Redesign of the Existing Combined Sewer System (CSS) of Novi Sad

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ABSTRACT

The city of Novi Sad with the catchment area of 1960 ha and the current population of 300.000 has a combined sewer system (CSS) constructed during the 1950s. Stormwater and wastewater are discharged directly into the river Danube through two central pump stations with no pretreatment. The drainage system was designed for wastewater and stormwater drainage with the return period of 2 years for the development level at the time. The system was surcharged and overflowed many times during the first decade of this century due to the city development and increasing population. Overflows at numerous locations in the city caused hours-long traffic jams and enormous structural damages. The hydraulic-hydrologic analysis has indicated the requirement for the CSS redesign. The paper presents the methodology applied to redesign the existing system into the combined sewer system with storage tank and overflow (CSO). The system surcharges of once in 5 years and once in 3 years are designed for the central city area and residential area respectively. The analysis of the existing and designed drainage conditions is made using the urban water management modelling 3DNet. The storage tank with overflow is designed for the reduction of the river Danube pollution. The designed flow to the future wastewater treatment plant (WWTP) is determined to be $2Q_{DWFm}$. The redesigned CSO can provide significant reduction in the system surcharge and overflow, favourable hydraulic flow conditions in pipelines, reduction in pollutant overload in the river Danube as receiving water as well as optimal flow relevant for the dimensioning of WWTPs in Novi Sad.

KEYWORDS

Combined sewer, modelling, overflow, storage volume

1 INTRODUCTION

The systematic development of urban drainage systems in Serbia started in the early 1950s. The concept of drainage in small towns was mainly developed as a semi-separated system. Combined drainage of sanitary and industrial wastewater and stormwater only from central urban areas is predominant in small towns (with the population of 50.000 to 100.000) like Sombor, Subotica, Zrenjanin (Stipić et al. 2004). Wastewater and some stormwater is transported to the WWTP for combined treatment. Stormwater drainage from the remaining urban areas (outside the town center) is provided through the stormwater management system with the immediate discharge into the receiving water with no pretreatment. Mixing of wastewater and stormwater can cause significant problems in WWTP operation even during moderate storms (Sombor). The structures become overloaded with diluted water causing unstable operation for a long period of time. Some areas of the town are also frequently flooded.

Wastewater and stormwater are discharged into the receiving water with no pretreatment through the combined sewer system in large cities in Serbia, in Beograd and Novi Sad first of all. The receiving water quality is deteriorated by the discharge of wastewater and stormwater into the receiving water with no preliminary treatment. In most cases the combined sewer system is dimesioned with the overloading frequency of 1 in 1 year or, sometimes, in 2 years. Due to recent rapid development and increased population in cities heavy rainfalls in the first decade of this century only caused the system overloading and overflowing at many locations in cities. It resulted in traffic collapses and significant damages.

Nowdays further developement of urban drainage systems in Serbia is at its turning point. The main issue is how to combine the old system, numerous urbanistic limitations and the requirement for increased reliability and reduced permanent environmental impact (Yufeng et al. 2008). The correct concept – redesign of the exisitng drainage systems in cities is required taking into account basic considerations of the orientation of Serbia to EU membership as well as the water policy through the Water Directive (European Water Framework Directive, WDF, 2000). The primary aim of this paper is to consider the methods and possibilities of the transformation of the existing urban combined sewer system into the combined sewer system with storage volume and overflow including sustainable system surcharge as well as sufficient protection of the receiving water (Kleindorf, 2009; Valentin et al. 2011). The sewer system redesign should provide unrestricted city development including sustainable wastewater and stormwater management (EPA, 1999) avoiding urban areas overloading and flooding as well as the protection of the receiving water following the EU Directive regarding the drainage.

The paper presents the case study of the sewer system redesign in the city of Novi Sad with the population of 300.000 and the total catchment area of 1960 ha. Novi Sad has the combined sewer system with two main immediate outflows into the river Danube. The paper describes the redesign into the combined sewer system with storage volume and overflow (Stipić et al. 2011). The combined sewer system with overflow (CSO) is dimensioned with the designed overload frequency of 1 in 5 years and 1 in 3 years for the city central and residential areas respectively (EN-752-4, 1997). The designed hydraulic load for the WWTP is 2 Q_{DWFm} (De Toffol, 2006). Mathematical simulation system modelling using such determined criteria enabled the verification of the sewer system surcharge, possible overflowing areas mapping, the verification of flow conditions in conduits, the analysis of the receiving water load and overflow operation as well as the verification of the optimal discharge relevant for the dimensioning of the WWTP structures.

