Coupling SWMM and MODFLOW: Developing and applying a model integration scheme for urban settings with wetlands and shallow groundwater

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Highlights

- An integration scheme to couple SWMM and MODFLOW was built adopting a script-based approach using the Phyton libraries PySWMM and FloPy.
- Spatial dynamics of surface/subsurface interactions were simulated achieving mass conservation.
- Significant differences were found comparing results against uncoupled models.

Introduction

The spatial and temporal dynamics of surface and subsurface interactions in urban environments is complex, case-dependent, and not easy to characterize. Coupled models are essential to understand the spatial-temporal distribution of surface/subsurface hydrological processes and their interactions. These interactions might be relevant in urban settings, something not fully considered in stormwater management models.

The goal of this study is to develop a free and open-source integration scheme for coupling SWMM and MODFLOW. The model integration routine is able to continuously simulate spatially distributed urban hydrologic processes, groundwater flows, and their interactions.

Methodology

To correctly simulate surface-groundwater interactions in urban settings, SWMM5 (Rossman, 2010) and MODFLOW (Harbaugh, 2005) are used as surface and subsurface models, respectively. To integrate both models we use two Python libraries, i.e., PySWMM (McDonnell & Llc, 2020) and FloPy (Bakker et al., 2016), which communicate bidirectionally.

Temporal Data Exchange, Spatial Integration and Continuity Analysis

In this study we propose an external coupling approach to represent the influence of the surface model on the groundwater model and vice versa, as shown in Figure 1.

To allow the exchange of fluxes and due to the differences between SWMM spatial discretization and the structured grid used in MODFLOW, subcatchments, storage units and nodes in SWMM are geolocated on the MODFLOW grid. This is made through spatial joins using a Geographic Information System and the GeoPandas library.

A major benefit of coupling models through the exchange of fluxes is that continuity can be ensured. The development of the general continuity equation of the entire coupled model requires the consideration of the individual continuity equations associated with SWMM, MODFLOW, and the fluxes exchange.

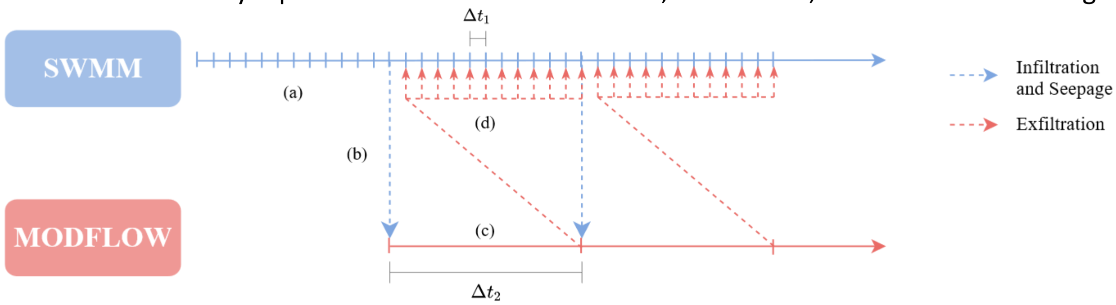

Figure 1: Temporal data exchange structure. (a) Surface rainfall-runoff is simulated using SWMM at a time step Δt_1. (b) The aggregated infiltration and seepage are transferred to the MODFLOW model as recharge. (c) Groundwater is simulated using MODFLOW at a time step Δt_2. (d) Drained water from MODFLOW is integrated as exfiltration at a constant rate back to SWMM.

Performance Comparison of coupled and uncoupled models

A simple synthetic test case was built to assess the performance of the coupled approach and compare it against an uncoupled SWMM model, and a SWMM model with a simple implementation of its groundwater simulation routine. For the coupled model mass conservation was verified and achieved reporting very low continuity errors. Not considering the bidirectional flux exchange with the uncoupled model (i.e. only SWMM) produces very different results.

Case Study: Llanquihue, Chile. City of Urban Wetlands

Llanquihue is located in south of Chile and is characterized by its constant interaction with a complex urban wetland network and the surrounding water bodies, which have had a strong pressure due to urban development. This change, as well as the lack of stormwater management and frequent floods, reveal a need for urban planning that allows the integration of the wetland network into the drainage system.

