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Use of Geographic Information Systems for Flooding Analysis in Urban Drainage

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***Abstract*—A detailed flooding analysis for extreme events is a more and more upcoming task in urban drainage studies. For such studies an integrated model simulating the flow in the sewer system normally as a 1-D approach and a 2-D model simulation the flow on the surface is needed. This allows for the simulation of the interaction between the flow in the sewer system and the surface.**

The simulation of flooding for a large urban catchment with a high resolution in time and space is not a technical problem but a computer time consuming process if one likes to simulate flooding the whole urban catchment.

The paper describes the methodology for a risk analysis in a stepwise procedure with the objective not to simulate the whole urban catchment but for those areas with a potential risk.

I. Introduction

FLOODING in residential areas poses great challenges to sewer network operators. The damage caused by waste water from sewer networks can be enormous due to high quality additions and installations in basements and underground car parks. Also, a restriction of public and private transport is barely tolerated. Aside from that, dangers to life and limb can occur not only during severe floods. In addition, the climatic conditions have noticeably changed, particularly the occurrence of local torrential rains. The trends found exceed the regional-specific and inter-annual fluctuation margins previously known from long series of measurements in some investigated quantities (KA-no. 8, 2006).

The clear consensus is that it is not economically justifiable to prevent floods during extreme precipitation by expanding sewer networks. Therefore, it is necessary to analyze the potential dangers that arise due to flooding, assess the associated risk, and establish a risk management program.

Up to now, research and practice have mainly been concerned with the probability of flooding. The analysis of the actual danger, i.e., whether a certain plot of land is also affected (flooded), and based on this the assessment of potential, more extensive damage, has not been considered.

The conventional practice for determining possible hazards from the precipitation runoff process is to set-up a rainfall-runoff model of the drainage system and to simulate the runoff process. Thus, sewer network models have statements about location, frequency and volume of an overflow. In principle, hazard areas can already be estimated with these models. The question as to where the water actually flows to on the surface and where it infiltrates again into a sewer network or collects on the surface or drains off into bodies of water, remains unanswered. For this reason, the risk of actual damage has to date not been estimated or only estimated in a very simplified way.

In order to describe the potential hazards in more detail, area-related geographic data can be used as it is normally collected and managed in geographic information systems (GIS). This approach concerns both the required basic data for the simulation, such as for example surface composition and topographic information, as well as local and surface-related potential damage.

For individual areas of the city of Dresden, a hazard analysis and risk assessment was performed as part of the REGKLAM project (Regional Climate Adjustment Program Model Region Dresden) (itwh, 2011).

II. Hazard analysis and risk assessment

A. *Manhole-related classification*

A hazard due to flooding in urban drainage basins can be posed by surface runoff of areas that are not directly connected to the sewer network and run off on the surface, by surface runoff that cannot penetrate into the sewer network, by flooding from the sewer system overflowing and by back-up through household drainage connections to the building. Normal sewer network models are able to calculate the flooding (overflow volume) at the manholes of the sewer network.

To characterize the hazards for a drainage area, a manhole-related classification is introduced. This is done using an assessment of the calculation results by a classification into five classes. Table 1 shows an example of the classification criteria. The classification must be determined in relation to the special conditions in the area under observation. The respective class of manholes is also assigned to the subsequent positions in the flow direction.

TABLE 1. MANHOLE-RELATED CLASSIFICATION

Hazard classes (GK)	Classification	Reason
0	No hazard	Water level ≤ 2.5 m under ground level
1	Slight hazard	Water level ≤ 1 m under ground level
2	Moderate hazard	Water level between 1 m under ground level and an overflow volume ≤ 5 m^3
3	Great hazard	Overflow < 1,000 m^3 *)
4	Very great hazard	Overflow ≥ 1,000 m^3 *)
*) or assessment in the form of a flood test		

Averaging the manhole- or position length related-classification produces a system number as a measure of the hazard to the entire sewer network or the observation area.

