A screening method for urban drainage zones

Tiina M. Komulainen[1] Tolli Lavrans Mørk[1] Ali Riyad Al-Shiblawi[1] Jakub Roemer[1,2]
[1]Department of Mechanical, Electronics and Chemical Engineering, Oslo Metropolitan University, Norway,
`{tiina.komulainen, jakub.roemer}@oslomet.no`
[2]AGH University of Science and Technology, Poland

Abstract

Due to climate change, the storms have intensified leaving the urban drainage system and wastewater treatment plants hard to tackle with the large water quantities. In this study we develop a data-based screening method to identify which drainage zones would benefit most of blue-green infrastructure to avoid spilling of uncleaned water. First the precipitation and drainage zone flow rate data are pre-processed and de-seasonalized to remove the flow rate due to consumer wastewater. Then, system identification is applied for the rain periods and transfer function parameters for first order plus time delay model are collected. The screening index is calculated from the transfer function model parameters. The results show that the system is very nonlinear, but the mean values for the screening index is statistically significantly different for the drainage zones included to this study. The screening index clearly separates the different types of drainage zones and gives a reasonable suggestion for which drainage zones should be considered further for implementation of blue-green infrastructure like nature-based solutions.

Keywords: dynamic modeling, system identification, urban drainage system, nature-based solutions, blue-green infrastructure, flood risk mitigation.

1 Introduction

It is expected that the climate change is going to have increasing impact on urban water resources. Currently, for the most European regions the rainfall patterns and temperature regimes are changing (Field, 2014). Precipitation frequency and temporal distribution leads to shorter but more intense rainfall events.

In rapidly expanding urbanization the urban drainage system and wastewater treatment plants are unprepared for treatment of large water quantities. This causes flooding in cities and disposal of uncleaned water to nearby sea/rivers/lakes. Flood damages the city buildings and polluted urban water systems have high economical and ecological consequences for the citizens and marine life (Leal Filho, 2019).

In recent years the idea of nature-based solutions (NBS) has gained significant attention for storm water mitigation (Dolman, 2020, Kalsnes, 2019). Nature-based solutions are blue-green infrastructures implemented at the human habitats (Somarakis, 2019). The main goal of NBS is to support sustainable and resilient city growth, mitigate climate change and restore the local ecosystem. Nature-based solutions can potentially be used for flood risk mitigation and water quantity and quality improvement. The principal of NBS lies in natural process of water evapotranspiration, phytoremediation and infiltration (Haase, 2015, Beloqui, 2020). Rainwater, instead of being transported directly into the storm channels grid, can be accumulated in NBS and slowly disposed hours or even days after the precipitation event. Thanks to this ability, the water runoff peak can be flattened and prolonged. Lowered runoff amplitude is easier to handle by wastewater treatment facilities, which makes the city more flooding resilient (Eisenberg 2018).

There are many types of NBS dedicated to support surface water regulation function in the city areas. The most effective are arboretums, residential parks, green roofs (intensive/smart), detention ponds (dry), retention ponds (wet), biofilters and mounds (Somarakis, 2019, Eisenberg, 2018). Recently, green roofs have been implemented at Fossum Terrasse in Bærum. At the moment the constructed wetlands are built at Hovseterdalen in Oslo.

1.1 Drainage zones and storm water problem

A drainage zone is an area of land, forest, buildings, infrastructure and a subterranean urban drainage pipeline network that leads the rainwater and wastewater from households towards a joint urban water tunnel. The joint urban water tunnel collects water from the drainage zones in Oslo, Bærum and Asker municipalities and leads the water to the Veas wastewater treatment plant. In Asker municipality the rainwater is flowing in its own pipelines whereas in many parts of Oslo and Bærum the rainwater and household water are flowing in the same subterranean pipelines. During heavy rain the joint urban water tunnel

DOI: 10.3384/ecp21185429

can get filled up with water, and the excess uncleaned water will be spilled to the Oslo fjord. This is a major threat to the marine life the Oslo fjord and closes of beaches along the fjord.

