

## Water balance modeling for hydrological ecosystem services assessment in Ogosta River Basin (NW Bulgaria) using GIS and remote sensing

Ekaterina Ivanova, Space research and Technology Institute, BAS, Sofia 1113, Acad. G. Bonchev Str., bl. 1,  
e-mail: [e\\_iivanova@abv.bg](mailto:eiivanova@abv.bg)

Margita Kiryakova, Sofia University “St. Kl. Ohridski”, Faculty of Geology and Geography, 15 Tsar  
Osvoboditel bld., e-mail: [margita.kiryakova@yahoo.com](mailto:margita.kiryakova@yahoo.com)

**Abstract:** The demand of fresh water is one of the key issue against the global warming and growing population of the world. The assessment and valuation of water resources as a natural capital is a new comprehensive powerful tool for better understanding the relationship "society-nature" and elaboration effective policies for sustainable development. A possible approach for assessing water resources in a given area is calculating the balance between incoming water from precipitation and outgoing water by evapotranspiration, groundwater recharge and runoff. A water balance calculation was applied in this study on the area of Ogosta River Basin, using GIS and remote sensing. Thornthwaite and Mather method (TM model) was chosen for this purpose in order to compute seasonal and geographical patterns of water availability. The technique uses spatial data for monthly precipitation, temperature, topography, land cover, soils and river network. Various thematic layers were integrated mathematically to provide a grid-based spatial patterns of monthly and annual surface runoff of the entire river basin taking into account evapotranspiration, soil retaining capacity and vegetation cover. The resulting digital maps, which indicate the water supply functions of the ecosystems, were transform in monetary valuated map of the ecosystem services flow, based on the price of drinking water.

**Keywords:** water balance, ecosystem services, GIS, Ogosta River Basin

### 1. Introduction

Large variety of services, that ecosystems provide to humans, are associated directly or indirectly with the hydrological cycle and are named hydrological ecosystem services or water related ecosystem services (Koshke et al., 2014). “Hydrologic services encompass the benefits to people produced by terrestrial ecosystem effects on freshwater” – from the water supply to the mitigation of flood damages (Brauman et al., 2007). Each hydrological service the authors characterize by the hydrological attributes of quantity, quality, location and timing.

Ecosystem services related to water and aquatic ecosystems are included in the general classifications of MAES (2014) and MARS (Grizzetti et al., 2015). MAES (Maes et al., 2012) have examined aquatic ecosystems per typology of ecosystem considering the services delivered from inland waters (rivers, lakes, groundwater and wetlands), those from the shelf and open ocean and the services provided by transitional waters in coastal areas. MARS (Grizzetti et al., 2015) have distinguished three large groups of ecosystem services: services provided by aquatic ecosystems, which can be linked to the water bodies; hydrological ecosystem services relevant to river basins; and ecosystem services at European level.

This study focuses on ecosystem services at the river basin scale, the most important of which are the water supply for drinking and not drinking purpose, irrigation, power generation and many regulating services such as water purification and erosion control (Table 1). Hydrological ES are most heavily dependent on ground characteristics of the watershed, such as topography, slope, depth of soil and especially on the natural vegetation status and land use within the watershed area (Terrado et al., 2013, Pattanayak and Wendland, 2007).

Table 1. Water related ecosystem services, representative of the Ogosta River Basin (ESs classification is adapted to MAES, 2014 and Grizzetti et al., 2015)

Water related ecosystem services				Biophysical Indicators
Section	Division	Group	Class	
Provisioning	Nutrition	Biomass	Food	Fisheries Aquaculture
		Water	Surface water for drinking purposes	Surface water availability (surface runoff)
	Materials	Water	Ground water for non-drinking purposes	Water storage capacity (AWC)
		Energy	Abiotic energy sources	Hydropower generation
Regulation and Maintenance		Water quality regulation	Water purification	Nitrogen removal
		Natural hazard protection	Erosion prevention	Soil erosion rate by land use type
		Water regulation	Flood protection	Water storage capacity; Trend in flooding frequency
		Lifecycle maintenance, habitat and gene pool protection	Maintaining populations and habitats	Species diversity or abundance; Hydromorphological status
		Climate regulation	Carbon sequestration	Total carbon storage

Cultural	Recreation and tourism		Aesthetic appreciation	Density of visits
			Hunting and fishing	Density of visits

In any case, the assessment of the hydrological ecosystem services uses an integrated approach to analysis of ecosystems and processes occurring in the river basin and it is directly related to river basin management (Guswa et al., 2014; Brauman et al. 2007; Grizzetti et al., 2015). The comprehensive approach for ecosystem services assessment at the river basin scale suggests the need to use of hydrological models as a means of information. In this context, the hydrological models should provide quantitative and qualitative information, while the assessment of ecosystem services focuses on land cover and land use, as emphasize Guswa et al. (2014). The choice of model will depend on the context of the decision to achieve desired biophysical indicator and dominating hydrological processes (Guswa et al., 2014).

