Regional flood impact assessment based on local land use patterns and sample damage records

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Abstract

Increasing land consumption and land demand particularly in mountainous regions entail further expansion of settlements to known hazard-prone areas. Potential impacts as well as regionally defined levels of 'acceptable risk' are often not transparently communicated and residual risks are not perceived by the public. Analysing past events and assessing regional damage potentials can help planners on all levels to improve comprehensive and sustainable risk management. In this letter, a geospatial and statistical approach to regional damage cost assessment is presented, integrating information on actual conditions in terms of land use disparities and recorded damage data from a documented severe flooding event. In a first step building objects are categorized according to their function and use. Tabular company information is linked to the building model via geocoded postal address data, enabling classification of building types in terms of predominant uses. For the disaster impact assessment the flood plain is delineated based on post-disaster aerial imagery and a digital terrain model distinguishing areas of long and short term flooding. Finally, four regional damage cost assessment scenarios on different levels of detail are calculated. The damage cost projection relies on available sample building-level damage records, allowing rough damage averaging for distinct building uses. Results confirm that consideration of local land use patterns is essential for optimizing regional damage cost projections.

Keywords: land use, building types, flooding, disaster management, impact assessment, damage cost projection

1. Introduction

In times of the omnipresent discussion on climate change and the related increase of extreme events, natural hazard and disaster researchers are challenged more than ever in order to provide models and tools covering and supporting all aspects and phases of disaster and emergency management. Spatial analysis and GIScience research have long proven fundamental in providing such models and improving our understanding of certain related processes (Johnson 1992, Cova 1999, Chen et al 2003, Goodchild 2006, Taubenböck et al 2008, Pradhan 2010). Disaster management has widely been regarded as a cyclic multi-stage concept, ideally starting with (1) risk analysis, followed by (2) mitigation efforts, and rounded off by (3) a response and recovery phase after a disaster event (Cutter 2003, Wattegama 2007). Visualizing the popular phrase ‘after a disaster is before the next disaster’ which refers to the PEPPER (pre-event planning for post-event recovery) approach first addressed in the late 1980s (Spangle 1987), the cycle is a way of explaining the varying focus during different (overlapping) phases before, during and after a disaster occurs. With all different stages featuring spatially and temporally variable components, the described well-established concept can be further elaborated by figuratively unrolling the cycle and moving to an infinite disaster management spiral (Aubrecht et al 2011, Van Westen 2011). Learning from past disasters and corresponding adaptation of disaster management processes is essential in minimizing impacts of future events. It is,
however, impossible to achieve zero risk. The residual risks keep the spiral on the loop despite continuous improvements in management practices.

Damage cost estimation in general is both related to the recovery phase in terms of assessing where help is needed and to the mitigation and risk reduction phases in terms of providing information on potential high vulnerabilities that could be reduced preventatively. Modelling of potential damages and losses has therefore grown in importance in recent years, considering data on various spatial and temporal scales such as regional population (Kang et al. 2005) and land use data (De Roo et al. 2006), as well as historical damage data (Pielke et al. 2002). Flood impact assessments mainly focus on direct economic losses using damage functions which relate property damage to damage-causing factors. Although the flood damage of a building is influenced by a multitude of factors, usually inundation depth and building use are primarily considered as the main factors in related damage assessment models (Merz et al. 2004). Dutta and Herath (2001), for example, used a GIS-based approach categorizing building use and integrating flood inundation simulations. Building types are also considered as the main cost-influencing factor by Blong (2003) in developing a new quantitative event-specific damage index.

In this study, which was first briefly presented by Steinnocher et al. (2009), documented damage data from the severe 2005 western-Austria flood event (Kanoner 2005) is analysed in relation to socio-economic information on a local scale. This letter aims at applying a geospatial approach of modelling land use patterns on building level through integration of various spatial and space-related data sources and using the resulting spatially and thematically high resolution data as proxy information for calculating regional damage potentials. This novel bottom-up approach illustrates the importance of considering local land use disparities and functional patterns on building level including the arrangement of business and residential structures for reasonable assessments of overall regional damage costs. Sparse data availability, unknown reliability, and little information on actual damages are common problems in emergency management (Cutter 2003). The presented original modelling approach is thus considered highly beneficial, particularly in the response and recovery phase after a disastrous event, both in terms of enabling improved assessment where help is needed and improved assessment of overall magnitudes and impacts, e.g. for insurance purposes.

