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PhD Thesis

CONTRIBUTIONS TO WETLAND RECONSTRUCTION AND ADJACENT ECOSYSTEMS

– Summary –

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BUCUREȘTI
2020

CONTENT

1. INTRODUCTION

Considering the extreme rainfall events occured in the last decades, which led to big floods and heavy damages (e.g. 2005, 2006, 2010, 2012, 2014), but also intensive concerns regarding environmental protection and the need for ecological friendly projects, the use of wetlands as a sustainable solution for water management inside the catchments and landscape improvement becomes more and more urgent.

Ecological engineering is defined as *„design of sustainable ecosystems, which should integrate civil society and environment, for the benefit of both"* (Mitsch & Jorgensen, 2003). Only by using the combination between ecological engineering and classical civil engineering principles we could find and deploy optimal and sustainable solutions, through which we could achieve higher protection level for the population and support next generations with sustainable ecosystems.

Ecological reconstuction of wetlands represents the sum of all actions taken to achieve general lines of restoration in terms of natural conditions (untainted) or those conditions existing up to a certain moment in time, related to the soil, hydrology, vegetation, habitat of the wetland.

Wetland development implies changes of wetland conditions in order to increase some processes for vegetation diversification or to intensify its rate of develpment.

Design of new wetlands represents contruction over an area that previously was not a wetland.

Ecological reconstruction of wetlands should be seen, first of all, as an adaptation measure to climate change and to human actions on the environment. Some examples of such actions are: levees, deforestation, land use changes, gravel and sand pits, increase of impervious urban areas, etc. Additionally, the guidelines of Water Frame Directive (2000/60/EC) regarding the flood risk management plans, could be achieved through ecological reconstruction and design of new wetlands by applying the concept „**more space for rivers**". Moreover, economical value of wetlands should be considered, not only related to water resources, but also to aquatic life, vegetation (biodiversity) and cultural heritage.

The research project was aimed to highlight the current stage of research at international level regarding wetlands and to emphasize best practices through which ecological reconstruction projects are conducted, focusing on hydrology – water balance, assuming that hydrology is the key component for the wetland ecosystem.

2. LEGISLATIVE FRAMEWORK

2.1. Ramsar Convention

Romania joined in 1991 at the *Convention on Wetlands of International Importance* through the **Law no. 5/1991**, known as **RAMSAR Convention** [1]. The scope of this international treaty is to preserve biodiversity and resources of wetlands, thus representing a tool through which sustainable development could be achieved. The Convention's mission is *„the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world”* (Ramsar Convention, 2014).

2.2. European Directives applied to wetlands

Directive on the protection of groundwater against pollution and deterioration, **2006/118/EC**, transposed into the Romanian legislation through the Governamental Decision no. 53/2009 regarding the approval of the national plan for groundwater protection against pollution and deterioration.

Council Directive on the conservation of natural habitats and of wild fauna and flora, **92/43/EEC**, is aimed to preserve natural habitats, wild fauna and vegetation through the design of Special Conservation Areas, which need to be maintained or restored so that „*favorable conservation status”* will be achieved.

Council Directive 79/409/EEC on the conservation of wild birds.

3. VALUES AND FUNCTIONS OF WETLANDS

Wetlands represents the complex interaction between water, soil, topography, micro-organisms, vegetation and animals, making from wetlands one of the most productive ecosystems on Earth (Barbier, Acreman, & Knowler, 1997).

Wetlands provide, case-by-case, some high-value benefits such as: fish, wood, raw materials, wildlife, the most fertile soil for agriculture, water supply, navigation, peat. These resources could be exploited directly (food resources, wood, peat) or can be used indirectly (groundwater recharge, flood protection), while others are highly appreciated only for their mere existence without exploiting them (biodiversity, cultural heritage).

Regarding the functions that wetlands provide, dominant functions can be identified on a case-by-case basis in relation with the type of wetland, its components, interactions with

[1] *Convenția Ramsar este un tratat interguvernamental prin care se oferă cadrul național de acțiune și cadrul internațional de cooperare în vederea conservării și utilizării inteligente a zonelor umede și a resurselor acestora. (Ramsar Convention, 2014). Tratatul a fost adoptat în anul 1971, în orașul iranian Ramsar (care dă și denumirea Convenției).*

environment. The function of the wetland means a process that it performs and which is measurable by one or more variables. The main functions that a wetland can provide are:

- **Control;**
- **Storm protection;**
- **Groundwater recharge;**
- **Sediment and pollutants retention;**
- **Nutrient retention;**
- **Evaporation;**
- **Conservation.**

4. DESCRIPTION AND CLASSIFICATION OF WETLANDS

In order to achieve a proper hydrological description of wetlands it is necessary to define three essential variables:

- water level;
- hydroperiod;
- retention time.

5. ECOLOGIAL RECONSTRUCTION

According to the definition given by the Society for Ecological Restoration (1996) „ecological restoration is the process to restore and manage the ecological integrity of an ecosystem. Ecological integrity includes biodiversity, ecological processes, regional structures, historical context and sustainable cultural practices”.

Projects related to ecological reconstruction of wetlands require multidisciplinary knowledge such as enigeering, bilogy, geology, chemistry and others. Determining the hydrogeomorphological conditions is the key objective, based on which the ecological reconstruction project is developed. Depending on the identified hydrogeomorphological conditions, the alternatives regarding the ecological reconstruction can be developed, from which the one considered optimal according to established criteria is chosen.

5.1. Processes related to wetlands

Physical processes through which wetland's functions are controlled are: geomorphological conditions, dominant water source and hydrodynamics. Knowledge of these three factors is essential for understanding the behavior of a wetland.

Chemical processes that occur in wetlands can usually target oxidation-reduction reactions, nitrogen, phosphorus, iron and manganese, sulfur, carbon and salinity.

Biological processes that take place in wetlands are associated with microbial activity, vegetation and animals. These processes play a key role in regulating the functions that the wetland provides.

5.2. Wetland Design

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6. MATHEMATICAL MODELLING OF WATER FLOW

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Finite Difference Method

Finite Element Method

6.2. Surface water flow

6.2.1. Wetland interaction with surface water

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6.2.3. Flow in open channels

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6.2.6. Flow in pressurized pipes

7. WATER BALANCE OF WETLANDS

Main components of water balance for a wetland are represented in Figure 44, together with the notes and direction of water flow (recharge and discharge).

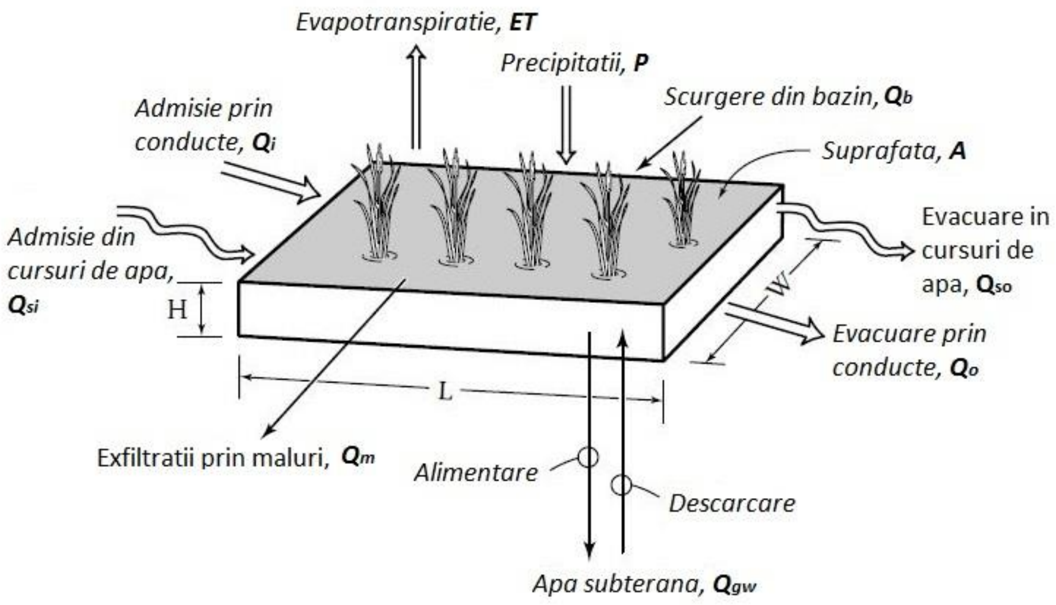

Figura 1. Components of water balance for a wetland
(*Kadlec & Wallace, 2009*)

The concept could be mathematically summarized as:

$$dQ = I - E = \frac{dV}{dt}$$

where: dQ is the difference between inlet (I) and outlet (E) , dV is the difference of volume storage into the wetland in time step dt.

Explaining inlets and outlets, it could be obtained:

$$Q_i - Q_o + Q_c - Q_b - Q_{gw} + Q_{sm} + (P \cdot A) - (ET \cdot A) = \frac{dV}{dt}$$

în care:

- A = wetland Area [m^2];
- ET = Evapotranspiration [m/day];
- P = Precipitation/Rainfall [m/day];
- Q_b = Discharge through the Banks [m^3/day];
- Q_c = Inlet from the Catchment [m^3/day];
- Q_{gw} = infiltration / exfiltration from/to groundwater [m^3/day];
- Q_i = Inlet from the sewage / drainage system [m^3/day];
- Q_o = Outlet to the sewage system [m^3/day];
- Q_{sm} = inlet from snowmelt [m^3/day];
- t = Time [days];
- V = Volume of water stored into the wetland [m^3].

The water level changes over time into the wetland could be described mathematically as follows:

$$dh = \frac{dV}{A} = \frac{dQ}{A} dt$$

where:

- dh is the water level change in the wetland ;
- $dV = dQ \cdot dt$ is the volume change;
- $dQ = I - E$ is the difference between inflows and outflows into the wetland;
- dt is the time step;
- A is the wetland area coresponding to a unit volume change.

7.1. Exchange with athmosphere

Exchanges between wetlands and the atmosphere occur in both directions. From the atmosphere to the wetland by precipitation or losses from the wetland to the atmosphere by evapotranspiration.

Precipitation can take two forms**:** liquid (**rainfall**) and solid (**snow**). The mechanism by which the wetland is fed in the two cases is different. The input of rain has almost instantaneous effects compared to the snowmelt, the latter being a slow process that takes place at least over few days.

Evapotranspiration (ET) represents the sum of two natural processes: evaporation – from the surface of water and soil (E); transpiration (T) – on the surface of plants.

In order to determine actual evapotranspiration (ET_r) from a catchment / area, it is recommended to start with the calculation of the potential evapotranspiration $\left(ET_p\right)$, considering that there is an unlimited water availability (saturated conditions). Further, (ET_p) calculated initially is adjusted according to the soil moisture / water content. To calculate (ET_p) several relations have been developed, based on theoretical or empirical models (Karlsson & Pomade, 2013). Below, some of them are mention, withaout detailing them[2]:

- **Penman** equation – it results based on the formula that provides estimation of evaporation from the water surface:

$$ET_p = \left(\frac{\Delta}{\Delta + \gamma}\right) \cdot Q_{ET} + \left(\frac{\gamma}{\Delta + \gamma}\right) \cdot Q_{ET} \quad [mm/day]$$

- **Thornthwaite** formula – it is based mainly on temperature adjusted with daylight hours. ET_p calculation is done for each month as follows:

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

- **Turc** formula – it was developed for agricultural needs, by extending empirical the method for actual evapotranspiration for obtaining potential evapotranspiration for a short time period:

$$ET_p = \frac{P + a + 70}{\left[1 + \left(\frac{P+a}{L} + \frac{70}{2L}\right)^2\right]^{0,5}} \quad [mm]$$

- **Blaney-Criddle** formula – it needs only the mean of montly temperatures and the ratio between daylight hours for a certain month and the number of total daylight hours over an year:

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

The Soil Moisture Deficit Model (SMD) represents a model that have been developed to count for different drainage rates for types of soil and also for previous moisture / water content of soil:

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

where: *SMD_t, SMD_{t-1} – represents humidity deficit at day t, respectively at day t-1 (mm);*
P – daily rainfall (mm/day);
ETR – actual daily evapotranspiration (mm/day);
D – daily drainage due to infiltration and/or surface runoff (mm/day).