2 METHODOLOGY

2.1 Design standards

SRPS EN 752-4 (SRPS EN 752-4, 2007) is the national standard in Serbia which sets basic principles that must be taken into account in hydraulic calculation and consideration of the environmental impact of the sewer systems functioning mainly as gravity systems. The design storm frequency – system surcharge and overflowing frequency (1 in ''n'' number of years) is recommended. Table 1 represents the recommended frequency for the system development as a function of the area it is applied to. The simulation flow model should be used in the design stage with large sewer systems to verify the frequency and adverse effects of the system surcharge.

Primary function of the storage volume and overflows in the combined sewer system is to protect the receiving water during the operation of the sewer system with no hydraulic surcharge (such as regular sewer system operation, overflow not in operation) and the WWTP from the large inflow of diluted water during overloading (when the diluted water surplus is directly discharged into the receiving water). The sewer overflow can be designed such that the peak overflow occurs when the critical rainfall intesity is exceeded. It usually ranges from 10 L/s.ha to 30 L/s.ha (for impervious areas) or the simple criteria of diluting 5-8 discharges with dry weather prior to the overflow is used (when self-cleaning and the capacity are not endangered).

Table 1. Recommended frequencies for the combined sewer system development

DESIGN STORM FREQUENCY* (1 IN ''N'' YEARS)	AREA	Design overflowing frequency (1 in ''n'' years)
1 in 1	Rural area	1 in 10
1 in 2	Residential area	1 in 20
	City centres, industrial/commercial areas	
1in 2	- with overflowing verification,	1 in 30
1 in 5	- without overflowing verification	-
1 in 10	Underground roads, underpasses	1 in 50

* No surcharge may occur.

Although the national regulation (SRPS EN 752-4, 2007) sets the recommended design storm frequency for the analysis of 1 in 2 years for residential areas due to high population density and directions of city roads, relevant design storm frequency-overload of 1 in 3 years is used for the redesign requirements for the sewer system in the city of Novi Sad. The relevant storm frequency of 1 in 5 years is applied for the city center and greater city area. The Decree (Official Gazette of the RS, 2011) specifies maximum number of samples that may deviate from limiting load values defined for treated urban water depending on the total number of samples taken within a year. Maximum deviation from the limiting values of 25 samples per year are allowed for daily sampling from the WWTP. Simulation flow models must be used to estimate matching with the limiting load values.

2.2 Description of the sewer system in Novi Sad

Novi Sad represents the administrative center of the northern Serbian Province of Vojvodina. About 360.000 people live within the greater city area. The catchment area within the combined sewer system boundaries is 1960 ha with the population of 250.000. Impervious areas make about 36% of the catchment area, Figure 1.

The catchment is devided into two city subcatchments, southern city subcatchment – the subcatchment of the pump station GC1 and northern city subcatchment – the subcatchment of the pump station GC2. Wastewater is discharged into the Danube with no preliminary treatment. Maximum capacity of the pump stations is 10.5 m^3/s each. At average, the pump stations pump water into the Danube during one half of the year and during the second half of the year wastewater is discharged by gravity.

The catchment area is located at elevations ranging from 76.50 to 81.00 m with the average inclination of 0.4% to the Danube. The river Danube is the eastern boundary of the city catchment area. The average six-month Danube volume is 2700 m^3/s. The city, and thus the catchment area, is protected from the 100-year event with the flood bank. The sewer system was developed, designed and started during the 1950s. It was designed for the drainage of wastewater and stormwater with 2-year storms.