Various tools in GIS software were developed in recent years for hydrological modeling of ecosystem services. Examples of such list Vigerstol and Aukema (2011): SWAT - Soil and Water Assessment Tool, VIC - Variable Infiltration Capacity model, InVEST - Integrated Valuation of Ecosystem Services and Tradeoffs, ARIES - Artificial Intelligence for Ecosystem Services.

Hydrological modeling in GIS environment for assessment of ecosystem services have been already applied to the watershed of Upper Ogosta River and some others regions of Bulgaria. Soil and Water Assessment Tool (SWAT model) have been used for water balance calculating and ecosystem services assessing in the Basin of Upper Ogosta River (Boyanova et al., 2016). Flood regulating ecosystem services capacities have been mapped in the area of the Malki Iskar River Basin and Municipality of Etropole based on the catchment hydrologic model KINEROS (Nikolova et al., 2009, Nedkov and Burkhard, 2012). Hydrological models KINEROS and SWAT have been used for floods hazard mapping and risk assessment in Yantra River Basin (Nedkov et al, 2006, Nikolova et al., 2007).

Specific data-base typologies and their respective lookup tables and needs from large amounts of data records are disadvantages of software-based modeling toolsets, which complicate implementation of the models (Boyanova et al., 2016). For that reason, Thornthwaite and Mather (TM) model (Thornthwaite and Mather, 1955, 1957) was chosen in this study, which allows adapting the available database to the model, using only the ArcGIS software toolset.

Water quantity is one of the most important attributes of hydrological ecosystems that provide drinking and irrigation water. Its components surface runoff and groundwater recharge feed the springs and flows of the rivers. Information about water quantity can be provided through water balance calculation. Three environmental factors affect the water balance: the climate, with its elements precipitation and temperature; the physical characteristics of the soils and rocks; and the plant communities. Water balance calculating of Ogosta River Basin for hydrological ecosystem services valuation is the purpose of this study by application of grid-based TM model in GIS. The model inputs are spatial variables of precipitation, temperature, soil structure and vegetation in a grid-cell of 27 m. The outputs of the model are monthly and annual evapotranspiration, soil moisture storage capacity of the root-zone and water surplus that is available for runoff. The outputs variables can be used as indicators for water ecosystem assessment and valuation. The potential of ecosystems was assess within the basin to provide water provisioning ecosystem services. Then, costing of services “Surface water for drinking purposes” and “Ground water for non-drinking purposes” was done based on indicators “Surface water availability” and “Water storage capacity” (Tab. 1).

## 2. Study area

This study covers the area of Ogosta River Basin and its river network developed in the northwestern part of Danube catchment area, including basins of the rivers Ogosta and Skat. East border of the study region is the Iskar River Basin and south border – the catchment area of Nishava River. To the southwest Ogosta River Basin extends to the state border with Republic of Serbia, and to the west it reaches the watershed of Lom River (the catchment area of Tsibritsa River). It occupies an area of 4351.2 km<sup>2</sup>, including parts of two administrative regions – Montana District and Vratsa District (Fig. 1).

