SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA

FACULTY OF CIVIL ENGINEERING

Department of Sanitary and Environmental Engineering

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Mathematical Modelling of Sewer Network Objects

Dissertation Thesis Abstract

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Content

1 Introduction

Water is a vital societal resource that underpins environmental stability and economic activity [1]. Rapid urbanization increases impervious areas and reduces natural infiltration, which amplifies surface runoff. Together with the Urban Heat Island effect and other anthropogenic pressures, this intensifies environmental and public-health stresses in cities [2, 3]. Climate change further increases the frequency and severity of extreme precipitation, frequently exceeding the hydraulic capacity of legacy drainage and wastewater infrastructure [4]. In combined sewer systems (CSS), these stresses manifest as frequent overloading and operational risks for wastewater treatment plants (WWTP) [5].

Combined sewer overflows (CSO) are intended to protect WWTP during storms by diverting excess flow to receiving waters, yet they can release pollutants and pathogens and many existing structures no longer meet current performance expectations or evolving EU regulatory requirements [6]. Addressing this gap demands engineering methods that quantify hydraulics and pollutant transport with sufficient spatial and temporal resolution to inform redesign and operation.

This dissertation thesis therefore focuses on mathematical modelling of the sewer system with an emphasis on CSO hydraulics resolved by Computational Fluid Dynamics (CFD) [7]. Using ANSYS Fluent and Siemens Simcenter Star-CCM+, the work simulates unsteady flows in realistic CSO geometries, evaluates velocity fields, turbulence, pressure gradients, and predicts overflow volumes and pollutant loads under representative storm scenarios.

The results support diagnosis of design deficiencies and provide evidence-based recommendations for retrofits and operational improvements applicable to Slovak urban contexts. Blue-Green Infrastructure is noted as a complementary, source-control measure that can reduce inflows and thereby lessen CSO activation, but the core of the study is CFD-driven hydraulic analysis and optimization [8].

2 Goals of the dissertation

The motivation behind this work arises from the need to support the transition of Slovak urban areas towards more resilient and sustainable water management practices. The Slovak Republic, as a member of the European Union, is committed to fulfilling strict regulatory requirements in the field of wastewater collection and treatment.

This dissertation seeks to advance engineering knowledge and practice by combining advanced computational modelling with an understanding of innovative stormwater management strategies. The insights gained from this research are intended to inform policy makers, engineers, and urban planners in their efforts to modernize urban drainage systems, protect receiving waters, and enhance the overall quality of life in cities.

Main goals of the dissertation thesis:

1. Diagnose the hydraulic performance of CSO “OK9B” in Trnava during dry-weather and rainfall regimes; determine the threshold flow Qcap, overflow onset, and the flow split to WWTP vs recipient.

2. Build CFD models in ANSYS Fluent or Siemens Simcenter Star-CCM+ and simulate unsteady inflows (100-300 %) for configurations with and without the fixedly mounted baffle wall.

3. Quantify overflow volumes and pollutant loads to the recipient across four fractions: total suspended solids, dissolved pollutants, particulate-bound nutrients, and heavy metals.

4. Compare scenarios with/without the fixedly mounted baffle wall to identify hydraulic deficiencies and the effect of geometric changes on overflow and pollutant transport.

5. Formulate practical, case-specific recommendations for CSO optimization and outline the role of Blue-Green Infrastructure in reducing inflows at the catchment scale.

3 Detailed description of the research area

The sewer system of the city of Trnava was selected as a model site based on recommendations from TAVOS, a.s., in close cooperation with the Association of Water Companies (AVS), with the aim of addressing the issue of precipitation-runoff processes and their impact on the operation of public sewer system. In recent years, there have been increasing complaints from residents about unpleasant odours from the sewer system during rainfall, which points to possible deficiencies in the hydraulic function of the system during extreme loads [79].

As part of the assessment of precipitation-runoff processes, a detailed assessment of the hydraulic behavior of flow in CSO was carried out. The methodological procedure included the collection and analysis of available data on flows, the identification of relevant chambers, the creation of their 3D geometric models, and subsequent numerical simulation of flow using CFD methods. Direct measurements of flows during rainfall events could not be carried out due to health and safety risks. The infrastructure operator does not have the equipment to collect this data and does not keep historical records of actual flows.

