https://doi.org/10.71573/7zn09q74

CSOptim: Assessing and Improving the Operation of Combined Sewer Overflow Structures

Karim Sedki[1,]*, *Yannic Brüning*[2] *& Ulrich Dittmer*[1] https://orcid.org/0000-0003-1723-3356

[1] *Institute of Urban Water Management, RPTU University of Kaiserslautern-Landau, 67663 Kaiserslautern, Germany*
[2] *Landratsamt Biberach, Wasserwirtschaftsamt, 88400 Biberach, Germany*
** Corresponding author email: karim.sedki@rptu.de*

Abstract

Flow-dividing structures in combined sewer systems serve to mitigate hydraulic overloads during storm events by providing retention capacity. Their operational performance can be enhanced by adjusting the continuation flows regulated by their flow control devices. To optimise system efficiency to reduce emissions, it is essential to use existing volumetric capacities more efficiently, e.g. by adjusting continuation flows. To assess this potential, statistical analyses are conducted on water level measurements from combined sewer overflow (CSO) structures (e.g. frequency analyses) to derive meta information used to assess the baseline functioning. Meta information, such as weir heights, basin base areas and continuation flows, with higher accuracy than would be feasible through manual measurements in the structures or extraction from construction plans, are derived solely from measured water levels. Derived meta information is employed to isolate events to determine reliably CSO occurrence and duration. The continuation flows are optimised using an emulator coupled with a genetic algorithm, with the objective of achieving enhanced operational performance. The case study, which involved eight CSO structures, revealed improvements in efficiency. Overall system efficiency increased from the baseline functioning to the optimized operational setup through the static adjustment of the continuation flows within a range of +/- 50%.

Highlights

- Mechanistic emulation based only on water levels optimizes volume usage of CSO structures
- Water level measurements are feasible to derive meta information for emulation of hydraulics
- Workflow for meta data derivation, implemented as a package of R functions

Introduction

Since the 1990s, impact-oriented measures such as static throttling optimisations or real-time controls have been employed to enhance storage utilization (Bachmann-Machnik et al., 2021; Dirckx et al., 2011). A comparison of the results obtained from both strategies reveals a high degree of similarity. It has been demonstrated that they have the capacity to substantially diminish overflow volumes and pollutant loads. An examination of the structure of sewer systems reveals that in many cases, particularly in France and the UK, only the final combined sewer overflow (CSO) structure leading to a wastewater treatment plant is equipped with a detention tank (Botturi et al., 2021; Fenz, 1999; Zabel et al., 2001). In Germany, more than half of all CSO structures have storage (25,909 of 46,250; Statistisches Bundesamt, 2023), which allows for a larger fraction of distributed retention volume to be utilised (Fenz, 1999). The implementation of measures to monitor water levels in these CSO structures has been steadily increasing until 2024, and it is anticipated that this trend will continue in the future, driven also by legal obligations pertaining to the monitoring of CSOs. The increasing analysis of operating data also provides new insights and supports these measures. However, a comparison of the results of different projects is difficult due to the frequent use of different methods. The initial condition of the respective plant exerts a considerable influence on the potential for improvement and must be taken into account when selecting optimisation strategies. However, research results indicate that the optimisation of operational management or control typically leads to a reduction in overflow volume by 20 to 50% (e.g. Dirckx et al., 2011; Kroll et al., 2018; van der Werf et al., 2022).

The objective of this study is to derive all necessary information from water level measurements alone in order to evaluate and improve the operation of multiple CSO structures within a system or strand. This aims to optimise the use of available storage volume and thereby reduce both the volume of overflowing combined sewage and the associated pollutant load to receiving water bodies.

To this end, a statistical evaluation of the event is to be formulated that considers the volume utilisation of the system as a whole and that of individual CSO structures, with particular reference to instances of system overflow.

The operational improvement is to be achieved solely based on the alteration in throttle discharge values (continuation flows). For the purpose of determining new water levels for the combinations of altered continuation flows, a heuristic (NSGA II, Deb et al., 2002) is to be employed with a hybrid emulator. This will facilitate the identification of a compromise solution for the static settings, which will result in the optimal theoretical efficiency of the system of CSO structures. Consequently, a quantitative alteration in the prevailing throttle discharge values should be attainable, thereby enabling the storage utilisation to be accomplished in a long-term simulation.

