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Data Analysis to Assess and Improve the Operation of Combined Sewer Overflow Structures with Static Optimization †

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Abstract: Combined sewer systems contain flow-dividing structures. These provide retention volumes for hydraulic overloads of the sewer system during storm weather events. The operation of these structures can be optimized by adjusting the continuous flows of their flow control devices. With that, it is possible to improve the efficiency of entire systems in terms of emissions by making better use of the existing volumetric capacity. To assess this potential, water level measurements from CSO storage tanks were analyzed using statistical methods such as scaling, deviation, and frequency analysis. The data analysis also obtained meta information, such as weir heights and continuation flows, which were more accurate than manual measurements taken in the tank or from construction plans. The main steps involved data preprocessing and meta data gathering to separate events and evaluate the system's basic functioning. This was followed by optimization of the settings of the flow control devices using an emulator and a genetic algorithm.

Keywords: combined sewer overflow; data analysis; deterministic optimization

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1. Introduction

Combined sewer overflow (CSO) structures are primarily based on economic considerations. In many cases, such as in France and the UK, only the last CSO structure leading to a wastewater treatment plant is combined with a storage tank [1–3]. In Germany, over half of all CSO structures have storage (25,909 of 46,250 [4]). This allows for a larger volume of distributed sewer volume compared to other countries [2]. Its operation can be optimized through real-time control or simpler static optimization [5,6]. For both strategies, similar effects can be achieved depending on the optimization goals, such as reducing overflow volume or emitted pollutant loads [5].

In order to assess the potential for improvement, it is necessary to analyze the current operation based on target efficiency parameters (baseline functioning) [6]. In Germany, recently, an increasing number of CSO tanks have been equipped with level measurements. This will improve our knowledge of understanding the baseline functioning of the CSO structures in a network from measured level data. In addition to continuous measurements, meta data, such as weir heights and settings of flow controls, are used to describe the reference for the evaluation of improvements. To ensure reliable results, we test the suitability of water level measurements to derive meta data using physics-informed statistics. This approach is necessary as manual measurements can be unreliable and structures may differ from construction plans. The physics involved comprise simplified hydraulic equations to cover the flow transformations, e.g., through backwater flows in online arrangements and weir overflow into the storage tank in offline arrangements of CSO structures.

2. Materials and Methods

2.1. Case Study

In this study, continuous water level measurements are taken from storage tanks from 8 CSO structures with storage, 7 of which are arranged offline and 3 are arranged in a series, while the others are parallel, representing the two common system structures. 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.

2.2. Meta Data Derivation Challenge

Recent survey results and experiences regarding data usually available for engineering companies indicate the need for the critical evaluation of meta data to assess system performance in terms of CSO. Therefore, existing meta data derivation methods, e.g., determining the weir height [7], were applied, enhanced, and new methods were tested.

Two main values needed for the evaluation of a CSO structure are the weir height and the maximum throttle flow. Both together regulate how the inflowing volume is retained and therefore need to be correct and accurate. The following Equation (1) describes the general balance and dependencies of inflow Q_{in}, continuous flow Q_{cf}, storage tank projected base area $A_{storage}$, and water level h in the storage tank for time t at time step i:

$$\frac{(\mathrm{Q_{in}} - \mathrm{Q_{cf}})_i \cdot \Delta t}{\mathrm{A_{storage}}(\mathrm{h_i})} = \Delta \mathrm{h_i} \quad (1)$$

The CSO tank retains the difference between inflow and outflow through the flow control device, as well as in the inflowing channel. In offline structures, retention in the inflowing channel is caused by flow division, typically with a weir. The inflow is transformed hydraulically by this weir, thus decoupling it from the aforementioned rule (Equation (1)). Therefore, in order to implement this rule in the overall optimization algorithm using water level measurements as the only input, several simplifications and transformation functions need to be made for $A_{storage}$ and Q_{in}, as well as Q_{cf}.

To derive real continuation flows Q_{cf} (maximum impoundment), the range of water level measurements below the weir height is used. This is because it is independent of the flow distribution over the weir. With the gradient of the level values, the inflow Q_{in} is recalculated and smoothed with moving window statistics respecting standard deviations.

For online arrangements, the backwater effects from the inflowing channel dampen the inflow with an increasing water level, and consequently, the water level changes the water level velocity v_h (water level change per time interval Δt from i to $i + 1$) too.

To derive the needed weir height accurately from the measured water level time series, a frequency analysis [7] is applied for 0.01 m water level steps. The obtained derivation is scaled and scored.

