C was recorded in 1976 and the maximum of 16.35 ^{o}C in 2008. According RAPS method (Bonacci et al. 2008) the data series was divided into two sub-periods: (1) 1951÷1991 and (2) 1992÷2010. The average annual air temperature for first period is 14.16 ^{o}C, and 15.16 ^{o}C for second sub-period.

ISSN: 2350-0328
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Vol. 3, Issue 4 , April 2016

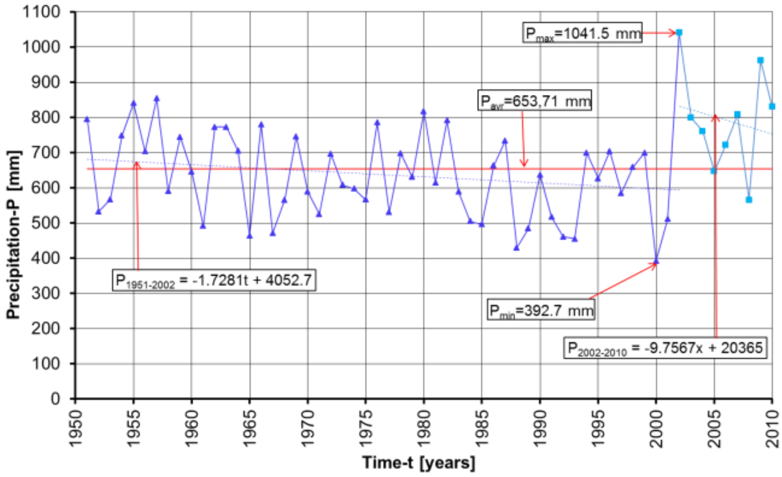

Figure 2: Annual sums of precipitation at Nov Dojran

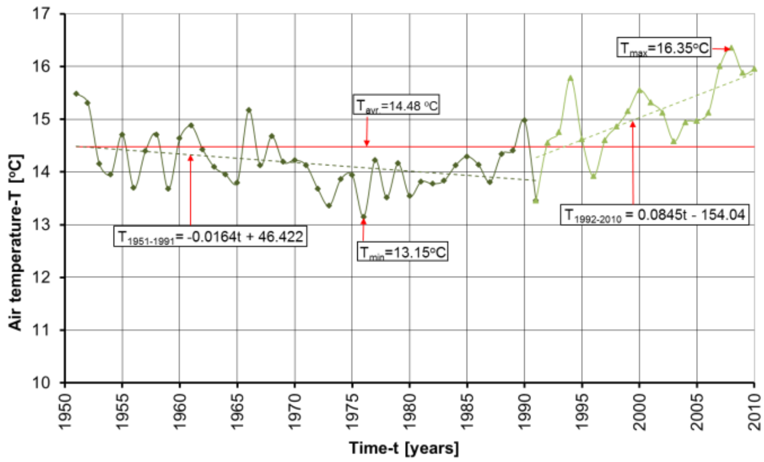

Figure 3: Annual air temperature at Nov Dojran

III. HYDROLOGICAL ANALYSIS

Average annual water levels of Dojran Lake for the period 1951÷2010 are presented in Fig.4. The level of the lake from 1951÷2010 showed a great variation over the last century.

This variation can be shown by dividing the time of record into three periods. Using Rescaled Adjusted Partial Sums (RAPS) method (Garbrecht and Fernandez 1994; Bonacci et al. 2008) the water level oscillations within the entire analyzed period are divided in the following three sub-periods: (1)1951÷1988; (2) 1988÷2002 and (3) 2002÷2010. For the first period, the water levels are high and rather stable. This period may be recognized as a natural and not disturbed Lake regime. The maximum water levels for the period 1951÷1988 are above the long term average water level with an amplitude of 307 cm, and after that, they are bellow it, with an amplitude of -385 cm. The long-term average water level for the whole period is 31 cm or 145.24 m asl. The maximum average water level is 244 cm obtained in 1956, and the minimum one is -360 cm in 2002. For the second period, the water level drop is continuous with a very steep trend line. The third period water level increases can be explained both by natural and artificial impacts. Natural impact may be referred to the precipitation increase and their spatial redistribution. The artificial or anthropogenic impact may be referred to the construction and start of operation of the Gjavato well system on the Macedonian side for additional water deliveryinto the lake.

