06 - IMPACT ASSESSMENT OF URBANISATION ON HYDROLOGY FOR THE RIVER TOLKA IN DUBLIN, IRELAND: A CASE STUDY OF REMOTE SENSING SUPPORTED HYDROLOGICAL MODELLING

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Abstract

Urban areas are characterized by a large coverage of sealed surfaces. Sealed surfaces play an important role in the hydrology of strongly urbanised catchments. They prevent water from infiltrating into the soil and water runs off faster than under natural conditions. As such an increase of these surfaces due to urbanisation will most likely have a considerable effect on the amount and intensity of the generated surface runoff. Within the framework of the MAMUD project (www.mamud.be) one of the aims was to assess the impact of urbanisation on hydrology in Dublin. Main focus is the use of earth observation based techniques to measure, understand and model urban dynamics and its impact on life and environment. Using a time-series of medium resolution satellite images (Landsat and SPOT - 1988, 1994, 1997, 2001 and 2006) urban development within the Greater Dublin Area was monitored, resulting in a set of urban masks. A land-use change trajectory analysis ensured the consistency of the sequence of urban masks and allowed correction in time. Additionally, instead of using subjectively defined expert-based average sealed surface values for static land-use classes, direct earth observation based estimates of sealed surface cover were used. These were obtained by applying a regression-based sub-pixel classification approach. Finally a land-use change model (MOLAND) was used to develop a number of urban growth scenarios for Dublin. The consistent urban masks and sealed surface fractions were integrated into a hydrological model. Use was made of the fully distributed, physically based rainfall-runoff model WetSpa, which was adapted for flexible input of remote sensing derived model parameters. The remote sensing supported hydrological model was applied on the River Tolka catchment. The results show that urban land use, with a rather limited coverage, accounts for a considerable amount of the generated surface runoff. The time-series of five sub-pixel sealed surface maps (1988, 1994, 1997, 2001 and 2006) was used to assess the urban growth processes and simulate the effects on hydrology. The simulations with sub-pixel sealed surface proportions yield considerable differences in discharge, confirming the importance of sealed surface cover as a key factor in describing the hydrological dynamics in urban catchments. The results of one urban growth scenario suggest an even bigger impact of urbanisation on runoff in the future.

Key words: urban dynamics, impact hydrology, sealed surfaces, Tolka River

1. Introduction

Every year several European cities are confronted with flood events of varying magnitude. Flood hazards seem to have become an inconvenient certitude in the urban context. Although the origin of these events often lies in a combination of factors (e.g. extreme rainfall in short time, saturated soils, hydraulic obstructions in rivers, etc.), the specific characteristics of the urban landscape most certainly plays a role.

Urban areas are characterized by a large coverage of sealed surfaces. The term sealed surface is preferred over impervious surface, because it better expresses the fact that pervious surfaces have been sealed due to urbanization.
Sealed surfaces play a key role in the hydrology of strongly urbanised catchments (Paul & Meyer, 2001; Jennings & Jarnagin, 2002; Dougherty et al., 2004; Mejia & Moglen, 2010). Sealed surfaces prevent water from infiltrating into the soil, flow paths are altered and water runs off faster than under natural conditions (Wessolek & Facklam, 1997; Dougherty et al., 2004). As a result sealed surface hamper groundwater recharge and contribute strongly to the occurrence of flood events. Typical examples of sealed surfaces are roads, sidewalks, roofs, parking lots, etc.
An increase of sealed surfaces due to urbanisation will most likely have a considerable effect on the amount and intensity of generated surface runoff in the future.

This paper focuses on a methodology to assess how urban growth and a resulting increase of sealed surfaces impact runoff and (peak) discharge in urbanised river catchments
The presented research frames within the MAMUD project (www.mamud.be). MAMUD is an acronym for Measuring And Modelling Urban Dynamics. The main goal of the project is to investigate how earth observation can contribute to a better monitoring, modelling and understanding of urban dynamics, and its impacts on the urban and suburban environment.
One of the aims of the MAMUD project is to integrate earth observation information on land cover and sealed surface proportions into the hydrological modelling process to assess the impacts of urbanization in the Tolka River catchment in Dublin. Chormanski et al. (2008) showed that the use of satellite imagery improves estimation of sealed surface proportions for hydrological modelling purposes. The Tolka River catchment in Dublin was selected because (1) Dublin has known a strong urban growth during the past decades (O'Sullivan et al., 2009) and (2) the Tolka River has a long history of floods (DCC, 2005). This combination of a steady urban growth and occurrence of flood events and the fact that the Tolka catchment shows a clear sealed surface gradient, makes Tolka and Dublin in general an excellent case-study to assess the impact of urbanisation on hydrology.