2. Data and study area

The data sets used for the assessment and classification of functional patterns include both physical real-world information such as 2D building layers (automatically derived from high resolution optical Earth Observation data such as ortho-rectified SPOT 4 and IRS-P6 satellite imagery and aerial photographs provided by the Land Survey Office Feldkirch), terrain and surface models (derived from Airborne Laser Scanning ALS data that had been acquired in the framework of a commercial terrain mapping project), and socio-economic information such as zoning (as defined by the Austrian Planning Law) and hazard plans, commercial company data bases (Herold Yellow Pages) and geocoded address points provided by the Austrian Post (Data.Geo). Further information on data quality and limitations is provided by Aubrecht et al. (2009c). Documented damage cases from the severe flooding event in August 2005 provided by the State Government of Vorarlberg for research purposes are used as the basis for the damage cost projection. Overall monetary damage information as declared by the municipalities serves as a reference for validation of the model. According to the MunichRe NATHAN (Natural Hazards Assessment Network) data base the total damage for the flood event under consideration spanning all affected areas in Germany and Austria was about 3000 million US$ (Barredo 2007). All required data sets are pre-processed and integrated in one data base.

The test site Bezau is located in the province of Vorarlberg in the westernmost part of Austria (figure 1). The study area is defined by geometric outlines (rectangular) and therefore covers only parts of the related municipalities (approximately 50% of the municipality of Andelsbach, 40% of Bezau, 23% of Reuthe, and 12% of Bizauro. As only part of the settlement area of Andelsbach falls into the study area, the analysis was limited to the other three villages. The village of Bezau is located 650 m above sea level and has almost 2000 inhabitants. Economic activities comprise tourism and agriculture.

3. Modelling of local land use disparities

The assessment of regional damage costs related to the huge flooding event in 2005 is carried out in consideration of local land use disparities. In order to be able to project available non-complete individual building damage information as provided by the Federal State Government to a wider spatial scale and hence derive an overall regional damage cost assessment, land use patterns are studied on a high level of both spatial and thematic detail.

As the available point-based extract damage data can easily be linked to individual building objects (figure 2(a)) it is essential for further processing that land use characteristics are determined on building level as well. In order to reach such a high level of thematic accuracy it is not sufficient for land use classification merely considering physical parameters as derived from remote sensing (e.g. building outlines). In fact, information on the function and use of individual buildings is needed to supplement the geometric and physical framework. An approach called functional object grouping is therefore used to derive the required information by integrating a variety of spatial and space-related data sets including zoning plans, addresses and company data. In order to integrate these different types of information a conceptive model was developed and finally implemented in ESRI’s ArcGIS model builder (Aubrecht et al. 2008).

Aubrecht et al. (2009c) provide a detailed description of an application integrating remote sensing and socio-economic information for high resolution modelling of urban land use. In the context of the presented letter, this process step, which is
carried out in a GIS environment, is seen as preparatory work for the final damage cost assessment.

The essential link between clearly defined real-world objects and thematic parameters (e.g. use of buildings) is provided by georeferenced address data. The Data.Geo data set, which is maintained by the Austrian Post and distributed by Tele Atlas, attributes individual addresses with precise geo-coordinates and provides a first discrimination of business and private buildings (Aubrecht et al 2009b). Unambiguous linking of building objects and spatial address information enables the follow-on integration of all kinds of address-based information to the building layer via the shared address attribute (assuming that the address information is similarly structured, i.e. street name, number, zip code, etc). The distinct address-building relation is achieved by creating Thiessen polygons on the basis of the address points (attribute preserving method) and spatially intersecting the resulting segments with the building objects. In order to derive a building use classification featuring real-world functional patterns, company data (Herold Yellow Pages) are attached to the building polygons in a next step. Company records include information on address and business type, which can then be classified in groups of objects featuring similar functional characteristics. Figure 2 shows the building use classification for a detail of the Bezau study site (on the right, (b)) compared to the spatial distribution of the available damage cases from the 2005 flooding event (on the left, (a)). The highly detailed land use classification is simplified and finally four building types are distinguished in that context, which turned out to be best suited for further damage cost assessments: (1) residential, (2) business/commercial, (3) hotels, and (4) mixed use.