[2] *additional information could be found into the bibliography (Karlsson & Pomade, 2013)*

7.2. Exchange with groundwater

7.3. Exchange with surface water

Exchanges between surface water and wetlands or in a different way wetland recharge and discharge , could occur due to:

- Runoff;
- Open channel flow;
- Flow over weirs;
- Flow in pipes;
- Combinations between previous mechanisms.

8. CASE STUDY (VĂCĂREȘTI LAKE)

8.1. History of the area and its actual condition

Văcărești wetland is located in the south area of Bucharest and it represents currently one of the most varied urban ecosystems in Romania. Hidrologically, it represents a part of floodplain of Dambovita river (**Figure 2**), being frequently flooded before the works for channel regulation had started in the 19th century.

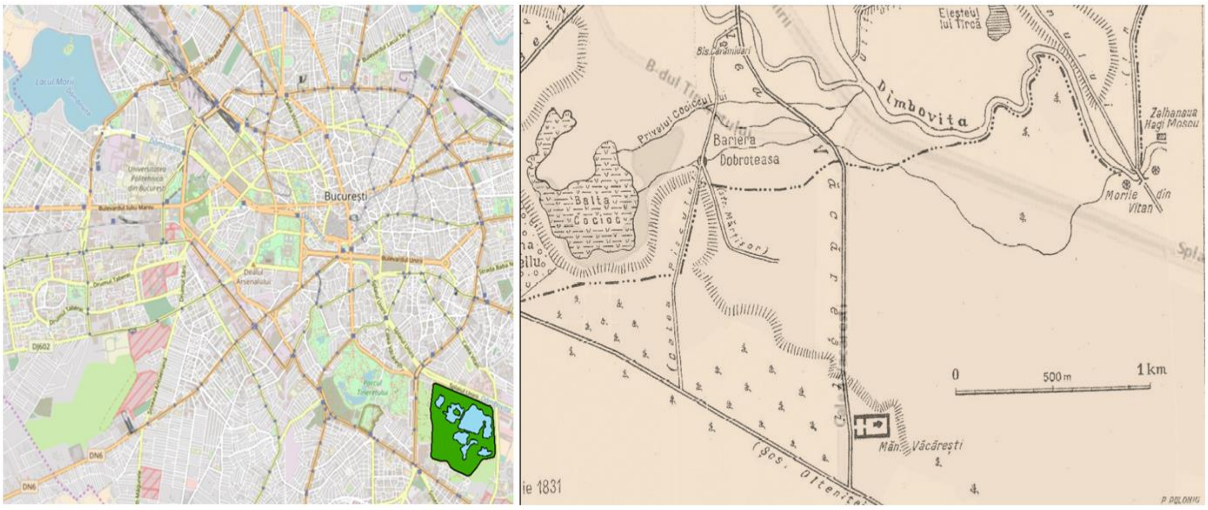

Figure 23. Current location of Vacaresti in Bucharest and its location based on map from 1831

A complex project for water management was conducted in Bucharest between 1980-1990. This involved, among others, the construction of two reservoirs, Morii Lake (finished and operational) and Văcărești Lake (almost finished but unfunctional). Each of them has a volume of over 10 milion of cubic meters and their mainly function was to prevent the city against floods. Văcărești Lake is currently an unfinished hydraulic structure.

The construction works for Văcărești Lake started in 1986 and were stopped after december 1989. The reservoir is made by dikes on 3 edges from 4 existing (excepting the southern edge which has a higher terrain elevation) and has an area of about 163 hectares (2,3 km length and 2,0 km width) and with average height of about 10 meters.

On 13th november 1989 Văcărești lake was filled with water pumped from Dâmbovița river and commissioned (although works would have continued after the commissiong). The country's leadership at that time participated at the opening ceremony by inspecting the hydraulic structure from the crest. Filling the reservoir from Dambovita river was a temporary solution because the flow rate was too low and also ehe enerfy costs were very high. Once the supply from Dambovita was stopped, the lake empied quickly, in few months due to high exfiltration rate.

In the initial project design, the lake was supplied from Arges river, through a channel with a length of around 27 km. In 1990 the channel was built from the intake till the discharge into Vacaresti excepting 5 km located inside Bucharest area. The lake supply could be achieved through a pumping station, located on east side of the lake. The works for the channel were stopped after 1990 and after abandoned because of lack of funds.

Based on the information gathered from the experts involved in the execution phase, the sealing screen is realised on the entire perimeter of the levee. The drainage system is also bulit entirely but from the 3 pumping stations only one was working, because the other 2 were not equipped. The pumping stations had to collect and discharge exfiltrations back to Vacaresti lake (see **Figure 3**).

Figure 3. Plan view of lake Văcărești: drainage system

Currently no pumping station of the drainage system is working. The drainage system from the west and north edges discharge water to the sewage system and the one located on the east edge discharge water to Dambovita river by gravity. The drainage system is currently clogged up to 80-90% of its cross-section area. Unfortunately, no as-built plans / documents were found in order to obtain more precise data on what was built exactly.

After the end of comunist political regime and due to high cost related to remaining necessary investment, the project was abandoned and thus, the nature reclaimed the lake area during the following years becaming a veritable wetland and one of biggest parks in urban area in Europe.

8.2. Assessment of water balance components

8.2.1. Exchange with atmosphere

Exchanges with the atmosphere are in close correlation with some natural factors such as precipitation regime and temperature, in order to assess the water losses from the wetland due to evapotranspiration.

Rainfall

Average annual rainfall depth for Bucharest is 620 mm/year, but for a more precise calculation of water balance, daily rainfall depths between 2005-2015 were used. Rainfall data were recorded at Filaret meteorological station, nearby downtown of Bucharest and 2 km nearby Vacaresti wetland.

Table 1. Average and maximum monthly rainfall depth (mm) in Buchare, at Filaret meteorological station (*Administrația Națională de Meteorologie, 2013*)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Monthly Average	30.2	33.7	38.3	44.3	68.6	82.3	60	51.6	43.2	43.3	46.2	42.9
Maximum monthly	132.3	121.1	127.9	159.2	259.7	259.5	212	182.9	316.5	143.3	206.6	184.6

Evapotranspiration

"Evapotranspiration depends on soil moisture and thermoenergetical conditions. Actual evapotranspiration has lower values than potential evapotranspiration because the soil in not continously saturated" (I.Ujvari, 1972).

In order to determine more precisely the actual evapotranspiration from Vacaresti lake, additional daily measurements are needed (through the installation of an evaporimeter) because such data are not available at this moment. In the same time, soil moisture should pe monitored during the same period of time.

Becuse during a one year period the soil is not continuously saturated, Soil Moisture Deficit model has been used. Soil moisture deficit is determined based on daily precipitation (P), Drainage rate (D) and potential evapotranspiration (ETP).

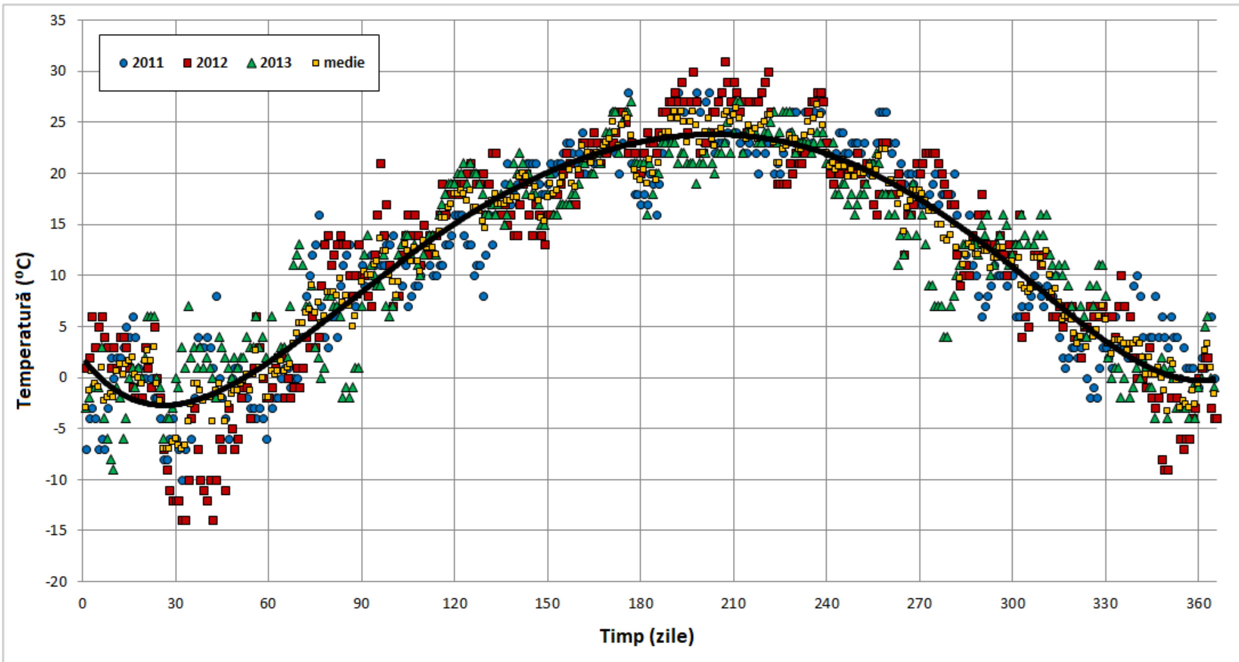

Figure 4. Mean daily temperatures between 2011-2013

Based on existing dat and according to Blaney – Criddle formula and Thornthwaite formula, the values for evapotranspiration obtained werw 505 mm/year, respectively 515 mm/year. As it could be seen in (**Figure 5**)., some differences between monthly evapotranspiration values could be noted.

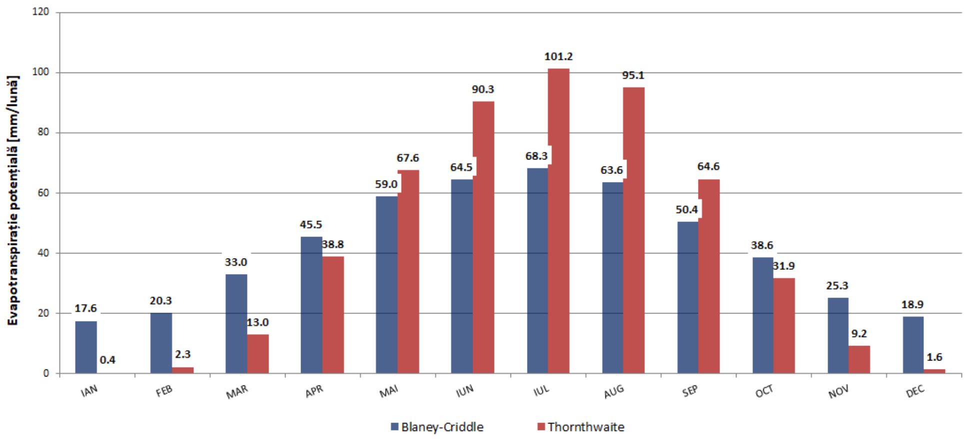

Figure 5. Monthly evapotranspiration values according to Blaney-Criddle and Thornthwaite formulas

Determining actual evapotranspiration using SMD model has been done by using precipitation measurements between 2005-2015, from which the first 2 yeaers were used to calibrate the model, and more precisely to calibrate the soil moisture and drainage rate, which impacts water balance.