The objectives of this study are:

- Assess urban dynamics (land use and sealed surfaces) in Dublin using earth observation information in an integrated land-use change modelling strategy.
- Assess the spatial and temporal impact of urbanisation on hydrology of the Tolka River catchment.
- Complement existing hydrological impact studies (e.g. hydraulic models within the framework of the Greater Dublin Strategic Drainage Study).

2. Methodology

Hydrological models are indispensable to describe and study hydrological conditions in (urban) catchments. Fully distributed hydrological models allow spatial and temporal analysis, but need spatially distributed input data, which are often difficult and/or expensive to collect. However, earth observation potentially offers a relatively easy and cheap way of collecting spatially distributed information of the earth surface.

The integrated methodology can be summarized as follows:

1. Land-cover classification for urban mask delineation.
2. Mapping sealed surface proportions.
3. Land-cover change trajectory analysis.
4. Land-use change modelling.
5. Hydrological impact modelling.

<u>1. Land-cover classification for urban mask delineation.</u>

In this study existing CORINE land-cover maps (1990, 2000 and 2006) are complemented with land-cover information derived from Medium- and High-Resolution (MR and HR) imagery. The medium resolution (15 to 30m) is too coarse to acquire information on individual urban objects. However continuous mapping of sub-pixel proportions of major land-cover components like sealed surfaces or vegetation may reveal important information on urban structure that are useful for monitoring urban sprawl and intensity of urban development (Van de Voorde et al., 2011).
Using an unsupervised land-cover classification approach, including a knowledge-based post-classification (Van de Voorde et al., 2007), the Landsat (1988-2001) and SPOT (2006) imagery are used to generate a time-series of urban masks.

<u>2. Mapping sealed surface proportions.</u>

Because of its conceptual simplicity the well-established linear spectral mixture analysis (LSMA) approach (van der Meer, 1999) has been selected as sub-pixel classifier. The only input it requires is the identification of endmembers. This method assumes that the spectral signature of each pixel is a linear combination of pure land-cover spectra, called endmembers (e.g. bare soil, vegetation, etc.). Once the endmembers have been identified, the fraction of each endmember in a mixed pixel can be determined. In this study the focus lies on the sealed surface fraction. Artificial surfaces used in urban areas are spectrally heterogeneous and are often confused with permeable surfaces such as bare soil, however, and can therefore not be represented by a single endmember (Small, 2004). Instead of deriving the sealed surface fraction directly from LSMA, we assumed that it is complementary to the vegetated fraction within the urban mask (derived in step 1). We used the HR classification as reference data for calibrating a linear mixture model that was then applied on the MR imagery. This calibration procedure involves a temporal filtering method to account for differences in vegetation state between the acquisition dates of the HR and MR images (Van de Voorde et al., 2009) The entire procedure was repeated for each Landsat/SPOT image from the time series. The result is a time-series of sealed proportion maps.

<u>3. Land-cover change trajectory analysis.</u>

Errors occurring in the derivation of the urban masks due to classification errors, as well as image registration errors, have an impact on the change trajectory observed for each MR-pixel in the time series. Urban mask errors also affect sub-pixel proportion maps. So we analysed the rationality of land-cover change trajectory in order to better understand the errors that occur and

possibly reduce errors or at least be able to take them into account in the data processing chain.
The five urban masks for the Landsat/SPOT time-series (1988, 1994, 1997, 2001 and 2006) were therefore subjected to a change rationality analysis. The status of a pixel in each urban mask was either 0 (non-urban), 1 (urban) or X (= no data due to cloud cover).
Based on this analysis the urban masks from step 1 are corrected assuring consistency in the urban/non-urban change trajectory or urban dynamics through time.

4. Land-use change modelling.
A spatially-dynamic land-use change model (based on cellular automata) for Dublin was developed as part of the MOLAND project (Engelen et al., 2007). Cellular Automata based models have perhaps become the most popular way to model land-use change because (1) they are intrinsically dynamic and thus represent change directly; (2) they have a high resolution and thus produce results with useful detail: and (3) they outperform other models in realistically modelling land-use change (Poelmans & Van Rompaey, 2010).
The MOLAND model for Dublin was complemented with remote sensing derived urban metrics representing urban form and structure. First the model was calibrated for a historical land-use time-series and was consequently run to forecast future land-use and urban growth patterns under alternative spatial planning and policy scenarios.
Four future development scenarios for Dublin were developed by University College Dublin (UCD). The four scenarios were simulated with the calibrated MOLAND model. However in this paper only the baseline scenario 'Continued Trends Approach' is considered. It explores the consequences of continuing the current settlement patterns, whereby actual settlement patterns have diverged from Regional Planning Guidelines policy. A detailed description of the scenarios can be found in Brennan et al. (2009).

