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Designing urban drainage structures in times of uncertainty

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Abstract

Designing urban drainage elements can be done by setting criteria for four components: 1) proper planning horizons, 2) indicators to limit the solution space, and 3) an unambiguous calculation method with 4) corresponding input data that together encompass the solution space. Design is then a relatively simple exercise of optimizing against a set of criteria such as economy and technical feasibility. Numerous UDM conferences have discussed these criteria and in particular which modelling principles could best be used to address a given problem. We have over the past years observed this paradigm being challenged. We discuss the challenges by considering the simplest possible urban design problem: designing a retention pond for storm water for an acceptable overflow frequency. Given that we in the small country of Denmark have more than 4000 retention ponds this should be easy. However, we find that we have reached a point where it is very difficult to be able to develop and apply design tools primarily because development of a training data set with corresponding objective function is impossible.

Highlights

- Urban drainage modelling uncertainty complexity continues to increase
- The main uncertainties arise from ambiguity in system understanding between different stakeholders
- Even the simplest design problems are affected by ambiguity uncertainty

Introduction

The Danish Water Pollution Control Committee has for decades been developing and maintaining a design practice that allowed both for a unified national approach for design and substantial innovations over time by incorporating results from national and international research. This way of maintaining a common methodology is increasingly being challenged. Some of the challenges are due to factors that are beyond the domain of environmental engineering such as financial considerations by the utilities etc. This is beyond the scope of this study. Rather we will in this paper focus on traditional design considerations. We do that by considering a well defined environmental problem: unsatisfactory environmental conditions in a surface water caused by storm water emissions that should be mitigated by sizing a retention pond with an interceptor capacity and a stipulated overflow frequency. This is the simplest possible problem in urban drainage and hence well suited to discuss the challenges of urban drainage modelling today.

Methodology

Design of a structure consists of defining four components: 1) proper planning horizons, 2) indicators to limit the solution space, and 3) an unambiguous calculation method with 4) corresponding input data that together encompass the solution space. Each of these components are described briefly below.

Proper planning horizon

Planning horizon for detention ponds has typically not been considered, because it was considered a permanent investment in order to achieve better environmental conditions. Economic depreciation implicitly assumes a planning horizon of 50-75 years. However, some planning authorities require that the hydraulic loading is considered using expected climate change impacts over the next 100 years while other stakeholders argue that the environmental legislation changes so fast that the actual planning horizon is about 10 years.

Indicators

Retention ponds are most often designed to protect surface waters from being overloaded with urban runoff, and hence, have two overall criteria they have to meet (Gregersen et al., 2023):

- They have a low, steady interceptor capacity in order to provide a steady flow of water to the recipient, that is expected to not cause any problems such as hydraulic capacity exceedance or erosion.
- They are allowed to overflow with a certain return period in order to limit the volume that needs to be installed to a reasonable level.

This simple set of indicators are being challenged in several ways. First of all the interceptor capacity is increasingly set to very low numbers, sometimes lower than natural runoff processes. Further, authorities may alter how to check compliance with the design criteria in ways that may influence the design.

Unambiguous calculation method

Several levels of detail can be implemented when a model for determining the volume of a retention pond is implemented. The simplest models implement an approach where the rainfall input is based on rainfall statistics (Intensity-Duration-Frequency curves) and the catchment description is reduced to connected paved area. In this case the inflow to the pond is determined as a simple unit hydrograph (i.e. rainfall intensity multiplied by the area) as direct inflow to the pond. For simple systems, this is often a reasonable approach.

For retention ponds in larger or complex catchments and/or far downstream in the catchment, more detailed catchment descriptions will most likely provide better results. Here two factors are often included to reduce the peak flow compared to the simple unit hydrograph method:

- Some form of simplified upstream collection network is added in order to describe the travel time of the water to the basin, which in turn will reduce the peak load hence the runoff will not arrive at the pond immediately
- Some form of simplified surface model is added, and an initial loss is introduced to represent the fact that not every drop of water that falls as rainfall ends up as stormwater flow.

Both concepts described above are well known by urban drainage modellers and many such models exist. However, with very low interceptor capacities these approaches are not sufficient. Evaporation and other components in a full hydrological catchment model are important to add. Given that measurements are rarely available even for traditional urban drainage models it is clear that such models will be difficult to identify and verify.

Corresponding input data

The required input data is a function of the other components. Usually rough designs can be derived from rainfall statistics (Intensity-Duration-Frequency curves), whereas more robust designs normally needs calculations with a sufficiently long representative measured rainfall time series, perhaps including spatial variation of rainfall and runoff processes. These are necessary in order to fully understand the conditions that lead to surcharge, and optimize the dimensioning against this criterion (Allen et al., 2022). The planning horizon adds complexity to the problem; measured rainfall per definition represents past climate, and most often the planning horizon is such that climate change has to be taken into account. Hence, either climate factors have to be added to the measured rainfall (Sørup et al., 2017), or more complex synthetic rainfall time series (Thorndahl and Andersen, 2021) has to be used to secure acceptable performance even at the end of the lifetime of the retention pond. The natural variation of these processes, notably rainfall, imply that the stochastic variation of rainfall series (or fields in the 2D example) will be an important design uncertainty.