The key hazard figure (GKZ) for the sewer network or the area of observation results in:

$$GKZ = \frac{1}{L_{ges}} * \sum_{1}^{n} (GK_i * L_i)$$

with

GKZ: Key hazard figure Drainage system
Li: Length of the position i in meters
GKi : Hazard class for position i
Lges: Total length of the positions considered in meters
n : Number of positions considered

In determining hazard classes 3 and 4, only the sewer network is observed for verification of flooding. Possible reserves on the surface that permit harmless storage or runoff outside of the sewer network on the surface will not be considered in relation to the process. Therefore, as an assessment process, the verification of flooding may yield risk classes that are too great.

In contrast, with a flooding test, additional effects of overflowing water quantities, which due to the complete filling of the sewer network cannot drain into it, are taken into consideration. Thus, an assessment based on a flooding test can properly estimate the actual hazard.

The problem-related system depicted in figure 1 can be used to assess model simulations of the sewer network. Whether the respective next analysis stage is required for classification depends on the respective results.

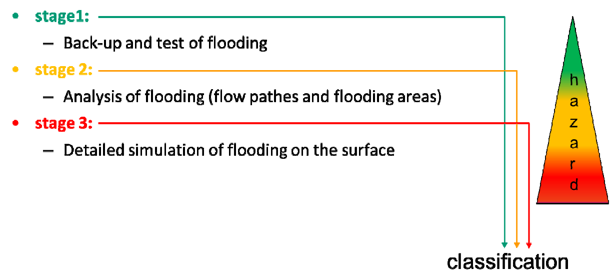

Fig. 1 Classification in stages.

B. *Stage 1 – backup and overflow testing*

A stressed condition of the sewage system is called an overflow, in which the water level exceeds a defined reference level (DWA-A 118, 2006). In practice, the reference level is most often equated with reaching the top of the ground surface. The computational proof of drainage systems with the target figure maintenance of the necessary overflow frequency is required. At least for large drainage systems, verification using hydrodynamic sewer network computation is the standard.

In order to quantify the effects of extreme precipitation on a drainage system, potential flooding points are identified using model simulations and assessed based on the criteria overflow-frequency, -volume and -length.

- The determination of frequencies for verification of flooding or overflow is ascertained by manholes, e.g, pursuant to DIN EN 752 or DWA-A 118. Different area usages can lead to various required frequencies and thus to multiple calculations.
- The simulations are performed using a design storm or multiple events for the actual state or for a planning state if hydraulic deficits in the existing system have already been detected and a re-structuring concept is available.

The calculations are performed with the hydrodynamic sewer network model Hystem-Extran (itwh, 2010).

- With the simulated cases of flooding, the hazard class can be determined manhole by manhole. This is done by an assessment of the calculation results by a manhole- or also positional assignment into the five classes. (Figure 1).

Figure 2 shows an example of a classification. The hazard classes are depicted as results of the backwater and overflow testing (stage 1).

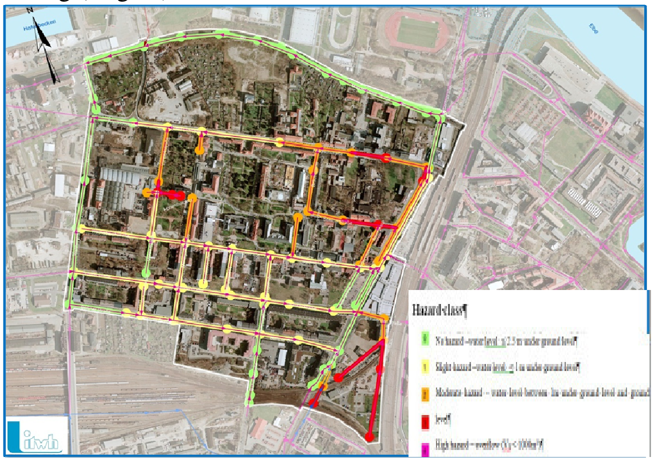

Fig.2 Classification as the result of backwater- and overflow testing

C. Stage 3 – Flood testing with assessment of potential hazard

In the observed context, flooding is defined as a condition in which sewage and/or rain water escapes from a drainage system or cannot infiltrate into this system and remains on the surface or seeps into buildings (DIN EN 752, 2008). In the German drainage practice, "flooding" is associated with consequent damages (e.g., flooding of basements) or functional breakdowns (e.g. with underpasses) (DWA-A 118, 2006).