The city of Trnava operates a public sewer system that flows into a mechanical-biological WWTP located south of the city near the village of Zeleneč. This CSS ensures the drainage of municipal, industrial and rainwater. As of 2015, the sewer system was 111.236 km long, with a total of 36 surrounding municipalities connected to the system. However, the older parts of the network, especially in the historic center, show signs of obsolescence and insufficient capacity, leading to frequent operational problems [79].

To ensure the functionality of the sewer system during rainfall, 22 CSO were installed on the network. Rainwater from the PSA and Technopol industrial zones is drained by a separate storm SS directly into the Trnávka stream, which flows through the town and naturally divides it into eastern and western parts [80]. The Trnávka also serves as a recipient for overflowed water from the sewer system and treated water from the WWTP. The long-term average flow rate of the stream is 0.76 $m^3 \cdot s^{-1}$, while the average minimum flow rate (Q355) reaches 0.08 $m^3 \cdot s^{-1}$.

All CSO in the city of Trnava are made of concrete and their shape is determined by the geometry and profiles of the connected sewers. An assessment of the structural and technical condition as part of the Trnava CSO Reconstruction project found that most of the chambers are in satisfactory to good condition. In the past, however, these structures did not meet the requirements of §6 of the relevant regulation, mainly due to the absence of equipment for the collection of floating substances. They are currently undergoing systematic reconstruction in accordance with the approved project documentation, with the aim of ensuring the hydraulic functionality and environmental safety of the system during rainfall events [79].

3.1 Monitoring of CSO "OK9B" and recipient's water quality

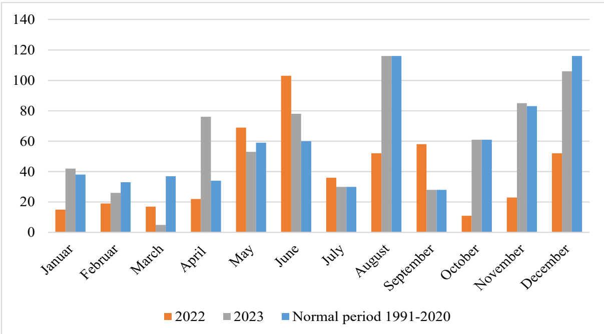
Laboratory analysis plays a crucial role in determining the concentrations of specific pollutants in overflowed waters. Standard analytical techniques are employed to measure parameters: nutrients (nitrogen and phosphorus compounds), heavy metals, pesticides, organic pollutants and microbiological contaminants. Samples collected from the field are transported to accredited laboratories where they undergo rigorous testing and analysis using established protocols and equipment [9].

The research took place in a city that the combined sewer system, the percentage of infiltration is average, except for the old city, however there is a rather small percentage of measures created to contain water in urban infrastructure during rainfall. To achieve maximum results and more samples, the weather conditions must be consistent with the fact that there will be a large amount of precipitation. Then there will be a lot of overflowed waters into the recipient.

In this way, the quality of research in this area can be improved. Analyzing the data of the Slovak Hydrometeorological Institute, it can be stated that the greatest amount of daily precipitation falls in the period from May to June, in August, from October to December [81]. Most of the heavy rainfall occurs during these months, placing undue stress on the sewer network.

Precipitation data from the Slovak Hydrometeorological Institute for 2022 and 2023 are presented in the following graphs. As is possible to see in the graph, 2022 was an abnormal year with a lot of dry days, and there were abnormal rainfall and drought in the EU and other countries that year.

Based on data from 2023 average statistical data, it is concluded that the optimal times for sampling overflowed waters are during the periods identified on the graph as the normal period from 1991 to 2020. During these times, the data collected will be most comprehensive. Sampling at different times of the day will ensure the maximum amount of data is obtained. The data of the monthly cumulative total of precipitations in researched area obtained can be seen in Graph 1.