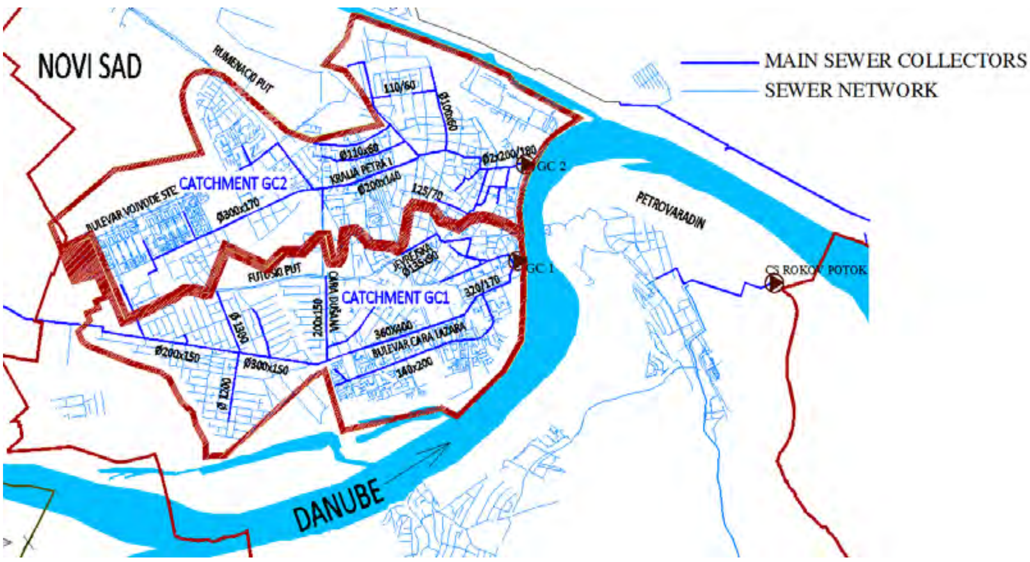

Figure 1: The existing combined sewer system of Novi Sad (sewer outflows are located at the stationary km: 1256)

The average daily dry weather flow, Q_{DWFm}, for the given catchment i 1 m^3/s and it is shown in Figure 2. Only downstream conduits before the pump stations GC1 and GC2 are designed for 3-year storms.

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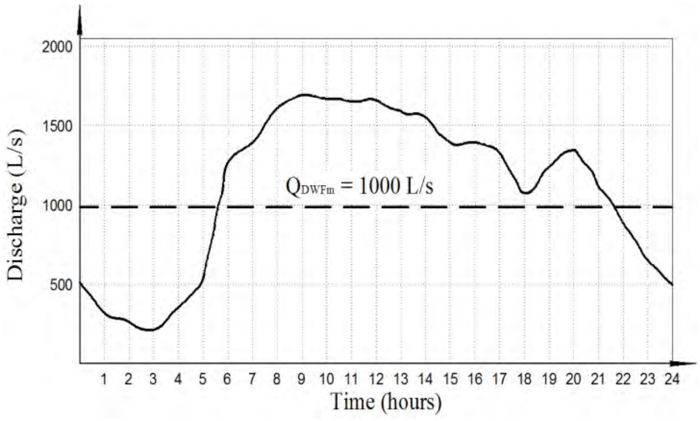

Figure 2. Average daily dry weather flow (for the catchment area of Novi Sad)

The diameter of the secondary and primary sewer network ranges from 300 to 1000 mm (with the total length of 280 km). The mains have rectangular profile 2.5x1.5 m, 3x1.7 m (with the total length of about 35 km) and pipe-arch 4x2.4 m with invert elevation at the bottom. The sewer system has connections from suburban areas with the total population of about 50.000. Approximately 35 million m^3 of wastewater per year is discharged into the Danube through the combined sewer system with two outfalls, of which about 5 million m^3 is stormwater.

The sewer system operation was significantly impaired due to well known events in Serbia during the last decade of the last century and improper maintenance. In addition, population growth and development have caused the increase in the runoff from the catchment. The city area was flooded some ten times at many locations only during the first decade of this century. The combined sewer system could not receive all the rainfall runoff so it ponded on the city surfaces, streets and squares. Large damage resulted at numerous locations in the city. Streets flooding caused hours-long traffic jams. Since first and second class state roads run through the city, traffic jams within the larger area occured as well.

2.3 Precipitation data

Precipitation data for the city catchment area are obtained from the nearest state weather station at Rimski Šančevi 8 km away from the catchment. The annual precipitation sum for the time period 1951 to 2005 is calculated based on further measurements, Figure 3. The average annual precipitation sum of 610 mm indicates the moderate climate region where most of the total precipitation is produced from low and moderate rainfalls whereas heavy rainfalls make smaller part.