Actual evpotranspiration is difficult to assess and it could be determined more precisily using field measurements (evaporimeters). Considering that the analysis period is long and the time step is small, soil moisture at moment t will be calculated based on evapotranspiration at a previous moment (t-1). Because of large amount of data that should be processed, a dedicated spreadsheet for calculation was built. The calculation method is based on soil moisture deficit model which assess the soil moisture deficit at moment t, based on daily precipitation, groundwater exchanges and evapotranspiration at moment t-1.Afterwards, actual evapotranspiration is calculated based on potential evapotranspiration and soil moisture deficit which is applied to the other hydrological processes which contributes to the water balance for the wetland in order to determine storage/volume variations.

In **Figure 6** actual and potential evapotranspiration were calculated for Vacaresti wetland considering soil moisture deficit model. As it could be seen, actual evapotranspiration depends on temperature, soil moisture, precipitation and exchanges with groundwater.

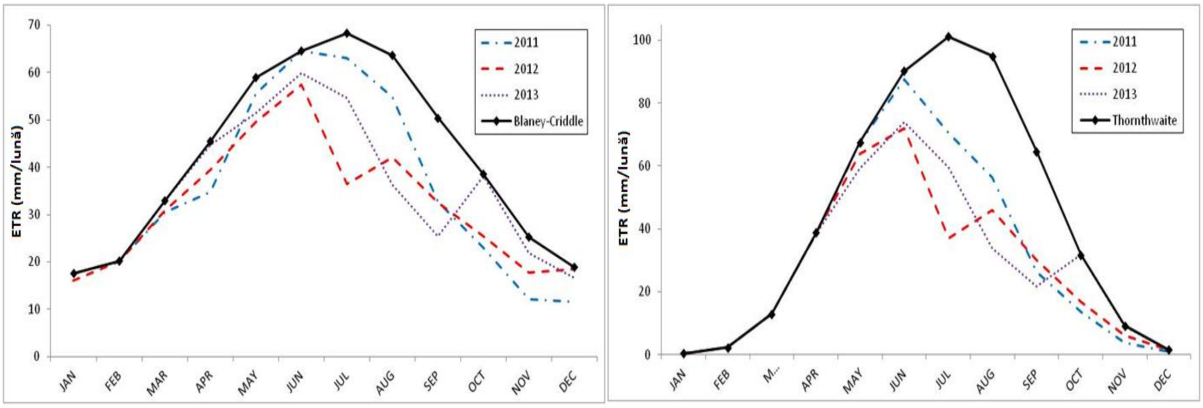

Figure 6. Actual monthly evapotranspiration for Vacaresti wetland using SMD model

8.2.2. Exchanges with groundwater

Geological layers that compose the underground enivronment of Bucharest in general, and particulary of Vacaresti area, are presented in **Figure 7**.

Starting from the ground level, a sequence of pervious and impervious layers could be observed. The aquifers are (from top to bottom):

- Colentina layer;
- Mostiștea layer;
- Frătești A layer;
- Frătești B layer.

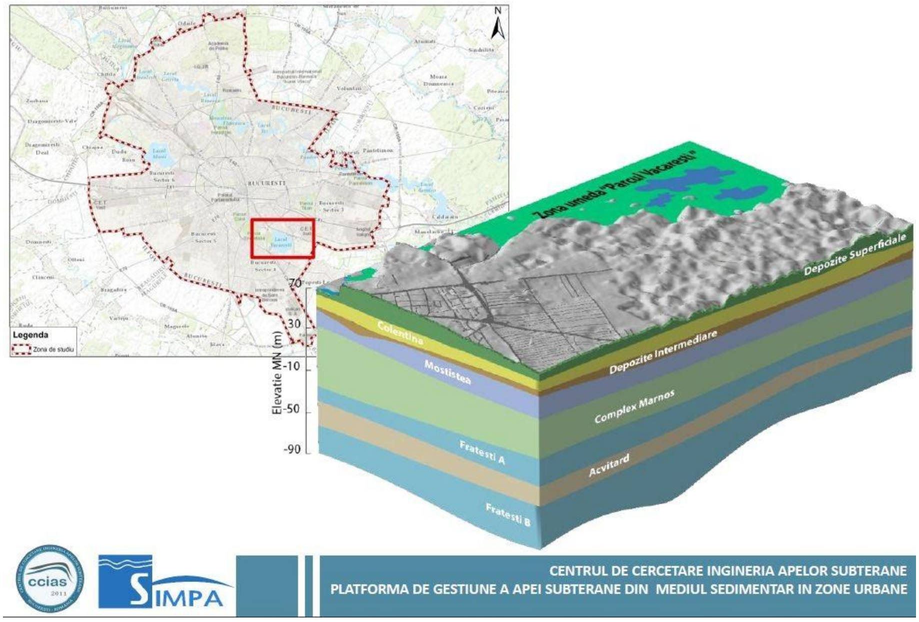

Figure 7. Geological layers at Văcărești area
(*Centrul de Cercetare Ingineria Apelor Subterane, 2013*)

For the analysis done in present case study, the first two aquifers are important/significant. Fratesti layers, deep aquifers, are not considered relevant. Based on studies conducted by Groundwater Research Center (CCIAS – Plaform for groundwater management in sedimentary environment in urban areas) it has been observed that piezometric head in Colentina layer is almost the same with the one of Mostistea. These two layers are directly connected in some areas (intermediary deposits are missing) and many other connections exist due to the high number of boreholes/wells realised through this two layers.

In order to highlight the connection between groundwater and Vacaresti lake, the piezometric head in these two layers is considered equal. In **Figura 8** two relevant cross sections on the study area are presented, together with the piezomtric head.

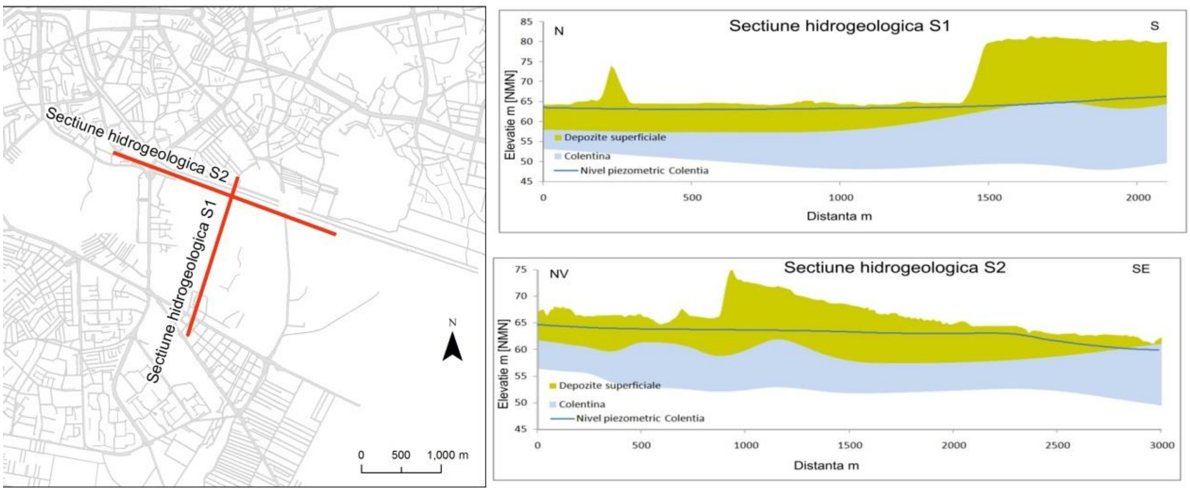

Figura 8. Hydrogeolocial cross sections in Văcărești area
(*Centrul de Cercetare Ingineria Apelor Subterane, 2013*)

It could be observed that the piezometric head is very close to the ground elevantion (differences are less than 0,5 meters) and also that in some areas it is equal with the ground elevation. Thus indicates that groundwater is recharging the wetland. The minimum differences could be observed at the base of the terrace, where springs occur, and where it is recommended to collect groundwater through a drainage pipe or through a open channel.

Using the hidrogeological model developed by CCIAS for Bucharest area, and assuming a steady state motion and a fixed head as a boundary condition (corresponding to the water level in the lake), the groundwater flow spectrum was obtained (**Figure 9**).

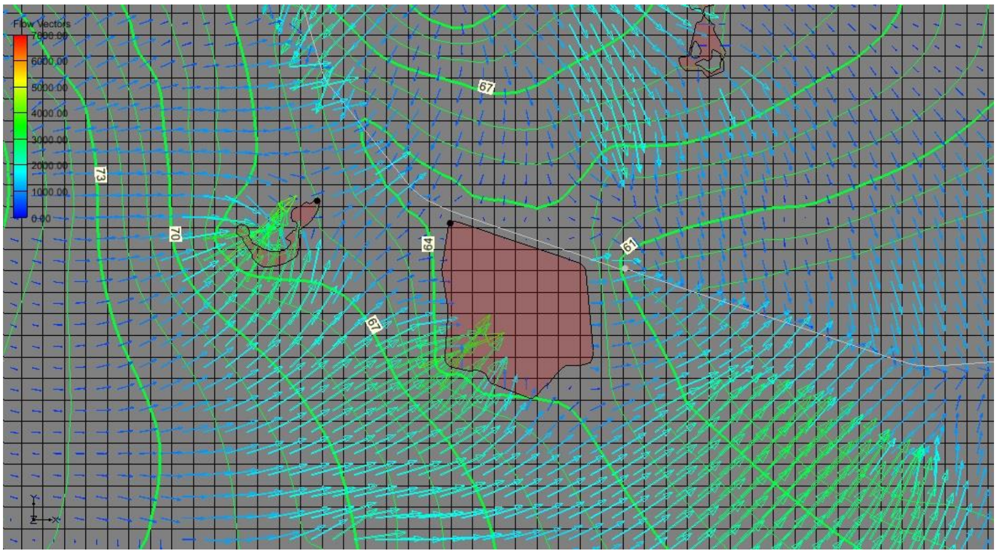

Figure 9. Groundwater flow spectrum in Vacaresti area in current conditions (*sursă: Centrul de Cercetare Ingineria Apelor Subterane, 2013*)

In order to obtain a better understanding of exchange mechanisms and to have a more precise assessment of flow exchanges with groundwater (especially the variability over an year) it is recommended to use monthly measurements of groundwater level / piezometric head in the wells nearby the lake. In the same time, field tests were conducted in order to determine vertical conductivity for superficial deposits (Houghoudt tests), to have a proper assessment of infiltration rate from the lake.

On the other hand, it is recommended to run simulations using a local-scale model which should contain also the drainage system of the lake under its actual conditions (regarding the clogging conditions). The local model will be useful to determine the effects of the drainage system rehabilitation works.