2.3. Efficiency Parameters and Optimization

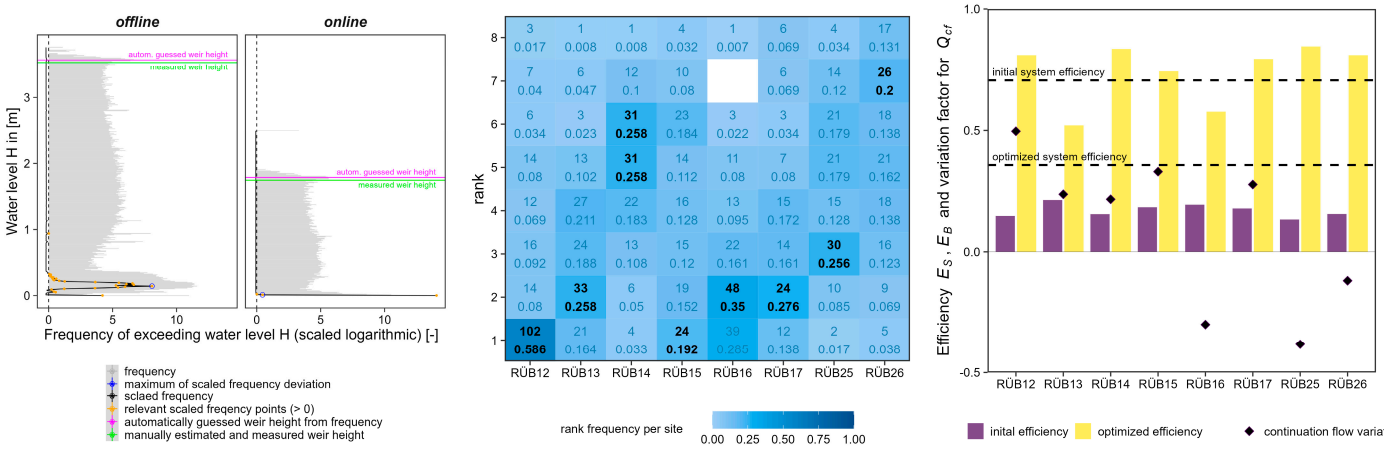
Efficiency parameters are defined to maximize volume usage in a system or its strands. The term 'basin efficiency' E_B refers to the volume usage during an impoundment or overflow in any CSO structure belonging to the system (strand) during a rain event. E_B enables the evaluation of the potential for reducing overflow volume in a specific basin by calculating the yearly mean of all individually analyzed events. On the other hand, 'system efficiency' E_S represents the potential for optimization of the system (strand). It is calculated per event if one CSO in the system occurs. It compares the volume usage in one CSO structure to the volume that is theoretically available in the relevant system (strand). Therefore, events were separated by defining a minimal dry period of 6 h and a threshold depending on the width of the standard inter-quartile range. For the identification of

anomalies as a starting point for impoundment events, a partition of the maximum percent of anomalies permitted to be identified is predefined. From all the determined single events of the CSO structures in a system, the system events are separated by the superimposed relative water levels of all the CSO structures. The relative water level is calculated by dividing the measured water level by the automatically estimated weir height.

The concept of static optimization is based on correlations and covariances of measured water levels to determine throttle adaptations to maximize the efficiency parameters E_B and E_S for the reduction in CSO volumes. To calculate the efficiency changes through changes in the continuation flow, an emulator is built up initially with the gathered information about the time lags between the CSO structures to respect spatially and temporally sequential processes. Furthermore, the recalculated initial flows only have to be modified by adding new throttle flows because the system's topology and catchment characteristics do not change. To find optimal solutions coming from a variety of continuation flow combinations, a multi-objective evolutionary algorithm is used for the efficiency parameters as target functions.

3. Results and Discussion

The initial findings in Figure 1a demonstrate that the automated determination of weir heights from water level measurements using simple sorting and scoring approaches produces comparable results to manual measurements or data-based estimations, regardless of the storage arrangement. Another method, which searches for changes to gradients as used for data validation in [8], produces comparable results. Furthermore, this method has been adapted for use in event separation and comparison as well as mostly used peak-over-threshold approach [9].



(**a**) (**b**) (**c**)

Figure 1. Analysis of water level measurements to gather meta data, system structure dependencies, and optimize continuation flow: (**a**) deviation of water levels in a CSO storage tank and derived overflow weir height; (**b**) ranking matrix for event offsets; (**c**) optimization results.

The assessment of CSO structures, classified by their design and arrangement in the system (on/offline), revealed notable similarities and differences in water levels during impoundment and overflow events. This information is crucial for evaluating the impact of current operations. To derive this, individual events from a two-year time series were normalized based on the maximum water level and duration of each event. The event, therefore, covers whole periods over activities at all CSO structures in the system (strand).

The analysis of interactions within a system (strand) was extended by using cross-correlations and -covariances. Depending on the catchment sizes and estimated flow times, similarities for impoundment interactions can be identified, and reciprocal influence can be determined through the lag for the best correlation and covariance (Figure 1b).

The first optimization results in Figure 1c show the overall maximum system efficiency E_S and maximum efficiency E_B per CSO structure. The optimisation was performed using a metaheuristic method that incorporates an evolutionary algorithm with NSGA-II (Non-Dominated Sorting Algorithm II, [10]) for the selection and mutation process. The volumetric capacity of the whole system is already used efficiently but can still be improved. As a consequence of the reduction in system efficiency E_S (Figure 1c), the selected compromise solution fails to meet the objective of the optimization process. Consequently, further development of objective functions and system representation within the algorithm is a matter of ongoing investigation.

4. Conclusions

Meta information can be gathered from water level measurements and was proven to be accurate. The applied statistical analysis covers the distribution of level occurrences and supports specifying the design and location of a CSO structure without relying on meta data, describing its geometry or location in the system (strand). When assessing inflow from water level data in a CSO structure, backwater can be problematic, especially for offline structures. Therefore, the optimization of continuation flows from continuous water level measurements (1 min resolution) still lacks the derivation of meta data. Water level measurements in offline storage tanks alone are insufficient. To improve accuracy, measurements should be expanded to include activated backwater volume in the inflow channel. This can be achieved by measuring inflow or, at the very least, water levels.

5. Outlook

The algorithm for flow estimation will be developed further to include flow transformations from backwater online and in flow distributions over weirs in offline CSO structures. Furthermore, the inflow and outflow time series from the CSO structures in the study area will be utilized to examine the uncertainty of the algorithms developed for deriving meta information and for static optimization. To overcome the backwater restrictions, water level measurements in the CSO tank and measured inflow or outflow (depending on the site) are used to find interactions with physics-informed machine learning.

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