RAIN MODEL FOR INVESTIGATING OVERFLOW IN COMBINED SEWER SYSTEMS UNDER REGULAR OPERATING CONDITIONS

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ABSTRACT

In combined sewer systems, even regularly occurring heavy rainfall can cause overflows to occur under regular operating conditions. These overflows result in a mixture of rainfall and raw wastewater being transported to the receiving water body. Though hydraulic models provide a means for calculating the amount of overflow resulting from a given rain event, correct estimations for the annual amount of pollution can only be made after processing multiple year's worth of rain event data. In order to reduce the time needed to complete the numerical simulations, a method is proposed for correctly modeling the overflow of a long series of historical rainfall data, using a reduced input dataset. Based on rainfall intensity measurements, a series of rain events was divided into block rains. The complete series of block rains was then replaced with 9 representative (weighted) block rains, each of equal rainfall. The method was tested on the hydraulic model of a 7500 ha catchment of the Budapest combined sewer system. When compared to overflow results attained by processing 3 years worth of rainfall data, sampled in 10 minute intervals, the overflow results of the 9 element numerical model deviated by less than 12%. The time necessary to complete the hydraulic simulations of the latter was 1/27th of the former. These faster numerical models will enable designers to search for optimal technological solutions from both an environmental as well as economic point of view.

KEYWORDS: *Combined system, Overflow, Rain model, Rainfall runoff, Sewer*

I. INTRODUCTION

Due to historical as well as economical reasons, many of the world's largest cities have their wastewater and rainwater flowing through combined sewer systems. Due to the growth of these cities, the increase of population density, and climate change, a continuous increase in sewage overflow resulting from rainwater can be expected ([1], [2]). Being that combined sewer overflows (CSO) are used to protect these systems from overloading, an increased level of rainwater and raw sewage, passing through the overflows, increases the loading of the receiving water body.

The following part of this paper is structured in the following manner: In section II a brief background is provided about CSO related pollution and the calculation methods currently used for determining overflow volume. Our proposed method, including detailed steps, is explained in section III. The validation of the methodology through a case study, including results, is given in section IV. Section V summarizes the presented work and section VI presents the possibilities for further development.

II. RELATED WORK

Today, an important area of research is the dispersion of pollutants through overflows: pharmaceuticals ([3]), bacteria ([4]; [5]) organic compounds ([6]) and heavy metals ([7], [8]). Fresh publications [9] have also brought other sources of danger to our attention, such as that of sedimentation resulting from pharmaceuticals and personal care products (PPCP) depositing in sewers and being washed away by rains. Pollutants dispersed through overflows have the following sources: (1) raw wastewater mixing with rainwater, (2) pollutants being washed from streets and rooftops, (3) settled sewage being resuspended ([10]).

Monitoring and control of CSOs have not been addressed in detail in water-related legislations until the Water Framework Directive [11] appeared, requiring the “good” ecological and chemical status for all surface waters by 2015. The Urban Waste Water Treatment Directive (UWWTD) 91/271/EEC is not specific concerning CSO control, but only suggests that control measures could be based on dilution rates, plant treatment capacity, or spill frequency ([12]). Hungarian ordinances 220/2004 and 28/2004 KvVM define discharge thresholds, but do not deal with overflows in detail, only specifying that sufficient dilution is necessary. European regulations regarding the monitoring of overflows are quite diverse, but, for the most part, do not require continuous monitoring.

Monitoring the amount of mixed water passing through overflows would require the continuous measurement of the volume flow rate, which is a considerably expensive and challenging technological assignment [13]. There exist other alternative solutions for determining when, and to what extent, overflow occurs, such as measuring the temperature of the overflow [14], or making turbidity measurements [15] in order to determine the extent of pollution resulting from a given occurrence, but the continuous evaluation of concentration and volume flow rate is only possible in a limited number of locations, and therefore an assessment of an entire cities discharge, for example, is not possible.

