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Tight coupling of groundwater and sewer models for compound flood modelling in coastal urban areas

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Abstract

Hydrological models often neglect the interplay of flooding mechanisms such as storm surge, rainfall, high tide, and groundwater emergence that may occur in coastal urban areas. Therefore, they could provide inadequate predictions.

In this paper, we report on a study aimed at developing an algorithm to tightly couple groundwater and sewer models that could be applied to effectively evaluate grey and green infrastructure performance during compound flooding in coastal urban areas. The models developed in open-source programs such as MODFLOW and SWMM were coupled with a custom-built Python algorithm. The coupled models were calibrated and validated for a test site located in Long Island (NY, USA).

Overall, tightly coupled MODFLOW and SWMM models can represent a substantial advancement in urban hydrological modelling, offering both immediate practical benefits for flood management and long-term strategic value for urban water infrastructure planning.

Highlights

- A Python algorithm to tightly couple MODFLOW and SWMM was created.
- The algorithm allows water flux exchanges between aquifer and sewer network.
- A coastal urban area was selected to calibrate and test the coupled models.
- Due to interaction seasonality, coupled models greatly improve hydrological calculations.
- The tightly coupled models can support flood prediction and infrastructure renovation.

Introduction

Urban hydrological models often overlook the complex interplay between natural water bodies and built infrastructure (Salvatore, *et al.*, 2015; Leandro *et al.*, 2016; Hayley *et al.*, 2024). A common oversight is the failure to account for real-time interactions between groundwater and sewer systems, as well as tidal influences in coastal urban areas. This simplification can potentially lead to substantial inaccuracies in hydrological simulations, particularly when modelling compound flooding events (Aziz *et al.*, 2024). Such events, which may involve a combination of storm surges, heavy rainfall, high tides, and elevated groundwater levels, require a more comprehensive approach to capture their full dynamics. By neglecting these interrelated dynamics, current models risk producing skewed results that may inadequately represent the hydrological behaviour of urban environments (Rossi and Toran, 2019; Shen *et al.*, 2019).

To address the complex interplay between groundwater and sewer systems during compound flooding events in coastal urban areas, we developed a novel algorithm. This algorithm tightly coupled groundwater and sewer models, utilizing the widely-adopted open-source programs MODFLOW (Langevin *et al.*, 2017) and SWMM (Huber, 1985). For our case study, we selected Greenport Village, a small town on Long Island, New York, USA. We implemented groundwater and combined sewer models using MODFLOW and SWMM, respectively. These models were then integrated using an algorithm written in Python. To calibrate and validate our coupled model, we used data from the 2010 when the nor'easter storm, a significant weather event that affected the region in the wintertime.

Methodology

An algorithm was developed in Python to couple groundwater models created in MODFLOW, and sewer models created in SWMM. The coupling however faces some challenges largely due to vastly different spatial geometries the two models are operating on. For instance, MODFLOW uses grid cells while SWMM consists of lines and polygons. In addition, MODFLOW is more on the scale of hours, days and even longer while SWMM usually runs on the scale of seconds or minutes. To resolve the spatial and temporal differences of these two models, enabling the simulation of real-time flow and mass exchanges between groundwater and sewer, an algorithm in Python was developed using Python Package MODFLOW API (Hughes *et al.*, 2022), flopy (Bakker *et al.*, 2016), and PySWMM (McDonnell *et al.*, 2020).

The algorithm establishes communications between MODFLOW and SWMM resolving the spatial and temporal differences of the exchanged variables. The exchange occurs through the WELL module of MODFLOW resolving the spatial and temporal differences of the exchanged fluxes. The flux exchanges are identified as groundwater infiltration into the sewer (I , m³/s) and exfiltration of wastewater into the groundwater (E , m³/s), which are calculated as (Karpf and Krebs, 2011),

$$I = i(h_{GW} - h_W)K,$$

$$E = e(h_{GW} - h_W)K,$$

where h_{GW} and h_W are the hydraulic head of the shallow aquifer interacting with the sewer and of the hydraulic head of the water within the conduit, m; K is the hydraulic conductivity of the soil surrounding the conduit, m/s; and i and e are empirical coefficients, m.

Case study

The selected test site is Greenport Village and is located on the North Fork of Long Island (NY). The ground elevation is between 0 and 4 meters above mean sea level and the total area of the land surface is 2.46 km².