1.2 Problem statement and research questions

More targeted efforts are needed to reduce disposal of uncleaned water to the Oslo Fjord during heavy storms. The Veas wastewater treatment plant and municipalities at Oslo, Bærum and Asker have challenged researchers at OsloMet to develop a screening method that can pinpoint drainage zones which have the greatest influence to the excess water into the Veas tunnel during rainy periods.

We aim to develop a screening method based on dynamic characterization of the drainage zones using collected time series. The screening method should illustrate which drainage zones could benefit most of blue-green infrastructures by slowing down the water flow through the drainage zone, and thereby flattening the flow profile into the tunnel.

Our research questions are: RQ1: Is it possible to approximate the dynamic behavior of water flow through a drainage zone with a simple time-series model? RQ2: Can the drainage zones be classified using an index based on the dynamic model parameters?

Table 1. Bærum drainage zones with precipitation stations, number of inhabitants and maximum values for precipitation and flow sensors.

Drainage zone	Precipitation station	Persons	Max precipitation [mm]	Max flow [L/s]
Bjørne-gård	Gjettum_II	914	15.4	92.2
Sør-aasen	Aurevann	2882	8.9	208.7
Evjebakken	Gjettum_II	2072	15.4	250.8
Jar	Øvrevoll	8497	6.0	341.8
Sand-vika	Bærum_kommunegården	9264	12.3	435.9
Ha-mang	Økeriveien, Bærums_verk,Øvre_Toppenhaug,Gjettum_II	34582	17.0	915.1
Sta-bekk	Storøya	9358	6.1	966.5

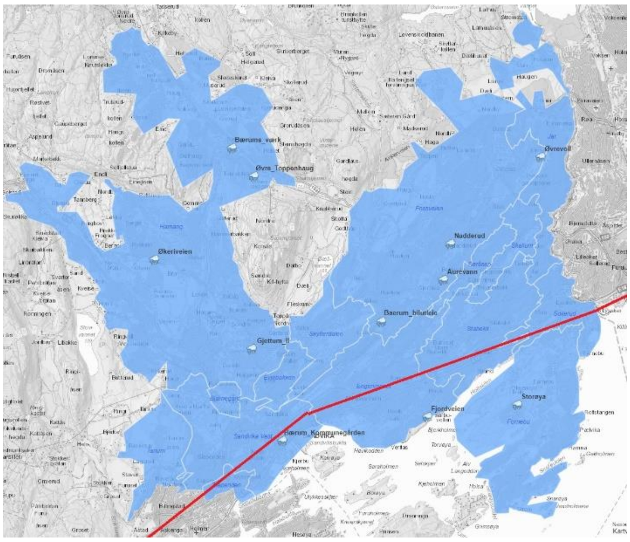

Figure 1. Drainage zones (blue text) and precipitation stations (black text) in Bærum municipality. The joint urban water tunnel (red line) is built along the coast.

1.3 Scope of the study, Bærum municipality

The scope of this case study is the urban drainage system in Bærum, because the data set for this area is more complete than data sets collected for Oslo and Asker municipalities. The drainage zones, the precipitation stations, the number of inhabitants and the maximum values for the precipitation and flow measurements are given in Table 1 and Figure 1. The drainage zones omitted from this study due to missing data are Engervann, Fossveien, Fornebu, Skallum Skytterdalen, Slependen, and Tanum.

Rainwater is measured at precipitation stations, located in different drainage zones. Some drainage zones do not have its own precipitation station, and therefore, the closest precipitation measurement is used to estimate the rain fall in this zone. The rainwater and wastewater from one drainage zone are led into an inlet point to the joint urban drainage tunnel. The flow measurement device is installed at this inlet point.