Methodology

Meta data derivation

Given the inherent difficulties in evaluating meta information derived from construction plans and manual measurements, an alternative method was developed to extract key information directly from water level measurement data. This approach encompasses especially detention tank arrangements (offline or online, based on definitions by Butler et al., 2018), weir heights, continuation flow rates of flow control devices, and inflow rates into a CSO structure.

The differentiation of CSO structures into two types (with and without detention tank) gives rise to two distinct dependencies between inflow and outflows in a CSO structure. For those with online volume, a direct relationship exists between all inflow and outflows, the result of which is reflected in the change in water level. For those with offline volume, this depends on the event duration and inflow volume as the offline volume is only claimed from a threshold value of the water level in the dividing structure (online part). In such cases, two water level measurements are often recorded, one in the dividing structure (online) and one in the detention tank (offline). When both water level measurements are analysed in relation to each other, for instance with the assistance of outflow transformations such as POLENI, the theoretical change in volume in the detention tank can be aligned with the change in the water level measured there. In the absence of pipe connections and special flow paths within the CSO structure, the ground area of the detention tank can be estimated.

A statistical analysis of the water level time series yielded meta information for subsequent assessments. This entailed transforming and interpolating missing values for equidistance, enabling frequency analysis to derive weir heights (automated scoring based method based on suggestions by Brombach and Wöhrle, 1997). The procedure proposed by Brombach and Wöhrle (1997) was further developed and automated. This resulted in the introduction of a metric that automatically assigns a ranking to water levels according to their frequency of occurrence. This metric is then weighted according to their height above the bed, with the objective of identifying the water level that is most likely to be just above the overflow threshold of the CSO structure. A high frequency of water levels close to the bottom, which result from dry weather discharges or pump sumps, was excluded from the analysis. This exclusion was made using a dynamic threshold depending on the maximum measured water level. In order to enhance the convention of manually determining the weir threshold height ('1 cm below this most frequent water level') based on data, a clustering methodology was introduced that facilitates the identification of discrepancies and variations in the ranking and the actual height around the most probable value determined. Consequently, this approach enables a more precise determination of the actual distance between the most frequent value and the weir threshold height. These heights permitted a comparison of water levels across different sites, facilitating a comprehensive 'basin view' and a unified 'system view' through water level superposition.

The combination of the ground area and the weir height results in a volume. The utilisation of this volume functions as a constant connection between inflow and continuation flow, thereby resulting in retention if the throttled continuation flow is exceeded by the inflow. The connection is analysed to determine the maximum continuation flow if the water level equals the derived overflow weir height in an online detention tank or the weir height of the dividing structure of an offline arranged CSO tank. Assuming that the effect of throttling the continuation flow is visible as a turning point in the probability distribution of the water levels. To estimate the throttle flow, a standard geometry for a CSO structure without detention tank is used.

The accuracy of recalculated flow values is constrained by the necessity of making assumptions about physical processes reflected in measured water levels and changes over time, such as geometry, friction, backwater, and measurement errors. It was determined that geometry and backwater were the most significant factors and thus were given the highest priority in the analysis. The simulation results, which compared the real water level volume curves with simplified linear cubatures for the detention tanks, were evaluated. To examine the impact of backwater, supplementary inflow data from a single CSO structure in the case study region was employed.

Delimitation of efficiency parameters

CSO structures, with or without detention tanks, acquire retention storage volume in the upstream sewer system, which is limited and can be optimized in a manner analogous to the volume usage in the detention tank. To utilise this volume more efficiently, it is proposed that an event-wise evaluation of each basin and the overall system efficiency will facilitate the decision-making process regarding a compromise solution for optimized operation, which will entail the tuning of the flow control devices.

The system structure establishes spatial and temporal dependencies between CSO structures and their inflows. Alterations in the upstream throttle discharge have the capacity to modify inflows, thereby rendering the original design parameters invalid. The efficient utilisation of volume is contingent not solely on spatial distribution, but also on temporal considerations. To assess both of these factors, relative water levels are evaluated per event by determining start, peak, and end times. When considered across all structures, these data facilitate the identification of system-wide activity and the establishment of a ranking of CSO structures. This ranking may indicate relative positions, though with high uncertainty due to unknowns in inflow origins, flow timing, and spatial dynamics. Whilst efficiency can indeed be assessed, the absence of precise spatial attribution inevitably results in generalisations.

