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ASPECTS OF WATER BUDGET IN VĂCĂREȘTI WETLAND

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Abstract: Wetlands located in cities are among the most diverse and productive natural based systems which provide important benefits such as water quality improvement, flood control, soil erosion protection, recreation opportunities, support for wildlife and natural products. This paper presents the water budget in Văcărești wetland in order to provide an overview of the hydrological processes that make wetlands unique. Văcărești wetland is located in south part of Bucharest city and represents the single urban Natural Park in Romania. The existing wetland has been formed on an area conceived initially as the bottom of an artificial lake where the nature and the wildlife developed on their own. Using historical data and several algorithms, this paper presents the analysis of the water budget on the considered area which would lead to a better assessment of the hydrological processes. The goal of the study was to gain knowledge on how the wetland is sustained and, as a result, to develop solutions to prevent the ecosystem deterioration conducted by external pressures like climate change with extended periods of droughts or anthropic influences.

Keywords: hydrological processes, soil moisture deficit, actual evapotranspiration

1. Introduction

According to the Ramsar Convention [1] wetlands are defined as: "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters".

Wetlands represent a unique feature of landscape and may consist of highly variable ecosystems defined through specific conditions such as water level fluctuation and the presence of saturated soil during the growing season. Conceptually, it can be assumed that they represent the transition zone between predominantly wet and dry environments.

Often wetlands are assimilated only with lakes or swamps, but beside their similarities, between the wetlands and lakes there is a major difference from the hydrological point of view, which consists in the fact that wetlands lose water into the atmosphere through the transpiration process that occurs at soil surface, while lakes lose water into the atmosphere, in particular through the evaporation process. Storage evaluation and its variation over time in a wetland represent a more complex process than in lakes because water is present almost all of the time in the soil.

A properly functional wetland needs to collect and store an optimal volume of water in a given period of time. In technical terms this requirement is called hydroperiod. The availability of water resource in wetlands is related to the hydrological cycle representing the underlying process which provides a sufficient amount of precipitation, more considerable than the amount of water infiltrated or evaporated.

The water level, hydroperiods and retention time are influenced and controlled by the hydrological connections: inputs and outputs. Exchanges may take place with following environments: the atmosphere (precipitation, evaporation, evapotranspiration), groundwater (infiltration, percolation), surface water (surface runoff) or tidal action (where appropriate).

Changes in water storage over a period of time can be assessed using the hydrological water budget. This represents the differences between the amount of water inflows and outflows in a specific period of time. Water level fluctuations indicate that wetlands store water during rain events and lose it during dry periods, revealing the storage variation in space and time based on the hydrological changes and therefore highlighting that wetlands are sensitive even to the smallest disturbances of environmental conditions.

2. Case study

Văcărești wetland is located in the south part of Bucharest city, on the former floodplain of Dambovita River, and it represents nowadays one of Romania's most diverse ecosystems located in urban areas. In the 1980, an extensive project was initiated in order to develop an integrated water management system for Bucharest city. This included, among other projects, the construction of a complex setup on Dambovita River, part of an ambitious plan to connect Bucharest with the Danube.

The reservoir consists of perimeter embankments on three of the four sides with clay sealing screens all over the edges to prevent seepage and water losses from what was intended to be a lake. It sums a total surface of 183 hectares (2.30 km length and 2.0 km width) and an average depth of 10.0 meters. According to the initial design and based on the information gathered from the specialists who took part during the execution phase, in order to reduce the exchange between the stored water and the groundwater, the bottom surface was coated with a uniform layer of clay.

