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Hydrodynamic Simulations Of Vacuum-Driven Storage Tanks

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HYDRODYNAMIC SIMULATIONS OF VACUUM-DRIVEN STORAGE TANKS

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The article presents the basics of reservoirs filled by creating a vacuum in the retention chamber. Their principal advantage over the traditional (gravitational) reservoirs is the possibility of retention of sewage above the free surface. In order to determine the effectiveness of their operation a hydrodynamic model was developed using SWMM5 software. Continuous simulations covered a period of four years and take into account the variable share of the vacuum retention in the total volume: from 25% to 75%. The result of the simulation makes possible estimate the cost-effectiveness of vacuum application in comparison to traditional constructions of storage tanks. The results indicated it is reasonable to use such constructions even if the retention of nearly 50% of total volume is under vacuum conditions.

INTRODUCTION

Storage tanks are the basic devices to effective control the flow rate in drainage systems during wet weather. The issue of how to increase the storage capacity of the sewage network gained in recent times an engineering priority. One of the basic and efficient solution in effective stormwater management is the construction of detention tanks located at selected nodes of the drainage system (Becker et al. [2], Brombach [3]). Detention facilities are also a required component during implementation of Real Time Control systems (EPA [5]). Thus, any development towards smaller dimensions of detention tanks or smaller depth of necessary excavations with maintained or increased storage capacity would decrease costs and disturbance during construction works (Saul and Ellis [12]). Construction of storage tank using vacuum-driven detention chambers bring possibility to achieve these goals (Kisiel [6], Dziopak and Niemczynowicz [4]).

Presented construction of vacuum-driven detention tanks allows to increase of the storage capacity by usage of space above the free surface water elevation at the inlet channel. Partial vacuum storage makes possible to gain cost savings by reduction of both the horizontal area of the detention tank and necessary depth of its foundations (Mrowiec and Kisiel [7, 9]). Hydraulic experiments conducted at laboratory scale in Cracow University of Technology and in Czestochowa University of Technology confirmed technical feasibility of this a construction [Kisiel 6].

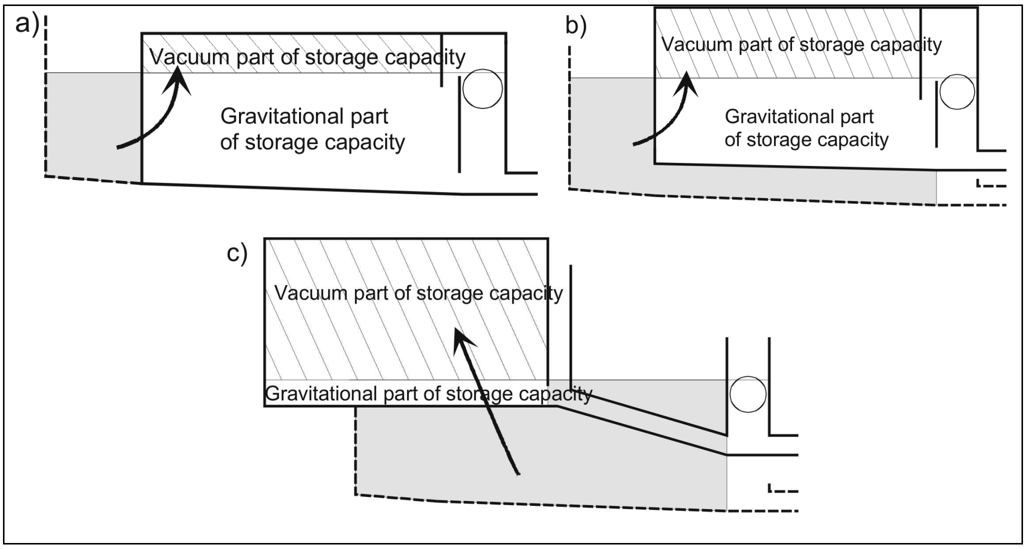

Figure 1. Possible profits of vacuum storage in comparison to a traditional reservoir – description in the text.

The main reason of vacuum storage application is the investment cost savings achieved by (Dziopak and Niemczynowicz [4]):

- reduction of the area of the detention tank maintaining the same storage volume as in gravitational tanks (fig. 1a).
- reduction of the necessary depth of foundation of the detention tank maintaining the same storage volume as in gravitational tanks (fig. 1b).
- construction of a detention tank on the level of the ground and it may be situated at some distance from the stormwater conduit, excavations on the street may be avoided (fig. 1c). Need of excavations is reduced to the minimum.