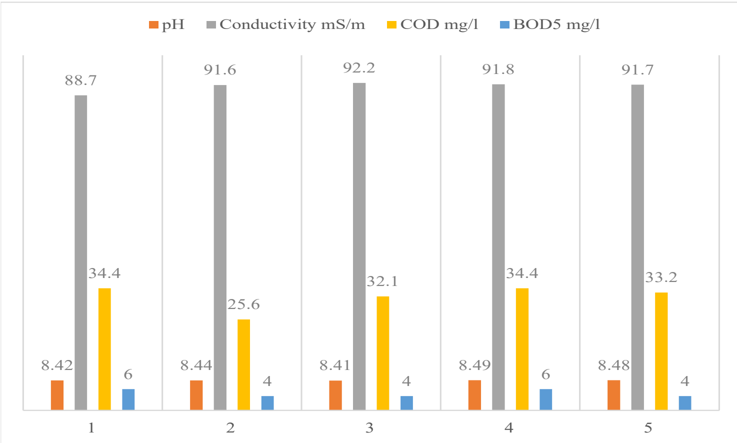


Graph 1 The data of the monthly cumulative total of precipitations [81]

As a result, five samples were collected from the recipient December 12, 2022. Obtained data of all results are presented in Table 1 and Graph 2.

Table 1 Obtained data (qualitative parameters) of the measurements 12.12.2022

Sample number		1	2	3	4	5
pH		8.42	8.44	8.41	8.49	8.48
Conductivity	mS/m	88.70	91.60	92.20	91.80	91.70
COD	mg/l	34.40	25.60	32.10	34.40	33.20
BOD_5	mg/l	6.00	4.00	4.00	6.00	4.00
Sampling	12.12.2022	09:10	09:17	09:22	09:31	09:34



Graph 2 Obtained data (qualitative parameters) of the measurements 12.12.2022

According to the law 269/2010 Regulation of The Government of The Slovak Republic, the data can be concluded that all indicators that were obtained during the first part of the sampling December 12, 2022 of water quality in the recipient comply with the norms of the law of the Slovak Republic.

3.2 Detailed technical description of CSO “OK9B”

As part of this scientific research, a specific CSO “OK9B” was selected for detailed analysis. This CSO is located in the northwestern part of the city of Trnava, near the roundabout between Trstínska cesta and Cukrová streets. The exact GPS coordinates are 48°23′09.2″N, 17°34′30.5″E [79].

The CSO receives municipal wastewater from nearby residential buildings, as well as stormwater runoff from rooftops, roads, and sidewalks. CSS in this area does not cover the entire city, meaning that not all rainwater is directed to this structure. The CSO is connected to the Trnávka stream, approximately 25 meters away from the structure, discharging diagonally into the right bank of the recipient.

Figure 1 Location of CSO “OK9B” [79]

Figure 2 Photo of CSO “OK9B” in real moment in 2025 (author)

Based on the available data and the technical drawings of the CSO modernization provided by TAVOS a.s., a 3D model was created using Space Claim software, however without a fixedly mounted baffle wall in the first case. A 3D model including the fixedly mounted baffle wall will be developed and utilized for the CFD simulation

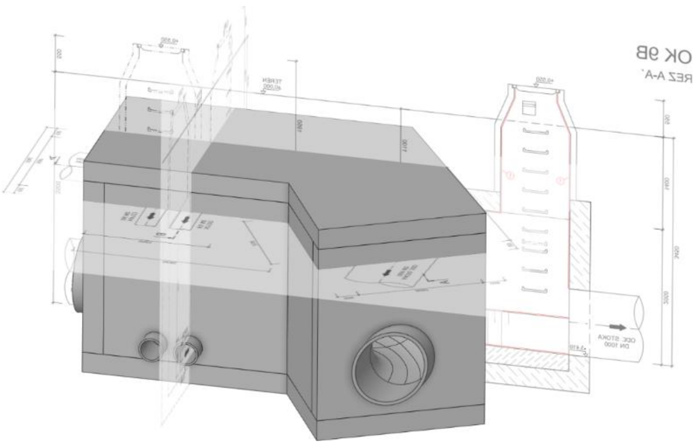


Figure 3 3D model of CSO “OK9B” after 2015 without a fixedly mounted baffle wall (author)

