Anticipating urban flooding due to extreme rainfall

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Abstract
Due to climate change, extreme rainfall intensities tend to increase. Recent extreme events in the Netherlands resulted in an overload of urban drainage systems, resulting in severely blocked main roads and flooded properties. Dutch legislation asks for efficient ways to deal with this surplus runoff. Hence, more efficient utilization of public space is necessary, although it is unclear what to do exactly.

The research program "Anticipating extreme rainfall in cities", conducted at Amsterdam University of Applied Sciences, develops a widely accepted and applied methodology that will help municipalities in deciding what actions need to be taken. The research addresses the following questions:

- What measures can municipalities take to prevent damage due to extreme rainfall?
- How can urban planners realize measures to reduce vulnerability to flooding?
- How can urban planners ensure the persistence of these measures in the future?
- What level of detail do simulation models need to have?
- In what way can engineers deal with shortcomings in different modeling approaches?

Since sewer systems are not able to deal with extreme amounts of rainfall, the surplus needs to be handled in other ways, causing measures in public space to be necessary. Communicating the causes of flooding and possible measures with all stakeholders that have a claim on public space leads to more robust and better supported urban planning. The research program investigates the optimization of this communication and the implementation of resulting measures.

Urban flood modeling techniques are powerful tools in both public and internal communication and transparently support design processes. To provide more insight into the (im)possibilities of different urban flood modeling techniques, a comparing case study has been carried out. Although modeling software tends to evolve towards complex 1D-2D simulation models, GIS techniques, using an accurate Digital Elevation Model, prove to be an easy and fast alternative to assess flood risks and to analyze the effect of mitigation measures. Depending on results of the GIS-analysis, practical experiences and characteristics of the area, locations can be chosen where complex simulation models complement the insight.

Keywords: Extreme Rainfall, Geographic Information Systems, Urban Flooding, Urban Flood Modeling, Urban Planning

INTRODUCTION

In recent years, overload frequency of urban drainage systems due to extreme rainfall has increased in The Netherlands, leading to damage by blocked main roads and flooded properties. This is caused by a combination of three factors (Kluck, 2011):

1. Increasing extreme rainfall intensities due to climate change;
2. Additional pavement and buildings, especially on low-lying locations;
3. Decreasing storage on street and surface level difference between buildings and street.

Dutch legislation asks municipalities to collect and process surplus runoff in an efficient manner. Hence, more efficient utilization of public space, also called the major system (Djordjevic et al., 1999; Figure 1), is necessary. To date however, municipalities tend to focus on the subsurface drainage system, also called the minor system. In the Netherlands, the minor system has usually been developed for a rainfall event with a theoretical return period of two years.

