Flood Modelling Tool

An integrated GIS and hydrological modelling tool for planning nature-based solutions in the urban environment

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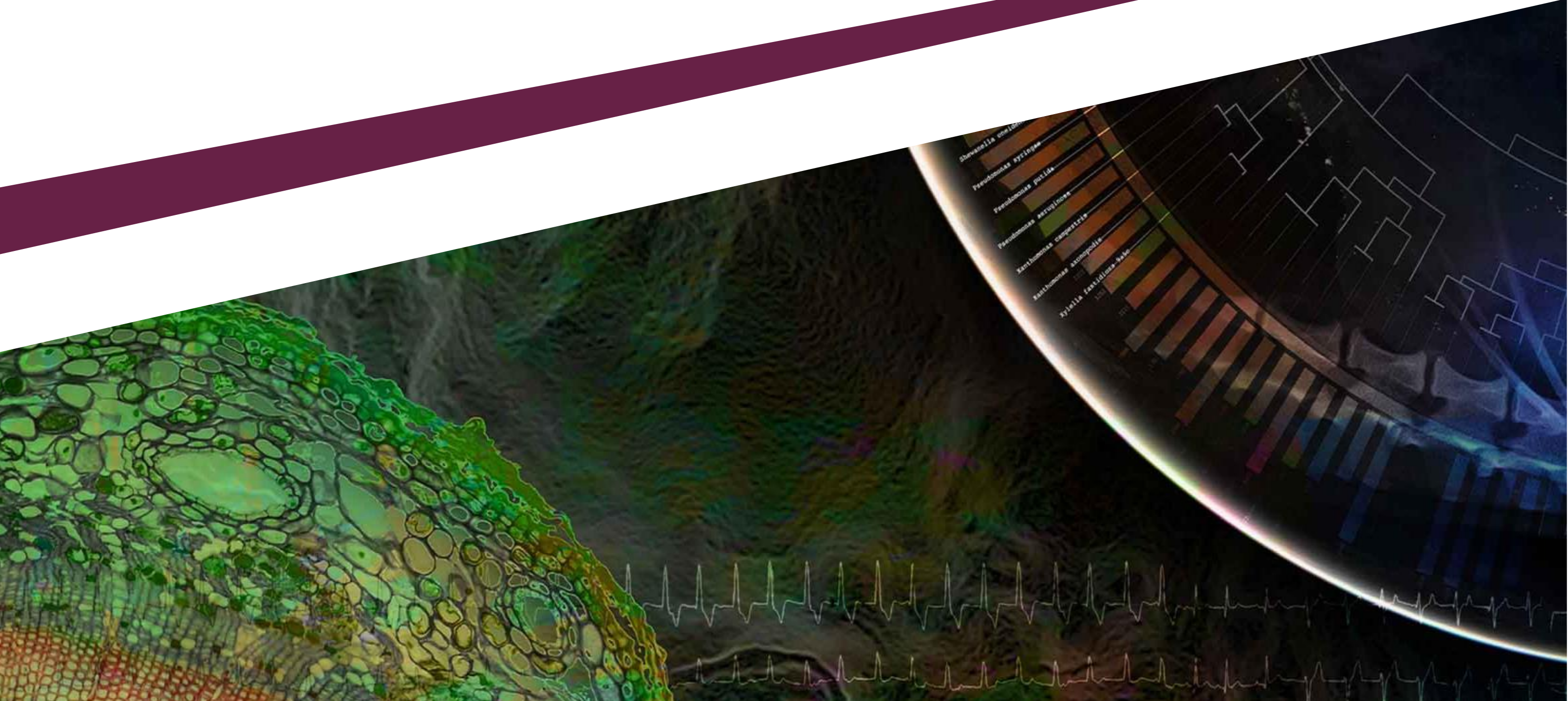

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Abstract

The risk of pluvial flooding is going to increase as climate change causes an increase in intense precipitation along with urbanisation leading to an increase in impermeable surfaces. In the last decade, cities such as Malmö and Copenhagen have already experienced severe pluvial flooding that has caused extensive damage. Adapting to climate change by creating flood resilient urban areas is therefore important and blue-green infrastructure (BGI) may be one measure to accomplish this.

A hydrological model called TFM-DYN has been used to investigate whether BGI can aid the mitigation of pluvial flooding. TFM-DYN can also assist in selecting the best locations of BGIs. The problem of modeling urban floods using distributed high resolution hydrological models while considering the hydrological process in the upstream area is difficult due to the limited current computation capacity. However, coupling a distributed hydrological model (TFM-DYN) with an other semi distributed models (HYPE) is crucial to enable simulate, predict and map floods with high-resolution for an urban area while considering its catchment area. With the using of the new suggested coupled hydrological model, it is possible to connect and use the output results from HYPE model as an input to a distributed model (TFM-DYN). The interaction between HYPE and TFM-DYN will consider the hydrologic process occurred outside the model boundary of the interested urban area. The coupling of the two models will help initiating the model with real water depth data that may lead to more realistic simulation. The procedure of input data manipulation using the two model interactions is explained in details.

The model is tested on a selected urban area to dynamically simulate the changes in the water depth with time using high resolution gridded data. The new coupled model can be of a great tool for wide range of user and stakeholders as an example to municipalities, water experts, insurance companies and to all other interested water organizations who have access to regional catchment models and in need for a high-resolution, flood simulation and mapping model.

