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A strategy towards improved hydrological model parameterisation in urbanized catchments using remote sensing derived impervious surface cover maps

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Abstract

Urbanization is strongly influencing the hydrological processes, often causing a reduction of groundwater recharge and severe flooding. Hence, there is an urgent need to approach urban water management in a more sustainable way. The problem analysis, planning and monitoring of sustainable urban water management requires reliable and sufficiently detailed information on the urban environment.

The biggest impact of urbanization on the hydrology is caused by the increase in impervious area. Precipitation over these impervious areas is hindered to infiltrate and will mostly flow overland towards sewers systems. The cover percentage and spatial distribution of impervious areas in a basin is therefore a parameter indicating the ‘health’ status of the basin.

Currently, land cover/use parameterisation of most rainfall-runoff models is largely based on classes. Typically, soil and land-use classes are parameterized with values from literature. For example the impervious area coverage in a pixel determines the infiltration capacity but is fixed per land-use type. Recently, methodologies have been developed which allow estimating the sub-pixel impervious area based on remote sensing images. This paper describes current methodologies to parameterize urban areas in distributed hydrological models, as well as possibilities of new remote sensing based techniques to parameterize impervious surfaces in hydrological models.

Keywords

Sub-pixel imperviousness; rainfall-runoff modelling; remote sensing; hydrology

INTRODUCTION

Urban change processes that have taken place over the last decades are affecting the human and natural environment, including the urban hydrology, in many ways (EU, 2006). As the population of urban environments is rapidly increasing, urbanized areas are changing rapidly. The United Nations Population Fund (UNFPA, 2007) has predicted that from 2008 onwards, more than half of the world’s population, 3.3 billion people, will live in towns and cities, a number which is expected to swell to almost 5 billion by 2030. As a result of the increasing population living in urban areas, the demand for land in and around cities is becoming increasingly acute (EU, 2006).

Urbanization almost inevitably leads to an increase in sealed surfaces. Impervious surfaces in the context of this paper are defined as every material that prevents water from infiltrating into the soil. Examples of impervious land-cover surfaces are: concrete, asphalt, rooftops, tiles or compact soils. Most of these impervious surfaces have an anthropogenic origin, as for example: roads, houses, shopping centres, pavements and parking lots (Bird et al., 2000).
The presence of anthropogenic impervious surfaces in general leads to more surface runoff (e.g. Grove, 2001). The increase in surface runoff is, in most cases, caused partly by reduced evapotranspiration but mainly by reduced infiltration. The increase in impervious surfaces cover causes a higher surface runoff and influences the flood hydrographs as shown on Fig. 1 (Arnold and Gibbons 1996, Paul and Meyer 2001). As a consequence, more flooding events are expected when urbanization is pushing through.

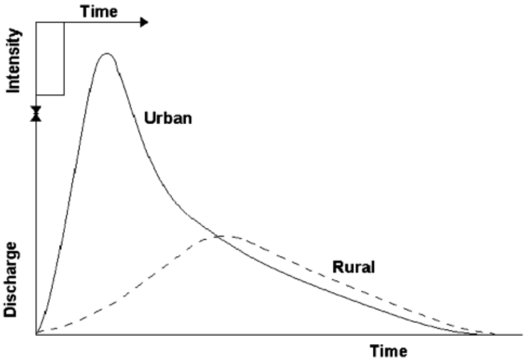

Figure 1: Flood hydrographs for urbanized and rural drainage basins

Apart from the quantitative effect that urbanization has on the hydrological processes, impervious surfaces also cause qualitative changes (Pitt, 1995; Paul and Meyer, 2001; Hatt et al., 2004). Urban runoff collects high amounts of waste particles originating from the urban atmosphere, traffic, household or industrial activities, etc. Instead of infiltrating into the soil where these particles could be retained and partly consumed by micro-organism, on sealed surfaces these waste particles will be directly transported towards the sewer system, a river or another surface water body (Bird et al., 2000). The latter scenario occurs strongest during storm events (Schueler, 1994).

Urbanization also affects stream ecosystem functioning. Several studies have shown that an increase in total impervious area of a catchment results in a decrease in stream biotic health (Stephenuck et al., 2002; Morse et al., 2003; Ourso and Frenzel, 2003). Furthermore, groundwater recharge will decrease in urbanized areas, resulting in low river discharges during dry seasons (Perkins, 2004). In combination with stream pollution, even an imperviousness area cover of around 10 to 15% will lead to a considerable decrease in aquatic biodiversity (Prisloe et al., 2000; Perkins, 2004).