2 Modeling of urban drainage systems

Hydrology refers to water, its occurrence, distribution, circulation as well as its physical and chemical properties (Marshal, 2013). Hydrological phenomena like rainfall, interception, infiltration, transportation, evaporation or storage are components of water cycle. There are many hydrologic models trying to represent water behavior. These models can be divided into three categories, depending on used parameters and physical principles applied (Devia, 2015).

First group consists of empirical models representing a data-driven approach. Water behavior modeling is based on finding relations between input (usually rainfall) and output (water runoff) without taking into account actual the complex physics. The second group covers parametric-based models. These models try to represent the water runoff behavior with a multi-parameter equations. The parameters are usually obtained empirically and calibrated for each specific case. The physically based models are the third group. Their principle of operation is based on modeling physics behind hydrological processes. The water dynamics is usually represented with differential equations.

2.1 Physically based approach

MIKE SHE is one of the most widely used physically based hydrological models (Ma, 2016). The principle of operation lies in dividing the watershed into a unit grid horizontally for discrete calculations of complex terrain. The relationship between the ecohydrological processes (precipitation, evaporation etc.) and water runoff is calculated through continuity and motion equations (Zhou, 2013). The MIKE SHE contains three modules: water body motion module, water quality module and water balance tool, as well as several submodules, including snow melting module, overland flow module, rivers and lakes module, evapotranspiration module, unsaturated flow module and saturated flow module. The accurate calculations require selection of proper set of modules. It is a complex and challenging task depending on multidisciplinary skills.

2.2 Parameter based approach

SWIMM model is one of well-recognized parameter-based models used for dynamic rainfall-runoff simulation (Rossman, 2015). It can be used for single event as well as for long-term simulations. The modeled land area is divided into subcatchment areas, which are characterized by different the soil types and ground covers. The SWIMM model collects the subcatchment areas that generate rainwater runoffs as a result of precipitation. The SWIMM model then simulates the water transportation through pipes and channels. Water storage and treatment devices (pumps and regulators) can be also implemented. The SWIMM can model both runoff quantity and quality, separately for each subcatchment area, pipe or channel.

2.3 Data-driven approach with system identification

System identification is a data-driven method to create models from time-series data (Ljung, 1999). The system identification toolbox in Matlab uses subspace algorithm to identify parameters for models with pre-defined structures such as transfer functions, state-space models and many more.

2.4 The idea for simplified modeling for urban drainage zone

In order to develop a simple screening method, we need to characterize the dynamic behavior between precipitation and flow. We assume that the hydrological system, i.e. the soil and built infrastructure, in a drainage zone can be approximated as a first order transfer function system. Further we assume that the hydraulic system, i.e. the water flow through the subterranean pipelines in a drainage zone, can be approximated as plug-flow. This gives us a first order plus time delay (FOPTD) transfer function model structure between precipitation P(s) and flow F(s) to the joint urban drainage tunnel:

$$F(s) = \frac{K_p}{T_p s+1} \cdot e^{-T_d s} \cdot P(s) \qquad (1)$$

Where K_p is the process gain, T_p is the time constant and T_d is the time delay.

2.5 The idea for screening method for urban drainage zones

Assume that the drainage zones can be modeled with FOPTD system and the dynamic characteristics of the precipitation are similar to a pulse signal. Then, the rainwater flow from each drainage zone will be a pulse response. Further, assume that these pulse responses from each the drainage zone can be summed up using the principle of superposition. The total flow profile into the joint urban water tunnel is then the sum of the flow profiles from each drainage zone.

Now, the drainage zone with the largest process gain and the shortest time delay and shortest time constant, will have the sharpest flow profile that contributes most to the problem of overflow in the joint urban water tunnel.

We suggest to construct the screening index for drainage zone i, S_i, as follows:

$$S_i = \frac{K_{pi}}{T_{pi}+T_{di}} \qquad (2)$$

Drainage zones with high Si have most aggressive flow profile whereas drainage zones with low Si index have smoother flow profile.