In order to reduce the level of overflow, designers need to take advantage of hydraulic models during the design process. The level of overflow can be regulated with the optimization of weir levels, or with the incorporation of rainwater tanks ([16]). In order to determine the optimal weir level, placement of rainwater tanks, or other hydraulic parameters, hydraulic simulations must be repeated multiple times during the optimization process, which can require a large amount of computational power, when investigating an extensive sewer system.

The literature gives examples of simplified, concentrated parameter hydraulic models, which utilize dynamic reservoirs, only providing information regarding the amount of water reaching the endpoint and the amount being separated off ([17]), but these models, for the most part, can only be applied to less complex, e.g. rural, territories. Extensive, complex systems, on the other hand, have many interconnected points and interactions which concentrated parameter models are not able to handle. A further issue regarding reduced hydraulic models is their limited ability to determine the amount of pollution being emitted. More precise emission levels can be determined using simulations which utilize data from geographic information systems [GIS], taking into consideration pollution transport and the spatial distribution of pollution sources ([16]).

The computational power required to calculate the overflow can also be reduced by conducting only one representative simulation for all similar rain events, the results of which are taken into account by a weighting factor, proportional to how frequently the rain event occurred. In order to help identify similar events, all rain events should be replaced by model rains which can be simply parameterized, examples for which could be a block rain characterized by a given intensity and time duration, or a peaked profile corresponding to the average ([18]). In determining the parameters of a rain model, such as the duration of a replacement block rain, the technical objectives of the application must be taken into account.

In the present paper, a method suitable for creating a series of replacement block rains consisting of 3x3 elements is introduced. The method is applied, processing a 3 year long data series of rainfall intensity measurements recorded in Budapest. The method is validated to results from an existing hydraulic model of the sewer system, comparing the discharged volumes of each overflow calculated from the 9 element rain model to those calculated from the complete reference series.

III. METHOD FOR PRODUCING REPRESENTATIVE MODEL RAIN SERIES

A series of model rains can be produced from a set of rainfall intensity measurements according to the following methodology:

1) Taking the data collected at the measurement station located close to the centroid of the catchment, which was sampled in ten minute intervals, the data was divided into independent rain events, which are separated by intervals of no precipitation. It is suggested that the minimum time interval separating two rain events be taken as the time of concentration of the entire sewer system (which should contain the time of concentration of both the surface flows and network flows).

2) Assuming that snowmelt does not cause overflow, all rain events belonging to days having an average temperature below freezing will be removed from the data set.

3) Defining block rains for each independent rain event. The magnitude of rainfall belonging to each rain event is calculated by integrating the measured rainfall intensity. Using the hydraulic model of the sewer system, a lower intensity limit is defined. Under this limit, no overflow can occur in the sewer system. Only the steady-state models, which should be available from the design stage of the sewer system, are necessary for identifying the lower limit. The effective starting and ending points of each block rain are defined as the beginning of the measuring periods when the rainfall intensity first exceeds the lower limit intensity, and the last time period when it still reaches it, respectively. The quotient of the total height of the rainfall collected during the duration of the rain event, divided by the effective duration of the rain event, gives the effective rainfall intensity of the event.

4) The series of block rains are divided into 9 groups, having approximately the same amount of rainfall in each. This is illustrated in Figure 2. The first step in accomplishing this, is to divide the series of block rains into 3 groups with the help of a variable $a=i*T^b$, which is a function of the frequency of occurrence, where i is the intensity and T_b the duration of the event. The series of block rains are placed in order according to “a”, and then divided into three groups having approximately the same amount of events in each. “b” is defined by taking an average of the exponents used in the calculation of the intensity based on duration and frequency (IDF, [18], [19]) typical of the events in the investigated region . These three groups are further divided into three groups according to rainfall duration, assigning approximately the same amount of events to each group. Figure 2 shows the resulting groups, outlined with light blue borders.