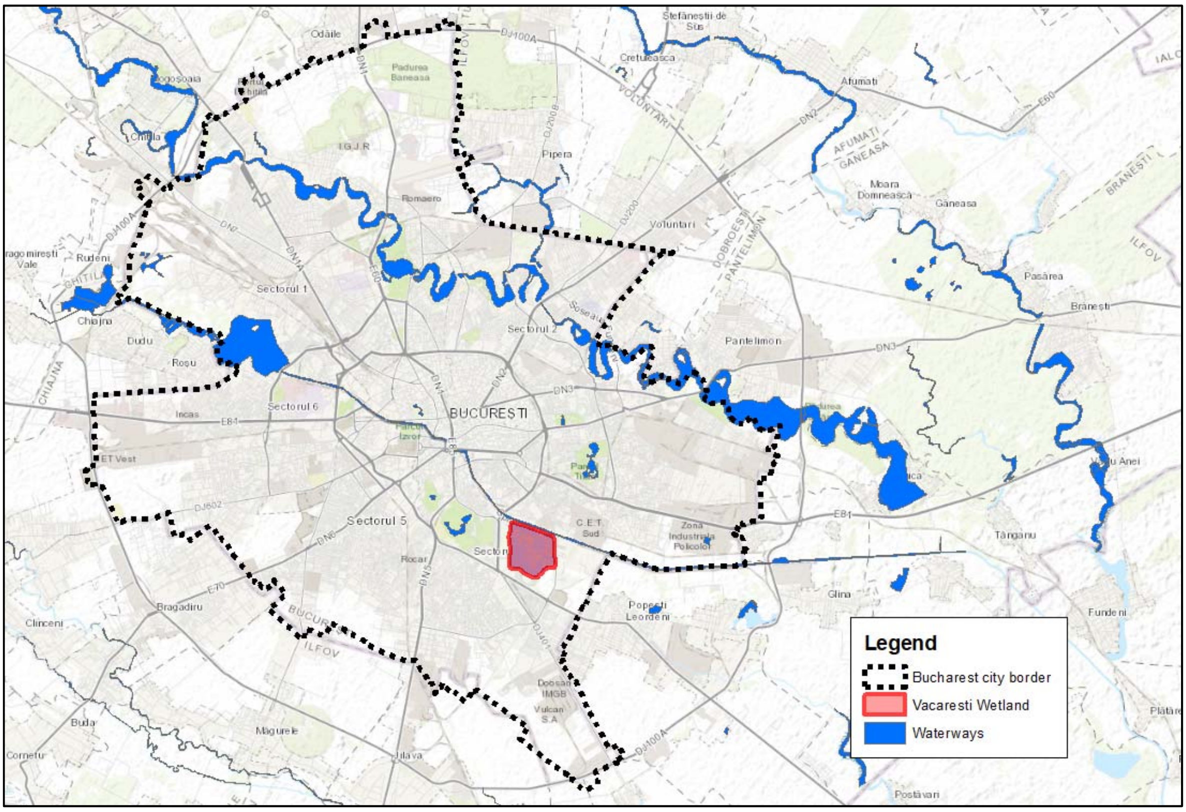

Fig. 1 – Văcărești wetland location on the Bucharest city map

For the commissioning step the reservoir was filled only once with water from Dambovita River. The initial solution consisted in diverting water gravitationally through an open channel from Arges River, 27 km away from Bucharest, from Mihăilești Reservoir.

While in an advance stage of completion, due to the changes in the political regime and the high costs for the remaining investments, the project was abandoned. Therefore without human intervention in the following years Văcărești reservoir was reconquered by nature and wildlife, became a veritable wetland and one of the biggest urban natural parks in Europe.

2.1. Hydrological processes and water budget in Văcărești wetland

The purpose of the hydrological balance is to give a proper understanding and assessment for all the considered water transfer mechanisms. Based on the continuity equation, the water budget represents the difference between the water inputs and outputs over a period of time and it can be expressed by using the following form:

$$I(t) - O(t) = \frac{\Delta S}{\Delta t}$$

where: *I* represents the inputs, *O* the outputs and $\Delta S/\Delta t$ changes in storage.

If the inputs exceed the outputs, a volume of water is stored, which will increase the water volume in the considered area. In this particular case a wetland and vice versa, if the outputs are larger than the inputs, a volume of water is removed through various processes, thus reducing the water volume.

In the studied area, based on a detailed analysis of historical data, it was concluded that the hydrological processes with significant impact on the water budget are the atmosphere exchanges, precipitation and evapotranspiration, and also groundwater exchange. As a result of those processes that occur, the water budget equation can be detailed accordingly to the each parameter:

$$P(t) = \Delta S + ET(t) + D(t)$$

where: P represent the amount of precipitation, ET represents the amount of water lost through evapotranspiration, D the amount of water exchanged with the groundwater being either infiltration or exfiltration and ΔS changes in water storage.

For an accurate assessment of the water budget, in addition to the hydrological mechanisms, the following features need to be defined properly: spatial boundaries, analysis duration and also the quality and quantity of data recordings.

The spatial boundaries were divided in two main categories: the atmosphere exchanges and groundwater exchanges. The catchment for the first phenomenon was assimilated with the limits of the perimeter embankments, because no runoff from adjacent areas can occur due to the 12 m high surrounding dikes, therefore limiting the input fluxes from the atmosphere only on the former reservoir footprint. The boundaries of the groundwater exchange phenomenon were very difficult to determine due to the involved features, such as the geological layers, the effect of Dambovita River, seasonal groundwater level fluctuations etc. To solve this aspect the hydrological model for the city of Bucharest developed by the Groundwater Research Center was used to evaluate groundwater effect [2].

The selection of the water budget period (monthly, seasonal, yearly) is determined depending on the objective of the study and the information required in this purpose. In most cases the precipitation data is recorded daily, while the groundwater level is monthly measured. It is obvious that the existence of long and continuous data recordings can provide the means to analyze the change in the precipitation / temperature patterns and magnitude consequence of the climate changes. Therefore, the assessment period and the time step was determined based on past recording at the nearest meteorological station from the studied area. Given the quantity and quality of the data a six year period analysis was considered, from 2009-2015, which consists in six growing and six non growing seasons with various amounts and patterns of precipitations.

2.1.1 Atmosphere exchanges

The most important natural factors that are in close connection to the water budget are the precipitation and the temperature, used in order to assess the wetland water losses into the atmosphere through evapotranspiration.

Precipitation can take two forms: liquid (rain) and solid (snow). The supplying mechanisms of the wetland are different in both cases, mainly because the contribution of the rain has an almost instantaneous response, compared to the melting snow that represents a slow process which takes at least several days.

In Bucharest area the average multiannual amount of precipitation is approx. 620 mm/year an. To determine the water budget in Văcărești wetland, average daily recorded values of rainfall between 2009 and 2015 were used.

An important step was to determine the daily values for the actual evapotranspiration *(AE)* that takes place in the Văcărești wetland which are lower than potential evapotranspiration *(PE)* due to the fact that during the year the soil is not permanently saturated. Therefore if we consider a permanent saturated state for the soil we can determine the monthly potential evapotranspiration using the following formulas [3]:

- Blaney-Criddle formula:

$$PE = p \cdot (0{,}46\,T + 8) \quad [mm]$$

where: T - average monthly temperature (^{0}C); p - the ratio between the number of daylight hours for the considered month and the total number of daylight hours per year.

- Thornthwaite formula:

$$PE = 16 \cdot N_m \left(\frac{10 \cdot \bar{T}_m}{I}\right)^a \quad [mm]$$

where: Nm - monthly adjustment factor based on daytime hours; $\bar{T}_m$ - average monthly temperature (^{0}C); I - annual caloric index.