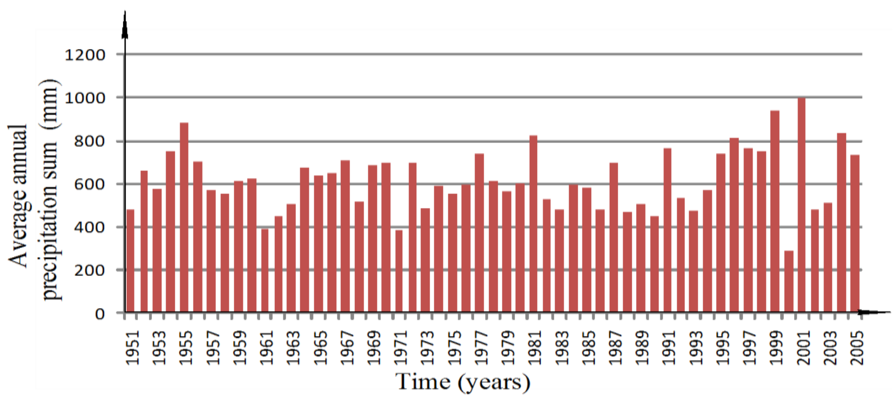

Figure 3. Annual precipitation time series at the weather station Rimski Šančevi, 1951-2005

Statistical rainfall analysis with the intensity-duration-frequency graph shown in Figure 4 is made for the given period of time based on the available data.

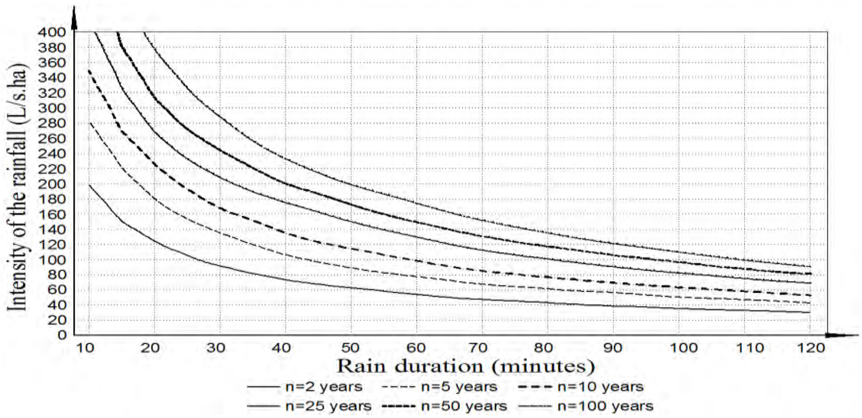

Figure 4. Duration dependent rainfall intensity (ITF curve – weather station Rimski Šančevi)

The newtork of modern rain gauges within the greater city area was installed in early 2010 by the system operator public utility ''Vodovod i kanalizacija'' from Novi Sad in order to provide better insight in the sewer system performance. The rain gauge at the location of GC2 was installed for the analysis of the runoff from the catchment of interest. Measurements at the rain gauge are used in the graph with hourly precipitation in the time period 2010-2011, Figure 5.

Several specific hyetographs of the rainfall with duration ranging between 20 and 45 minutes and intensity of 5 to 26 mm relevant for the drainage analysis are taken from the same rain gauge. Measuring data from own rain gauge provide a more complete insight into all important properties of the city drainage system (Linmei et al. 2009).

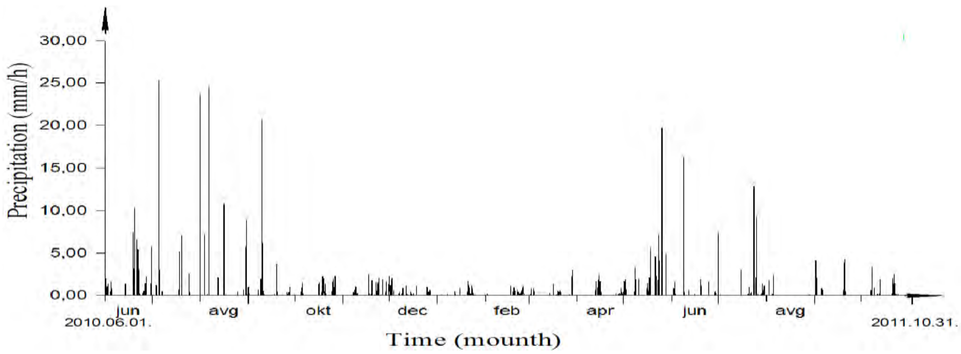

Figure 5. Precipitation time series in the period of time 2010-2011 (GC2 location in Novi Sad)

