GIS-based methodology for pluvial flood risk analysis in Hamburg

Méthodologie SIG pour l'analyse des risques d'inondation pluviale à Hambourg

C. Scheid[1], T.G. Schmitt[2], G. Bischoff[3], N. Hüffmeyer[4], K. Krieger[5], A. Waldhoff[6], C. Günner[7]

[1]University of Kaiserslautern, christian.scheid@bauing.uni-kl.de
[2]University of Kaiserslautern, theo.schmitt@bauing.uni-kl.de
[3]Hamburg Wasser, Gerrit.Bischoff@hamburgwasser.de
[4]Hamburg Wasser, Nina.Hueffmeyer@hamburgwasser.de
[5]Hamburg Wasser, Klaus.Krieger@hamburgwasser.de
[6]Hamburg Wasser, Axel.Waldhoff@hamburgwasser.de
[7]Hamburg Wasser, Christian.Guenner@hamburgwasser.de

RÉSUMÉ

Une des nombreuses conséquences du changement climatique en cours est l'augmentation de la fréquence des pluies extrêmes qui peut provoquer une surcharge des systèmes d'assainissement en milieu urbain ; des inondations en zone urbaine sont attendues en Europe Centrale au cours des prochaines décennies. En conséquence, le développement de stratégies d'adaptation et de prévention adéquates pour réduire les dommages dus aux inondations pluviales nécessite une bonne analyse des risques, basée sur l'évaluation des dangers et des vulnérabilités. Au cours des dernières années, diverses méthodologies et approches, en particulier de l'analyse de risque, ont été introduites et établies. Dans le projet AISP (Adaptation des InfraStructures à la Pluie), la méthodologie SIG suivante a été développée pour une analyse des risques et dangers de la pluie, pour la ville de Hambourg, par le biais d'une étude de cas. Les objectifs clefs de la méthodologie sont une utilisation optimale des sources de données municipales disponibles, un degré élevé d'automatisation dans l'application et une bonne transférabilité à l'ensemble de la ville, associée à une qualité fiable des résultats.

ABSTRACT

As one of many consequences of the ongoing climate change an increasing frequency of occurring extreme rainfall events which may cause surcharged urban drainage systems and flooded urban areas is expected for Central Europe within next decades. Therefore the development of appropriate adaptation and prevention strategies to reduce pluvial flood damages requires a sound risk analysis based on the assessments of hazards and of vulnerabilities. In the last few years, various methodologies and approaches in particular of hazard analysis have been introduced and established. Within the RISA project (Rain InfraStructure Adaptation) the following GIS-based methodology for a pluvial hazard and risk analysis has been developed for the city of Hamburg by the means of a case study. The key objectives of the methodology are an optimal use of available municipal data sources, a high degree of automation in the application and a good transferability to the entire city area combined with a reliable quality of results.

KEYWORDS

GIS, Hazard, Pluvial flood, Risk assessment, Vulnerability

1 INTRODUCTION

Dealing with and coping urban flooding, caused by rainfall extremes, is one of the major challenging tasks of urban drainage, especially under the influence of climate change. The current global climate projections consider increasing frequencies and intensities of extreme precipitation patterns over the coming decades as very likely in most areas of Central Europe (Bates et al., 2008). Already today it is obvious that the hydraulic performance of conventional, runoff-oriented urban drainage infrastructure is not sufficient for these impacts and therefore can’t offer adequate solution approaches against urban flooding.

Against this background, there is an urgent need of a paradigm shift in the municipal flood protection, consisting of a risk-based analysis and assessment of the hydraulic capacities and overflow performance of municipal drainage systems instead of the present concepts of design and safety verification and promises (Schmitt 2011).

Fluvial flood risk assessments are well established and tested on case studies for several years (e.g. Dawson et al., 2008; Morita, 2008; FLOODSite, 2009) and their application is also specified as mandatory by the European Flood Risk Management Directive (EC 2007/60). The transmission of this methodology on the issue of pluvial floods caused by extreme rainfall runoff is still at the beginning (Niemann and Illgen, 2011; Zhou et al., 2012). However, reliable tools for a detailed risk analysis are available with the application of geographic information systems (GIS), sewer network simulations and the coupled 1D/2D-simulation of sewer and surface runoff and have been improved in recent years (see Djordjevic et al., 1999, 2005 and 2007; Schmitt et al., 2005; Obermayer et al., 2010).

