Highway Drainage System Efficiency

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Dražen Vouk

Abstract: Starting from 1980, all highways in ecologically sensitive areas in Croatia, have specially designed drainage systems. That includes system of closed or open conduits for runoff collection with oil-grit separators before the final disposal. In more sensitive areas, different BMPs are added after oil-grit separators, to improve overall treatment efficiency. Overflow structures are allowed on big watersheds to avoid large pipe diameters. While overflow structures in urban sewage systems are designed upon German ATV – Rules and Standards, water authorities in Croatia, for the same type of structure prescribe more stringent criteria, namely critical rain intensity from 15-25 l/s/ha depending on ecological sensitivity of the recipient. At the same time, the mentioned criteria are not correlated to local climatic conditions i.e. duration of dry and wet weather, and mean annual rainfall. The question is how much that stricter criteria, which have impact on final cost of highway drainage, contribute to overall drainage efficiency.

On the example of two Croatian cities with considerably different climatic characteristics, the runoff volumes and masses of pollution for different overflow criteria are modeled on the same hypothetic section of highway. Using input data from the case studies on pollution buildup and washoff undertaken in USA, results of simulation with USEPA SWMM-5, are analyzed and compared with overall highway drainage efficiency. As a final conclusion some recommendations regarding design criteria are given.

Keywords: highway drainage, pollution buildup, pollution washoff, SWMM-5

1. Introduction

Since 1980s, in the Republic of Croatia there have been special regulations imposed for the drainage design, while building the highways. The aim of those rules is the protection of underground and surface waters and soil, from the adverse impact of the highway runoff.
The drainage system consists of water resistant open and/or closed conduits, which collect the runoff, oil-grease separators (OGS) where the floatables and settleables are separated, and the outfall to the ground or the watercourse. If the roads go through the ecologically more sensitive areas, besides the OGS, additional best manage practices BMPs must be used, in order to achieve additional effects in the runoff treatment [1].

At the very large catchment areas, the overflow structures (OS) with immersed baffles are allowed. They prevent the outflow of floatable oils and greases. The criterion for dimensioning of OGS and OS is the critical rain intensity, i.e. critical inflow that runoff produces at the facility site. Critical inflow determines the beginning of overflow at OS, and with OGS, it determines the necessary area between two emerged baffles.

2. Problem definition

The first OGSs built in Croatia were dimensioned according to Swiss regulations [2]. Actually, the directives for designing highway drainage in the Swiss canton of Zurich were completely copied. In these directives, the critical rain intensity $i_{kr} = 10 \text{ l/s/ha}$, which is the rain with 15% exceedance frequency. The data are valid for the Swiss canton Zurich, of course.

As time went by, Croatian waters (Croatian Water Resources Management agency) started regulating higher critical intensities, explaining that they want to increase the efficiency and safety of OGS operation, and lessen the polluting impact at the ecologically sensitive area. First figures of $i_{kr}$ of 10 l/s/ha rose first to 15, then 20 and finally 25 l/s/ha, which increased the separator building costs. There is some logic in that, but the question is: Is the higher efficiency of the drainage system worth those higher costs of building?

3. Possible solutions

In order to answer this question, it is enough to obtain rainfall intensity data for the specific location, for the last 10 years. By statistic data processing, it is possible to determine the frequency or duration of certain rain intensities. From the intensity – duration curve, it is very easy to determine area of intensity values, which is interesting from the engineers’ point of view. Besides the intensity and duration data, it is possible to determine the ratio of rain volume above and under the critical intensity figures. For performing that, it is enough to have rainfall database and statistic data processing software. The rainfall database should be obtained anyway, for the IDF curve calculation. This kind of analysis could be enough for final defining of critical rainfall.

Computer long-term runoff simulations from the specific drainage area could achieve better solution. The retardation, drainage area shape and slope, flow through open and closed conduits, can greatly influence the formation of runoff hydrograph. In this way, the ratio of
volume of water running through OGS or OS structure, and the volume released trough overflow could be calculated more precisely.

Both above mentioned possibilities are actually based on the hypothesis that relatively small quantities of untreated water will be released into the environment, and that most of the water will undergo the treatment. In the whole this procedure, however, it is not the quantity of released water that matters, it is the mass of pollution released, suspended or dissolved in that water. In order to determine the balance of pollution, it is necessary to know its dynamics of buildup and washoff at the drainage area.