4. Estimation of flooding damages

4.1. Flood plain delineation

For estimation of the potential overall damage costs, it is first essential to get an idea of which areas were flooded and to what
Figure 3. Comparison of pre-disaster (left) and disaster (right) imagery. Flooded areas appear as bright fans surrounding the stream network.

Figure 4. Overlay of flood plain (additionally classified in long term and short term) and building objects, giving an impression of potentially flood-affected buildings.

extent. This enables the assessment of potentially affected building objects which forms the basis for the damage cost projection.

Flood plain delineation in that context is performed in an interactive process considering both geomorphologic conditions as described by the ALS-based surface models and aerial imagery acquired shortly after the flooding event took place. Visual interpretation of the disaster-related aerial photographs and comparison with pre- and post-disaster imagery reveals to a large extent the spatial dimension of the flooding event (figure 3). The aerial imagery showing immediate post-disaster conditions was acquired jointly by the Austrian Federal Office of Metrology and Surveying (BEV) and the Austrian Military (aerial reconnaissance unit) in a separate flight campaign covering the affected valleys on a total length of 650 km. Imagery in slightly downscaled spatial resolution was provided for free to the public on the internet (still available at www.bezaubernde.info/luftbilder-hochwasser-2005.html, 09/30/2011). People living in affected areas got access to the full resolution data, particularly with regard to conservation of evidence in terms of insurance matters. The downloaded images are manually georeferenced to the available pre- and post-disaster data in order to guarantee full usability within a GIS environment.

After integrating the disaster imagery into the GIS project a first visual delineation of flooded areas is carried out. Furthermore geomorphologic information as provided by the digital elevation model is used to differentiate long term and short term flooded areas (figure 4). Event-specific details such as the locations of emersion points caused by dike breaches and jams at gorge portions are provided in communal documentation records and reports by fire fighters, mountain and water rescue services (e.g. Kanonier 2005), allowing some fine-tuning in the flood plain mapping.

4.2. Cost estimation

The objective of this analysis is to estimate the entire damage costs within the municipality of Bezau. Intersection of the flood plain with the building layer gives an indication of which buildings were potentially damaged. The fact that only for a minor part of these buildings are damages recorded leads to the assumption that the available documentation is incomplete. Authorities on a federal level in Austria often only have access to damage information officially recorded by insurance companies. However, there usually is a ‘grey area’ of damages not listed in those records which increase the total damage costs and are only documented at the local level. This is further confirmed in the present case by a statement of the local municipality government, declaring that the overall damage sums up to more than 15 million Euros, while the total of the documented damage cases only comes up to 11.6 million Euros.

In addition, four damage records stand out due to their extremely high damage costs, adding up to a total of more than 9 million Euros. These cases are considered singularities and are therefore not taken into account for the regional cost assessment. Keeping such singularities as part of the extrapolation would imply using extremely exaggerated average building damage estimates as a basis and would therefore lead to vast misconfiguration of the regional impact assessment. Assuming that the remaining 57 damage cases are representative for all buildings, the overall damage costs
For the first scenario (S1) the average damage costs per building are calculated from the documented cases and extrapolated to all buildings located within the flood plain. No differentiation between building functions or intensity of the flooding is made. The first line in table 1 illustrates this scenario: based on 57 documented cases the average costs of €35 214 are calculated and projected onto 370 buildings located within the flood plain. The overall costs sum up to approximately 13 million Euros.

For the second scenario (S2) the average damage costs per building are calculated for the four functional groups and extrapolation is based on these function classes as well. Table 1 (lower part) shows the different average costs per functional group that result in a total sum of approximately 9 million Euros. It is important to note that by using the functional grouping a residual class remains (other), including 124 buildings with only two damage records. As this class is very heterogeneous, no projection is performed and only the documented damage costs are used.

For the third (S3) and the fourth (S4) scenario the long term and short term flooded areas are considered as further parameters. For scenario 3 the average damage costs per building within each of these two areas are calculated and extrapolated to all buildings within the respective sub area (table 2). This leads to a damage projection of more than 16 million Euros which is clearly larger than any other scenario outcome.

In the fourth scenario (S4) both the two flooding types and the functional groups are taken into account. Average calculation and extrapolation are based on all available parameters, finally yielding the lowest total of overall damage costs of approximately 8 million Euros (table 3). The rule of the residual class is applied as described above.