MODEL OF VACUUM-DRIVEN STORAGE TANK

Functional scheme of the vacuum-driven storage tank is shown in Figure 1.

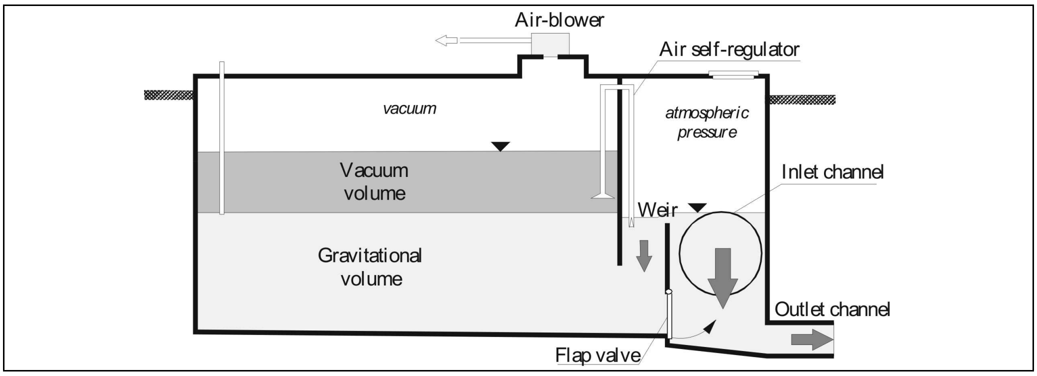

Figure 2. Scheme of partially vacuum-driven detention tank

The main disadvantage of vacuum-driven tanks is the higher operational costs associated with the energy consumption of the air-blower. The economic analysis based on comparison of investment costs and long-term maintenance costs usually should be enough to determine the optimal share of vacuum storage in total volume of the reservoir. The second disadvantage is the possibility of odours during air-blower activities. This problem is especially troublesome if the storage tank operates on combined sewer system (i.e. to reduce CSO discharges) and is located near the residential areas. In such cases odours problem can be resolved by the usage of biofilters. Alternative option is to use the this air-flow to aerate discharged stromwater - then the outlet pipe form air-blower is connected to outflow channel.

The vacuum can be applied in existing underground detention facilities in order to increase the storage capacity. Instead of construction additional, deeply founded chamber, the simple modernization works can be done, include:

- air-tight sealing in detention chamber (above the max. water elevation only)
- construct the partition that split inlet chamber and upper part of storage chamber,
- installing the air–blower and air-regulator.

The additional capacity to be activated by the vacuum is restricted by the height between maximum stormwater elevation and the tank' ceiling. Maximum depth of underground detention reservoirs is on the average 2÷3 meters, so the usage of only meter above the free surface water elevation allows to reach a large capacity increase of 33÷50%. The extra volume is used only when the lower (gravitational) chamber is completely filled.

The vacuum-driven reservoirs as the other underground devices will be subjected to extremely harsh operating conditions (high humidity, organic sludge deposits, corrosive gases, intermittent operation, microbe and fungal attack). Some of the operational problems can be mitigated by appropriate design, especially (Urbonas and Stahre [13], Mrowiec and Kisiel [8]):

- access openings for maintenance personnel and equipment,
- provide effective ventilation - (the use of air-blower to ventilate storage chamber is another advantage for these types of reservoirs) ,
- effective flushing devices preventing permanent sludge deposits.

All electrical equipment has to be corrosion resistant, flood-proof and explosion-proof. The latter is because methane gases have been shown to accumulate inside an underground storage basin in combined storm sewer systems.

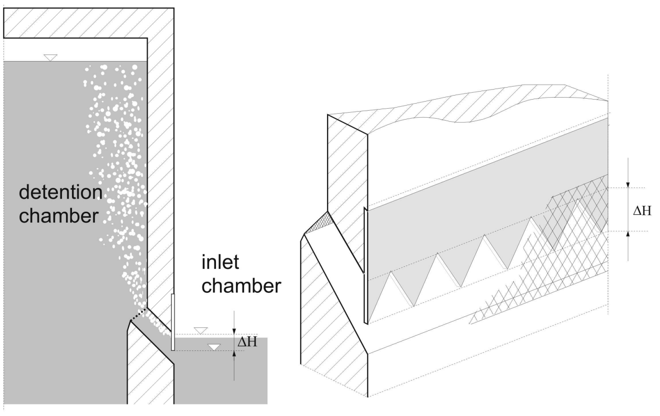

Figure. 3. Air flow control during emptying phase of vacuum part of detention chamber and isometric view of air-regulator made as saw profile.

