A methodical framework for analysing the cause of urban pluvial flooding in a hillside settlement

Lena Simperler, Florian Kretschmer and Thomas Ertl

ABSTRACT

Pluvial flood risk is increasing in urban and rural areas due to changes in precipitation patterns and urbanization. Pluvial flooding is often associated with insufficient capacities of the sewer system or low surface drainage efficiency of urban areas. In hilly areas, hillside runoff additionally affects the risk of pluvial flooding. This article introduces a methodical approach and related evaluation criteria for a systematic analysis of potential causes of urban pluvial flooding. In the presented case study, the cause of pluvial flooding at two selected sites in a hillside settlement is investigated based on a coupled 1D/2D model of the whole hydrological catchment. The results show that even though bottlenecks in the sewer system are important, the effect of low surface drainage efficiency and hillside runoff greatly influence pluvial flooding. The knowledge of different causes of flooding can be further used for selecting and positioning appropriate adaption measures. The presented approach proved its practicability and can thus serve as a guidance and template for other applications to gain better understanding and knowledge of local specific pluvial flooding events.

Key words | 1D/2D coupled modelling, catchment perspective, hillside runoff, settlement runoff, sewer runoff

INTRODUCTION

Pluvial flood risk is increasing in European cities due to changes in precipitation patterns and increased urbanization (Kovats et al. 2014; Skougaard Kaspersen et al. 2017). This creates the need for appropriate planning of adaptation measures for protecting urban settlements in the future (Löwe et al. 2017). Based on literature, three main causes of urban pluvial flooding can be distinguished (Sörensen & Mobini 2017; Palla et al. 2018): (1) bottlenecks in sewer systems, (2) low surface drainage efficiency of urban areas or (3) overland flow. In order to make an informed decision, a proper understanding of the processes behind pluvial flooding is of crucial importance (Sörensen & Mobini 2017).

According to ÖNORM EN 752 (2017), four aspects of investigating the performance of sewer systems can be distinguished: hydraulic, environmental, structural and operational. Hydrodynamic modelling is considered an appropriate tool for detecting sewer bottlenecks (Möderl et al. 2009), for identifying potential pluvial flooding (Henonin et al. 2015) as well as for evaluating the efficiency of sustainable urban drainage systems (SUDS) (Haghighatafshar et al. 2018). In Austria, hydrodynamic modelling is also state of the art in assessing the hydraulic condition of sewer systems (OEAW 2015). In hydrodynamic models, the runoff from the drainage areas can be connected to the sewer system through hydrographs or by a hydrodynamic 2D overland flow (Chang et al. 2015). With the first method, however, the effects of insufficient drainage efficiency of surface areas cannot be detected (Palla et al. 2018) and surface flow is not represented outside defined routes (Mark et al. 2004). With the second method, these problems usually can be avoided. However, related urban drainage modelling practice in many cases still has a rather strict focus on the settlement area (Chang et al. 2018; Jamali et al. 2018), not considering large undeveloped areas adjacent to settlements (OEAW 2008).

Although the importance of runoff from periurban areas is already recognised (DWA 2016) and an increase in damage by and number of pluvial flood events in alpine regions in Austria has been identified (Zahnt et al. 2018), methodical approaches to systematically analyse and
evaluate the potential contribution of the three sources of pluvial flooding (sewer bottlenecks, low surface drainage efficiency, overland flow) appear to still be missing in international literature. Consequently, the aim of this paper is to introduce a methodological framework for systematically analysing the cause of pluvial flooding in hilly settlements incorporating the application of different evaluation criteria. Both the approach and the evaluation criteria are tested on a case study. This work can support the development of a better understanding and knowledge on the potential causes of urban pluvial flooding from a catchment wide perspective. The results will foster sound decision making as they can be used to prioritise measures in a catchment as well as to identify appropriate locations for flood mitigation measures.

**MATERIALS AND METHODS**

**Framework of the sequential step analysis**

To determine the main cause of pluvial flooding in a settlement a stepwise process for analysing the 1D/2D simulation results was developed. The process consists of successive steps used to evaluate the contribution of the three main causes of pluvial flooding, which were characterized as follows:

- Sewer borne
- Settlement borne
- Hillside borne

For determining the contribution of the different causes, characteristic indicator parameters were selected. The chosen indicator parameters represent simple criteria, providing a guideline. The analysis of the different steps is built on a coupled 1D/2D model covering the whole hydrological catchment of the settlement area. In Figure 1 the individual steps of the approach are illustrated.

