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IS WATER QUALITY BASED STORMWATER MANAGEMENT ACTUALLY FEASIBLE? A SWMM-BASED STUDY ON THE TRADE-OFFS OF VARIOUS STORMWATER MANAGEMENT APPROACHES

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Abstract

Extreme weather events caused by climate change are becoming more frequent all across the world, particularly in the Northern Hemisphere, where these events manifest themselves as more severe or long-lasting rainfalls. Because the typical response, infrastructure refurbishment, is costly and time consuming, it is necessary to develop and implement alternative, more resource efficient, stormwater management methods. The methods must benefit both the urbanites as well as the natural environment, but they must be grounded on a comparative examination of alternatives.

The purpose of this paper is to evaluate the trade-offs between several stormwater control strategies in the context of climate change, such as no intervention, water quality-based intervention, water quantity-based intervention, and a combined approach. Each of the aforementioned approaches is considered to have intrinsic advantages and disadvantages that should be examined and quantified. Analysis of these trade-offs is critical because it provides some insight into the feasibility of implementing various stormwater management strategies for protecting the environment.

The SWMM software was used to analyse the various scenarios, and the model was built using data from multiple national databases as well as data sets provided by the Municipality of Viimsi in Estonia.

This study confirmed that water quality protection can be prioritized even in densely populated areas without jeopardizing citizens' well-being or causing unnecessary floods. This can be accomplished even with simple rule-based control if the necessary hardware, such as sensors and flow devices for digitalizing and combining inter-linking stormwater infrastructure are installed on-site. Through the SWMM simulations it was determined that digitalization of the stormwater solutions allows for a 30-92% reduction in flow, and consequently a 50-90% reduction in pollution load entering the Baltic Sea.

Keywords
SWMM, stormwater water quality, rule-based control, e-monitoring, stormwater management, feasibility.

1 INTRODUCTION

In recent years various agencies, consultancies, and international organizations have produced a plethora of reports covering the state of global water infrastructure [1, 2, 3]. Despite the fact that these documents have been composed by different organizations, they all have come to the same conclusion: globally there exists a massive infrastructure investment gap (drinking water, wastewater, and stormwater systems), which according to the Global Infrastructure Outlook (A G20 Initiative) could be worth up to $700 billion [1]. The bulk of this money is required to replace outdated pipes, pumps, storage facilities, and ensure the proper operation of sewage and stormwater treatment facilities, and thus protect the people and environment from the harmful effects of floods and pollution. If this growing investment gap is not bridged, then in the future, the reliability of water infrastructure shall decrease, and the frequency of emergencies caused by the infrastructure breaks and failures shall increase and the effects of these malfunctions may cascade and cause wide scale and severe disruptions in the urban environment.

Undoing the effects of years of chronic underfunding in the water sector is a challenging task, particularly if the goal is to bridge the gap without jeopardizing stakeholders' long-term financial stability. Achieving such a goal requires deliberate planning and foresight, as well as a shift in stakeholder engagement. It is necessary to change the way that we think about, organize, and manage stormwater, our urban environments and infrastructure [4]. Today's typical stormwater management solution is technical, relying on a network of engineered systems, however, such systems are designed for specific scenarios and modifying or refurbishing such systems in response to climate change is costly and time-consuming. A good attempt for reconciling these inherent weaknesses is done through the implementation of nature-based solutions. These systems, although requiring extensive planning and large initial investments may offer significant long-term benefits through increasing the resiliency of the urban environments to climatic fluctuations [5]. A plausible approach for leveraging the strengths and weaknesses of technical and natural systems is digitalization as it may allow to further reduce the volume of required infrastructure investments, lower the long-term operating and maintenance costs, and improve the provision of environmental and climate services. Overall, these hybrid systems are expected to be superior in every aspect in comparison to the individual systems as they enhance the strengths of individual systems by mitigating the weaknesses of them. Thus, these systems provide improved capacity to attenuate, buffer, retain, treat, and route stormwater flow and they are seemingly an adequate solution for future proofing the urban environment in face of climate change [6, 7].

Finding an optimal stormwater management solution requires balancing three objectives: cost (energy consumption, land use, construction, maintenance, rehabilitation, future proofing related to climate change), stormwater quantity and stormwater quality. It is necessary to strike a balance between these objectives while accounting for model-related uncertainties (stochastic or deterministic models) and the type of infrastructure on site (e.g., combined sewers or separate sewers) [8]. Many researchers have investigated the digitalization of stormwater systems and the various control approaches for their management and the control approaches have fallen broadly into two categories: static and dynamic [8. 9, 10, 11, 12]. Both of these approaches can be implemented for either the goal of stormwater quantity or stormwater quality management. The quantity-based approach typically focuses on the prevention of flooding and reduction of combined sewer overflow events through the control of runoff, and the quality-based approach typically focuses on pollutant reduction through the manipulation of hydraulic retention time and limiting the first flush effect. These approaches, however, are not inseparable from one another, as for example managing water quantity through peak reduction may also improve the water quality, however, it is typically not the primary goal of such approach.

Dynamic control in hybrid stormwater systems has long been regarded as an appealing stormwater management approach, however, its viability has so far been limited due to a lack of appropriate technologies and/or large costs associated with implementing the solutions [8, 9, 13]. The development of increasingly reliable, accurate, and low-cost sensors, along with advancements in data storage, processing, and transfer technologies has enabled concepts such as internet of things (IoT) to emerge, which has enabled the development of large-scale, decentralized solutions. Another catalyst for the widespread application of dynamic systems is the increase in the availability of off-grid solutions as their costs have dwindled and their energy production and storage capacities have increased [14, 15]. The primary advantage of a dynamic system over a static system is its efficiency in responding to a variety of highly stochastic and time critical environmental conditions. Although dynamic systems are considered to be more beneficial, they are not without their shortcomings as they are typically very complex, data intensive and costly to set up and maintain [11, 16].

The advent IoT solutions, the dwindling sensor and off-grid solution costs, and an annual increase in the body of knowledge on stormwater quality and quantity aspects gradually prepare us for the transition from static to dynamic systems. The purpose of this study was to determine the feasibility of implementing various stormwater management strategies on a small scale at a site in Viimsi Parish, Estonia. The research used SWMM modelling software and looked at the viability of three different control strategies: quality-based control, quantity-based control, and a combined control approach, as well as their viability in various climate scenarios.

2 MATERIAL AND METHODS

2.1 Data and modelling environment

The first step of any modelling task is to define the minimum data accuracy and requirements. The data requirements for the given study can be divided into three categories:

- Information needed to define the design storm and climate scenarios.
- Information needed for water quantity modelling.
- Information needed for water quality modelling.