To reduce negative impacts of urbanization on a watershed scale, effective urban management approaches based on the notion of sustainable development should be implemented. Such a sustainable urban management plan requires reliable and sufficiently detailed information on the urban environment (EU, 2006). The catchment impervious cover has been shown to be a powerful proxy indicator that accounts for many of the factors mentioned above (Schueler, 1994; Morse et al., 2003). Measures of the catchment impervious cover and its dynamics would therefore reveal important information for sustainable development of the urban hydrological system.

CURRENT PARAMETERIZATION METHODS OF URBAN AREAS IN PHYSICALLY BASED, HYDROLOGICAL MODELS

Integrated water management requires detailed knowledge of the hydrological processes on basin

scale. Hydrological models are crucial tools to predict and allocate flooding events and groundwater recharge on basin scale. Spatially distributed simulations are in this case important to predict where the river will flood and where the groundwater system will be recharged or where it will discharge its water. Therefore, the first spatially distributed hydrological model was already developed in the late sixties (Freeze and Harlan, 1969). In the mean time different spatially distributed hydrological models have been developed as for example: TOPMODEL (Beven et al., 1995), SWAT (Nietsch et al., 2002), WetSpa (Liu et al., 2002; Wang et al., 1996), MIKE-SHE (Abbott et al., 1986).
Parameter optimalisation of hydrological processes in spatially distributed models has been an important research topic in the past. However, parameterisation is often difficult due to a lack of spatially distributed information. Current methods to parameterize the urban areas in hydrological models differ with respect to the description of the land-surface processes in the model.

Often indirect methods are used to estimate the percentage of imperviousness of a certain land-use type (Prisloe et al., 2000). For example in the current WetSpa version (Liu et al., 2002), all pixels in the distributed hydrological model are linked to a certain land-use type. In hydrological modeling on basin scale the present day grid resolution is mostly in the range of 50-500 m. The land-cover in the grid cells are often a mixture of different land-cover types. For example, a pixel indicated as urban is likely to contain some grass and tree cover (gardens and parks) next to the road, houses and paved area. To incorporate this heterogeneity urban land-use types are linked to an assumed percentage of imperviousness. The imperviousness of urban areas has an impact on the potential runoff coefficient, which in the WetSpa model is used to calculate the infiltration and excess rainfall in each pixel. The imperviousness percentages can be changed during the calibration process. The drawback of this approach is that there is no standardized method for the derivation of this average percentage imperviousness per land-use type. Furthermore, variability in the amount of imperviousness within the same land-use class is not incorporated.

Also in the MIKE-SHE model (Abbott et al., 1986) a paved runoff coefficient, obtained by calibration, can be included for each land-use type. Usually a relatively high value is given for the paved runoff coefficient for paved and urban areas, while for other land-use types the coefficient is mostly put to a low or zero value (Oogathoo, 2006).

The Soil and Water Assessment Tool (SWAT), developed by the USDA Agricultural Research Service, is a widely used physically based, time continuous, semi-distributed river basin scale model. SWAT aims to quantify the impact of land management practices on water quantity, sediment and water quality in large complex watersheds with varying soil, land-use and management conditions over long periods of time. The semi-distributed characteristics of the model are linked to the division of the catchment into sub-catchments, which are divided into Hydrological Response Units (HRU's): portions of the sub-basin containing a unique combination of land use and soil. The processes are lumped at the HRU level and the discharge of the sub-catchments is routed through the river network to the main channel and the basin outlet. The HRU's that represent the urban areas consist of a certain percentage of impervious area and grass for the remaining area.
For the surface runoff, SWAT provides two methods: the SCS curve number method (Soil Conservation Service, 1972) and the Green & Ampt infiltration method (1911). The SCS curve number is a function of the soil's permeability, land-use and antecedent soil water conditions. The Green & Ampt infiltration method highly depends on the value of the hydraulic conductivity and the moisture condition of the soil (Neitsch et al., 2002).

TOPURBAN (Valea and Moin, 2000) is an adapted version of the TOPMODEL (Beven et al., 1995), which can be used to incorporate catchment urbanization. In the TOPURBAN model, urban areas are integrated using an alternative topographic index, while the mechanisms for runoff generation are adapted. Regarding the overland flow resulting from urbanization, two versions of

TOPURBAN have been developed. The first model assumes that precipitation onto impervious surfaces will immediately become overland flow (Valea and Moin, 2000). Flow generated by urban areas within a sub-catchment is calculated using a calibrated parameter that accounts for the fraction of imperviousness in the urban area (Valea and Moin, 2000). The second version of TOPURBAN takes into account storage ponds that collect urban runoff.