5) A representative model rainfall is assigned to each of the 9 groups marked by red circles in Figure 3, the time duration of which is taken as the average of the time duration of each block rain within the group, and the intensity of which is taken as the quotient of the sum of all the heights of rainfall for the entire group, over the sum of all the time durations for the entire group.

Since the main goal of the present investigation was the validation of the above described methodology, the length of the time series was chosen to include hydraulic simulations of all possible rainfall intensities. This meant that 209 simulations of varying rainfall intensity needed to be executed on the given hydraulic model (which consisted of approximately 36 000 pipe sections) in order to process the investigated 3 year long time series, which will be described in detail in the following section.

It is evident that the results of a three year rainfall intensity time series cannot be used to appropriately approximate a long term average, but since the computational power required to produce and evaluate the series of 9 block rains is minimal, the method is suitable for evaluating statistically more exact rainfall models, taking local conditions into consideration, when longer time series of rainfall intensity – specific to the examined territories – are available.

IV. VALIDATION OF THE METHODOLOGY

The catchment area of the Buda Main Conduit (BMC) is 7500 ha (Figure 1.). This is Budapest’s second largest catchment, serving 400 000 residents. The sewer sections belonging to the catchment are predominantly combined sewer systems, with only being located along the perimeter of the catchment. The endpoint of the system is located at the Lágymányos Pump Station, from where the sewage is pumped over to the Central Wastewater Treatment Plant for treating. Fifteen overflows, regulated by weirs, secure the safe operation of the sewer system, with the river Danube serving as their receiving water body. The hydraulic model of the sewer system requires 32 000 pipe segments for modeling the system, totaling 700 km in length. The hydraulic model was created in KANAL++ system (see [20]) on behalf of and in cooperation with the Budapest Sewage Works Ltd., the sewer system operator.

The basic geometrical data required for the hydraulic model was provided by the geoinformatical database, which is maintained by the sewer system operator. Geometrical inaccuracies in the data were corrected in part by automated processes, and in part by manual processes. Subcatchments were defined and parameterized with the help of digital maps and according to land use (street, residential etc.). The slope and capacity of the hydraulic model was compared and validated to dry season filling and runoff time measurement data. The imperviousness and runoff dynamics of the subcatchments were validated to rainy season volume flow rate measurements conducted in multiple points of the system.

This model is often utilized in supporting the design process of new sections of the system and in the redesign of existing subsections. Beyond this use, the sewer system operator has allowed the hydraulic model to be used in the present investigation.

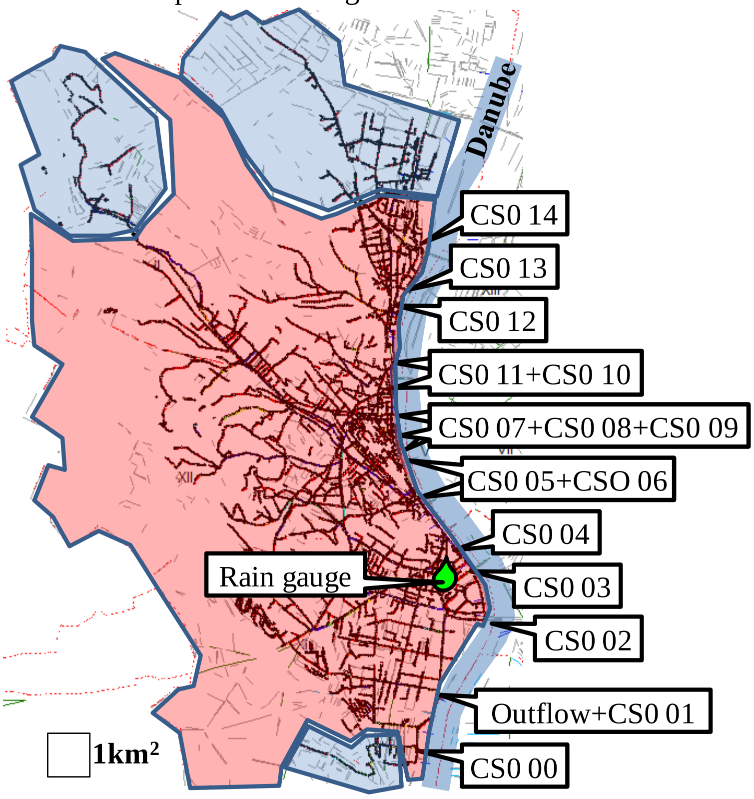

Figure. 1. Catchment of the BMC, including sewer segments of diameter greater than 500mm, the endpoint, and overflows