Keywords: Hydrological modelling, HYPE; TFM-DYN, Blue-green infrastructure, Nature-based solutions, urban flood, pluvial flood

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Abbreviations

TFM-DYN	Triangular Form-based Dynamic Model
HYPE	HYdrologic Predections for the Envirinment
BGI	Blue-Green Infrastructure
NBS	Nature-Based Solution
DEM	Digital Elevation Model

1. Introduction

1.1 Foreword

Blue-Green infrastructure (BGI) as nature-based solutions (NBS) can contribute to sustainable urban water management by increasing infiltration, enhancing evapotranspiration, providing storage areas for rainwater and removing pollutants. To prevent the risk of urban flooding, rainwater must be effectively drained away from areas where it can accumulate and harm people and cause damage to infrastructure. (Raymond et al. 2017). The creation of artificial water bodies or ecosystems in urban areas or the preservation and improvement of natural water bodies can retain and store rainwater and urban runoff. The aim is to prevent rainwater from flowing directly into the sewer system (overloading the system) in order to reduce and delay flood peaks and allow for controlled runoff. NBS for water retention include creating natural spaces for temporary water storage (green spaces and urban wetlands), improving infiltration (green spaces, plants that improve infiltration) and improving evapotranspiration (trees, green spaces, parks). Rainwater and graywater storage can also preserve water for -on-site reuse (e.g., green space maintenance) and to meet water demands (Young et al., 2014), providing additional water resources and reducing pressure on existing freshwater sources. Using nature-based solutions (NBS) instead of traditional grey infrastructure for water storage allows more water to infiltrate into the ground, helping to replenish groundwater and improve water availability.

By combining NBS for water storage and stormwater management with methods to improve water quality and water use efficiency, a portion of stored wastewater and urban runoff can be treated so that it can be safely reused, discharged into water bodies or infiltrated into the ground. These measures can help conserve freshwater resources and increase drought resilience (Sang N. 2020).

NBS can transform urban areas with hard surfaces into urban water bodies with restored ecosystems and integrate water flows and functions into the larger watershed. Nature-based or mixed grey-green solutions for water management provide additional benefits such as promoting urban biodiversity, improving the urban environment and living conditions, improving air quality, cooling urban areas through evapotranspiration, reducing the urban heat island effect, and mitigating climate change (Sörensen et al. 2016).

However, one of the main objectives of this report is to demonstrate the benefits of using BGI as nature-based solutions for flood prevention and mitigation. To this end, number of possible water management actions are defined;

- Creation of artificial water bodies for short-term water storage
- Creation of new underground water bodies for water storage - Establishment of areas for temporary flooding along rivers (floodplains) through the relocation of flood protection infrastructure
- Restoration, creation or expansion of wetlands in river catchment areas
- Use of vegetation in urban areas (e.g. street trees, green spaces, green roofs and walls, infiltration gardens, urban forests)
- Creation of new green surface waters (ponds, drainage systems, lakes, bio-retention cells).

1.2 Approaches to floods modelling

There are currently two approaches to flood modelling: distributed hydrological or hydrodynamic models (2D rainfall models) and semi-distributed hydrological modelling systems (1D catchment modelling systems). With current computing capacities, it is not possible to create a high-resolution hydrological model for most river catchments that covers the entire catchment with a distributed model and has an acceptable runtime. It is also not possible to create a high-resolution semi-distributed hydrological model that can be used for high-resolution flood mapping. Most hydrological models currently used in flood forecasting are of the catchment model type (e.g. EFAS, HYPE, SWAT, etc.). Catchment models are particularly suitable for large-scale modelling, where sub-catchments are used as the basic unit for model calculations, and are usually low-resolution models (i.e. the size of the sub-catchments is large). For example, the average resolution of the official Swedish hydrological model for flood forecasting, S-HYPE (Strömqvist et al. 2012) and the two official European operational flood forecasting systems (E-HYPE and EFAS) is 13, 250 and 25 km2 respectively. Such low-resolution flood forecasting models are important to issue warnings in reasonable runtime when flood might occur in the sub-catchments, but these models are not very useful when detailed distributed flood maps are needed. On the other hand, high-resolution hydrodynamic models (e.g. HEC-RAS, MIKE FLOOD, etc...) can provide detailed flood maps, but require very long runtimes for a correspondingly large model area and are not open source models with limited possibilities for research and development. Since neither the distributed nor the semi-distributed hydrological models are superior and suitable for all hydrological modelling purposes, the dynamic hydrological model TFM-DYN (Nilsson et al. 2021) was selected to be further developed and coupled with another semi-distributed model HYPE model (Lindström et al. 2010).

1.3 Pluvial Flood

The increase in heavy rainfall events combined with urbanisation increases the risk of flooding. Urbanisation has increased in Sweden since the early 1900s and 85% of the population now lives in urban areas (Svanström 2015). One of the problems of urbanisation and the densification of urban areas is that the risk of flooding can increase significantly. This is because the increase in impermeable surfaces such as roads or roofs leads to an increase in runoff water and rapid overland flow. As the water cannot infiltrate the ground, the natural storage of rainwater is disrupted. If the intensity of rainfall exceeds the infiltration capacity of the soil, the increase in impermeable surfaces can lead to flooding (Wheater 2006). Flooding can cause major damage and result in high costs for municipalities and cities.

The exceptional 1000-year rainfall in Copenhagen in July 2011 is estimated to have cost around 8.7 billion SEK(Beredskabsstyrelsen 2012). In August 2014, the 100-year rain in Malmö caused flooding at a cost of 0.6 billion SEK(Malmö Stad and VA SYD 2016). Protection against pluvial flooding should therefore be a high priority. Especially as the risk will most likely increase in the future.

To reduce the risk of flooding, technical solutions such as stormwater drainage systems are often used. Stormwater systems in Sweden can be open or closed and are designed to cope with a 10-year rain event (a rain event with an intensity that is estimated to occur only once a decade). If the rainfall intensity exceeds the capacity of the stormwater system, flooding can occur (Hernebring and Mårtensson 2013). In this study, a water depth of 10 centimetres is used as the definition of flooding. If the water depth is more than 10 centimetres, there is a risk of flooding and damage or disruption to society may occur (Lunds Kommun and VA SYD 2018).

1.4 Blue-green infrastructures BGI

The factors associated with reducing impervious surfaces are often highly controllable, meaning that municipalities or urban planners can easily reduce flood risk by altering the physical environment. One way to achieve this would be, for example, to retrofit the area with blue-green infrastructure (BGI) (Berndtsson et al. 2019).

Since the stormwater system is not able to process a rain event with a higher intensity than a 10-year rain, it is important to implement measurements to delay the water or create areas that can be flooded in the case of an extreme rain. One way to do this is to use BGI or so-called multipurpose solutions (Malmö Stad and VA SYD 2016).

