Urban flash flood modelling based on soil sealing information derived from high resolution satellite data

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Abstract Long-term studies of heavy precipitation and an analysis of reported flash flood events over the last 30 years already reveal an increase in such events for parts of Southern Germany. Whereas part of the increase of flash flood hazard can be ascribed to climate change, urban development leads to an increase of impervious areas and thus heavily affects surface runoff. To study the effects of surface sealing on urban flash flood hazard, high resolution satellite imagery of the city of Tuebingen, Southwest Germany is used to determine the percentage of impervious areas, which is then used as input data in a storm runoff model. The study shows that the approach is well suited for an analysis of the effects of urban surface sealing. Together with high quality LiDAR-based Digital Elevation Models, a detailed analysis of urban flash flood hazard is possible.
Keywords flash floods; surface runoff; hydrologic/hydraulic modelling; impervious areas; soil sealing; LiDAR-DEM; QuickBird; remote sensing

INTRODUCTION

Over the last years there has been a growing public and scientific interest in the phenomenon of flash flooding in urban areas. Long-term studies of heavy precipitation reveal an increase in storm events for Southern Germany. Parallel to these findings, analyses of the reported number of flash flood events over the last 30 years in Germany also show a positive trend (Hydrotec 2008). Whereas part of the increase of flash flood hazard can be ascribed to climate change, the increase of impervious areas as a consequence of urbanisation also has a great effect on the local water balance.

A general problem in modelling surface runoff in urban areas is the lack of information about the characteristics and distribution of urban soils. Another major disadvantage is the lack of knowledge about the spatial distribution of soil sealing, which highly influences the amount of surface runoff.

To summarize, in urban hydrology modellers have to cope with the paradoxical situation that especially for those areas where detailed spatial information would be necessary to make useful predictions for flooding (i.e. urban areas), there is such a tremendous information gap concerning input data. Whereas information on urban soils is very difficult to obtain and usually associated with time-consuming field work, the degree of surface sealing can be estimated using optical aerial photography or satellite imagery and elaborated classification approaches (Esch et al. 2008, Bachofer et al. 2009).

The objective of this study is to find out if high resolution QuickBird satellite imagery can be used to model the surface sealing in an urban environment and if this information can be used as an input to calculate surface runoff for storm events with a physically based rainfall-runoff model.

OBJECT-BASED LAND USE AND LAND COVER CLASSIFICATION AND SOIL SEALING MODELLING

For this study, a high resolution QuickBird satellite image with a multispectral resolution of 2.44 metres and a panchromatic resolution of 0.61 metres was obtained for 27 June 2007 for the city of Tuebingen, Southwest Germany. The spatial and spectral heterogeneity of such imagery, resulting from the high spatial resolution, makes urban landuse and landcover (LULC) classification a challenging task. Object-based image analysis (OBIA) provides the possibility to use shape parameters and neighbourhood relations in addition to spectral information for the classification.

A crucial point in object-oriented classification is the process of image segmentation. The challenge is that image objects should represent meaningful structures which vary significantly in size and shape, like for instance buildings (small objects), open spaces/parks (large objects) or streets (long and thin objects). For that reason, the classification was based on 3 levels representing different object sizes using a multiresolution segmentation algorithm for each level (Baatz & Schäpe 2000) and class descriptions with fuzzy logic.

The Java-based software iSurf-A (Impervious Surface Analyst) used in this study has been developed at the University of Wuerzburg, Germany. It is based on a support vector machine (SVM) approach and can be run either with digital aerial or satellite imagery. SVMs belong to the latest methods of supervised classification and evolved from statistical and automatic learning theory. The LULC classes were reclassified in binary classes, representing pervious and impervious areas. A subset of the reclassified raster was used as training area to generate a regression model in iSurf-A, which was then applied to the whole satellite image to derive the percentage of impervious area for each image pixel of the satellite image (see Fig.1).

Fig. 1 Soil sealing derived from high resolution QuickBird image (blue box: map extent in Fig.2).

URBAN FLASH FLOOD MODELLING

Calculation of excess rainfall (surface runoff)

The resulting raster file of the surface sealing modelling contains information about the pervious and impervious portion of each grid cell. This sub-grid variability can be used to calculate spatially distributed excess rainfall values. The widely used SCS Curve Number Method (USDA 1986) was adapted to calculate a pixel-based composite curve number (CCN) for each grid cell according to the following formula:

$$CCN = CN_i \cdot a + CN_p \cdot (1 - a) \qquad (1)$$

Variable a represents the degree of surface sealing reaching from a = 0 (no surface sealing) to a = 1 (100% impervious). The curve number (CN) is a runoff coefficient which is dependent on land use and hydrologic soil group. For the impervious part of each grid cell, a is multiplied with CN_i = 98 as commonly used for impervious areas. According to the LULC classification the prevailing land cover of the pervious parts is grass. The hydrologic soil group B (USDA 1986) was selected according to the major soil type of the area surrounding Tuebingen. The combination of land cover type grass and soil group B leads to a CN_p value of 71 (USDA 1986). The excess rainfall is calculated with the Curve Number formula using the CCN for each grid cell:

$$Q = \frac{\left(P - \frac{5080}{CCN} + 50{,}8\right)^2}{P + \frac{20320}{CCN} - 203{,}2} \qquad (2)$$