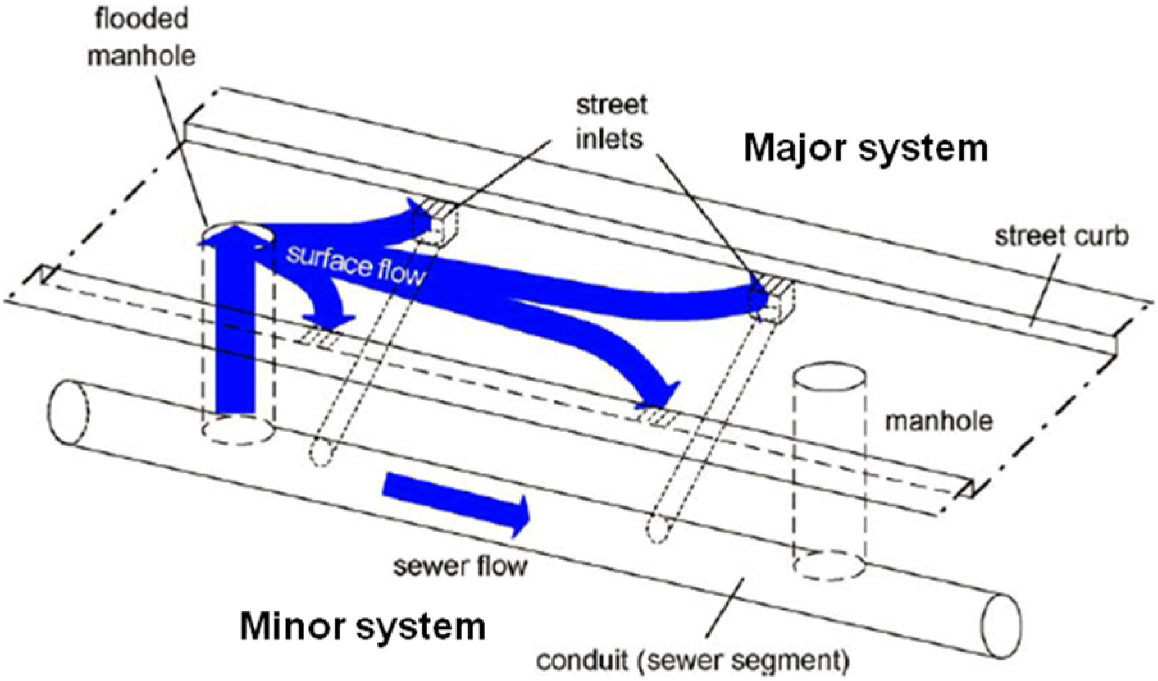

Figure 1 Interaction of major and minor system (Schmitt et al., 2004)

Since extreme rainfall does not occur frequently, many municipalities do not have any insight into the vulnerability of their public space to pluvial flooding (Geldof and Kluck, 2008). Furthermore, they have not considered a desired level of protection (Ten Veldhuis, 2010). However, when damage due to extreme rainfall occurs, prevention of recurrence becomes urgent, leading to very expensive measures instead of a solid plan that is realised over many years.

The research program “Anticipating extreme rainfall in cities”, conducted at Amsterdam University of Applied Sciences, develops a widely accepted and applied approach for coping with surplus runoff. The research addresses fundamental issues often faced in practice:

- What measures can municipalities take to prevent damage due to extreme rainfall?
- How can urban planners realize measures to reduce vulnerability to flooding?
- How can urban planners ensure the persistence of these measures in the future?
- What level of detail do simulation models need to have?
- In what way can engineers deal with shortcomings in different modeling approaches?

The research program takes two years and is accompanied by a consortium consisting Amsterdam University of Applied Sciences and several municipalities, research institutes and engineering companies.

REALISING MEASURES IN PUBLIC SPACE

Since sewer systems are not able to deal with extreme amounts of rainfall, the surplus needs to be handled in other ways, causing measures in public space to be necessary. The first step for municipalities to obtain a solid plan for the improvement of efficiency of measures in public space is obtaining more insight into vulnerability and desired levels of protection. Discrepancies between these two factors lead to a consideration about what locations have most priority for spatial redesign. Hence, some parts of a city will always be more vulnerable than others. It is desirable that municipalities communicate this with inhabitants by giving insight into the maximum amount of precipitation for which they are protected and by communicating that damage prevention at higher amounts is not facilitated by the municipality.

The next step is reducing vulnerability of public space by taking measures in the major or minor system. Simple measures that make the system more robust are preferred. Preferably, these measures are sustainable and flexible and fit into future spatial changes. However, they need to be accepted by people that are confronted with them every day. Hence, stakeholders should be involved in decisions that are made for their living and working environment (Figure 2). Furthermore, municipal water managers also have interest in a clear internal communication since the number of stakeholders claiming private space rapidly grows. Working together with city planners and managers of public roads and village green is necessary to devise and work out plans on a common basis.

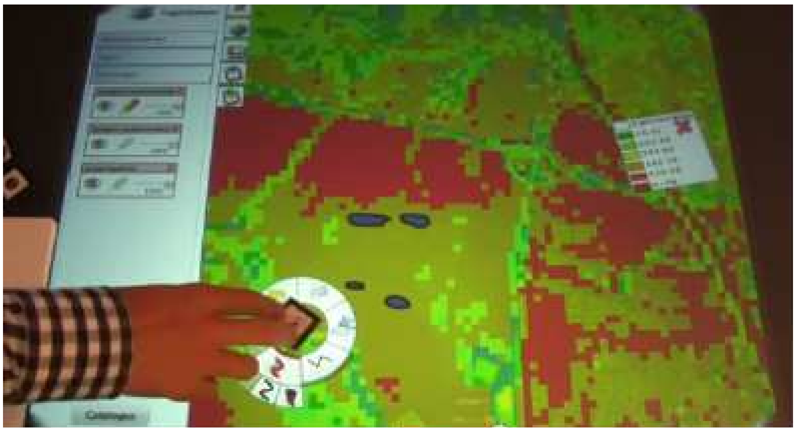

Figure 2 Use of a touch table to communicate with stakeholders

The research program investigates what tools and methods are useful to raise the importance of water on the political agenda. What can be learned from experiences of implementation of water management projects (success and failure)? What stakeholders play a role in public space and what are their interests? In which plans do measures and strategies have to be embedded? What amount of damage do stakeholders have to accept at a certain return period?