Modelling software

SWMM was chosen as the modelling software because it is open source and it has a large user base in the scientific community, and it can simulate changes in both water quality and quantity. The input file was generated by utilizing GIStoSWMM5 [17], this tool required the preparation of 23 input files composed of data on the atmospheric, land surface, sub-surface, and conveyance compartment, and running them concurrently as a batch file. Although not all data had to be detailed, it was necessary to provide as much information as possible for at least the following: physical characteristics of the existing stormwater system, rainfall characteristics, elevation, land use, and flow directions, in order to create a model with a high level of utility. High utility in the context of modelling refers to a model that is as accurate as possible in terms of the interactions between flow routes, sub-catchments, and the stormwater network.

Digital Elevation and Land use data

The majority of the data needed to create the input files was obtained through consultations with Viimsi Municipality and various open-source databases in Estonia. The Municipality contributed the stormwater infrastructure data, which included historical geodetic surveys, as-built projects, and other digitalized data.

The Estonian Land Board website was used to obtain land use and elevation data (5x5 m resolution) [18]. The land use data was composed of various layers, such as waterbodies, buildings, green areas, roads and many more, and it was used to define the percentage of imperviousness of sub catchments. The elevation data was processed with an open-source toolbox TauDEM [19, 20] in ArcMap, as a result the shape, slope, area, and width of each catchment was obtained, and this information was used to create the flow direction file (.dir). The direction file was one of the main files required for running GIStoSWMM5 tool [17].

Water quality model and data requirements

Total suspended solids (TSS) were chosen as a proxy for stormwater quality estimation. TSS was chosen because it has been found to be frequently associated with several known contaminants, including metals (Cu, Cd, Zn, Pb, Cr, As, Ni), nutrients, persistent organic pollutants, and petroleum hydrocarbons, and thus it is frequently regarded as one of the main routes of contaminant transmission into urban waterbodies. Thus, TSS may be considered a source of concern for long-term human and ecological well-being. The risks related to suspended solids bound fraction of metals/metalloids are primarily related to the potential for phase shift into more bioavailable forms, resulting in chronic toxicity [12, 21, 22, 23, 24].

Another important factor in selecting TSS as a proxy for water quality status is its frequently discovered relationship with water turbidity, which is a parameter that can be monitored in situ in real time [21, 24, 25]. Because the TSS load reaching the waterbody is frequently linked to hydraulic retention time, time was chosen as a water quality control parameter. The modelling goal was to keep the water in the system as long as possible in order to limit the amount of TSS reaching the outfall and thus limit the export of pollutants from the urban environment to the aquatic environment. According to Gaborit et. al. 20 hours of hydraulic retention time is sufficient for approximately 50% of TSS removal and 40 hours of hydraulic retention time is sufficient for about 90% of TSS removal [26].

Another important factor in water quality was the point of occurrence of pollutant transport. According to the general body of literature, the pollution load is typically limited by the accumulation of contaminants from the previous dry days, and they are mobilized by the kinetic energy of rain drops and the turbulence created by stormwater runoff [27]. A common phenomenon observed in stormwater quality measurements is first flush, which occurred within the first 30 minutes at a nearby site in Estonia and ended up flushing at least 50% of pollutant load. A unitless concentration-volume curve represents this relationship (Figure 1).

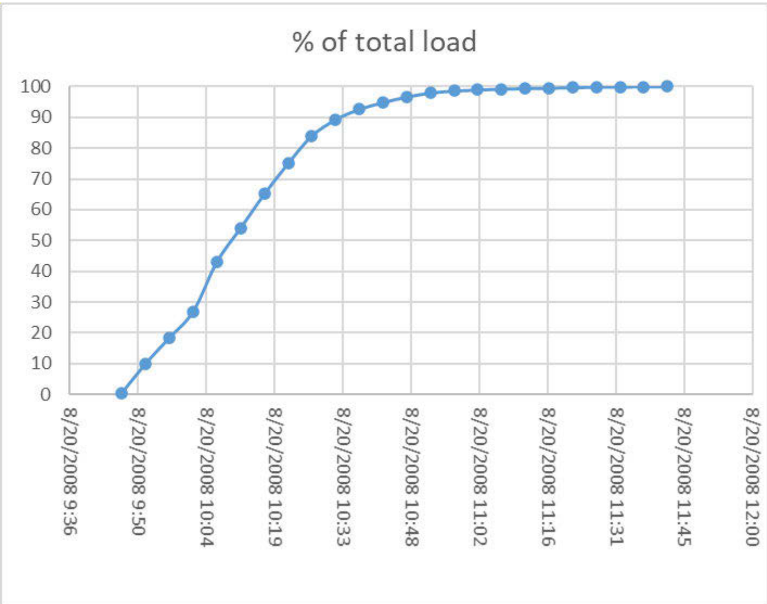

Figure 1 Pollutant concentration curve (unitless)

The authors anticipate that by retaining stormwater at appropriate times, it will be possible to reduce the amount of pollutant load entering the Baltic Sea during storm event while also reducing the number of storage units and thus the amount of money spent on water quality management.

2.2 Design storm and climate scenarios

The design storm is the acceptable hazard threshold for stormwater systems. This rigid, frequency-based approach (e.g., based on the probability of the occurrence of a 1-in-10-year event or 1-in-100-year event occurring) assumes that climate is stationary, and it is heavily reliant on the accuracy of the previously collected rainfall data. However, it is now widely accepted that our climate is constantly changing, and the intensity and the variability of climate hazards is increasing. This means that the past may no longer be representative of the future and a large part of our previously designed infrastructure may become overwhelmed. To offset the uncertainties related to the futureproof design of stormwater infrastructure it is necessary to emulate the effect of various climate scenarios on the stormwater infrastructure [28].

A design rainfall suggested by Estonian Design Standard (EVS848:2021) [29] with a return period of 10 years was used to build the NULL scenario of the rainfall. This was achieved by utilizing the following equation (1):

$$q_s = \frac{aP^b}{t^c} \tag{1}$$

Where q_s refers to average rainfall intensity (mm/h), t refers to the duration of the rainfall (in minutes), P refers to the return period (years) and b, c are empirical factors which depend on the location of the site (a= 325.7, b = 0.324, c = 0.77). Following the aforementioned formula an average precipitation intensity of 68.24 mm/h was calculated.

The runoff distribution acquired from outfall flow measurements was utilized to distribute the calculated average precipitation across a synthetic rainfall event of two hours. Thus, the total precipitation was assumed to be 136.48 mm over two hours and the distribution time step was 5 minutes. The distribution may be seen under the Null Scenario in Figure 2.

