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ASSESSING STREAM WATER QUALITY INFLUENCED BY STORM OVERFLOWS FROM SEWERS

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Abstract: For open channels significant pollution sources during the intensive precipitations are outflows from storm-water overflows on the sewer network. When combined with low discharges in rivers, the water released from overflows can cause high concentration of pollution in receiving open channels. In this paper, the results of computer modeling of the impact of storm-water overflows on the stream water quality in three municipalities in Czech Republic are shown. The local river networks are the main receivers in the cities where storm-water overflows are led in. The results serve as a base for the proposals on the measures, improvements and structural modifications.

Keywords: Stream water quality, Storm overflows

1. Introduction

The municipalities have been traditionally provided with combined sewer systems. Over the decades, newly built urban areas have been appended to the existing sewer mains, causing their frequent overloading. Various technical and environmental measures have been adopted in order to provide sustainable storm-water management [1]. One of the technical measures for improving the insufficient capacity of combined sewers is to construct Storm-Water Overflows (SWO) and storm-water retention tanks.

In the European context, the European Water Framework [2], formulates objectives concerning stream water quality. In the Czech Republic, the immission and emission standards for the release of both municipal and industrial effluents to the surface streams are specified in the [3] and [4]. They are expressed in terms of maximum permissible concentration limits for individual water quality indicators like Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), nitrogen compounds, etc. In practice, majority of permanent effluent discharges for example Waste Water Treatment Plants (WWTP) are subject to periodic water quality checks carried out by authorized bodies. The water quality might be also influenced by interaction ground water are river flow [5].

However, the limit values are not prescribed for instantaneous releases of sewage water from storm-water overflows, which is mostly due to difficulty of measuring released wastewater during heavy rainfall [6]. For this type of effluents, permissible limits have to be specified individually based on the character and quantity of the released wastewater, on the water flow and quality in the receiving stream and its environmental value. Cost-benefit analysis is required to indicate the effectiveness of the measures proposed. During the last decades, numerous studies have dealt with both municipal and industrial effluents to the surface waters [7] and others. Special attention has been paid to water quality monitoring, measurement and contamination tracking in relation to drainage system [8], [9], [10]. Here various pollution indicators and polluting agents have been studied. These were dissolved oxygen, BOD_5 and COD, nitrogen and phosphorus compounds, temperature, fecal contamination, and many others.

The appropriate tool for the assessment of the impacts of sewer overflow effluent discharges into surface streams is pollution transport modeling [11], [12]. In practice, both single models of sewer and open channel networks and coupled models including both systems are used [13]. In this study the single stream water quality model was used, which enables easier, faster and more transparent data handling. The paper deal with water quality issues and standards and discusses quantification of the effluents from storm-water overflows.

2. The studied open channel systems

The general water management plans are elaborated as a part of urban plans for individual municipalities. These plans also include the studies quantifying the effect of sewer network on the stream water quality during heavy rainfall events when the storm overflows are in operation.

The purpose of the presented study was to assess the changes over time in the concentration of six water quality indicators, namely BOD, COD, Ammonia nitrogen ($N\text{-}NH_4$), total Nitrogen (N_t), total Phosphorus (P_t), and Suspended Solids (SS) in the principal rivers (*Table I*) in the city of Brno, Vyškov (*Fig. 1*) and Kuřim. Assessed rivers represent small and middle size streams. *Table I* summaries all concerned rivers.

In case of the cities of Brno and Vyškov, the improvements of existing SWO and also the design of new ones have been planned. The rehabilitation of sewerage also involves the design of storm-water retention tanks, which attenuate the peak discharges in the sewers and so decrease the released amount of polluted water to receiving streams via storm-water overflows. For these arrangements water quality improvement was also assessed.