URBAN FLOOD MODELING TECHNIQUES

Urban flood modeling techniques are powerful tools in both public and internal communication and transparently support design processes. For design of sewer systems, computer models are used in which flow through the minor system is simulated. However, these models are not suited for calculation of flow through the major system. When water levels rise above surface level, this is schematized as a water column above the manhole. This is not a realistic assumption in case of situations where the minor system is heavily overloaded and water will flow over the surface.

In recent years, existing software packages for sewer calculations have been extended to include flow through the major system, creating so-called dual drainage models (Djordjevic et al., 1999). Basically, there are three possibilities to simulate flow through the major system:

- GIS-based surface analysis tools;
- Simple 1D-1D simulation models;
- Complex 1D-2D simulation models.

GIS-based tools

The most simple way of modeling is using GIS-based surface analysis tools that do not take the minor system into account and hence, only focus on the major system. It is assumed that a certain amount of precipitation flows to the minor system and that the remaining precipitation flows through the major system. A Geographic Information System (GIS), using an accurate Digital Elevation Model (DEM), indentifies flow paths, water depths and locations of ponds. For each damage location, one can determine the origin of the water and the effect of possible measures much faster than with more complex flow simulations.

Although GIS-tools do not take the interaction between major and minor system into account, specific characteristics of the minor system, e.g. spills and inflow capacity, are important for the flooding extent. In addition, most surface analyses use the so-called “rolling ball” routing algorithm which tracks overland flow paths by determining in each grid cell which of the adjacent grid cells is the lowest. Hence, the algorithm always determines only one preferred flow path instead of distributing water over multiple flow paths.

1D-1D simulation models
One-dimensional (1D-1D) simulation models for both the major and minor system provide a fast insight into flow through the major system, taking flow through the minor system into account. These simulation models assume streets to be open channels and calculate water depths and flow velocities in cross sections perpendicular to the flow direction.

By schematizing streets as open channels between manholes, two-dimensional elements of the major system are neglected, e.g. speed bumps, ramps and alleys. In reality however, variation of surface level and slope leads to non-preferential flow paths. Small surface level differences have large influence since water depths in the major system are small. Furthermore, presence of gullies influence local flow direction and uncertainties are expected around crossroads (Mark et al., 2004).

In addition, 1D-1D simulation models do not simulate flow correctly when water levels rise above the curbs. In that situation, they underestimate storage capacity of the major system and overestimate water depths on street. In some cases, extending street profiles with extra storage beneath curbs offers a solution for this problem. However, when water continues its way through non-preferential flow paths, extra flow paths are necessary and extension of profiles is not sufficient (Boonya-aroonnet et al., 2007).

Finally, especially in flat lowland areas, large ponds can develop in depressions that are not connected to the minor system. Although these ponds evaporate after a while, 1D-1D simulation models assume that all pluvial water flows to the minor system and hence, overestimate the inflow. This has large consequences for the water balance and the time during which the minor system is overloaded. Due to these uncertainties, these models tend to overestimate overloading time of the minor system and tend to underestimate the time during which water on street is observed.

1D-2D simulation models
Where both interaction between major and minor system and local effects in the major system are relevant, 1D-2D simulation models of the minor (1D) and major (2D) system provide an even more realistic representation. These simulation models differ from surface analysis tools by taking the minor system into account and from 1D-1D simulation by simulating the major system in a two-dimensional way. They offer the possibility to evaluate the effect of combining measures in the major and minor system.

The main challenge in the development of 1D-2D modeling is improving the description of the interaction between the minor and major system. Sizes of gullies, their connection to the sewerage and their connection to the DEM are decisive for this interaction, especially at low flow depths (Bertram et al., 2009). Inflow by gullies leads to higher water depths and longer flooding times compared to inflow by manholes that are directly connected to the minor system. Although model validation improves interaction descriptions, this is hampered by a lack of calibration data from overland flooding events. Given the infrequent occurrence of such events and particular difficulties to set up monitoring of overland flow characteristics, such data are difficult to obtain.