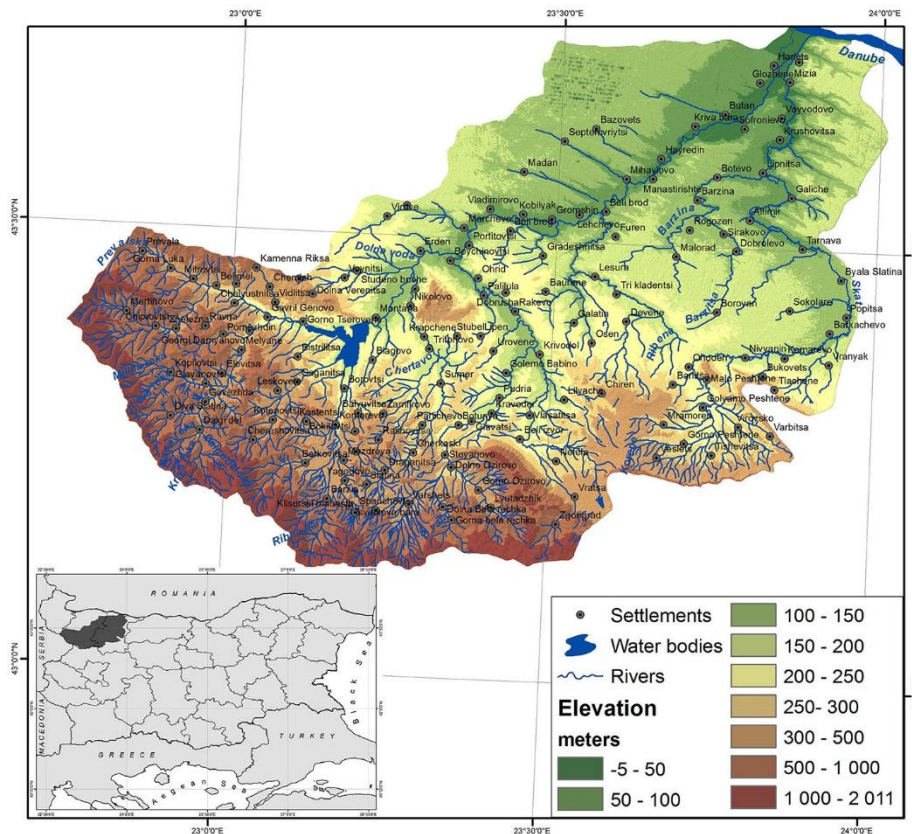


Figure 1. Location map of the Ogosta River Basin

Some northern slopes of the Western Balkan Mountains and parts of western Danubian Plain are included in the area of research. The Stream of Ogosta takes many first-order tributaries forming a right asymmetric river system (Hristova, 2012). The continental feature of the climate are emphasized by its elements temperature and precipitation. The climate is characterized with high temperature amplitude and well expressed maximum in the spring and minimum in the winter. The average annual temperature ranges from 4.8 ° C to 12.2 ° C and annual precipitation sum – between 518 and 1163 mm, depending on the elevation (Climate Reference book for Bulgaria, 1983; Koleva and Peneva, 1990). The annual discharge of the Ogosta River is 23.8 m<sup>3</sup> / s and it is characterized by a relatively low variability. The coefficient of variation is between 0.32 and 0.34. The annual discharge varies from 1.22 m<sup>3</sup> / s measured at the upstream gauging stations to 23.8 m<sup>3</sup> / s measured at the mouth of the river (Hydrological reference book, 1981; Zaharieva, 2005). Total annual water volume of the river was estimated at 1794.3 million m<sup>3</sup> (Hydrological reference book, 1981).

The main soil types presented in the researched area are following: Calcic Chernozems (Phaeozems), Fluvisols, Dystric Cambisols, Chromic Luvisols and Orthic Luvisols (Soil map of Bulgaria, 1956; FAO, 1998). Forest communities are represented mainly by deciduous and account for only 19.7 % of the total area of the basin (CLC 2012, National Reference Centre, Executive Environmental Agency at the Bulgarian Ministry of Environment and Waters). There is high anthropogenic impact on the hydrologic ecosystems of the Ogosta River Basin, expressed by use of water for drinking and industrial purpose, irrigation, power generation and recreation (Zaharieva, 2005). A large number of settlements (149) are included in the watershed area, 9 of which are towns.

### 3. Materials and methods

The methodology of this study can be divided into several stages, which include: identification of hydrological ecosystem services provided potentially from ecosystems of Ogosta River Basin and choice of model for water balance calculation; creating a database necessary for the application of the model in GIS environment and generating the relevant information layers; applying the TM model for water balance calculation and generating the model outputs, representing grid-based spatial variables of potential evapotranspiration, soil moisture storage capacity and surface runoff; and finally, implementation of direct valuation of water supply ecosystem services. Among the various methods for water balance calculation the TM model is one of the most widely used and its application in GIS makes it possible to find out location and timing of water surplus and water deficit for an entire basin (Jasrotuia et al., 2009). The technique relies on long term average monthly rainfall, long term average temperature, soils and vegetation characteristics of the catchment area. Several advantages the TM model has. It is one of the simplest model, uses easily accessible climatic data and can be used for different periods and at different spatial scales.

#### a. Data collection and processing

As a first step, 24 grid-layers were generated representing spatial variation of temperature and precipitation within the watershed area using linear regression method based on DEM and climatic data for average monthly long-term observations. The Digital

Elevation Model (DEM) is based on satellite data with cell size 27 meters (ASTER Global DEM, modified version 2012). Climatic data from 30 ground-based meteorological stations was used in order to calculate the regression coefficients. These stations are located in the northwest region of Bulgaria, including the territory of the researched area. The observation periods are 40 years for the temperature and 55 years for the precipitation, from 1931 to 1970 and from 1931 to 1985 respectively (Climate Reference book for Bulgaria, 1983; Koleva and Peneva, 1990). The soil water content (Tab. 2), i.e. available water capacity (AWC of the root-zone) was calculated based upon the land-use, soil texture and rooting depth, using the method suggested by Thornthwaite and Mather (1955, 1957). Digital soil map in scale 1: 200, 000 (Soil map of Bulgaria, 1956) and digital map of soil structure from European Soil Database – ESDB v2.0 (JRC of the IES, EUR 19945 EN, 2004; Panagos, 2006, 2012) were used for this purpose.