ISSN: 2350-0328
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Vol. 3, Issue 4 , April 2016

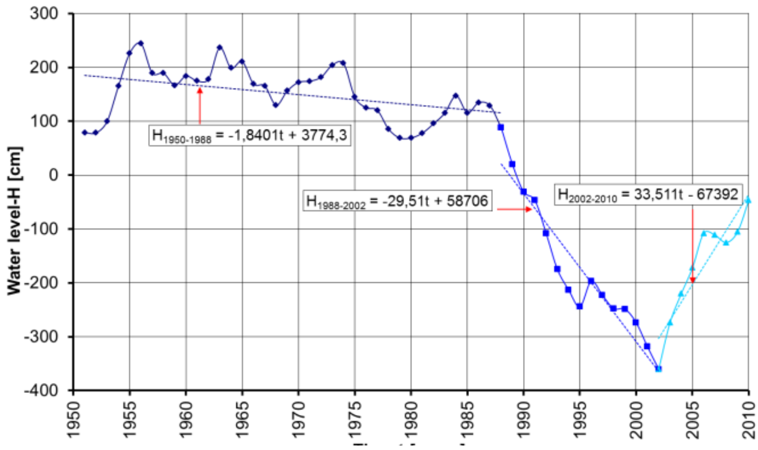

Figure 4: Average annual water level of Dojran Lake

Comparative analyses between the annual precipitation sums and average annual water levels into three periods: (1) 1951÷1988; (2) 1988÷2002 and (3) 2002÷2010 are presented in Fig. 5. The precipitation trend line has a small increasing gradient that is not followed by the water level oscillation in second and thirty periods. So, it is obvious that there is no uniform relation between the precipitation and water level.

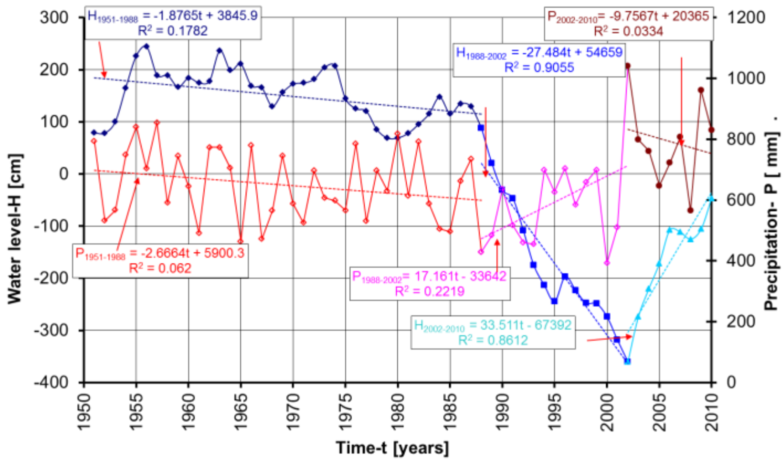

Figure5: Comparative analyses between the average annual water levels and the annual sums of precipitation.

Comparative analyses between the annual air temperature and average annual water levels into three periods: (1)1951÷1988; (2) 1988÷2002 and (3) 2002÷2010 are presented in Fig. 6. For the first sub-period, the relation between precipitation and water level oscillations is insignificant, while for the last two sub-periods the correlation coefficient is higher. It should be taken in mind that two last sub-series are very short.

ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

Vol. 3, Issue 4 , April 2016

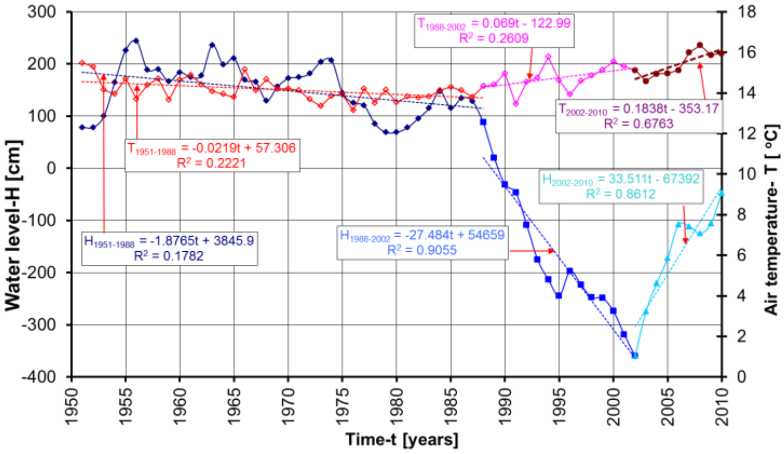

Figure6: Comparative analyses between the average annual water levels and the average annual air temperature.

IV. WATER BALANCE

A. *Methodology*

The water balance of Dojran Lake can be expressed as a storage change and may be showed as input- output=storage change or:

$$V_t + U_{(\Delta t)} - I_{(\Delta t)} = V_{t+\Delta t}$$

where: V_t and $V_{t+\Delta t}$ are the storage in the watershed/volume of water in the lake at the start and at the end of time interval (Δt) , $U_{(\Delta t)}$ is the sum of all components entering the lake (inflow) and $I_{(\Delta t)}$ is the sum of all components leaving the lake (outflow) in time interval (Δt).

The inflow of Dojran Lake represents a set of components of precipitation that falls directly into the lake (V_p), surface inflow from the watershed (V_Q) and water which is taken from the Gjavato system (V_{pum}) (after 2002). The outflow consists from components of evaporation from the water lake surface (I_E), evapotranspiration (I_{ET}) and the outflow from the lake (surface and underground outflow, water from the lake's surface or underground water used for water supply or irrigation)(I_Q). The unit of all components is the volume. The equation of the water balance is:

$$V_t + (V_p + V_Q + V_{pum}) - (I_E + I_{ET} + I_Q) = V_{t+\Delta t}$$

B. *Components of water balance*

➢ ***Precipitation*** **.**The components of precipitation that falls directly into the lake were calculated by the following relation:

$$V_p = \sum P_{(\Delta t)} \cdot \frac{A_{t+\Delta t} + A_t}{2}$$

where: ($\sum P_{(\Delta t)}$) is the sum of rainfall in time (Δt), (A_t) and ($A_{t+\Delta t}$) are the water surface area at the start (t) and at the end (t+Δt) of time interval (Δt), respectively.

➢ ***Underground inflow.*** Measured data on surface and underground inflow are not available. By using all the available data (topographical, geological and hydro geological) the underground inflow from the Macedonian side was estimated. According to the calculations, based on the size of aquifers (20÷30 m), the values of this component varied between (50÷60) l/s.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 4 , April 2016

➢ ***Runoff.*** The volume of surface inflow is calculated by using the following relation: $V_Q=Q \cdot A$, where (Q) is the actual direct runoff in (mm) or the effective precipitation ($Q=\Sigma Pe_{(\Delta t)}$), (A) is the area of the lake watershed.