A flood test with assessment of the potential hazard can be performed with a description of the flow paths on the surface and the determination of depressions in the environment of the overflowed manholes. The following procedure is offered:

- Summary of the manholes with significant overflow volume in the sewer network model to potential hazard areas.
- Determination of the depression using the digital terrain and surface area model. Depressions are areas that lie deeper than the surrounding area by a specified measure.
- Determination of the flow paths on the surface using analysis of the digital terrain model (DGM) and aerial photographs.
- Identification of possible flooding areas using the simulated overflow volume.
- Compilation of the potentially threatened depressions in the area and rough quantifica-tion of possible damages and risks.

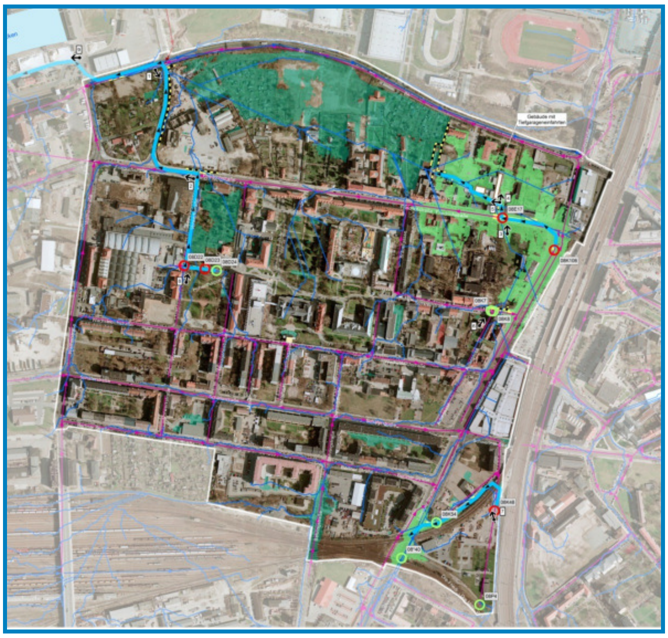

Fig. 3 Flow path and depression analysis as results of the flooding test (stage 2)

Figure 3 shows the flow paths and depression for an example area. In many cases, the visual analysis of local conditions and estimation of the local situation (e.g., edge of the road) is recommended.

D. Stage 3 – Technical model flooding calculation

In order to create concrete flood hazard maps, e.g. with flooding heights or flow intensities, a detailed 2-D simulation of the flooding on the surface from the sewer network is needed. The sewer network model is coupled with a detailed surface runoff model for this purpose For the coupled simulation, the hydrodynamic sewer network model Hystem-Extran (itwh, 2010) and a 2-D surface runoff model are used (Fraunhofer ITWM, 2010).

The surface runoff model offers the possibility of a detailed 2-D simulation of the surface runoff and is based on the numerical solution of two-dimensional shallow water equations.

The surface runoff of the water is influenced by the topography, the sealing of the soil surface, and the geometric direction of line elements such as street boundaries and curbs, among other things. The availability and reliability of this data, as well as its implementation in physical parameters, affects to a considerable degree the quality of the simulation results (Fraunhofer ITWM, 2010).

The topography and line elements are depicted by a triangulated terrain model whose triangles simultaneously form the cells of the numerical calculation approach.

Compared to equidistant terrain models, a more precise depiction of structures is achieved with the same number of cells by using triangle meshing.

The bidirectional coupling between sewer network model and surface model allows the re-infiltration of flooded water into the sewer network. In contrast to conventional approaches, the water does not necessarily reenter at the same spot where it originally came from, but rather reenters where it flows to due to the topographical conditions. In this way, a dynamic relationship of the whole system is achieved that permits statements to be made about the chronological course of flooding events.