This is a standard type of chamber. From a hydraulic point of view, it is a CSO with a front overflow. The total length of the chamber in the direction of flow is approx. 6.40 m, the width is 1.80 m. The height of the ceiling above the overflow edge is 1.92 m. The overflow edge is not straight, the lowest point is approx. 280 mm above the bottom of the throttling sewer [79]. Inlet pipe is DN 1000, throttle pipes are 2x DN 300, overflow pipe is DN 1000

4 Simulations

The simulation process will be divided into several steps. Since it was not possible to measure the exact inflow into the selected CSO, a theoretical approach will be applied using the critical flow rate Q_{th}=0.1 $m^3 .s^{-1}$ (100%) [73]. This value will serve as a basis for estimating the volume of water and pollutants that will continue through the sewer system, as well as the quantity of contaminants that will be discharged into the recipient.

It is important to note that in each case, three samples will be analyzed at specific time intervals during the simulation: 1 – at the initial moment of the simulation (up to 0.75 seconds); 2 – up to 2.5 seconds; 3 – up to 10 seconds

Stage 1 of the simulation process is carried out under baseline conditions, assuming 100% flow without the presence of the fixedly mounted baffle wall.

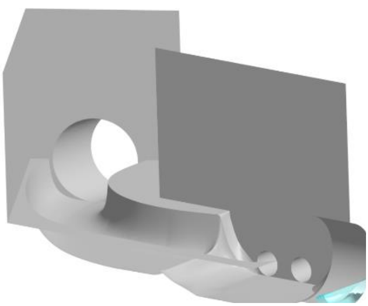


Figure 4 (a) 100% flow without the presence of the fixedly mounted baffle wall (up to 0.75 seconds) (author)

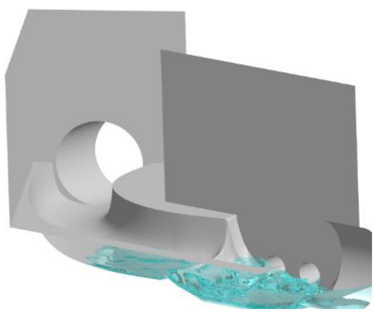


Figure 4 (b) 100% flow without the presence of the fixedly mounted baffle wall (up to 2.5 seconds) (author)

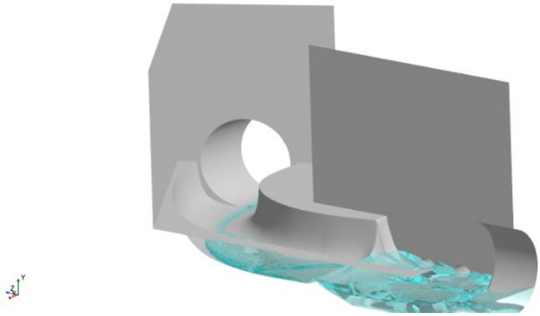


Figure 4 (c) 100% flow without the presence of the fixedly mounted baffle wall
(up to 10 seconds) (author)

Stage 2 of the simulation process is carried out under baseline conditions, assuming 100% flow with the presence of the fixedly mounted baffle wall.

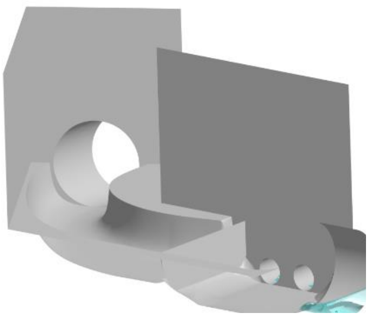


Figure 5 (a) 100% flow with the presence of the fixedly mounted baffle wall
(up to 0.75 seconds) (author)

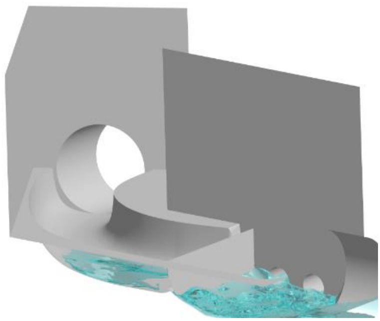


Figure 5 (b) 100% flow with the presence of the fixedly mounted baffle wall
(up to 2.5 seconds) (author)