Constructing blue-green infrastructure to drainage zones with high Si would flatten the total flow curve into the joint urban water tunnel. Thus, inhibiting the sharp flow peaks into the tunnel that forces the excess water to the Oslo fjord.

3 Materials and methods

3.1 Data collection

The data was collected from Bærum municipality during January 2018 – December 2019 using resolution of 10 minutes. The data consists of precipitation measurements in [mm] at the 11 precipitation stations and flow rate measurements in [L/s] at the Veas tunnel inlet points from the drainage zones.

3.2 Software tools

Matlab R2021a with system identification toolbox was used for data pre-processing and modeling.

3.3 Data pre-treatment

The dataset contains flow rate and precipitation measurements collected by several stations in Bearum municipality. Some of the drainage zones do not have a measuring station. Thus, the first data pre-treatment step was to assign the closest precipitation measurement to those areas which do not have their own station. In the next step, all winter months (November-April) were excluded from further processing. Snow melting impact is hard to evaluate and including winter months could affect further modelling. In the next step, data were synchronized in the manner that flow rate measurement sampling was changed from 1/minute to 1/10minutes.

3.4 Removal of seasonal trends

The joint urban drainage tunnel collects stormwater, but also municipal wastewater. The municipal wastewater flow with daily and weekly variation had to be removed to improve the data quality for modeling. In the first step, the data was split into four quarters: May 2018 to June 2018, August 2018 to October 2018, May 2019 to June 2019 and August 2019 to October 2019. In the next step, a full no-rain week was manually selected from each period. It was assumed that no-rain week is a good representation of municipal wastewater production. Lastly, for each period, no-rain week was subtracted from the data.

3.5 Selection of data for modeling

After data pre-treatment and removal of seasonal trends, the rain periods were chosen manually. It was decided that only periods at least 2 hours long will be taken into account for further analysis.

3.6 System identification procedure

System identification toolbox was used to calculate the dynamic parameters of each drainage zone. The first order transfer function with delay was chosen (2). Parameters were calculated independently for each rain period. Initial result assessment shows that some of calculates parameters has non-physical values. Therefore, all the transfer functions with very large Kp or very large Tp were removed, as these are seen not sensible considering the geographical distances between the drainage zones and the joint urban water tunnel. Transfer functions with negative Kp were also removed as these are seen physically impossible.

3.7 Screening index and statistical analysis

The screening index was calculated based on the transfer function parameters Kp, Tp and Td for each of the rain periods in each of the drainage zones. The box plots were prepared for each drainage zone. The screening indices were then imported to SPSS, and the null hypothesis of equal means between the different drainage zones was tested with Student T-test.

3.8 Multivariate correlation analysis

Multivariate analysis was applied to find linear corrections between the transfer function model parameters (Kp, Tp and Td) and features extracted from the precipitation data (total accumulated precipitation during rain shower, maximum precipitation, and duration between rain showers). The Matlab Statistics and Machine Learning toolbox, Regression Learner App with different linear regression models, regression trees and support vector machines were used.

4 Results

This section shortly presents the results for data pre-processing and system identification, and the results for the proposed screening index.

4.1 Results for system identification

The characterization of the system dynamic model parameters Kp, Tp and Td for the different drainage zones are given in Table 2. The box plots are given in Figure 2 for the process gains, Kp, Figure 3 for the time constants Tp and Figure 4 for the time delays Td.

The results for process gain Kp between precipitation and tunnel inlet flow rate seem reasonable; Large drainage zones like Sandvika, Hamang, Stabekk “harvest” more rain and therefore they have larger process gains than small drainage zones like Bjørnegård and Evjebakken.

The results for time delay Tp between precipitation and tunnel inlet flow rate seem reasonable; rain seeps faster through drainage zones with lots of buildings, roads and infrastructure like Sandvika than drainage zones with lots of private houses, parks and forest like Hamang.

The results for time delay Td between precipitation and tunnel inlet flow rate seem reasonable; Drainage zones close to the joint urban water tunnel inlet like Sandvika and Stabekk have shorter time delay than drainage zones further away like Søraasen, Jar and Hamang.