The interfaces for the exchange between both models are manholes and road drains. At these locations, there are exchange nodes that are known from the point of view of both models, and through which the exchange of water volume and additional relevant information for the calculation occurs.

III. Example of a Coupled Network- and Surface Simulation

For the coupled simulation, the existing sewer network model for the city of Dresden can be used, including the runoff-forming hydrologic drainage area, which for instance is already being used in processing stage 1, the backwater and overflow test.

The objective of step by step processing for the hazard analysis and risk assessment is to minimize the processing expense. The detailed surface runoff model is therefore only set up for the areas in processing stage 2 that were determined to be threatened. The work steps are divided into preprocessing, model generation, simulation and post-processing. Geographic information systems are used during pre- and post-processing and for model generation.

A. Preprocessing and model generation

Preprocessing comprises the collection, selection and preparation of raw data so that it can be used for creating the surface runoff model. The following basic data is essentially needed for the preprocessing:

- Laser scanner data of ground points
- Building polygons
- Linear structures (e.g., curb edges)
- Location information about the street drains
- Location and names of the manholes
- Land use map to determine roughness coefficient

The captured data as well as the laser scanner data are customized to the areas to be examined. Building polygons, linear structures and street drains in the project area were extracted from the cadastral map of the city of Dresden. In the terrain model, buildings are cut out as insurmountable runoff obstacles. In order to take into account the runoff-guiding effect of linear structures, such as for instance curb corners, in the calculation of the runoff, these structures are integrated into the model as breaklines.

Furthermore, the use of orthophotos for area analysis and validation of the raw data has proved to be necessary. If needed, the raw data must be manually supplemented with these orthophotos.

The usage classes from the land use map are assigned roughness coefficients, which are set in the respective calculation cells for the simulation of the surface runoff. Figure 4 shows the data prepared in the GIS for the model generation.

This data is the input data of the model generator. The result of the model generation is a model that can be used for the 2-D simulation.

Fig. 4 Depiction of the data for model generation

B. Simulation and post-processing

The simulation is done in a parallel manner in the sewer network and surface model, and these simulations are bidirectionally coupled. In this way, an exchange between the runoff processes on the surface and the sewer network takes place. In practical terms, this means that water escaping to the surface due to flooding at a drain runs off according to the slope conditions, and only reenters the sewer network where drains exist and there is enough capacity in the sewer network.

The follow-up work and preparation of results of the simulation is termed post-processing. In this process, the large quantities of data produced in the simulation are transformed into a clear presentation form, for example in graphs and animations.

Figure 5 depicts the maximum water levels from the coupled simulation for an example area in Dresden. It is evident from which overflowed manholes the floods come from. In addition, different colors depict which areas are potentially affected with which maximum water level.

Based on this analysis of the potential hazard, an estimation of the possible risks to buildings and municipal infrastructure, but also to life and limb, can be made.

If there is a need for action, preventive measures based on coupled sewer network and surface runoff simulation can be reviewed with regard to their effect and interaction for minimization of the flooding hazard.

Fig. 5 Maximum water levels on the surface in the flooding areas (stage 3)

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III. SUMMARY

For effective risk management to cope with the danger of heavy urban rains, it is necessary to analyze in as much detail as possible the potential hazards. Geo information systems are an indispensable tool for preparation of the basic data needed for this purpose and for presentation and analysis of the area-related potential hazards. This is the foundation for risk assessment.

An example of hazard analysis and risk assessment was performed as part of the REGKLAM project (Regional Climate Adjustment Program Model Region Dresden) for individual areas in the city of Dresden.

For this project, a method was developed that is adjusted to the potential hazard in a gradually higher degree of detail. The respective stages provide for a manhole-related classification through backflow and overflow testing using hydrodynamic model calculation (stage 1), a flood test by analysis of the flow paths and depressions in the terrain (stage 2), and a detailed flood simulation using coupled sewer network and surface calculation (stage 3).

The presented method offers an effective approach to create flood hazard maps. The affected areas can be analyzed with regard to risks, potential damages and special vulnerabilities, and thus the method is the basis for effective risk management.

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