Both the formulas take into account the monthly average temperatures for the determination of the potential evapotranspiration. Therefore, to determine the PE for Bucharest the daily average values were used to create a monthly pattern. To confirm the best “fit” / precision of the data, the r^2 coefficient (r squared correlation coefficient) was included between the observed outcomes (temperatures) and the observed predictor values (pattern). The equation for the Pearson product moment correlation coefficient, r, uses the following parameters [4]:

$$r = \frac{\sum(x-\bar{x})\cdot(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\cdot(y-\bar{y})^2}}$$

where: x – represents the observed data (in this case temperatures), y - represent the predicted value using a polynomial 6 order function, $\bar{x}$ and $\bar{y}$ represent the average values of the above mentioned.

The correlation coefficient ranges between 0 and 1 with the following statements:

- if $r^2 \geq 0.5$ significant correlation;
- if $r^2 < 0.5$ poor correlation.

Figure 2 reveals a high correlation coefficient therefore the prediction can be used to determine the average monthly values for the temperature in order to estimate the potential evapotranspiration for Bucharest area using the two formulas.

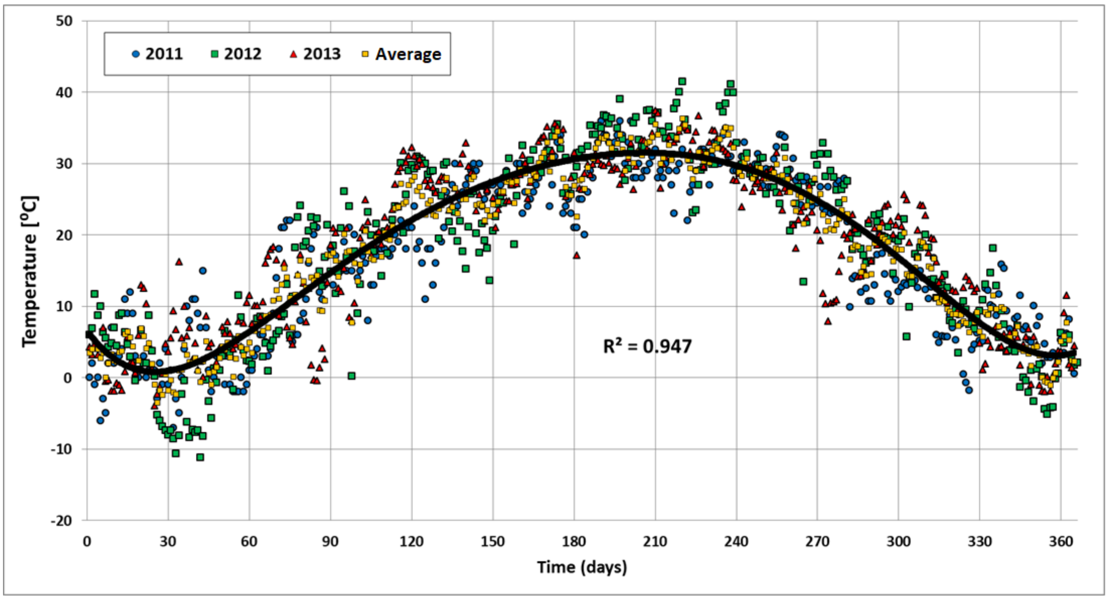

Fig. 2 – Average daily temperatures 2011-2013

Accordingly to the estimated data a value of 505 mm/year has resulted for the PE for Bucharest, using the Blaney-Criddle formula and 515 mm/year using the Thornthwaite formula, with differences of the average monthly values as can be observed in Figure 3.

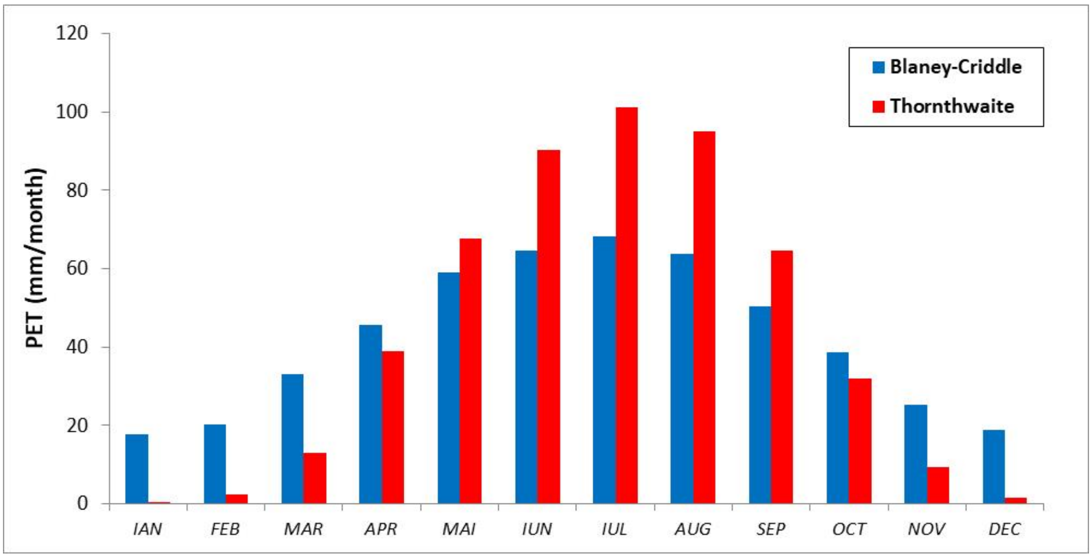

Fig. 3 - Potential evapotranspiration for Bucharest city

2.1.2 Soil Moisture Deficit Model (SMD)

The soil moisture deficit (SMD) can be defined as the amount of precipitations (depth) needed to replenish the soil water content back to field capacity.