Instead of convenient scoring metrics such as Root Mean Squared Error (RMSE), which offer only a relative assessment of prediction accuracy in comparison to measurements, we have elected to introduce the efficiency metrics as 'system efficiency' and 'basin efficiency'. They provide an evaluation that is independent of reference measurements, focusing solely on the quality of the predictions themselves.

The 'system efficiency' (E_S) is a quantitative metric that is used to determine the optimisation potential of a system. It does this by comparing the actual usage of the system during overflow events with the total theoretical capacity of the system. E_S is a measure of the system's utilisation during overflow events at specific structures. However, it should be noted that E_S may lack precision if the volume distribution among structures is not known. This phenomenon, known as equifinality, occurs when different parameter sets yield analogous outcomes, thereby rendering ES alone inadequate for evaluation, particularly in the context of sensitive receiving waters. Consequently, each structure is also assessed via the 'basin efficiency' (E_B).

E_B is a metric used to quantify the proportion of basin capacity utilised during events of backflow or overflow. The calculation of the overflow threshold assumes of a linear relationship between water level and volume, extending up to the point of overflow. The total available system volume can be estimated by the number of structures.

Data preparation

In addition to water levels, meta information, and efficiency definitions, the recalculated inflow represents a crucial input for optimizing water level emulation under altered continuation flow conditions. The inflow to a CSO structure reflects the catchment's unchangeable dynamics, including precipitation, surface interactions, and sewer system interactions during the measurement period. This inflow is derived from measured water levels at the CSO or dividing structure for detention tanks. Assumptions include straight tank walls and idealised water-level-continuation-flow curves based on German guidelines (DWA, 2010), using sigmoid transformations.

In order to recalculate the balance between inflow (Q_{in}), continuation flow through a flow control device or maximum flow of a throttling pipe (Q_{cf}), overflow (Q_{ue}) and change of retention volume, it is necessary to define water level dependent values. For the initial state, $Q_{cf}(h,t)$ equals Q_{in} until the maximum throttle flow Q_{cf} is reached (with factor $f_{cf} = 1$ for initial/reference state) and V is substituted by the change of the water level (h) assuming straight walls of the detention tank. With that, the basin base area A does not change with level or time. Two further scenarios are distinguished on the basis of the unknown constructive details pertaining to the CSO structure for a measured weir height (h_{weir}) that is higher than the determined value. The velocity of water level changes is employed to identify trends and to smooth the recalculated inflow.

$$V(h,t) = \int_{\mathbf{0}}^{t} Q_{in}(h,t) - Q_{cf}(h,t) \cdot f_{cf} - Q_{ue}(h,t)\, dt \qquad (1)$$

With the introduction of a variation factor f_{cf} for the maximum throttled flow is twofold: firstly, to restrict changes in the throttled outflow within technically feasible bounds, and secondly, to enable a quantitative assessment of the optimised outflow value.

Figure 1 shows schemes of storage arrangement in CSO structures with description of inflow (Q_{in}), Continuation flow (Q_{cf}) and Spill flow or overflow (Q_{ue}).

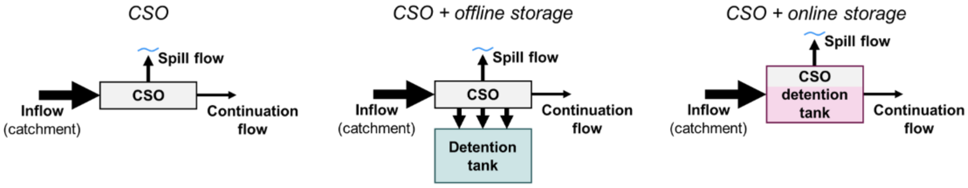

Figure 1. Schematic comparison of combined sewer overflow (CSO) structures (left) with detention tank in online (mid) and offline (right) arrangement (based on definition of terms by Butler et al., 2018)

The description and emulation of the three quantities inflow, continuation flow and overflow following the mass balance in eq. (1) serves as basis to re-calculate the required "inflow" values based on the measured water level.

For the purposes of this study, it is hypothesised under consideration of simplifications that the equifinal relationship between the geometry of the storage chamber, the configuration of the inlet/flow-dividing structure, and the inflow rate (including its temporal variation) can be reduced to its final component, the inflow variation. This simplification is necessary because the relationship of water level and volume, derived from the measurements, can only be obtained under conditions of steady inflow. While this steady-state condition may be approximated in practice on occasion, it is not the norm and should therefore not be assumed to be the case in general.