The paper describes a methodology for pluvial flood hazard and risk analysis, which on the one hand provides an important contribution in understanding the causes of past flood events. On the other hand it supports the development of a comprehensive approach to risk management by the recognition of potential hazard and risk areas in the urban area.

The methodology was developed and validated within the RISA project (Rain InfraStructure Adaptation, RISA, 2012) and aims to provide a maximum of automation procedures in application, primarily from using a geographic information system (GIS). Hence, it focuses on manageable efforts for application combined with the attainment of a reliable quality of results. Usually on the municipal side there is a lack of sufficiently powerful simulation models and of available extensively survey data on topography of large catchments. For this reason, the application of detailed simulation models as dual drainage modelling is not considered by municipalities as the preferred approach for a comprehensive initial flood risk analysis (see Fuchs et al., 2012).

Instead of that it should be examined which level of information accuracy to the flood hazard and risk assessment is attainable with a rather common GIS-based approach. Particularly, the description of methodological limitations of flow path and sink delineation processing for rather flat terrain, as also to be found in Hamburg, is of high significance (see Niemann and Illgen, 2011).

2 METHODOLOGY

The introduced methodology (Fig. 1) consists of a two-part workflow. The first processing step is the parallel determination and identification of the potential location-specific flood hazards and vulnerabilities. Following is a superposition of these two risk components to the description of the potential pluvial flood risk according to the general definition of risk as interaction of hazard and vulnerability. Appropriate applications of this definition are described in (e.g. Leitao et al., 2012; Niemann and Illgen, 2011; Apel et al., 2009, Barroca et al., 2006). All processing steps are implemented by GIS automation. Additionally a subsequent first step of validation based on a selected case study of Hamburg is performed. The methodology is also focused on an optimal implementation of the various, available municipal and spatial data sources. For the issue of a flood hazard and risk assessment the following datasets are of essential importance and relevance:

- A high-resolution digital surface model (DSM) (at least 4 elevation points/m², resulting grid resolution 1m)
- digital land register Hamburg with building utilisation and land use patterns
- digital aerial photos (LIDAR data) with detection of paved and unpaved areas
- urban drainage system database with results of hydraulic simulations
- documentation of emergency calls caused by heavy rainfalls, provided by fire department and disaster protection