The standard deviation for all the dynamic parameters is high, which can also be observed from the box plots. This indicates that water flow through the urban drainage zone is a very nonlinear phenomenon.

Two approaches to “linearize” the system were attempted. First, to preprocess the input data by taking an inverse of the precipitation data $p(t)^{-1}$ before system identification, and second, by taking a square root of the precipitation data $p(t)^{(1/2)}$ before system identification. Both of these preprocessing approaches resulted in similar variation in the dynamic process parameters Kp, Tp and Td.

Table 2. Number of rain periods included N, average value and standard deviation for dynamic model parameters Kp, Tp and Td for the drainage zones.

Drainage zone	N	Kp_ ave	Kp _std	Tp_ ave	Tp_ std	Td_ ave	Td_ std
Bjørnegård	63	5,5	3,9	35	82	54	97
Søraasen	61	392	907	439	925	86	105
Evjebakken	71	127	159	172	439	25	61
Jar	52	684	1164	480	1340	40	52
Sandvika	52	225	188	82	171	24	37
Hamang	69	511	868	409	721	39	51
Stabekk	61	765	810	178	227	26	52

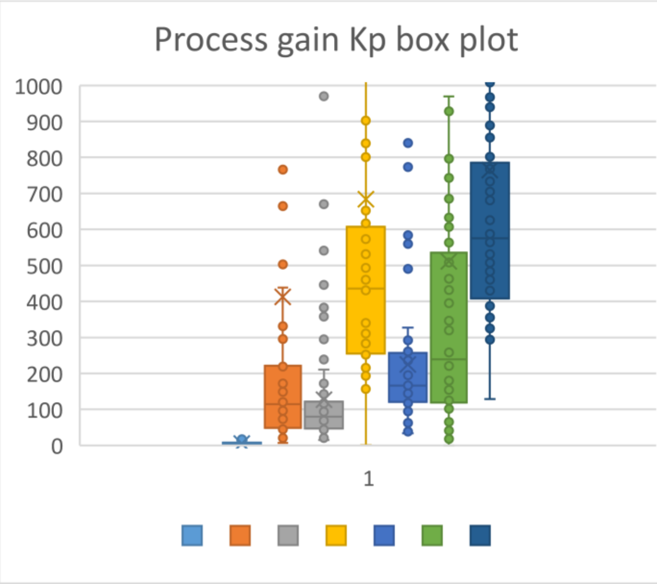

Figure 2. Box plots for identified process gain K_p in drainage zones Bjørnegård, Søraasen, Evjebakken, Jar, Sandvika, Hamang, Stabekk.

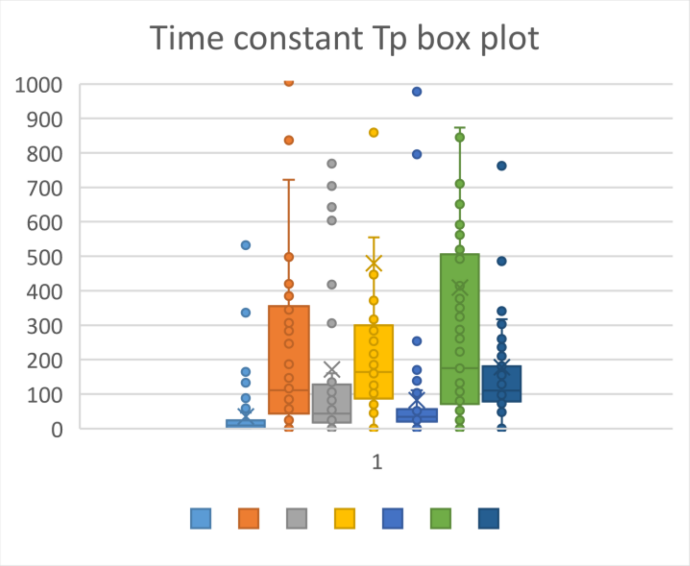

Figure 3. Box plots for identified time constants T_p in drainage zones Bjørnegård, Søraasen, Evjebakken, Jar, Sandvika, Hamang, Stabekk.