To simulate the hydrologic response and the behavior of the wetland network and its interactions with groundwater, we built a coupled SWMM-MODFLOW that was continuously run for two years

Results and discussion

General Performance

Due to the absence of information for calibration and validation, to better understand the model performance we implemented a one-at-a-time sensitivity analysis by varying the main parameters affecting the flux exchange between models considering broad value ranges. Most sensitive parameters of the coupled model include the aquifer hydraulic conductivity, the conductance of the cells with drain capacity, and the infiltration parameters of wetlands. The response to the changes differs among wetland.

Frequency Analysis of Daily Peak Volumes

To quantify the flooding volume and the associated risk in critical flooding zones of Llanquihue we performed a frequency analysis of daily peak volumes in each location. The frequency curves obtained with the coupled model are compare against those obtained with an uncoupled SWMM. As shown in Figure 2, larger and more frequent flooding events were obtained with the coupled model.

Spatial Results - Water Depths

Study the water table depths reveals the relevance of using a coupled surface-subsurface model as a tool for planning and design of sustainable drainage systems in cities with shallow groundwater. Figure 3 shows that most of Llanquihue has water table depths smaller than 1 m (red tones) consistently during the wet season. Thus, drainage system of the city must consider this and avoid infiltration techniques and prioritize storage and conduction as control techniques.

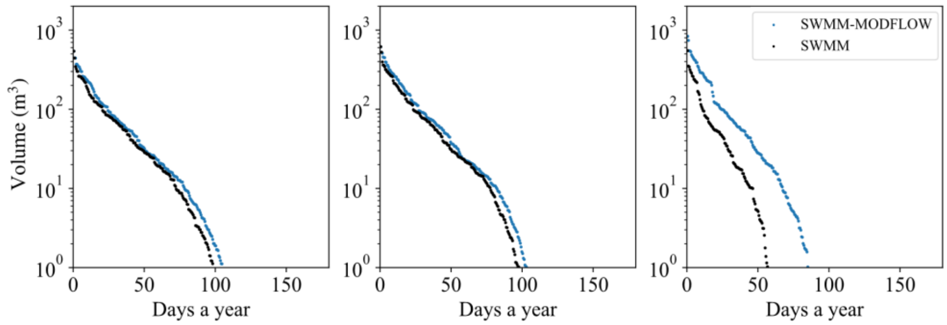

Figure 2. Frequency analysis of daily peak volumes at the three of the six critical zones. Results obtained with the coupled SWMM-MODFLOW and the uncoupled SWMM models are presented

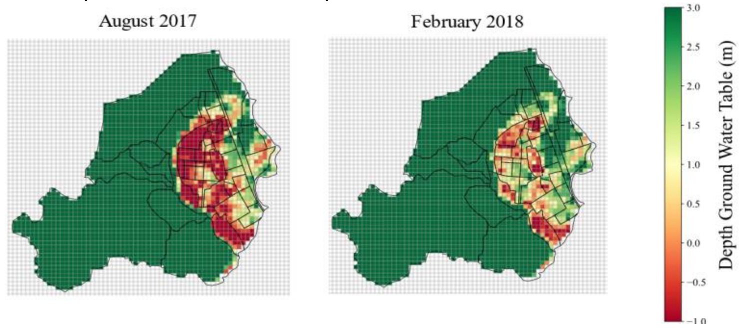

Figure 3. Water table depth for August 23, 2017, wet season (left) and February 15, 2018, dry season (right).

Conclusions and future work

This paper presented a new integration framework for coupling SWMM and MODFLOW. The tool allows the continuous and spatially distributed simulation of surface and subsurface hydrological processes and interactions in urban environments. Our main conclusions are the following:

- Continuity of the new framework was verified and achieved in both study cases. Mass conservation in continuous and integrated simulations in coupled models are rarely studied and reported.
- With the coupled model, larger and more frequent flooding events were obtained. Working with uncoupled models in humid environments might imply an underestimation of the flooding risk.
- Continuous and integrated surface-subsurface simulations might be a key tool for stormwater planning and management in cities with strong interactions with a shallow groundwater table. Frequency curves might be used to compare different stormwater management alternatives against the uncontrolled situation, with a focus on reducing the frequency of flooding in a specific time window and locations. (2) Simulations allow studying the feasibility of infiltration practices

Future work should focus on the calibration and validation of the coupled model in the study area, as well as the implementation in other regions with surface-subsurface interactions where different variables can be studied under the influence of the groundwater table. Additionally, a Python library should be developed to facilitate the widespread use of the new codes by modelers in these regions.

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