Maps of pluvial floods and their consequences: a case study

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ABSTRACT

GIS based methods represent a helpful tool set for analyzing pluvial floods and their consequences. Focusing on the consequences for buildings, we use a two-step procedure to exemplify such an analysis with a well-documented event in the city of Graz (Austria) and to highlight possible methodological pitfalls and limitations. (i) We compute spatially distributed inundation depths using the software FloodArea. (ii) Based on inundation depths and a set of rules and functions, we derive the exposure, vulnerability and risk for each building. (iii) We scale the results to the level of postal code zones. The official cadastre is used as input in combination with the building register, a DEM and soil and land cover data. Verification is based on loss reports, photos and videos. We demonstrate a certain potential of the suggested procedure to reproduce the documented damages at the level of postal code zones. However, the results are highly sensitive to the model assumptions and parameter settings, and a satisfactory back-calculation of even well-documented events remains a major challenge.

KEYWORDS

pluvial floods; flood routing; risk analysis; scaling

INTRODUCTION

Short but intense rainfall events often trigger heavy short-time flooding causing severe damage to residential housing, roads, critical infrastructures, agricultural lands and other types of private and public assets. These damages are not only related to assets concentrated in flood plain areas, but also to those located in hilly terrain, thus where water is running along pathways such as slope cuts or through villages along roads. Therefore, besides the generally well established frameworks for fluvial floods, much more attention has to be paid to pluvial floods (Maksimović et al., 2009; Henonin et al., 2013), which should not be confused with flash floods.

Every year society suffers from financial losses according to such pluvial flooding (Zhou et al., 2012, Smith et al., 2001 and Richard, 1995). The choice of appropriate adaptation and mitigation strategies often relies of GIS-supported analyses of expected inundation depths and consequences thereof. Such models have been used increasingly in the previous years (Leandro et al., 2009; Henonin et al., 2013). The effects of various key parameters on the

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model results were explored. Examples of such parameters include infiltration and surface roughness (Aronica et al., 1998; Singh et al., 2002; Casa et al., 2006; Choromanski et al., 2008; Sangati et al., 2009), and the influence of sewer systems (Masimović et al., 2009; Saul et al., 2010; Sun, 2011).

The present paper focuses on the GIS based back-calculation of a well-documented pluvial flood event in the city of Graz (Austria). The aim is to:

– propose a consistent and flexible work flow to derive the inundation depth and its possible consequences for buildings at varying levels of spatial aggregation, to
– identify the possibilities, but also the challenges related to such an approach, and to
– highlight the sensitivity of the analysis to some key parameters.

STUDY AREA

Graz is the capital of the province of Styria. With a population of approx. 270,000 it represents the second largest metropolitan area in Austria. In the present study we consider the city of Graz (Austria) along with some neighbouring municipalities. The area surveyed covers 302 km², ranging between 321 m and 1339 m a.s.l. (Figure 1). Four control points for evaluation of the modelled inundation depths are chosen according to the availability of reference data (photo and video recordings during the event).

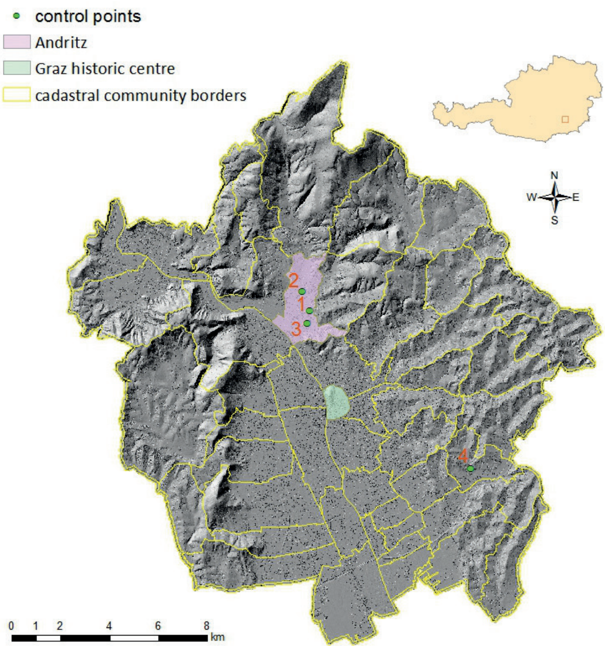

Figure 1: The study area. The green dots show the control points evaluated in detail in Table 3.