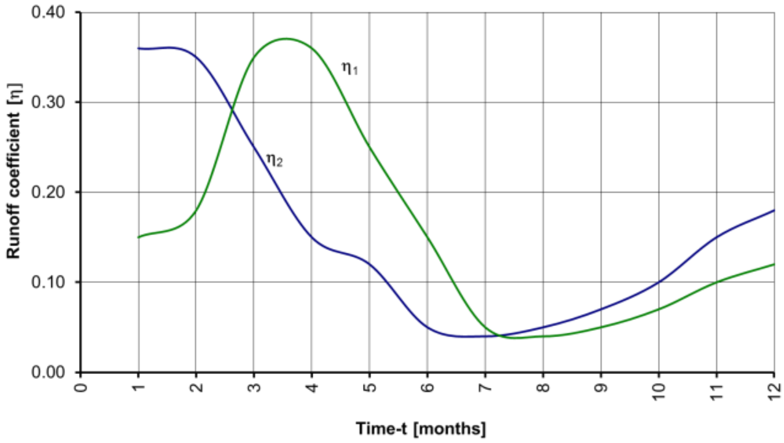

Figure 7:Value of monthly runoff coefficient

The transformation model of the rainfall to surface runoff (rainfall-runoff model) was created simply by using the precipitation data from only one hydrological station (New Dojran) and the well-known topography of the drainage basin of Dojran Lake. If one analyses the results obtained by two different models, it is apparent that the surface water flow coefficient gained with the Langbein model, which is 0.108 is lower compared to the coefficient of 0.15 acquired by using the effective rainfall method. The input data in Langbein model (Model P-Q) are the air temperature and the precipitations. The precipitations due to the spatial imbalances are corrected by coefficient k=1.16. This value of coefficient was determined based on hypsometric curve of watershed and changes of amount of precipitations in terms of altitude (on 100 m altitude precipitations growing up for 50 mm). Effective precipitation, $\Sigma Pe_{(\Delta t)e} = \eta \cdot \Sigma P_{(\Delta t)}$, is calculated by using the annual runoff coefficient (η=0.15), and the monthly runoff coefficient that is different for each month. Figure 7 shows the monthly runoff coefficient η_1 [according Blagoja Todorov,1977] and η_2 (coefficient determining by calibration). The monthly coefficients of surface water flow were defined by calibrating the rainfall-runoff model (P-Q) and the measurement data on the lake's water level. These monthly coefficients are useful when analysing the seasonal influence of the surface water flow. According to the results, these values of coefficients are the biggest in winter and spring and the smallest in summer when the temperature of air and the evaporation are very high.

Daily runoff data were obtained by hydrological model HEC-HMS. This model uses data from DTM (30 m) and daily rainfall data worked out in HEC-DSS files. The watershed was delineated into 25 sub-watersheds, Fig. 8.

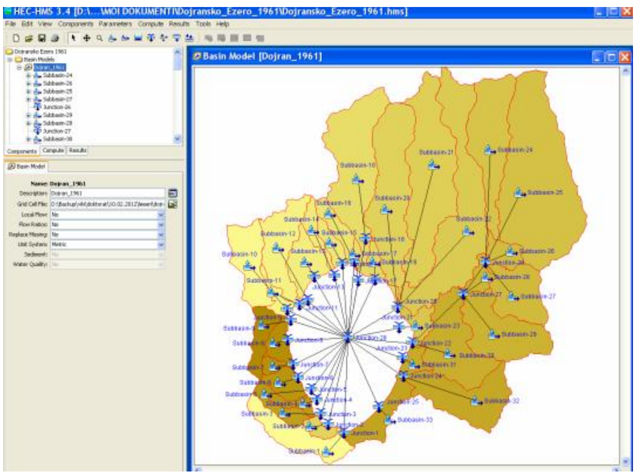
Figure 8: Dojran Lake Model in HEC HMS

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 4 , April 2016

➢ ***Gjavato system.*** The capacity of the Gjavato system for bringing water to the lake is $1m^3/s$, but the system operated at 30% of capacity. In the water balance model, this component was taken at 300l/s.

➢ ***Evaporation and evapotranspiration.*** The components of evaporation and evapotranspiration were calculated by using the heat balancemethod and the streamline theory [Penman, 1950]. Annual sums of evapotranspiration for Nov Dojran (1961-2008) are shows in Figure 9.

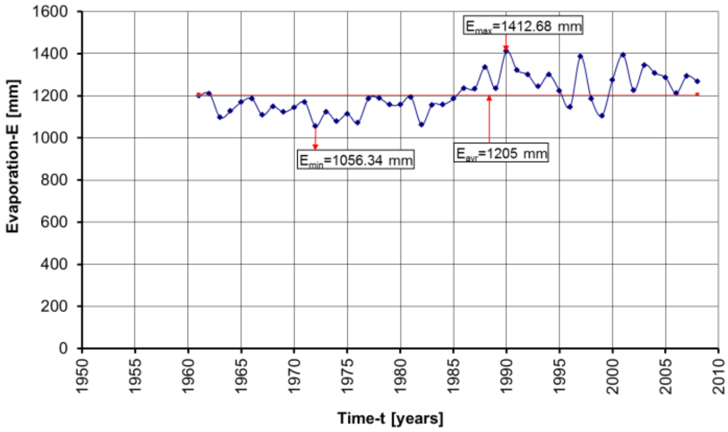

Figure 9: Annual sums of evapotranspiration for Nov Dojran (1961-2008)

The values indicated that the annual evaporation sum of Dojran Lake varied between 1056.34 mm in 1972 to 1412.68 in 1990, where the average evaporation sum for this period was 1205.5 mm. The calculation showed that the annual evaporation sums were higher than the annual precipitation sums in the analysed period.

