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# Dynamic CA-ffé in Austria: Fast flood modelling in alpine regions

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## Abstract

Heavy precipitation events frequently cause flooding, leading to significant damage in affected areas. Simulation models play a crucial role in improving heavy rain management, particularly as climate change is expected to increase the frequency of extreme precipitation events. However, conventional hydrodynamic models are computationally intensive and unsuitable for real-time applications. This study explores the use of the fast flood modelling approach "Dynamic CA-ffé" for pluvial flood management in Austria. Previously tested in two smaller case studies in Australia with promising results, this model is now applied to four Austrian case studies, including larger (up to 50 km<sup>2</sup>) and partially alpine regions. The adaptation of the model to these new contexts highlights challenges such as increased inflow from alpine surrounding areas and the integration of multiple rain gauges. To address these challenges, a simplified runoff coefficient based on land use categories, adaptation of the digital terrain model using a buildings layer and the use of raster data for precipitation were introduced. The findings demonstrate the feasibility of Dynamic CA-ffé for larger-scale and alpine applications, offering a promising tool for efficient and fast flood simulation in pluvial flood management.

## Highlights

- Application of the Dynamic CA-ffé Model Approach to four Austrian case studies
- Challenges and adaptations for large-scale alpine citywide applications
- Results show fast and promising results on a citywide scale.

## Introduction

In recent years, the intensity of precipitation events has increased, leading to frequent pluvial flooding that causes significant damage, particularly in urban areas such as in Ahrtal in 2021 (Seidel, 2024) or Valencia in 2024 (Mukherjee and Darlington, 2024). Unlike river flooding, pluvial flooding is caused by heavy precipitation events that frequently exceed the capacity of drainage systems. With the frequency of such events expected to rise due to climate change (Berndtsson et al., 2019; O'Donnell and Thorne, 2020), there is a pressing need for reliable models to predict pluvial floods and mitigate their impacts.

Hydrodynamic models are widely used for flood prediction and management, broadly categorised as 1D sewer network models, 1D surface models, 2D surface models, coupled sewer-surface models (1D-

1D or 1D-2D) and hybrid models (Bulti and Abebe, 2020). Coupled 1D-2D models provide detailed representations of flood events but are computationally intensive, making them unsuitable for real-time applications. Faster models, like those using cellular automata (CA) or simplified flood dynamics to enable rapid simulations while maintaining acceptable accuracy. However, these models often neglect sewer systems, which play a critical role in urban flood dynamics (Leitão et al., 2009).

The Dynamic CA-ffé model (Maziar Gholami Korzani et al., UNDER REVIEW) based on Jamali et al. (2019) integrates a CA-based surface model with a 1D sewer network using the Storm Water Management Model (SWMM) (Gironás et al., 2010; Rossman, 2015). This approach synchronizes surface runoff and sewer flows, providing accurate, rapid flood simulations suitable for real-time applications and scenario testing.

Motivated by its fast computation time, we adopted the model to improve the resilience to floods and to strengthen the flood management in Austria in the face of growing climatic challenges. This study presents for the first time the advanced modelling approach of Dynamic CA-ffé for several case studies in Austria. The study shows the challenges of applying this modelling approach to larger catchments in partly alpine locations.

## Methodology

The Dynamic Cellular Automata Fast Flood Evaluation (Dynamic CA-ffé) modelling approach, invented by Jamali et al. (2019) and further developed by Gholami Korzani et al. (UNDER REVIEW), was employed as the computational model for the four cases studies in Austria. The results of the preliminary study (Maziar Gholami Korzani et al., UNDER REVIEW) with two smaller case studies in Australia (300ha and 2.9km<sup>2</sup>) showed good results compared to a corresponding MikeFlood model (Löwe et al., 2017). The application of the model to larger areas with mountainous environment arose several issues due to the size and mountainous environment compared to the previous Australian case studies. This required some modifications and extensions to the original approach, i.e. the implementation of multiple rain gauges or runoff coefficients. The extended model was used to simulate all four case studies to proof the transferability on other case studies.