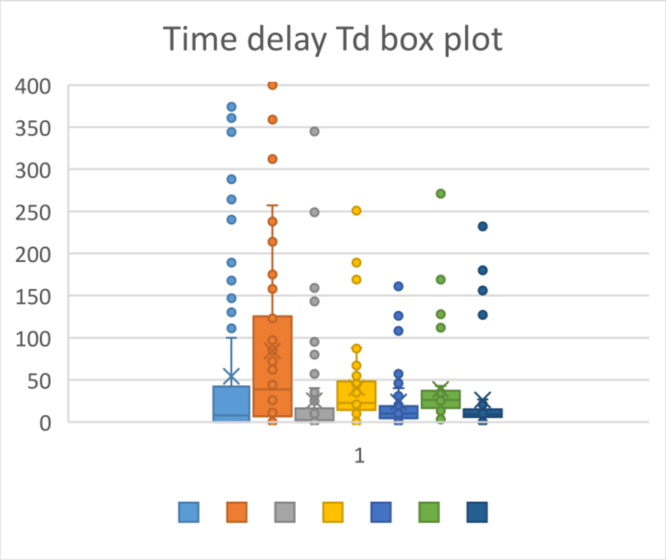

Figure 4. Box plots for identified time delays T_d in drainage zones Bjørnegård, Søraasen, Evjebakken, Jar, Sandvika, Hamang, Stabekk.

4.2 Results for multivariate analysis of the dynamic parameters

In order to explain the variation in the dynamic parameters Kp, Tp and Td, different explanatory variables were constructed from the available data, i.e. the precipitation measurements. To characterize the rain intensity, two indicators for each rain period j were constructed: Maximum precipitation during the rain period $P_{max,j}$, and total rain during the corresponding rain period $P_{tot,j}$. To characterize the water absorption capacity of the soil, one indicator was constructed, dry period before the rain period $T_{dry,j}$.

Linear regression models, regression trees and support vector machines in Matlab regression Learner app were applied to find linear correlations between dynamic parameters and constructed explanatory variables of the drainage zones, but no correlations with R^2 index over 0,3 were found. It is suggested to find other explanatory variables to characterize the water flow through the drainage zone and to use nonlinear multivariate methods such as neural networks to find the correlation.

4.3 Results for screening index

The screening index was constructed using the identified dynamic process parameters K_p, T_p and T_d for each drainage zone. The screening indices are presented in Figure 5 and the average values and standard deviations are given in Table 3. The standard deviation for the screening indices Si are much smaller than for the dynamic process parameters K_p, T_p and T_d. The results for screening index Si seem logical, small drainage zones like Bjørnebård and Søråsen and drainage zones further away from the joint urban water tunnel like Hamang have smaller S_i index, and therefore contribute less to the excess water in the joint urban water tunnel. Larger drainage zones close to the urban water tunnel like Sandvika and Stabekk have large Si index, and therefore contribute more to the excess water in the joint urban water tunnel. Based on the Screening index, we suggest that possibilities for blue-green infrastructure will further be investigated in these two drainage zones.

SPSS was used to run t-test on equality of means between two drainage zones. The null hypothesis states that the means of two drainage zones are equal. Equal variances are not assumed. The decision criteria are: For a two-tailed test with n-2 degrees of freedom, the level of significance is 0.05. The results of the independent samples t-test are given in Table 4. As the t-test values are much higher than 1.96 or much lower than -1.96, the null hypothesis is proven false. Thus, the mean values for screening indices between the Bærum drainage zones are statistically significantly different.

Table 3. Number of rain periods included N, average value and standard deviation screening index Si for the different drainage zones.