Soil Moisture Deficit Model represents a hybrid SMD Model that has been developed in order to consider the differences in drainage rates between different types of soil [5, 6]. It consists of a daily time step water budget method based on the amount of precipitation, actual evapotranspiration and drainage regimes for various soil types: well, moderately or poorly drained.

$$SMD_t = SMD_{t-1} - P + AE + D \quad [mm]$$

where: SMD_t, SMD_{t-1} – are the soil moisture deficits at day *t* and *t-1*; *P* – daily precipitation [mm/day]; *AE* daily actual evapotranspiration [mm/day]; *D* – the amount of water drained daily by percolation and/or surface runoff [mm/day].

It is commonly assumed that the relationship between *AE* and *PE* is linear between a critical *SMD* and the maximum *SMD*. When the value of the current *SMD* is smaller than the critical value then moisture is not limited and *AE* equals *PE*. Therefore for each drainage soil class a critical *SMD* can be defined [5, 6]:

- Well Drained: Soil never saturates, remains at field capacity even on very wet days in winter. Minimum *SMD= 0*. When *SMD > 0 mm AE* is less than *PE*, decreasing linearly to zero when *SMD* is at a theoretical Maximum of 110 mm;
- Moderately Drained: May saturate on wet winter days, but return to Field Capacity on first dry day. Minimum *SMD= -10 mm.* When *SMD > 0 AE* is less than *PE*, decreasing linearly to zero when *SMD* is at a theoretical Maximum of 110 mm;
- Poorly Drained: Saturates on wet winter days, water surplus is drained at very slow rates, in the order of 0.5mm per day. Minimum *SMD= -10mm*. When *SMD > 10mm AE* is less than *PE*, decreasing linearly to zero when *SMD* is at a theoretical Maximum of 110 mm.

Therefore when the *SMD > SMDc* the actual evapotranspiration can be assessed using the following:

$$AE = PE \cdot \frac{SMD_{max} - SMD_{t-1}}{SMD_{max} - SMD_c} \quad [mm]$$

where: the value of *SMCc* for well and moderately drained soils is zero and for poorly drained soils is 10 mm. The value of the SMD_{max} is 110 mm for all three soil types.

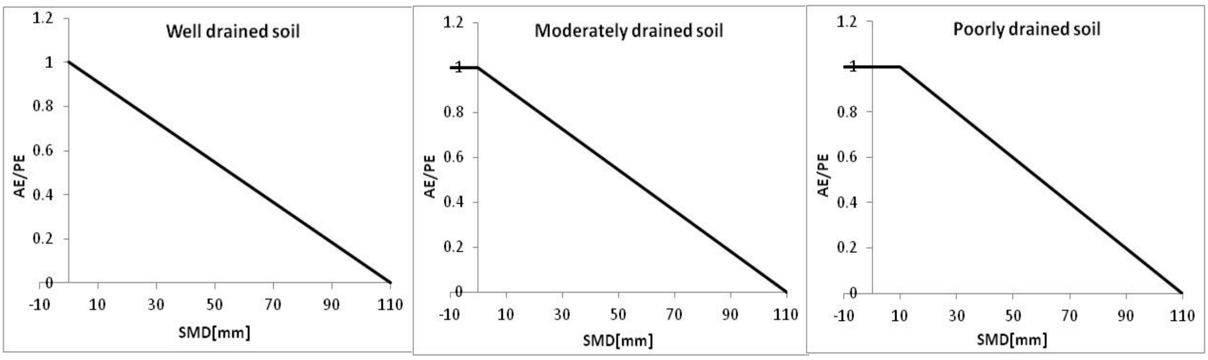

Fig. 4 - AE/PE variation depending on SMD [5, 6]

Due to the fact that the *AE* is difficult to evaluate and because of the small time step and long analysis period, the current *SMD* will be calculated on the basis of the *AE* at a previous time step. Therefore, for the *SMD* model and the water budget estimation an algorithm was created to ease the calculation due to the amount of data to be processed respectively an eight year period analysis. The algorithm consists in a daily time step that evaluates the *SMD* based on the daily amount of precipitation, the groundwater exchanges and, as mentioned, the actual evapotranspiration established at a previous step.

Afterwards the current *AE* is computed from the *SMD* and *PE*, which is applied together with the other hydrological processes that participate in the water budged to determine the storage fluctuations.

2.1.3 Groundwater exchanges

From the engineering point of view, the assessment of the exchange mechanisms between wetlands and groundwater represents a particular case of interaction. In terms of geological layers under the area of Văcărești, The Holocene deposits beneath the area are represent by the alternation of permeable (aquifers) and less permeable strata (aquitards and aquiclude) [2].