5. Hydrological impact modelling.
Currently most physically based hydrological models use a land-use class based approach, often disregarding the spatial variability of imperviousness in urban areas. The objective of this study is to integrate earth observation derived information on sealed surface proportions into a hydrological modelling approach.
The WetSpa model (Wang et al., 1996; Liu & De Smedt, 2004) is used to simulate the hydrological rainfall-runoff processes within the Tolka River catchment. WetSpa is a fully distributed, physically based rainfall-runoff model. Instead of using subjectively defined expert-based average sealed surface values for static land-use classes, direct measures of sealed surface coverage are integrated into the WetSpa model.
The Tolka model has a spatial resolution of 30m. The main inputs are a DEM, a time-series of consistent land-use maps (step 1 & 3) and a soil map. Time-series of 6 meteorological stations (Source: National Meteorological Service of Ireland Met-Eireann) for the period 1985-2005 were processed at an hourly timescale and form the meteorological input. Next to this input also the 5 sealed surface fraction maps (step 2) are used.
Hourly discharge time-series (for the Botanic Garden station) are used for calibration of the model using the widely used automated parameter estimation method PEST. The Nash-Sutcliffe efficiency (NSE) is used as a criterion for the calibration and validation.
Once calibrated the model is used to simulate the impact of urbanisation on hydrology. Firstly, the impact for the time period 1990-2011 is assessed. Secondly, also the future impact is assessed using the input from the land-use change scenario modelling (step 4).

3. Results

1. Urban masks and sealed surface proportion maps

As described in the methodology section (steps 1 and 3) the five urban masks obtained from a classification of the Landsat/SPOT time-series are subjected to a change rationality analysis. In this way a 5-code change trajectory for each pixel is obtained. E.g. 011X1 is referring to NOT URBAN in 1988, URBAN in 1994, URBAN in 1997, CLOUDS in 2001 and URBAN in 2006. In case we would have used only the 2001 image, no information for this specific pixel could be obtained. However the change analysis of trajectories allows filling of missing data (e.g. the pixel covered by clouds can be rationally assumed to be urban). The analysis also showed that the use of the SPOT image (2006) with a finer resolution (15m) enables to "sharpen" and improve results from the coarser Landsat derived urban masks (30m).

Figure 1 shows the final urban masks after correction based on the change trajectory analysis. Almost half of the current urban mask already existed in 1988, with a steady increase (13%) every 5 year period. While the extension of the urban fabric between 1988 and 1994 consist mainly of a densification of the existing fabric, the extension in the past decade was concentrated in the suburban rim of Dublin.