At the moment, disadvantages of 1D-2D simulation models are a large data requirement, in particular with respect to digital terrain information, and large computational efforts. Due to long computation times, 1D-2D simulation models are not suited for operational management and quick predictions. Allitt et al. (2009) found computation times for 1D-2D simulation models of about ten to one-hundred times higher than for 1D-1D simulation models.

CASE STUDY

To compare different urban flood modeling techniques, a case study was carried out for an extreme rainfall event in the Dutch coastal municipality of Noordwijk. Two different GIS-tools (WOLK, Tauw Consultants; WODAN123, Grontmij Consultants) were compared with both 1D-1D and 1D-2D simulation models (SOBEK, Deltares) under the following conditions:

- Uniform distributed precipitation of 60 mm in one hour, which is the hourly rainfall amount with a statistical frequency of once every hundred years;
- Both the GIS-tools and the 1D-2D simulation models used a DEM with a resolution of 1x1 m.

Since it was expected that conclusions can differ between different types of areas, three areas were investigated in more detail (Figure 3):

- Noordwijk aan Zee (A): a bowl-shaped area between dunes with height differences up to about twenty meters with free flowing sewerage to Noordwijk Binnen;
- Noordwijk, Van Panhuysstraat (B): an area on the transition from Noordwijk aan Zee to Noordwijk Binnen. This area is built at the foot of the dunes with height differences up to about seven meters and a large surcharge of storm water coming from Noordwijk aan Zee;
- Noordwijk Binnen (C): a flat area with height differences of less than a meter.

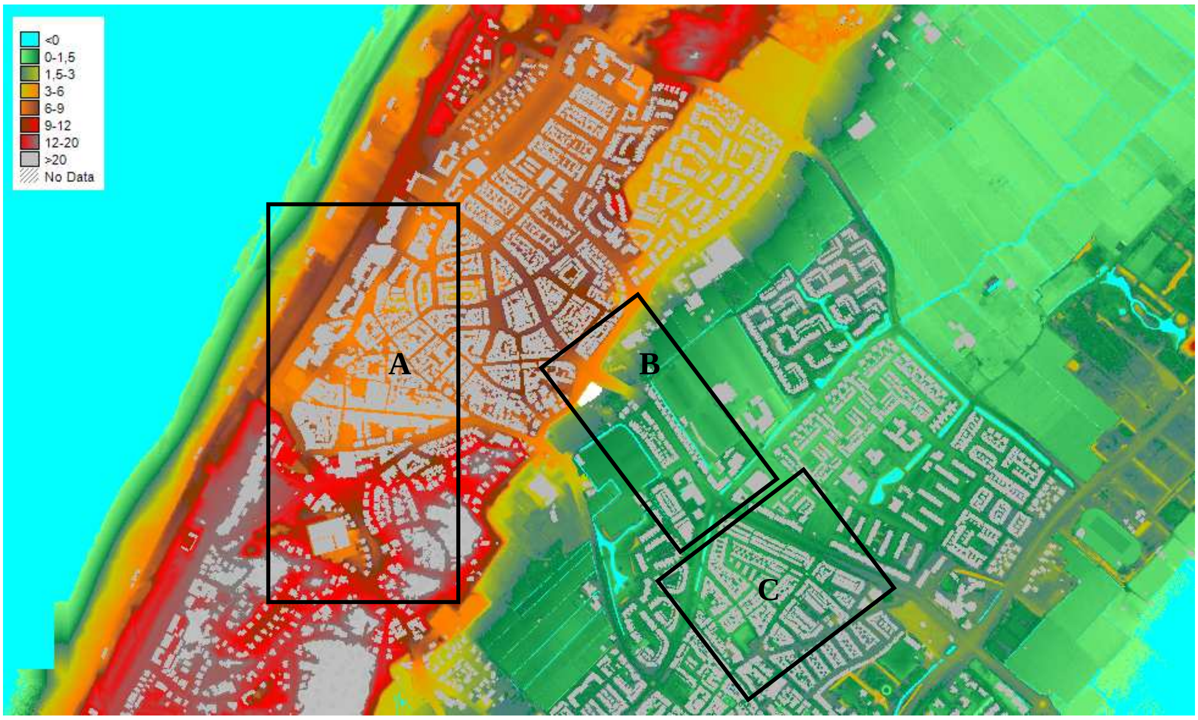

Figure 3: Digital Elevation Map of Noordwijk (m + sea level) and locations investigated in more detail.