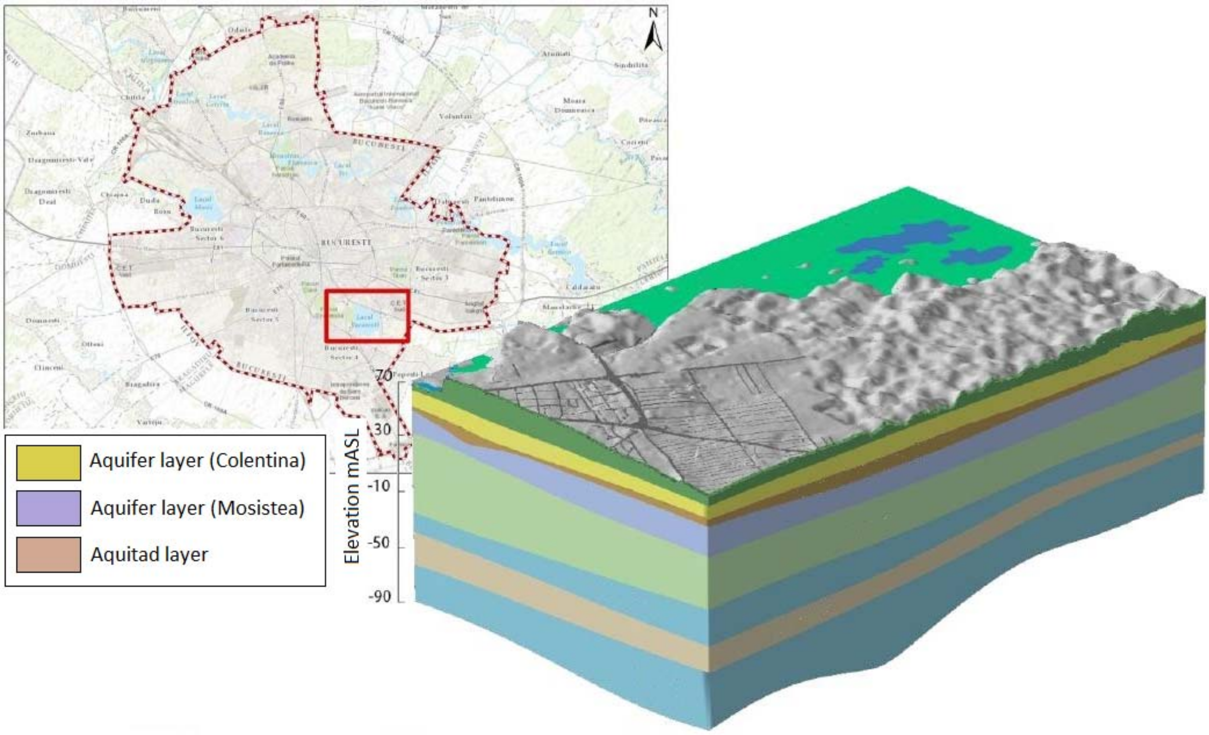

Fig. 5 - Geological structures of Văcărești wetland area [2]

As it can be observed in Figure 6 the hydraulic head of the first aquifer layer is very close or even equal to the ground level (differences less than 0.5 m), thus revealing that the wetland is supplied by groundwater seasonally or all throughout the year. If considering the initial design and construction specifications, this process does not exist due to a uniform layer of clay that was used to reduce the lake water losses, The conceived hydraulic conductivity has been considered 0.5 mm/day creating in an almost impermeable bottom layer.

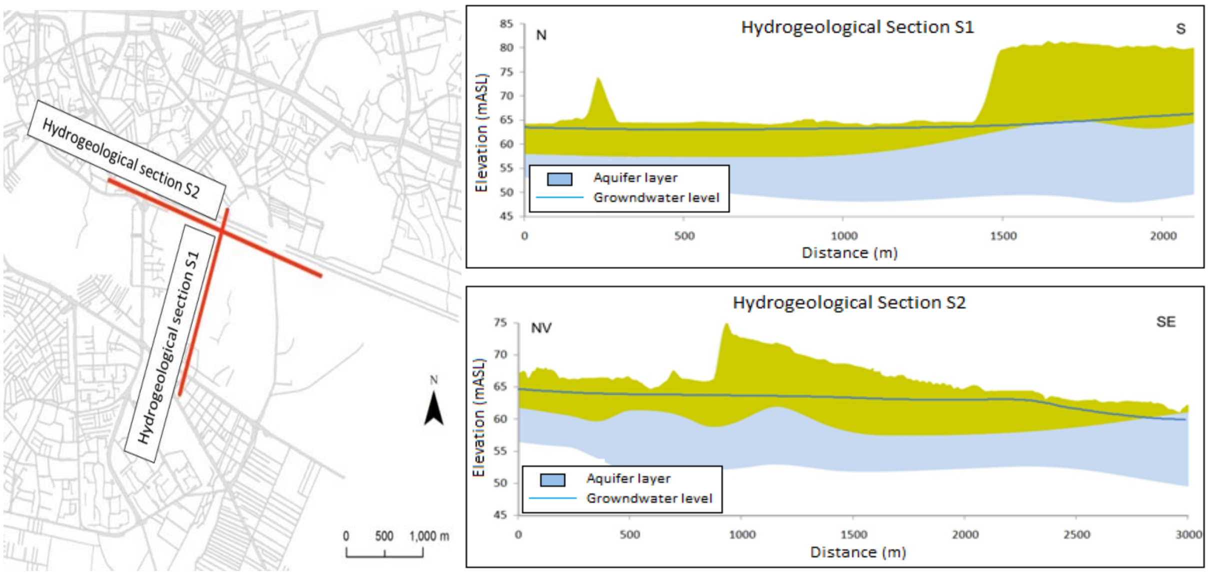

Fig. 6 - Hydrogeological section of Văcărești wetland area [2]

The hydrogeological model developed by the Groundwater Engineering Research Center for the city of Bucharest show, in steady state conditions and under the current stress factors, the groundwater flow nearby the area of interest [2]. The model simulates the groundwater flow corresponding to the current hydraulic head in the wetland (specified head boundary – Dirichlet condition). If the specified hydraulic head is changed then the hydrogeological spectrum will be different.