At the beginning, the catchment flooding is analysed and priority areas, where pluvial flooding has occurred within the settlement, are identified. The identification from the model results is based on the evaluation criteria ‘minimum water depth’ and ‘minimum surface covered’. For surface flooding, a minimum water depth of 5 cm was used as the lower limit to be considered flooding and a minimum of 5 m² needed to be covered. Priority areas are chosen depending on the extent of flooding and their location within the settlement. In this step, a simple validation of the model is performed by comparing the location of flooded areas in the model with observed flood areas.

**Figure 1** | Schematic representation of the sequential step analysis.
In the priority areas, first the contribution of the sewer system is defined, by determining if sewer borne flooding is occurring. For this manhole, surcharge is analysed by retrieving the location of manholes with discharge to the 2D model from the software. If there is discharge from the sewer system to the surface, a sewer bottleneck is contributing to pluvial flooding. A minimum of 50 m$^3$ of surcharge was chosen as the limit for the evaluation criterion ‘significant discharge’. To determine the contribution to the selected area, the evaluation criterion ‘location’ is analysed. For this, the location of the flooded manholes is visually compared to the location of the flooded area. Furthermore, the analysis of discharge patterns at single manholes (surcharge, inflow) can be used to support the pre-evaluation of potential restrictions considering surface runoff.

To confirm the pre-evaluation in regard to potential limitations in surface runoff, the contribution of surface runoff to pluvial flooding is determined in detail. For this purpose, a preliminary investigation evaluates the extent of contribution from sewer surcharge to surface flooding by comparing the surcharge volume to the total flood volume on the surface. The total flood volume in the priority areas is estimated using the water depth at the end of the simulation.

In the following, surface borne flooding is further divided into two categories. One is settlement borne flooding, which is associated with a low surface drainage efficiency, where runoff from the settlement does not reach the sewer system. The other is hillside borne flooding, where surface runoff from periurban areas causes flooding inside the urban catchment. To distinguish between settlement borne flooding and hillside borne flooding, the temporal flood volume development is evaluated. This underlies the assumption that surface ponding caused by low surface drainage efficiency reaches its maximum extent within the time of concentration. The time of concentration depends on the topography, the flow path and other characteristics of the catchment (NRCS 2010). The time of concentration for runoff from the settlement is shorter than the rainfall event. The ‘time at the maximum water depth’ was chosen as a simple evaluation criterion for the temporal flood volume development. If the time at the maximum water depth occurs during the rain event, it is considered settlement borne flooding, otherwise hillside runoff from periurban areas has a significant contribution to the flooding.

The external inflow was further evaluated by analysing external settlement inflow (paths) of the hillside runoff to define the impact on the settlement. This was carried out by visually analysing the evaluation criterion ‘maximum flux’ derived from the simulation results. High fluxes were associated with preferential flow paths.

Table 1 summarizes the set values for the different evaluation criteria.

In addition, the influence of different rainfall intensities to the contribution of the three causes was analysed by modifying the model in terms of repeating the analysis with altering rain events. For this study, the analysis was carried out for two rain events with different intensities.

**Model concept**

The contribution of three sources to pluvial flooding is analysed using a coupled 1D/2D hydrodynamic model covering the whole catchment area. Different design storm events are used in the model.

The 1D hydrodynamic drainage model was set up in MIKE URBAN (DHI 2017). The pipe network was built according to existing data. Minor adjustments to the system were made where data were missing (diameters from five storm sewer pipes). The roof tops were connected directly to the drainage systems whereas all other areas drain into the sewer system through the 2D overland flow model.

The 2D overland flow simulation was carried out in the MIKE URBAN environment using a MIKE21 model (DHI 2017). The model has a resolution of 1 x 1 m cells derived from a digital elevation model (DEM) with the same resolution. The DEM represents the terrain elevation including roads. The elevation of raster cells representing buildings was raised by 5 m to create a barrier. Small structures like curbs and fences are not considered in the model. The friction value of the surface was determined according to land use information from the provincial government of Lower Austria distinguishing between buildings, roads, commercial

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**Table 1** Evaluation criteria and set values for limits