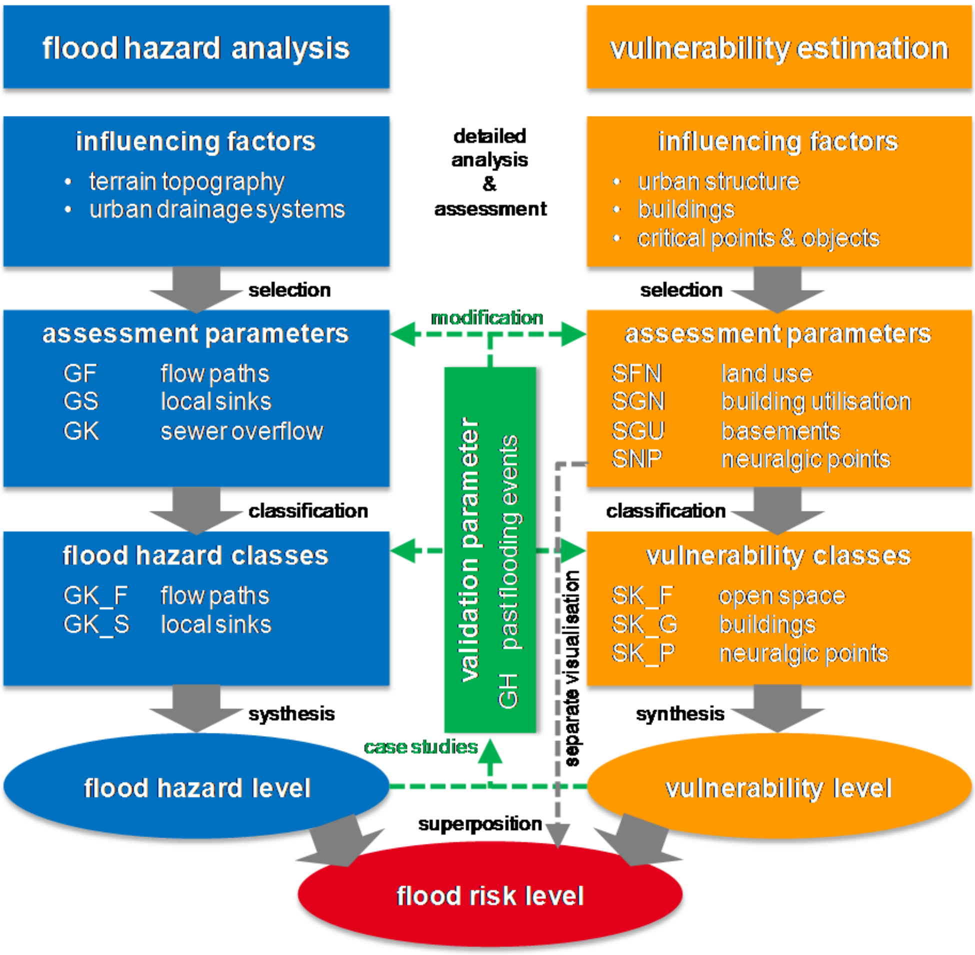


Fig. 1. Workflow of flood hazard analysis, vulnerability estimation and flood risk assessment for pluvial flooding

2.1 Flood hazard analysis

2.1.1 *Influencing factors and assessment parameters of hazard*

To describe the potential flood hazards, it is essential to perform a thorough investigation of all possible influencing factors of hazard with direct relation to the specific local conditions and circumstances (see Table 1). These influencing factors are subsequently evaluated concerning the relevance and availability of data according to the requirements of an automated application. As the result of this step a selection of assessment parameters for the potential flood hazard is available consisting of the location of local topographic depressions and sinks (GS), surface flow paths (GF) and simulated overflow frequencies of the urban drainage system (GK).

Table 1. Overview matrix of influencing factors & assessment parameters of flood hazard potential; Legend of rating: ++ (very high); + (high); o (medium); - (low); -- (very low)

influencing factor	nr.	details, aspects	data applicability	data relevance	assessment parameter
terrain topography					
terrain characteristics	T1	geomorphology, relief energy	++	o	
	T2	slope inclination, gradients	o	o	
characteristics of surface runoff & flooding	T3	flow paths & delineation	++	++	GF
	T4	local sinks & depression delineation	++	++	GS
external hillside areas	T5	gradient, soil type, runoff capacity	+	--	
drainage systems					
surface waters & ditches					
hydraulic capacity	E1	full charge capacity, water levels	-	+	
	E2	distance to fluvial inundaton areas	++	++	
hydraulic bottlenecks	E3	culverts, pipe siphons	++	++	
	E4	bridges, planks & crossing conduits	o	++	
	E5	Einbauten, flow obstacles (e.g. pillars, bar screens, fences)	-	++	
drianage ditches	E6	geometry, covered or uncovered	*in progress*	+	
urban drainage system					
hydraulic capacity	E7	overflow frequency of manholes / nodes	++	++	GK
	E8	pipe geometry: shapes, slopes, diameters	++	o	
	E9	sewer infiltration, extraneous water	-	o	
hydraulic bottlenecks	E10	flow obstacles, deviations in pipe position, pipe collapses	o	+	
private sewerage systems & street drainage systems					
hydraulic capacity of street drainage systems	E11	dimensioning & operating state (inlets, drain channels)	o	+	
hydraulic capacity of private sewerage systems	E12	dimensioning & operating state (inlets, connection pipes, downpipes)	-	+	
	E13	backflow prevention, lifting units	-	+	
	E14	sewer infiltration, extraneous water	-	o	
hydrologic catchment area					
hydrogeology	E15	soil type, ifiltration capacity	++	o	
	E16	depth of groundwater table	++	o	