Case study

We focus on design using the best available rainfall information for an artificial catchment in Denmark. We calculate the needed detention pond unit volume in millimetres depending on:

- Return period for overflow occurrence (capacity exceedance). Here exemplified by 0.5, 1 and 5 years.
- Outlet flow (interceptor) capacity (here from 0.05 to 10 µm/s).
- Minimum time between overflow events (capacity exceedance). Here: 6, 24 hours, and "empty basin" indicating that the pond needs to be completely empty between events.
- Inclusion of initial loss per rainfall event (defined by 1 hour between events)

The applied methods are:

- A numerical reservoir model simulating the continuous inflow and outflow to and from the detention pond
- An analytical IDF-based method based on unit hydrographs with and without a 20 % additional volume. This method is purely statistical with regards to rainfall input, thus the pond volume depends on the rain return period and the intensity over a given duration. It does not consider time between events nor initial loss.

Results and discussion

There is a clear divergence in required volumes between the different methods and assumptions depending on especially the outflow (interceptor) capacity, see Figure 1. With a small outflow capacity, the detention pond empties slowly, and the required volume becomes very dependent on the defined time between individual rain events. The volume is therefore dominated by coupled or succeeding smaller rain events rather than for larger outlet capacities which are dominated by single large events. The IDF-based method assumes single and independent statistical events, which is the reason that the departure between the approaches is larger for smaller outflow capacities. Especially for very low outflos (interceptor) capacities the uncertainty from choosing a suitable rainfall series becomes important.

The influence of return period is not very evident from Figure 1, but larger return periods requires longer rainfall time series for reliable estimation which in turn causes a higher uncertainty on the estimated pond volumes. The large influence of independence time between individual surcharge events suggest that how authorities define these has a major influence on the resulting designs; also, here it is worth pointing out that it is the same rainfall data that are used for the different simulations, and thus the difference between rainfall events and surcharge events becomes extremely evident. The model assumes an initial loss for each rainfall event, but it could be argued, that this model in unreasonable because of the large integrating effect of the retention pond. Indeed simulations show that the resulting design is highly dependent on the runoff model (not shown).

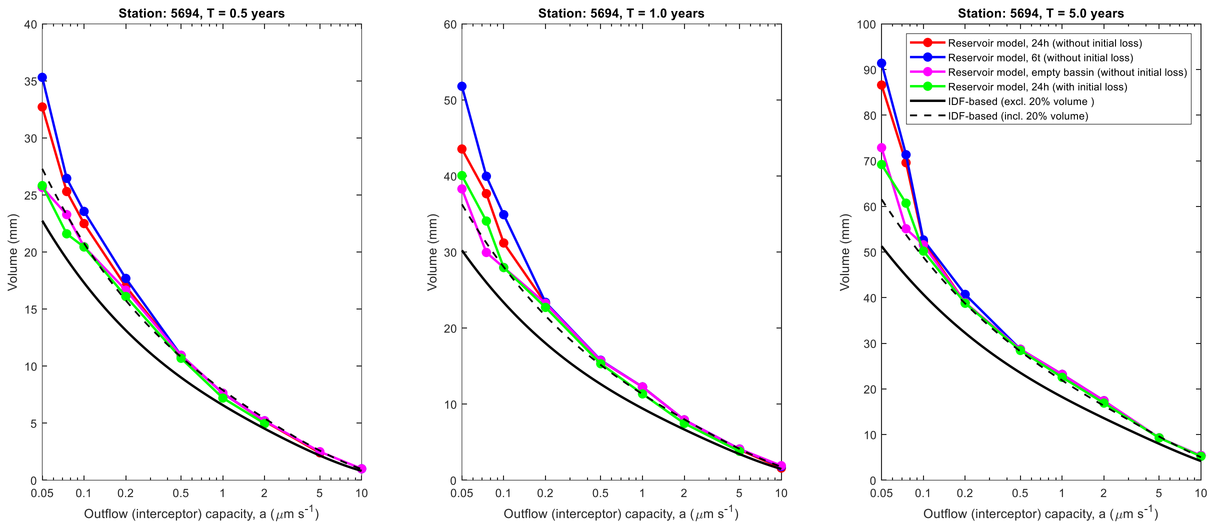

Figure 1. Example of six different methods used to design simple retention ponds with a range of outflow capacities and with overflow at different return periods.

The modelling choices one make, and the way requirements for the design are formulated all have marked influence on the resulting design, making it very difficult to put forward simple rule based design rules that works well in all cases.

Conclusions and future work

Traditional design has focused on identifyability of variables in a model formulation that linked design criteria to data describing the local conditions. As demonstrated this paradigm is under pressure, notably by authorities stipulating performance criteria that goes beyond the understanding of the function of a detention pond in a sewer system, whereby the design process becomes flawed. However, also the lack of a clear description of uncertainties and how they are handled adds to the complexity of design. In total this leads to model ambiguity uncertainty as discussed by Refsgaard et al (2013). As many design problems are more complex than a detention pond problems is becomes difficult to formulate models of relevance for urban drainage modelling.

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