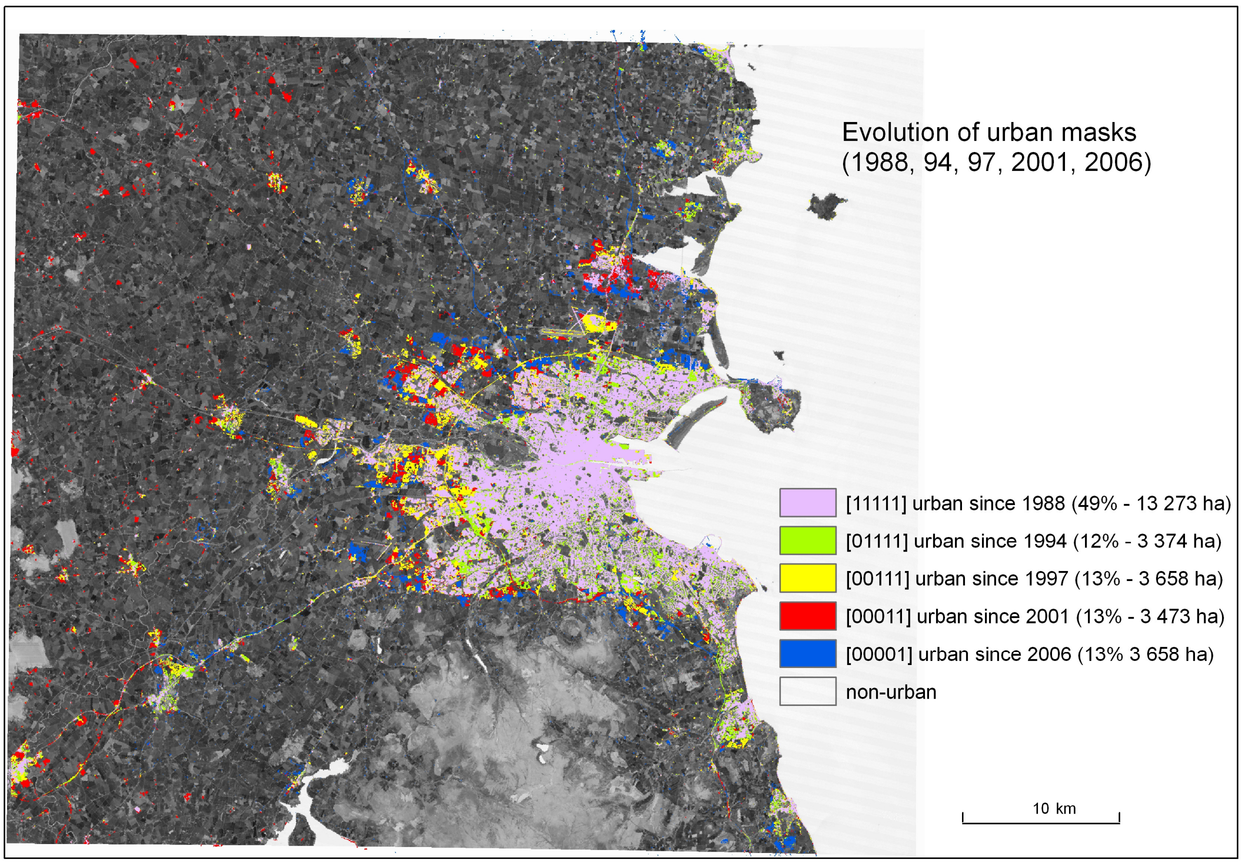

Figure 1: Evolution of urban masks for Dublin City in the period 1988-2006 (Background: SPOT image 2006)

Based on the linear spectral unmixing (step 2) also a time-series of 5 sub-pixel sealed surface proportion maps was obtained. Figure 2 shows the sub-pixel sealed surface proportion map for Dublin City in 2001. The sealed surface proportion varies between 0 (black) and 100% (white).

Looking at the map clearly gives a clear picture of the densely (e.g. City centre along the Liffey) and sparsely (e.g. suburbs) built-up areas in Dublin.