Different types of BGI solutions can be used to prevent the risk of flooding. The city of Copenhagen, for example, uses green roofs, infiltration trenches and green infrastructure in urban squares to delay rainwater runoff. The city of Copenhagen also uses parks as detention basins where water can aggregate after a heavy precipitation event (COWI et al. 2012). BGI has also been successfully implemented in several Swedish municipalities such as Augustenborg, Malmö, which has led to a decrease in flood damage (Sörensen and Emilsson 2019).

The use of green infrastructure is also a step towards Goal 11 of the United Nations 2030 Agenda for Sustainable Development, sustainable Cities and Communities. The criteria for sustainable cities include access to green and public spaces, mitigating and adapting to climate change and increasing resilience to disasters (United Nations 2019).

The use of distributed hydrological models is an important aspect of adapting urban areas to climate change. To adapt to or mitigate flood risk, it is necessary to know where it can occur and the depth of flood that needs to be prevented. Hydrological modelling shows which areas will be flooded and how high the flood will be. There are many different aspects that can be incorporated into a hydrological model and there are a variety of different models (MSB 2017).

Flood simulation using the distributed hydrological models allows the user to try out retrofitting different types of BGI for different locations and different amounts of rainfall. It is also easy to run the model several times until the result of implementing the BGI turns out as desired. Then you can build the BGI in the city based on the desired results of the model.

1.5 Objective

The main objective of this study is to adapt a hydrological modelling method to test BGIs as nature-based solutions. This includes the development of the hydrological modelling tool and its evaluation.

2. Methods

For this study, a hydrological model called Triangular Form-based Multiple flow algorithm (TFM-DYN) (Pilesjö and Hasan 2014) was used to simulate and map the inundation depth. It was also used to determine where new BGI areas could be established and to simulate the effects of BGI on flood depth.

2.1 TFM-DYN model

TFM-DYN is a dynamic runoff simulation model (Nilsson et al. (2021), which uses the TFM Flow Distribution Algorithm (Pilesjö & Hasan 2014) for runoff distribution. It is generally used to simulate rainfall events and the subsequent overland runoff. As input data for the model simulation, a DEM and various other data layers must be entered, e.g. infiltration capacity, surface friction and precipitation in each cell. In addition, the inflows and outflows to the subsurface system are used to simulate the exchange of runoff with the subsurface stormwater network. Figure 1 shows a conceptual diagram to explain the model flow and input data of TFM-DYN.

Once the simulation begins, the runoff for each time step is calculated using the eight facets in each cell (Nilsson et al. 2021). The output includes the water velocity and water depth for each cell and time step. In the model, the water depth in each cell is dynamic in the sense that the cumulative water depth on each cell of the DEM changes dynamically. For example, runoff into a depression in the ground can cause it to fill, while the DEM is updated by the water depth in the depression at each time step. Once the depression is filled, further runoff can be directed to other cells.