Based on the results from the model, it was concluded that both type of connections occur between the lake and groundwater. On the south and west edges of the lake, groundwater supply the lake and on the north and east edges, the lake recharge the aquifers. Also, it could be noted the infiltration intensity is different, according to the vectors symbology in the map.

For the water balance calculations the following conditions for interaction between the surface water and groundwater were used:

- According to the intial data of the project, all lake area was covered with a clay layer in order to reduce exfiltrations (small hydraulic conductivity 0.5 mm/day);
- Hooghoudt field tests conducted revealed that below the surface clay layer there is a layer with high hydraulic conductivity, of about 0,012 cm/s, cca. 10 m/zi.

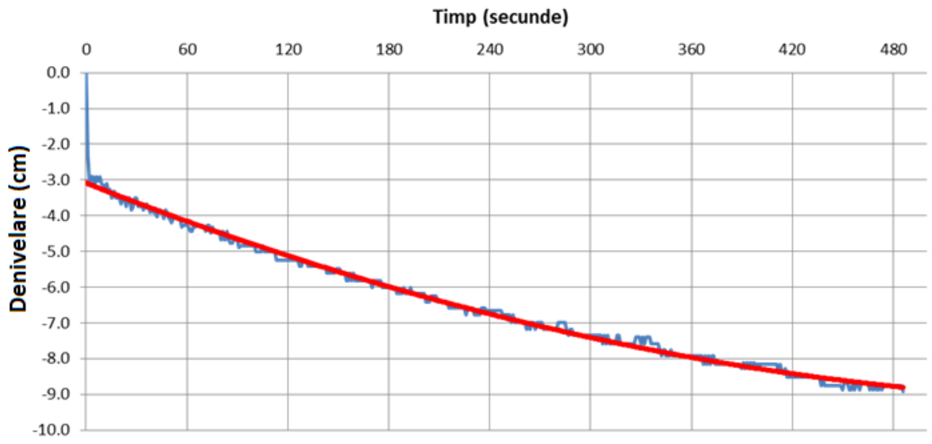

Figure 10. Field measurements using Hooghoudt tests to determine hydraulic conductivity of permeable layer in the study area

8.3. Calculation of water balance in actual conditions

Digital Terrain Model (cell size 2x2 m) could be seen in **Figure 11** together with the capacity curve of the lake (relation between stored volume and water surface level. Because the DTM was realised during a period when some pools were present inside the lake without batimetry additional measurements, sattelite imagery has been used starting with 2000 till present in order to determine more precisely the volume of depression areas inside the lake. Practically, considering the availabilty of sattelite imagery for each year, the surface covered with water was determined for the dry and wet season respectively for a more precise calculation of the volume variation.

Model calibration has been done according to groundwater exchanges scenarios, because it is the only compomenent of the water balance that present significant variations.

Thus, for the first scenario the following hydrological processes were considered: daily measured precipitation, actual evapotranspiration using SMD model and a constant drainage rate of 0,5 mm/day (assuming that the clay layer is continous over the full lake area according to the design project). In this scenario, inlets into the wetland are higher than oulets from the wetland, concluding that there is a continous increase of the water storage in the lake. Thus, the assumptions considered for the first scenario do NOT confirm field observation, concluding that the impervious clay layer is not continuous, and it presents direct contact areas between aquifer and surface water and/or cracks (preferred communication channel between groundwater and surface water).

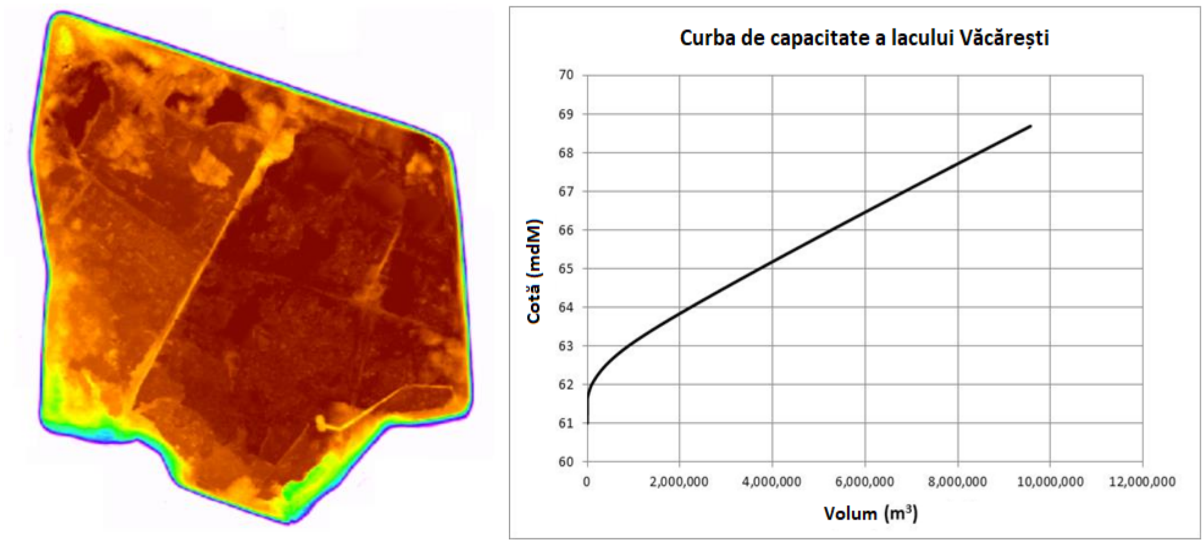

Figure 11. Digital Terrain Model and capacity curve of Vacaresti lake

The second scenario has been built based on results from hydrogeological model and considering a minimum contact area between surface water and groundwater. Using this assumptions it has been observed that the volume and water level variations confirm the connection between surface water and groundwater and also the values for actual evapotranspiration (**Error! Reference source not found.** / **Figure 12**).

Table 2. Water balance for Vacaresti wetland betweeen 2009 - 2015

Water Balance for Văcărești wetland							
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
P (mm)	659	668	466	672	629	861	703
ETR (mm)	364	382	333	306	379	389	423
I (mm)	132	166	58	200	150	232	195
E (mm)	-41	-59	-92	-39	-43	-35	-25

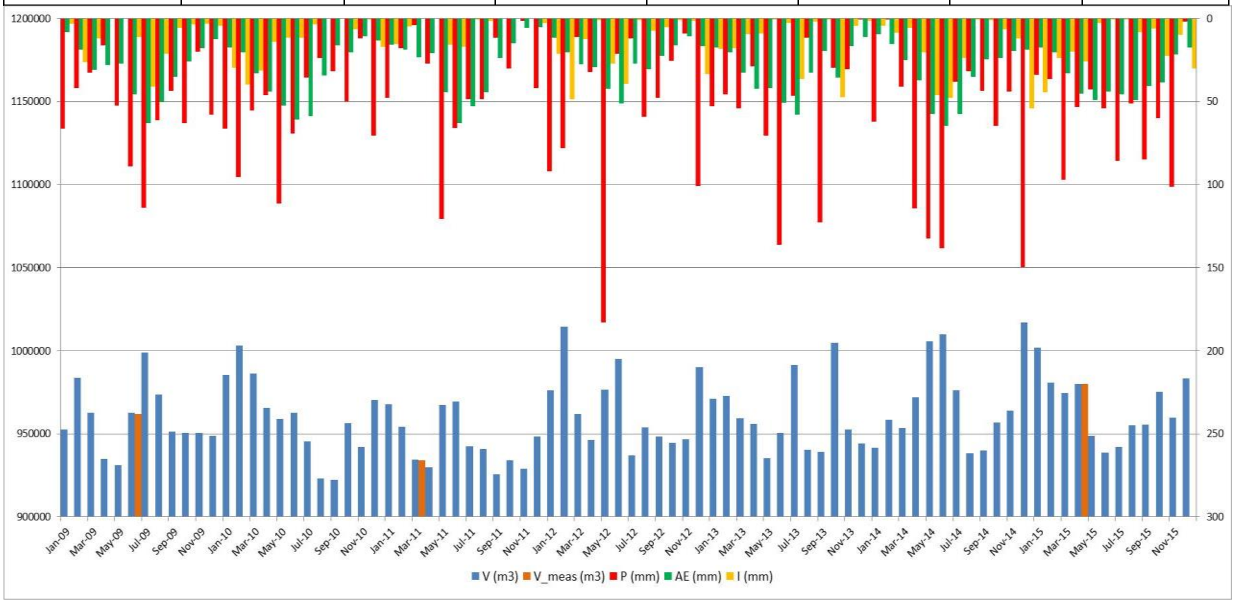

Figure 12. Water balance for Vacaresti wetland betweeen 2009 - 2015

8.4. Simulation of water balance calculation considering future threats

Considering future threats that could impact the services provided by the wetland and to protect existing ecosystem, two other scenarios were developed in order to assess the impact over the volume stored in Vacaresti area.

First scenario is defined based on climate change impact in general, but also more specific on urban areas – thermal island (*Bojariu și colaboratorii 2015*), considering an increase of average temperature of +1,5ºC. This hypothesis will impact both potential and actual evapotranspiration and will lead to an increase of water consumption from the wetland.

The second scenario is based on construction phenomena that occurs in the nearby area of the wetland and which could have a significant impact over the flow rates between wetland and groundwater, thus resulting a lower recharge rate of the wetland from the groundwater. In the second scenario a reduction with 20% of the recharge rate from groundwater was considered.

For these two scenarios related to future threats, the analysis was done for 2016 and 2017, for which the precipitation are known (recorded at Filaret meteorological station). The comparison was done between the current condition and future condition according to each scenario.

In **Figure 13** it could be observed that the temperature increase with +1,5ºC will lead to an increase of potential evapotranspiration with 4% in case of Blaney-Criddle formula and 12% according to Thornthwaite formula.

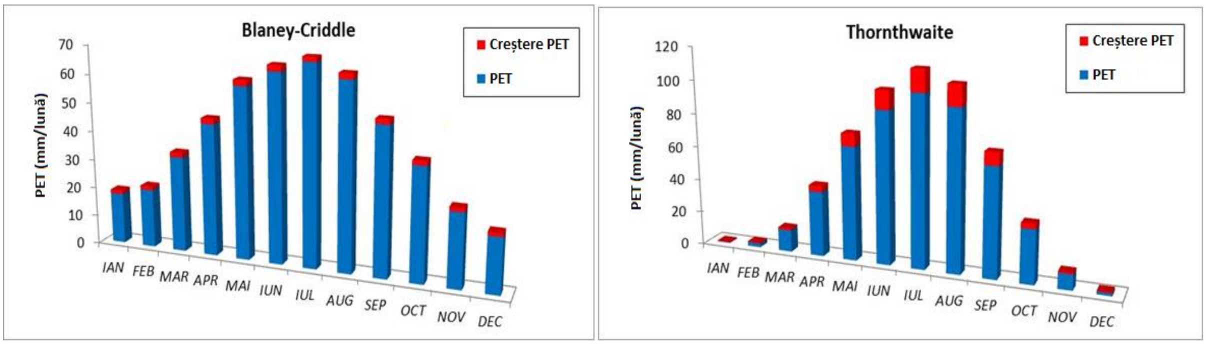

Figure 13. Changes of potential evapotranspiration considering an increase of average temperature with 1,5^{O}C

The results from first scenario indicates that an increase of water losses into the atmosphere of 27 000 m^3 due to increase of actual evapotranspiration (**Figure 14**). From the computations that have been done results that the water storage into the wetland will decrease significantly. Beacuse of climate changes, the dry periods will be higher as a frequency but also as magnitude and could lead to the disparition of the existing pools and also the adjacent ecosystem.