An investigation was carried out regarding the influences of the effective time duration, as well as the temporal change of rainfall intensity (for a given effective time duration), on the overflow volume. The comparative calculations were carried out on 12 test rain events depicted in Figure 2., varying in temporal change of rainfall intensity. The overflow volumes calculated with the hydraulic model are compared in Table 1. The first elements (#1) in both series, providing the basis for comparison in the group, are block rains, each having a return period of 1 year. The overflow volumes of the other 5 events are compared to these and a percentile difference is provided in the last row of the table.

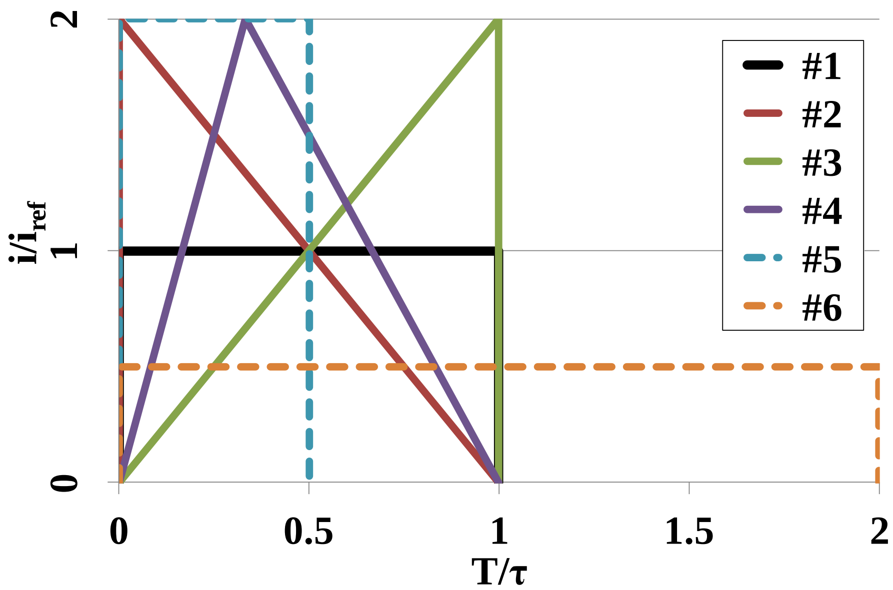

Figure 2. Temporal distribution of the rainfall intensity for the test rain events. Series 1.: 6 variations, τ=60min and i_{ref}=38.6 l/s/ha; Series 2.: 6 variations, τ=180min and i_{ref}=18 l/s/ha.

Table 1. Overflow volumes resulting from synthetic rain events, given in thousands of m^3, for all the overflows in the system, summation of all the overflows pertaining to one rain event, and percentile difference in overflow volume as compared to the first element in the series

	1. rain series						2. rain series					
Rain #	#1	#2	#3	#4	#5	#6	#1	#2	#3	#4	#5	#6
Spill volume	109.6	109.9	113.4	111.7	116.9	97.3	152.4	153.3	163.9	159.5	173.5	109.8
Diff. [%]	0.0	0.3	3.5	1.9	6.6	-11.2	0.0	0.6	7.5	4.7	13.8	-28.0

It can be seen from the results of the two series in Table 1, that the temporal variation of the rainfall intensity has minimal effect on the overflow volume. Investigating the spill volumes in Table 1, it can be seen that the percentile difference with regard to #1 is less than 5% for instances #2-#4 in the 1st series, and less than 10% for instances #2-#4 in the 2nd series. For instances #5-#6, we can see that the percentile differences are much greater, with the percentile difference doubling in magnitude, as compared to instances #2-#4. This demonstrates that overflow calculations are much more sensitive to the average rainfall intensity than to the temporal change of rainfall intensity, which underlines the importance of the way the effective time duration is modeled when substituting measured rainfall intensity profiles with block rains.