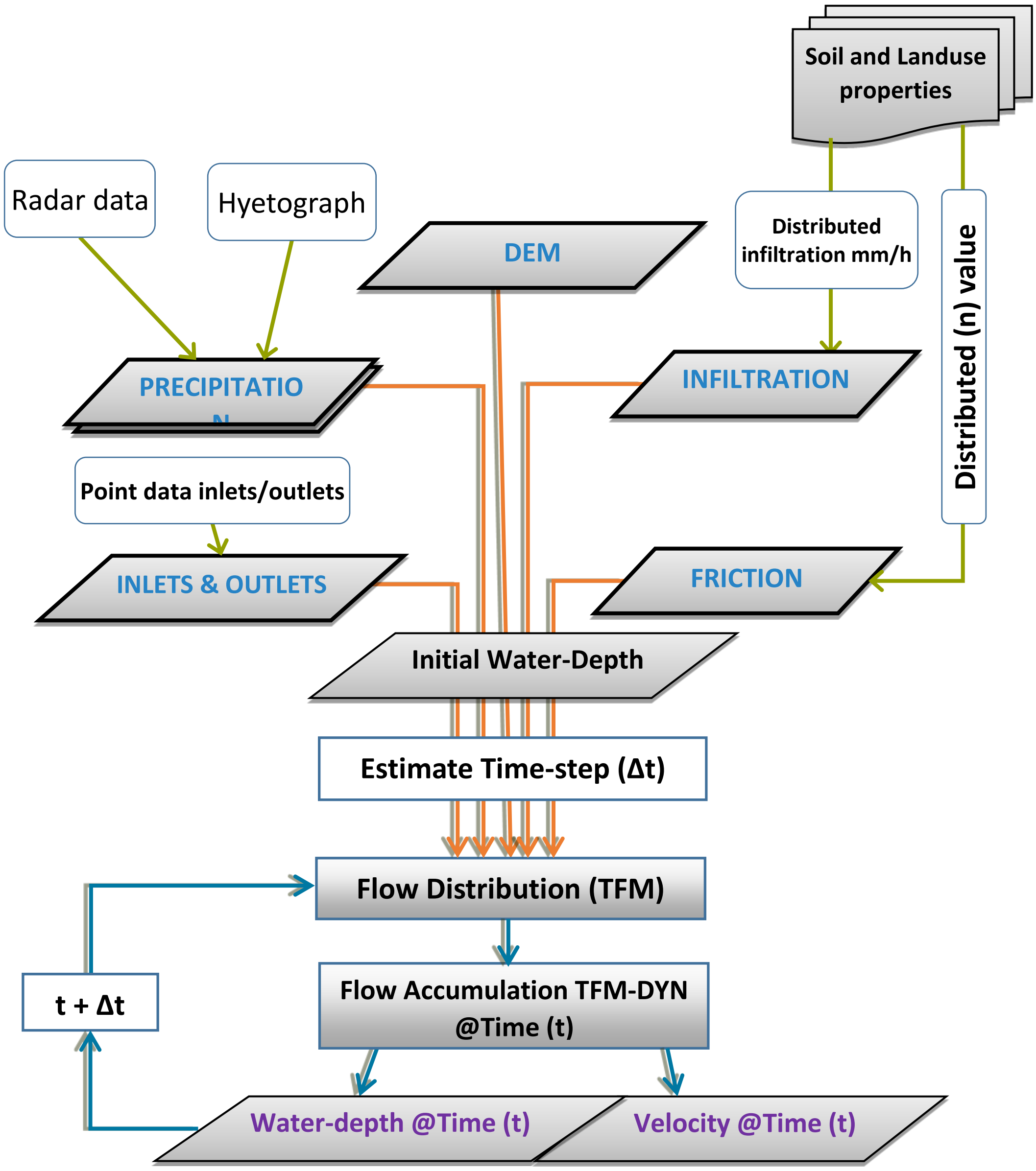

Figure 1. A conceptual diagram to explain the model sequence and input data of TFM-DYN (Nilsson et al. 2021)

2.2 HYPE model

The HYdrologic Prediction for the Environment (HYPE) model is a semi-distributed rainfall-runoff simulation model developed to support the implementation of the EU Water Framework Directive in Sweden (Arheimer and Lindström, 2013). It was originally developed to estimate water quality status, but is now also used by the Swedish hydrological warning service SMHI for flood and drought forecasting (e.g. Pechlivanidis et al., 2014). The water and nutrient model is used on a national scale for Sweden (Strömqvist et al., 2012). It also provides operational hydrological forecasts for Europe on a short-term and seasonal scale and has been used in several large-scale applications worldwide. One of the main reasons for the application of HYPE is climate change impact assessments, for which the results of the model have been compared with other models in selected catchments around the world (Crochemore et al. 2019).

The HYPE model code (Lindström et al., 2010) is a rather traditional integrated catchment model that describes the main water pathways and fluxes in a catchment. It is driven by precipitation and temperature in daily or hourly time steps and starts with the calculation of the water balance of Hydrological Response Units, the finest calculation unit in each catchment.

2.3 Coupled model simulation

The HYPE model and its results can be used to initialise the input data required for the TFM-DYN model. In addition, the processes at the model boundary can interact with the processes in the rest of the river catchment through input/output data across the model boundary. A schematic representation of the coupled modelling to illustrate the workflow of the chain and the model coupling of the TFM-DYN model with the HYPE modelling is shown in Fig. 2. The manipulation and initialization of the input data are listed and explained below to enable a fully distributed and more realistic flood modelling.

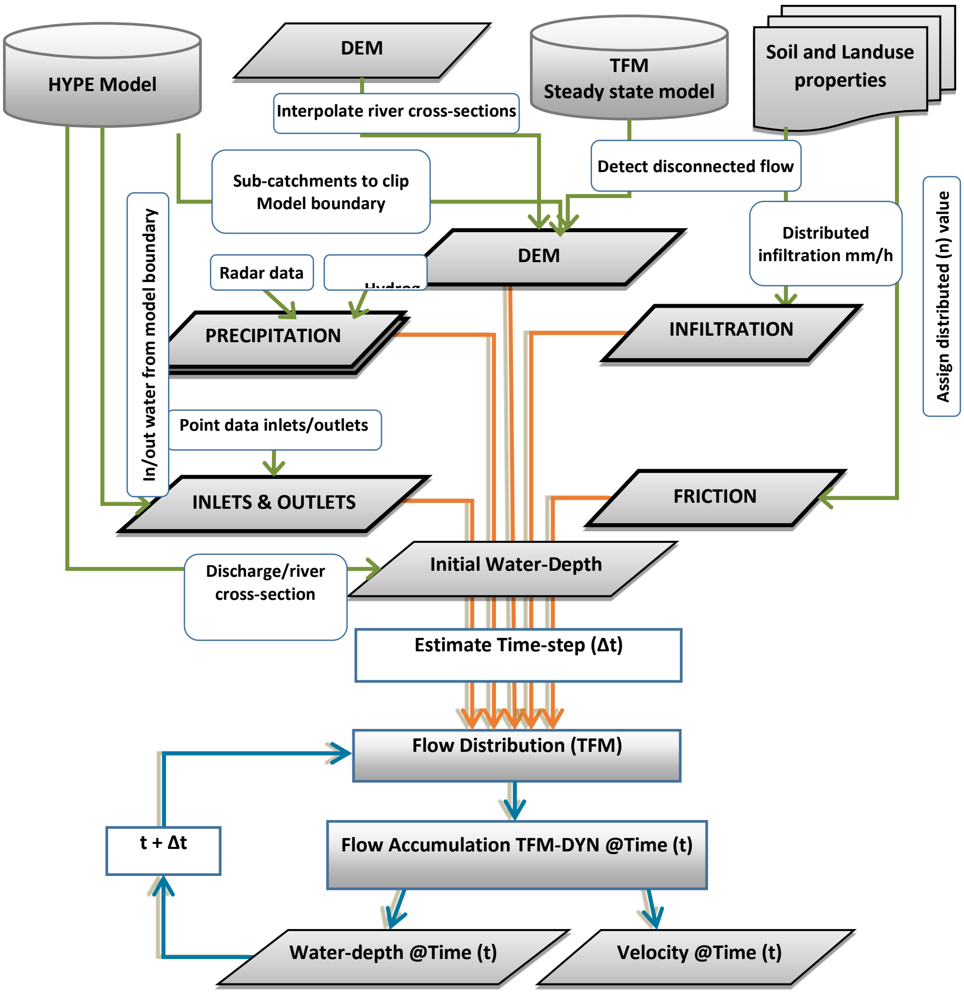

Figure 2. A schematic diagram to illustrate the TFM-DYN model with HYPE modelling chain and model coupling work flow. The manipulation and initialization of input data utilizing HYPE model is needed for a fully distributed flood modelling.

2.4 Input Data

To create and set up the coupled TFM-DYN & HYPE model, five different raster data are required. The required raster data are: DEM geometry data, precipitation, infiltration, inflows, outflows and Manning roughness coefficients (n). The following describes how these data are generated as vector or raster layers using the HYPE results, the TFM algorithm and data from the Swedish Land Survey authority (Lantmäteriet) (see Figure 2).