Table I

Summary of modeled rivers

City	River	Reach length [km]	Average width of the river bed [m]	Number of SWO
Brno	Svratka	15.0	20	24
Brno	Svitava	12.0	12	28
Brno	Ponávka	3.5	4	1
Brno	Leskava	2.5	2	1
Vyškov	Velká Haná	0.7	5	3
Vyškov	Malá Haná	0.4	4	1
Vyškov	Drnůvka	2.0	3	13
Vyškov	Roštěnicky potok	1.0	4	5
Vyškov	Haná	5.0	9	31
Kuřim	Kuřimka	6.4	3	8
Kuřim	Luční potok	1.4	1	2

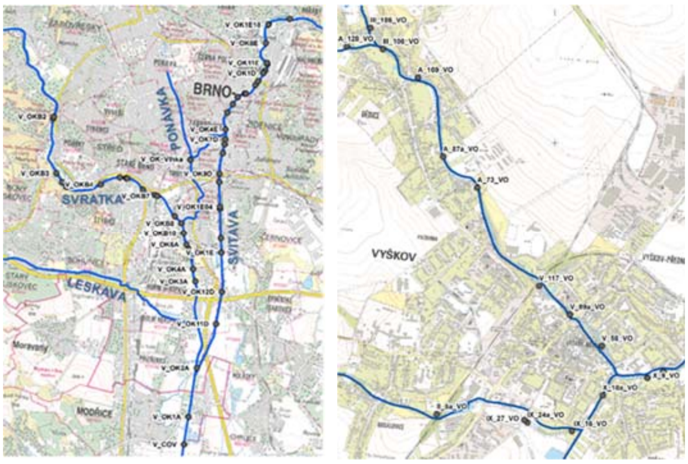

Fig. 1. The extent of modeled river network in the cities of Brno and Vyškov

3. Methods

The complex urban projects comprise two parts, namely studies of the sewer systems and studies of the river networks. Within both parts, hydraulics and water quality are being assessed for various hydrologic scenarios and also for proposed variants of facilities built on the sewer network (storm-water retention tanks, storm overflows). All studied projects were realized in co-operation with Aquatis consulting engineers, who were responsible for the solution of the sewer network issues. They provided input values for the stream water quality model in the form of water discharges from overflows during the design storm event, and also the water quality of sewage water released into the streams. For the cities Brno and Vyškov the variants of remedial measures were also subject of the solution.

The studies of water quality in open channels consisted of:

- the problem formulation and set-up of a numerical model;
- basic data assembly and analysis;
- numerical modeling of pollution transport in streams;
- evaluation of the obtained results, discussion.

Mathematical model

A mathematical model was applied to evaluate the present state of water quality in the streams and to assess the effects of proposed improvements and arrangements on the principal sewer mains. A model consisted of hydrodynamic and pollution transport modules.

The hydrodynamic module was one-dimensional unsteady open channel flow model described by continuity equation [14]:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=q, \quad Q=u\cdot A, \tag{1}$$

and momentum conservation law:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right)+gA\frac{\partial h}{\partial x}=gA\left(J_0-J_f\right), \tag{2}$$

where A is the cross-sectional area; Q is the discharge; q is the lateral inflow; u is the mean stream velocity; g is the acceleration due to gravity; h is the water depth; β is the momentum coefficient; J_0 is the bed slope; J_f is the friction slope. Generally all variables are function of time (t) and river stationing (x).

Initial conditions express known discharge Q_0 and water stage h_0 at the beginning of the modeling. This was represented by the steady state before the storm event and corresponding to two modeled scenarios with average annual discharge Q_a and 270-days discharge Q_{270}

$$Q(x,t=0)=Q_0(x), \tag{3}$$

$$h(x,t=0)=h_0(x). \tag{4}$$

Boundary conditions hold:

$$Q(x=0,t)=Q_U(t), \tag{5}$$

$$h(x=L,t)=h_D(Q), \tag{6}$$

where Q_U is the discharge at the upstream end of the modeled streams; $h_D(Q)$ stage-discharge relation at the downstream end of the flow domain.