For validation of the scenario results the cost statement in a municipality report by the mayor of Bezau (Fröwis 2007) is used. According to this report the overall damage costs for the affected region sum up to more than 15 million Euros. Subtracting the documented costs of the singular cases of 9.7 million Euros leaves approximately 5.3 million Euros as reference. Table 4 gives an overview of the scenario results and shows the deviations from this reference value.
5. Conclusion and outlook

Land use data on building level derived from an integrated analysis of remote sensing and socio-economic information was used for the assessment of overall regional damage costs caused by the severe 2005 flooding event in the Austrian province of Vorarlberg. A sample of documented damage cases for the municipality of Bezau provided the basis for a damage projection to all potentially affected buildings located within an estimated flood plain derived from post-disaster aerial imagery and elevation data. Four projection scenarios on different levels of detail were calculated.

Comparing the results of the scenario calculations with a given reference sum for the total damage costs as provided by local authorities clearly shows the improvement achieved by introducing building-level land use data. While the simple projection based on buildings alone leads to an overestimation of almost 150%, the differentiation of building use types reduces the error to half that amount. The differentiation of the flood plain with respect to the duration of flooding—indicating different degrees of damage—eventually limits the overestimation to 50% for the scenario considering building use variation. Using the flood plain differentiation alone (i.e. without accounting for building use) proved to be the weakest scenario featuring an overestimation of more than 200%. This clearly indicates that the integration of functional building information is essential for improving the quality of damage cost estimation. We conclude that the presented method can be considered valuable for estimating standard damage costs. In any case it is necessary to exclude singularities from the assessment, i.e. finding those buildings or infrastructure objects featuring significantly high damage outliers. For finding these objects, information on building use is again essential.

Referring to the availability of building use information, we would like to highlight that the geocoded address data as well as the company data used for functional building classification are available for all of Austria. The presented method is therefore basically very easily transferable and applicable to other regions and events. Additionally being dependent on the availability of post-disaster imagery for floodplain delineation and sample impact records, the approach could also be applied in other countries.

Further enhancement of the regional impact assessment method might be achieved by introducing additional parameters both on the hazard side (e.g. flood depth) and on the vulnerability side (e.g. structural building type and age). Using a less simplified building use classification, i.e. more functional types, is, however, not expected to significantly improve the method at the present stage.

Living in areas at risk from natural hazards is a common phenomenon particularly in mountainous regions. Increasing land consumption and land demand entail further expansion of settlement systems to areas with known potential for hazard impacts such as floods, landslides and avalanches. Regional land use planning concepts define formal levels of ‘acceptable’ risk (e.g. frequent event, design event), but whether these residual risks are perceived as such by the public is a topic often not addressed. Planners on all levels are requested to play an active part in comprehensive and sustainable hazard management. Metaphorically speaking just ‘elevating the levees’ might not be the exclusive solution. Active public communication and integration of all stakeholders, including local residents, is a first step to coping with future problems in terms of hazards and risks in a sustainable and effective way (Aubrecht et al. 2009a).

The presented modelling approach can be further expanded as a valuable application in the context of land use planning and management or as input for communication and governance activities. Using the distinct spatial information on local land use disparities, including the arrangement of business and residential structures, damage cost assessment could be succeeded by cost reduction estimations. Additionally, considering hazard zoning and other planning-relevant variables would enable analyses of potential savings that could, for example, be accomplished through relocating particular structures and assets to less vulnerable areas.

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References

Aubrecht C, Freire S, Zuccaro G and Steinnocher K 2011 The infinite spiral of disaster management: spatio-temporal modeling aspects in the context of reducing residual risk AAG Annual Mtg, Special Symp. on Space-Time Integration in Geography and GIScience (Seattle, WA)
Aubrecht C, Köstl M and Steinnocher K 2008 Functional object grouping—an advanced method for integrated spatial and space related data mining Digital Earth Summit on Geoinformatics 2008: Tools for Global Change Research ed M Ehlers, K Behncke, F-W Gerstengarbe, F Hillen, L Koppers, L Stroink and J Wächter (Heidelberg: Herbert Wichmann) pp 94–9
Aubrecht C, Köstl M, Knoflacher M and Steinnocher K 2009a The importance of active public communication—settlement systems and land use patterns seen from a disaster perspective REAL CORP 2009: 14th Int. Conf. on Urban Planning, Regional Development and Information Society-Strategies, Concepts and Technologies For Planning the Urban Future ed M Schrenk, V Popovich, D Engelke and P Elisei, pp 895–900
Environ. Res. Lett. 6 (2011) 044014 C Aubrecht et al