2.4.1 Digital elevation model (DEM)

One of the most important data needed to create a hydrological model is a digital elevation model (DEM) of the surface of the study area. However, the DEM data needs to be manipulated (hydrologically corrected) so that it can be used as input data for the proposed coupled model.

To define the model boundaries and clip the DEM data, the DEM data should have elevation values inside the boundary and NODATA outside the boundary. This affects the processing time of the model and concentrates the calculations on the areas of interest. The model boundary can be defined using the sub-catchment information from the HYPE model. The sub-catchments containing the urban areas we are interested in need to be selected and then an overlay function is applied to clip the DEM.

A DEM created from LiDAR data can produce artifacts that can lead to interruption of the flow (Hasan et al. 2012). The heights of the riverbed and more generally the heights of water bodies may not have been estimated correctly when creating the DEM data. For example, bridges crossing a river can block the water flow. In addition, LiDAR beams and other remote sensing methods may not correctly capture riverbed elevations of the riverbed. Before a hydrological model can be created, the DEM must be manipulated. To connect runoff in rivers and large streams and to simulate base flow in rivers, the DEM must be hydrologically corrected. In order to simulate the natural water flow, bridges must be breached and the heights of the riverbed surface corrected. The height of the riverbed can be altered so that it is lower. Based on the measured data of the river cross-sections, a linear interpolation of the heights is performed for all cells forming the river catchment. A semi-automatic method has been developed to detect possible points of disconnected river flow in each DEM. The proposed method consists of first calculating the runoff distribution and accumulation with the TFM model in steady-state mode, without filling the sinks that might be present in the DEM. Subsequently, a spatial analysis of the runoff accumulation results helps to identify runoff centerlines and interrupted runoff.

2.4.2 Infiltration grid

Land use and soil types maps can be used to prepare a gridded infiltration raster. A zonal overlay of the land use/soil type layer with the DEM can be applied to transfer the assigned values to the grid. The method for estimating infiltration values in mm/hour for a land use/soil type can be estimated based on infiltration tests for the study area or based on infiltration tests conducted for similar soil types in other areas. Table 1 shows different soil types and land use classes with the assigned infiltration rates based on field tests in the Swedish environment (Larsson, R., 2002).

2.4.3 Roughness grid

A Manning's roughness coefficient (n) is estimated for each cell from the surface roughness. The n values can be between 0 and 1 depending on the surface roughness. An estimated roughness/friction value (n) for different types of surfaces can be found in Table 1. A grid with spatially distributed n-values must be prepared from all cells of the model domain. A zonal overlay function can be used to overlay different land use zones over the DEM cells and assign n-values to each cell (similar to assigning infiltration values to the cells.

Table 1. estimated Friction and Infiltration values assigned for the standared soild types and landuse classes. The landuse classes are from the Swedish Land Survey authority (Lantmäteriet).

classID	name	Friction	Infiltration
1	Natural_Bare_land_1	0.30	10
2	Water_2	0.001	0
3	Artificial_Other_paved_3	0.10	2
4			
5			
6	Natural_Shallow_vegetation_6	0.60	5
7	Natural_Dense vegetation_7	0.70	8
8	Farmland_	0.75	15
9	Artificial_Paved_road_9	0.15	1
10	unpaved_road_10	0.25	6
11			
12			
13			
14			
15	bare_rock_15	0.50	3
16	Artificial_Building_16	0.10	1

Figure 3 shows a graphical model created using ArcGIS Pro Model Builder to create the attribute table for the land use layer and link the attribute table (value) to the above table (ClassID). Then the lookup tool is used to assign the value from the table (infiltration and friction). When you run the graphical model, you can easily determine the two grids (infiltration and friction).

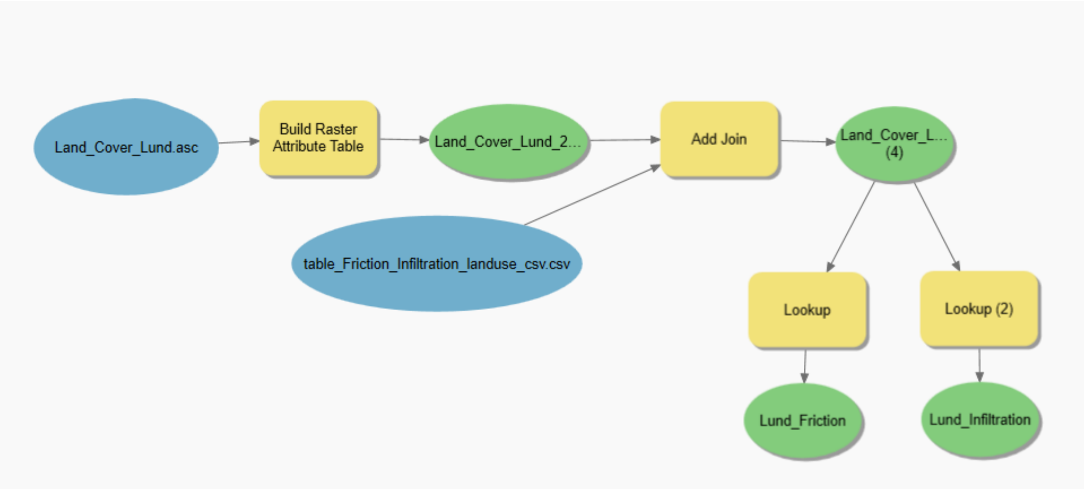

Figure 3. graphical model to help in processing the landuse data to generate the required infiltration and friction rasters

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The graphical model in Figure 3 is used to demonstrate the creation of infiltration and friction grids from the land use data in the study area in Lund. The grids are shown in Figure 4 for infiltration and in Figure 5 for friction.