However, it is reasonable to hypothesise that the effect is amplified by the transformation of the outflow as water passes over a weir crest, since even minimal changes in water level can lead to significant changes in discharge. Consequently, the balance is constructed based on a presumed relationship between variations in water level and throttled outflow. This facilitates the reconstruction of the inflow hydrograph, thereby establishing a foundation for modifying the throttled discharge as part of operational optimisation.

However, the quality of the reconstructed discharge values during periods of dry weather is significantly lower in comparison to those recorded during wet weather periods. This can be attributed to the limited amount of information that can be obtained from the relationship between water level and small flow depth. This is insufficient to guarantee reliable emulation of values during these phases, not least due to uncertainties associated with water level measurements.

Optimization

The optimization is performed using a metaheuristic method that incorporates an evolutionary algorithm with NSGA-II (Non-Dominated Sorting Algorithm II, Deb et al., 2002) for the selection and mutation process. For the baseline functioning the factor to vary the determined continuation flow values is set to $f_{cf} = 1$. To find an optimized setup with a compromise solution of maximised efficiencies E_B and E_S (pareto) the variation of f_{cf} in eq. 1 results in new water levels. As throttle devices are limited concerning alteration, f_{cf} is varied within boundaries of 50 % increase and decrease of the estimated maximum continuation flow value.

In order to map the runoff processes in a CSO structure, the hybrid emulator in this study determines data-driven limit values and calculates new water levels for changed boundary conditions using mechanistic knowledge. It is assumed that this task could be improved by a prediction algorithm that learns, categorises and prioritises patterns on and across different spatial and temporal scales from the measurement data. The utilisation of artificial intelligence is deemed appropriate for this purpose, e.g. transformers (Burrichter et al., 2024). However, the availability of reliable input data is a prerequisite. In this particular instance, reliability is characterised by the scope, accuracy and, consequently, the robustness and representativeness of the measured water levels for a CSO structure. Given that this is not guaranteed, particularly in the context of measured environmental data such as water level and flow measurements, it is imperative to emphasise the indispensability of mechanistic knowledge (Carbajal et al., 2017). This necessity arises from the inherent uncertainties associated with measurement procedures and the subsequent data verification processes (Bertrand-Krajewski et al., 2021; Deletic et al., 2012).

Case study

In this study, continuous water level measurements from 8 CSO structures with storage. The system in Figure 2 represents the two common CSO structures (7 with offline arranged detention tank) and layouts (3 in a series and 5 parallel). As reference data for the investigations in this study, water level measurements in the main stream and the storage tank for offline arrangements, inflow, and continuous flow measurements, throttle control curves, and construction plans of the CSO structures are available. All measurements have a 1 min temporal resolution over two consecutive years. The resolution of the level measurement is 0.01 m.

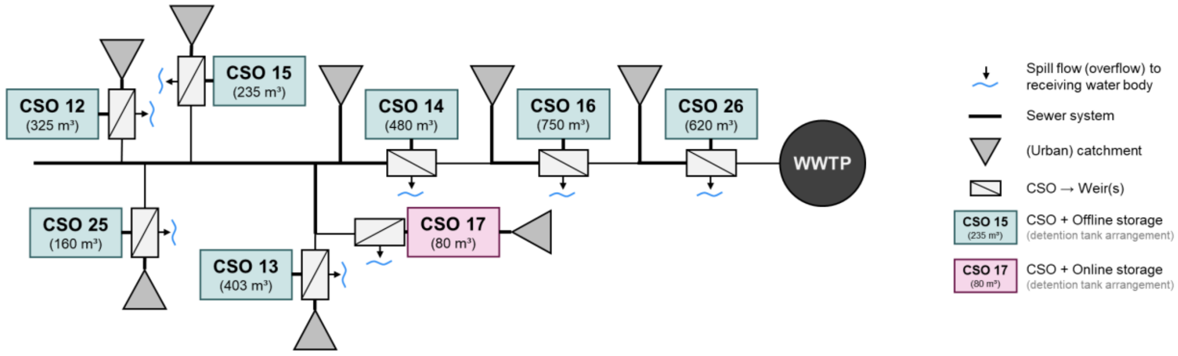

Figure 2. Network scheme of the case study combined sewer system structures.