The NULL Scenario was then adjusted to account for climate change related precipitation increase by implementing the IPCC's Representative Concentration Pathway (RCP) methodology. Two alternative scenarios were chosen – RCP4.5 (intermediate scenario) and RCP8.5 (worst case scenario). In their report [30], the Estonian Environmental Agency translated the RCP methodology for Estonian climatic conditions and found that RCP4.5 forecasts an increase of rainfall intensity by 30% from the baseline conditions (approximately 88.72 mm/h) and RCP8.5 forecasts an increase of 80% from the baseline conditions (approximately 122.84 mm/h). The RCP4.5 and RCP8.5 scenarios are represented on the same hyetograph as the Null scenario (Figure 2).

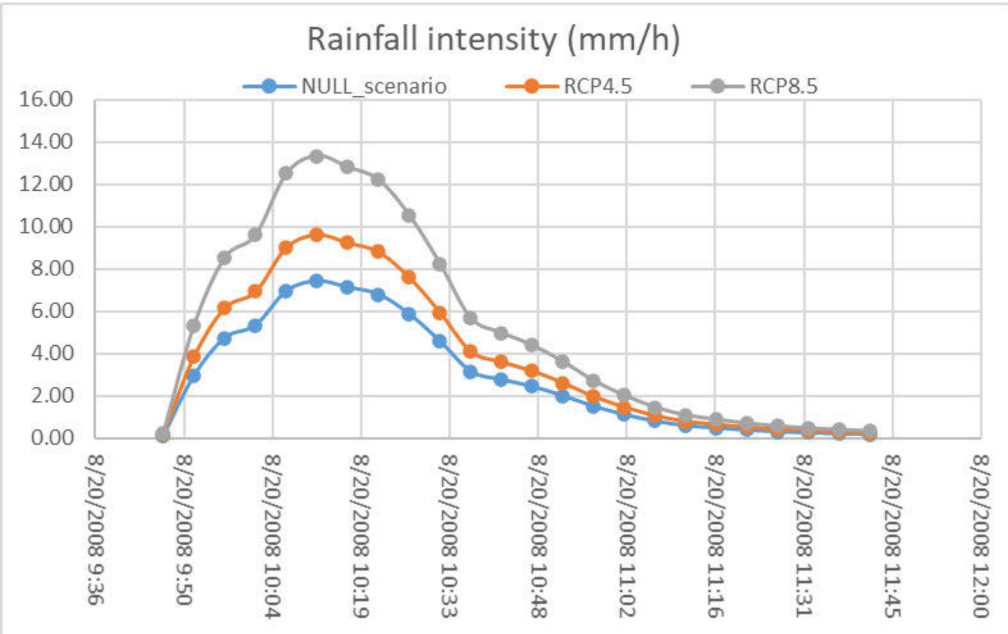

Figure 2 Design rain intensity

2.3 Pilot site description

The study site is located in Viimsi Parish, northeast of Tallinn, on the Viimsi Peninsula. The climate in this area is considered to be temperate and mild and characterized by warm summers and cold winters. The average summer temperature is about 20 °C and in the winter about -8°C and the average yearly precipitation is about 700 mm [31]. The municipality is regarded as one of the fastest developing areas, and it is actively seeking opportunities to mitigate the negative effects of development, such as increased runoff and deterioration of stormwater quality. The deterioration of stormwater quality is expected to contribute to further deterioration of Baltic Sea water quality and the emergence of potential health hazards for residents who use the Haabneeme Beach for recreational purposes. The study site size is approximately 271 ha, and it is composed of large chunks of green areas, such as Laidoner Park and Haabneeme-Klindiastangu landscape protection area and some still un-developed land parcels near the urban centre. The Parish also has all of the typical land use types that are commonly in the city, such as residential areas, as well as commercial, industrial, and recreational space.

The stormwater infrastructure at the study site is currently a mix of typical structural (pipes, culverts, and manholes) and non-structural (ditches, detention ponds) infrastructure, and there is no capacity to control this system. The total length of the system is about 57214 meters, with non-structural infrastructure accounting for 18% of it and structural infrastructure about 82% of it. Plans are in place to augment this system with modern technologies such as sensors, weirs, and actuators in the future to enable control. However, there is currently no preliminary assessment of the optimal placement and potential catchment scale effects of using these devices. Figure 3 depicts an overview of the site.

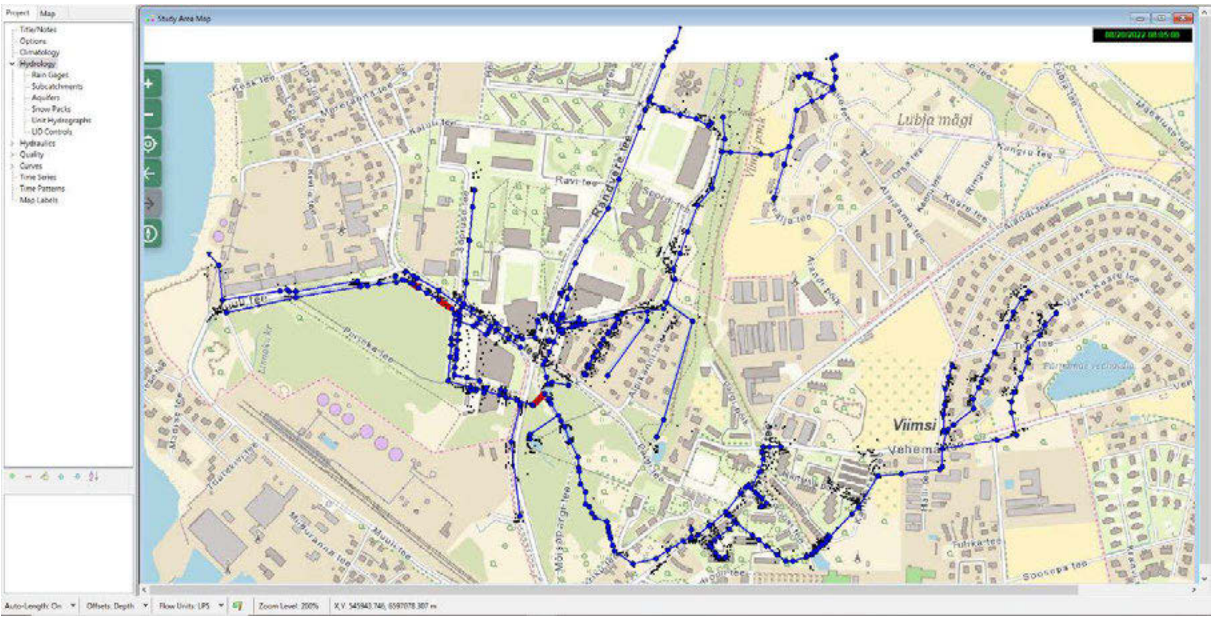

Figure 3 SWMM model of the study site

2.4 Identifying control locations

The proper placement of inundations is critical for stormwater quality and quantity control because it can increase the efficiency of the control system while significantly reducing potential economic, environmental, and health hazards. There are several methodologies for selecting control sites [e.g., 8, 32], but these are beyond the scope of this paper.