With P = Rainfall [mm] and Q = Excess rainfall [mm]

Overland flow modelling using GRASS GIS module *r.sim.water*

The model *r.sim.water* is incorporated in the open-source GIS software GRASS (Geographic Resources Analysis Support System, GRASS Development Team 2009). It is based on a path sampling approach which means that the process of water flow is modelled for each sample (or particle). It uses the concept of duality between particle and field, where the density of particles in space represents a field and vice versa. In this case, the evolution of particle density represents the process of shallow water moving on the landscape surface and accumulating in channels and depressions. The incorporation of a diffusion-like term enables the water flow to spread in flat areas and to fill depressions until it flows out in the prevailing direction (see Mitasova & Mitas 2001 for a detailed description). A LiDAR-DEM with 1 m cell size and ±0.15 m vertical accuracy and the excess rainfall grid were used as input in *r.sim.water*.

RESULTS AND DISCUSSION

Flow depths were calculated in 5 minute intervals for a rainfall intensity of 30 mm h^{-1}, which is the amount of rainfall of a storm event in 2002 causing local inundations in Tuebingen. The results show that surface runoff mainly follows the streets and accumulates in a depression where several streets meet. The location of high flow depths are in relatively good accordance to buildings which were inundated in the 2002 event (Fig. 2). The model results clearly show that in areas of high surface sealing (e.g. in the inner city) the danger of local flooding is increased.

The approach presented in this study can serve as a basis for an assessment of urban flash flood hazard. Scenarios like rainfall events of different intensity or changes in urban development (e.g. reduced or increased soil sealing) can be simulated und their effects can be studied in detail.

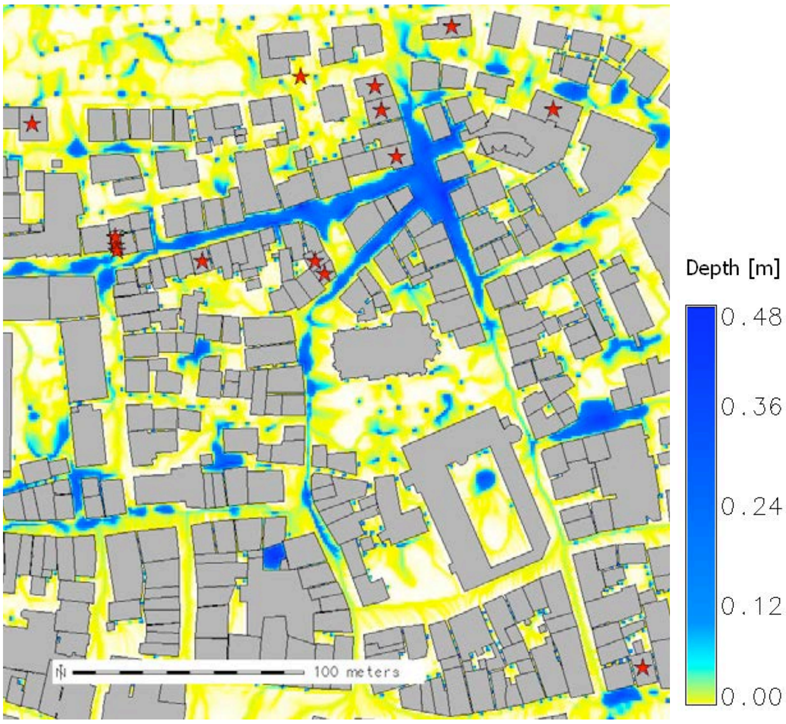

Fig. 2 Flow depth after 1 hour with a rainfall intensity of 30mm h^{-1} for the city centre of Tuebingen using a 1m-DEM and soil sealing information as input. Red dots show inundated buildings for the 2002 event.

Remotely sensed soil sealing information proved to be a good method to calculate storm runoff for urban areas. To further improve the model, a simplified method could be incorporated to account for losses of surface flow into the urban drainage system. As an alternative, the GRASS model *r.sim.water* could be coupled with a sewage model that is able to simulate surcharge and outflow from the sewage system. A drawback of the approach is that *r.sim.water* is computationally intensive and limited to an area of approximately 3.5 km² for a DEM resolution of 1m and a number of 2 samples per grid cell (i.e. 7 million samples in total).

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