For the GIS-tools and the 1D-2D simulation models, similar flood patterns were found for the bowl-shaped (A) and flat (C) area. Local differences were found, although no unambiguous conclusions could be drawn about the location and extent of differences. Furthermore, for some locations, GIS-techniques predicted the largest water depths, as for other locations, 1D-2D simulation models predicted the largest water depths. The flood pattern predicted with the 1D-1D simulation model clearly differs from the other patterns, which can be clearly traced back to the sensitivity of its results to uncertainties in surface heights at manholes and poorly defined surface elements.

The 1D-1D simulation model predicts highest water depths for most of the known vulnerable locations (Figure 4) due to:

- Defining a standard road profile for the entire urban area. Especially on vulnerable locations, the extent of this profile is too small, leading to overestimated water levels;
- Neglecting areas without sewerage. These areas are assigned to the nearest sewerage pipe.

For the area at the foot of the dunes (B), GIS-tools predict a smaller water depth and flood extent than the other modeling techniques due to the fact that this technique neglects the sewer surcharge from the subsurface catchment that is much larger than the surface catchment for this location. Since in reality high water depths and a large flood extent are observed very frequently, it can be concluded that it is crucial to take the minor system into account for areas like this.

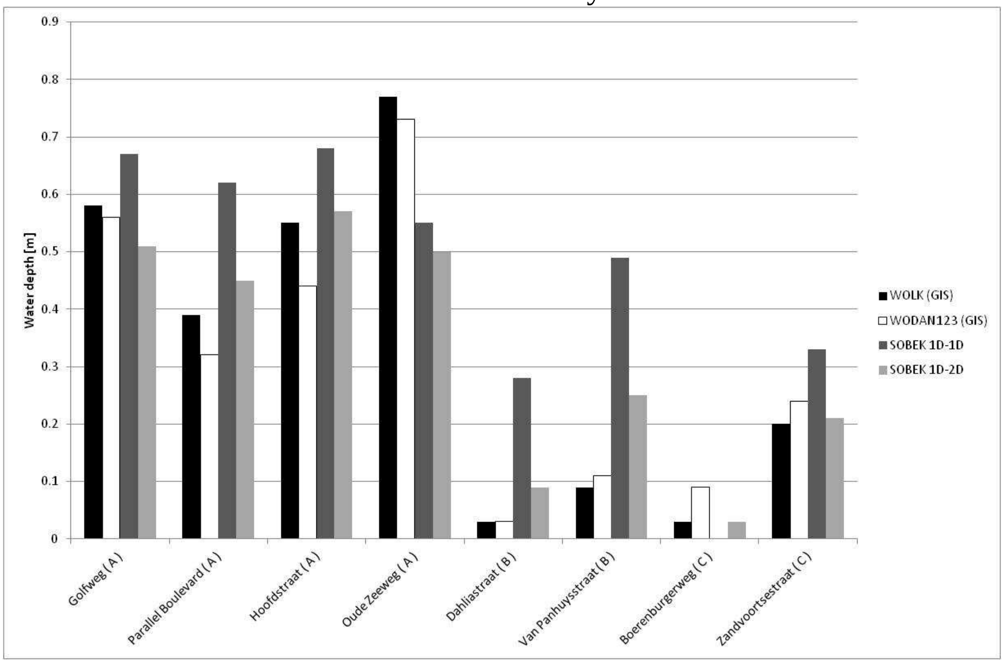

Figure 4: Maximum water depths for different modeling techniques on vulnerable locations

CONCLUSIONS AND RECOMMENDATIONS

Since sewer systems are not able to deal with extreme amounts of rainfall, the surplus needs to be handled in other ways, causing measures in public space to be necessary. The first step for municipalities to obtain a solid plan for the improvement of efficiency of measures in public space is obtaining more insight into vulnerability and desired levels of protection. It is desirable that municipalities communicate this with inhabitants by giving insight into the maximum amount of precipitation for which they are protected and by communicating that damage prevention at higher amounts is not facilitated by the municipality. The next step is reducing vulnerability of public space by taking measures in the major or minor system. Since they need to be accepted by people that are confronted with them every day, stakeholders, municipal water managers and urban planners should be involved in decisions that are made for their living and working environment.