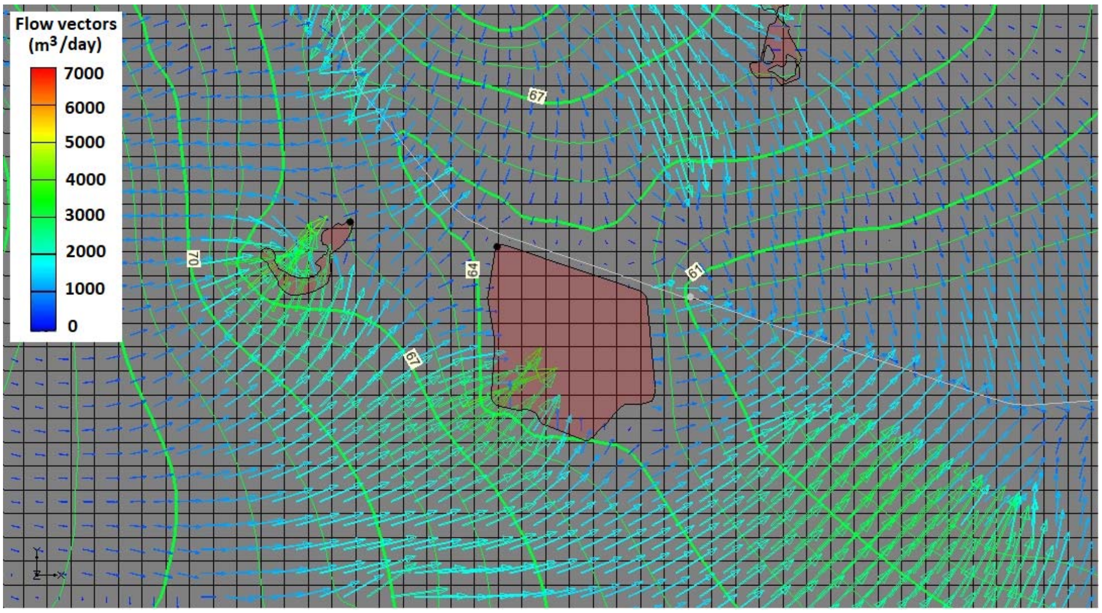

Fig. 7 - Hydrodynamic flow model results for the considered area [2]

The groundwater model strengthens the hypothesis that the exchange exists in both senses: from Colentina aquifer to Văcărești wetland – in the south and west, as well as from Văcărești wetland to Colentina aquifer – on the northern and eastern sides. The velocity vectors (represented by magnitude and direction) highlight the processes of infiltration and percolation (Figure 7). In real conditions (transient regime) the velocity vectors could be different in terms of directions and values.

Field measurements (Hooghoudt tests) were carried out to confirm and establish the hydraulic conductivity of the aquifer. The Hooghoudt test reveals a value of 0.012 cm/second, approx. 10 m/day.

2.1.4 Results

The first step focuses on the determination of the daily actual evapotranspiration using the SMD model based on precipitation data within a perod of 8 years, from 2007-2015. For first 2 years the data was used to calibrate the soil moisture content and the drainage regime which intervene in the daily time step water budget (SMD model). Both graphs of Figure 8 are used to understand the relationship between the monthly AE and PE, PE being determined based on the two formulas: Blaney-Criddle and Thorntwaite. As expected the AE is in dependence with the temperature used to determine the PE and the soil moisture content which is in close connection with the amount of precipitation and groundwater supply.

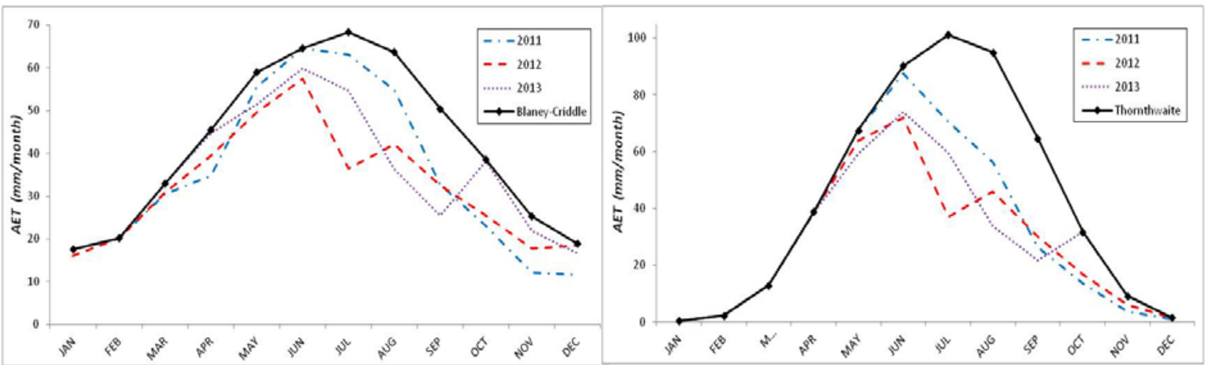

Fig. 8 - Monthly actual evapotranspiration for Văcărești wetland based on the SMD Model

To determine the variation in water storage the digital terrain model (DTM with 2 by 2 m cell size) and satellite imagery for Văcărești wetland were used in various periods over the considered time interval. Practically, for each year two extensions of the ponds inside the wetland were determined: one for the growing season and the other and for non-growing season, in order to properly calculate the water volume variation (Figure 9).