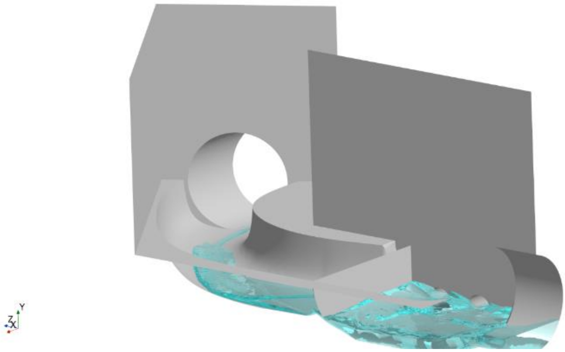


Figure 5 (c) 100% flow with the presence of the fixedly mounted baffle wall
(up to 10 seconds) (author)

Stage 3 of the simulation process is carried out under baseline conditions, assuming 150% flow without the presence of the fixedly mounted baffle wall.

It is important to note that, at this stage, the simulation does not start from the very beginning. Instead, an inflow of 150% is applied to the simulation that was previously conducted with a 100% inflow. This approach allows us to observe, within the previously established time intervals, how the flow dynamics within the CSO change under increased hydraulic load.

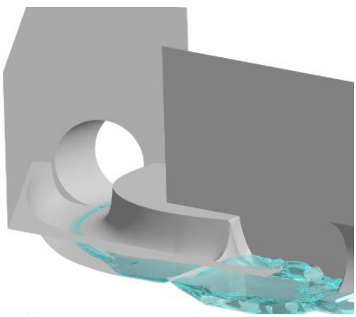


Figure 6 (a) 150% flow without the presence of the fixedly mounted baffle wall
(up to 0.75 seconds) (author)

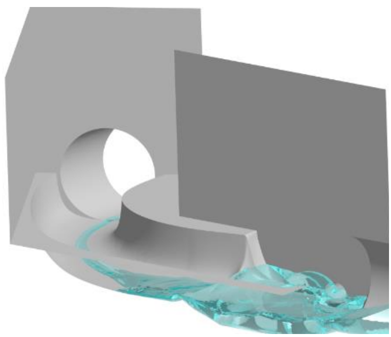


Figure 7 (b) 150% flow without the presence of the fixedly mounted baffle wall
(up to 2.5 seconds) (author)

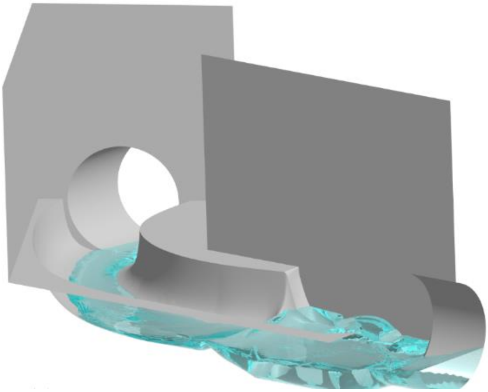


Figure 6 (c) 150% flow without the presence of the fixedly mounted baffle wall (up to 10 seconds) (author)

In the following figure, the change in the water flow is presented in an alternative view.

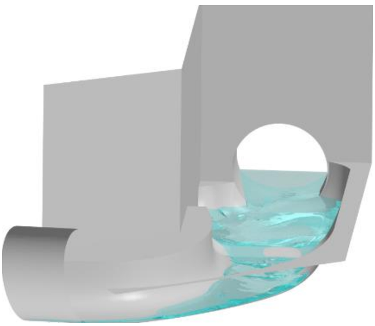


Figure 7 (a) 150% flow without the presence of the fixedly mounted baffle wall (alternative view) (up to 2.5 seconds) (author)

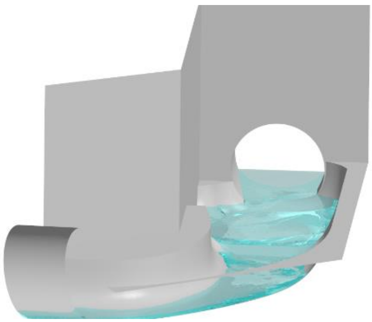


Figure 7 (b) 150% flow without the presence of the fixedly mounted baffle wall (alternative view) (up to 10 seconds) (author)

Stage 4 of the simulation process is carried out under baseline conditions, assuming 150% flow with the presence of the fixedly mounted baffle wall.