Urban flood modeling techniques are powerful tools in both public and internal communication and transparently support design processes. It is expected that the use of advanced 1D-2D simulation models will increase next decade. So far however, computational efforts, data requirements and a lack of calibration data have been limiting factors (Boonya-aroonnet et al., 2007; Allitt et al., 2009).

To compare different modeling techniques with one another, a case study has been carried out that showed that in most cases, GIS-based surface analysis tools predict the same flood extent as advanced 1D-2D simulation models. Hence, they provide a first insight and they are an easy and fast alternative to assess flood risks and to analyze the effect of mitigation measures. However, extra attention has to be paid to areas where the subsurface (minor) catchment differs from the surface (major) catchment. Finally, the results of 1D-1D simulation models are very sensitive to uncertainties in surface heights at manholes and poorly defined surface elements and hence, can pass over crucial flooding locations or overestimate street water levels.

Based on the case study results, it is recommended that municipalities carry out a GIS-analysis, taking model uncertainties into account. Depending on results of the analysis, practical experiences and characteristics of the area, locations can be chosen where complex simulation models complement the insight.

DISCUSSION

Advanced simulation models take more physical processes into account than GIS-analyses and hence, are expected to provide the most accurate results. However, not only accuracy has to be considered when choosing an efficient modeling technique. Efficiency means balancing computation time, reliability, data need and communication possibilities. Based on the case study, GIS-analyses show the best results on computation time and data need. Furthermore, they have proven to provide reliable results for quick scans and are powerful communication tools. For some types of areas however, advanced simulation models are a necessary extension to such quick scans. More research in this field is necessary and will be carried out in the next phase of the research program.

Although GIS-analyses neglect the influence of the minor system and hence, introduce an extra source of uncertainty, one is also faced with a large uncertainty when using 1D-2D simulation models, justifying the question if one should put effort into coupling the models of the major and minor system. During 1D-2D simulation for the case study, initially very uncertain values were found for the exchange of water between major and minor system. This is also stated by Bertram et al. (2009). Furthermore, 1D-2D simulation models assume that overland runoff only occurs because of surcharging of the sewer system. However, most uncertainty is introduced by general shortcomings and sources of uncertainty such as the spatial resolution of the DEM, that has to be smaller than the typical size of landscape elements, and the surface discharge of unpaved areas, that depends on soil type, slope, presence of vegetation and rainfall intensity.

1D-1D simulation models give a coarse prediction of flooding extents since the results of this modeling technique are very sensitive to uncertainties in surface heights at manholes and poorly defined surface elements. As also stated by Mark et al. (2004), describing street channels as prismatic and flow in those channels as one-dimensional are clear shortcomings under extreme rainfall conditions, leading to an overestimation of street water levels. When extra attention is put to surface elements and flow beneath curbs, 1D-1D simulation models are an improvement on models that only take the minor system into account. However, this improvement is based on insights that are obtained by two-dimensional information, so that it is only a short next step to use 1D-2D simulation models.

Although for the case study, different modeling techniques were investigated separately, it is expected that a combination of different flood modeling techniques extent the insight into the total urban system even more (Schellart et al., 2011). It is important to get an overall insight at first and zoom in afterwards. E.g., one can start by simulating flow through the minor system with a 1D sewerage flow model and by determining flow paths and potential damage locations with a surface analysis. On critical locations, the interaction between both systems can be analyzed with a 1D-2D simulation model or a 1D-1D simulation model, in case the water do not overtop curbs. These critical locations can be potential damage locations, areas where the subsurface (minor) catchment differs from the surface (major) catchment or areas where flow paths differ from the road pattern (in the latter case 1D-2D simulation is necessary; Leandro et al., 2009). Finally, it is also possible to combine different techniques within one model. Since most modeling software can only take a limited size of grid cells into account, combining a 1D-1D simulation model of a city with a 1D-2D simulation model for a specific area of interest can be an alternative approach. This combines the advantages of a 1D-1D approach (speed, less data) with those of a 1D-2D approach (accuracy).

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