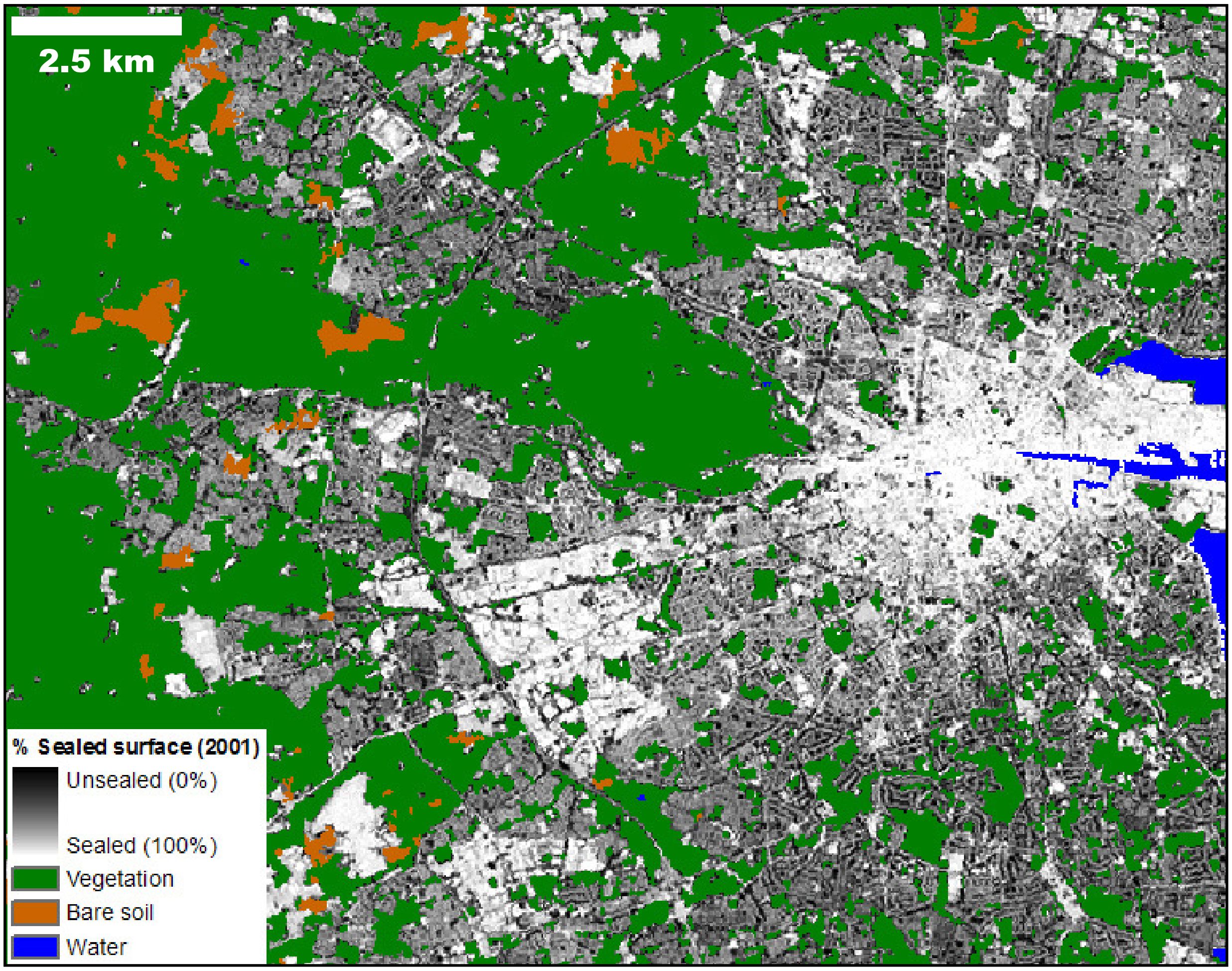

Figure 2: Spatially distributed sub-pixel impervious fraction map 2001 for Dublin City

Figure 3 shows the results of the land-use change modelling with the calibrated MOLAND model. Baseline for the simulation is the 1990 land-use map (a). The MOLAND model was calibrated to obtain a map for 2006 (b) which matches the manually classified CORINE land-cover map for the same year. Next also the future land-use map can be simulated according to a certain future development scenario. This scenario accounts for development trends (population, activities, etc.), spatial planning strategies, etc. Figure 3c shows the simulated land-use map for 2030 according to the 'Continued Trends Approach'. The land-use simulation clearly shows a further steady increase of the urban fabric in and around Dublin. Especially sub-urban expansion to the North and the South-West is expected according to this scenario. Within the Tolka catchment the expansion seems to be more limited. There is a further extension of the industrial fabric, but also an important expansion of the existing residential cores in the rural part of the Tolka catchment.