<table>
<thead>
<tr>
<th>Focus of analysis</th>
<th>Evaluation criterion</th>
<th>Set limits</th>
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</thead>
<tbody>
<tr>
<td>Priority areas</td>
<td>Minimum water depth</td>
<td>0.5 m</td>
</tr>
<tr>
<td></td>
<td>Minimum surface covered</td>
<td>5 m$^2$</td>
</tr>
<tr>
<td>Manhole surcharge</td>
<td>Significant discharge</td>
<td>50 m$^3$</td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>no limit applied</td>
</tr>
<tr>
<td>Temporal flood volume development</td>
<td>Time at maximum water depth</td>
<td>30 min</td>
</tr>
<tr>
<td>External settlement inflow</td>
<td>Maximum flux</td>
<td>0.03 m$^3$s$^{-1}$m$^{-1}$</td>
</tr>
</tbody>
</table>
areas, gardens, agriculture and pasture, forest and water bodies, and the Manning’s roughness coefficient n value for the different surfaces (Chow 1988). Each manhole is connected to the closest cell of the DEM.

Both the sewer model and the 2D surface model were set up as relatively coarse models excluding detailed representation of the inlet structure at manholes and small structures on the surface. As the model was primarily used to test the applicability of the methodical approach and the related evaluation criteria it was not calibrated but validated with observed flooding events. In the authors’ opinion, even simplified models can already provide great yield in information by giving a general overview on sources and cause of pluvial flooding implying targeted solution approaches.

For precipitation, 30 min Euler type II design storms (OEWAV 2008) were calculated for different return periods (1 and 10 years) with design rainfall data (BMNT n.d.). The rainfall duration is based on the time of concentration of the analysed catchment. The design rainfall events are provided by the Austrian Federal Ministry for Sustainability and Tourism and interpolated between maximum modelled rainfall data and data from monitoring stations (BMNT 2018). In an Euler II design storm the rainfall intensity for each interval is calculated and the first third of the period is inverted so the maximum intensity is reached after one third of the design storm duration (DWA 2006). In this study the rainfall intensity is changing every 5 min and the peak value is reached after 10 min. The total simulation time was 1 h.

The total depth of rainfall was 13.4 mm for the 1 year return period (R01) and 34.7 mm for the 10 year return period (R10). The maximum rainfall intensity lasting for 5 min is 85 mm/h for the rain event R01 and 222 mm/h for the rain event R10. In this study, a saturated soil was taken as the baseline condition, as the consideration of infiltration capacities and preceding conditions increases the complexity. As the case study is primarily used to test the sequential step analysis, infiltration was not taken into account to simulate a scenario where soil is saturated, corresponding to a runoff coefficient of 1. Therefore, the runoff in the model is expected to be higher (Huza et al. 2014) and more rapid, than it would be if infiltration or only the impervious area was considered. Furthermore, the runoff response is also considered more rapid. In addition, Tuyls et al. (2018) have shown that the return periods of water levels from flooding do not necessarily correlate with the return periods of rainfall intensities as it depends on the complexity of the urban drainage system. Consequently, even though the return period is short the analysed scenarios are extreme.

Study area

The study area is located in a valley in Lower Austria, where pluvial flooding is a known problem. The catchment has an area of around 120 ha. About half of the area is covered in pasture and forest, the other half is covered by a settlement. The elevation of the modelled area ranges between 330 m and 630 m with a slope ranging between 10 and 90% uphill of the settlement. The time of concentration in the catchment is approximately 30 min. The land use of the area as well as the elevation above sea level are presented in Figure 2. The northern boundary of the study area is a river, so only the settlement area south of the river was considered in the analysis and the southern boundary is the highest elevation of the hill. The hydrological catchment determines the extent of the study area. For the analysis of the result, only the settlement area was used. The model extent is exceeding the extent of the hydrological catchment in most areas.

RESULTS AND DISCUSSION

Catchment flooding

In Figure 3, the maximum inundation within the settlement is displayed. The two priority areas (A and B) analysed in detail in the following chapters are indicated in the figures. The areas were chosen due to the extent of flooding occurring and its location in the settlement. Area A covers approximately 17,000 m² and area B has a size of slightly more than 43,000 m². For both areas, the sequential step analysis was carried out and the results of the individual steps are presented in the following sections.

As the model used for the analysis is built on a DEM with a 1 × 1 m cell resolution, underrepresentation of small surface features such as kerbstones, fences or driveways might influence surface drainage efficiency. Furthermore, drainage systems on private property are not included. Therefore the model results can only be used as a rough estimation on which areas are prone to flooding. A more detailed model containing more details needs to be built for a more accurate representation.