Table 2. Values of Available Water Capacity (AWC) for combinations of soil textures and vegetation types (Thornthwaite and Mather, 1957)

Vegetation	CLC 2012 classes	Soil texture	AWC of the root-zone
Shallow rooted crops	112; 121; 122; 124; 131; 333; 411; 511; 512	Fine Sandy Loam	75
		Clay-Loam	100
		Silt-Loam	125
Moderately rooted crops	211	Fine Sandy Loam	150
		Silt-Loam	200
		Clay-Loam	200
Deep rooted crops	142; 221; 231; 242; 321; 324	Fine Sandy Loam	150
		Silt-Loam	250
		Clay-Loam	250
Orchards	141; 222; 243; 333	Fine Sandy Loam	250
		Silt-Loam	300
		Clay-Loam	250
Mature forests	311; 312; 313	Fine Sandy Loam	300
		Silt-Loam	400
		Clay-Loam	400

Firstly, the soil map was georeferenced and digitized, and then the information on the soil structure from ESDB was referred to the national classification. Hydrological land cover types were derived from the CORINE Land Cover model 2012 Bulgaria, freely available on the website of the Executive Environment Agency of the Minister of Environment and Water, Bulgaria.

#### b. TM model procedure

The execution of the model involves several steps (Thornthwaite and Mather, 1955, 1957). First, monthly potential evapotranspiration is calculated:

$$PET = 1.6 * C * (10 * T/I)^a \quad (1)$$

where  $PET$  is the potential evapotranspiration (mm / month);  $T$  is the mean monthly temperature ( $^{\circ}$  C);  $I = \sum i$  is the annual heat index for the 12 months in a year;  $i = [T/5]^{1.514}$  is the monthly heat index;  $a$  is Thornthwaite and Mother coefficient expressed as:

$$a = 6.75 * 10^{-7} * I^3 - 7.71 * 10^{-5} * I^2 + 1.792 * 10^{-2} * I + 0.49239 \quad (2)$$

and  $C$  is monthly correction factor, calculated by following equation:

$$C = [m/30] * [d/30] \quad (3)$$

where  $m$  is the number of days in the month and  $d$  is the monthly mean daily duration (i.e. number of hours between sunrise and sunset and expressed as the average for the month).

Next,  $P - PET$  with  $P$  as precipitation is calculated, which express water excess (if  $P - PET > 0$ ) or water deficit (if  $P - PET < 0$ ). Then the accumulated values of  $(P - PET)$ , i.e. the accumulated potential water loss ( $APWL$ ) for each month, are calculated. This will be zero for months having positive  $(P - PET)$  and starting with the first month having a negative value. Then the actual storage of soil moisture ( $STOR$ ) for each month are calculated as follows:

$$STOR = AWC * e^{APWL/AWC} \quad (4)$$

where  $AWC$  is the moisture storage capacity (i.e. the available water capacity) of the soil. This is calculated based upon the land use, soil texture and rooting depth as suggested by Thornthwaite & Mather (1955, 1957). Changes of actual storage ( $\Delta SM$ ) for all the months are calculated as:

$$\Delta SM_{month} = STOR_{month} - STOR_{previous\ month} \quad (5)$$

A negative value of  $\Delta SM$  implies subtraction of water from the storage to be used for evapotranspiration, whereas a positive value of  $\Delta SM$  implies infiltration of water into the soil and its addition to the soil moisture storage.

The actual evapotranspiration ( $AET$ ) are computed for all the months, using equations (6) and (7):

$$AET = \Delta SM + P \quad (\text{for } \Delta SM < 0) \quad (6)$$

$$AET = PET \quad (\text{for } \Delta SM > 0) \quad (7)$$

The water deficit ( $DEF$ ) for crop evapotranspiration in each month are calculated for the months having negative ( $P - PET$ ) as follows:

$$DEF = PET - AET \quad (8)$$

The amount of excess water that cannot be stored is denoted as moisture surplus ( $SUR$ ). When storage reaches its capacity,  $SUR$  is calculated using equation (9):

$$SUR = P - PET \quad (9)$$

When the soil storage is not at its capacity, no surplus exists. In a month in which the soil moisture storage capacity is just satisfied,  $SUR$  is obtained using equation (10):

$$SUR = P - (AET + \Delta SM) \quad (10)$$

where  $\Delta SM$  is the change in actual soil moisture storage.