2.4 Model used for the runoff simulation

Mathematical numerical hydraulic simulation model SIPSON used and implemented in the software 3DNet was developed at the Faculty of Civil Engineering in Belgrade (Đorđević et al. 2005). The model is based on solving complete St Venant equations and Preissman method of finite differences (Đorđević, 2001). The model can calculate the runoff when the hydraulic capacity of the sewer system is exceeded, the flow in pipes is pressurized and the water overflows from the underground conduits onto the streets and roads. The runoff interaction is provided in mathematical model through underground conduits and pipelines including the ground surface configuration. Procedures and limiting conditions in the software describe the shaft volumes and shapes, conduit cross-sections, local micro and macro depressions, soil characteristics and hydrograph distributions between the surface runoff and underground flow. The software used provides hydraulic calculation of unsteady flow in the conduit and pipeline network. The software using GIS routings can prepare geographic, topographic, morphological, hydrogeological (soil properties: porosity, void ratio, soil roughness factor, estimated surface micro depression areas) and other soil properties for the hydraulic calculation with the precise layout of the conduit and pipeline network.

The basic model concept includes the following: the catchment is divided into subcatchments with assumed homogenous properties (pervious and impervious areas ratio and their parameters). The sections defined by digitally input nodes (in GIS surrounding) are assigned section subcatchments according to the chosen geometry system that is, outlined based on the digital model of the terrain. The subcatchments are grouped into: roofs, other impervious (streets, pavements, car parks, markets) and pervious areas (parks, gardens, sport grounds). Roofs and other impervious areas are then grouped into areas from which runoff flows straight into the sewers or surface channels and areas from which stormwater first overflows onto pervious surfaces where its large quantity is infiltrated with the remaining runoff stored. SIPSON version used for hydraulic calculation takes into account all the members of the dynamic equation in the unsteady flow model. Small grades as well as propagation delay and bottlenecks in the conduit network assume pressurized flow. These instances are included in the calculation by taking into account downstream limiting conditions. Outflows are results of differences between the land elevation and water level in the conduit (in its downstream node) at the moment of the peak flow. Properties of the network and structures are taken from the existing design documentation, utility installations and GIS database from the system operator.

3 RESULTS AND DISCUSSION

The results of the hydrodynamic calculation of the existing combined sewer system (CSS) of the city of Novi Sad and the redesigned combined sewer system with storage volume and overflow (CSO) are given below. The calculation is performed using relevant loading for the design storm frequency-overloading of 1 in 3 years and 1 in 5 years for the city center and greater city area respectively. The effects of the redesigned network will be verified in the model following the definition of the critical sections in the existing system such that the required relevant loading conditions are met.

3.1 Hydrodynamic simulation – the existing combined system

Hydrodynamic flow simulation is run for three different storms (with 2-, 3- and 5-year return periods). First, the simulation is run for the 2-year storm for the residential area. Figure 6 shows the nodes with the system surcharge that is, with overflows. Further, the simulation is run for the 3-year storm for the same area. It can be concluded that the system surcharge occurs in most of the residential area. A similar overflow analysis is made for the city central and greater areas. In addition to 2- and 3-year storms 5-year storm is verified