It can be concluded that most physically based hydrological models use the amount of impervious area in the watershed, whether in a distributed, semi-distributed or lumped manner, to incorporate urbanization effects. The degree of imperviousness is estimated or calibrated on a sub-pixel scale (WetSpa and MIKE-SHE), on the HRU scale (SWAT) or on sub-basin scale (TOPURBAN).

MEASURING THE IMPERVIOUS SURFACE COVER

Available techniques

Different methodologies are able to generate impervious surface area maps: ground surveys, Global Positioning Systems (GPS), aerial photo interpretation and photogrammetry, and satellite remote sensing (Slonecker, 1994). Ground surveys, using GPS as a tool to collect the field data, are very reliable but expensive and generally not practical for mapping large areas (Bauer et al., 2004). Impervious surface areas can be readily interpreted from aerial photography, therefore aerial photos have been an important source of land-use/land-cover information in the past (Draper and Rao, 1986). However, also the cost of these aerial photography acquisition and interpretation of cover types is expensive for large areas (Bauer et al., 2004). An alternative is to use digital satellite imagery to measure the impervious surface cover.

According to their spatial resolution RS imagery can be divided into high, medium and low resolution imagery. High-resolution sensors like Ikonos or Quickbird have a spatial resolution of respectively 4 and 2.8 metre for their multispectral bands. Although these high-resolution images are not as detailed as most aerial photographs, the use of automated or semi-automated image interpretation methods, using the multi-spectral information content of the imagery, substantially reduces the effort to derive the impervious surface cover (Chormanski et al., 2008). Disadvantages of high-resolution data are their relatively limited footprint, 11 by 11 km for Ikonos and 16.5 by 16.5 km for Quickbird, their relatively high cost and their low spectral resolution. Both Ikonos and Quickbird have a panchromatic band and a blue, green, red and near infrared band. In order to obtain very accurate classification results, object oriented characteristics should be included (Zhang, 2001). However, object oriented classifications require specialized knowledge and software.

In order to cope with the previous mentioned disadvantages of high resolution imagery for impervious surface mapping, models have been developed that allow estimation of the degree of imperviousness inside medium-resolution image pixels (type: Landsat ETM+, ASTER, SPOT, etc.). Medium resolution images have a larger footprint for example 185 by 185 km for Landsat ETM+ and 60 by 60 km for ASTER. Besides, the cost for medium resolution images is much lower, while the spectral resolution is higher: Landsat ETM+ has seven spectral bands and an additional panchromatic band, ASTER has fourteen spectral bands. Typically, medium resolution images have a spatial resolution between 15 and 100 m. Landsat ETM+ images have a resolution of 30 m for the visual and near infrared bands and 60 m for the thermal bands, ASTER images have a resolution of 15 m for the visual and near infrared, 30 m for the short wave infrared and 90 m for the thermal bands. Hence, in most cases the land-cover in the pixels is a mixture of different land-cover types.

Recently, models have been developed that allow estimating the percentage impervious fraction per pixel. Methods that estimate the degree of imperviousness inside image pixels are based on mixture modelling techniques. Mixture modelling aims at finding the mixed reflectance from a set of pure end-member spectra (Van der Meer and De Jong, 2000). This implies that these mixture techniques assume all land-covers should be composed from a few basic components (called end-members), such components could for example be impervious areas, vegetation, water, etc. It is assumed that these end-members have a constant spectral signature. Spectral unmixing, is a deconvolution technique that is able to estimate the surface abundance of a number of spectral components that cause the measured (mixed) spectral signature of the pixel (Settle and Drake, 1993). Different unmixing techniques have been developed.

Remote Sensing unmixing techniques

Linear spectral unmixing. The idea behind linear spectral mixture analysis is that the spectrum recorded for every image pixel by the sensor is a linear combination of different endmember spectra (Tompkins et al., 1997). This means that the value of a pixel in an image for a band equals the weighted sum of the radiance values for that band of all targets present in the pixel (Kärdi, 2007). Choosing appropriate endmembers and spectral signatures is of high importance for accurate linear spectral unmixing. Linear spectral unmixing has been used for impervious surfaces extraction by Ji and Jensen (1999), Phinn et al., (2002), Wu and Murray (2003) and Lu and Weng (2004).