#### 4. Results

Potential evapotranspiration ( $PET$ ) was calculated by means of equations (1), (2) and (3). Then,  $P - PET$  was calculated for all the months. The resulting maps show water excess ( $P - PET > 0$ ) for each month. Consequently, the water balance of the Ogosta River Basin is positive through all the year (i.e. no water deficit exist). Therefore, the soil storage is at its capacity and the actual soil moisture for each month is equal to AWC. Hence, changes of actual storage ( $\Delta SM$ ) for all the months were zero and surplus was calculated using equation (9). The actual evapotranspiration is equal to potential respectively.

Monthly and annual water surplus trend is inverse to the evapotranspiration and goes parallel with the rainfall rate, simultaneously with increase of the elevation. Annual evapotranspiration for the researched watershed ranges from 40 mm / year in the high mountain areas to 74 mm / year in the low part of the territory (Fig. 2).

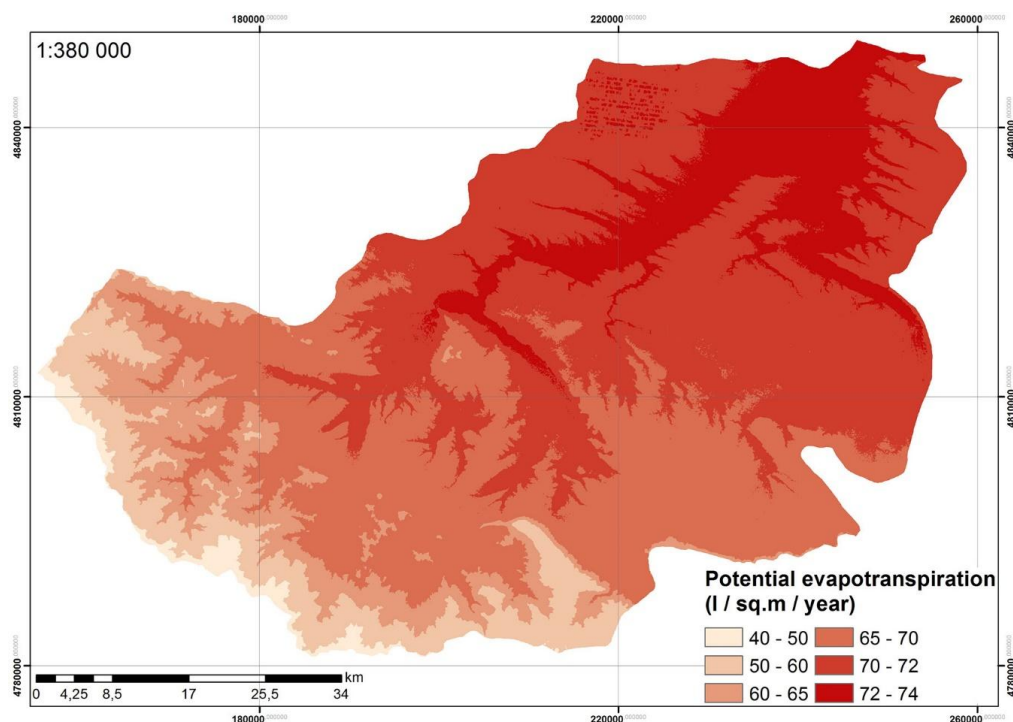


Figure 2. Annual evapotranspiration for the Ogosta River Basin

Minimal water surplus is calculated for months February (from 33 to 72 l / m<sup>2</sup> / year), August (from 31 to 88 l / m<sup>2</sup> / year) and September (from 32 to 77 l / m<sup>2</sup> / year) and maximal in May (from 66 to 155 l / m<sup>2</sup> / year) and June (from 70 to 165 l / m<sup>2</sup> / year) for the various surface units. Annual surplus ranges from 531 to 1164 l / m<sup>2</sup> / year (i.e. from 0.53 to 1.6 m<sup>3</sup> / m<sup>2</sup> / year) – Fig. 3. Principally, the surplus should be available to the runoff. However, due to the gap of time between the rainfall and the moment when water actually passes through the gauging station, monthly computed surplus is higher than monthly runoff (Thornthwaite and Mather, 1957, Singh and Prasad, 2004, Jasrotia et al., 2009).