3.1 Pollution buildup and washoff
This study does not go further into the history of theoretical and practical development, but states the following: Dust and dirt (DD) buildup on the road or urban catchment is generally non-linear phenomenon. At clean catchment, DD buildup at first has linear characteristics, but after some time the unit increment starts diminishing, and stops at some maximal value. That means that the local wind and the turbulences of the vehicles cause a certain quantity of pollution to “get lost” from the controlled catchments of the road. The quantity of the loss grows with the time between two rain events. That is the reason why the drainage system in the drier areas, will take less pollution through the BMP, than those in the wetter regions.

Pollutant buildup that accumulates within a land use category is described by either a mass per unit of catchment area or per unit of curb length. The amount of buildup is a function of the number of preceding dry weather days, and can be computed using different functions [3] [4].

The dynamics of the pollution washoff depends on numerous factors, but mostly on: rainfall energy, its duration, slope and texture of the catchment area. The rainfalls of greater intensity on steep and smooth surfaces will wash out more quickly and with more pollution from the catchment area, so that the concentration and mass of the washed out pollution will be greater than in the cases of slight rainfalls over flat and rough surfaces. Besides, it is important to say that different kinds of pollution have different dynamics of washing out, which mostly depends on the size and thickness of particles, and their connection with inorganic particles – carriers.

The dynamics of the pollution buildup and washoff from the catchment has been described by different mathematical models, that take account of the whole range of different variables, but the reliability of the simulation results is very little, if there are not enough data on the dynamics of the processes themselves. In that sense, there hasn’t been done anything in the Republic of Croatia. An analysis done at the illustration level has been done here. The intention was to show that the initial standards for drainage facilities designing, for the same level of protection, change according to the locations with different climate characteristics.

Well-known US-EPA software SWMM5 [5] was used as a tool, since it can do long term simulations of the runoff, estimating at the same time the buildup and the washoff from the catchment. While doing so, it is possible to calculate the concentration of pollution in time, and the total mass in the time intervals wanted.
Two weather services in Croatia were taken as examples. The first one was in Slavonski Brod, which is in the Continental part of the country, with the average rainfall of 700 mm, and the other one is situated in Parg, a small place in the region of Gorski Kotar, with the average rainfall of 1200 mm. Just the parallel sequence of rainfall data for three years was analyzed. The data time step is 5 minutes. It was supposed then, that a classic highway with exactly the same dimensions (length 1 km, width 20 m and slope 0.5%) was built at the areas of weather services. At the end of the section there is OS, from which the water flows to BMP, and the excess is relieved without treatment, directly in the environment.

It was supposed that DD build-up follows the saturation function [3]. Buildup B begins at a linear rate that continuously declines with time, until a saturation value is reached,

\[ B = \frac{C_1 \cdot t}{C_2 + 1} \]

where \( C_1 \) = maximum build-up possible (kg/ha) and \( C_2 \) = half-saturation constant (days to reach half of the maximum build-up).

Half-saturation time of 5 days was chosen, and with maximal value of build-up of 80 kg/ha. DD was the only indicator of pollution because it is the best representative of the total pollution.

Pollutant washoff from a given land use category, occurs during wet weather periods and can be described in different ways [4]. In this specific case, exponential washoff function was used. The washoff load (W) in units of mass per hour is proportional to the product of runoff raised to some power and to the amount of buildup remaining, i.e.,

\[ W = C_1 \cdot q^{C_2} \cdot B \]

where \( C_1 \) = washoff coefficient, \( C_2 \) = washoff exponent, \( q \) = runoff rate per unit area (mm/hour), and \( B \) = pollutant buildup in mass (kg) per unit area or curb length.

In the case we are discussing, \( C_1 \) value was chosen to be 0.1, and \( C_2 \) value was 1.

4. Simulations

The sequences of rain intensities were analyzed first, and the intensity – duration calculation was done. The total quantity of rainfall in the period monitored was 1609 mm for Slavonski Brod and 3184 mm for Parg. The results for \( i_{kr} \) from 10 – 25l/s/ha were calculated, and can be seen in the Table 1.