The air-regulator assure gradual equalization of the pressure with a quasi-constant water elevation at the inlet chamber. The air-regulator works without any external power and is a simple device that can be made in a various ways. Principle of the operation is showed on figure 3 where the air regulator is made as a saw profile. If the water level drops below upper edge of regulator then air flows through the pipe into the storage chamber and vacuum decreases. The air flow-rate depends on the water level at inlet chamber: decreasing of stormwater causes increasing of air flow-rate to the detention chamber. It effects the outflow-rate is equal to the maximum allowable value (Q_{0max}) during this phase, so the time of emptying (t_{EV}) is reduced to a minimum (fig. 4) and is significantly shorter than t_{EG} (emptying time of gravitational part of storage volume). The emptying phase of detention facilities are often omitted at design stage because determination of storage capacity requires only the characteristics of filling phase (inflow vs. outflow) (Paoletti et al. [10]). Profits from effective and quick emptying phase are more clearly visible during long-term simulations (Adams and Papa [1]).

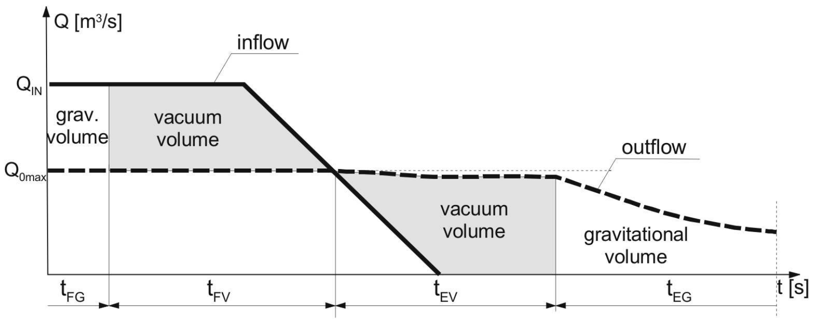

Figure 4. Outflow hydrograph during emptying phase of storage tank with partially vacuum-driven chamber.

To determine changes of water elevation under vacuum conditions, the two differential equations have to be solved simultaneously:

- the change of air mass (m_A) above the water surface:

$$\frac{dm_A}{dt}=\frac{\rho_0}{p_a}\left[\left(V_T-V_{Vh}\right)\frac{dp}{dt}-p\frac{V_{Vh}}{dt}-V_{Vh}\frac{dp}{dt}\right] \tag{1}$$

- the change of pressure (p) above the storm water surface:

$$\frac{dp}{dt}=-\gamma\left(\frac{dh_V}{dt}-\frac{dh_G}{dt}\right) \tag{2}$$

where: p_a - atmospheric pressure [Pa],
p -pressure (vacuum) above water level at detention chamber [Pa],
ρ_0 - air density [kg/m^3],
γ - specific weight of stormwater/wastewater [N/m^3],
V_T - total volume of detention chamber [m^3],
V_{Vh} - vacuum-driven volume (for given depth h_V) [m^3],
h_V - depth at vacuum-driven chamber [m],
h_G - depth at lower (gravitational) chamber [m].

After some simplification the equations are easy to resolve for a given time step with use of basic numerical methods.

HYDRODYNAMIC SIMULATIONS OF VACUUM-DRIVEN STORAGE TANK

Hydrodynamic model has been developed using the EPA Storm Water Management Model (SWMM) (Rossmann et al., [11]). Modeled catchment Based on a numerical maps and aerial photographs the selected catchment (32 ha) was divided into 51 homogeneous subcatchments (area from 0.2 to 1.7 ha) taking into account their shape, slope, land-use type (average 32% imperviousness) and soil conditions. The whole network consist near the 55 links (diameters between 300 mm and 600 mm). Main subcatchment properties (%imperv, width, n-imper, D-store perv etc.) have range of values typical for an urban catchment.

For the hydraulic validation, a very accurate adjustment in terms of time and variation of flows was obtained, and the total volume simulated presented only a difference of 5% with respect to the measured volume. Observed peak flows were greater than simulated ones by 10÷15%.