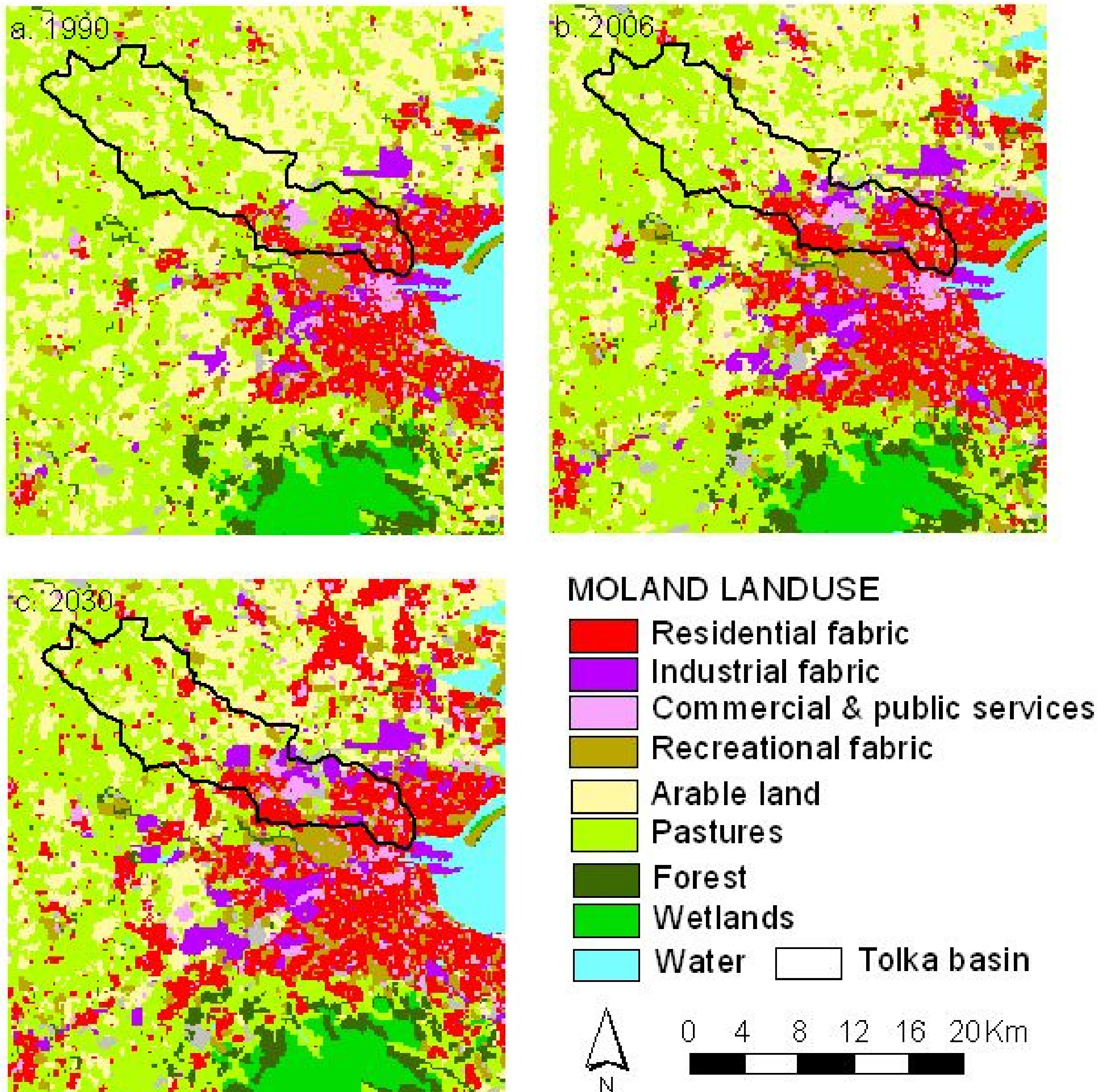

Figure 3: Historic (1990), current (2006) and simulated (2030) MOLAND land-use maps considering the baseline scenario ('Continued trends approach').

2. <u>Earth observation based parameter maps.</u>

Based on the land-use maps and the sub-pixel sealed surface fractions (step 1, 2 and 3), hydrological parameter maps are calculated for each time period. Figure 4 shows the simulated potential runoff coefficient map for the Tolka catchment in 2006. Scale: the colours vary green (low) over yellow (medium) to orange and red high). The potential runoff coefficient for urban fabric is clearly higher, with values between 0.6 and 1, than those in the rural upstream part of the catchment. The use of sub-pixel proportions allows to assess spatial variation within the urban zone. The urban core of Dublin city has potential runoff coefficient close to zero, while the residential suburbs are slightly lower (0.6-0.8). Creating similar maps for simulated future land use under different scenarios allows assessment of potential high runoff risk zones, which offers crucial information for storm drainage design and water planning and management in Dublin..

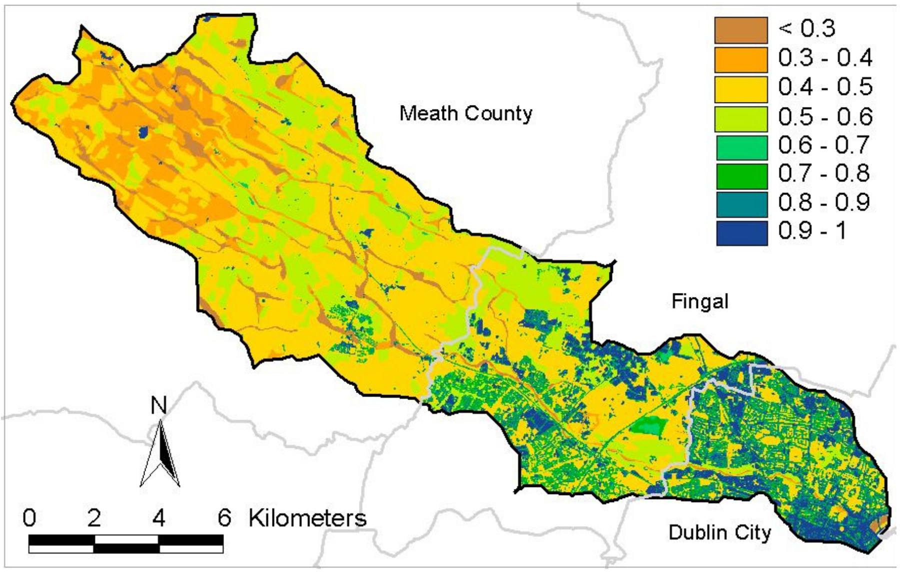

Figure 4: Potential runoff coefficient map for Tolka catchment – 2006

Figure 5 shows the evolution of the average potential runoff coefficient per County within the Tolka catchment over the period 1988 to 2006. If we look at the overall picture, we see there is a clear difference in the evolution of the potential runoff coefficients for the 3 counties through which the Tolka flows. While the average runoff coefficient in Meath, the rural part, remains nearly unchanged over time, there is a strong increase of the average potential runoff coefficient in Fingal. This is a direct result of urban growth, as this is the zone where the urban fringe of Dublin is located. Also in Dublin City there is a steady increase, but this can most probably be attributed to a densification of the existing urban fabric.