A typical dynamic stormwater management system is composed of the following hardware: sensors, actuators, power supply, data storage and transfer technology, and a shut-off device, such as a weir or an orifice. All of this hardware as well as local conditions, such as the slope, inundation capacity and regulatory constraints, impose concrete limitations on the placement of control devices. In this study the most appropriate locations were identified based on the following criteria: possibility of electrification to avoid data loss, ease of access for the maintenance crew, and no backflow is caused by the inundation (only controlled floods are allowed). Figure 4 depicts the final locations chosen based on these criteria.

Figure 4 Points of inundation (red lines)

2.5 Control strategies

The points shown in Figure 4 were chosen for stormwater system control as they matched the expectations of the Municipality and were relatively important from an engineering perspective. The control points were relatively spacious (pond around 250 m^3 and ditch around 350 m^3), assuming that the water level at both of the waterbodies is at 0,5 meters. If the total depth is to be considered, then the inundation capacity would increase by about 2-3 times.

SWMM model was used to confirm the suitability of the chosen sites and to determine their actual maximal retention capacity. The modelling compared the following control strategies:

- Option 1: NULL scenario; no control was imposed, and the catchment behaviour was simulated during design rainfalls of varying intensities. Capacity of the infrastructure to withstand intense rainfall events was assessed.
- Option 2: Quantity based scenario; controls were imposed based on water quantity – the priority was to avoid flooding at all costs. Maximum extent of local flooding was compared with the capacity of the foreseen inundations.
- Option 3: Quality based scenario; controls were imposed based on water quality and it was assumed that 40 hours of water retention is sufficient to provide at least 90% of TSS reduction in the outfall.

- Option 4: Combined scenario; both water quality and quantity were assessed, the goal was to retain as much water as possible, while keeping the pollutant load (TSS) as low as possible. It was assumed that 20 hours of water retention is sufficient to provide at least 50% of TSS reduction in the outfall.

The control logic is shown in Figure 5.

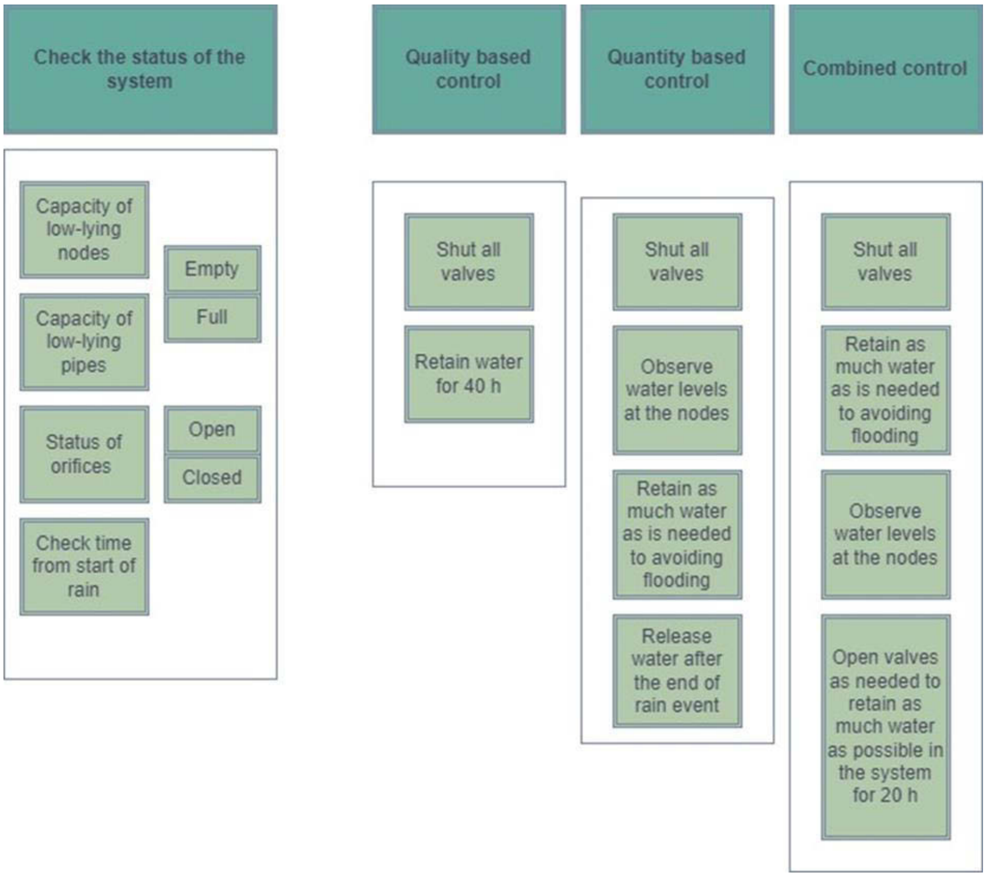

Figure 5 Control Scheme

3 RESULTS AND DISCUSSION

Several rainfall scenarios were simulated to assess their impact on the performance of Viimsi's stormwater system, and controls were designed to implement various stormwater management scenarios, including water quality-based, water quantity-based, and combined. These scenarios were compared using a 2-hour rain event as a baseline, without considering the effect of consecutive rainfalls.

Because the stormwater system is not a hypothetical one, the emphasis was on utilizing the existing space within the system and the environment as a means to increase the hydraulic retention time of the system. It was assumed that increasing retention time would help to restore the natural hydrological cycle (through increasing infiltration, evaporation, groundwater recharge) and improve water quality (through increasing sedimentation, biotic degradation, and physico-chemical transformations). The stormwater system as a whole was found to be quite well designed, as the 2-year rainfalls did not cause any flooding within the catchment area, even when accounting for climate change scenarios RCP4.5 and RCP8.5, which predict 30% and 80% increase in rainfall intensity. As a result, the resiliency of the stormwater system had to be further tested with rainfalls of various return periods, such as 5-years and 10-years, which were also adjusted in accordance with the aforementioned climate scenarios.