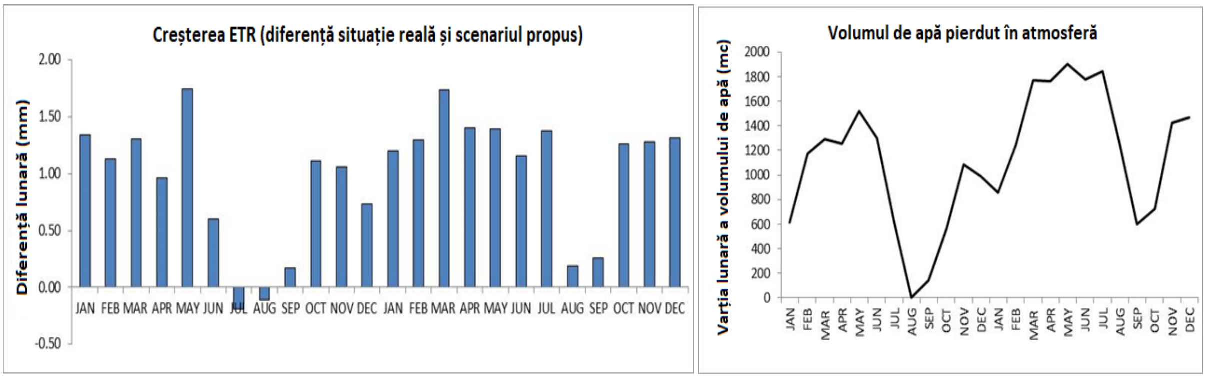

Figure 14. Actual evapotranspiration and water losses due to increase of average temperature with 1,5^{O}C

In the second scneario, major changes of the volume of water stored into the wetland could be observed. By reducing the rate of wetland recharge from groundwater with 20%, a significant decrease of about 300 000 m^3 of volume stored could be observed during the analysis period. In **Figure 15** it could be observed that the reduction of wetland recharge rate occurs mainly during the hot season when the vegetation is growing, thus threatening the existing ecosystem

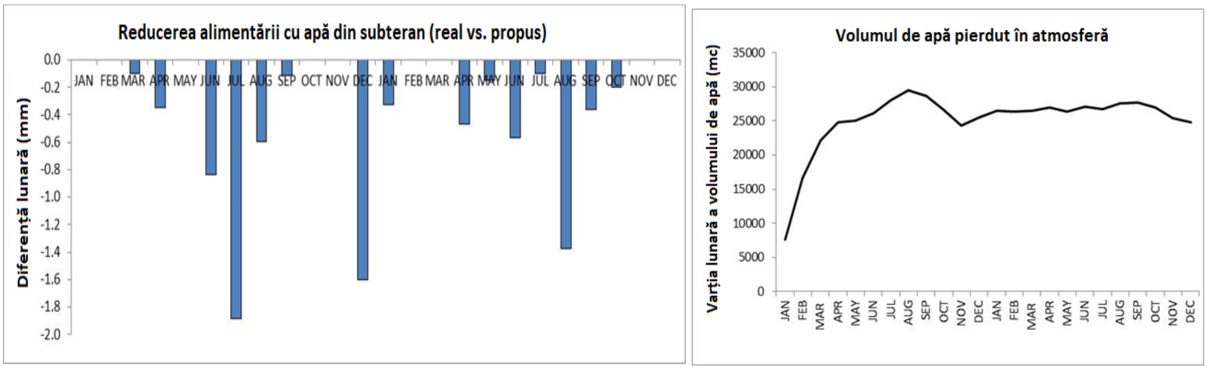

Figure 15. Exfiltration from the wetland and monthly reduction of the wetland recharge from groundwater

After running and combining the impact from the scenarios related to future threats, it could be concluded that the hydrological balance of the wetland will be highly changed and will lead to disappearence of existing pools and adjacent ecosystem inside the wetland.

8.5. Solutions for wetland recharge

8.5.1. Interaction with the sewage system

Văcărești lake is crossed from south to north by a street, under which an abandoned sewage collector is located (**Figure 16** and **Figure 17**). The path of the collector has been changed when the construction works for the lake started and the segment that is crossing the lake was abandoned.

Figure 16. Path of abandoned A3 collector inside Vacaresti lake
(*swww.google.ro/maps*)

Figure 17. Photos from the field with the top of abandoned collector

Main collector A3 (Dn = 350 cm) is collecting both wastewater and rainwater from the southern area of Bucharest, crossing the city from west to east and serving an area of about 4700 hectares (**Figure 18**).

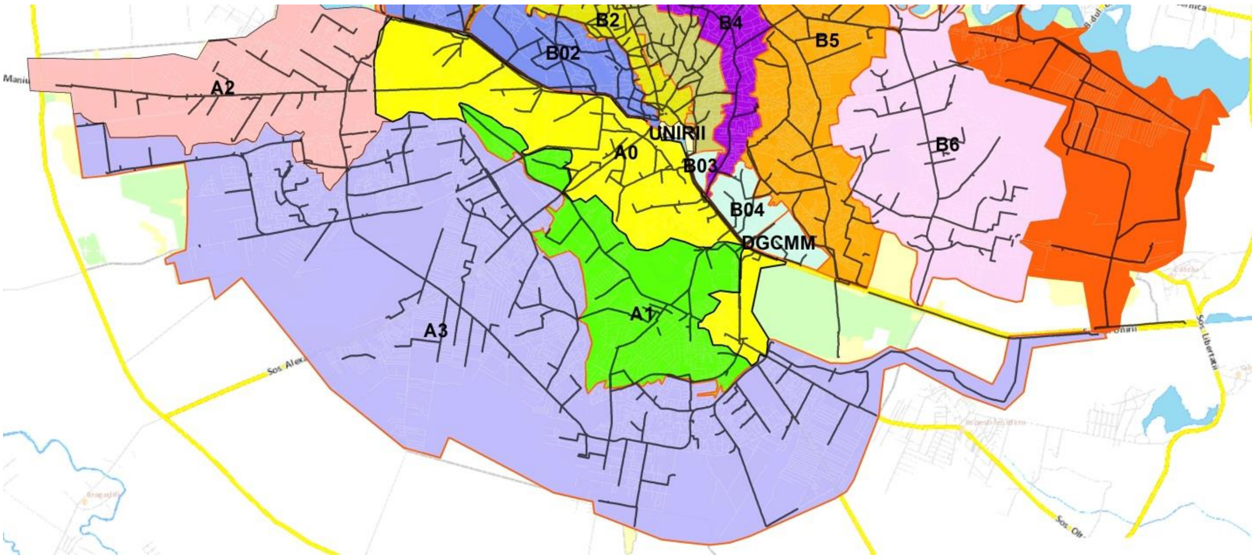

Figure 18. Map with main collectors basins in the southern area of Bucharest

The path of A3 collector has been changed at the end of Lunca Bârzești street (in **Figure 19** current path could be observed), where a large chamber exist (aprox. h x L x w = 6 x 10 x 5 m). Currently, the collector has 90º elbow in the camera and its slope is incresing in the downstream side. Based on operational data, during dry wather conditions water level is at 80 cm in the upstream side and at 30 cm in the downstream side of the chamber. This status generates some issues in the upstream of the chamber related to flow conditions, especially during intense rainfall events, when surcharging of the collector occurs and some areas in the catchment are flooded.

Dry wheather flow in the collector is up yo 2 m^3/s. During rainfall events it could reach over 30 m^3/s. In the **Figure 20** flow measurements from october 2013 at the discharge point are presented.

Flow rate corresponding to a dilution ratio of 1:5 has the value of 12 m^3/s. Consequently, a CSO (Combined Sewer Overflow) should be functional at flow rater over than 12 m^3/s, in order to provide proper environmental protection .

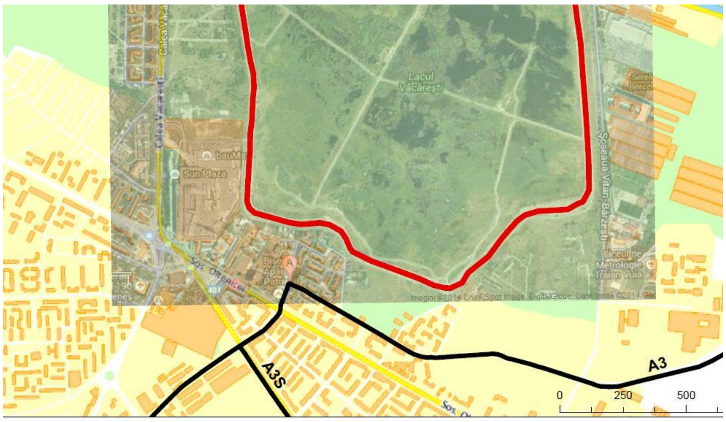

Figure 19. Current path of A3 collector nearby lake Vacaresti

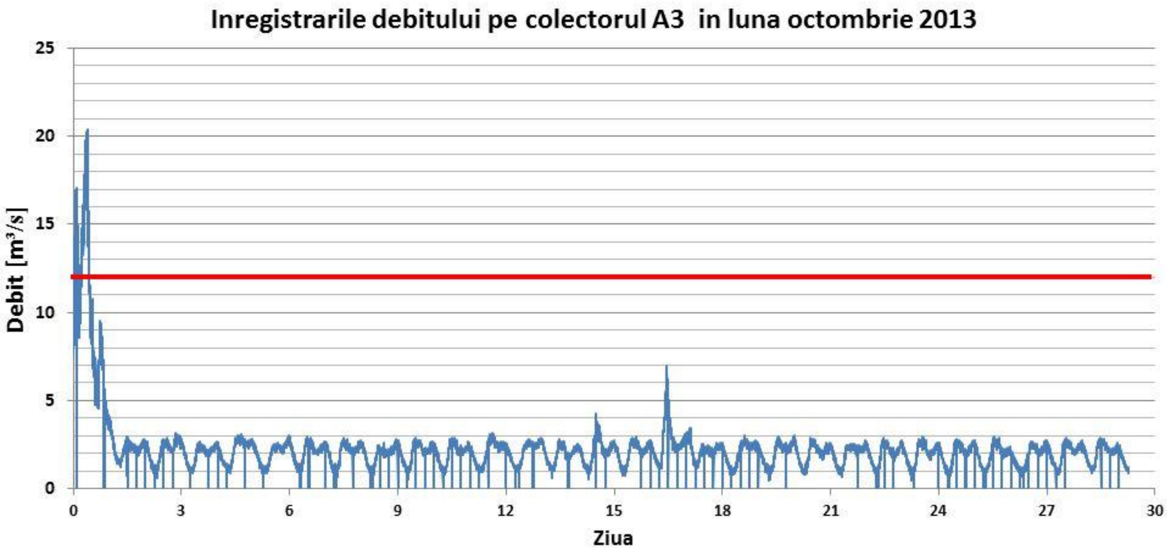

Figure 20. Flow rate in A3 collector during october 2013, at the discharge point (source: *Apa Nova București*)

Using the sewage network model of Bucharest (which contains only collectors – **Figure 21**, detailed in study area – **Figure 22**) it has been followed to highlight which areas are sensitive to flood events due to surcharge of A3 collector, as well as the impact that a CSO to Vacaresti lake could have. Several simulation had been done for different design rainfall events (5 years return period, 10 years return period) but also for 2 histical rainfall events recorded in the last years (without the rainfall event from 30.09-1.10.2013, which was used for calibration).