The annual rainfall for Graz in the period 1971–2010 is on average 819 mm, for the month of May it averaged at 86 mm (Provincial Government of Styria, 2015). In May 2013, 219 mm of precipitation were measured. An event between May 6, 2013 at 8 pm and 8 am the next day with a total amount of 82.3 mm is considered in the present study. The recurrence interval for this event ranges between five and ten years (Austrian Federal Ministry of Agriculture, Forestry, Environment and Water, 2015).

METHODS

General work flow

An integrated approach to compute inundation depths H (cm) and their possible consequences is applied. H is derived through flow routing and applied to each building in the study area in order to derive the vulnerability V (-) through a vulnerability function. The risk R (expressed as the expected cost of reconstruction in €) is computed by combining V and the associated building values (exposure E in €). The results are scaled to postal code zones and evaluated against point observations of inundation depths and the documentation of damages.

Inundation depth

We use the flood routing software FloodArea developed by Geomer to compute spatially distributed values of H from an input pluviograph, a digital elevation model (DEM) and further derivatives of the data listed in Table 1. A detailed description of the software FloodArea is provided by Rodriguez et al. (2003); Assmann et. al. (2007) and Geomer & Ruiz Rodriguez+Zeisler+Blank (2014).

A set of nine model runs is used to quantify the effects of every single determinant on the simulation results with regard to H (Table 2). For all model runs, the amount of the twelve hours rainfall event (82.3 mm) is evenly distributed over twelve equal time steps, each of them representing one hour with an amount of approx. 6.9 mm. The surface roughness is defined on the basis of the land use classes provided by the national digital cadastral map for Austria (Federal Office of Metrology and Surveying, 2012; Table 1) and Manning-Strickler roughness coefficients associated to each land use class (Fritsch, 2011; Rössert, 1996).

A 2 m DEM is used as reference. As the pixel size strongly influences the computational times, we repeat the computation with a pixel size of 4 m (Model runs 1 and 2 in Table 2). The present paper only considers pluvial flooding. In order to exclude the influence of possible fluvial flooding and potential backwater effects, the stream network is deeply incised into the DEM. Fritsch (2011) already pointed out the advantage of this approach. We perform this step based on an automatically generated stream network (Model run 3 in Table 2).

Model run 4 evaluates the influence of infiltration on the inundation depth (Table 2). In the model runs 1–3, inundation is neglected (runoff coefficient r = 1). For further improvement, r

Table 1: Key data used for the analyses.

Description	Source	Inundation depth	Consequences	Evaluation
Pluviograph for the event	Austrian Federal Ministry of Agriculture, Forestry, Environment and Water	●	–	–
Digital Elevation Model (DEM)	Federal Office of Metrology and Surveying	●	–	–
Official cadastre (DKM)	Federal Office of Metrology and Surveying	●	●	–
Building register (GWR)	Statistik Austria	–	●	–
CORINE Land cover	Environmental Agency Austria	●	–	–
eBod	Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW)	●	–	–
Photo documentation	Fire department of the city of Graz	–	–	●
Damage database	Austrian Insurance Association	–	–	●
Postal code zones	Austrian Post	–	●	●

Table 2: Set of nine model runs. N = not considered; Y = considered; B = before; A = after; I = increased capacity of sewer system.

Model run	Pixel size (m)	Automatic incision	Infiltration	Manual incision	Sewer system
1	2	N	N	N	N
2	4	N	N	N	N
3	4	Y	N	N	N
4	4	Y	Y	N	N
5	4	Y	Y	Y	N
6	4	Y	Y	Y	A
7	4	Y	Y	Y	B
8	4	Y	Y	Y	A, I
9	4	Y	Y	Y	B, I

in the range 0–1 is introduced, based on soil properties and vegetation cover. Building on the code of practice of the Federal Research and Training Centre for Forests, Natural Hazards and Landscape (Markart et al., 2011) a rough estimation of r is attempted. For this purpose we firstly use the Austrian soil map eBod (Federal Research and Training Centre for Forests, Natural Hazards and Landscape, 2013). The only free available release of this data set builds on raster of 1x1 km. For those raster cells where no data are available we assume r = 1. Secondly, we explore the CORINE land cover map (Environmental Agency Austria, 2012).