Initial and boundary conditions were expressed by the average annual and 270-days discharges. The discharge varied between 4 - 13 m^3/s for the Svratka river, 2.5 - 5 m^3/s for the Svitava river and 0.2 - 0.7 m^3/s for the Haná river. Discharges of all the other minor tributaries were less than 0.2 m^3/s. The upper boundary conditions were introduced in the stream profiles upstream of the cities, which were not influenced by sewer overflows. The downstream boundary conditions were set up as the rating curves (6) at the downstream profiles of the Svratka, Haná and Kuřimka Rivers located far enough from the downstream profiles of interest.

At the stream water quality model the effect of transversal mixing was neglected as the sewer separators are in most cases located on both banks of the streams, and also due to the relatively small width of the streams. A one-dimensional convection-dispersion model was applied:

$$\frac{\partial c}{\partial t}+\frac{\partial (u\cdot c)}{\partial x}-\frac{\partial}{\partial x}\left(D_L\cdot\frac{\partial c}{\partial x}\right)=f+R \tag{7}$$

with concentration c; coefficient of longitudinal dispersion D_L; constitutive changes f and pollution sources R. Mean stream velocity u was determined by the hydraulic module Eq. (1) to (6).

The initial condition was represented by a constant concentration in the streams during the 'no pollution' period:

$$c(x,t=0)=c_0(x), \tag{8}$$

where c_0 is concentration taken from the *Table II*.

Table II

Concentrations [mg/l] in surface streams during 'no pollution' period

Stream	BOD_5	COD	N-NH_4	N_t	P_t	SS
Brno (Qa, Q270)	4.0	22	0.3	5.5	0.4	10
Vyškov (Qa)	8.0	32	3.5	8.0	0.6	10
Vyškov (Q270)	8.5	37	5.0	9.1	1.2	12
Kuřim (Qa)	2.0	28	0.25	1.7	0.7	10
Kuřim (Q270)	1.8	19	0.2	1.5	1.0	12

The dispersion coefficient D_L was expressed as a product of stream velocity u and dispersivity α [15], [16]:

$$D_L=u\cdot\alpha. \tag{9}$$

Upstream boundary conditions were specified as known concentrations in the river profiles upstream of the municipalities (*Table II*). The downstream boundary condition was set as a zero concentration gradient for the downstream profiles mentioned above:

$$\left.\frac{\partial c}{\partial x}\right|_{Downstream} = 0. \tag{10}$$

Data assembly and analysis

The following data were collected for the stream water quality analysis:

- river network topology (reach lengths, confluence locations, etc.);
- the geometry of streams (cross sections) including data about structures (weirs, bed drops, bridges, water intakes, outflows and transfers, etc.);
- hydrologic data (catchment area, annual and m-day discharges, measured concentrations of individual water quality indicators);
- location of pollution sources - storm-water overflows, outlets from industrial facilities and WWTPs;
- time series of wastewater discharges from individual separators, and the water quality (concentration) of the released wastewater.

The data for the catchments, topology and geometry of open channels were obtained from archival sources owned by the Morava River Board Administration, while hydrologic data in the streams were provided by the Czech Hydro-meteorological Institute [17], [18]. The discharges in streams during 'no pollution' periods when the storm overflows were not in operation were represented by annual average discharge Q_a and 270-day discharge Q_{270}. Time-dependent discharges released from the sewer system via storm-water overflows (*Fig. 2*) were determined by the hydraulic model of the three analyzed sewer networks set up by Aquatis consulting engineers with the use of MOUSE software [16].

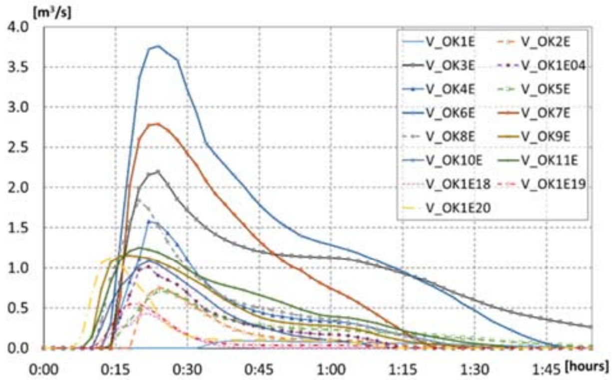

Fig. 2. An example of hydrographs at the storm-water overflows in Brno (the legend lists the IDs of the storm-water overflows)

Based on the long-term water quality sampling average concentrations in streams before the storm event were evaluated. The analysis showed practically identical concentrations for both discharge scenarios (Q_a, Q_{270}) in the streams in the city of Brno and only minor differences in the streams in the Vyškov and Kuřim.