The effective time duration of any given rain event could be calculated according to the instructions given in step 3 of the methodology for producing a model rain series, on the basis of the lower intensity limit characterizing the given phenomena. The lower intensity limit used in transforming the block rains needs to be independent from all dynamic effects in characterizing the overflow of a system. Therefore, the lower intensity limit is defined here as being the maximum, steady-state, spatially evenly distributed rainfall, which does not yet cause any overflows anywhere in the system. In determining the lower intensity limit, the last overflow located in flow direction in the system will be the most critical point.

The 3 years worth (2005-2007) of rainfall intensity measurement data, which was analyzed in this investigation, was provided by the Hungarian Meteorological Service. The rainfall intensity data was collected at the meteorological station marked in Figure 1, having a temporal resolution of 10 minutes and rainfall height resolution of 0.1mm, which is measured using a tipping spoon. The spatial diversity of rainfall intensity can be accounted for by a territorial reduction constant for rainfall intensity. This correction was not applied to the data in the present investigation.

The rainfall intensity data set was divided into 263 independent rain events. Taking the lower temperature limit into consideration (according to step 2 of the method for producing representative model rain series), 54 of those events were excluded, resulting in 209 rain events of temporally varying intensity, which will hereafter be referred to as a reference rain series.

According to step 3 of the method for producing representative model rain series, the elements of the reference rain series of temporally varying intensity were converted into block rains. All measured rain events had at least one 10 minute interval of time when their intensity exceeded the 1.5mm/h lower intensity limit characteristic of the given system, and therefore the conversion to block rains did not result in the number of events being reduced.

According to the methods described in steps 4 and 5, the series of block rains was divided into groups, each consisting of elements having similar parameters, after which the parameters of the 9 representative block rainfalls, located in the centroids of the given sections, could be determined. Figure 4 visualizes the conversion process, while Table 2 presents the parameters of the 9 representative model rainfalls.

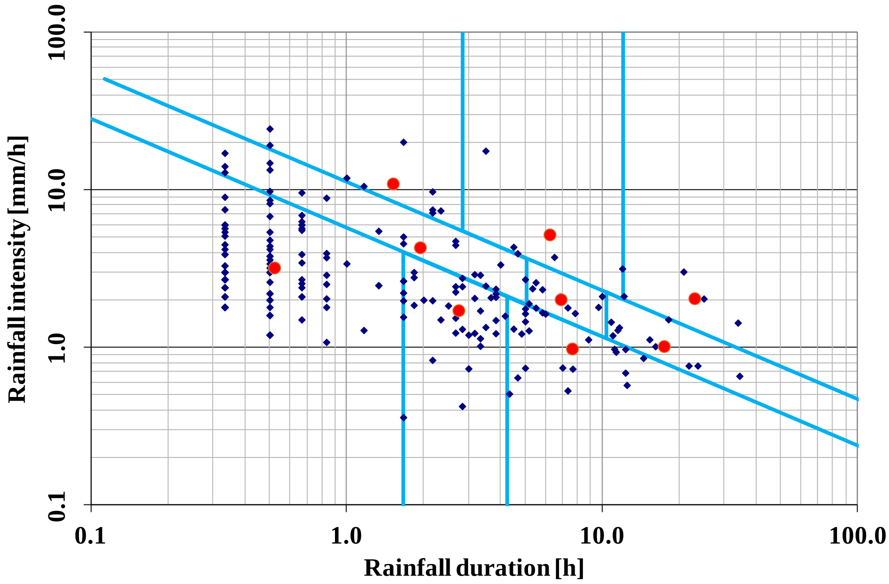

Figure 3. The reference rain series, which was converted into block rains, depicted in a rainfall intensity as a function of rainfall duration diagram (blue rhombuses), including group borders (light blue lines), and the centroid of each group (red circle)