➢ ***Outflow.*** The volume of water usage for irrigation in Macedonia is 32,5 l/s or a total of $1{,}25 \cdot 10^6$ m^3/year, and 50 l/s or $1{,}576 \cdot 10^6$ m^3/yearfor water supply, [12]. Data on the surface and underground outflow, water usage directly from the lake, from the surface and the underground for water supply or irrigation on the Greek side of the watershed are not available.

C. **Resalts and discussions**

The components from the water balance model of the Dojran lake watershed were defined at an annual, monthly and daily level (annual water balance, monthly water balance and daily water balance). Using the water balance model, the water level in the lake was computed annual water balance and monthly water balance in two variants for the period 1961÷2008. In water balance model were used different methods for calculation of the components of runoff. Variant 1 for annual water balance ware used Langbein model, for monthly water balance were used runoff coefficient η_1 [according Blagoja Todorov,1977]. Variant 2 for annual water balance were used annual runoff coefficient (0.15), for monthly water balance were used runoff coefficient η_2(coefficient determining by calibration). The water balance model was used to investigate the influence of the underground inflow on water level simulations. The influence of this component is insignificantly small in all alternatives. This investigation was made in order to prove the correct choice of algorithm for the water balance model, recommended for a water balance model of a natural lake [10]. A daily water balance simulation is performed for 1961 and in the rainfall runoff modelling, a different curve number was included (CN = 60-89) with respect to the heterogenic land cover and land use characteristics in the entire watershed. The results show that the presented water balance model is well calibrated and verified and may be used in the future to obtain the impact on the Lake by any natural or anthropogenic change in the Lake watershed.
The results from the water balance model (water level changes in the lake) in different variants were compared, as well. Figure 10 shows a comparison between the estimated and the observed average annual water level of Dojran Lake, Figure 11 shows a comparison between the estimated and the observed monthly water level of Dojran Lake and Figure 12 shows a comparison between the estimated and the observed daily water level of Dojran Lake.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 4 , April 2016

The comparison between the calculated and the measured water level shows that the error of the annual water balance model was 0,02 ÷ 1,0 m before 1988 and maximum 5,5 m; 5,8 and 5,46 m (for different variants) after 1988 year. The cause for the errors in the period from 1961 to 1965 is the average value of the components. In the period 1965 to 1988, the reasons for errors can be related to the unknown regulation regime of the artificial channel. The causes for errors in the water balance model for the period after 1988 are not clearly noted. The causes can be associated with the uncontrolled use of the water from the lake (mainly on the Greek side). The hydrological analysis of the available historical data on the studied area shows seasonal variability in the hydrological response. Correlations between average annual air temperature and water level and average precipitation and water level are not very strong.

The water balance model for Dojran Lake and its watershed was applied using data from the measurements done on the Macedonian side only. The value of the outflow on the Greek side of the watershed was not available. The difference between the volume of the simulatedand the observedwater level was defined in the same way as the value of these components.The difference in computed and recorded water levels show water volume loss of about 200 million m^3 (in 2002 year) which can be related to human activities in water over abstraction from the lake and the watershed.