The dispersivity α for individual river reaches was taken from the results of previous extensive research carried out in the areas of interest [19] with respect to the available literature data [20]. The dispersivity was assigned the value 11 for the Svratka River, 8 for the Svitava River and 6 for the rest. These values correspond to hydrodynamic dispersion D_L = 5-8 m^2/s.

The concentrations of individual components of released sewage water were derived from the observed data taken from the sewer network during extreme rainfalls. However, the regular water quality monitoring at sewer systems is still not a standard in the Czech Republic. Therefore, only few sampling 'campaigns' were organized by the sewer operators to gather realistic pollution data from the sewers during storm events in various parts of the cities. The campaigns showed random results with no typical trend or behavior. In several cases, probably due to accidental scour or flush out of sediments from a sewer network the concentrations increased more than 10 times instantaneously with the duration of several minutes. Moreover, the change in concentration occurred for different indicators in different moments not corresponding to changes in discharge. The obtained data were therefore compared with generally used wastewater data published in the literature [21] and experienced in other localities. Finally, constant-time averaged concentrations of released sewage water along typical sewer mains corresponding to river catchments were agreed by the sewer operators and the board of consultants (*Table III*).

Table III

Time-averaged concentrations [mg/l] at storm-water overflows at individual catchments

River catchment	Svratka	Svitava	Ponávka	Haná	Kuřimka
BOD_5	167	93	169	284	75
COD_{cr}	508	288	260	753	220
$N\text{-}NH_4$	11	17	5	27	9
N_t	26	32	34	38	17
P_t	4.3	3.1	7.5	6.5	2.7
SS	921	435	896	468	300

The differences between concentrations of pollutants coming from SWO at individual catchments are given by the following factors:

- higher BOD, COD, N-NH4, N_t and P_t concentrations occur at relatively small and highly urbanized catchment (the Haná River catchment) where pollution from inhabitants dominates;
- on contrary the mentioned pollution indicators are rather smaller at the Kuřimka catchment where more outdoor areas and parks are connected to the sewer system;
- higher SS at the Svratka River catchment corresponds to the sewer mains (along Svratka and Ponávka) with large portion of unpaved areas drained directly to the sewer. The higher values of concentration are also related to sudden flush out of

SS from the sewer. This may represent historically accumulated amount of SS depending on network topology, rainfall history, etc.

Pollution sources R in Eq. (7) were specified as mass outflow during the release of sewage water from the storm-water overflows. It was calculated as the product of concentration (*Table III*) and instantaneous discharges released via storm-water overflows (*Fig. 2*). As the entire event at the related streams was relatively short (a few hours only) the system was considered to be conservative with no constitutive changes i.e. $f = 0$ in Eq. (7).

4. Proposed remedial measures

Based on the results of water quality modeling in streams for the present state the arrangements to the sewer systems (i.e. the location, arrangement and hydraulic parameters of retention tanks and storm-water overflows) were proposed in the cities of Brno and Vyškov.

As an example the arrangements on the Brno city sewer system are described. There are 50 existing storm-water overflows in the Brno sewer system. The proposal is to add another 12 overflows along the main sewer collectors (named A, B, C, D, E) and to modify 13 existing overflows to improve their hydraulic function, and also to remove 14 existing unsatisfactory overflows. Volume of newly proposed retention tanks is 50 000 m^3. The arrangements on the Vyškov city sewer system involved removal of 20 overflows out of 54 existing and proposal of 16 new overflows. The effect of arrangements on the sewer system in the Brno and Vyškov is discussed below.