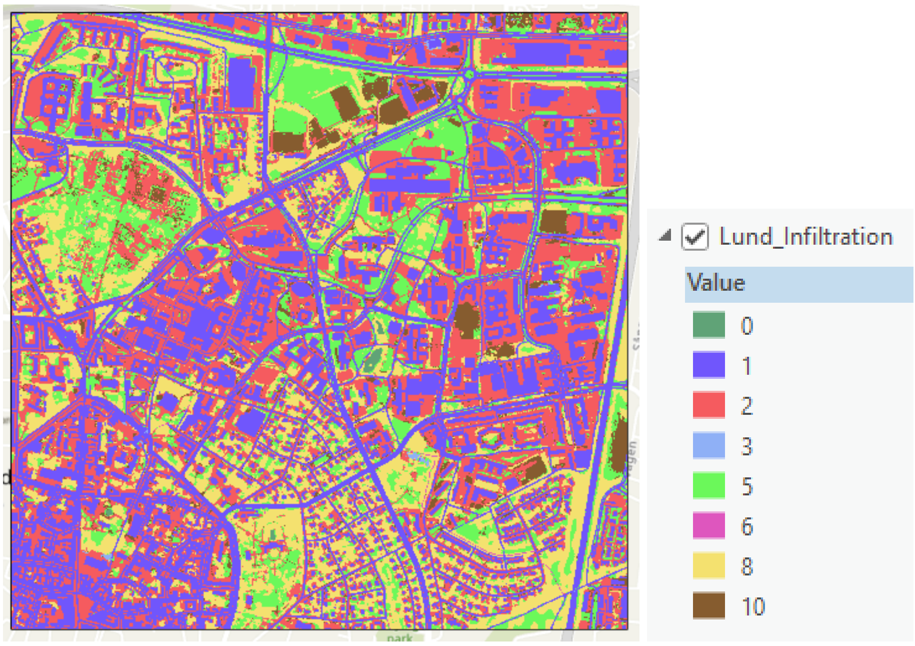

Figure 4. Infiltration values are distributed to all cells in the grid for the study area in Lund.

Figure 5. Friction values are distributed to all cells in the grid for the study area in Lund.

2.4.4 Inlets/outlets

Inflow and outflow points are the points at which water can be withdrawn from or added to the model (e.g. manholes, pumping stations, inflows and outflows from or to the model boundaries, etc.). The amount of water in L/sec must be assigned to the cells and has a negative sign if it is an outflow (the water flows out of the model area) and a positive sign (inflow) if the water is to be supplied to the model area. The water discharge values (L/sec) for manholes and pumping stations can be assigned to the corresponding cells, depending on the information from the city network and the manhole specification tables. The quantities of water entering or leaving the boundaries of the model area can be taken from the semi-distributed model (HYPE). The values assigned to these cells at the model boundary can be calculated from the runoff values simulated by the HYPE model at the discharges of the sub-catchment.

2.4.5 Precipitation (rain event)

The gridded precipitation data should be generated directly from the gridded RADAR precipitation data. In this way, spatially and temporally distributed precipitation data could be used as input for the coupled model. The gridded precipitation data, which have the same spatial resolution as the DEM, are generated by overlaying the two grids. For scenario-based modelling and if no gridded RADAR precipitation data is available, the hytographic data of the rainfall event (time series of precipitation depth) could also be used to generate temporally distributed precipitation data. In this case, a constant precipitation value is distributed, but can change over time according to the hytographic time series to produce gridded data.

2.4.6 Initial water depth

The discharges of the river sections within the model domain are simulated with the HYPE model and can be used to determine the initial water depth in these sections. The initial water depth (base flow) at the time immediately before the coupled model runs can be estimated by dividing the discharge simulated by the HYPE model by the river cross-section. The flow in the river (water depth) changes during the model simulation depending on how much runoff is exchanged from/to the model boundaries (inflows/outflows) and how much water has accumulated in the river due to precipitation within the model domain. In this way, the river can flow into or out of the river basin.

3. Results

To apply the new coupled modelling idea, two tests were conducted, one in the city of Lomma and another for a selected area in Lund. Both test areas are located in the same river catchment (HÖJE Å). The data for the Höje å catchment area is available from SMHI.

The sub-catchments of the Höje å HYPE model are shown in Fig. 6. The blue sub-catchments are the upper reaches of the station, the green sub-catchments are the lower reaches of the station and the yellow sub-catchments are the downstream area of the station.

