Science behind STORMEE - STORMwater Environmental Efficiency toolkit: 1) infiltration basin

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ABSTRACT

Introduction. When designing the road drainage system special attention is given to environmental protection, which requires the removal of potentially hazardous elements via separators to the required degree, usually defined by the local stakeholders and legislation. Afterwards, water is simply transferred to a nearby convenient recipient. Modern engineering practice however dictates the design of sustainable drainage systems (SuDS) for the collected water, which need to provide attenuation of the runoff and must be designed to mimic the natural catchment conditions with as little disruption of natural processes as possible [1]. SuDS are designed to maximize opportunities and benefits that can be secured from surface water management: water quantity, water quality, amenity and biodiversity [2]. Construction of roadside infiltration basins is one of the measures used for these purposes. Infiltration basins are relatively simple engineering objects designed and constructed as excavations with a corresponding filter layer at the bottom (gravel or crushed stone) [3]. Essentially, they are retention spaces for permanent water retention that receive collected stormwater runoff and drain it slowly into the surrounding soil. Retention space of infiltration basin provides a reduction in the maximum peak runoff value [4], while runoff quality is also improved by filtration through the filter layer and soil. There are number of similar type objects that can be used for this purpose, applicable to different sizes and types of surface purpose (residential, parking lots, etc.) [2]. The main advantages of infiltration basins' application are 1) the relatively inexpensive cost of construction, 2) low space usage and 3) possibility of application in areas where there is no conventional stormwater sewer network or river that could serve as a recipient of stormwater runoff. This makes them particularly suitable for construction next to the roads of significant importance such as highways [5]. The retention of runoff contaminants using infiltration basins have been proven through the testing of such facilities after many years of use [6]. On the other hand, inefficiency in the operation of infiltration basins can be caused by the construction on land of poor water permeability and high groundwater levels. The stability of the surrounding structures can also be compromised given that infiltration increases the moisture of the surrounding soil [7]. Over time, there may be a decrease in the efficiency of infiltration due to clogging of the filter layer, caused by sedimentation of suspended particles. A common mistake being made in the design procedure is wrongful selection of the design storm for sizing the infiltration basin, i.e. the same design storm is used both for the collection system and the infiltration basin. Short duration, high intensity design storms are used for the design of the collection system as they result in maximum runoff peak values. Long duration, low intensity design storms should be used for the design of the infiltration basin itself as they result in much greater runoff volume which is essential for sizing of the infiltration basin.

To ensure the efficiency and sustainable functioning of the infiltration basin, design procedure should carefully address the following: 1) selection of the proper design storm and 2) all aspects relevant for soil infiltration. Basic guidelines and recommendations for the design of similar type objects can be found in literature but are lacking in detailed description of the design procedure and infiltration calculation ([2], [8]). This paper presents a comprehensive methodology for the design and operational analysis of infiltration basins for road runoff that is incorporated into STORMEE – STORMwater Environmental Efficiency toolkit. Presented methodology encompasses all relevant hydrological and hydraulic analyses in detail, which overcomes the shortcomings present in currently available regulations and design guidelines, and is packed into a user-friendly interface. Showcased here is the analysis of a field scale infiltration basin

intended for runoff control from the section of the railway in Serbia. STORMEE allows the user to efficiently perform analyses for different input data and investigate alternative designs.

Methodology. The methodology presented in this paper consist of three distinctive parts:
1) Generation of the design storm,
2) Generation of the design inflow hydrograph into the infiltration basin and
3) Calculation of time dependent infiltration and water level changes in the infiltration basin.

Hydrological analyses present the basis for the selection of the design storm and resulting stormwater runoff to be used for the design of road drainage systems. The use of constant intensity design storms for longer rainfall durations is not recommended, as it lacks naturally observed rapid fluctuations in rainfall intensity and this can lead to underestimated design flows. Therefore, it is necessary to define design storms that would result in more reliable and realistic design hydrographs. For this purpose, alternating block method is applied here. Method is based on locally available IDF curves and allows the definition of the design storms for all durations shorter than 24 hours. Adequate block size, or time interval, is selected first (Δt). Then, for all durations D_k= Δt, 2Δt, 3Δt,… rainfall intensities i_k are determined from the IDF curve. Corresponding precipitation depths (P_K) are determined as $P_k=i_k*D_k$. Incremental precipitation depth (ΔP) for each duration D_k is then derived as difference. Design storm hyetograph is created by placing the maximum incremental precipitation (ΔP_{max}) in the centre of hyetograph and remaining arranged in descending order alternating right and left. User is given the option to alter the distribution of the rainfall by changing the time position of the maximum incremental precipitation (ΔP_{max}). This is done through r_factor input value which takes values in the range [-1,1].