5. Results and discussion

Assessment of present state

The results of the modeling in terms of maximum calculated concentrations along the individual river reaches for Q_a are summarized in *Table IV*. When compared with required standards according the [3] it can be seen that the maximum concentrations in streams during the storm event significantly exceed the immission limits (IL in *Table IV*). The rate of exceedance can be hardly generalized as it depends on the size of the stream, characteristics of the catchment, mixing ratio between sewage and runoff water, on the history of storms and their randomness in terms of intensity, duration, etc. However following conclusions may be formulated.

Higher pollution concentrations may be expected in smaller receiving streams at which during small 'no storm' discharges the resulting concentration after mixing nearly corresponds to that of the released wastewater.

At present, the pollution concentrations during extreme rainfall events exceed the limits more than by 50 times (small streams Roštěnicky and Drnůvka - N-NH_4). In case of larger rivers in the area of Brno city the ratio exceptionally exceeds 30. More detailed results for particular streams may be seen by comparing data in *Table IV* and *Table V*.

See also example in *Fig. 3*. An exceedance of stream water quality limits is more significant for BOD_5, $N\text{-}NH_4$ and P_t.

Table IV

Maximum calculated concentrations of WQ indicators in [mg/l] and immission limits (IL) - present state at discharge Qa

indikátor	Svratka*	Svratka**	Svitava	Leskava+	Podávka	Haná	Roštěnicky	Drnůvka	Kuřimka	Luční.	IL
BOD_5	116	65	62	4	166	238	274	277	72	74	6
COD_{CR}	293	193	195	22	252	639	732	762	213	213	35
$N\text{-}NH_4$	6.0	5.6	11.1	0.3	5.0	22.9	26.1	26.4	8.7	8.8	0.5
N_t	25.6	16.1	22.1	5.5	32.6	31.9	36.1	37.9	16.2	16.5	8
P_t	4.8	2.5	2.1	0.4	7.1	5.4	6.1	6.3	2.4	2.6	0.2
SS	662	351	281	10	888	381	437	447	281	286	25

Note: Svratka* at km 44.11, Svratka** at km 40.19, the River Svitava at km 11.2 and the Leskava River at km 1.15, + there are no storm-water overflows at the Leskava river for present state scenarios.

Table V

Maximum calculated concentrations of pollutants in [mg/l] and the immission limits - after proposed improvements at discharge Q_a

indicator	Svratka*	Svratka**	Svitava	Leskava	Ponávka	Haná	Roštěnicky	Drnůvka	IL
BOD_5	65	35	30	90	91	164	157	191	6
COD_{CR}	178	105	98	242	225	440	423	507	35
$N\text{-}NH_4$	3.5	3.0	5.1	4.8	4.7	15	14	17	0.5
Nt	14.8	10.0	11.1	18.7	17	21	20	24	8
Pt	2.8	1.5	1.1	3.8	3.8	4.1	3.6	4.6	0.15
SS	405	191	137	567	592	264	253	310	25

Note: *. ** see *Table IV*.

The water quality limits are exceeded for more than several hours depending mainly on the stream water velocity and the length of the river reach equipped with sewer overflows. The peaks mentioned in *Table IV* and *Table V* occur usually less than 30 minutes. In general smaller streams suffer from more extreme concentration for a relatively shorter period than in case of larger streams (even up to 10 minutes).

The spatial location of SWOs along the streams and interference of releasing wastewater crucially affects achieved maximum concentrations. Similarly the significant role in stream water quality management and effect on the concentration downstream of stream confluences may have location of retention tanks and SWOs causing time lag of maximum concentration at the tributaries (see *Fig. 3*, km 40.2).