Drainage zone	N	Si_ave	Si_std
Bjørnegård	63	0,3	0,3
Søraasen	61	0,7	0,7
Evjebakken	71	1,3	0,9
Jar	52	2,2	1,7
Sandvika	52	3,0	1,6
Hamang	69	1,2	0,8
Stabekk	61	4,3	1,5

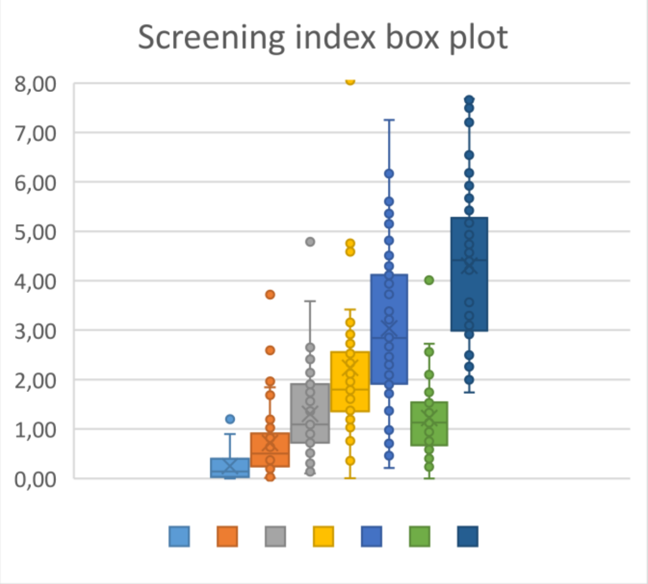

Figure 5. Box plot of the proposed screening index S_i for drainage zones Bjørnegård, Søraasen, Evjebakken, Jar, Sandvika, Hamang, Stabekk.

Table 4. T-test results for null hypothesis testing equality of means between drainage zones.

Drainage zone1	Drainage zone2	t	df	2-tail sig.	Mean diff	Std diff
Bjørnegård	Søraasen	-5,1	78	0,000	-0,48	0,09
Søraasen	Evjebakken	-4,2	129	0,000	-0,58	0,13
Evjebakken	Jar	-3,7	71	0,000	-0,93	0,25
Jar	Sandvika	-2,5	102	0,016	-0,79	0,32
Sandvika	Hamang	7,3	71	0,000	1,8	0,25
Hamang	Stabekk	-14	90	0,000	-3,1	0,22
Stabekk	Bjørnegård	20	64	0,000	4,1	0,20
Stabekk	Sandvika	4,5	106	0,000	1,27	0,30

5 Discussion

This is study is first stage in modeling of nature-based solutions at urban drainage zones. To answer our first research question (RQ1), we applied system identification to the available, pre-processed and de-seasonalized data sets consisting of precipitation and drainage zone outlet flow rates. We conclude that it is possible to approximate the dynamic behavior of water flow through a drainage zone with first order plus time delay transfer function model. The model parameters highly nonlinear, and dependent on explanatory variables that were not included into the data collected.

To answer our second research question (RQ2), we introduced a screening index calculated with the dynamic parameters of transfer function model. The screening index was applied to all the rain periods at all of the drainage zones. The mean values of the screening index were statistically significantly different from each other. The classification of the drainage zones to high contributing and low contributing areas was based on the size of screening index. Small areas and areas far away got relatively small indices whereas large areas close to the water inlet point got relatively high indices. We conclude that the drainage zones can be classified using the proposed screening index. The drainage zones with high screening index should be considered for construction of blue-green infrastructure like NBS to avoid water spill to Oslo fjord.

6 Conclusions and further work

This study is a proof of concept that the available measurements, precipitation and drainage zone outlet flow rates, are enough to create a screening index that can separate the flow profiles of the different drainage zones according to their contribution to the excess water in the joint urban drainage tunnel. The simple dynamic modeling method with screening index is less accurate than traditional physically based and parameter based modeling methods, but a much faster and more cost-effective method to classify the drainage zones.