Results and discussion

As the process is data-driven, particularly in the context of metadata derivation, and the outcomes are intended for practical implementation, there is a strong motivation to enhance the precision of the boundary conditions. The most crucial parameters, i.e. weir crest level for overflow and maximum throttle flow (from a legal perspective), have been the focus of in-depth research. The automated procedures that have been developed (see Table 1) result in minor deviations when compared to the carefully manually set crest levels.

Throttle flow deviations are more evident in this instance, and these deviations can be associated with the variability and uncertainty observed in minor flows. However, the conditions involving strong selectivity of throttling devices, as evidenced in the case study, should result in more reliable values. The tested methods proved to be inadequate. The estimation of such values, based solely on water level measurements upstream of the throttling device, is only possible for large throttle discharge values. Furthermore, the question as to whether the gradation of the throttle discharges (CSO 26 with Q_{cf} = 200 l/s following CSO 16 with Q_{cf} = 220 l/s) is logical with respect to the flow logic of the system (see Figure 2). This fact already offers potential for improvement, which should be achieved as a boundary condition for any form of optimisation (e.g. static or real-time) as baseline functioning.

Table 1. Resulting weir crest levels and maximum throttle flow values compared for manual and automated procedure for determination from water level measurements

CSO	Successing CSO	Weir crest level [m]			Maximum throttle flow [l/s]		
		manually	automated	deviation [%]	setup	automated	deviation [%]
12	14	4.06	4.25	+ 4.7	15	9	- 40.0
13	14	2.80	2.80	± 0.0	40	43	- 7.5
14*	16	4.14	4.16	+ 0.5	180	38	- 78.9
15	14	3.20	3.15	- 1.6	20	18	- 10.0
16	26	3.45	3.61	+ 4.6	220	215	- 2.3
17	14	1.75	1.77	+ 1.1	5	4	- 20.0
25	26	3.53	3.57	+ 1.1	10	7	- 30.0
26*	WWTP	3.69	3.60	- 2.4	200	117	- 41.5

*measurement errors are suspected for sites in dividing structures of CSOs 14 and 26 from the data review; complex structure of CSO 14 with two dividing connected to the offline arranged detention tank by pipes

Figure 3 (top) illustrates the transformed water level measurement and the resulting recalculated inflow to CSO 26, along with the measured inflow for validation purposes. In this instance, two level measurements are available for consideration. One measurement was obtained from the dividing structure, which was used for the initial recalculation (Figure 3, bottom), and one measurement was obtained from the detention tank, which was used for the optimization.

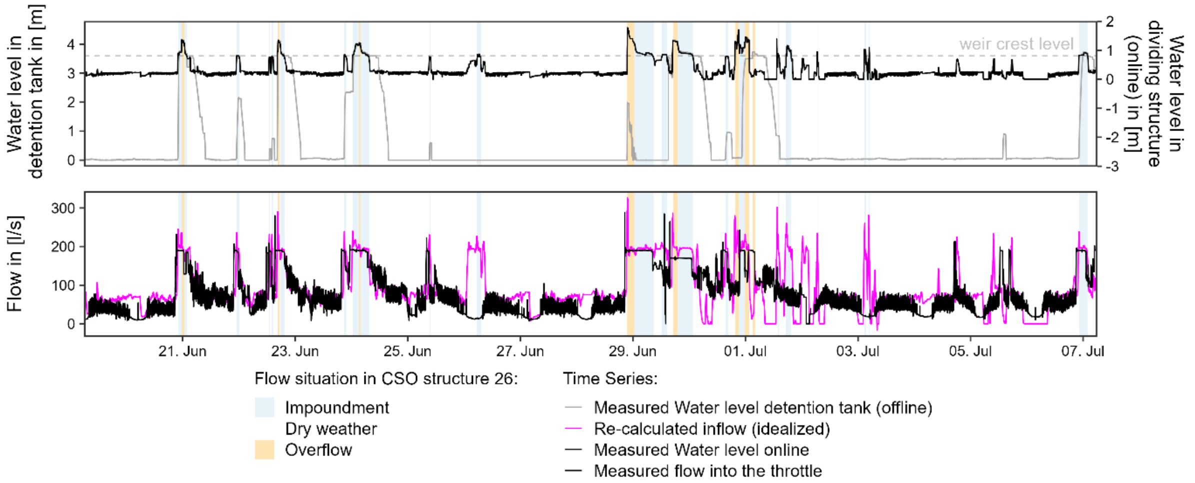

Figure 3. Time series slice of the initial inflow recalculation at CSO 26 showing measured water levels from the dividing structure and the detention tank (top) and measured continuation flow overlayed with re-calculated inflow (bottom) with color indications for impoundment and overflow phases.