Small water courses not depicted by the incised stream network layer can still cause unrealistically high modelled water levels when dammed by bridges or other flow obstacles. Manual deepening of the DEM is necessary at selected locations in order to avoid impoundments (model run 5).

In urban areas the sewer system represents a key factor for runoff. The capacity of the sewer system in Graz is designed for the discharge of an event with a return period of one year for 15 minutes duration with 111 l/ha/s (pers. communication W. Sprung, 03.09.2015). In consequence a corresponding sewer discharge for an event of twelve hours with a return period of one year is estimated (Austrian Federal Ministry of Agriculture, Forestry, Environment and Water, 2015), leading to an assumed sewer capacity of 43.8 l/m². Two approaches are compared: in model run 6 the sewer capacity is subtracted from the results of model run 5 (activation of the sewer system after flood routing), whilst in model run 7 the sewer capacity is integrated in r (activation of the sewer system before flood routing).

In order to explore the effects of an increased sewer capacity (as it is available in some other cities) the capacity of the sewer system is expanded to 73.5 what equals an event with a return period of five years (Austrian Federal Ministry of Agriculture, Forestry, Environment and Water, 2015; model runs 8 and 9).

CONSEQUENCES

The possible consequences of pluvial flooding are computed separately for each of the nine model runs summarized in Table 2.

The extent of each building is extracted from the DKM, the surface area of each building A (m²) from the GWR (Table 1). We use the sum of the areas of all floors. As a first estimate we assume a cost of reconstruction E_0 of 2,000 €/m² (modified after Austrian Economic Chambers, 2014) independent on the function or building material. E is computed as $E_0 \cdot A$.
An approximation to the vulnerability function presented by Hsu et al. (2011) is used to compute V of each building:

$$V = 0.8 \cdot e^{-0.575\left(\tan\left(\frac{I_R \cdot \pi}{2}\right)\right)^{-1.5}},$$

Equation 1

where I_R is the ratio between the relevant inundation depth H_R (m) and the (in our case estimated) height of the building (m) (relative intensity; Totschnig et al., 2011). H_R is approximated by the mean value of H derived with the software FloodArea within a buffer area of five metres around each building. Finally, R of each building is computed as V · E.

SCALING

An automated procedure building on the Python programming language and the R package for Statistical Computing (R Core Team, 2015) is employed for scaling the object-based values of H_R, E, V and R to any desired spatial unit (large pixels, administrative units, catchments etc.). Diagrams displaying for defined threshold levels of each variable the fraction of objects equal or above the value of the variable are produced for each spatial unit. Further, the number and the fraction of objects with H_R, E, V or R > 0 are displayed as well as the zone-specific averages and (for E and R) sums. Ranges are given for E and R. In the present study we scale the results to postal code zones.

EVALUATION

To verify the results of the simulation, we qualitatively compare the modelled inundation depths to observed inundation depths documented by photographs (Table 1). Further, we use damages related to the simulated event reported to the insurance business in order to validate the expected cost of recovery at the level of postal code zones.

RESULTS AND DISCUSSION

The key results for the nine model runs – inundation depths at four selected points, and the sums of R for two selected districts – are summarized in Table 3. H displays a certain degree of levelling when increasing the pixel size rather than a general change of the results. The calculation time for a single model run can be reduced from 6 days to 36 hours. In contrast, the incision of the stream channels significantly reduces H, and the values of R drop from severe overestimates to fairly realistic estimates. Whilst infiltration appears to exert a rather moderate effect on the results, the manual removal of artefacts at selected locations signifi-