The table clearly shows that the intensity of 10l/ha covers the presumption from the Swiss rules.

In the long-term simulation of the outflow from hypothetic catchments, the kinematic wave routing method with 5-minute time step was used, and the results are given in the Table 2.
Table 1  Exceedance frequencies of rain intensities for Slavonski Brod and Parg in period 2001-2003.

<table>
<thead>
<tr>
<th>iᵢ (l/s/ha)</th>
<th>Sl. Brod</th>
<th>Parg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exceedance frequency (%)</td>
<td>Exceedance frequency (%)</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>15</td>
<td>7</td>
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<td>20</td>
<td>3</td>
<td>5</td>
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<tr>
<td>25</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2  The ratio of treated and non treated volume of runoff and mass of DD

<table>
<thead>
<tr>
<th>iᵢ (l/s/ha)</th>
<th>Slavonski Brod</th>
<th>Parg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vᵢ/Vᵣ (%)</td>
<td>DDᵢ/DDᵣ (%)</td>
</tr>
<tr>
<td></td>
<td>DDᵢ/DDᵣ (%)</td>
<td>Vᵢ/Vᵣ (%)</td>
</tr>
<tr>
<td>10</td>
<td>16,2</td>
<td>16,2</td>
</tr>
<tr>
<td>15</td>
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<td>10,8</td>
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<td>8,0</td>
</tr>
<tr>
<td>25</td>
<td>6,0</td>
<td>6,1</td>
</tr>
</tbody>
</table>

Vᵣ  non treated runoff
Vᵣ  total runoff volume
DDᵣ  non treated mass of DD
DDᵣ  total mass of DD

The results from Table 1 and 2 are shown graphically in Fig. 1.

If daily build up of DD is supposed constant (t=1 day) in the period of 3 years, as the simulation period is that long, 14600 kg of DD settles on the road surface.
Table 3 shows the efficiency of the drainage system before entering BMP. If we suppose that the efficiency of BMP is 80%, we can get the overall efficiency of the drainage system.

### Table 3 Ratio of treated and total DD, and overall efficiency of the drainage system.

<table>
<thead>
<tr>
<th>(i_{kr}) (l/s/ha)</th>
<th>Sl.Brod</th>
<th>Parg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DD\text{tr}/DD\text{t} (%)</td>
<td>Overall eff. (%)</td>
</tr>
<tr>
<td></td>
<td>DD\text{tr}/DD\text{t} (%)</td>
<td>Overall eff. (%)</td>
</tr>
<tr>
<td>10</td>
<td>44</td>
<td>35</td>
</tr>
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<td>15</td>
<td>47</td>
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<td>49</td>
<td>39</td>
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<tr>
<td>25</td>
<td>50</td>
<td>40</td>
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</tbody>
</table>

DD\text{tr} treated DD

For the 2.5 times increase of useful surface of OGS, we get only 5 – 6% increase of overall efficiency of the drainage system.

5. **Comment on the results**

The presumptions for the choice of critical intensity of 10 l/s/ha taken from Swiss regulations, would be valid in Croatia, but with higher deviations for the areas with average annual rainfall above 1000 mm.

The results show that the increase of the \(i_{kr}\), does not correspond with equal improvement of the highway drainage system efficiency, but it only increases the cost of building. This can be proved with hydrologic and hydraulic analysis, as well as with the analysis of pollution buildup and washoff, and especially by calculating the overall efficiency.

Additional analysis by changing the catchment geometry can prove the changes caused by the size or slope of the catchment, and the same thing could be done with change of the pollution buildup and washoff dynamics.

**Summary**

The present criteria for dimensioning of OGS and OS within the highway drainage system in Croatia are not satisfying. The critical intensities of rainfall above 15 l/s/ha are generally unreasonably high and never elaborated. According to the possibilities so far, the rainfall data supply or the purchasing computer software is not a problem, and neither should be the minimal hydrologic rainfall analyses, from which an optimal critical intensity can be chosen. It should be enough that the water authorities regulate the minimal duration and minimal volume of the rainfall that must be let through the treatment system, before the final release.
The pollution buildup and washoff dynamics estimate gives the best indicators of drainage system efficiency, and it is a real challenge for the researchers. In that sense, the first field researches should be finally done.

References

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