Location of modeled storage tanks was the result of observed frequent floods during intensive rainfalls. The main problem is because SWMM does not contain a module for simulating of vacuum-driven tank due to its innovative nature. Therefore, it was necessary to apply a combined model (fig. 5) comprising two chambers connected by a weir. Chamber number 1 is the gravitational part of the tank, emptying by a flow regulator (fixed value Q_0). Chamber no 2 is the vacuum-driven part of storage volume, emptying by pumps. Additional control rules and condition clauses makes possible to reflect operation of storage tank partially filled by created vacuum.

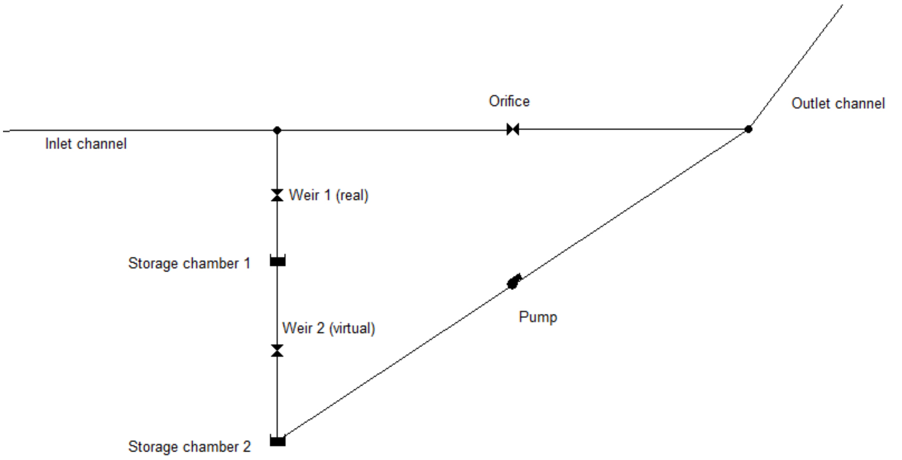

Figure 5. Scheme modeled vacuum driven storage tank in SWMM5.

Basic dimensions of modeled storage tank: area A=400m2, total height H=2.8m, total storage volume V_T=1120m^3. Simulations have been done for various share of chamber filled under vacuum conditions (V_V): 25% (280 m^3), 33% (373 m^3), 50% (560 m^3), 66% (746 m^3), 75% (840 m^3). For each construction variant a four values of unit outflow-rate from the storage tank were considered: q_0=4 dm^3/s·ha, q_0=8 dm^3/s·ha, q_0=12 dm^3/s·ha, q_0=16 dm^3/s·ha (ha of impervious area). Source of rainfall data: continuous records covering years 2009–2012 (without winter months due to limited capabilities to simulation of snowmelt process) with temporal resolution Δt=10minutes.

SIMULATION RESULTS

Hydrodynamic simulations performed using model described above, make possible to determine number of rain events resulted in partial filling of vacuum-driven volume. The volumes have been presented as unit values (referred to ha of impervious hectare m^3/ha) and applied to point diagram for each year and for different diversion of storage volume (V_V/V_T) – see sample diagram on fig. 7.

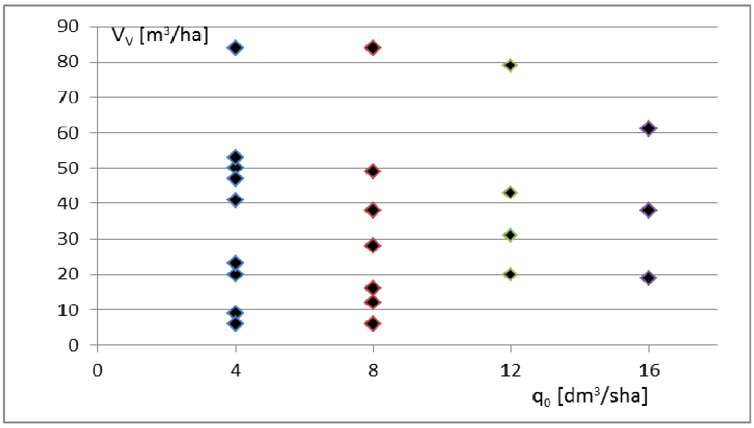

Figure 6. Point diagram of events that filled vacuum-driven part of storage volume (share of vacuum-driven volume 75%, year 2011).