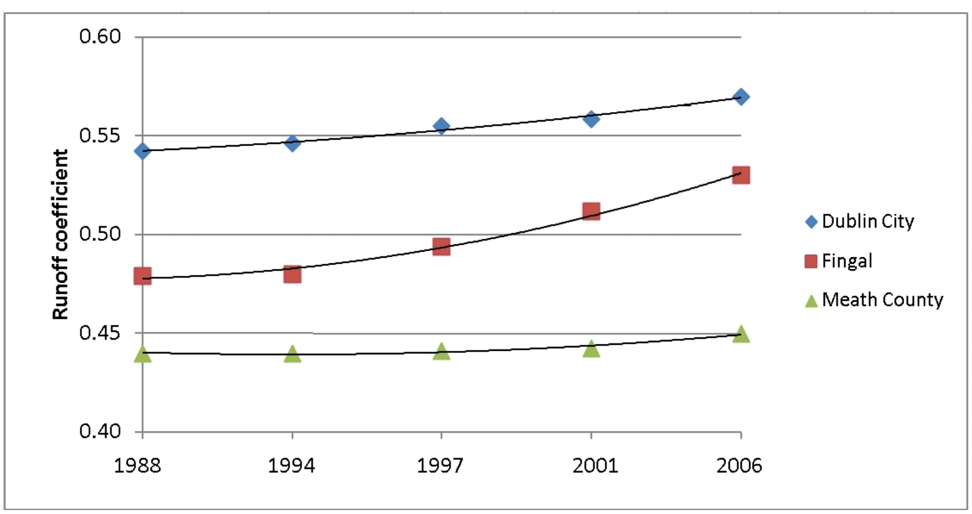

Figure 5: Evolution of potential runoff coefficients in the Tolka catchment in Dublin over the period 1988 to 2006.

3. <u>Hydrological impact assessment.</u>

Calibration was performed for a 2.5 year period (Jul.2000-Dec.2002), containing the flood events of 2000 and 2002 (Fig. 6). A NSE of 0.68 was obtained, For a 4 month period (Oct 2000-January 2001), including the flooding event of November 2001, a NSE of 0.78 was obtained. Also the low and high flows yield good NSEs of 0.78 and 0.82 respectively. This event is used to assess the impact of urbanisation on the hydrology in the Tolka catchment. The model was also validated for a 1 year period (2004), yielding an acceptable NSE of 0.64.Figure 6 shows the hydrograph, simulated versus observed discharge in time, for the calibration period. While discharge during some extreme peak events was underestimated, a slight overestimation of discharge during a succession of smaller storm events occurs.