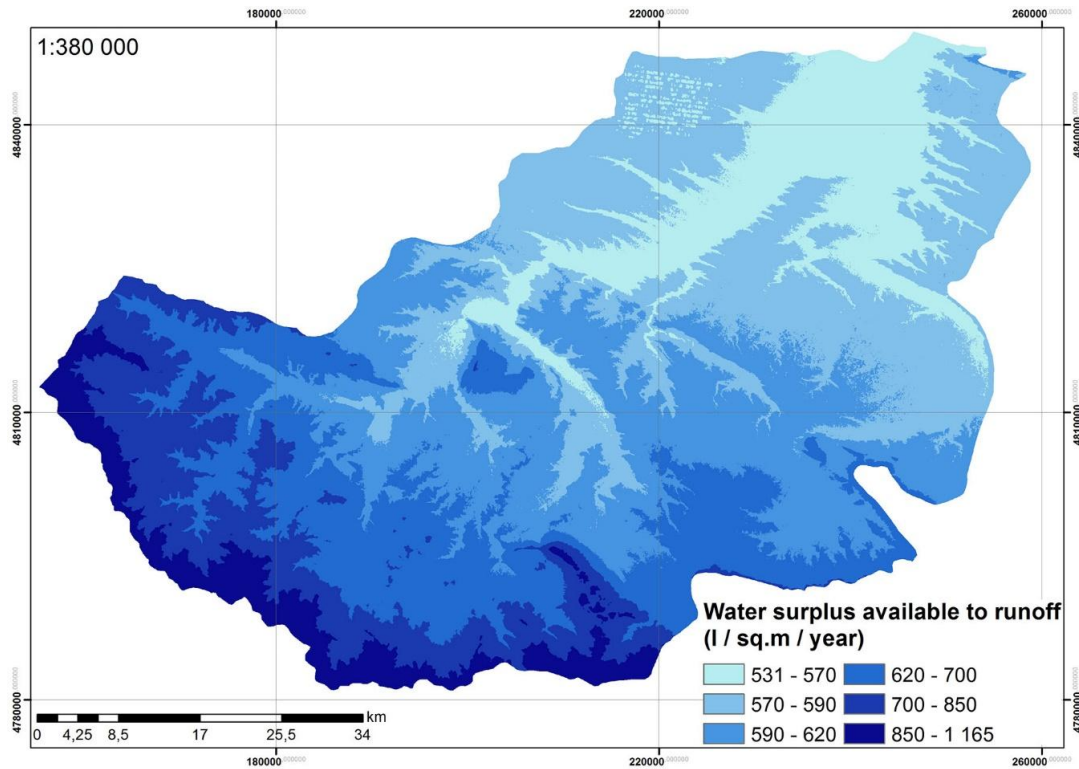


Figure 3. Annual water surplus available to runoff for the Ogosta River Basin

Available Water Capacity of the root-zone range from 75 to 400 l / m<sup>2</sup> for different soil and vegetation hydrological ecosystem units (Fig. 4).

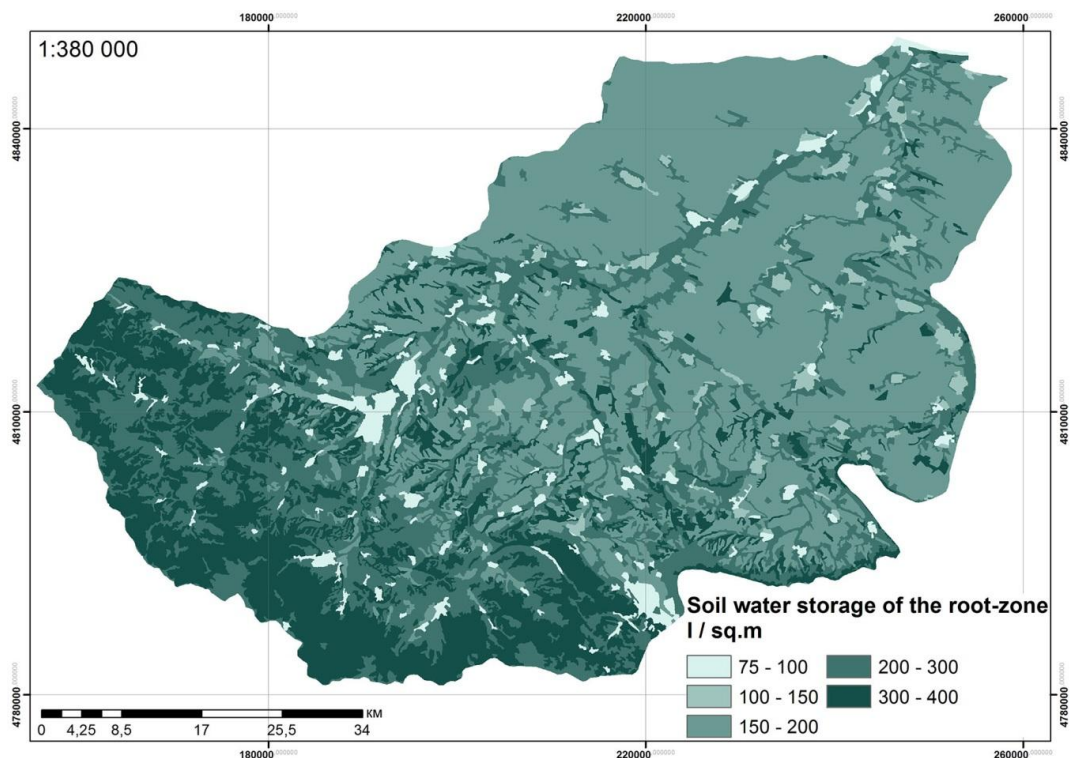


Figure 4. Soil water storage for the area of the Ogosta River Basin

The most of water is stored in the forest ecosystems – from 300 to 400 l / m<sup>2</sup>. Agricultural ecosystems, that cover the largest part of the river basin area (60 %), retain from 150 to 200 l / m<sup>2</sup> of water. The urban areas, where the demand of water is highest, have the lowest water-retaining capacity.