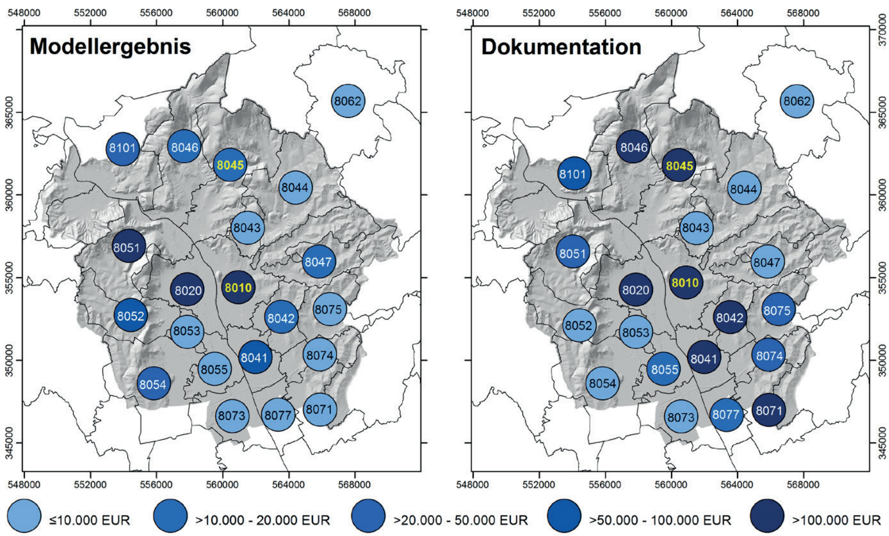

Figure 2: Modelled sums of R and documented damages for the postal code zones of Graz. Left: Sum of R for each zone yielded with model run 6; Right: sum of documented damages. The labels of the zones considered in detail in Table 3 are highlighted.

cantly reduces the inundation depth at point 4 whilst it does not affect R in the central city and in the district of Andritz (Figure 1). Assuming the sewer system to alleviate flooding leads to significant reductions of both H and R. Particularly with regard to R, this effect dramatically increases when (i) activating the system before instead of after the flood routing or (ii) increasing the capacity of the sewer system. In summary, the incision of the stream network and the activation of the sewer system exert the most significant impacts on H and R for the event under investigation.

Figure 2 illustrates the documented damages and the modelled distribution of R aggregated to the level of postal code zones. The summed values of R, as displayed in Figure 2, are problematic for model evaluation as they are strongly influenced by the number of objects in a given postal code zone, so that a certain level of correspondence with the documented damages is likely. Figure 3 therefore shows the average (out of all buildings properly registered in the DKM and the GWR) of the documented damages and the modelled

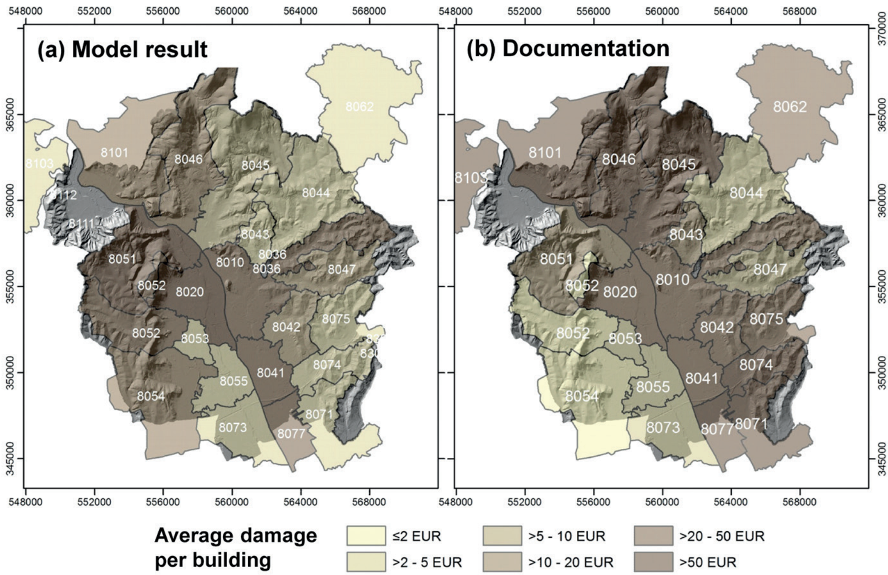

Figure 3: Modelled averages (out of all buildings properly registered in the DKM and the GWR) of R and documented damages for the postal code zones of Graz. (a) Average of R for each zone yielded with model run 6; (b) average of documented damages. Note that also those buildings with R = 0 or with no documented damages are included in the averaging procedure.

distribution of R. Both figures refer to the model run 6 yielding the most realistic results for the central city. From a visual comparison we deduce that the model results show some reasonable correlation with the documented patterns in general, but that there are a number of postal code zones with significant disagreements.

Table 3: Key results of the nine model runs. H = inundation depth (cm), the subscripts in the column headers indicate the dots shown in Figure 1 the numbers refer to. R = risk (expected cost of recovery in million Euro) for the central district of Graz (postal code 8010) and Andritz (postal code 8045). The numbers given in brackets in the header refer to the documentation.