The figure 7 shows the simulation results, including all the events that resulted in partial filling of the vacuum-driven storage volume (V_V) during period of four years. The increase of V_V in total storage volume results in an exponential growth of rain events that filling the volume under vacuum conditions (and obviously the frequency of switching on/off air-blowers). For outflow-rate q_0=4 $dm^3/s \cdot ha$ and with the $V_V=0{,}75 \cdot V_T$ air-blowers are switching on 10 times a year (average value).

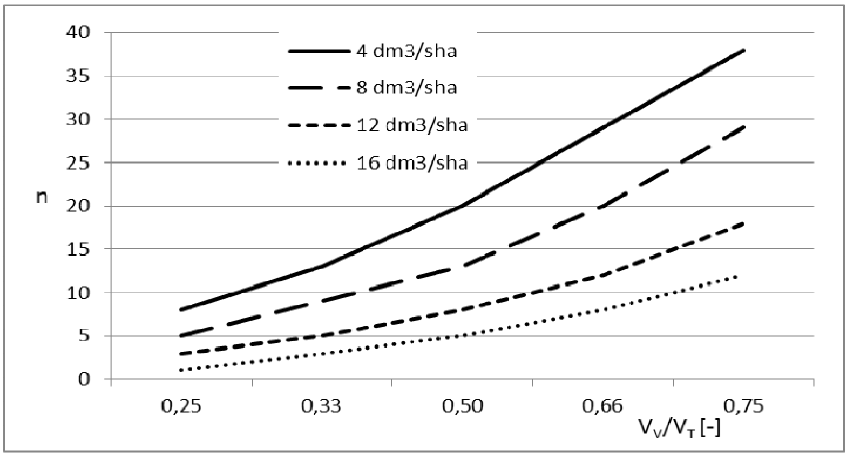

Figure 7. Number (n) of partial filling of vacuum-driven chamber for varying share of V_V in total volume V_T and unit outflow-rate $q_{0.}$

Figure 7 shows annual unit volume of stormwater (m^3 per hectare of impervious surface) stored under vacuum conditions. Significant increase of V_R can be observed for $q_0<8{,}0$ dm^3/sha for $V_V/V_T \in 66\% \div 75\%$, in other cases, the stored volume decreases in direct proportion to the increase of unit outflow-rate.

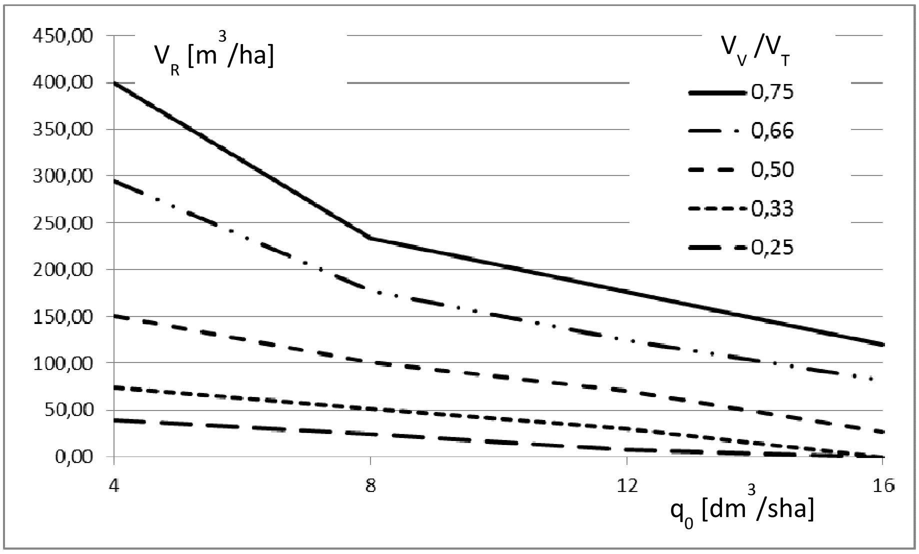

Figure 8. Average annual unit volume (m^3/ha of impervious surface) of stored stormwater for varying q_0 and ratio V_V/V_T .

Since presented construction of the vacuum-driven tank has not yet been built in a technical scale, it's difficult to accurately determine total investment costs as well as maintenance costs. Thus cost-effectivness analysis of the use of vacuum to accumulate stormwaters was carried-out considering: a) 25-year period of operation; b) standard geological conditions, c) investment, labour and energy costs specific for the Polish conditions, d) air-blower efficiency is 20% lower than for standard variable speed pump, e) annual maintenance costs of vacuum-driven storage tank are 15% higher than similar construction equipped with standard set of pumps.