### Dynamic CA-ffé Model

Dynamic Ca-ffé (Maziar Gholami Korzani et al., UNDER REVIEW) is an extension of the original CA-ffé model developed by Jamali et al. (2019). It computes the final flood extent and depth by repeated application of cellular automata (CA) rules until convergence - only relying on topography and the continuity equation. Especially in urban areas, the sewer network plays an important role and needs to be considered (Leitão et al., 2009). Therefore, it is important to apply a 1D-2D coupled approach. Tavakolifar et al. (2021) have developed a model that considers this interaction between surface and subsurface networks, but requires long computation times. The novel approach of the Dynamic CA-ffé model fills this gap and provides a hybrid solution for the time-efficient computation of urban floods. The hybrid 1D/2D structure of the approach uses a Stormwater Management Model (SWMM) (Gironás et al., 2010; Rossman, 2015) to integrate the sewer network. To represent reality as closely as possible, a bi-directional approach allows water to escape from the sewer system, run off at the surface and also to re-enter through a manhole. The model therefore uses a CA-based 2D simulation for the stationary surface runoff and couples this with the dynamic discharge of the sewer system (Maziar Gholami Korzani et al., UNDER REVIEW). The dynamic CA-ffé thus allows a constant interaction between the surface and the sewer system, with data exchange between them at specified coupling intervals to ensure interaction between the two flows. The coupling interval affects the results and should therefore be chosen critically. In this study, the coupling interval is equal to the time steps in the precipitation data. The parameter  $h_f$ , representing the temporary water depth, was set to a value between 0.04 and 0.09. The increment constant, which increases the height of a central cell if it is equal to or less than the height of a neighbouring cell, was set to 0.001.

The innovative approach improves and accelerates flood forecasting, making it possible to quickly and easily assess flooding in urban areas.

### Investigations

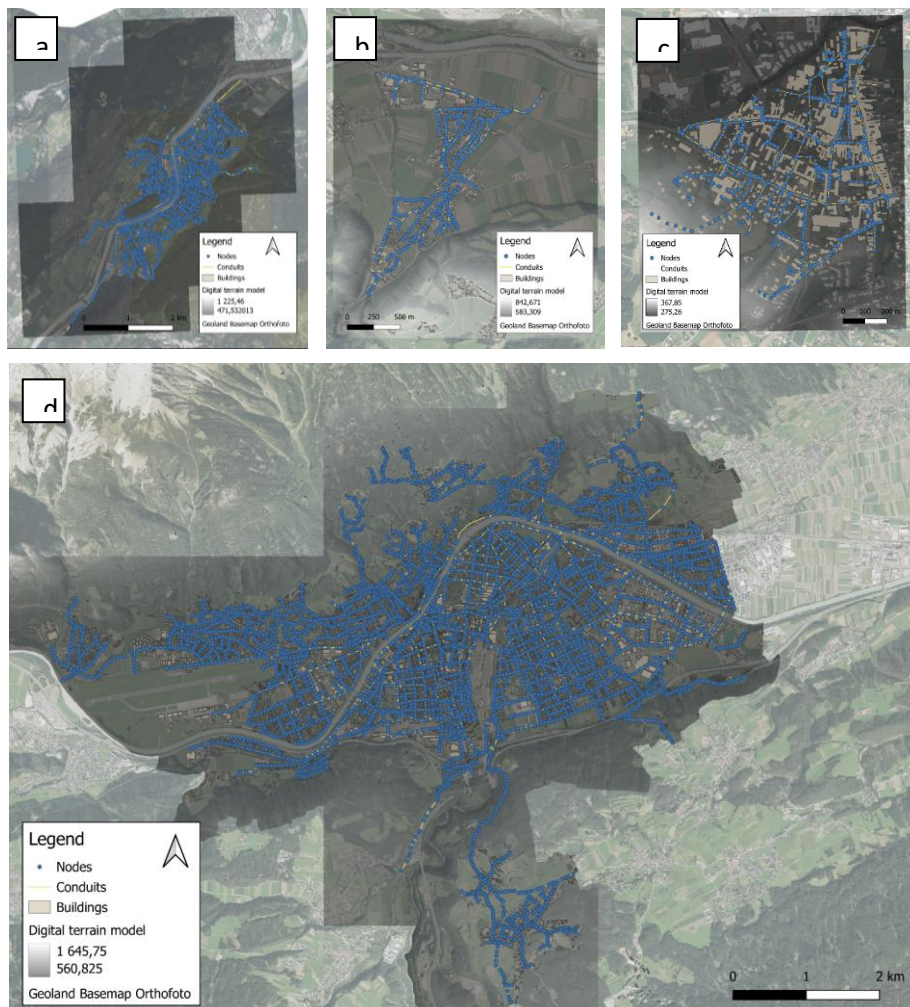
The aim of this study was to develop a fast flood model for four Austrian case studies. During the process of adapting the existing Dynamic CA-ffé to the Austrian case studies, several problems arose. In the following, we summarize the main challenges and the necessary modifications, as well as the simulation results with a focus on flood extent and simulation time.