Sewer runoff

In order to analyse the contribution of sewer borne flooding to the pluvial flooding shown in Figure 3, the discharge from the sewer system to the settlement was analysed. Figure 4 displays the maximum discharge from each manhole for...
the rain events R01 and R10. It shows that sewer bottlenecks are present already at the rain event R01 as a total of six manholes have a discharge to the surface of more than 50 m$^3$. Three manholes are located in area A with a total surcharge of around 430 m$^3$. In area B, two manholes have a surcharge with a total sum of around 180 m$^3$. It may surprise the reader that there is sewer surcharge at a rainfall return period of one year (Austrian national standards demand no surcharge for a return period of two years (OEWAV 2008)), but this is caused by the saturated soil conditions and the resulting high runoff deliberately defined to investigate the worst case scenario. Consequently, the surcharge from the sewer does not indicate a general system failure but potential sewer bottlenecks.

As in the current case, the sewer system is already overloaded with the rain event R01, pluvial flooding from the sewer system is consequently increasing with higher rainfall intensities. Simulating the rain event R10 increases the total...
number of manholes with surcharge to 20. Five of these manholes are located in area A and three in area B, resulting in a total flood volume from the sewer of about 730 m$^3$ and 450 m$^3$, respectively. Sewer borne flooding is therefore contributing to pluvial flooding in the urban catchment.

In order to further evaluate the contribution to pluvial flooding coming from the sewer system, the discharge of manholes close to the selected areas were analysed in more detail for the one year return period. The hydrographs of the five individual manholes from areas A and B labelled in Figure 4 are shown in Figure 5. Positive values express a surcharge from the sewer, while negative values show discharge (inflow) from the surface into the sewer network. Null values represent no flow between manhole and surface.

Figure 5 shows that the surcharge from the sewer exceeds by far the volume entering the sewer from the surface. Furthermore, in the last 15 min of the simulation no discharge (inflow) into the sewer is happening at all, even though the simulation shows free runoff capacity in the sewer at the same time. Sewer borne flooding is therefore not considered the only problem in the urban catchment. As a result, the surface perspective needs to be analysed to better understand the cause for pluvial flooding in both areas.

**Surface runoff**

When comparing the amount of discharge from the sewer manholes to the total flood volume in the two areas, it becomes evident that the contribution of sewer borne flooding differs between the two priority areas. An estimation of the sewer surcharge and surface flood volume of the two areas and return periods is given in Table 2.

As the model used in this case study is not calibrated, the volumes are only used to analyse the proportion between volume discharged and flood volume in the priority areas. While in area B, sewer surcharge from the sewer contributes roughly 10% to pluvial flooding, in area A, four times more water is discharged from the sewer than prevailing on the surface.

In area A, the surcharge from the sewer is most likely flowing out of the boundary of the priority area either through the sewer system by discharging into non-flooded manholes.
or on the surface to the adjacent river. Even though sewer surcharge has significant contribution to pluvial flooding in area A, other causes might have an impact on the extent of flooding in the area. In area B, on the other hand, additional sources to sewer surcharge must contribute to pluvial flooding as the flood volumes differ substantially. Also, here the origin of pluvial flooding needs to be evaluated in more detail.

Settlement surface runoff

In order to determine the effects of settlement borne flooding and hillside borne flooding the criterion of temporal flood volume development was analysed. Figure 6 shows that in area A for rain event R01, the maximum water depth is mainly reached during the duration of the rain event and latest within 15 min after the end of the rain event. In area B, on the other hand, in about half of the inundation area the maximum water depth is reached at the end of the simulation period.

For rain event R10, the same trend for the two areas is visible with a peak in inundation depth in area A during the rain event and a later peak in a major part of area B. The time of maximum inundation, however is, shifted towards earlier time steps for the rain event R10. In general, the results indicate that pluvial flooding in area B is influenced by water flow with a longer concentration time.

The evaluation criterion ‘time at maximum water depth’ is highly dependent on the time of concentration of runoff from the urban and the periurban catchment. Therefore, the relevant time period to distinguish between urban and periurban runoff needs to be adjusted for other studies depending on the characteristics of the catchment. Furthermore, the proportion of flood volume resulting from settlement borne flooding and hillside borne flooding cannot be differentiated with the chosen evaluation criterion. Extending the analysis with additional criteria might therefore be beneficial to achieve an improved understanding of the contribution of different causes with the analysis process. These could include the temporal development of flood volume at selected points in the area to distinguish between the flood volume accumulating during the rain event and after the rain event. For this case study, the evaluation criterion, however, is considered sufficient for a first analysis.