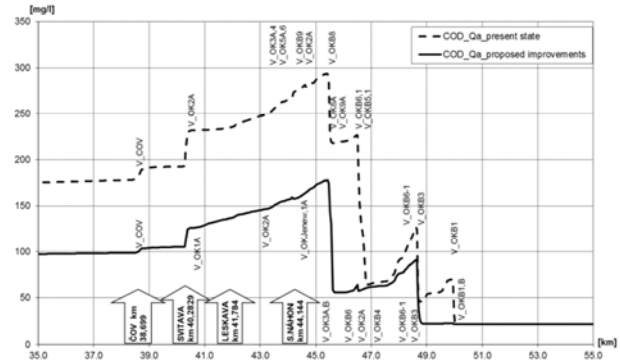

Fig. 3. Comparison of the present and proposed state for the Svratka River maximum COD concentration envelope at the discharge Q_a (description over lines indicates the location of the storm-water overflows)

Certain decrease of peak concentration is caused by hydrodynamic dispersion. As the dispersion coefficient is governed by stream velocity the more significant peak concentration attenuation due to dispersion can be seen in larger streams and also in reaches with higher effluents from SOWs. The qualitative trend of concentrations along the streams is similar for various water quality indicators.

In graphical form the maximum concentration envelopes are shown for the Brno city in *Fig. 3*. Sudden increases in maximum concentration along the streams appear in several locations. The cause is either SWO with high discharge or concurrent spills from several SWOs. The significant increase of concentration is also caused by closely located SWOs.

Especially in case of small stream (e.g. Drnůvka) with SWOs regularly distributed along the channel the wastewater in the sewer foreruns the stream flow which results in reducing peak concentrations at the cost of prolonging the increased concentrations.

The effect of arrangements on the sewer system

To improve the pollution amount coming from sewer network to the receivers the technical measures were adopted at sewer systems in the cities Brno and Vyškov. They consisted in the improvements of hydraulic function of SWOs and also by proposal of additional storm retention tanks. The modeling was carried out for both variants i.e. for present state and proposed improvements. The results for the state after improvements are summarized in *Table V* for the discharge scenarios corresponding to Q_a. The maximum calculated concentrations of pollutants are compared with immission limits according to the [3].

The improvements mentioned above would decrease the maximum concentration of released pollution up to 50% (see *Fig. 3*). Generally the arrangements bring up decrease of maximum concentration about 30% in average. However, stream water quality standards (immission limits) are still significantly violated during extreme events.

The immission limits are exceeded significantly in all modeled scenarios. Thus the immission standards and thresholds given by [3] are not fulfilled and significantly exceeded during the extreme storm events. However, [3] and [4] should not be directly applied for spills from overflows and water quality in rivers during storm events as these standards have originally been intended only for permanent pollution effluents.

6. Conclusions

It the study the influence of pollution released form the sewer system via storm overflows on the water quality in receiving streams is assessed for three localities in the Czech Republic. The study also quantifies the effects of proposed measures on the sewer system on stream water quality. Water courses of different scale were assessed. For the assessment the 1D numerical modeling was used.

It must be noted that only limited water quality data from monitoring in the sewer systems and also in the receiving streams during storm events were available for reliable stream water model calibration.

It can be expected, that in the water courses immission water quality limits are exceeded in average about 30 times in case of small streams (with maximum exceedance ratio higher than 50) and approximately 3 to 10 times in case of medium size streams. The proposed measures on the sewer system (retention tanks, overflows) can attenuate peak concentrations of individual water quality indicators by 40% to 60% of those during the present state. The duration of the concentration peaks varies from 10 minutes in the upper river reaches and small rivers up to few hours at downstream reaches of the main rivers.

Traditional emission and also immission standards should not be directly applied for occasional effluents from sewer overflows. Acceptable thresholds should be set individually on the basis of the ecological condition of each watercourse by the agreement of concerned experts (sewer system managers, ichthyologists, water quality engineers and others). In general, two criteria should be applied. These are the resulting maximum instant concentration of pollution in surface water and its duration, and also the overall annual mass of pollution (e.g. in t/year) or during individual storm events with given periodicity. These data, when linked to the investment cost of the considered measures, can provide basic information for the decision making process. The basis for decisions like this can be obtained via sewer and open channels hydraulic and water quality modeling.

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