It is important to note that, at this stage, the simulation does not start from the very beginning. Instead, an inflow of 150% is applied to the simulation that was previously conducted with a 100% inflow.

This approach allows us to observe, within the previously established time intervals, how the flow dynamics within the CSO change under increased hydraulic load.

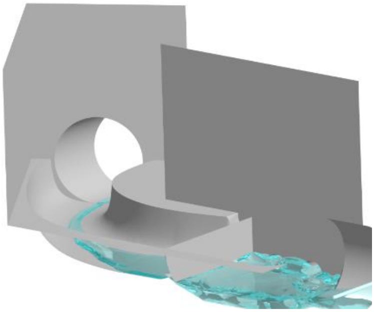


Figure 8 (a) 150% flow with the presence of the fixedly mounted baffle wall (up to 0.75 seconds) (author)

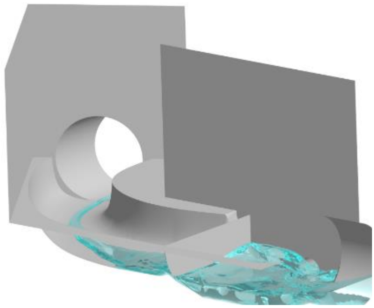


Figure 8 (b) 150% flow with the presence of the fixedly mounted baffle wall (up to 2.5 seconds) (author)

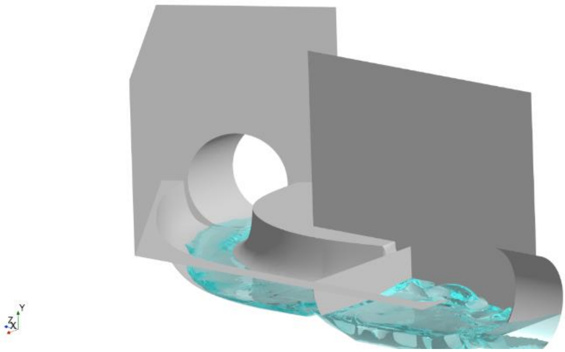
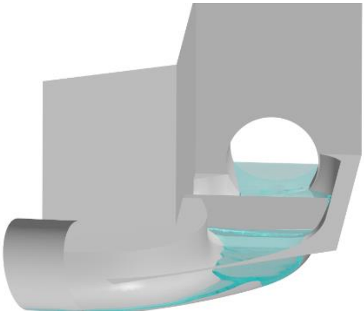


Figure 8 (c) 150% flow with the presence of the fixedly mounted baffle wall (up to 10 seconds) (author)

In the following figure, the change in the water flow is presented in an alternative view.



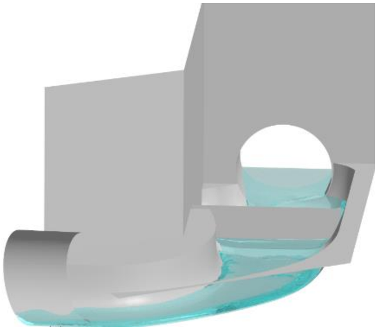


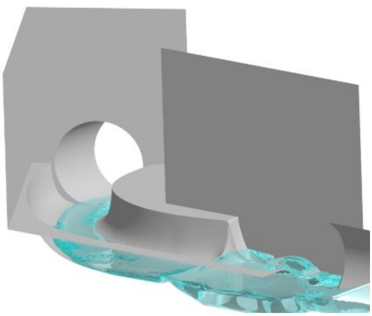
Figure 9 150% flow with the presence of the fixedly mounted baffle wall (alternative view) (up to 2.5 seconds) (author)

Figure 9 (b) 150% flow with the presence of the fixedly mounted baffle wall (alternative view) (up to 10 seconds) (author)

Stage 5 of the simulation process is carried out under baseline conditions, assuming 200% flow without the presence of the fixedly mounted baffle wall.

It is important to note that, at this stage, the simulation does not start from the very beginning. Instead, an inflow of 200% is applied to the simulation that was previously conducted with a 150% inflow.