The 10-year return period scenario (RCP8.5) was chosen as the scenario for further modelling because it had the greatest impact on the stormwater system performance. The model was initially run without any interventions to determine the behaviour of the system at the critical nodes and links, as well as the total volume of water leaving the catchment via the outfall. The baseline scenario, in which no control was implemented, predicted that a 2-hour storm event with a rainfall intensity of 122 mm/h would result in 3652 m^3 of stormwater reaching the Baltic Sea. Because such a scenario lacks controls, it was assumed that significant improvements could be made with minor adjustments.

The first approach aimed to reduce the volume of water reaching the Baltic Sea while avoiding flooding in the urban areas. Similarly, to water quality-based management, orifices were added at critical nodes and links of the system. During the simulation it was monitored that the capacity of the system's nodes was not exceeded. The exceedance of capacity of the nodes refers to avoidance of floods of the manholes and maintaining the fill of pipes below 0.8. The quantity-based control demonstrated that by controlling the water level at a few key nodes, the volume of water reaching the Baltic Sea could be reduced by about 30%. Overflows were used in this approach to avoid flooding while still utilizing the system's full capacity. In this case, approximately 2563 m^3 of stormwater was discovered to make its way to the outfall. Because the purpose of this scenario was not water quality control, the system was emptied as soon as the rainfall event ended.

The second scenario tested on the system was centred on water quality, with the goal of reducing the pollutant load reaching the Baltic Sea by increasing the volume of water retained in the system. It was assumed that at least 40 hours hydraulic retention time would suffice to reduce total suspended solids (TSS) load by approximately 90%. It was determined that by simply maximizing the utilization of capacity of the existing stormwater pond, pipelines, and ditches within the catchment by installing orifices in key locations and implementing a simple rule-based control that focused on retention time and ignored the occurrence of floods in the urban environment, the volume of water reaching the Baltic Sea could be reduced by about 92%. Only 279 m^3 of stormwater reaches the Baltic Sea in this case. This method ignored the effect of multiple sequential rainfall events, and the authors acknowledge that significant flooding may occur if a rainfall even of sufficient intensity and/or total volume occurs.

The third scenario (Figure 6) was a hybrid scenario that aimed to reduce both the volume of water reaching the Baltic Sea and improve the runoff water quality. The results were obtained by implementing both time-based control for capturing first flush, observing water level at key nodes and links, and attempting to keep the stormwater within the system for approximately 20 hours in total to achieve a 50% reduction in TSS load. Overflows were extensively used in this approach, resulting in 43% reduction in stormwater volume reaching the Baltic Sea. The estimated total volume reaching the outlet was about 2092 m^3.

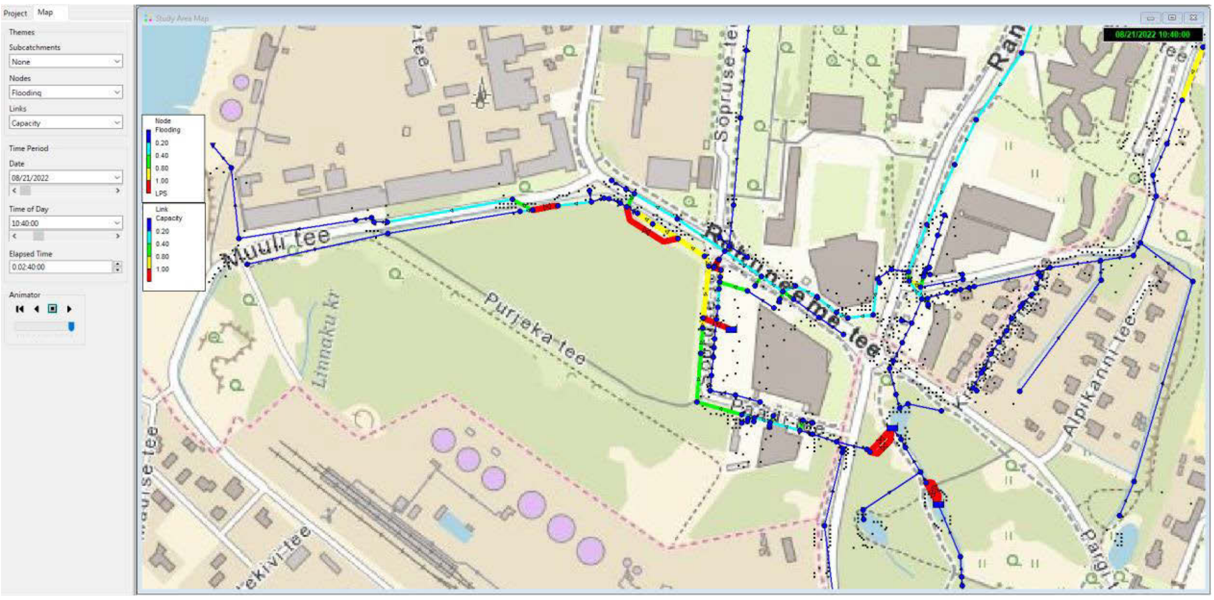

Figure 6 Snip of the model (combined scenario)

An overview of the results may be seen in Table 2 and the dynamics of the outfall are presented in Figures 7, 8, 9, 10.

Table 1 Control results

	Baseline scenario	Water quantity	Water quality	Combined
Total volume of runoff (m^3)	3652	2563	279	2092
Reduction (%)	-	30	92	43
Max flow (l/s)	285.72	455.58	28.83	202.97
Min flow (l/s)	58.54	202.97	3.79	32.73