The application of spatial GIS tools (e.g. flow accumulation, sink evaluation) on the available high resolution DSM of Hamburg (> 4 pts/m², aggregated to a grid resolution of 1m) quantifies the defined assessment parameters GF and GS. Since a detailed elevation model of the buildings was not available, all DSM elevation points in the field of buildings have been elevated by three meters to account them as virtual flood barriers. The geoprocessing of flow accumulation requires a prescreening of sinks by filling small depressions and pits by threshold definition for the minimum drainage area or sink depth as described in e.g. Nichler et al. (2011). Particularly in flat terrains, such as are present in large areas of Hamburg, this processing step and the threshold definition is of high sensitivity for the obtained results. The definition of a rather large threshold for the sink prescreening results on the one hand in longer flow paths, on the other hand it may cause a loss of important information about smaller local hazard areas. Furthermore, shallow depressions with depths of few decimetres in flat terrains frequently already reach to a rather large spatial expansion. Conversely, the quantification of the threshold has to take into account all elevation inaccuracies and fault tolerances to the available DSM. Therefore a sensitivity analysis to the sink prescreening was performed to include the automatically prefilled areas as ‘subsinks’ in the evaluation of results (see Fig. 2a). These process steps finally provide a flow path and sink map (Fig. 2b) that descriptively visualizes the topographic induced pluvial flood hazard potential.

The assessment parameter GK for sewer overflow considers methodologically the influence of surcharged drainage systems and overflows by exceeding the hydraulic performances on the pluvial flood risk. Existing deficits in the hydraulic capacity of the drainage system, which appear in higher overflow frequencies, provide a significant contribution to the potential risk for flooding especially at moderate heavy rainfall events above dimensioning intensities. Exiting water from street inlets and sewer manholes induces surface runoff to the closest sink. Additional recommendations for implementing a manhole-related classification of the flood hazard potential are introduced in (Fuchs et al. 2012).

(a) (b)

Fig. 2. Flood hazard analysis: (a) sensitivity analysis of sink prescreening: subsinks (black) and (b) flow path and sink map: sinks (light blue), sink drainage areas (green), flow paths (dark blue)

2.1.2 *Flood hazard assessment*

To determine the total potential flood hazard, all assessment parameters are classified by assigning a hazard score from 1 to 6 and superposed to the total flood hazard potential GPM. The flood hazard class of sinks (GK_S) arises from the so-called retention depth (defined as the area-specific sink volume from bottom to the elevation of its spill point) and an additional charge due to the influence of sewer overflows (GK). The flood hazard class of the detected flow paths (GK_F) derives from its length and its direct drainage area, but with a lower weighting compared to GK_S. GPM is visualized as grid-based flood hazard map with a four-staged illustration of different potential flood hazard levels from ‘very low’ to ‘high’ (see Fig. 3).

GPM	flood hazard level
5, 6	high hazard
3, 4	medium hazard
2	low hazard
1	very low hazard

(a)

(b)

Fig. 3. Flood hazard assessment: (a) flood hazard levels and (b) four-stage flood hazard map GPM

2.2 Vulnerability estimation

2.2.1 Influencing factors and assessment parameters of vulnerability

In analyzing the potential for flood damages any objects that may be affected and damaged during heavy rainfall events and pluvial flooding (e.g. buildings, municipal infrastructure, facilities and other protected goods and assets) are examined and evaluated in terms of their vulnerability. The expected vulnerability therefore also determines the particular property-related protection requirements.

The workflow of vulnerability estimation is comparable to the flood hazard analysis and starts with a research and summary of all possible influencing factors on the potential of flood damages (Table 2). Subsequently an evaluation of the influencing factors' suitability as assessment parameter is performed. The suitability is characterized by a high relevance and good data quality, as described above. Flood vulnerability is not limited to the existing buildings, but also includes the different land use patterns of urban spaces. Hence, building utilization (SGN), land use (SFN) and the existence of basements and underground constructions (SGU) arise as assessment parameters of vulnerability and potential flood damage. This data can be obtained from the municipal property information (digital cadastre) of Hamburg.

Though it is methodologically assumed that the vulnerability and the protection requirements will be significantly affected by the respective use of the potential damage object (buildings, open space), it should be noted that a wide spread of vulnerabilities for different individual objects even with the same building or land use is possible. Therefore the methodology defines an average damage potential or vulnerability by type of use, which provides a preliminary assessment of flood risk with sufficiently accuracy. Particularly vulnerable buildings, such as hospitals, nursing and retirement homes, kindergartens and schools, as well as other technical or structural facilities, so-called critical infrastructures (e.g. of supply and waste management, energy, transport, security, emergency and disaster management) are taken into account with a correspondingly high vulnerability for potential damages. Furthermore the existence of basements or even complete underground constructions is considered methodologically as a sensitive aspect increasing the vulnerability of these buildings and objects.