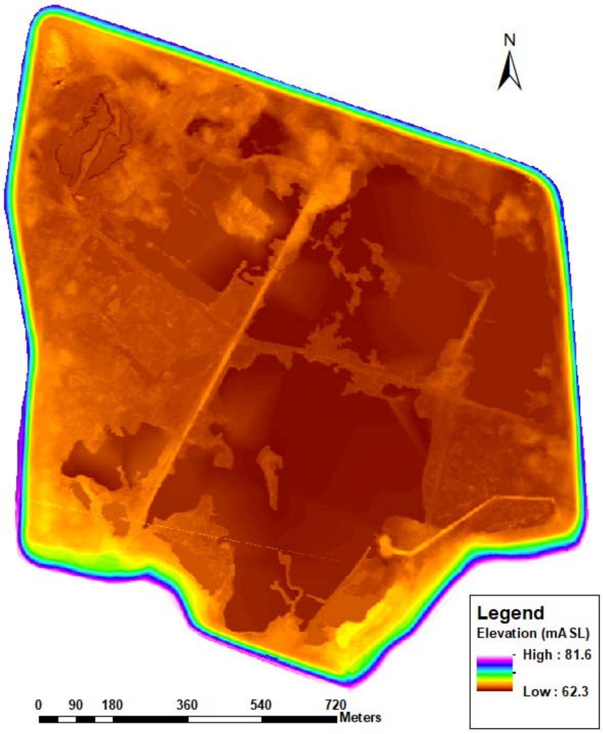

Fig. 9 - DTM of Văcărești wetland

The first scenario taken into consideration consisted in the following hydrological analysis steps: introduce the measured daily precipitation and establish the actual evapotranspiration with the *SMD* model and a constant drainage rate of 0.5 mm/day for a uniform and flawless bottom layer of clay. If we considered the mentioned above processes, the volume of water determined in the wetland will gradually increase one year after another, due to the fact that the yearly amount of water is significant higher than the combined effect of the loss processes (actual evapotranspiration and drainage rate). Although this is a very benefic, this assumption is not valid due to the very high water volume fluctuations that actually occur in the wetland (in the last decade during growing season many ponds were drained). This leads to the presumption that the bottom layer that helps contain the water is not completely impervious.

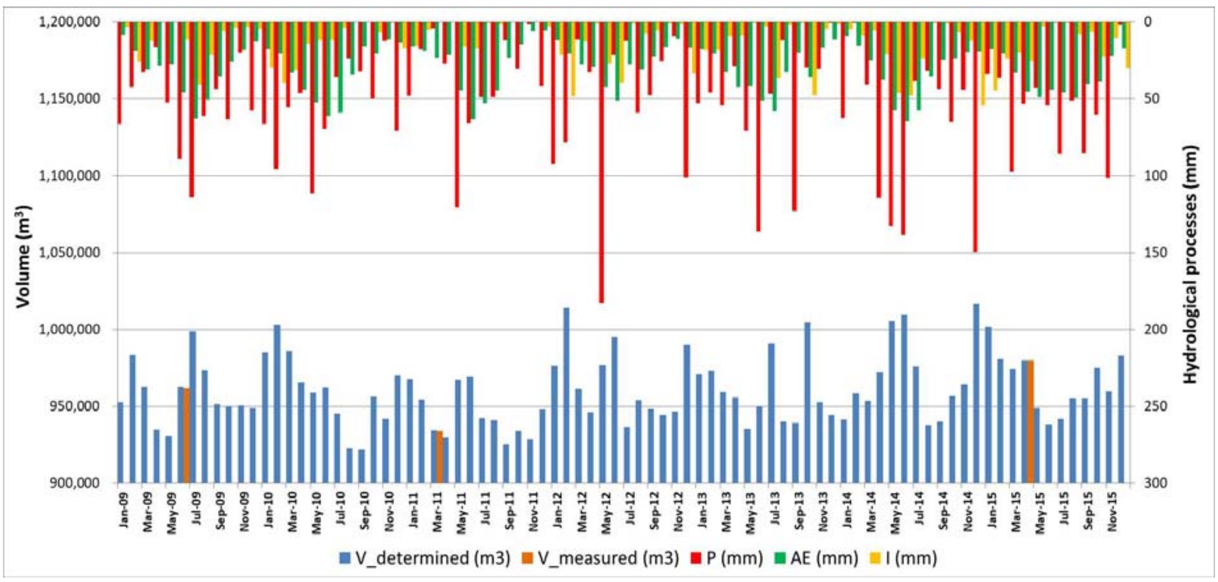

Fig. 10 - Water budget for Văcărești wetland between 2009 – 2015

The second scenario has been built based on (1) the results from the regional groundwater flow model developed by the Groundwater Engineering Research Center and the superposition of (2) a minim contact surface between the surface water and groundwater. After applying this assumption into the water budget equations, the water volumes and storage fluctuations confirm the connection between the two zones and the estimated values for the actual evapotranspiration (Figure 10).

2.2. Proposed scenarios

In the context of future threats which can affect the services the wetlands are offering and also for the protection of the existing ecosystem, based on the created algorithm, a couple of scenarios have been concluded in order to assess the future water storage fluctuations in Văcărești wetland.

The first scenario consist on the overall temperature increase by +1.5^{O}C due to the climate change and also due to the heat island effect which is present in crowded urban areas. This will increase the potential evapotranspiration and in consequence triggering a faster soil water depletion.

Another major concern is represented by the intensive construction activity that takes place in the nearby area which can have a significant impact on the water flow magnitude, therefore decreasing the supplying of the wetland from the groundwater. This scenario will assume a 20% decrease of the groundwater inflow.

The temperature variation will increase the potential evapotranspiration estimation with 4% (from 505 mm/year to 526 mm/year) when using Blaney-Criddle and with 12% (516 mm/year to 579 mm/year) when using Thornthwaite (Figure 11).

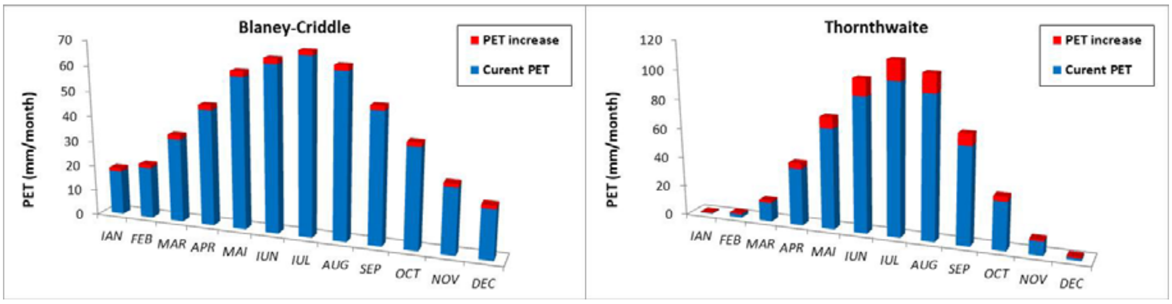

Fig. 11 – Increase of PET due to the average monthly temperature increase with +1.5OC

The control period will be made for the year 2016 and 2017 where the daily average precipitations are known from measured data. Therefore this will be established using results obtained with the current situation and with those proposed in the scenarios mentioned above.