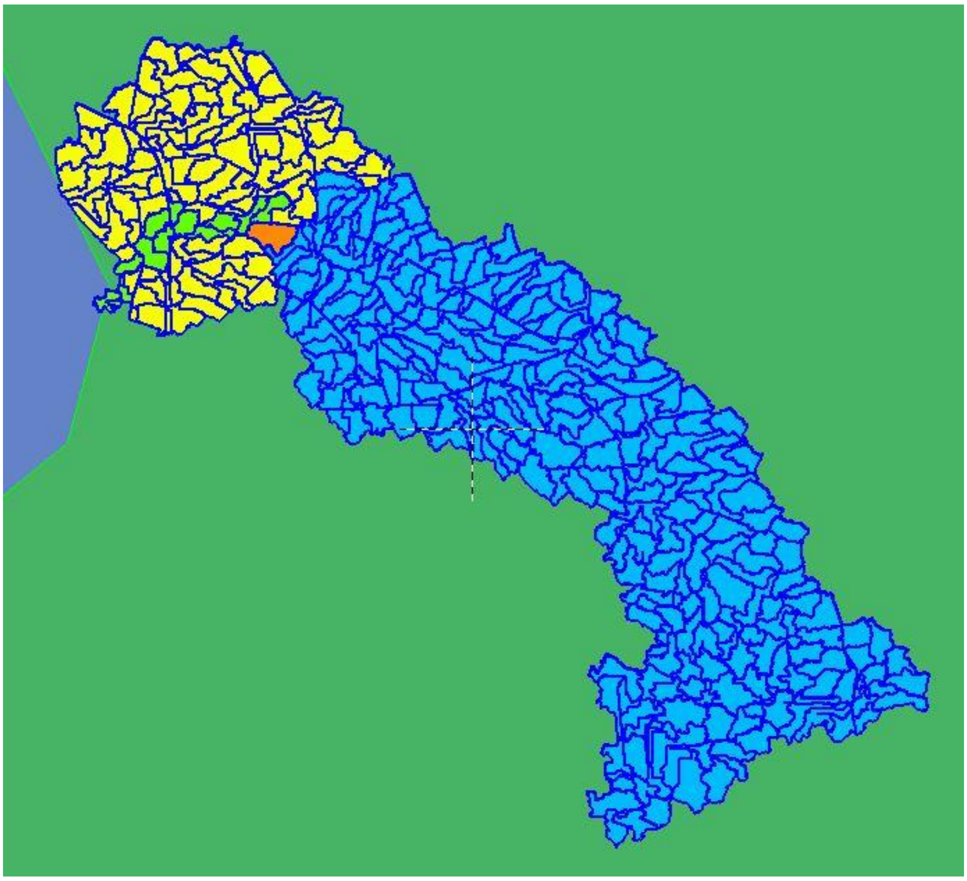

Figure 6. Sub-catchments of the Höje å HYPE model, modified and increased resolution from hypeweb data at SMHI.

Three different measures were necessary to prepare the data in the two test areas for the TFM-DYN simulations.

- The boundaries of the modelled areas in Lomma and in Lund were clipped according to the sub-catchments of the HYPE model for the river HÖJE Å.
- The initial base flow in the main river sections of the two studied areas was taken from the HYPE model.
- The runoff from contact points at the boundary of the clipped area is assigned as output points (water added to the model at the contact points).

All other input data (DEM, infiltration, friction and the underground stormwater network (inflows and outflows) were prepared according to the instructions in the methods. (see Input data in the methods). For the two model simulations, an extreme rainfall event (rainfall time series) with 89 mm/hour is used as a driver for the flood risk simulation.

3.1 Lomma flood simulation

The TFM-DYN model is run on the clipped model area, which includes the city of Lomma, while the boundaries of the sub-catchments from the Höje å HYPE model are retained. Figure 7 shows the clipped model domain of the Höje å HYPE model and the simulated distributed global maximum water depth in each cell of the study area. It should be noted that the time for the maximum water depth is different in each cell. These times are also recorded in a separate raster file.

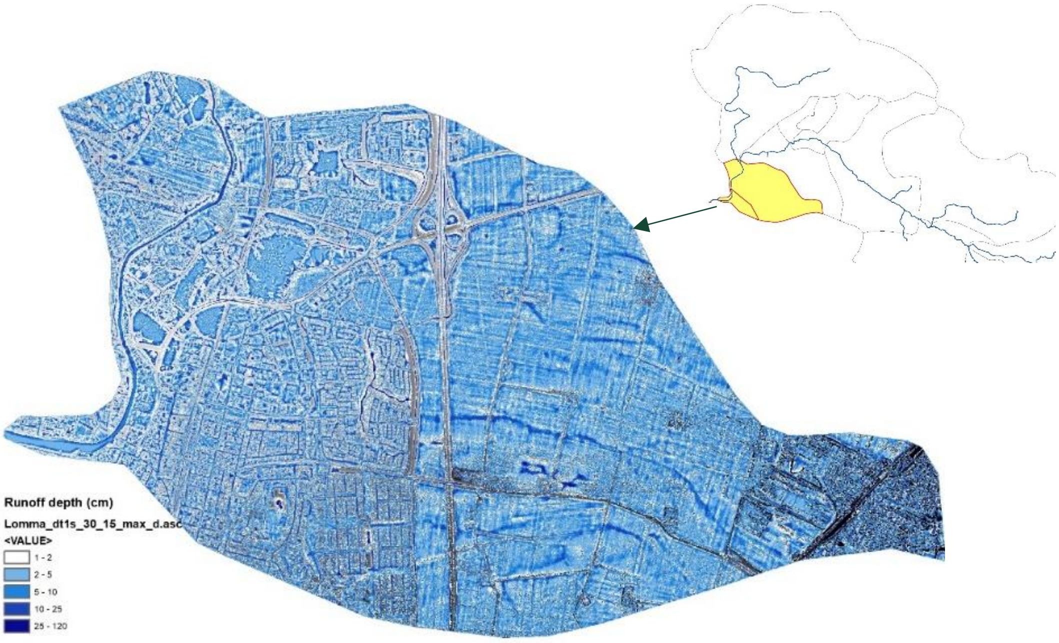

Figure 7. Model area and global maximum water depths after an extreme rainfall event.

The distributed water depth and velocity at each time step for all cells is recorded in addition to the global maximum velocity, but the results are not presented in this report.

3.2 Lund flood simulation

The second test area in the city of Lund. The area includes both permeable surfaces such as parks and green areas as well as a large number of built-up areas with predominantly impermeable hard surfaces. The simulated area is also cut out of the Höje å HYPE model, taking the boundaries into account. In addition, the topographical data is hydrologically corrected, which corrects the artifacts of the interrupted runoff. An area of 2 x 2 km is selected for the visualization of the results. There is a slight topographic gradient to the south, which is between 81 and 44 meters above the local vertical reference point.

From this simulation, a series of water depth and velocity maps are produced over time. It is decided to save the results every 5 minutes during the simulation. A very realistic simulation of water depth, where after 20 minutes the water depths have accumulated at low lying points and where the flow paths converge (Figure 8).