Table 2. Overview matrix of influencing factors & assessment parameters of vulnerability;
Legend of rating: ++ (very high); + (high); o (medium); - (low); -- (very low)

influencing factor	nr.	details, aspects	data applicability	data relevance	assessment parameter
urban development conditions					
urban structure	**F1**	settlement characteristics	**+**	**+**	
	F2	site occupancy index (GRZ)	*undetermined*	**--**	
open space characteristics	**F3**	area & percentage of open space	**++**	**o**	
	F4	degree of soil sealing	**--**	**+**	
	F5	degree of soil pavement	**++**	**+**	
	F6	type of land use	**++**	**++**	**SFN**
buildings					
building utilisation	**G1**	type of buliding utilisation	**++**	**++**	**SGN**
architectural design	**G2**	basements	**++**	**++**	**SGU**
	G3	underground buildings	**++**	**++**	
	G4	population density	**+**	**+**	
vulnerable elements	**G5**	light wells	**-**	**++**	
	G6	building openings (doors, windows)	**-**	**++**	
arrangement of buildings, exposition	**G7**	distance between buildings and sinks & flow paths	**++**	**++**	
	G8	elevation differences between building and (street) surface	**-**	**++**	
neuralgic & critical points					
critical traffic spots	**P1**	underpasses	**+**	**++**	**SNP**
other critical points	**P2**	underground entries (subway, shopping malls etc.)	**+**	**++**	
street environment design	**P3**	cross sections	*undetermined*	**++**	
	P4	curb heights	*undetermined*	**++**	

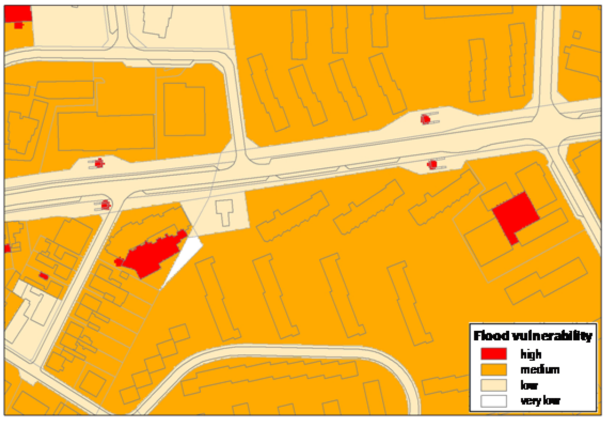
Apart from the buildings there are also spatially limited areas, so-called neuralgic and critical points, with a distinct, significantly higher vulnerability and protection requirement than in the immediate surrounding area. Those points that are often located in the range of underpasses, approaches and entrances to underground car parks or other underground facilities and buildings, are also considered and classified as assessment parameter (SNP) within the GIS-based methodology, partly supplemented by manual entry.

2.2.2 Estimation of vulnerability

The determination of the total vulnerability (SPM) is comparable to the workflow of the total potential hazard classification as described above. It is realised by assigning a potential vulnerability score (classification from 1 to 6) to each assessment parameter of vulnerability. The flood vulnerability classes of urban open spaces (SK_F) and of buildings (SK_G) as well result from their use, but for the latter with an additional consideration of existing basements and underground construction. The classification of neuralgic and critical points (SK_P) is graded according to their criticality, but at least with class 3, which represents a medium vulnerability. SPM is visualized as grid-based flood vulnerability map comparable to the GPM map with a four-staged illustration of different flood vulnerability levels from ‘very low’ to ‘high’ (see Fig. 4).

SPM	flood vulnerability level
5, 6	high vulnerability
4	medium vulnerability
2, 3	low vulnerability
1	very low vulnerability

(a)



(b)

Fig. 4. Flood vulnerability estimation: (a) flood vulnerability levels and (b) four-stage flood vulnerability map SPM

2.3 Flood risk analysis

The methodology of flood risk assessment due to extreme rainfall events is based on a superposition of the potential hazard and vulnerability in accordance with the definition of risk (see Fig. 1). On this a discretized superposition is applied by combining the described flood hazard and vulnerability levels to risk levels according to a defined a risk matrix (see Leitao et al., 2012; Niemann and Illgen, 2011). Basically, a positive correlation between risk and vulnerability is noticed. Concretely, this means that a high flood risk prevails in those areas where there is a coincidence of a high potential hazard (e.g. a sink) and an exposed damage object with a high vulnerability (e.g. access to an underground shopping mall). However, there are various degrees of freedom and also uncertainties in the methodical implementation of risk superposition, which can be done as for example a purely qualitative, additive or multiplicative process. Beside this, it has to be defined, whether hazard and vulnerability levels determine the resulting flood risk level with the same weighting and priority. Some general rules for defining risk matrices are described in (Cox, 2009).