Figure 21. Sewage network model for Bucharest
(*source: Apa Nova București*)

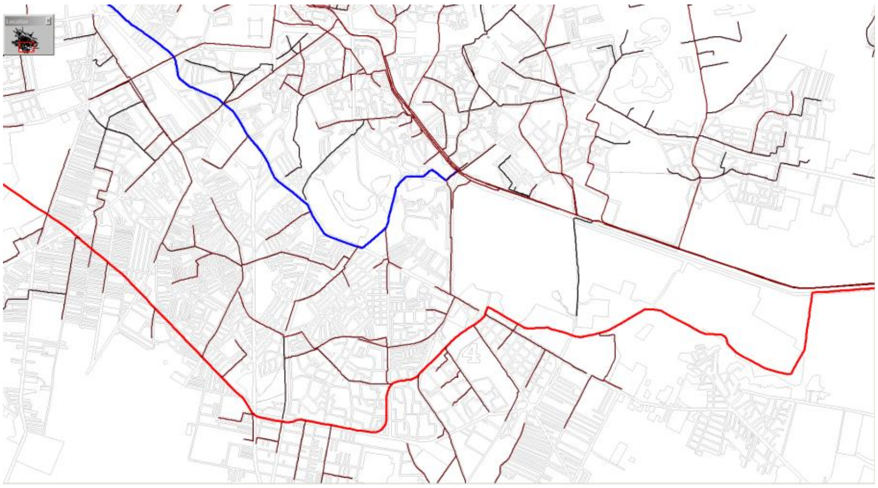

Figure 22. Sewage network model for Bucharest. Deatil from sudy area
(*source: Apa Nova București*)

It could be concluded that in current network configuration, at all rainflall events, there are issues due to surcharge of A3 collector, in both upstream and downstream sides. In the same time all secondary collectors that discharge in A3 collector have the same issues.

In case of historical rainfall events analysed, the sewage system is surcharged but there is not a risk for flood occuring on the collector. On the other hand, the tributary collectors to A3 are facing issues due to low discharge capacity available during the events on A3 collector.

It should be noted that the historical rainfall events analyzed led to floods and that could not be remarked on the simulations did, because several changes were done to the system between the simulated conditions and the real one at the moment when evens occured, such as: cleaning of large collectors, end of discharge points, removal of large blockages from the main sewage collector. It could be concluded that if that events will occur again, the impact would be much more lowerâ due to imporvements done on the sewage system components.

In the second phase, the elevation of weir crest was determined according to the dilution condition described previously. It was found out that water depth likned with a flow rate of 12 m3/s is 2,15 meters on the upstream side of the elbow. Thus, the weir crest elevation should be set up at 68,60 mMN. The invert level of Vacaresti lake is 63,55 mMN which allows a discharge by gravity into the lake, considering also all necessary space for installations for mechanical treatment.

Comparing the results from each scenario (with CSO and without CSO), it is concluded that significant improvements could be achieved, especially during intense rainfall events (maximum flow rates on A3 collector on the upstream side of the CSO are presented in **Table 3**). Piezometric head is reduced a lot on the downstream side of the CSO, leading to free surface level conditions up to the discharge point of A3 collector and on the upstream side the positive significamt effects (reduction of piezometric head) could be observed on a length of 2000 meters and lower but still positive effects on a length of 4000 meters more. In the same time, a significant improvement of hydraulic capacity was observed on tributary collectors to A3, that discharge close to the CSO.

Table 3. Increse of hydraulic capacity of discharge from A3 collector. Comparison between current and proposed solutions

Rainfall event	**Maximum flow rate [m^3/s]**		**% Increase of maximum flow rate**
	Current conditions	**Scenario with CSO**	
1:5	30,96	38,00	23%
1:10	33,90	43,30	28%
19-21.09.2005	27,12	31,53	16%
30.06-1.07.2013	27,88	33,09	19%

Moreover, according to Master Plan of Bucharest, some connections between collectors are planned to be realized between A2 and A3 collector and also between A1 and A3. Their objective is to derive water from the central area to outside city's area. Because of these works, the loads on A3 collector will be higher, especially nearby Vacaresti area.

In order to quantify potential annual volume from A3 collector to Vacaresti lake it will be considered that A3 collector represents 30% from total flow rate in Caseta, where continous flow rate recordings exist.

Applying an iterative process, the relation between total flow rate transported by A3 collector and discharge rate in Vacaresti lake was determined. Thus, the correlation from **Figure 23** was obtained.

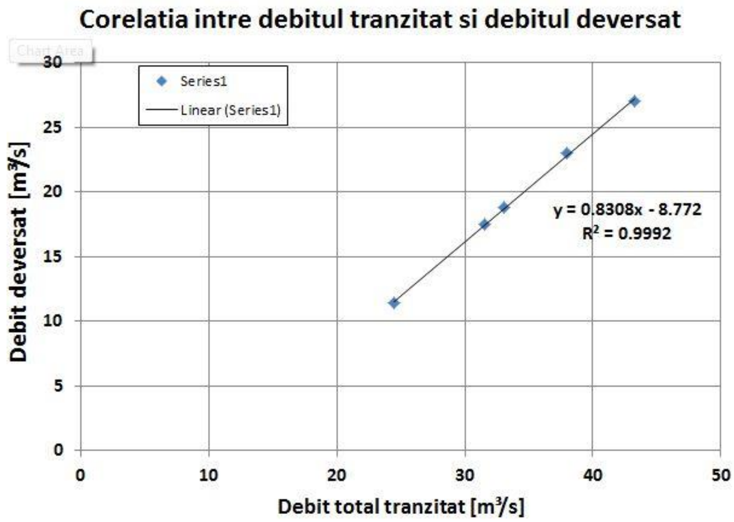

Figure 23. Correlation between total flow transported by A3 collector and discharge rate in Vacaresti lake

Observing a very good correlation between the two variables ($R^2 \rightarrow 1$), a linear equaton for all values of flow rate higher than 12 m3/s could be adopted. Thus, the quation is presented in **Figure 24**.

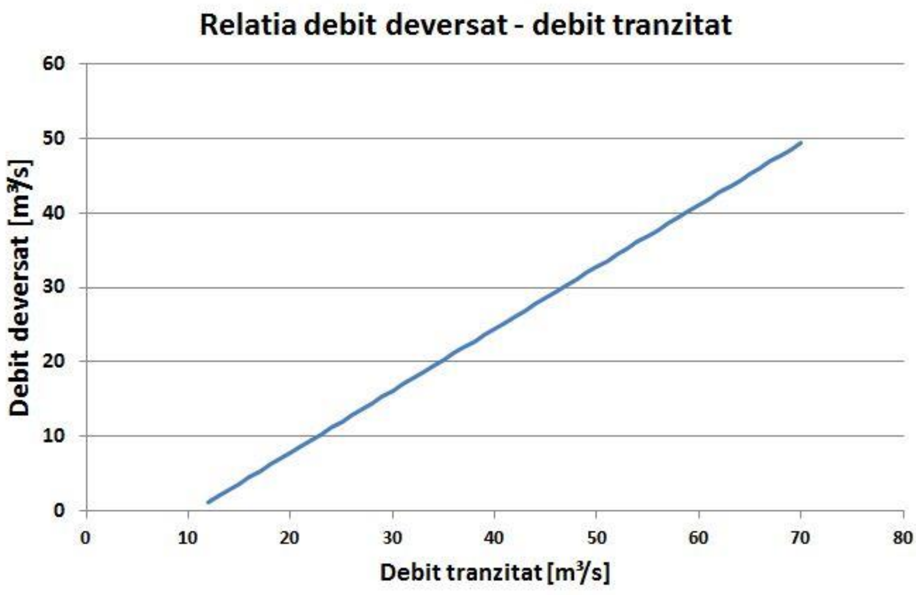

Figure 24. Relation between $Q_{TRANSPORTED}$ - $Q_{DISCHARGED}$

Applying the same concept for all flow rate recordings durin 2013, the hydrograph presented in **Figure 25** was obtained**. It could be observed that there are 20 events when the discharge would occur, or about 2 discharges/month,** being more frequent during spring and summer seasons.

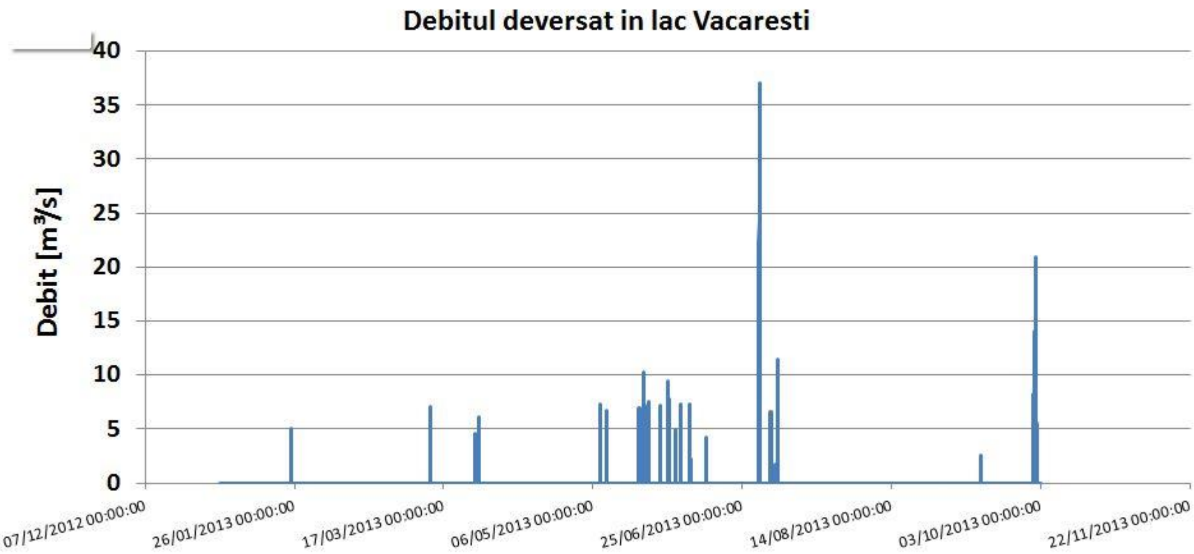

Figure 25. Flow rate potentially discharged in Vacaresti lake, calculated for 2013

It was determined that the volume of water that could represent an inlet into Vacaresti lake would be of 3 millions of m3.

8.5.2. Water quality

In order to achieve quality standards related to discharge of water to natural water bodies, the solution proposed should be equipped with adequate installations for this purpose (Regulation Act NTPA 001/2002 regarding wastewater discharge in natural receptoors). Additional and continous monitoring points should be established.