This approach allows us to observe, within the previously established time intervals, how the flow dynamics within the CSO change under increased hydraulic load.



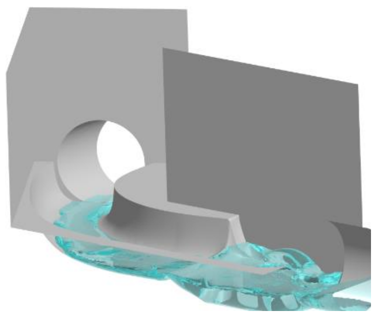


Figure 10 (a) 200% flow without the presence of the fixedly mounted baffle wall (up to 0.75 seconds) (author)

Figure 10 (b) 200% flow without the presence of the fixedly mounted baffle wall (up to 2.5 seconds) (author)

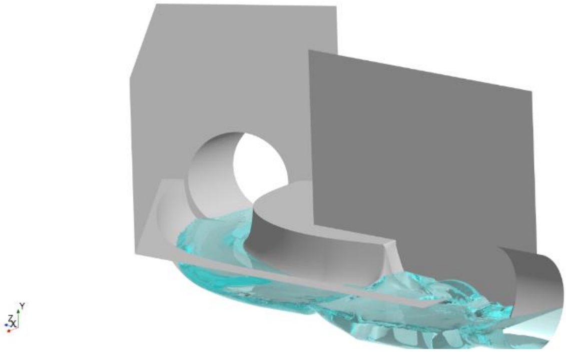


Figure 10 (c) 200% flow without the presence of the fixedly mounted baffle wall (up to 10 seconds) (author)

Based on the results of the CFD simulations conducted for the CSO, it can be concluded that even under moderate rainfall conditions and at an average limiting inflow of 0.1 m^3/s, pollutants begin to overflow into the recipient within just a few seconds of the event onset.

The simulations clearly demonstrated that the CSO does not provide sufficient retention time or hydraulic capacity to prevent the discharge of contaminants during stormwater events.

Pollutant transport was assessed across four representative fractions – total suspended solids, dissolved pollutants, particulate-bound nutrients, and heavy metals. The analysis revealed that the likelihood of pollutant discharge into the recipient depends on the physical characteristics of each fraction. Heavier and larger particles, such as coarse total suspended solids and sediment-bound pollutants, tend to settle and are less likely to be released, while dissolved substances and fine suspended materials exhibit a significantly higher probability of entering the receiving water body.

These findings underscore the urgent need for structural optimization of the CSO and the implementation of complementary measures, such as BGI, to increase surface retention, reduce inflow, and prevent rapid pollutant discharge into natural watercourses.

5 Conclusion

This dissertation thesis examines combined sewer performance in Trnava through a CFD-led lens, connecting chamber-scale hydraulics with catchment-scale stormwater management. By pairing high-resolution simulations with fraction-resolved pollutant accounting, the work clarifies how geometry and approach-flow conditions govern overflow behavior. The research bridges engineering diagnostics and environmental protection, offering a practical route from assessment to actionable improvement.

1. Diagnosed the hydraulic performance of CSO "OK9B" in dry-weather and rainfall regimes; determined the threshold flow Q_{cap}, the timing of overflow onset, and the flow split to WWTP vs recipient.
2. Built and ran high-fidelity CFD models in Siemens Simcenter Star-CCM+ for unsteady inflows (100–300 %) with and without the fixedly mounted baffle wall.
3. Quantified overflow volumes and pollutant loads to the recipient across four fractions – TSS, dissolved pollutants, particulate-bound nutrients, heavy metals reporting mass fluxes for each scenario.
4. Compared scenarios to identify hydraulic deficiencies. The simulations indicate that the permanently installed baffle does not materially improve the flow split toward WWTP; consequently, its removal was recommended.
5. Formulated case-specific optimization measures (weir/baffle geometry, outlet arrangement, approach-flow guidance) and outlined how Blue-Green Infrastructure can reduce catchment inflows and CSO activation.