We suggest to continue the work by collecting data for the rest of the drainage zones in Bærum and the drainage zones in Oslo, and repeating the analysis for these drainage zones. As this is a data-driven approach, it is suggested that the method will be applied for large amounts of data, i.e. long time series of at least one year.

The next goal in the project is dynamic modeling of the different NBS approaches and testing of the effect of NBS for the Bærum and Oslo drainage zones. We are suggesting to create a simple NBS model that can evaluate the performance of the NBS for a certain size and type of drainage zones. Further we propose to apply multi-criteria analysis to consider the effect for excess water and the costs for building and maintaining the NBS at high risk drainage zones.

Acknowledgements

The authors greatly thank the VEAS senior manager Hilde Johansen for the project idea, contacts to the municipalities and active participation in the data collection. VEAS system engineer Jonas Pettersen and Bærum municipality engineer Anne Ellekjær Stavang are greatly tanked for collecting the data from their respective data systems and visualization of the measurement stations. This work has been also supported by EU Water JPI Project “Research-based Assessment of Integrated approaches to Nature-based SOLUTIONS (RainSolutions)” 2019-2021, Reference Number: WaterJPI-JC-2018_11. We would also like to thank Alida Alves Beloqui for insights in her modeling work at Wageningen university.

References

V. Barros, et all. Climate Change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32. 2014.

A. Beloqui. Combining Green-Blue-Grey Infrastructure for Flood Mitigation and Enhancement of Co-Benefits. CRC Press. 2020. doi.org/10.1201/9781003041818

G. Devia, B. Ganasri, G. Dwarakish. A review on hydrological models. Aquatic Procedia, 4: 1001-1007. 2015. doi.org/10.1016/j.aqpro.2015.02.126

N. Dolman. Nature-based solution in cities, In Proceedings - GPSC Resource Team Webinars. 2020. doi.org/10.13140/RG.2.2.20996.07049

B. Eisenberg, B. Polcher. Nature-based solutions – Technical Handbook. In UNaLab Project, Deliverable D, 5. 2020.

D. Haase. Reflections about blue ecosystem services in cities. Sustainability of Water Quality and Ecology 5: 77-83. 2015. doi:10.1016/j.swaqe.2015.02.003

W. Filho, et al. Assessing the impacts of climate change in cities and their adaptive capacity: Towards transformative approaches to climate change adaptation and poverty reduction in urban areas in a set of developing countries. Science of The Total Environment, 692: 1175-1190. 2019. doi.org/10.1016/j.scitotenv.2019.07.227

B. Kalsnes, V. Capobianco. Nature-based solutions. Landslides Safety Measures. SINTEF Community, Høgskoleringen 7 b, PO Box 4760 Sluppen, N-7465 Trondheim. 2019.

L. Ljung. System identification: theory for the user (2nd ed.). Prentice Hall PTR. 609 p. 1999.

L. Ma, Ch. He, H. Bian, L. Sheng. MIKE SHE modeling of ecohydrological processes: Merits, applications, and challenges. Ecological Engineering, 96: 137-149. 2016. doi.org/10.1016/j.ecoleng.2016.01.008

S. Marshal. Reference Module in Earth Systems and Environmental Sciences. Hydrology. 2013. doi.org/10.1016/B978-0-12-409548-9.05356-2

L. Rossman and W. Huber. Storm Water Management Model Reference Manual Volume I, Hydrology. U.S. EPA Office of Research and Development, Washington, DC, EPA/600/R-15/162A, 2015.

G. Somarakis, S. Stagakis, N. Chrysoulakis. Thinknature Nature-based solutions Handbook. 2019. DOI:10.26225/jerv-w202

X. Zhou, M. Helmers, Z. Qi. Evaluation of the MIKE SHE model for hydrologic modeling in a small agricultural watershed. Applied Engineering in Agriculture. 2013. DOI 10.13031/aea.29.9568