To generate infiltration basin's input hydrograph, it is necessary to perform modelling of rainfall-runoff process. A simple linear reservoir model is used here to transform the previously generated design storm hyetograph to corresponding storm runoff from the road. Linear reservoir model assumes linear relationship between the reservoir volume (*S*) and its' outflow (Q_{inflow}). Balance equation for linear reservoir is rearranged to solve for unknown reservoir volume at time *t* (*S(t)*) and then integrated in [t-Δt, t] interval to yield the average outflow from the reservoir, i.e. the inflow to the infiltration basin (Q_{inflow}):

$$\overline{Q_{inflow}}=\frac{S(t\text{-}\Delta t)}{\Delta t}\left(1\text{-}e^{-\Delta t/T_c}\right)+A_cC_{roff}\,\mathrm{i}\left(1\text{-}\frac{1\text{-}e^{-\Delta t/T_c}}{\Delta t/T_c}\right)$$

where *Tc* is time of concentration [s], A_c is road catchment area [m^2], C_{roff} is runoff coefficient [-], and *i* is rainfall intensity [m/s]. The product $A_cC_{roff}i$ is essentially effective rainfall that is being transformed into infiltration basins' inflow hydrograph.

As previously stated, infiltration basins are usually designed and constructed as simple excavations with filter layer on the bottom to allow infiltration through the bottom. If natural topsoil layer permeability is not high enough to provide sufficiently effective infiltration through the bottom, additional boreholes that will penetrate to the lower layer, with better filtration characteristics, can be constructed at the bottom of infiltration basin (Figure 1). Infiltration basin can also be designed with emergency weir (e.g. to existing sewer network) to prevent uncontrolled overflow. After generation of inflow hydrograph, following processes are modelled in the infiltration basin:
1) Infiltration through the bottom of the basin (Q_{inf}),
2) Infiltration through the boreholes in the bottom of the basin (Q_b) and
3) Weir overflow (Q_w).

Infiltration through the bottom of the basin is calculated based on the modified Green-Ampt (GA) method which assumes a homogeneous soil with constant hydraulic conductivity (K_f), initial water content (θ_0), and head at the wetting front. The saturated wetting front is assumed to move downwards as a single piston and its' position is denoted with y(t), measured from the bottom of infiltration basin. The modification of the original GA method refers to the introduction of a time-changing ponding depth (H(t)) which allows for continuous calculation of the wetting front position, without changes in the boundary conditions at every time step [9]. Resulting equation for the wetting front position is a non-linear one and it is solved using Newton-Raphson method, after which infiltration (Q_{inf}), dependant on water level in infiltration basin (H(t)) and soil characteristics, is calculated as:

$$Q_{inf}(\overline{H})=(y(t)-y(t-\Delta t))(p-\theta_0)\frac{\overline{F}}{\Delta t}$$

where p is the soil porosity [-] and F is the average water surface area [m^2].

Equation for modelling of infiltration through the borehole (Q_b) is simply derived from Darcy's low of filtration and borehole geometry:

$$Q_b(\overline{H})= K_{f,BL}\pi D_b(\overline{H}-GWL)$$

where $K_{f,BL}$ is hydraulic conductivity of the bottom soil layer [m/s], *GWL* is static ground water level [m] and D_b is borehole diameter [m]. For the modelling of the weir overflow (Q_w) it is necessary to provide a flow-head (Q-H) curve for the weir.

Finally, the water level in infiltration basin (H(t)) can be calculated from the balance equation:

$$\overline{F}\frac{H(t)-H(t-\Delta t)}{\Delta t} = \overline{Q_{inflow}}-\left[Q_{inf}(\overline{H}) + Q_b(\overline{H}) + Q_w(\overline{H})\right]$$