In order to infer the transformation from the weir in the dividing structure, it is necessary to relate the two water level measurements to each other. This procedure was introduced due to the significant impact that the transformation through a weir has on the correlation between the inflow and the water levels in an offline arranged detention tank.

As illustrated in Figure 4 (left), the correlation is evident in the scatterplot, with a Pearson coefficient of 0.62 for the visible time series slice. For the entire time series spanning two years, a Pearson correlation of 0.55 is attained. However, the accuracy and correctness of the recalculation are questionable due to the significant dependency of the water level changing velocity and backwater effects, as well as flow division over the weir to offline arranged detention tanks. Figure 4 (mid) shows a Q-Q-plot of the measured and re-calculated values. It shows a tendency of overestimation for peak flows, indicated by the color.

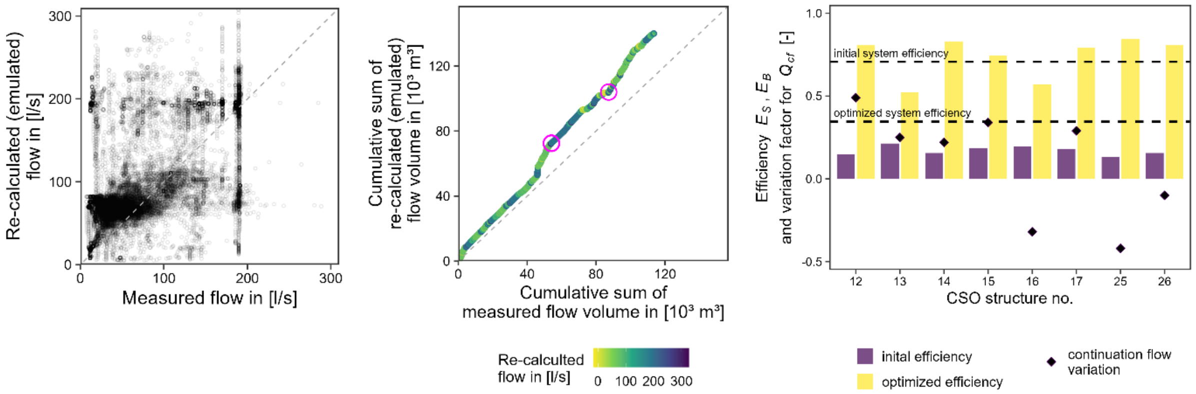

Figure 4. Time series slice of the initial inflow recalculation at CSO 26 contrasting the measured and emulated inflow for the slice in a scatter plot (left) and in a Q-Q-Plot (middle) and comparison of efficiencies for baseline functioning and optimized operational setup (right).

The discrepancy in the degree of accuracy and correctness in the main input ‘recalculated inflow’ has resulted in a change in system efficiency as Figure 4 (right) shows. Above, it illustrates the changes in basin efficiency E_B for each CSO within the case study, as well as the corresponding varying factor f_{cf}.

Conclusions and future work

The results demonstrate that mechanistic emulation based on water level measurements optimizes CSO volume usage. From these measurements meta information for the emulation of hydraulic processes such as flow division and retention is derived accurately. The recalculation of inflow will be enhanced through the implementation of advanced decision-making techniques and a comparison to a machine learning approach, which will serve as a pivotal initial step. The viability and transferability of the presented approach will be evaluated in additional case studies to demonstrate its relevance in a variety of system contexts. A software toolkit (R-package) will facilitate the implementation process, and the performance will be assessed in comparison to existing real-time control (RTC) methodologies in one of the additional case studies.

Future work will explore the application of artificial intelligence methodologies, such as Physics Informed Neural Networks (PINN) and physics-leveraged approaches, in conjunction with mechanistic knowledge, for the present use case or with the developed emulator. In order to ensure the quality of the results, approaches to explainability (Oberascher et al., 2025) are taken into account.