Taken together, the results show that overflow can begin within seconds once Q_{cap} is exceeded, and that fine TSS and dissolved fractions have the highest pass-through probability, elevating environmental risk during storms. The findings confirm that gray-only strategies are insufficient under contemporary rainfall extremes, while targeted CSO retrofits combined with distributed BGI materially reduce overflow frequency and pollutant loads.

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7 Publishing activities

V3 Vedecký výstup publikačnej činnosti z časopisu

V3_01 PORTNOV, Maksim - HRUDKA, Jaroslav - WITTMANOVÁ, Réka [Csicsaiová, Réka] - ILAVSKÝ, Ján - STANKO, Štefan. Monitoring the quality of overflowed waters in Slovakia. In *Pollack Periodica*. Vol. 20, no. 2 (2025), online, s. 101-106. ISSN 1788-1994 (2024: 0.385 - SJR, Q3 - SJR Best Q). V databáze: SCOPUS: 2-s2.0-85211104317 ; DOI: 10.1556/606.2024.00807. Typ výstupu: článok; Výstup: zahraničný; Registrované v databáze: SCOPUS; Kategória publikácie do 2021: ADM

V2 Vedecký výstup publikačnej činnosti ako časť editovanej knihy alebo zborníka

V2_01 HRUDKA, Jaroslav - RÓZSA, Gergely - PORTNOV, Maksim - STANKO, Štefan. Possibilities of sump water treatment in the Slovak Republic. In *Young Scientist 2022 (YS22) : proceedings of the 14th Conference of Civil and Environmental Engineering for PhD Students and Young Scientists. Slovak Paradise, Slovakia, 27-29 June 2022*. 1. vyd. Melville, NY : AIP Publishing, 2023, online, [5] s., art. no. 020041. ISSN 0094-243X. ISBN 978-0-7354-4600-7. V databáze: DOI: 10.1063/5.0159593. Typ výstupu: príspevok z podujatia; Výstup: domáci; Kategória publikácie do 2021: AFD

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V2_04 PORTNOV, Maksim - TARABRINA, Ekaterina - MARKO, Ivana - STANKO, Štefan. Modern problems of water purification in the regions of the Russian Federation on the example of the Tambov region. In *Proceedings from 10th Conference of Young Researchers - KOMVY 2021 [elektronický zdroj] : virtuálny priestor, Bratislava, SR, 29. - 30. 4. 2021*. 1. vyd. Bratislava : Spektrum STU, 2021, CD-ROM, s. 109-116. ISBN 978-80-227-5092-9. Kategória publikácie do 2021: AFD

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V2_10 PORTNOV, Maksim - STANKO, Štefan. CFD modeling as a method for modernizing the sewer network. In *Proceedings from 12th Conference of Young Researchers - KOMVY 2023 [elektronický zdroj]*. 1. vyd. Bratislava : Spektrum STU, 2023, CD-ROM, s. 32-38. ISBN 978-80-227-5323-4. Typ výstupu: príspevok z podujatia; Výstup: domáci; Kategória publikácie do 2021: AFD

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V2_16 PORTNOVA, Ekaterina - PORTNOV, Maksim - MARKO, Ivana - STANKO, Štefan. Vodovodná a kanalizačná sieť, výhody a nevýhody na príklade regiónu Tambov. In *Proceedings from 11th Conference of Young Researchers - KOMVY 2022 [elektronický zdroj] : Osrblie, SR, 2. - 6. 5. 2022*. 1. vyd. Bratislava : Spektrum STU, 2022, CD-ROM, s. 42-48. ISBN 978-80-227-5209-1. Typ výstupu: príspevok z podujatia; Výstup: domáci; Kategória publikácie do 2021: AFD

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V2_19 RACZKOVÁ, Andrea [Staňová, Andrea,] - RÓZSA, Gergely - PORTNOV, Maksim - ŠKULTÉTYOVÁ, Ivona. Vplyv zelených striech pri zmierňovaní mestských tepelných ostrovov z pohľadu trvalo udržateľného rozvoja. In *Proceedings from 11th Conference of Young Researchers - KOMVY 2022 [elektronický zdroj] : Osrblie, SR, 2. - 6. 5. 2022*. 1. vyd. Bratislava : Spektrum STU, 2022, CD-ROM, s. 49-54. ISBN 978-80-227-5209-1. Typ

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