### Case studies

The model has been adapted for four case studies in Austria: Innsbruck, Kematen, Feldbach and Kufstein. The case studies vary in size and topography which are summarized in Table 1. All case studies have densely populated parts including the drainage network in the flatter areas and hillside area in one or more parts of the case study (Figure 1). Depending on the size of the case study, there are one or more rain gauges distributed across the urban area.

**Table 1.** Austrian Case study areas including case study area and additional information.

	Case study area (km <sup>2</sup> )	Additional information
Innsbruck	~ 50	Mountains in north and south
Kufstein	~ 35	3 streams with large catchments outside
Kematen	~ 7	Small hills in the south
Feldbach	~ 2	3 streams with large catchments outside



**Figure 1:** The case studies (a- Kufstein, b-Kematen, c-Feldbach, d-Innsbruck), showing example results of the dynamic CA-ffé model for the city of Innsbruck, including the input data: Rain gauges, sewer network and digital terrain model.

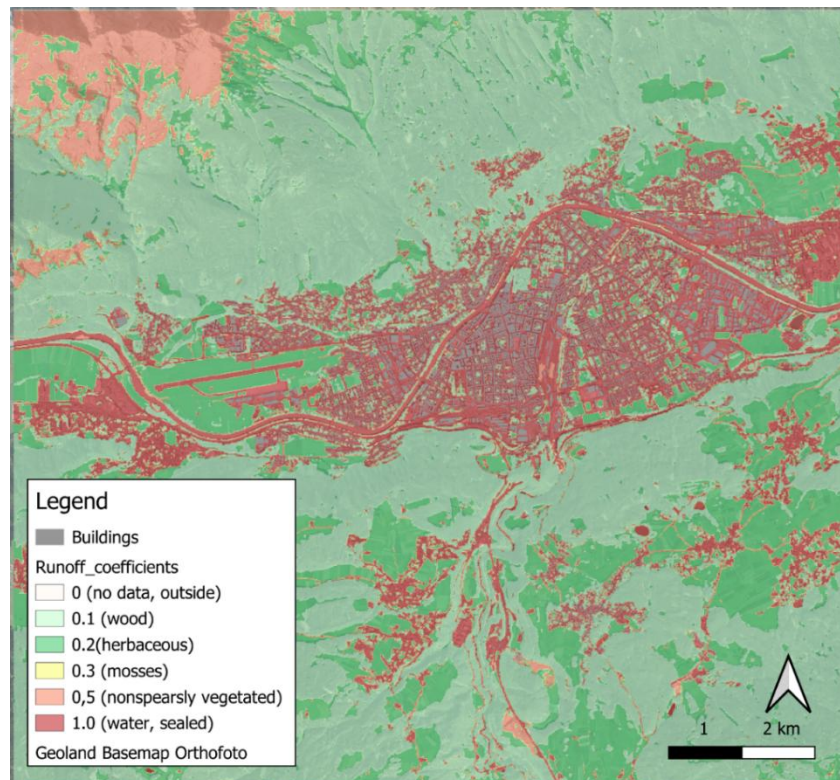
## Results and discussion

### Model adaptation

The application of the Dynamic CA-ffé approach to the Austrian case studies raised some issues and the code had to be adapted to the new circumstances which required the implementation of mainly two extensions, a) the introduction of a run-off coefficient, b) the spatially varying precipitation from multiple rain gauges and c) the integration of buildings in the DTM.

- Runoff coefficient

The mountainous environment of Alpine cities raises the question of how to deal with runoff from outside areas. Such considerations were not necessary in the initial approach due to the small and only urban case studies. Especially in the Innsbruck model, the model results overestimated the flood volume due to massive runoff from outside areas. To mitigate this effect we incorporate a runoff coefficient map, which is automatically extracted from the Corine Land Cover - CLC classification layer (Copernicus Land Monitoring Service, 2021) based on the extents of the DTM raster. The coefficients for each CLC class were chosen empirically (see Figure 2).