8.5.3. Separative system dedicated to rainwater collection for adjacent area

Because nearby area of Vacaresti lake doesn't have or have undersized sewage collection system, the second scenario consist of rainwater collection and discharge into Vacaresti lake, considering also a minimum mechanical treatment installation before discharge. In order to determine the volume of water that could be discharged, the following parameters specific for the area will be used:

- Average catchment slope: *I = 0.3 (%);*
- Catchment length: *L = 4.68 (km);*
- Catchment area: $F = 12.51\ (km^2)$;
- Concentration time: $T_c = 2.04$ *(ore)* = *122 (min);*
- Storage coefficiente: *R = 3.79 (ore);*
- Curve Number (dense and continous urban area): *CN = 89 (-).*

Figure 26. Catchment area proposed for rainwater collection

The hydrographs for the proposed catchment have been calculated for different design rainfall events, using Soil Conservation Service (SCS) model to determine infiltration curve and Clark Unit Hydrogrph to count for runoff translation and catchment storage.

Tabel 4. Maximum flow rate and volume for different design rainfall events over the study area

Rainfall return period	**1:1**	**1:2**	**1:3**	**1:5**	**1:10**	**1:20**	**1:50**	**1:100**
P (mm)	22.2	28.8	32.4	37.2	44.4	50.88	59.64	66
Q_{max} (mc/s)	3.69	6.49	8.15	10.55	14.29	17.9	22.95	26.74
PE (mm)	5.26	9.27	11.71	15.17	20.70	25.95	33.34	38.88
V (m^3)	65 783	115 999	146 500	189 765	258 987	324 648	417 142	486 346

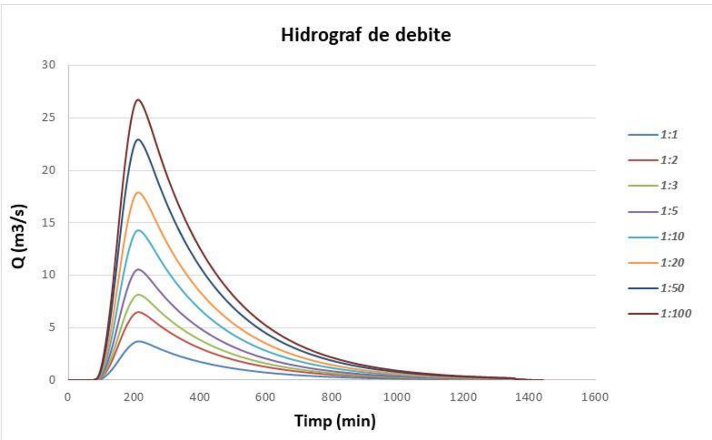

Figura 27. Hidrograful de debite pentru suprafața considerată

According to the technical regulation in place, for Bucharest the sewage system should be designed to a 10 years return rainfall event. A relation between the rainfall depth and the volume discharged into the lake has been calculated in order to determine the latter one.

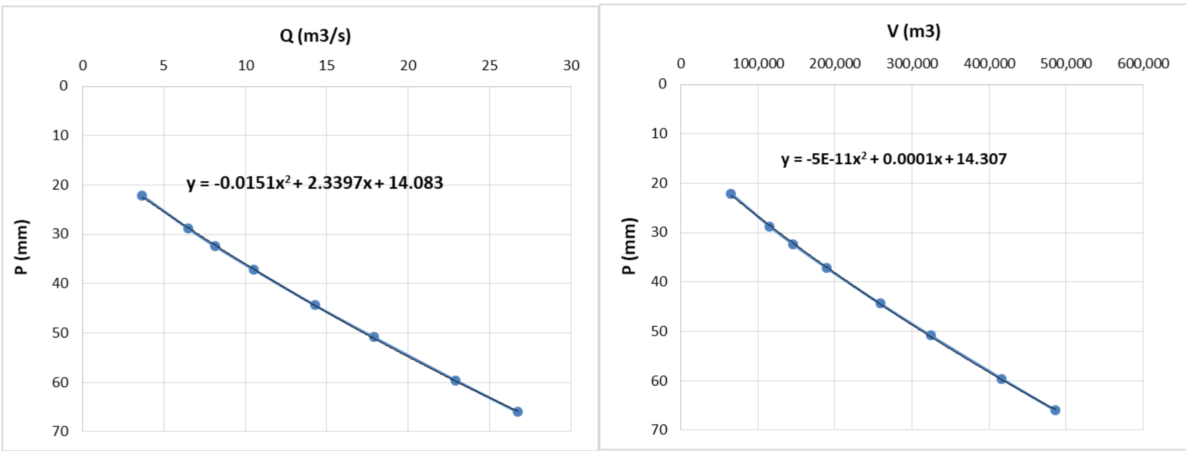

Figure 28. Correlation between rainfall depth and discharge into Vacaresti lake

8.5.4. 2D Modelling of the wetland

The objective of 2D modelling is to determine the impact of a potential discharge point on the south edge of Vacaresti wetland. The topography and spatial distribution of existing pools have been followed in order to identify proper location for inlets to the future pools. The results from previous scenarios related to flow rate (CSO from A3 collector or new separative sewage system) were used as inlets for the 2D model as imposed flow rate over time. In **Figure 29** flow hydrographs are presented for 10 years return period, respectively for 100 years return period rainfall events.

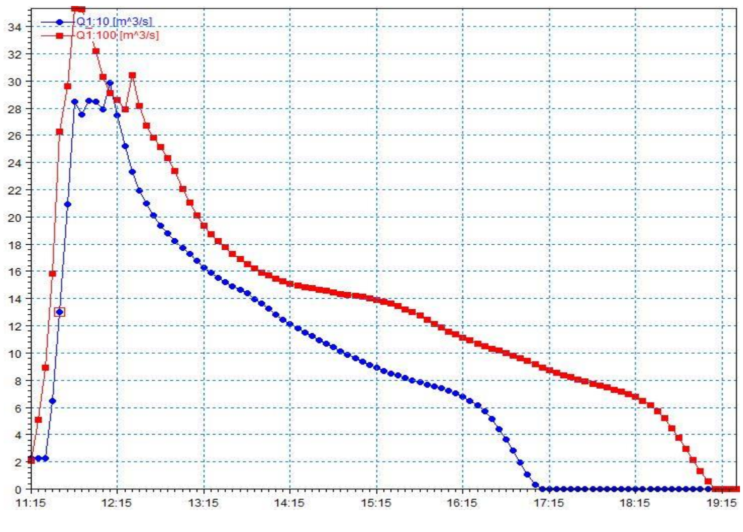

Figure 29. Flow hydrograph of discharge in Vacaresti wetland

Resulted volumes are: 197 400 m^3 for 10 years return rainfall event, respectively 401 200 m^3 for 100 years return rainfall event. The discharged quantities bring multiple betefits for (1) sewage system – by increasing its hydraulic capacity during intense rainfall events and reduce frequency of flooded areas; (2) wetland – which has an additional source of recharge, providing a better control of water balance and ecosystem than currently.

In **Figure 30** and **Figure 31** the impact over the wetland area could be observed in terms of water depth. On the existing pools it could be observed that water level will increase and thus, the volume stored will increase.

The discharged volume is distributed relatively uniform over a 50% of wetland area on the east syde for the analyzed rainfall events. In order to achieve a proper supply for all existing accumulations during rainfall events with smaller intensities, it is recommended to design control levees and additional open channels. Thus, a continuous water flow and recharge of wetland could be achieved, supporting the actual ecosystem.

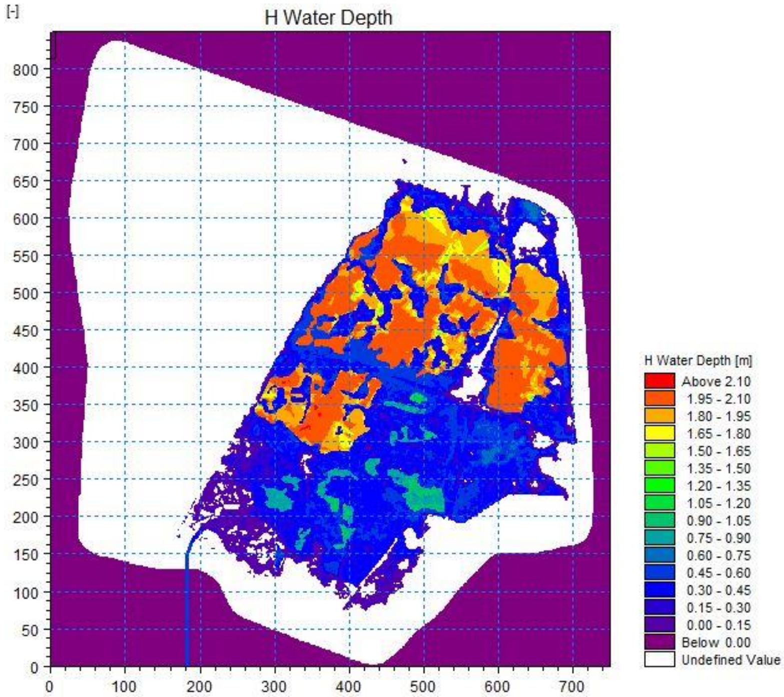

Figure 30. Water depth into the wetland for a 10 years return period rainfall event

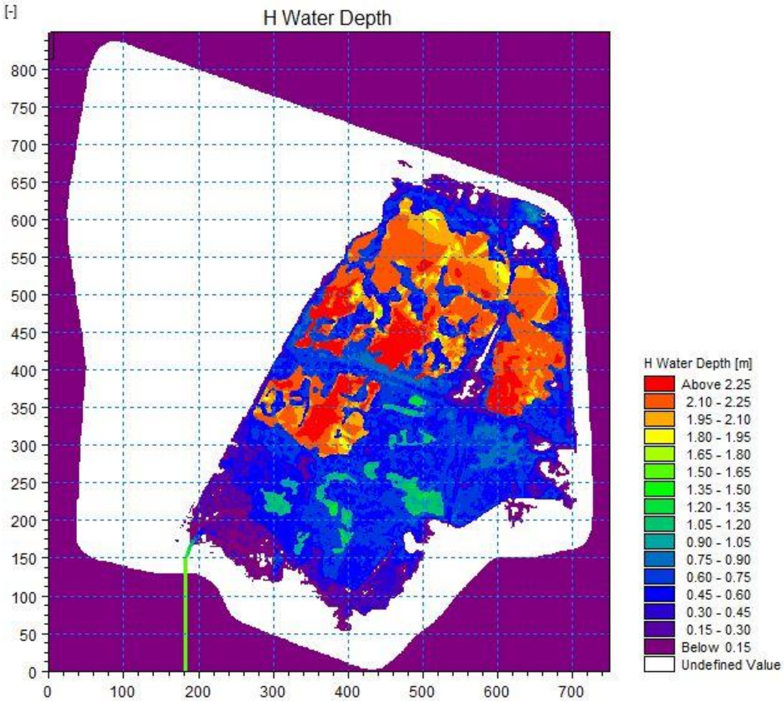

Figure 31. Water depth into the wetland for a 10 years return period rainfall event

8.5.5. Proposed solution

In order to take into account both contructive and ecological conditions and requirements for Vacaresti lake reconstruction, the following solution is proposed. It is not exhaustive, being possible to improve it further. It contains: rehabilitation of some existing hydraulic structures, execution of new hydraulic structures, a set up of continous monitoring system for parameters describing ecologial condition of the water body and of the ecosystem.

A. REHABILITATION WORKS

Rehabilitation works of existing hydraulic structures consist of:

- drainage system – especially the drainage system of east edge of the lake (șos. Vitan-Bârzești) which is 80-90% clogged;
- restoration of A3 collector at the points where it was interrupted with the construction of the dam (2 points) to allow discharge of water into the lake; build a discharge point of water inside the lake – it is recommended to be located near the southern edge of tha lake, close to the A3 collector;
- rehabilitation and equipment of the drainage system's pumping stations, that will be used to recharge the lake with water collected by the drainage system in order to have a better control of the water balance.