The sewer network of Greenport Village is a combined system of channels, pressurized pipes, and pumping stations distributed across the town and built between 1920 and 1950.

Figure 1 shows the map of the site together with the sewer model as implemented in SWMM (a) and an example of simulation results of the MODFLOW groundwater model (b).

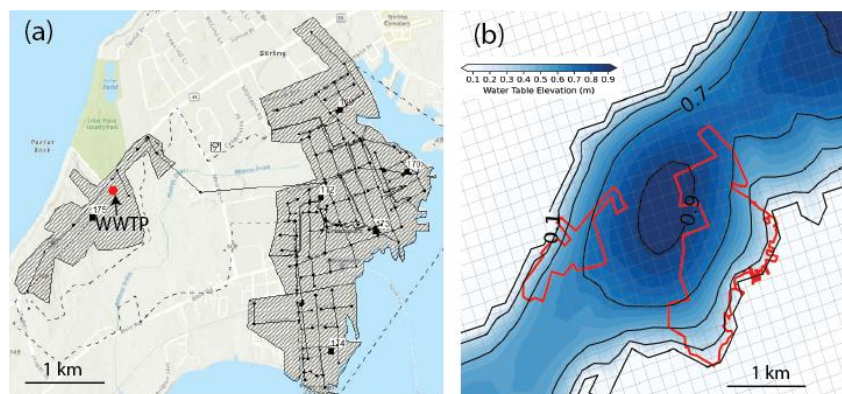


Figure 1. (a) Greenport Village (NY, USA) and sewer network as implemented in SWMM, and (b) Example simulated water table elevation (January 1, 2010).

Results and discussion

In our model application, we simulate the interactions between groundwater and the combined sewer network in two ways. Within the sewer network, we account for the infiltration and exfiltration processes. While, in the unconfined upper aquifer, we modelled these interactions as leaking and draining wells.

Our simulations revealed seasonal variations in the water table elevation. Consequently, at any given node, both infiltration and exfiltration can occur, depending on factors such as the time of year, storm intensity, and the age of the infrastructure.

This dynamic was confirmed by flow measurements at the sewer outlet, which clearly indicated infiltration during winter months and exfiltration during the summer.

To match our model simulation with observed data, we employed an inverse modelling approach. We calibrated the model using flow measurements from the sewer outlet, focusing on estimating the coefficients in the infiltration and exfiltration rate equations at each interaction node (Figure 2). This process allowed us to fine-tune our coupled model to accurately represent the complex groundwater-sewer interactions observed at the site.

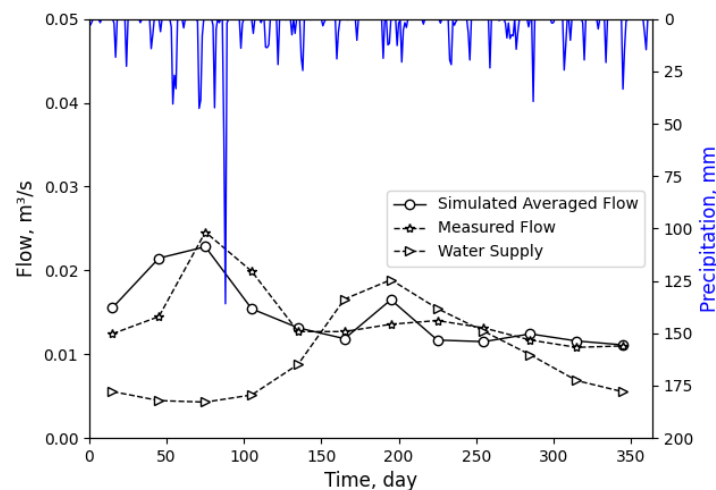


Figure 2. Measurements of drinking water supply (triangles), wastewater flow into the wastewater treatment plant (WWTP) (stars) and simulations results of the WWTP inflow (circles) in year 2010.

Conclusions and future work

Tightly coupled MODFLOW and SWMM models can offer substantial advantages in evaluating the performance of both gray and green infrastructure in coastal urban areas during compound flooding events. These integrated models account for the complex interactions between groundwater and aging sewer systems, providing a more comprehensive understanding of urban hydrology.

Beyond their immediate application in flood assessment, these coupled models may serve as valuable tools for strategic planning. They can inform decision-making processes related to infrastructure maintenance and guide future improvements, ensuring more resilient and efficient urban water management systems.

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