Table 2. Parameters of the representative model rainfalls located in the centroids of the formed groups: n number of elements in the group, H total rainfall level, h rainfall level per rainfall event, T average duration of rainfall, i intensity of the group centroid

	n	H	H	T	I
[-]	[pcs]	[mm]	[mm]	[h]	[mm/h]
1	95	158.6	1.669	0.521	3.20
2	35	164.9	4.711	2.743	1.72
3	21	157.3	7.490	7.635	0.98
4	19	158.6	8.347	1.939	4.31
5	11	152.8	13.891	6.894	2.01
6	10	177.6	17.760	17.467	1.02
7	9	149.5	16.611	1.519	10.94
8	5	161.9	32.380	6.233	5.19
9	4	188.2	47.050	23.000	2.05

In reducing the rainfall intensity measurement data set and calculating overflow volumes (steps 3-5), the magnitude of the error resulting from the introduction of the method is to be determined, along with the amount of time which can be saved in applying the simplified model rains. In order to evaluate the method, the rainfall runoff simulations of the following four kind were carried out on the system's hydraulic model:

A) 209 simulations of the reference rain series of temporally varying intensity;
B) 209 simulations of the block rains created from the reference rain series;
C) 9 simulations of the representative block rainfalls, taken as the centroids of each group of block rains having similar parameters;
D) 25 simulations of the temporally varying rainfalls having the largest rainfall levels.

Figure 4 presents the volume of rainfall - wastewater mixture passing through each overflow (per annum) for simulations A-D. The comparative diagram shows us that the deviation from the reference case changed most significantly when the block rains were introduced. As a result of this modeling step, the volume of rainwater and raw wastewater mixture passing through most overflows was reduced, while in a few scarce instances (e.g. CS8 and CSO9) it was increased. It can be seen that substituting the 9 representative block rains for the 209 block rains created from the reference rain series had a less significant effect on the change of overflow volume. In comparing the overflow volumes of the reference case (case A) to those of the simulations for the 25 largest rainfalls occurring over the course of 3 year (case D), it can be seen that the smaller rainfalls were responsible for over 1/3 of the overflow volume, in the case of the sewer system being investigated here.

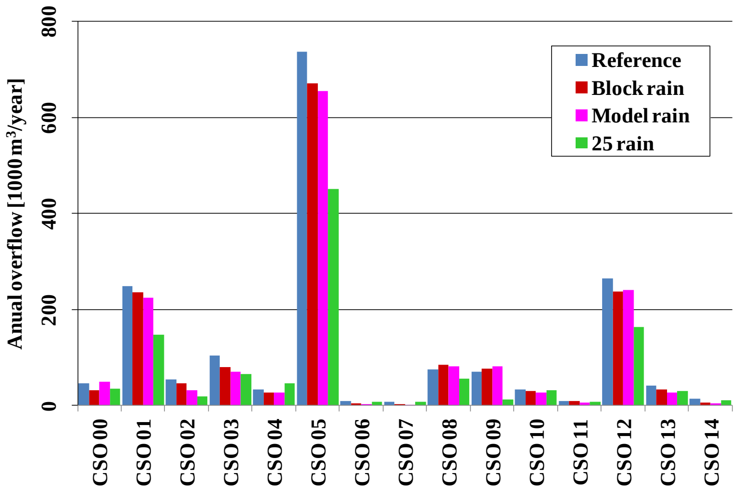

Figure 4. Volume of rainfall and raw wastewater mixture passing through each overflow (per annum)

Table 3: The relative processor times and the accuracy of the different overflow calculation cases