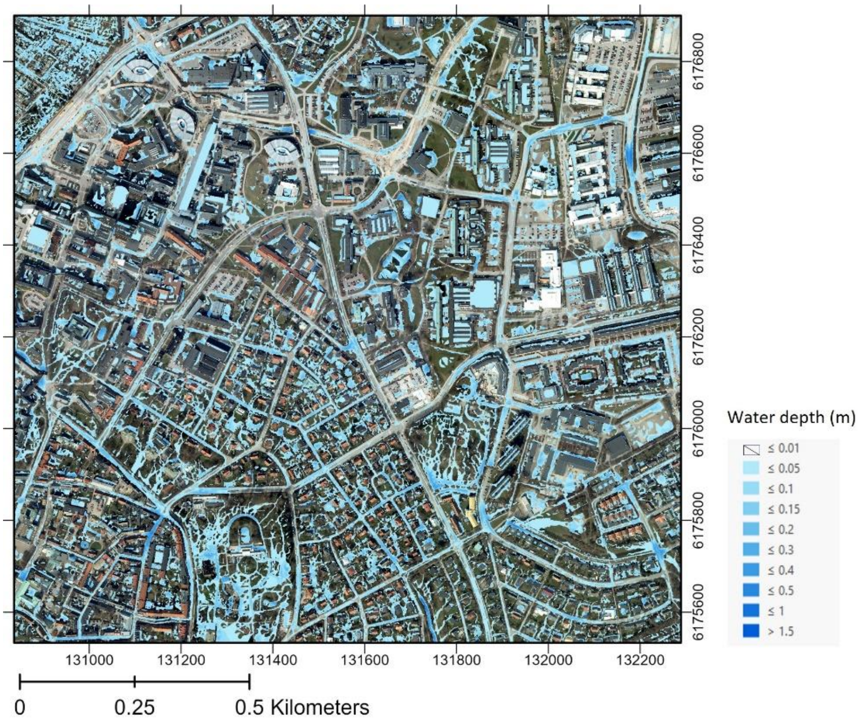

Figure 8. Water depths after 20 minutes of simulated rain. Background aerial image: © Lantmäteriet.

Towards the end of the rain event after 2 hours, the water depths in the landscape have increased at low points and along buildings where the water accumulates.

At the end of the simulation, a period without precipitation was included and the simulated water depths have decreased due to the lower amount of precipitation and the continuous infiltration and inflow into the stormwater drainage system.

The map with the global maximum water depths is shown in Figure 9. It should be noted that the time of maximum water depth is different for each cell.

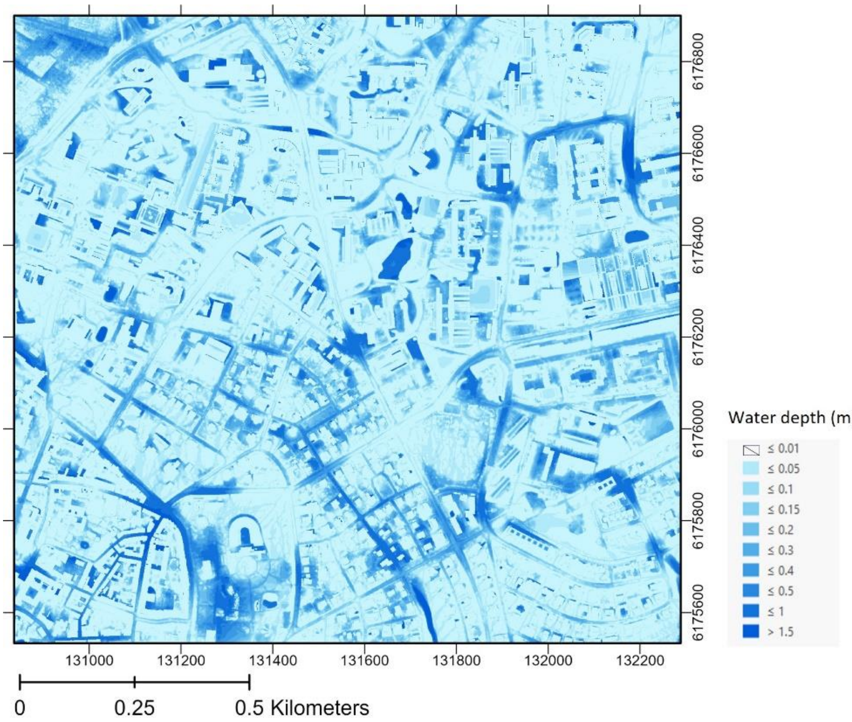

Figure 9. Global maximum water depths, Lund simulation.

Today, data and results are often presented in 3D. They improve spatial understanding through additional depth and perspective and enable more precise analyses. 3D visualisations support better decision making in urban planning, e.g. in the planning of blue-green infrastructure (BGI) and other nature-based solutions. For such visualisations, the water depth data can be combined with 3D data in a GIS (Figure 10).

Figure 10. Water depth data overlaid with 3D buildings data. Background aerial image: © Lantmäteriet. 3D buildings data: ©Lund Kommune.

4. Discussion and conclusions

The enrichment and initialization of the input data for the TFM-DYN simulation with data from another semi-distributed model such as the HYPE model plays a crucial role and has a significant impact on the simulation accuracy. High-quality digital elevation models (DEMs), which are often derived from LiDAR data, need to be manupulated for hydrological correction. An accurate and high-resolution DEM is essential for the planning of blue-green infrastructure (BGI) and nature-based solutions (NBS), as it enables a detailed analysis of the influence of the terrain on water flow and accumulation.

When planning BGI and NBS, the distinction between permeable areas with high friction and impermeable surfaces with low friction helps in modeling the interaction of water with different urban landscapes and in planning measures that increase permeability and reduce runoff.

On the other hand, infiltration rates in urban areas are also complex, as permeability can vary widely. Understanding these variations is crucial for effective flood simulations and for the placement and type of BGI and NBS. By using baseline data and field measurements, models can better estimate infiltration in permeable and impermeable areas, supporting designs that maximize natural infiltration and mitigate urban flooding.

The use of real or projected rain patterns enables detailed simulations of storm events, which are also critical for evaluating the effectiveness of BGI and NBS.

The capacity of stormwater inlets plays a critical role in managing urban runoff. By incorporating data on the location and capacity of inlets, the models can simulate potential bottlenecks in stormwater systems. This information is important for BGI and NBS planning as it identifies areas where interventions can reduce pressure on existing infrastructure.

GIS tools improve the visualization of simulation results and allow stakeholders to explore dynamic processes through maps and animations. This capability supports informed decision making in the planning of BGI and NBS and ensures that interventions are effectively communicated and understood.

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