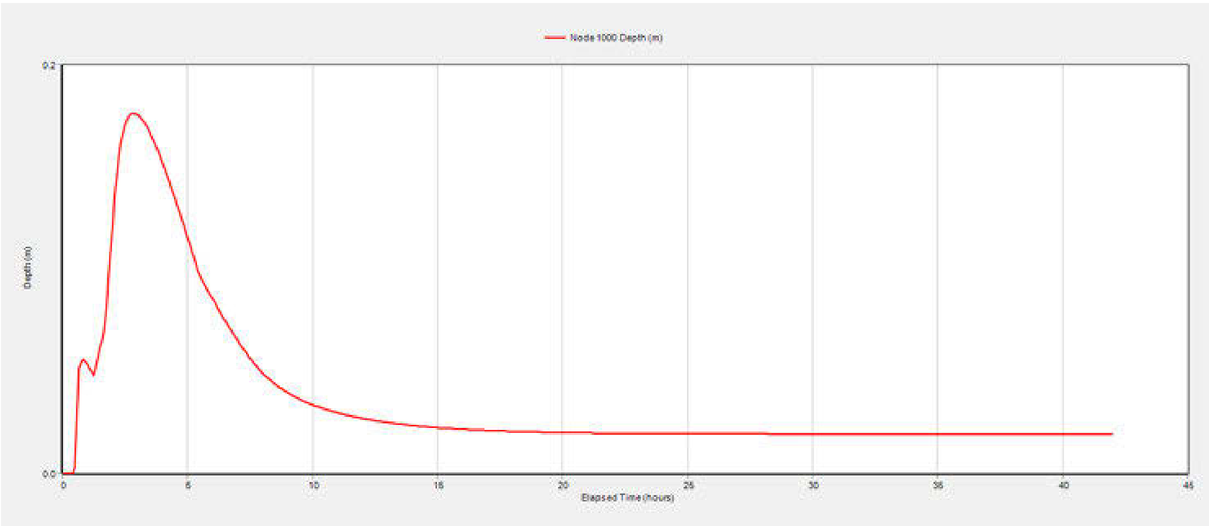

Figure 7 Baseline scenario (no control)