Non lineair unmixing. Apart from the linear spectral unmixing techniques also non-linear unmixing methodologies have been developed. Non-linear unmixing methods that have been implemented include neural networks, fuzzy classifiers, regression and decision trees, Gaussian mixture discriminant analysis and maximum likelihood classifiers (Liu and Wu, 2005). Non-linear unmixing models require training data. Often a high-resolution land-cover classification is performed over a part of the medium resolution image. Information derived from the co-registration of the high and medium resolution image can be used as training and validation data. In most cases non-linear unmixing models outperform simple linear unmixing models (Liu and Wu, 2005).

Statistical methods. Because linear and non-linear unmixing models require quite some effort, statistical based methods have been tested to measure the degree of impervious inside a medium resolution pixel. Using information from a co-registration of a high resolution image over a part of a medium resolution image, Yang (2005) developed a relationship between the degree of imperviousness and the brightness and greenness derived from tasselled-cap transformation of the ETM+ image. Braun and Herold (2003) used a linear spectral unmixing technique based on pure endmembers to estimate the imperviousness fraction and showed there was a strong relationship between the Normalized Difference Vegetation Index (NDVI) and the degree of imperviousness.

Although sub-pixel techniques are generally not able to reach the same level of accuracy as the high resolution classification, Chormanski et al. (2008) reports that in most studies the average per pixel proportional error of estimated impervious surface is not higher than 10%. As the resolution of medium resolution imagery is in most cases comparable with the resolution of distributed models on basin scale, the resulting end-member fractions are often relatively easy to incorporate in the hydrological models.

RESEARCH STATUS ON THE IMPLEMENTATION OF REMOTE SENSING DERIVED IMPERVIOUS COVER MAPS FOR RAINFALL-RUNOFF MODELING

Impervious surface cover maps have been used in hydrological research for quantifying the long-term effect of the rainfall-runoff relation (Dougherty et al., 2007). However, little research has been done on implementing measured impervious maps in hydrological models.

Chormanski et al. (2008) recently incorporated sub-pixel information, derived from RS observations, into a distributed rainfall-runoff model WetSpa. The WetSpa model was adapted for this sub-pixel imperviousness input. The degree of imperviousness is used for the calculation of the runoff coefficient and the depression coefficient. The runoff coefficient determines the amount of excess rainfall and the infiltration. The depression coefficient determines the surface storage. Chormanski et al. used three different scenarios; scenario one assumed a non-distributed impervious surface value for all urban classified area, scenario two assumed six different urban land-use classes all having a different degree of imperviousness derived from sub-pixel and high resolution estimation, the third scenario used the fully distributed imperviousness degree derived from the high resolution classification and the sub-pixel classification. The highest peak discharges were obtained by the fully-distributed scenario (scenario three), lower peak discharges were obtained for the semi-distributed scenario and the lowest for the non-distributed scenario. The results using the fraction of imperviousness obtained from the sub-pixel classification based on a Landsat ETM+ image differs less then 10% from the results obtained by the high resolution classification.

CONCLUSION

As cities are expanding, sustainable urban management is becoming increasingly important to maintain or increase the quality of life in urban areas. Several studies conclude that impervious surface cover is a key factor for hydrological changes due to urbanization. Assessing impervious surface cover deserves therefore the highest attention in hydrological models, which incorporate urban regions.

Currently, most hydrological models describe artificial impervious surfaces in a simplified manner: most distributed hydrological models estimate the degree of imperviousness by an empirical value or as a parameter which should be calibrated. However, sensitivity analysis has shown that in many cases the impervious surface cover has an important impact on the model predictions. A constant impervious percentage per land-use type could be used as a calibration parameter to improve the model evaluation result. However, because in most cases only one discharge time series at the outlet of the basin is used for model calibration and validation, an improvement of the model evaluation after calibration of the impervious percentage per land-use does not imply an improved model prediction at other places than the basin outlet. It is evident that a pixel based calibration of the urban imperviousness without additional information apart from the outlet discharge is impossible, if not due to time constraints, due to the problem of equifinality. Spatially distributed measurements of the surface impervious land cover could therefore improve the model predictions, including the spatial variation of the output, considerably.

Recently, methodologies based on RS observations, have been developed, which simplify the estimation of the degree of imperviousness compared to field observations or aerial photography interpretation. RS techniques using unmixing models to estimate the sub-pixel impervious fraction of imperviousness have show to be practical tools for large area imperviousness mapping. Hence, it is expected that these obtained imperviousness maps will significantly improve the parameterisation of physically based hydrological models.

In future research it is planned to prepare a case-study to verify if better modelling results can be obtained with hydrological models when spatially distributed impervious land cover maps are incorporated.

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