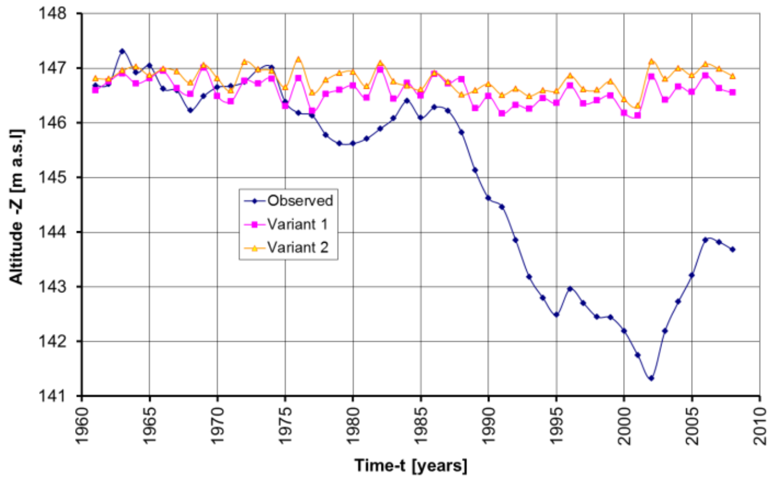

Figure 10:Comparative analyses between observed and simulated average annual water levels

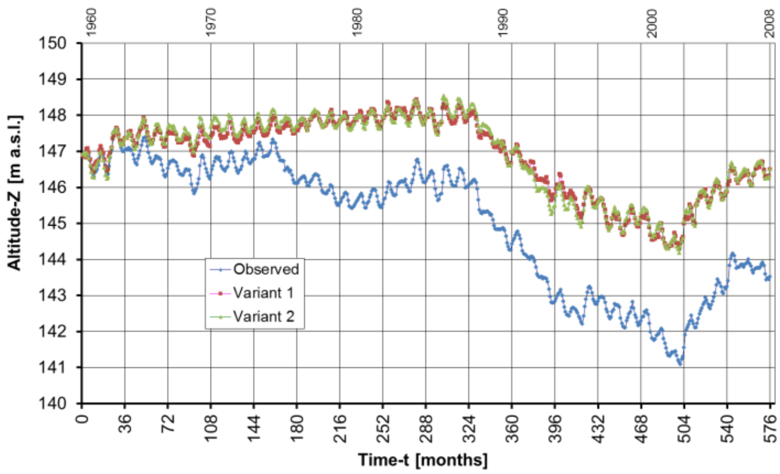

Figure 1:Comparative analyses between observed simulated averagemonthly water levels

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 4 , April 2016

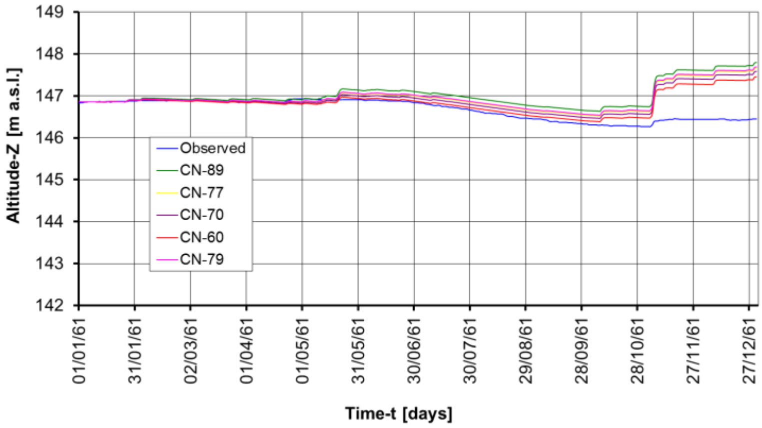

Figure 12: Comparative analyses between simulated and observed daily water levels for the period from 1 Jan. to 31 Dec. 1961.

V. CONCLUSION

Dojran Lake is mainly filled by precipitation, direct surface inflow and underground inflow. The components of the water balance model were estimated by use of existing data and hydrological models. The surface inflow was defined mainly by using precipitation data and watershed characteristics (rainfall-runoff model). By hydrological analysis, it can be concluded that the changes of the water level of the lake took place after the changes of the value of precipitation. The component of underground inflow was estimated by use of the existing data on the hydrogeological characteristics of the watershed (on the Macedonian side only). The obtained results indicate that the water balance model is not sensitive to this component. The most important parameter of the water balance of Dojran Lake is the evaporation. The models used for calculation of this component showed that the annual evaporation sums were higher than the annual precipitation sums in the analyzedperiod.

The high errors of prediction can be attributed to human activity and uncontrolled using water from Lake and it watershed. Defining the components of the water balance model is recommended to be done by use of data on precipitations and all factors related to the watershed on both Macedonian and Greek side.

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