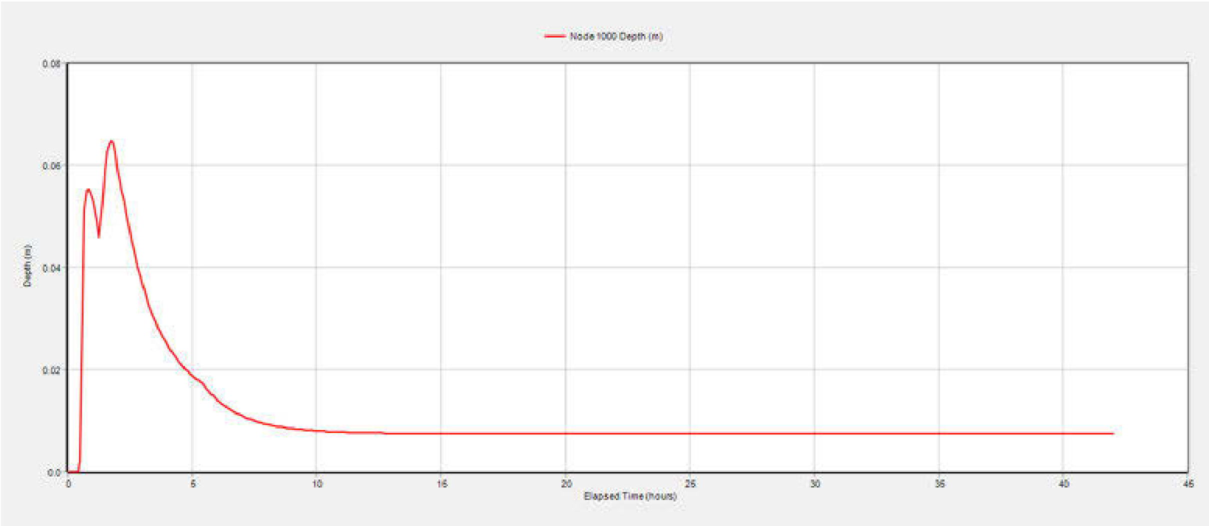

Figure 8 Water quantity control scenario

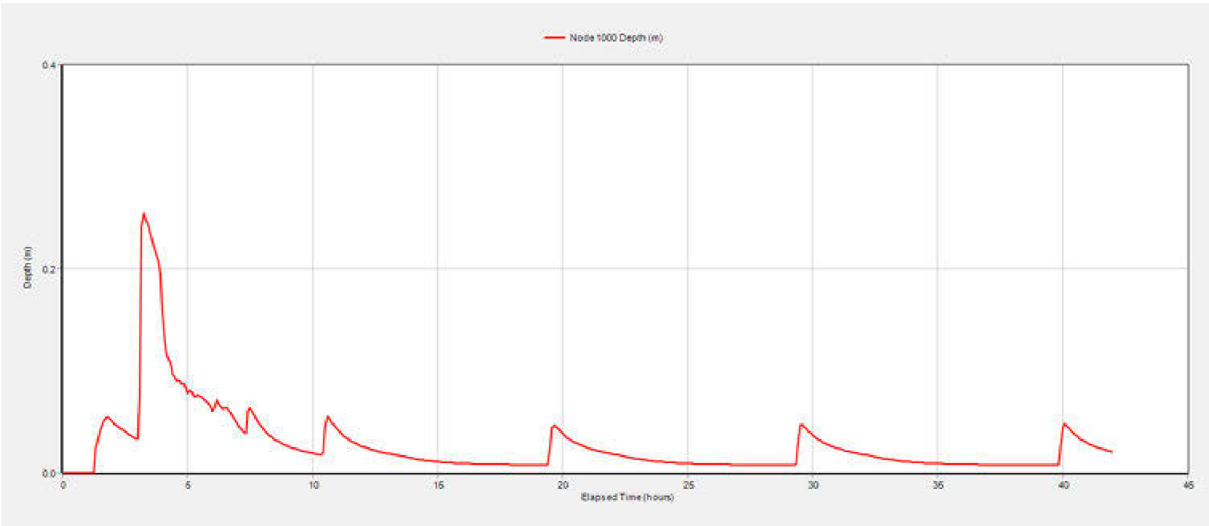

Figure 9 Water quality control scenario

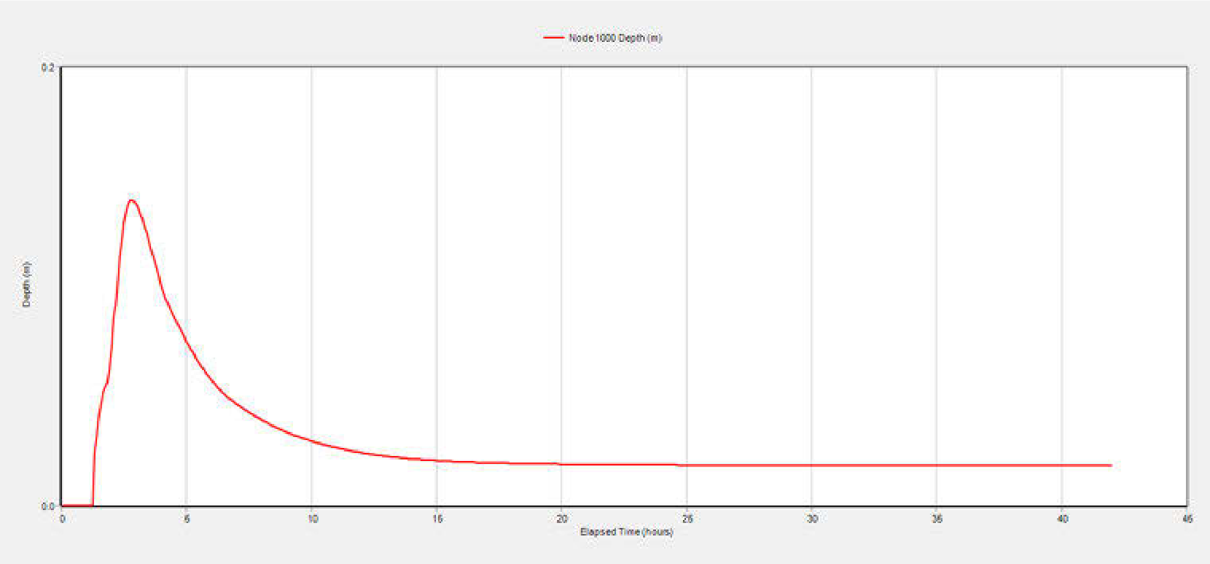

Figure 10 Combined control scenario

This simulation demonstrated that even small-scale interventions can reduce the total volume of polluted water reaching the Baltic Sea, as well as optimize the use of the existing stormwater system and the urban environment, avoiding costly investments in various stormwater infrastructure such as tanks, pipes, and pumping stations, and limiting the energy spent on water pumping. In our case, system digitalization enable us to create 1089 to 3373 m^3 of relatively low-cost storage space. The capacity of the entire stormwater network is even greater, so further system adjustments in appropriate locations promise to increase utilization of the system's free capacity even further.

This work was only a preliminary assessment of the potential for digitalization of stormwater systems in Viimsi, Estonia. Further steps will be taken in the future to assess the feasibility and practicability of this approach. Simple rule-based control could be expanded by increasing the number of control nodes and links to which various terms are assigned, as well as water quality measurements and modelling could be undertaken to confirm the TSS reduction. The water quality-based control could aim to keep the TSS load at the outfall below 35 mg/l by regulating and slowing the flow and allowing enough time for sedimentation to occur. A criterion of keeping the node and link capacity below a certain threshold value (e.g., 0.8) could be tested in the case of the links. These tests could begin with rule-based control and then be expanded to include proportional-integral-derivative (PID) and even model-predictive controls (MPC). Furthermore, a concept of traffic data-based stormwater management could be explored, in which a rule is added to the control algorithm, that some sites within the urban environment can be used as extra storage space if the data indicates a low volume of movement through the area at certain times of the day.

4 CONCLUSIONS

The study case based on the Viimsi Parish urban drainage system (UDS) successfully demonstrated how, by installing sensors and orifices and implementing RTC (even simple rule based), it is possible to significantly improve the operation of a stormwater system. The investigation revealed that all types of control strategies allow for a closer relationship to the natural hydrological cycle by retaining water in the system and reducing the volume of water released into the Baltic Sea. It also revealed that stormwater management focused on water quality is feasible; however, caution must be exercised in terms of observing rainfall events –

various scenarios should be preliminarily investigated, and proper overflows should be installed to avoid extreme flooding events in the system. An optimal solution appeared to be a combined solution that seeks to extend the retention period while avoiding floods; this is also the approach that was deemed to have the most potential for optimization, but this is a matter future research. In any case, there are trade-offs between various scenarios, and the suitability of a control solution is heavily dependent on the characteristics of the site – such as the availability of space, the size and goodness of design of the existing stormwater system, the topography of the area, and the percentage of impervious area on site.

Replicating this assessment of the stormwater system with rainfalls of different return periods and for different climate conditions is a promising first step toward further developing a more complex control logic for a stormwater system of a particular catchment. So far, the results indicate that realizing RTC may help to create a triple bottom line, this is accomplished through i) reducing the need for additional infrastructure investments by better utilizing the existing system's capacity, ii) reducing the risk of urban flooding, and iii) significantly improving water quality.

This research confirmed that even a densely populated catchment may be improved so that water quality protection is prioritized without jeopardizing citizens' well-being or causing unnecessary floods. In order to achieve this water levels at the most critical nodes must be monitored and the most low-impact sites for inundation must be identified. It was also observed that RTC has the potential to realize the benefits even in future conditions, where rainfall intensity may increase by 30% (RCP4.5) or by 80% (RCP8.5).

Acknowledgements

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5 REFERENCES

[1] Oxford Economics. (2017). Global infrastructure outlook. Global Infrastucture Hub: Sydney, Australia, 64. https://www.oxfordeconomics.com/recent-releases/99f4fa86-a314-4762-97c6-fac8bdcbe40a%0Ahttps://outlook.gihub.org/%0Ahttps://www.oxfordeconomics.com/recent-releases/Global-Infrastructure-Outlook

[2] United Nations. (2018). Water infrastructure and development. United Nations, 10(9). https://sustainabledevelopment.un.org/content/documents/hlpwater/08-WaterInfrastInvest.pdf

[3] The American Society of Civil Engineers. (2020). The Economic Benefits of Investing in Water Infrastructure: How a Failure to Act Would Affect the US Economic Recovery. 1–40. www.downstreamstrategies.com

[4] Monstadt, J., Colen Ladeia Torrens, J., Jain, M., Macrorie, R. M., & Smith, S. R. (2022). Rethinking the governance of urban infrastructural transformations: a synthesis of emerging approaches. Current Opinion in Environmental Sustainability, 55, 101157. https://doi.org/10.1016/j.cosust.2022.101157

[5] Andersson, E., Grimm, N. B., Lewis, J. A., Redman, C. L., Barthel, S., Colding, J., & Elmqvist, T. (2022). Urban climate resilience through hybrid infrastructure. Current Opinion in Environmental Sustainability, 55, 101158. https://doi.org/10.1016/j.cosust.2022.101158

[6] Browder, G., Ozment, S., Rehberger Bescos, I., Gartner, T., & Lange, G.-M. (2019). Integrating Green and Gray: Creating Next Generation Infrastructure. World Resources Institute. https://doi.org/10.46830/wrirpt.18.00028

[7] Mullapudi, A., Wong, B. P., & Kerkez, B. (2017). Emerging investigators series: Building a theory for smart stormwater systems. In Environmental Science: Water Research and Technology (Vol. 3, Issue 1, pp. 66–77). https://doi.org/10.1039/c6ew00211k

[8] Shishegar, S., Duchesne, S., & Pelletier, G. (2018). Urban Water Journal Optimization methods applied to stormwater management problems: a review Optimization methods applied to stormwater management problems: a review. H