Acknowledgement

Authors thank MINISTERIUM FÜR UMWELT, KLIMA U. ENERGIEWIRTSCHAFT BADEN-WÜRTTEMBERG for funding the project, as well as WOLFGANG LIEB and CHRISTIAN GATTERER for providing data.

References

Bachmann-Machnik, A., Brüning, Y., Ebrahim Bakhshipour, A., Krauss, M., Dittmer, U., 2021. Evaluation of Combined Sewer System Operation Strategies Based on Highly Resolved Online Data. Water 13 (6), 751.

Bertrand-Krajewski, J.-L., Clemens-Meyer, F., Lepot, M. (Eds.), 2021. Metrology in Urban Drainage and Stormwater Management: Plug and Pray. IWA Publishing.

Botturi, A., Ozbayram, E.G., Tondera, K., Gilbert, N.I., Rouault, P., Caradot, N., Gutierrez, O., Daneshgar, S., Frison, N., Akyol, Ç., Foglia, A., Eusebi, A.L., Fatone, F., 2021. Combined sewer overflows: A critical review on best practice and innovative solutions to mitigate impacts on environment and human health. Critical Reviews in Environmental Science and Technology 51 (15), 1585–1618.

Brombach, H., Wöhrle, C., 1997. Gemessene Entlastungsaktivität von Regenüberlaufbecken. Korrespondenz Abwasser, Abfall (KA) 44 (1), 44–66.

Burrichter, B., Da Koltermann Silva, J., Niemann, A., Quirmbach, M., 2024. A Temporal Fusion Transformer Model to Forecast Overflow from Sewer Manholes during Pluvial Flash Flood Events. Hydrology 11 (3), 41.

Butler, D., Digman, C., Makropoulos, C., Davies, J.W., 2018. Urban drainage: Fourth edition, Fourth edition ed. CRC Press Taylor & Francis Group, Boca Raton, London, New York.

Carbajal, J.P., Leitão, J.P., Albert, C., Rieckermann, J., 2017. Appraisal of data-driven and mechanistic emulators of nonlinear simulators: The case of hydrodynamic urban drainage models. Environmental Modelling & Software 92, 17–27.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evol. Computat. 6 (2), 182–197.

Deletic, A., Dotto, C., McCarthy, D.T., Kleidorfer, M., Freni, G., Mannina, G., Uhl, M., Henrichs, M., Fletcher, T.D., Rauch, W., Bertrand-Krajewski, J.L., Tait, S., 2012. Assessing uncertainties in urban drainage models. Physics and Chemistry of the Earth, Parts A/B/C 42-44, 3–10.

Dirckx, G., Schütze, M., Kroll, S., Thoeye, C., Gueldre, G. de, van de Steene, B., 2011. Cost-efficiency of RTC for CSO impact mitigation. Urban Water Journal 8 (6), 367–377.

DWA, 2010. Hydraulische Dimensionierung und betrieblicher Leistungsnachweis von Anlagen zur Abflussund Wasserstandsbegrenzung in Entwässerungssystemen. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., Hennef DWA-A 111, 34 pp.

Fenz, R., 1999. Combination of emission standards and ambient water quality standards for storm water management.

Kroll, S., Weemaes, M., van Impe, J., Willems, P., 2018. A Methodology for the Design of RTC Strategies for Combined Sewer Networks. Water 10 (11), 1675.

Oberascher, M., Bakhshipour, A., Sedki, K., Autengruber, A., Kahl, A., Hesarkazzazi, S., Haghighi, A., Dittmer, U., Sitzenfrei, R., 2025. Evaluation of the Explainability and Reliability of Two Surrogate Models for Predicting Outflow of Combined Sewer Systems: submitted for special issue “Digital Water”. Water science and technology : a journal of the International Association on Water Pollution Research.

Statistisches Bundesamt, 2023. Umwelt, Öffentliche Wasserversorgung und öffentliche Abwasserentsorgung, 2.1.3 - 2019 ed. Fachserie 19, Wiesbaden.

van der Werf, J.A., Kapelan, Z., Langeveld, J., 2022. Towards the long term implementation of real time control of combined sewer systems: a review of performance and influencing factors. Water science and technology : a journal of the International Association on Water Pollution Research 85 (4), 1295–1320.

Zabel, T., Milne, I., Mckay, G., 2001. Approaches adopted by the European Union and selected Member States for the control of urban pollution. Urban Water 3 (1-2), 25–32.