Concluding, pluvial flooding in area B can be considered hillside borne while pluvial flooding in area A is mainly settlement borne. Including the entire hydrological catchment into the model is therefore of significant importance in order to evaluate pluvial flood risk. An analysis of the criterion ‘external settlement inflow’ (hillside borne flooding) into area B is performed in the next step.

### Table 2 | Estimated flood volume after 1 hour of simulation in the analysed areas

<table>
<thead>
<tr>
<th></th>
<th>R01</th>
<th>R10</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Sewer surcharge [m³]</td>
<td>Surface flood [m³]</td>
</tr>
<tr>
<td>Area A</td>
<td>430</td>
<td>100</td>
</tr>
<tr>
<td>Area B</td>
<td>180</td>
<td>2,000</td>
</tr>
</tbody>
</table>

Figure 5 | Discharge of selected manholes (MH) for the rain event R01.
Hillside surface runoff

The definition of the cause of pluvial flooding is completed at this point. In a last step, the flow paths of the hillside runoff are analysed to evaluate the impact of hillside borne flooding on the urban catchment. The analysis therefore focuses on area B, as there is influence of hillside runoff as shown before. The maximum water flux illustrated in Figure 7 shows that several preferential flow paths to area B are present. Especially the rain event with a 10 year return period leads to a high diversification of flow paths. The most pronounced paths towards area B are indicated with an arrow in Figure 7.

The flow paths show that the highest flux occurs at the border of the settlement (arrow 3) and is diverted to an adjacent area in the north of area B in the model for the rainfall return period of one year. A second preferential flow path (arrow 2) appears in the middle of the settlement. Its origin lies within the settlement for the rainfall return period of one year. When looking at the maximum flux of the rainfall return period of 10 years, it becomes evident that hillside runoff has a significant impact on the settlement. Arrow 1 shows a third flow path into area B, which is only associated with area B for the 10 year return period.

Several flow paths run directly through the settlement. Here, the resolution of the terrain model could be a restriction to showing the actual flow path as small structures, which potentially act as barriers, are not represented. Including the small structures might divert the flow path from some house, but as no general flood protection exists on the slope above the settlement a threat from hillside borne pluvial flooding can be derived from the simulation results.

Model modification

The stepwise process analysis is concluded at this point and can be rerun with different design storms or measured rain data. The knowledge gained about the causes of pluvial flooding can be further used to prioritize points of intervention and to determine appropriate locations for flood mitigation measures.

CONCLUSIONS AND OUTLOOK

In recent years, urban pluvial damage has been increasing in Austria (Zahnt et al. 2018). Due to the fact that flooding can have different causes (sewer bottlenecks, restrictions in surface drainage, hillside runoff) good knowledge and understanding of the underlying processes is imperative for a targeted solution approach. This article introduces a methodical framework, including different evaluation criteria for systematically analysing the causes of urban pluvial flooding in a settlement.

The practical application in a case study revealed all three causes contribute to pluvial flooding in the investigated hillside settlement under extreme rainfall scenarios. However, as shown before, the contribution differs between the areas. Even though, the 1D/2D hydrodynamic model used has a relatively coarse resolution and detailed structures are not represented, it provided valuable information as the clear identification of flooding causes can be further used to determine targeted solutions and appropriate locations for potential measures. In the case study, bottlenecks in the sewer are of significant importance during the rain event. In addition, low surface drainage efficiency of some areas contributes to flooding. The largest flooded area in the case study is, however,
significantly influenced by hillside runoff. This shows the importance of modelling not only urban areas, but the hydrological catchment including also periurban areas to properly assess causes for pluvial flooding in hilly areas. This information can be used in the future for a targeted solution approach in which the effect of the potential measures can be tested by incorporating these changes in the model (Löwe et al. 2017). Furthermore, looking into scenarios including infiltration or looking at the effect of variations in the rainfall duration will be valuable to gain a deeper understanding of pluvial flood causes.

The application in the case study has proven that the suggested sequential step analysis, as well as the related evaluation criteria, are suitable to evaluate pluvial flooding in a settlement. Although developed under local specific boundary conditions, the presented methodology and criteria can serve as a guidance and template for other locations and topographies to provide better understanding and basis for targeted mitigation planning for pluvial flood protection.

**ACKNOWLEDGEMENT**

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