As a rule, according to Thornthwaite and Mather (1957), for large catchments approximately 50 % of the surplus water actually runs. The remainder part is detained by aquifers, small lakes and reservoirs and is available for runoff during the next month. The excess water in Ogosta River Basin, calculated by the model applied, amount to 2773 million m<sup>3</sup> / year for the total area. The annual water volume, reported to be passed through the gauging station, is 1794.3 million m<sup>3</sup> / year (i.e. 64.7 % of the annual water surplus). However, it should be borne in mind that 55 dams has been built on the Ogosta River, the largest of them has capacity of 506 million m<sup>3</sup>. For that reason, the total volume of water surplus we have taken into account in water ecosystem services valuation, since the rest of 35.3 % would be available for use in emergency or for supplying areas with high demand of water.

It can be seen from Table 3 that the water balance of the Ogosta River Basin is positive. There is no water deficit and annual surface runoff depend on the rainfalls completely. The seasonal variability of the water surplus is low. The potential evapotranspiration is equal to zero or is near to zero during the months of December, January and February.

Table 3. Calculations of the water balance elements in the Ogosta watershed area

Water balance elements	Monthly variations of the water balance elements												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual
<i>P (mm)</i>	39 – 77	33 – 72	37 – 75	54 – 98	76 – 161	83 – 172	58 – 130	45 – 96	40 – 83	47 – 79	48 – 85	44 – 76	606 – 1205
<i>AET = PET (mm)</i>	0	0 – 0.1	0 – 1.7	1.3 – 5.5	5.1 – 9.6	7.3 – 12.9	8.8 – 15	8.4 – 13.7	5.6 – 9	3.2 – 4.8	0.7 – 1.8	0 – 0.1	40.5 – 74.5
<i>APWL (mm)</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Runoff = P – PET (mm)</i>	39 – 77	33 – 72	35 – 75	49 – 97	66 – 155	70 – 165	43 – 121	31 – 87	32 – 77	42 – 76	46 – 85	44 – 76	531 – 1165

## 5. Valuation of water supply ecosystem services

List of 206 proposals for biophysical indicators for assessing ecosystem services related to water (Grizzetti et al., 2015, Annex 4, Table A4.1), have been compiled by MARS, based on Maes et al. (2014), Egoh et al. (2012), Layke et al. (2012), Russi et al. (2013) and Lique et al. (2013). “Surface water availability” and “Water storage capacity” are most commonly mentioned as indicators for the different classes of ecosystem services. These two indicators we chose in this study, aiming valuation of water provisioning ecosystem services for drinking and non-drinking purposes, based on available economic indicators for the price of water for different use in the region. Delivery cost of a gravity water for human consumption in the region is 0.91 BGN / m<sup>3</sup>, and the price of water for other use is 1.12 BGN / m<sup>3</sup>.

The indicator “Available water surplus”, brought into cubic meters and multiplied by the price of drinking water, is used to generate a map of the economic value of the provisioning service “Surface water for drinking purposes” (Tab. 1), because the water supply in the researched area is carried out by surface water, collected into large reservoirs (Ogosta Dam and Srechenska Bara Dam). The Soil Water Storage was used as indicators for valuation of service “Ground water for non-drinking purposes”. The accumulation of the service flow generates a map of the economic potential of the area to provide water supply ecosystem services (Fig. 5).