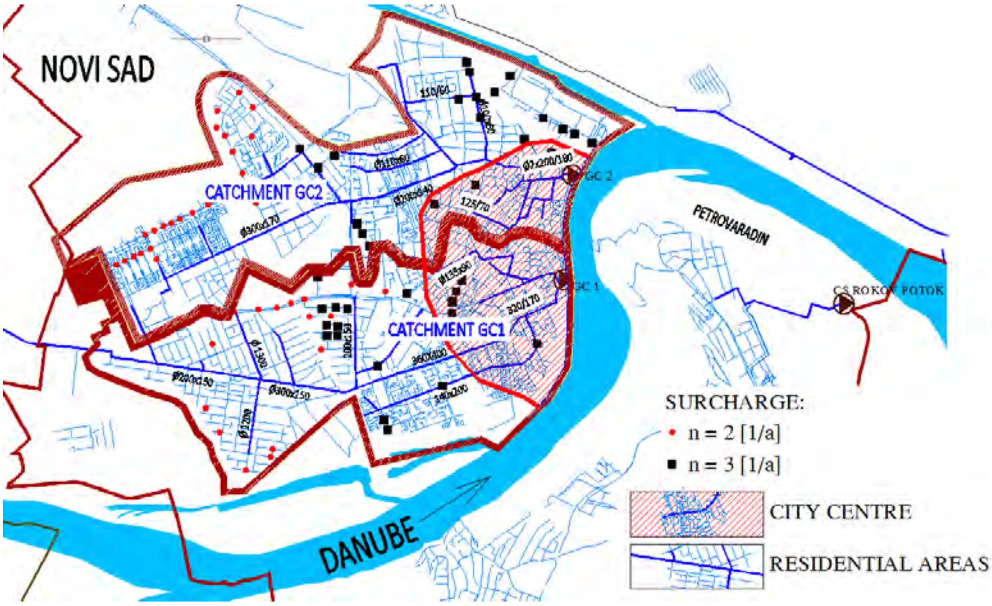

Figure 6. Hydrodynamic model of the combined sewer system of Novi Sad – overloading for 2- and 3-year storms

The results obtained from the hydrodynamic modelling of the existing sewer system are then compared with the history of flooding thus providing verification of the existing mathematical model. The model indicates that 2-year storms can cause the system surcharge and overflows from catch basins. The simulation results show that the existing CSS is not capable of receiving and draining storms larger than 2-year storms. It is obvious that the existing sewer system requires redesigning according to the accepted recommendations in order to prevent frequent system overflows and surcharge that is, the CSS needs to be extended with new conduit sections.

3.2 Hydrodynamic simulation – future combined system with overflow

The future sewer system in Novi Sad should provide the relevant design overloading frequency of 1 in 3 years and 1 in 5 years for the city residential and greater areas. In addition, it is necessary to consider structures that control the allowable discharge into the receiving water that is, the protection of the receiving water with no system surcharge and diminishing effects of the treatment at the WWTP. It is therefore necessary to consider the required storage tank volume and determine the required discharge to the WWTP during storms.

In order to protect the receiving water two existing outfalls are first connected such that the southern catchment, GC1 catchment, is connected to the northern catchment, GC2, at the location of GC2. The construction of the central pump station, GCS, settling storage tank and overflow is foreseen. The complete wastewater flow Q_{WWTP} is pumped to the future WWTP on the right Danube bank all year round. Figure 7 shows the plan of the operation of the central pump station, storage tank and overflow.

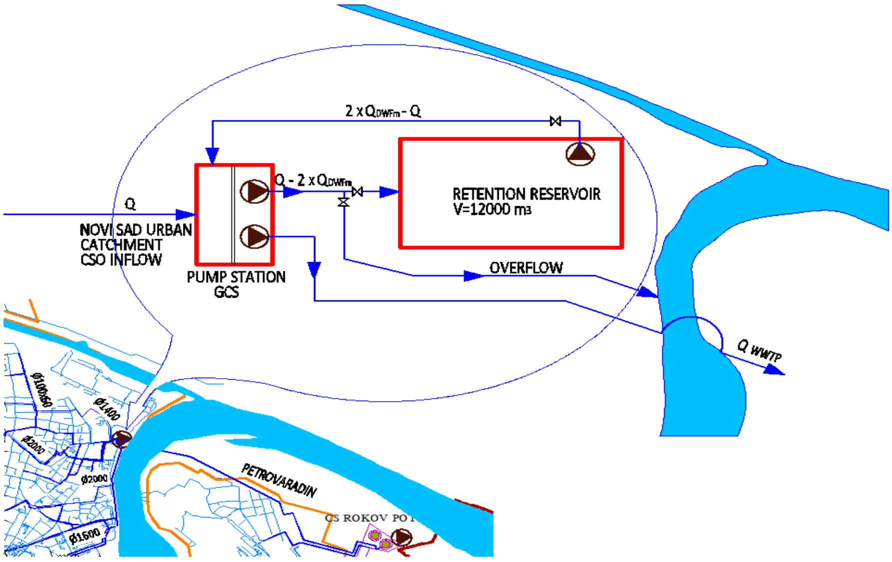

Figure 7. Operation plan of the GCS, storage tank and overflow

It is assumed that the maximum flow to the WWTP is Q_{WWTP}^{max} = 2 Q_{DWFm}. The flow Q of up to Q_{WWTP}^{max} in the inflow conduit is conveyed to the WWTP. If the inflow Q is higher than Q_{WWTP}^{max} the surplus is conveyed to the settling storage tank, Q- Q_{WWTP}^{max}. When the intensity of the storm is such that the storage tank is full the overflow occurs, Q- Q_{WWTP}^{max} and the discharge is redirected to the overflow with the outfall into the receiving water. The storage tank is emptied with the flow Q_{WWTP}^{max}-Q after the storm. The connection of the outfalls into a joint one with GCS provides the conditions for the analysis of the new required conduit sections in the sewer system (Figure 8) and modifications as well as increased permeability at critical points in particular.