In the present case, both an addition and a multiplication approach are defined and applied. The subsequent validation based on a case study showed a preference for the addition approach, as shown in the risk matrix of Fig. 5a. It defines the resulting flood risk RPM as the addition of the two components of risk (hazard class and vulnerability class) and provides by aggregation four flood risk levels from "very low" to "high". The flood risk levels are visualized in a four-staged risk map (see Fig. 5b). The map also contains a distinct visualization of the major neuralgic points, such as underground car parks, pedestrian passages and basements, as these may require further detailed risk analysis.

+	vulnerability class 1	2	3	4	5	6
hazard class 1	2	3	4	5	6	7
2	3	4	5	6	7	8
3	4	5	6	7	8	9
4	5	6	7	8	9	10
5	6	7	8	9	10	11
6	7	8	9	10	11	12

pts.	count	flood risk level
10 - 12	6	high flood risk
7 - 9	15	medium flood risk
5 - 6	9	low flood risk
1 - 4	6	very low flood risk

(a)

(b)

Fig. 5: risk analysis: (a) risk matrix (addition approach), and (b) four-stage flood risk map RPM

2.4 Validation

The described methodology for flood hazard analysis and vulnerability estimation with evaluation of potential flood risk includes different methodological degrees of freedom and uncertainties due to the used data base. Therefore, a thorough validation of the methodology is urgently required. As a first basic step of validation, observed past flood events which are documented by extensive information about performed fire department operations and operational messages of Hamburg Wasser are compared with the methodical results displayed in the GIS maps. Objectives of the validation are on the one hand a plausibility check of the results and on the other hand the quantification of limits of visualization and significance.

Furthermore it has been shown that especially in large cities and in regions with correspondingly high population the implementation of social media applications seems in fact to be a promising approach to support a validation. Especially for extraordinary rainfall events in the meantime a large variety of photos and video documentation of observed floods which are uploaded to e.g. YouTube ™ or Facebook ® provide at least as complementary, 'soft' information.

The validation of the methodology was carried out on a pilot area located in the east of Hamburg with a spatial extension of approx. 16 square kilometres. The pilot area includes both urban and rural areas. Its settlement structure and land use patterns are sufficiently heterogeneous and of a high diversity, hence, a good transferability of the methodology is supposed to be guaranteed. The main findings of validation are:

- The addition approach of risk superposition provides more reliable results than the multiplication approach.
- The described GIS-automated methodology for a comprehensive identification of potential flood hazards disposes of a high practicability and provides with the flood hazard map despite few assessment parameters an appropriate overview of the hazard situation in the examined project area.
- The GIS-supported estimation of vulnerability is subject to greater uncertainty arising from the given data base and methodological approaches.
- The transferability of the methodology to the entire municipal area of Hamburg is generally ensured, if necessary by adjusting individual parameters.
- As a further validation step of the flood hazard assessment the application of surface runoff models (e.g. 1D/2D simulations) should be considered to evaluate the uncertainties of hazard classification and to describe the relation between flood hazard classes and flood probabilities.

3 CONCLUSION

Based on a case study for Hamburg a manageable and comparatively easily applicable GIS-based methodology for hazard analysis and risk assessment was developed and evaluated. Due to the limited number of considered influencing parameters and without the application of a detailed hydraulic simulation it is suitable for a comprehensive, largely automatic initial analysis of pluvial flood risks in urban areas. The resulting GIS maps, consisting of flood hazard, damage and risk maps provides helpful information and planning backgrounds for the introduction of a customized pluvial flood risk management for urban areas, for a target group focused risk communication with potentially affected residents and property owners, or as a planning basis for further analysis steps, e.g. detailed investigations of local flooding processes by the usage of dual drainage modelling approaches.

LIST OF REFERENCES

Apel, H., Aronica, G.T., Kreibich, H., Thieken, A.H., 2009: Flood risk analyses—how detailed do we need to be? *Natural Hazards*, 49, 79-98.