As expected the temperature increase will affect directly the actual evapotranspiration, thus reducing the storage of water in the wetland. As it can be observed in Figure 12 the *AE* that occurs will lead to the water loss of approx. 27 000 cubic meters in the two years used for comparison (10 500 in 2016 and 16 500 in 2017).

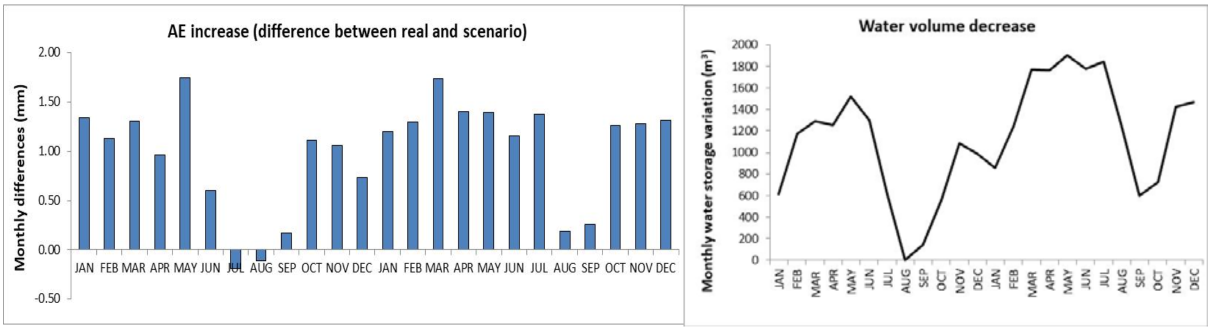

Fig. 12 – AE and water volume variation for a temperature increase of +1.5^{O}C

The computed data reveals that a minor increase of temperature will cause a significant volume loss. In addition, a long period of drought will amplify the effects of this presumed change.

In the second scenario major changes can be observed in the water storage. The reduction of the groundwater flows with 20% will cause an average decrease of approximatively 300 000 cubic meters of water in the wetland (Figure 13). As shown in the graph below the decrease of water exchange takes place during the growing season (during the period with the highest temperature) which can endanger the ecosystem.

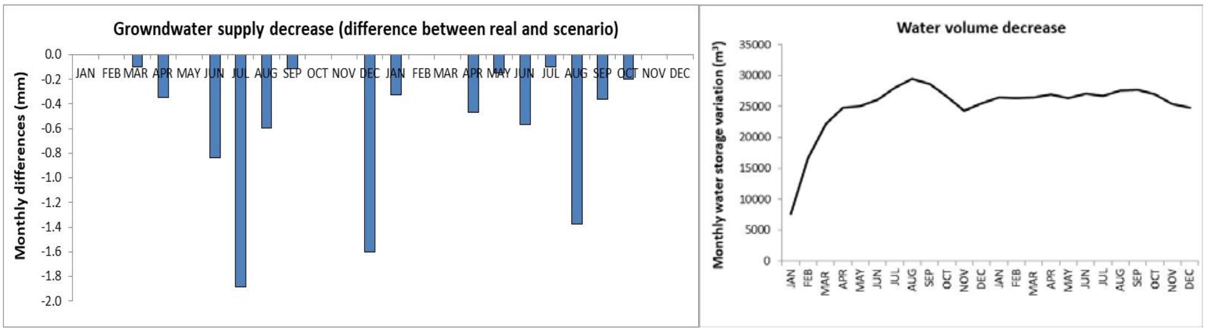

Fig. 13 – Exfiltration and water volume variation for 20% supply decrease

If consider the superposition of the effects and also future changes of analyzed pattern and period of the precipitations, the results can produce devastating consequences for the wetland.

4. Conclusion

The case study confirms that the water exchanges of the wetland with the groundwater are taking place in both senses, with a benefic action for the wetland which is supplied through multiple hydrological processes. This also reveals the presence of openings and/or cracks in the clayey coating layer presumed to be uniform, which could have been developed over time due to inadequate execution.

The *AE* reaches values close to the *PE* during the non-growing seasons. This can be explained by the fact that the soil moisture is permanently saturated in this period and after that the extended periods between rain events and high temperatures during the growing season cause strong evapotranspiration and water depletion in the soil.

Despite the fact that the wetland is in direct connection to the groundwater and supplied in certain periods, of the year, the effects of the extended meteorological droughts can lead to a decrease of the hydraulic head, thus suspending the wetland recharge produced by the groundwater. This effect is magnified by the intensive building process which is taking place around the wetland, activity that modifies the groundwater flow paths and consequently changes the boundary conditions (hydrological budget), due to the presence of deep foundations..

To prevent the extinction of the wetlands, particularly those located in an urban environment which are subjected to future threats or in an advance state of deterioration, solutions need to be adopted in order to monitor / rebuild / restore these areas.

In the past decade Bucharest was greatly affected by the urbanization phenomenon.The manner that the adjacent districts increased their impervious surface has overwhelmed the existing sewage system. A solution that needs to be taken into consideration for Văcărești wetland, consists in supplying the ponds with treated rainwater collected from the adjacent areas by a storm water system (or a rainwater harvesting system) that will help preserve the ecosystem and prevent the deterioration/extinction, as a consequence of the new imposed conditions.

Developing alternatives for the reconstruction of the wetland represent a permanent challenge, which must be based on the periodically establishment of the hydrological budget and a continuous monitoring of the targeted area.

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