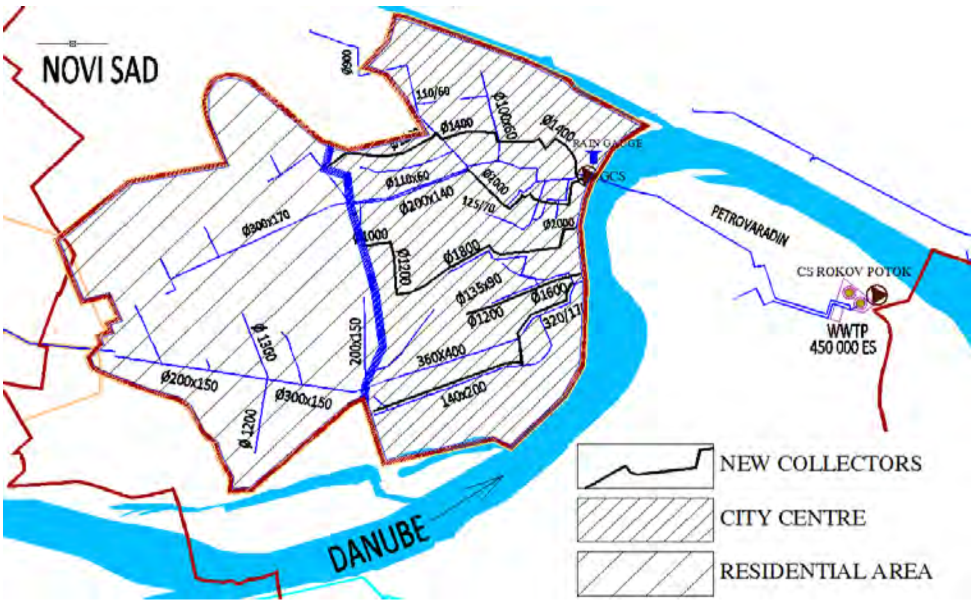

Figure 8. Hydrodynamic model of the combined sewer system with overflow – new conduits and the area arrangement

First, the simulation is run for 3-year storms for the residential part of the catchment area with the aim of preventing the system surcharge and overflowing. It is performed by successive addition and replacement of the conduits in critical sections including flow verification taking into account urbanistic limitations in particular in the old city area. Multiple additions and certain modifications result in new sewer system.

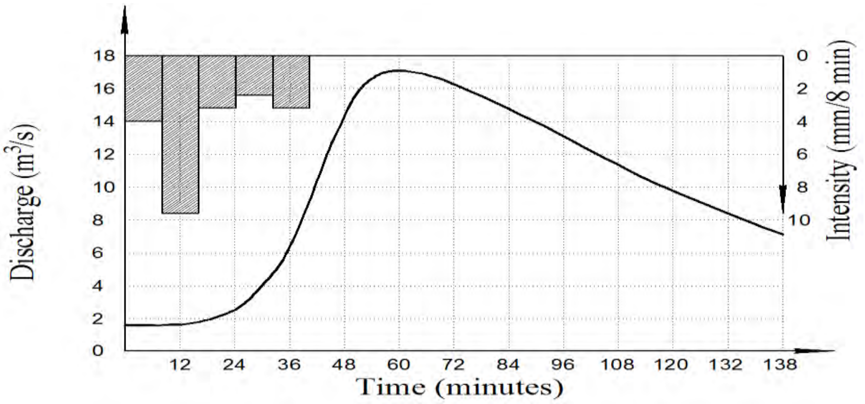

Figure 9. Hydrograph of the inflow to the GCS for the desing storm frequency

Urban area of the catchment, central and greater city areas, is then loaded with design 5-year storm with hydrographs of the residential rainfall runoff added at the upstream end. New conduit sections are added such that the system is not surcharged. Joint simulation of the discharge from both subcatchments is then run with the newly produced sewer system. The redesigned sewer system meets the requirements of the relevant design storm frequency – system surcharge. Figure 9 represents the hydrograph of the inflow to the GCS for the design storm frequency.