Barroca, B., Bernardara, P., Mouchel, J.M., Hubert, G., 2006: Indicators for identification of urban flooding vulnerability. Nat. Hazards Earth Syst. Sci. 6 (4), 553–561

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P. (Eds.), 2008: *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Cox, L.A. (2009). *Risk analysis of complex and uncertain systems*. International Series in Operations Research & Management Science 129. Springer Science + Business Media.

Dawson, R.J., Speight, L., Hall, J.W., Djordjevic, S., Savic, D. and Leandro, J., 2008: Attribution of flood risk in urban areas. *Journal of Hydroinformatics* 10 (4), 275–288.

Djordjevic, S., Prodanovic, D. and Maksimovic, C. 1999: An approach to simulation of dual drainage. *Water Science and Technology* 39(9), 95–103.

Djordjevic, S., Ivetic, M., Prodanovic, D., Savic, D. and Maksimovic, C., 2005: SIPSON – Simulation of interaction between pipe flow and surface overland flow in networks. *Water Science and Technology* 52(5), 275-283.

Djordjevic, S., Chen, A., Leandro, J., Savic, D., Boonya Aroonnet, S., Maksimovic, C., Prodanovic, D., Blanksby, J. and Saul, A. 2007: Integrated Sub-Surface/Surface 1D/1D and 1D/2D Modelling of Urban Flooding; in *Special Aspects of Urban Flood Management*; Proceedings Cost Session Aquaterra Conference 2007.

EC 2007/60: Directive of European Parliament and of the Council on the assessment and management of flood risks, 23 October 2007. Official Journal of the European Union L 288/27 11/6/2007. http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:288:0027:0034:EN:PDF

FLOODsite, 2009: *Flood Risk Assessment and Flood risk Management*. An Introduction and Guidance Based on Experiences and Findings of FLOODsite (an EU-funded Integrated Project). Deltares - Delft Hydraulics, Delft, the Netherlands

Fuchs, L., Lindenberg, M. and Egger, U., 2012: *Investigation of flooding for a large urban catchment*. Proceedings of the 9th International Conference on Urban Drainage Modelling, Belgrade 2012

Leitao, J., Almeida, M.C., Simoes, N.E. and Martins, A., 2012: *Methodology for qualitative urban flooding risk assessment*. Proceedings of the 9th International Conference on Urban Drainage Modelling, Belgrade 2012

Morita, M., 2008: *Flood Risk Analysis for Determining Optimal Flood Protection Levels in Urban River Management*. Blackwell Publishing Ltd., 142–149.

Nichler, T., Illgen, M. and Schäfer, E., 2011: Risikobewertung von Starkregen am Beispiel der Stadt Stuttgart. Proceedings 44. Essener Tagung für Wasser- und Abfallwirtschaft, GWA Band 223 57/1-57/17.

Niemann, A. and Illgen, M., 2011: Urbane Überflutungsvorsorge – Was die Siedlungsentwässerung vom gewässerseitigen Hochwasserschutz lernen kann. Proceedings 10. DWA Regenwassertage 2011, Frankfurt/M.

Obermayer, A., Günthert, F.W., Angermair, G., Tandler, R., Braunschmidt, S. and Milojevic, N., 2010: Different approaches for modelling of sewer caused urban flooding. *Water Science and Technology* 62(9), 2175–2182.

RISA, 2012: The RISA-Project – Rain InfraStructure Adaption. Project information available from: http://www.risa-hamburg.de/index.php/english.html (accessed 11/20/2012)

Schmitt, T.G., 2011: Risikomanagement statt Sicherheitsversprechen - Paradigmenwechsel auch im kommunalen Überflutungsschutz? (Risk Management instead of Security Pormise – a Paradigm Shift in Municipal Flood Protection?). *KA-Korrespondenz Abwasser Abfall* (58), Nr. 1, 40-49.

Schmitt, T.G., Thomas, M. and Ettrich, N., 2005: Assessment of urban flooding by dual drainage simulation model RisUrSim. *Water Science and Technology* 52(5), 257–264.

Zhou, Q., Mikkelsen, P.S., Halsnaes, K. and Arnbjerg-Nielsen, K., 2012: Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. *Journal of Hydrology* 414-415 (2012), 539-549.