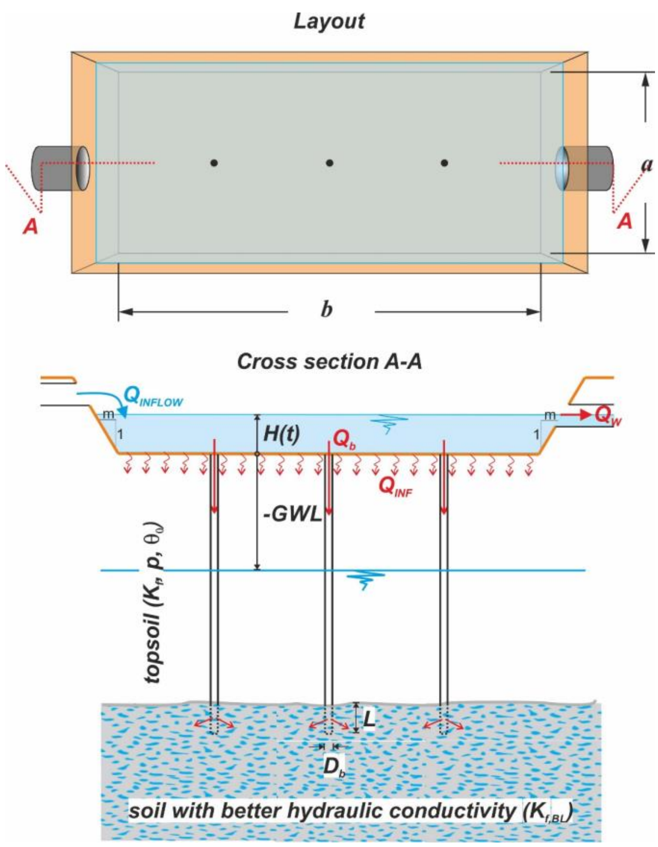

Figure 1. General layout and cross section of infiltration basin

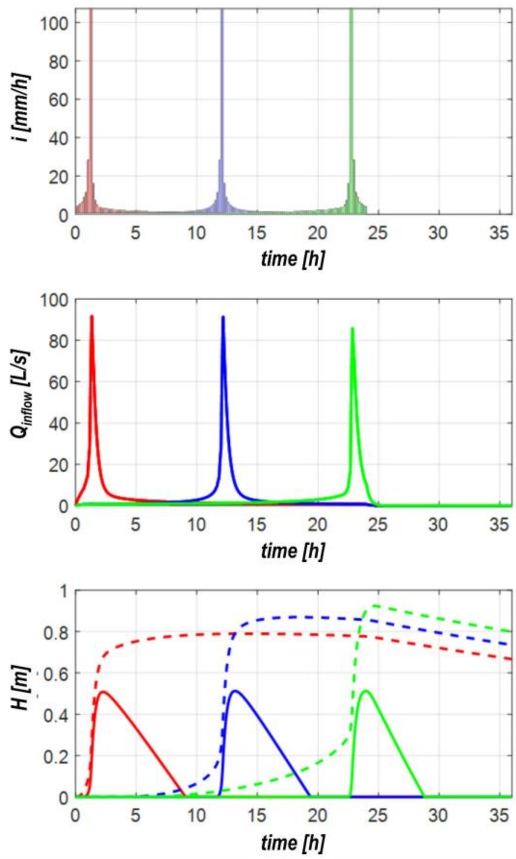

Figure 2. STORMEE outputs: Operational analyses for the designed infiltration basin

Results & Discussion. The previously described methodology for calculation and analysis of the infiltration basin is implemented in an integrated software tool that relies on: 1) MATLAB software functionality to perform all necessary calculations and graphical interpretations and 2) integration of the former into the EXCEL software for user interaction, i.e. data input and review of the results.

Presented methodology is tested on a field scale infiltration basin designed on the side of a railway corridor in Serbia. Available input data included: 1) geometric data for the designed infiltration basin, 2) soil characteristics 3) GW levels and 4) local IDF curve. Total railway catchment area gravitating to this infiltration basin is A_C= 6630 m2 and time of concentration is Tc=17.5 min, determined based on FAA equation [10]. Maximum designed allowable water level in the infiltration basin is Hmax=0.8 m and the ground water level is 2.0 m bellow the ground. Operational analysis of the designed infiltration basin has been investigated for three 24-hour 10-year design storms with different temporal distributions represented through the r_factor (r_factor=-0.9, 0 and 0.9) to assess the proposed basin design and investigate its' functionality. For the design of storm hyetograph time interval Δt=10 min is adopted. Results of the analysis are shown in figure 2 – top graph shows three different design storms, middle one shows resulting inflows into the infiltration basin and bottom one shows simulated water levels in the infiltration basin. Dotted lines refer to infiltration basin without boreholes at the bottom and solid lines refer to construction of the basin with six identical boreholes at the bottom of diameter Db=400 mm.

Presented STORMEE results on the bottom graph (H) suggest that water level in the basin will exceed maximum allowable value of 0.8 m for two of the three designed storms (r_factor = 0 and 0.9), which will result in infiltration basin overflow. Additionally, it can be concluded that water infiltration through the topsoil of relatively low hydraulic conductivity (K_f=1.5x10^{-6} m/s) is very slow, and it can take several days, questioning basins' ability to accept runoff from consecutive rainfalls. Contrary to this, simulation results for case where 6 boreholes are constructed in the bottom of the basin show that for all design storms maximum achieved water level is H=0.52 m and infiltration time after the rainfall is reduced to reasonable 4-7 hours.

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