3.3 Storage tank with overflow

The national standard (SRPS EN 752-4, 2007) does not specify the required capacity of storage tanks – settling tanks but it provides framework for the dimensioning of the overflow into the receiving water. It is foreseen that the overflow of peak discharge occurs when the critical rainfall runoff value is exceeded, usually ranging between 10 and 30 L/s.ha (for impervious areas). Retention in the storage tank can reduce the stormwater overflow into the receiving water. It can be therefore concluded that stormwater remains in the storage tank until it reaches the critical range. National guidelines applied in Austria and Germany were considered in detail for the determination of the storage tank volumes taking into account practice (Gamerith, 2006; Achleitner, 2006) in European countries as well as the annual precipitation sum at the catchment. Austrian guidelines OEWAV Regelbat 19 specifies the storage tank volume of 15-25 m^3/ha (for impervious areas). Where the receiving water is not too sensitive the lower value of 15 m^3/ha (for impervious areas) can be applied. German ATV 128 (ATV A 128, 1992) represents guidelines for the dimensioning and construction of stormwater overflow structures in the combined sewer system. The required storage tank capacity is specified within the range of 10-40 m^3 (for impervious areas). Most tanks (there are over 20.000 in Germany) are designed with storage tanks of 20 to 25 m^3/ha (for impervious areas).

As the total catchment area is 1960 ha with impervious area of about 36% the storage tank capacity of 15 m^3/ha (for impervious areas) that is, the total storage tank capacity including the settling (clarifier type) of 12.000 m^3 for the entire catchment is adopted (Brombach H. et all. 2008). Several scenarios of hydrodynamic flow describing the operation of the tank are assumed given the determined functioning of the central pump station, GCS and relevant flow to the WWTP. Hydrodynamic simulations enable determination of the storm intensity at which the tank does not overflow that is, the storm that can fill the tank without overflowing. The system operation is verified with tank overflowing that is, with the outflow into the receiving water. Critical storm intesity causing the storage tank overflow into the receiving water is higher than 8 mm during one event. The sum of these storm events, with storm intensity higher than the critical value, does not exceed 10 events in an average year. Moreover, it can be concluded that the requirement set in the Decree (Official Gazette of the RS, 2011) for the maximum number of samples that may deviate from the limiting load values for treated urban water discharged into the receiving water within a year is met.

4 CONCLUSION

The paper presents the combined sewer system (CSS) of the city of Novi Sad as being currently overloaded. The system is transformed, redesigned into the combined sewer system with storage volume and overflow (CSO) according to the national standard (SRPS EN 752-4, 2007) such that it meets current design criteria with maximum protection of other infrastructure. The existing CSS was dimensioned for 2-year storm. The following was applied in the CSS redesigning into the CSO:

- National guidelines applied in European countries are used to determine relevant WWTP loading of $Q_{WWTP}^{max} = 2\ Q_{DWFm}$.
- The sewer system, CSO, is dimensioned and redesigned with the design surcharge frequency of 1 in 5 and 1 in 3 years for the city central and greater areas and residental area respectively. This is provided by the addition and replacement of a number of mains in the system. The results of the hydrodynamic flow simulation indicate that the future system can meet the required system surcharge and overflowing.
- Measurements at facilities and the rain gauge performed by the system operator public utility ’’Vodovod i kanalizacija’’ for their own needs are used for the storm analysis and flow simulations.
- The settling storage tank capacity (clarifier type), before the overflow, is 15 m^3/ha (for impervious areas). The settling storage tank with the capacity of 12.000 m^3 for the entire catchment can retain the storms of the intensity lower than the critical value of 8 mm prior to the discharge into the receiving water. The annual number of storms lower than the critical value causing the overflow into the receiving water is lower than 10.

The software package 3DNet used provided the verification of a large number of different discharge scenarios in the system. First, all the locations of the system surcharge and overflowing are determined and compared with the history of flooding zones. Then the iteration is used to redesign the system such that the required design surcharge frequency is met.

The results produced by the developed methodology indicate that the old existing CSSs can be successfully redesigned into modern CSOs, which is the first instance of the kind in Serbia. CSO system including the adopted storage tank capacity can significantly reduce the pollution of the receiving water and provide its protection. In addition, hydraulic flow conditions in the conduits are improved and the pressurized flow time and overflowing are significantly reduced.

Total investment value of the additional conduits and storage tank in case of Novi Sad is 52 million euros. Ongoing CSO construction works worth 15 million euros are provided from the loan of the European Investment Bank.

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