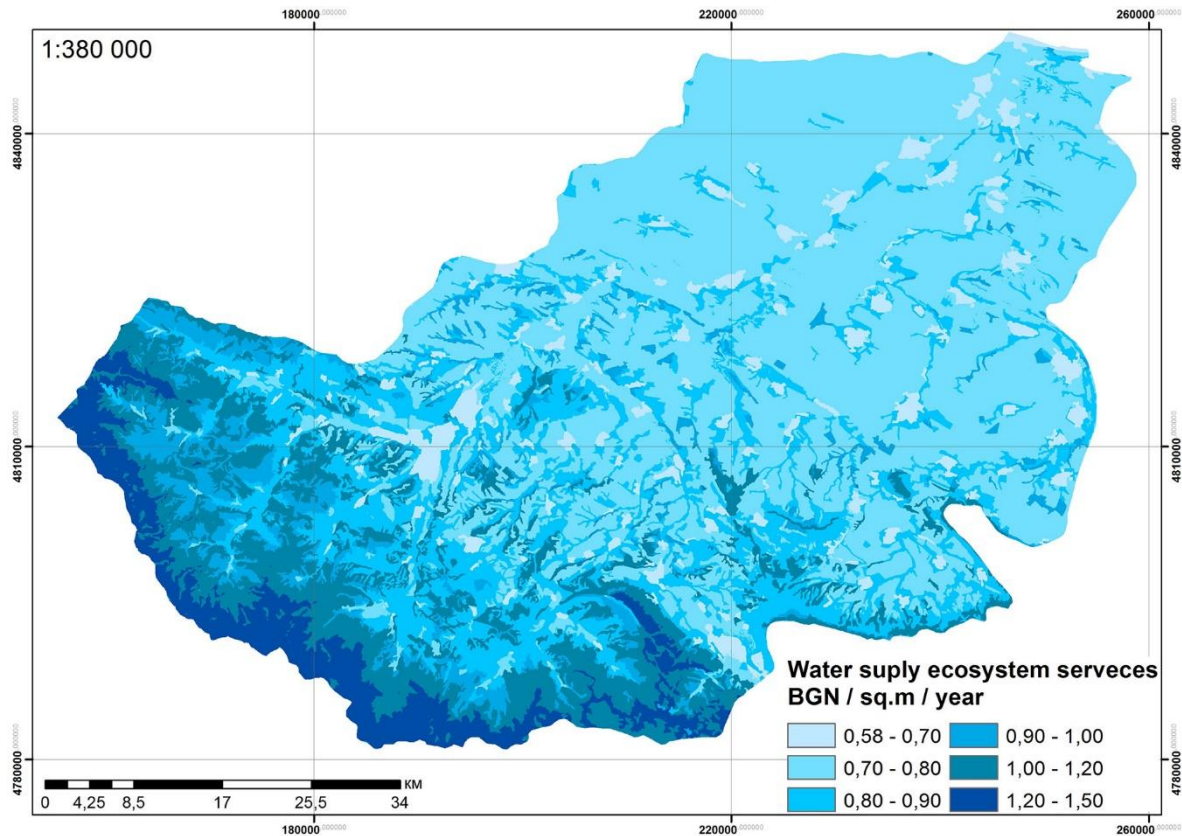


Figure 5. Provisioning water services provided from ecosystems of Ogosta River Basin

The results show that the values of hydrological ecosystem services in the Ogosta Watershed vary from 0.58 to 1.50 BGN / m<sup>2</sup> / year for individual water holding and water providing zones. That results in 3735.9 million BGN / year (approximately € 1870 million / year). In other words, the ecosystem assessment of the total volume of water that Ogosta River Basin is able to provide for use by both humans and ecosystems themselves can be estimated at about 860 000 BGN from square kilometer per year.

## 6. Conclusion

The computing water balance is one of the main methods for assessing the condition of water resources in a given region (Singh and Prasad, 2004). The Thornthwaite & Mather (TM) model applied by the tools of GIS has established itself as one of the commonly used approaches for water balance assessment, especially in geographic areas where the water deficit is a serious problem – India (Singh and Prasad, 2004 , Jasrotia et al., 2009), Iran (Barkhordari and Yazdi, 2015), Mexico (Jujnovsky et al., 2010). The TM model was used in this study aiming to evaluate the hydrological ecosystem services of the Ogosta River Basin. The ArcGIS toolset was used in order to provide spatial patterns of water provisioning capacity. The model uses as inputs climatic data for monthly temperature and precipitation, which can be easily accessible. The individual water holding zones was calculated, based on soil structure and land-use classes. The outputs of the model were spatial variables of monthly and annual evapotranspiration, soil moisture storage capacity of the root-zone and water surplus that is available for runoff. The water balance calculation shows that no water deficit exist in the watershed of Ogosta River and annual surface runoff depend on the rainfalls. Therefore, the resulting maps shows that the maximum annual runoff (1164 l / m<sup>2</sup> / year) results from the upper part of the watershed area, where the annual rainfall sum is higher. The seasonal variability of the water surplus is low. Total annual water volume of the drainage area was estimated at 2773 million m<sup>3</sup>, based on the model applied. The economical values of hydrological service flow of individual ecosystems range from 0.58 to 1.50 BGN / m<sup>2</sup> / year. Total economic value (TEV) of the Ogosta watershed area amounts to 3735.9 million BGN.

To conclude, it can be said that the researched catchment area has a well-balanced potential to provide hydrological ecosystem services. The results submit a wealth of information for future valuation of the others water related services (Tab.1). In addition, the variety of thematic maps, generated by the model applied, could be used for other targets, associated with waters management in the national river basin management plans.

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