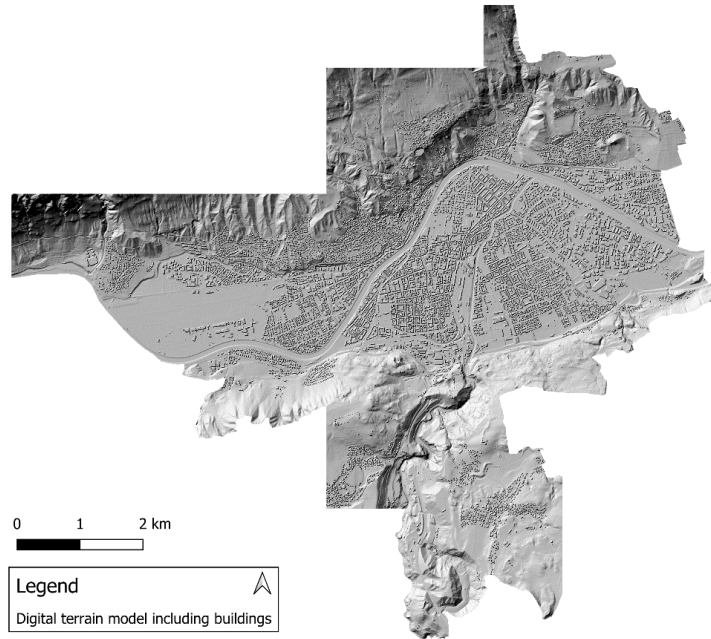
**Figure 2.** Runoff coefficients based on CLC-Cluster, example case study Innsbruck.

- Rain gauges

Given the comparatively large size of the catchments (especially in the Innsbruck model), it was necessary to implement several rain gauges to realistically represent the rainfall pattern. The original Dynamic CA-ffé had only one rain gauge, which was sufficient for small case studies. To represent spatially varying rainfall, a raster-based precipitation was introduced, as well as enabling the implementation of multiple rain gauges. For raster-based precipitation the INCA dataset was used. Former event data was provided by GeoSphere Austria with a spatial resolution of 1 km x 1 km and a temporal resolution of 15 minutes (only available internally). GeoSphere also provides open-source forecasting data with the same resolution and a time horizon of three hours. (GeoSphere Austria, 2023; Haiden et al., 2011).

○ Buildings

Buildings strongly influence flow paths and flooded areas. To account for this effect, buildings were incorporated into the urban model. A building layer was overlaid on the digital terrain model (DTM), with the elevation of all cells containing buildings increased by +15 m. This approach represents buildings as impermeable blocks that prevent water from entering and force it to flow around them. However, since the elevation adjustment is applied directly to the grid cells, the accuracy is highly dependent on the DTM resolution. In particular, the 5 × 5 m resolution introduces uncertainty in the representation of the building layer.