Taking into account capital and operating expenditures in 25 years period for a standard geological conditions the use of retention under vacuum conditions is economically justified if the annual unit volume of stormwater does not exceed 135 m^3/ha (for q_0=16 $dm^3/s\cdot ha$) to 180 m^3/ha (for q_0=4 $dm^3/s\cdot ha$). In the case of difficult ground conditions (i.e. high groundwater level or rocks) it was in the range from 175 m^3/ha (for q_0=16 $dm^3/s\cdot ha$) to 275 m^3/ha (q_0=4 $dm^3/s\cdot ha$). It's obvious that estimated values are dependent mainly on: a) local characteristics of rainfalls, b) investment and maintenance costs specific to the region/country, c) size of the storage tank.

CONCLUSIONS

The following conclusions can be drawn from the present study:

- Presented vacuum-driven storage tanks are characterized by uncomplicated construction and control systems, thus can be applied in newly developed as well as in the existing urban drainage systems. Their use is specially justified in areas where there is no available space to build traditional tanks (i.e. in central parts of towns) or difficult ground conditions occurs (high groundwater levels, rocks, etc.).

- The application of vacuum in underground detention facilities makes possible to increase of the storage capacity of existing reservoirs by usage the space above the maximum depth. Possible increase of storage capacity can achieve even a few dozen percent at relatively low investment costs.
- It was showed in the paper that vacuum driven storage tanks can be included in existing simulation software (i.e. SWMM) using options intended for pumping stations (with additional action rules and conditional clauses). Continuous simulations should be applied to determine cost-efficiency of vacuum application.

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REFERENCES

[1] Adams B.J. and Papa F., „Urban Stormwater Management Planning with Analytical Probabilistic Models", John Wiley and Sons, (2000).

[2] Becker M., Prinz R. and Liebig T., "Effectiveness of a stormwater tank with overflow with a downstream stormwater holding". *KA-Wasserwirtschaft, Abwasser, Abfall,* 1/2001, pp16-24,

[3] Brombach H., "Sewerage System and Stormwater Tanks as Reflected in Statistics", *KA - Wasserwirtschaft, Abwasser, Abfall*, 4, (2002), pp 33-40.

[4] Dziopak. J. and Niemczynowicz J., "Vacuum driven CSO detention tanks", *Urban Water*, 1, (1999), pp 105-107.

[5] Environmental Protection Agency, " Real Time Control of Urban Drainage Networks", *US EPA Report*, no EPA/600/R-06/120, (2006).

[6] Kisiel A., "Hydraulic analysis of gravitational-vacuum storage tanks", *Monograph no. 238*, Cracow University of Technology, (1998). (text in Polish).

[7] Mrowiec M. and Kisiel A., "Dimensioning methods for the vacuum-driven storage tanks", *Proceedings of 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK*, (2008), pp 1-10.

[8] Mrowiec M. and Kisiel A., "Vacuum storage as effective way to increase capacity of detention facilities", Water Practice and Technology, vol.2 no 2, (2007), pp 1-8.

[9] Mrowiec M. and Kisiel A., "Innovative structure of on-line storage tank", *Proceedings of International Conference on urban Drainage*, Copenhagen (2005), pp 1-10.

[10] Paoletti A., Sanfilippo U. and Becciu G., "Filling and emptying cycles for stormwater storage tanks in separated systems", *Proceedings of Novatech 2007, Sustainable Techniques and Strategies in Urban Water Management, 5th International Conference, Lyon, France*, Vol. 2, (2007), pp 1123-1130,

[11] Rossman L.A., Dickinson R.E., Schade T., Chan C., Burgess E.H., Huber W.C., "SWMM5: The USEPA's newest tool for urban drainage analysis", *10th International Conference on Urban Drainage, Copenhagen*, (2005), pp 1-8.

[12] Saul A.J. and Ellis D.R., "Storage tank design in sewerage systems", Proceedings of the *5th International Conference on Urban Storm Drainage, Osaka, Japan*, (1990), pp 713-718.

[13] Stahre P. and Urbonas B., "*Stormwater detention for drainage, water quality and CSO management",* Prentice-Hall, New Jersey, (1990).