Case	Elements	Change in computational demand	Overflow volume
[-]	**[db]**	**[%]**	**[%]**
A	209	100	100
B	209	58	90.1
C	9	3.7	88
D	25	12	62.5

The processor times associated with the simulations of cases A-D can be found in Table 3. Upon introducing the block rains (case B), the processor time was halved, resulting partially from the shortening of the investigated time length (shorter rain events), and partially from the increase of the convergence speed, while, on the other hand, the total level of the volume passing through the overflow deviated from that of the reference case by 9.9%. For a merely three year long data set, a significant increase in speed (by a factor of 27) was experienced when substituting the 9 block rains, the centroids of each group, for the large series of block rains, while only increasing the deviation from the reference by less than 2%. For a longer time series, more representative of a long term average, the rate of acceleration will grow proportionally to the length. It can also be seen that it is not worth leaving out rainfalls of smaller intensity, as only an eightfold increase in speed was reached, the results having a 37.5% discrepancy with regard to the reference case. In turn, for a longer data set, since the examination quantity criteria, which determines the number N of rainfalls needed for an examination, N will increase proportionally with time, nevertheless the simulation time of the representative model rain series will be the same.

In the present work only the overflow volume occurring under regular operating conditions was investigated, but the wastewater / rainwater rate of the emitted overflow water can vary greatly throughout the duration of any given overflow. The statistical investigation of the ratio of wastewater making up the overflow volume will be an important part of further work.

V. CONCLUSIONS

Sewer models based on transient hydraulic simulations are widely used for assessing the stochastic loading of networks during the design process. These same models can be used in assessing the quantity of overflowing volume under regular operating conditions. Being that even small intensity rainfalls can cause a significant amount of overflow, all rain events occurring over many years need to be taken into consideration when determining the expected value of the overflow volume, making this a difficult task. Performing these calculations for all elements of a long rainfall intensity measurement data series, even if taking advantage of modern hardware and software tools, can take multiple weeks to complete. In order for the simulation methodology to be applicable in forecasting the environmental impact of sewer systems, and in the optimization of the system, from an environmental point of view, the simulation model must be able to produce results within a reasonable amount of time.

1. A method was introduced, which reduces the characteristic rainfall intensity measurement data series of a given territory to a small series of representative model rains, which can then be used to calculate overflow volume quantity with a level of accuracy that is deemed acceptable in the engineering practice. The method was tested on the model of a catchment of the Budapest sewer system having a territory of 7500 ha.
2. Testing the model on multiple temporal distributions of the rainfall intensity, it was determined that, depending on the value of the average intensity, the level of the overflow volume varies significantly, but does not change much when the temporal variation of intensity is altered and the average intensity is kept constant. The measured trends for the rainfall intensity can therefore be substituted by block rains, if the intensities are chosen correctly. In defining the block rains, our method takes into consideration the lower rainfall intensity limit of the given sewer system, which would cause overflows to occur under steady-state conditions. Therefore the rain model is not only specific to a given territory, but also specific to a given sewer system.
3. Simulations were carried out on the rain events of a 3 year rainfall intensity measurement series, and compared to simulation results for the series of 9 representative model rains, which were created from the data set. Results showed that the model calculations could be carried out 27 times as fast, with the level of the overflow volume deterring from the reference value by 12%. It was shown that the largest portion of the calculation error (9.9%) was resulting from the conversion of the rainfall intensities to block rains. Combining the block rains having similar parameters only increased the error by a minimal amount (2.1%). With the help of a similar test, it was shown that the sum of the overflow volume cannot be accurately approximated with a rainfall model which simply discards the rain events having small levels of rainfall.

VI. FUTURE WORK

In the present investigation only the level of the overflow volume occurring under regular operating conditions was discussed. It should be mentioned that the makeup of the emitted overflow water can vary greatly throughout the duration of any given overflow. The transient hydraulic sewer model can be further developed, making it suitable for taking into account the makeup of the emitted wastewater, and therefore also suitable for calculating the extent of environmental loading.

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