[9] Sadler, J. M., Goodall, J. L., Behl, M., Bowes, B. D., & Morsy, M. M. (2020). Exploring real-time control of stormwater systems for mitigating flood risk due to sea level rise. Journal of Hydrology, 583(April). https://doi.org/10.1016/j.jhydrol.2020.124571

[10] Saliba, S. M., Bowes, B. D., Adams, S., Beling, P. A., & Goodall, J. L. (2020). Deep reinforcement learning with uncertain data for real-time stormwater system control and flood mitigation. Water (Switzerland), 12(11), 1–19. https://doi.org/10.3390/w12113222

[11] Xu, W. D., Burns, M. J., Cherqui, F., & Fletcher, T. D. (2021). Enhancing stormwater control measures using real-time control technology: a review. Urban Water Journal, 18(2), 101–114. https://doi.org/10.1080/1573062X.2020.1857797

[12] Khiem Ly, D., Maruéjouls, T., Binet, G., & Bertrand-Krajewski, J.-L. (2019). Urban Water Journal Application of stormwater mass-volume curve prediction for water quality-based real-time control in sewer systems Application of stormwater mass-volume curve prediction for water quality-based real-time control in sewer systems. https://doi.org/10.1080/1573062X.2019.1611885

[13] Xu, C., Tang, T., Jia, H., Xu, M., Xu, T., Liu, Z., Long, Y., & Zhang, R. (2019). Benefits of coupled green and grey infrastructure systems: Evidence based on analytic hierarchy process and life cycle costing. https://doi.org/10.1016/j.resconrec.2019.104478

[14] Oberascher, M., Rauch, W., & Sitzenfrei, R. (2022). Towards a smart water city: A comprehensive review of applications, data requirements, and communication technologies for integrated management. Sustainable Cities and Society, 76(October 2021), 103442. https://doi.org/10.1016/j.scs.2021.103442

[15] Nižetić, S., Šolić, P., López-de-Ipiña González-de-Artaza, D., & Patrono, L. (2020). Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future. Journal of Cleaner Production, 274. https://doi.org/10.1016/J.JCLEPRO.2020.122877

[16] Shrestha, A., Mascaro, G., & Garcia, M. (2022). Effects of stormwater infrastructure data completeness and model resolution on urban flood modeling. Journal of Hydrology, 607, 127498. https://doi.org/10.1016/J.JHYDROL.2022.127498

[17] GitHub - AaltoUrbanWater/GisToSWMM5: An automated subcatchment generator for SWMM5 model. (n.d.). Retrieved March 28, 2022, from https://github.com/AaltoUrbanWater/GisToSWMM5

[18] Download Topographic Data | Geoportal | Estonian Land Board. (n.d.). Retrieved March 28, 2022, from https://geoportaal.maaamet.ee/index.php?lang_id=2&page_id=618

[19] David Tarboton: Hydrology Research Group-Terrain Analysis Using Digital Elevation Models (TauDEM) Version 5. (n.d.). Retrieved March 28, 2022, from https://hydrology.usu.edu/taudem/taudem5/

[20] GitHub - dtarb/TauDEM: Terrain Analysis Using Digital Elevation Models (TauDEM) software for hydrologic terrain analysis and channel network extraction. (n.d.). Retrieved March 28, 2022, from https://github.com/dtarb/TauDEM

[21] Rügner, H., Schwientek, M., Beckingham, B., Kuch, B., & Grathwohl, P. (2013). Turbidity as a proxy for total suspended solids (TSS) and particle facilitated pollutant transport in catchments. Environmental Earth Sciences, 69(2), 373–380. https://doi.org/10.1007/s12665-013-2307-1

[22] Nasrabadi, T., Ruegner, H., Schwientek, M., Bennett, J., Valipour, S. F., & Grathwohl, P. (2018). Bulk metal concentrations versus total suspended solids in rivers: Time-invariant & catchment-specific relationships. PLoS ONE, 13(1), 1–15. https://doi.org/10.1371/journal.pone.0191314

[23] Sun, C., Romero, L., Joseph-Duran, B., Meseguer, J., Guasch Palma, R., Martinez Puentes, M., Puig, V., & Cembrano, G. (2021). Control-oriented quality modelling approach of sewer networks. Journal of Environmental Management, 294, 113031. https://doi.org/10.1016/j.jenvman.2021.113031

[24] McDonald, S., Holland, A., Simpson, S. L., Gadd, J. B., Bennett, W. W., Walker, G. W., Keough, M. J., Cresswel, T., & Hassell, K. L. (2022). Metal forms and dynamics in urban stormwater runoff: New insights from diffusive gradients in thin-films (DGT) measurements. Water Research, 209, 117967. https://doi.org/10.1016/J.WATRES.2021.117967

[25] Wang, Q., Zhang, Q., Dzakpasu, M., Lian, B., Wu, Y., & Wang, X. C. (n.d.). Development of an indicator for characterizing particle size distribution and quality of stormwater runoff. https://doi.org/10.1007/s11356-017-1074-z

[26] Gaborit, E., Muschalla, D., Vallet, B., Vanrolleghem, P. A., & Anctil, F. (2012). Urban Water Journal Improving the performance of stormwater detention basins by real-time control using rainfall forecasts https://doi.org/10.1080/1573062X.2012.726229

[27] Wijesiri, B., Egodawatta, P., Mcgree, J., & Goonetilleke, A. (2016). Understanding the uncertainty associated with particle-bound pollutant build-up and wash-off: A critical review. https://doi.org/10.1016/j.watres.2016.06.013

[28] Markolf, S. A., Chester, M. V., Helmrich, A. M., & Shannon, K. (2021). Re-imagining design storm criteria for the challenges of the 21st century. Cities, 109 (July 2019), 102981. https://doi.org/10.1016/j.cities.2020.102981

[29] EVS 848:2021 - Estonian Centre for Standardisation and Accreditation. (n.d.). Retrieved May 5, 2022, from https://www.evs.ee/en/evs-848-2021

[30] Luhamaa, A., Kallis, A., Mändla, K., Männik, A., Pedusaar, T., & Rosin, K. (n.d.). Keskkonnaagentuur Eesti tuleviku kliimastsenaariumid aastani 2100.

[31] Sademed |Keskkonnaagentuur. (n.d.). Retrieved May 5, 2022, from https://www.ilmateenistus.ee/kliima/kliimanormid/sademed/

[32] Kändler, N., Annus, I., & Vassiljev, A. (2022). Controlling peak runoff from plots by coupling street storage with distributed real time control. Urban Water Journal, 19(1), 97–108. https://doi.org/10.1080/1573062X.2021.1958235