**Figure 3.** Digital terrain model with adapted cell elevations to account for buildings using a building layer.

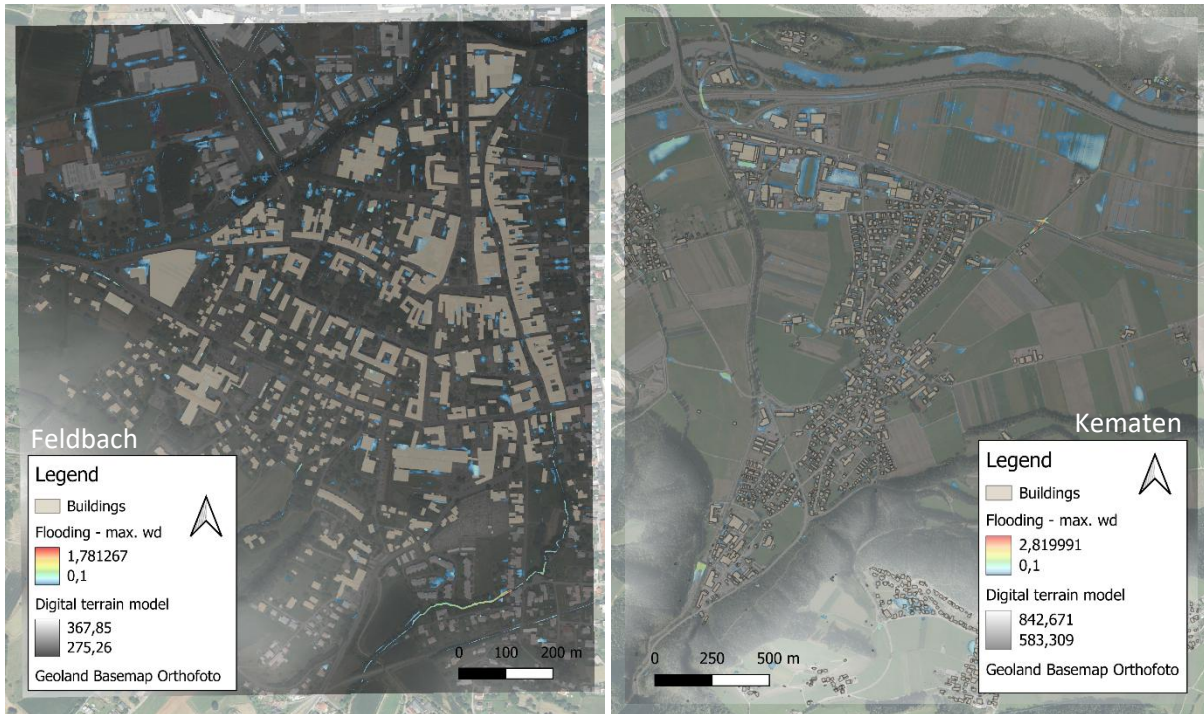
**Model results**

The models were simulated using different precipitation events. Table 2 shows the computation times for four real events using the four different case study areas (Innsbruck, Kufstein, Kematen, Feldbach), calculated using a 1x1m grid for the digital terrain model (DTM) and one or more time series for precipitation data (based on the availability of rain gauges and precipitation data) - executed with 24 threads to parallelize the CA-rules on the LEO5 HPC infrastructure at the University of Innsbruck. In addition to the resolution and size of the terrain model, the overall computation time depends heavily on the amount of precipitation and subsequently the amount of water to distribute on the surface.

**Table 2.** Simulation times for four real precipitation events for the different case study areas.

Event	Real event duration	(max) Precipitation sum	Simulation time
Innsbruck - 2016	24h (inca data)	50.7 mm	1h 39min
Kufstein - 2021	1d 18h	167.7 mm	11h 32min
Kematen - 2024	2h 20 min	57.9 mm	27 min
Feldbach - 2020	3h	78.7 mm	1h 36min

The results demonstrate that a city-wide simulation with reasonable computation time is feasible (see Figures 4a and 4b for example flood results in Feldbach and Kematen), showing the extent of flooding across the city. As the model is CA-based, the flood extent depends heavily on elevation, but also on surface characteristics and model parameters. This means that, in particular, areas of lower elevation tend to fill up, so careful interpretation or correction of the DTM is required to avoid misinterpreting hotspots. For example, there may be construction sites or retention ponds with outlets that are not shown on the DTM. Overall, however, the flood extent is realistic and allows hotspots to be identified on a city scale.



**Figure 4a.** Flooding results of Feldbach (Figure 4a) and Kematen (Figure 4b).

## Conclusions and future work

The study demonstrated how the 'Dynamic CA-ffé' fast flood model approach can be applied to different Austrian case studies. The main adaptations for applying the code to larger alpine case studies were:

- the need for a simplified, land-use-based runoff coefficient to reduce the inflow from the surrounding mountainous areas,
- the use of spatially distributed precipitation data,
- the implementation of buildings in the digital terrain model.

Following these adaptations, Dynamic CA-ffé was able to simulate floods on a city scale for the Austrian case studies within a reasonable computation time. Testing the model on four different case studies approved the high transferability and the usefulness of the model. Further work includes further adaptations and improvement of the model as well as the validation based on operational data of the fire stations and a 1D/2D SWMM model of the case study Feldbach. The ultimate goal is to use the validated model for real-time flood forecasting. Therefore, the GeoSphere forecasting data has already been implemented in the model adaptations, and simulating a three-hour forecast is possible. This application is essential for urban flood management, helping decision makers before and during the event. Another useful application of the model is simulating climate change scenarios to gain a deeper understanding of how future conditions will influence pluvial flood risk. An analysis of vulnerability and exposure could provide a deeper understanding of pluvial flood risk in the case studies and enable a combined approach with the modelling results of flood extent and water depth.

In conclusion, dynamic CA-ffé is able to simulate Austrian case studies at a city scale providing fast results, that lay the foundation for promising future work.

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