Aubrecht C, Köstl M, Steinnocher K and Hackner-Jaklin N 2009b Georeferenced address data: the essential link between geometric and thematic features in an urban data management system UDMS’09: 27th Urban Data Management Symp. (Ljubljana, June 2006) p 8
Aubrecht C, Steinnocher K, Hollaus M and Wagner W 2009c Integrating earth observation and GIScience for high resolution spatial and functional modeling of urban landuse Comput. Environ. Urban Syst. 33 15–25

Barredo J 2007 Major flood disasters in Europe: 1950–2005 Natural Hazards 42 125–48
Blong R 2003 A new damage index Natural Hazards 30 1–23
Chen K, Blong R and Jacobson C 2003 Towards an integrated approach to natural hazards risk assessment using GIS: with reference to bushfires Environ. Manag. 31 546–60

Cova T J 1999 GIS in emergency management Geographical Information Systems: Principles, Techniques, Applications, and Management ed P Longley, M Goodchild, D Maguire and D Rhind (New York: Wiley) pp 845–58
Cutler S L 2003 GI science, disasters, and emergency management Trans. GIS 7 439–46

De Roo A, Kucer J, Bonk R, Barredo J J, Bodis K, Szabo J and Thielen J 2006 Flood extent and damage estimation in Hungary during the floods in spring 2006 Report EUR 22712 EN (Ispra: Joint Research Centre, Institute for the Environment and Sustainability) p 33
Dutta D and Herath S 2001 GIS based flood loss estimation modeling in Japan 1st Workshop of US-Japan Cooperative Research for Urban Earthquake Disaster Mitigation (Kobe, Jan. 2001) p 7
Fröwis G 2007 Objektschutz in der Gemeinde-Erfahrungen nach dem Hochwasser im August 2005 und September 2006 Fachtagung Integraler Hochwasserschutz-Von der Risikobeurteilung zum Objektschutz (Wolfurt: Federal State Government of Vorarlberg)

Goodchild M F 2006 GIS and disasters: planning for catastrophe (Editorial) Comput. Environ. Urban Syst. 30 227–9
Johnson G O 1992 GIS applications in emergency management URISA J. 4 66–72

Kang J-L, Su M-D and Chang L-F 2005 Loss functions and framework for regional flood damage estimation in residential area J. Mar. Sci. Technol. 13 193–99

Kanoner J 2005 Das Starkregen-und Hochwasserereignis des August 2005 in Vorarlberg Ein Bericht des Amtes der Vorarlberger Landesregierung (Feldkirch: Federal State Government of Vorarlberg) p 54
Merz B, Kreibich H, Thieken A and Schmidtke R 2004 Estimation uncertainty of direct monetary flood damage to buildings Natural Hazards Earth Syst. Sci. 4 153–63
Pielke R A Jr, Downton M W and Barnard Miller J Z 2002 Flood Damage in the United States, 1926–2000: A Reanalysis of National Weather Service Estimates (Boulder, CO: UCAR) p 86
Pradhan B 2010 Role of GIS in natural hazard detection, modeling and mitigation Disaster Adv. 3 3–4
Spangle W E 1987 Pre-earthquake planning for post-earthquake rebuilding (PEPPER) Southern California Earthquake Preparedness Project (Pasadena, CA)

Steinnocher K, Aubrecht C, Köstl M and Knoflacher M 2009 Flood-related damage cost assessment—regional projection considering local conditions Geospatial Crossroads@GIForum’09. Proc. 3rd Geoinformatics Forum Salzburg ed A Car, G Griesenbner and J Strobl (Heidelberg: Herbert Wichmann) pp 191–9

Taubenböck H, Post J, Roth A, Zosseder K, Strunz G and Dech S 2008 A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing Natural Hazards Earth Syst. Sci. 8 409–20

Van Westen C J 2011 Remote sensing and GIS for natural hazards assessment and disaster risk management Treatise on Geomorphology vol 3, ed J Schroeder (Amsterdam: Elsevier)
Wattegama C 2007 ICT for Disaster Management (United Nations Development Programme—Asia-Pacific Development Information Programme (UNDP—APDIP) and Asian Pacific Training Centre for Information and Communication Technology for Development (APCICT)) p 48