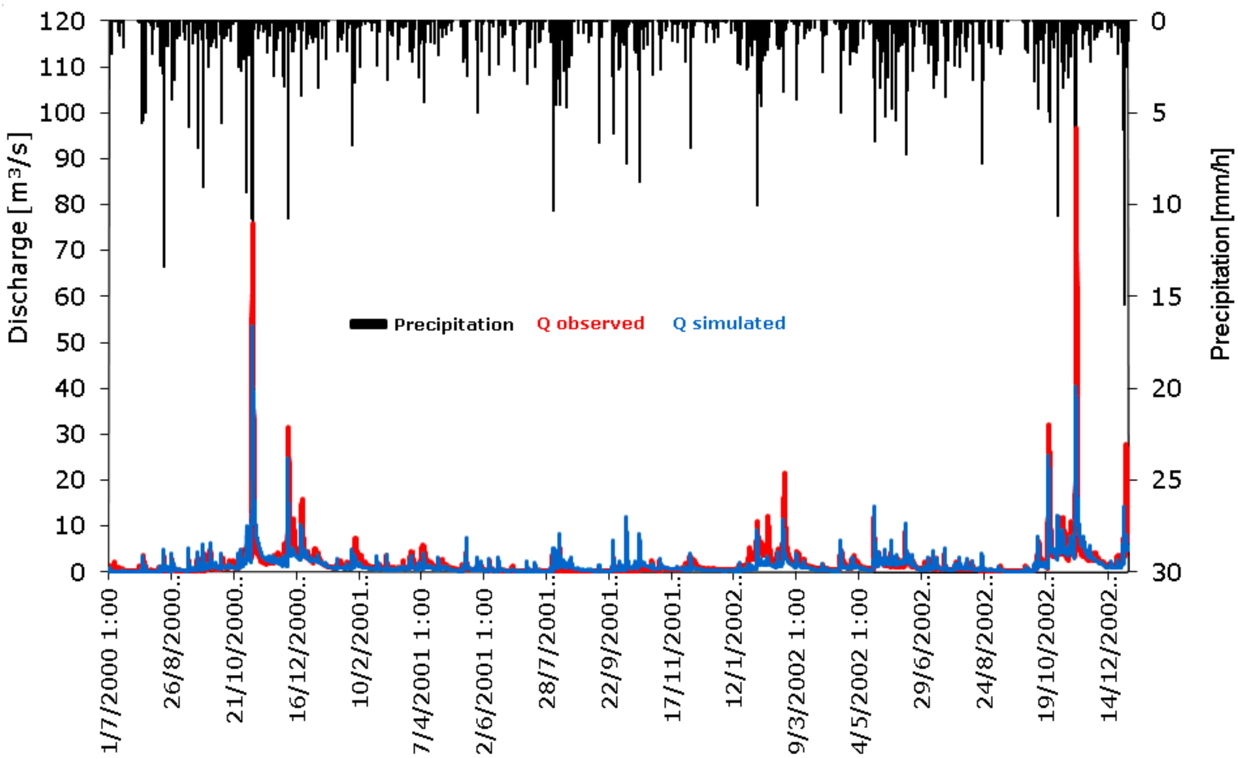

Figure 6: Observed (red) versus simulated (blue) discharge hydrograph for the Tolka river at Botanic Garden station for the 2.5 years calibration period (July 2000 – December 2002).

To assess the impact of past and future urbanisation the WetSpa model is simulated using the meteorological data for the calibrated 4 month period. Figure 7 shows the simulated hydrographs for the years 1990 (historic), 2006 (current) and 2030 (future). The impact of urbanisation for the past (1990-2006) and the future (2006-2030) is similar, with an total increase of discharge of around 6%. The left graph (Fig.7) shows the simulation results for an important peak event (discharge around 45 m³/s). The simulations show that the urbanisation between 1990 and 2006 had a considerable higher impact (+12%) on peak discharge then the expected urbanisation up till 2030 according to the 'Continued Trend Approach' scenario (+5%). The right graph (Fig.7) shows impact for a series of smaller events (discharge between 4 and 15 m³/s). These simulations show a similar trend, but even stronger. The urbanisation between 1990 and 2006 had a considerable higher impact (+36%) on smaller event discharges then the expected urbanisation up till 2030 according to the 'Continued Trend Approach' scenario (+12%).

As described above this discharges can also be presented as a spatially distributed map, allowing to determine the zones of high runoff production contributing to higher peak discharges.

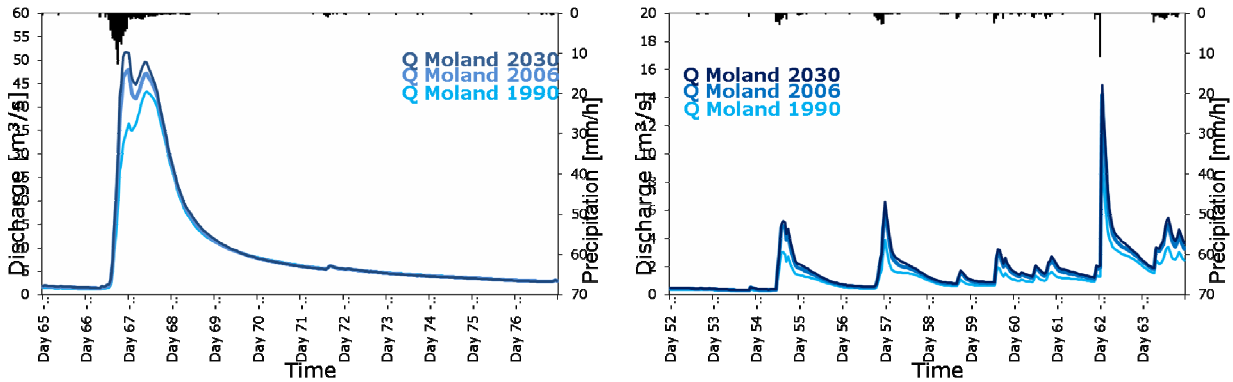

Figure 7: Hydrological response (discharge Q) during a big rainfall event (left) and some smaller successive rainfall events (right)

4. Conclusions & discussion

This paper describes an earth observation based methodology to assess urban dynamics. A time-series of five sub-pixel sealed surface maps (1988, 1994, 1997, 2001 and 2006) was used to assess the urban growth processes and consequently simulate the effects on hydrology. The simulations with sub-pixel sealed surface proportions yield considerable differences in discharge, confirming the importance of sealed surface cover as a key factor in describing the hydrological dynamics in urban catchments. The results of one urban growth scenario suggest an even bigger impact of urbanisation on runoff in the future. The use of earth observation derived information enables the dynamic estimation of sealed surface coverage and spatially distributed and time-varying runoff coefficients. This approach and case-study shows the potential for earth observation derived parameters in fully distributed hydrological models.

The methodology also allows assessing the potential city-wide risk for high runoff production zones for different scenarios. For the Tolka catchment also the hydrological impact (discharge) can be simulated.

The research also aims to complement existing studies (e.g. the Tolka flooding study within the framework of the Greater Dublin Strategic Drainage Study) and (hydraulic) models. The results could be used to assess future needs and lead to an adequate planning and management of water resources in an urban context.

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