B. NEW WORKS

New works are proposed to be realized inside the lake. Those works should be able to provide multiple functions of the wetland (minimum water level, seasonal variability, flood protection, nutrients retention, maintain the groundwater level at a specific value, support ecosystem and biodiversity, etc.) through environmental friendly solutions.

Basen on this approach, a starting design shema is proposed for internal arrangements of Vacaresti lake, which follows the principles of ecological engineering (**Figure 32** – plan view) that will be able to produce a positive environmental impact.

From the total lake area of about 163 hectares, only a part of about 96 hectares (60%) will be used for water storage, located on the eastern side. That is needed to extend the hydroperiod over an year. The other part of the lake is not subjected to water storage and it could be set up as a green/park area or other leisure objectives.

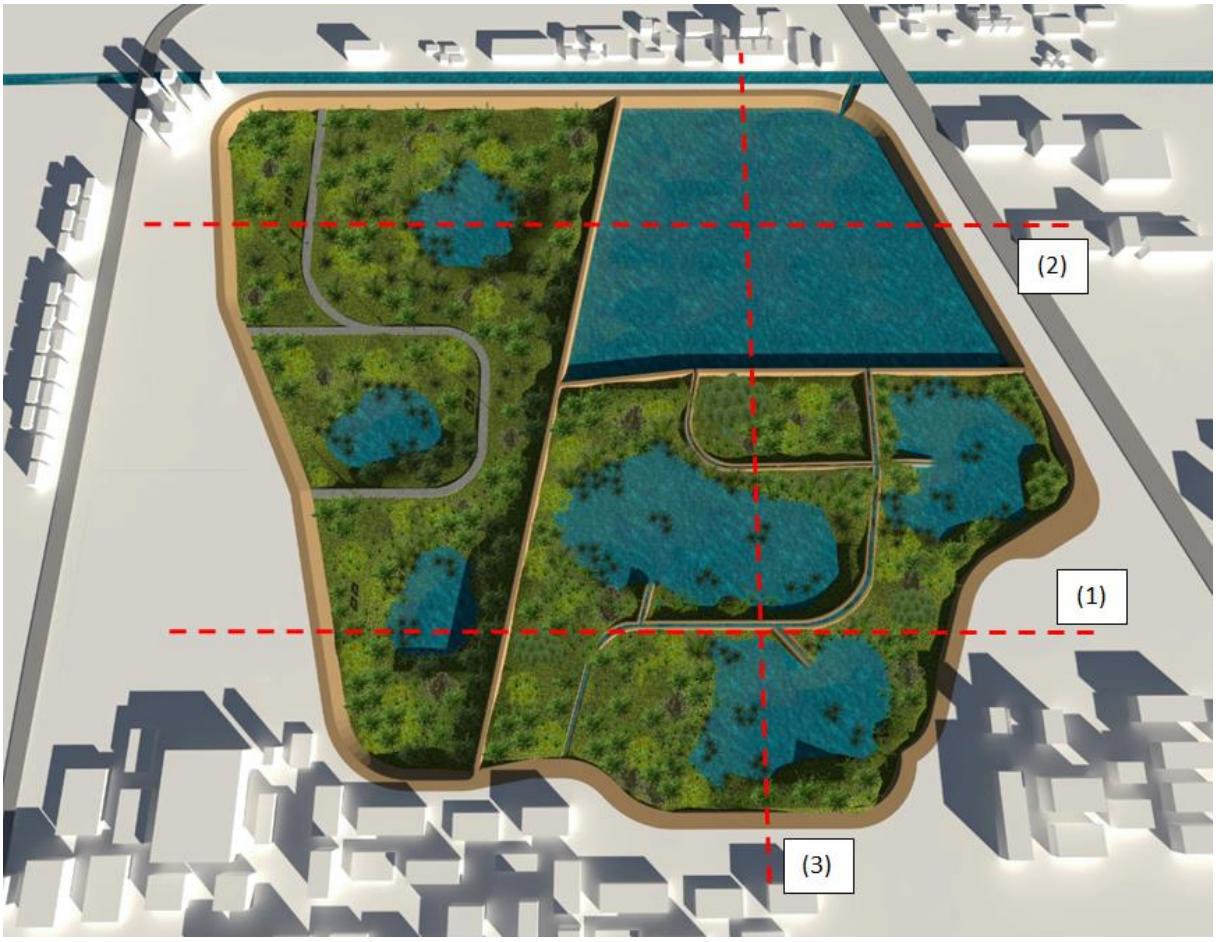

Figure 32. Proposed schema for interior design in Vacaresti lake – plan view

8.5.6. Conclusions

- the complex hydritechnical arrangement Morii lake – Dambovita open channel – Caseta collector – Vacaresti lake is practically unfinished;
- average annual precipitation depth for Bucharest is about 620 mm/year;
- for a better understanding of hydrological processes that impact Vacaresti wetland, it is needed: monitor groundwater level, additional tests to determine hydraulic conductivity, build a local model to assess properly the effects of drainage system rehabilitation and to quatify exfiltration from the lake.
- currently, Vacaresti lake reprents an abandoned hydrotechnical structure that doesn't provide any of its designed functions: flood control, runoff storage, recreational area, etc.
- the drainage system is not functional and it is almost fully clogged;
- Vacaresti lake is crossed from south to north by the A3 collector, which was derived during the execution works at the lake and its initial flow was interrupted;
- A3 collector has now a catchment larger than that one considered in the initial design; it was observed that during rainfall events occured in the last years, some areas from its catchmement were flooded due to insufficient hydraulic capacity;

- considering the works included in the Master Plan of Bucharest, loads on A3 collector will increase due to execution of new interceptors aimed to divert rainwater from central area to outside city's area;
- all the considerations presented indicate that Vacaresti lake could be used to achieve its initial functions, using an environmental friendly approach – wetland reconstruction;
- for discharge of combined wastewater and rainwater into natural water bodies, technical regulations in place indicates that a minimum dillution rate of 1:5 is needed, together with other installations for pollutants retention;
- a scenario based on a Combined Sewer Overflow (CSO) was built, in order to supply Vacaresti lake with additional water and also to improve hydraulic capacity of A3 collector;
- positive effects obtained through the CSO were observed after simulations and comparison in case of various design rainfall events between the actual conditions and the proposed one.
- Technical solution for wetland arrangement should take into account the quality of potential water discharge into the lake but also the quality of existing water;
- using the results of samples it could concluded that 6 of the water quality indicators will decrease their concentration after the discharge, and , on the other hand, 4 indicators will increase their concentration (nitrogen, phosphorus, chlorides, detergents);
- if a natural treatment solution will be set up, it should consist of stages for: settlement, phosphorus and nitrogen removal using specific vegetation and dedicated installations for detergents and chlorines concentration reduction;
- proposed solution for wetland arrangement have 2 main axes: constructive one and ecological one;
- constructive solution includes 3 types of works: rehabilitation (drainage and pumping stations, abandoned A3 collector); new works should provide function achievement (minimum water level, seasonal variability, flood protection, retention time, etc.); continous monitoring of water quality indicators;
- schematic drawing of proposed solution is presented in **Figure 32**;
- surface used for reconstruction is 96 hectares (about 60% from the lake area), from which 57 hectares for green area and 39 hectares for water surface;
- the maximum volume of water that can be stored without exceeding partition levees is of about 2 milions of cubic meters;
- water inlet from A3 collector could be realized using abandoned A3 collector. At least a mechanical stage for treatment shoud be designed;
- Outlet from the wetland will be done to Dambovița river through existing discharge for abandoned A3 collector;
- calculated evapotranspiration for Vacaresti lake is around 500 mm/an; additional measurements for evapotranspiration should be conducted;
- Using field measurements it was found out that below the clay layer which cover the lake, there is a saturated aquifer layer which is saturated and have a hydraulic conductivity of 10 m/day;

- Hidrogeological study shows that the piemzometrical level in the area is 63-64 mMN, which is similar with the level of surface water in the lake;
- The results from hydrogeological simulations indicate that ehe exchanges occur in both directions between surface water and groundwater;
- The connection between the surface water and groundwater impacts the water level into the lake, both during precipitation but also seasonally;
- Separative sewage system which was proposed, will bring a significant flow contribution into the lake and in case of internal arrangement of the lake surface, a continous water surface will be maintained.

9. CONCLUSIONS , OWN CONTRIBUTIONS AND FUTURE DIRECTIONS FOR RESEARCH ACTIVITIES

9.1. Conclusions

The research project was aimed to emphasize the methods and best practices at international level over the ecological reconstruction of wetlands. The objective was realized through scientific documentation, by analyzing projects and research studied for wetland reconstruction and other commendations of international experts on this topic.

As it was anticipated, it has been identified that the key element of wetland it is represented by the hydrological regime which characterizes them. The water flow to the wetlands, inside them and discharge require a complex approach, which need to ne able to reproduce accurately the physical natural phenomena.

Mathematical models designed to replicate water flow are largely used all over the worls. The computing power has reached very high levels which were not foreseen few decades ago. Therefor, mathematical modelling is used almost unconditionally to reproduce actual physical phenomena but also to run scenarios with their future evolution. By use of such tools, it is easier to obtain results of high quality, which could be applied with confidence in engineering solutions.

Wetland reconstruction involves combining engineering knowledge with those from other fields, such as chemestry or biology. As it was shown in the present research project, the wetland values could be assessed economically up to a certain point. Furthermore, their values could not be quantified because they concern the quality and safety of life, cultural benefits and ecological diversity.

The case study demonstrate show a wetland in an urban area and in an advanced degradation condition can be reconstructed so as to meet actual requirements in terms of hydrology and enivronmental protection. The principles that are guiding such a project are those of **ecological engineering.**

9.2. Own contributions

Within the research project were analyzed: global research studies regarding wetland reconstrucction; key elements of ecological reconstruction were found; processes that occur into wetlands were described; mechanisms through which wetlands interact with groundwater and surface water were presented ; mathematical models that describe water flow were summarized; methods to quantify water flows; and how different types of models could be interconnected. In the last section of the phd thesis, a solution for complex reconstruction of Vacaresti lake was proposed, following the principles of ecological engineering and the guidelines drawn by the international bodies qualified and experienced in the wetland reconstruction and management.

Own contributions of the author within the phd thesis „*Contributions to wetland reconstruction and adjacent ecosystems*" consist of:

- A summary of global wetland situation, wetland threats and european and national regulatory documents to be applied to such projects;
- A synthesis that includes the values and functions of wetlands, descriptive variables and wetland classification systems;
- Description of essential knowledge and objectives to be followed in ecological reconstruction projects;
- Presentation of mathematical background used in water flow processes, highlighting the main techniques used by the calculation tools;
- Description of hydraulic phenomena through which wetlands are supplied and those through which water is discharged;
- Study in detail the components of the hydrological balance for wetland and methods for assess them;
- Establishing a geographical database for lake Vacaresti with all hydrological parameters;
- Design and run scenarios through the hydrogeological model of Bucharest in order to evaluate groundwater exchange with lake Vacaresti;
- Design and run scenarios with sewage model of Bucharest and analyze results with proposed solution for the connection with lake Vacaresti;
- Design a solution for a complex arrangement of lake Vacaresti, in order to achieve multiple functions of it.

9.3. Future research guidelines

(...)

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