Model run	H_1 (≤6)	H_2 (≤7)	H_3 (≤12)	H_4 (-)	R_{8010} (0.18)	R_{8045} (0.24)
1	10	184	1.5	854	23.64	79.03
2	11	105	1.4	770	48.43	44.24
3	3.5	0.1	0.3	770	0.86	0.04
4	6.0	0.1	0.5	737	0.80	0.06
5	6.0	0.1	0.6	193	0.80	0.06
6	4.7	0.1	0.3	155	0.26	0.01
7	2.9	0.1	0.3	93	0.01	0.00
8	2.5	0.1	0.1	119	0.00	0.00
9	0.6	0.0	0.1	21	0.00	0.00

Whilst the modelled inundation depth corresponds reasonably well to the depth observed at point 1 (except for model run 9 where it is rather underestimated), it is underestimated at point 3 and obviously strongly governed by the stream network at point 2 (Table 3). The tendency of the model to underestimate H at the points 2 and 3 represents an unwanted local effect of the incision of the stream network (both points are located closely to incised streams). Further, the incision of the stream network is the likely cause for the underestimate of R for Andritz, where large buildings are located closely to a water course, compared to the central city (Table 3). Therefore, the usefulness of incising the stream network remains controversial. With regard to the modelled inundation depths (Table 3) one may conclude that the incision leads to a decreased quality of the results and other strategies have to be developed to separate the effects of fluvial and pluvial floods, as far as a clear separation is possible at all. A particular challenge consists in dealing with underground sections of water courses. In contrast, manual lowering of selected spots definitely leads to the disappearance of some artefacts in the model results.

The sewer system appears to represent a key factor for flooding and its consequences (Ettrich, 2007; Illgen and Niemann, 2011). It is therefore essential (i) to obtain more information on its real capacity to alleviate flooding and (ii) to develop improved generalization strategies to include its effects in flood routing algorithms. With regard to soil infiltration, Schumann et al. (2007) pointed out that it is certainly possible to reach locally acceptable results by generating clustered roughness parameters conditioned on remote sensing. However, the regionalization of infiltration remains a critical issue due to the poor spatial resolution of the eBod and CORINE data. Due to the possibly limited degree of validity for fine scales, the estimation of the runoff coefficient can be considered as a rather coarse approximation to reality only. However, surprisingly, infiltration seems not to affect the model results significantly under the assumptions taken.

The interpretation of the modelled values of R requires utmost care. Firstly, not all the damages are necessarily reported to the insurance companies. Secondly, also the DKM and the GWR are not complete at all, so that the modelled values of R may represent underestimates. Strategies to deal with those issues of incompleteness have to be applied in the future. Thirdly, due to the exponential character of the function even a moderate misestimation of inundation depths may strongly affect the estimate of V and, therefore, R. Fourthly, we use the mean inundation depth as H_R, and not the maximum which might be more appropriate. However, using the maximum, few artefacts in the raster map of H may result in very high vulnerabilities of selected buildings and cause extreme overestimates of R for the corresponding zone.

Furthermore it has to be considered that the vulnerability function represents a generalization, considering some features of the vertical structure of a building, such as a cellar, only in an indirect way. Consequently, we build on the assumption that damages occur also at low inundation depths, which is often not the case in reality. The estimates of the buildings' values, in contrast, only affect the model results in a linear way and are therefore considered less critical.

Finally it shall be emphasized that the displayed evaluation of R against the documented damages (Figs. 2 and 3) allows to draw conclusions at the level of postal code zones only. Due to the lacking availability of suitable reference data there is currently no possibility to evaluate the model results at the level of objects.

CONCLUSIONS

We have shown that the modelled inundation depths of pluvial floods and – in particular – their consequences in terms of the expected losses react in a highly sensitive and nonlinear way to changes in the model assumptions and parameter settings. Even though the suggested procedure shows a certain potential to reproduce the patterns in the documented damages at the level of postal code zones, it remains a challenge to back-calculate well-documented events in a satisfactory way. More parameter studies as well as the modification of some of the model functions and additional validation efforts will be necessary to allow reasonably reliable forward calculations of possible future events of defined frequency and magnitude, and the costs of such events. In this context it is highly important to provide uncertainty estimates associated to the results.

ACKNOWLEDGEMENTS

The support of the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water, the Austrian Insurance Association (Dr. Thomas Hlatky), the fire department of the city of Graz and the Austrian Post is acknowledged.

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