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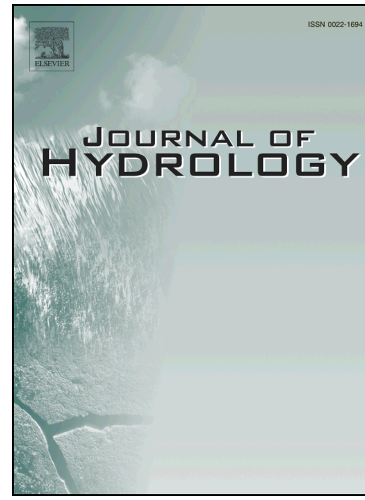

Research papers

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Trajectory analysis of land use and land cover maps to improve spatial-temporal patterns, and impact assessment on groundwater recharge

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Abstract

Land use/land cover (LULC) change is a consequence of human-induced global environmental change. It is also considered one of the major factors affecting groundwater recharge. Uncertainties and inconsistencies in LULC maps are one of the difficulties that LULC timeseries analysis face and which have a significant effect on hydrological impact analysis. Therefore, an accuracy assessment approach of LULC timeseries is needed for a more reliable hydrological analysis and prediction. The objective of this paper is to assess the impact of land use uncertainty and to improve the accuracy of a timeseries of CORINE (coordination of information on the environment) land cover maps by using a new approach of identifying spatial-temporal LULC change trajectories as a pre-processing tool. This ensures consistency of model input when dealing with land-use dynamics and as such improves the accuracy of land use maps and consequently groundwater recharge estimation. As a case study the impact of consistent land use changes from 1990 until 2013 on groundwater recharge for the Flanders-Brussels region is assessed. The change trajectory analysis successfully assigned a rational trajectory to 99% of all pixels. The methodology is shown to be powerful in correcting interpretation inconsistencies and overestimation errors in CORINE land cover maps. The overall kappa (cell-by-cell map comparison) improved from 0.6 to 0.8 and from 0.2 to 0.7 for forest and pasture land use classes respectively. The study shows that the inconsistencies in the land use maps introduce uncertainty in groundwater recharge estimation in a range of 10 to 30%. The analysis showed that during the period of 1990 to 2013 the LULC changes were mainly driven by urban expansion. The results show that the resolution at which the spatial analysis is performed is important; the recharge differences using original and corrected CORINE land cover maps increase considerably with increasing spatial resolution. This study indicates that improving consistency of land use map

timeseries is of critical importance for assessing land use change and its environmental impact.

Key words: LULC, Trajectory analysis, land use accuracy, land use uncertainty, groundwater recharge.

1 Introduction

Groundwater is a precious source of fresh water throughout the world. About 2 billion people worldwide depend on groundwater supplies (WWAP, 2015). As the world population continues to grow, more people will rely on groundwater resources, particularly in arid and semiarid areas (Simmers, 1990). However the distribution, quantity, and quality of groundwater are affected by human activity (Gehrels et al., 2001). Therefore, assessing human impacts on the groundwater systems is a major scientific challenge (Tang et al., 2005). Land use change is one of the important human interventions altering groundwater flow systems (Calder, 1993) and will continue in the future to impact recharge dynamics and vadose zone globally (Kim and Jackson, 2012).

Land use change is a complex, dynamic process, which has direct impacts on soil, water and the atmosphere (Meyer and Turner, 1994). Therefore understanding the impacts of land use/land cover (LULC) change on the hydrologic cycle is needed for optimal management of natural resources (Scanlon et al., 2005). Previous studies have mostly focused on LULC variability impacts over bidirectional feedbacks between surface/subsurface and atmospheric flow processes (Betts, 1999; Pielke et al., 1998; Pitman et al., 2004; Yasunari, 2007). Impacts of LULC change on subsurface hydrology, especially recharge of aquifers is not well studied (Scanlon et al., 2005). Both field experimental (e.g. Scanlon et al., 2005; Zhang and Schilling, 2006) and hydrologic modeling application (e.g. Batelaan et al., 2003; Schilling et al.,2008; Albhaisi et al., 2013) have been previously used to investigate LULC change impacts on groundwater hydrology. Spatially distributed hydrologic models have the advantage that they can account for the spatial patterns of the hydrological impact of LULC (Wang et al., 2013). Although, these models can make predictions in the future, few studies take future land use change into account.

To overcome these limitations, land use change models have been developed to predict future land use dynamics (Eshleman, 2004; Verburg et al., 2004). These models have been used in conjunction with hydrologic models but the applications have been limited to surface-runoff and flood prediction (Niehoff et al., 2002; Tang et al., 2005; Tong and Liu, 2006; Lin et al., 2007; McColl and Aggett, 2007). A few recent studies coupled hydrological models with land use change models to assess the impact on groundwater systems (Dams et al., 2008; Poelmans et al., 2010). Dams et al. (2008) coupled a land use change model (CLUE-S) with a water balance model (WetSpass) and a steady-state groundwater flow model (MODFLOW) to estimate the impact of future land use change on the groundwater system of the Kleine Nete basin, Belgium for the period 2000 to 2020. Results showed that urbanization decreased the average groundwater recharge and consequently the groundwater levels and base flow are reduced. Poelmans et al. (2010) used the same hydrological model (WetSpass) and coupled it with an urban expansion model to study the effect of urban expansion on groundwater systems in Flanders, Belgium for 1976 to 2050. The study predicts a decrease in groundwater recharge in Flanders with an increase in built-up area.

However, land use change models are suffering from uncertainties, which result from different sources such as land use maps for initialization of the models (Verburg et al., 2013). Hence, there is a need to evaluate the effect of such uncertainty on regional hydrology, as land use/land cover variability affects hydrological processes, including groundwater recharge.

For example, the CORINE Land Cover Project database provides free comparable digital maps of land cover for each European country (CLC, 1990, 2000, 2006). These maps are often used for initialization and/or calibration of land use change models. However, the accuracy of these land cover maps remains uncertain. Willaarts (2012) reported different LULC trends in the Spanish CORINE land cover maps compared to the Forest National Inventory datasets. Based on a case study in Dublin, Ireland Verbeiren et al. (2013) showed that consistent remote sensing derived land use maps are preferred over CORINE land cover maps to avoid overestimation errors and interpretation inconsistencies. Bach et al. (2006) proved that the CORINE land cover map has the lowest accuracy compared to land use maps based on digital topographic maps of Germany (ATKIS), and Landsat 5 TM. Hence, an accuracy assessment approach should be performed before integrating these land cover maps in hydrological impact analyses. There are several accuracy assessment methods, but there is not a standard procedure and the choice of a methodology depends on factors such as time, money and human resources (Caetano et al., 2005). The general approach of accuracy assessment is to compare land use maps with reference information that we assume as true (Caetano et al., 2005). Liu and Zhou (2004) proposed a complementary methodology to evaluate the accuracy of land cover change trajectories where a set of rational rules can be defined to evaluate the land cover change. Powell et al. (2008) developed spatio-temporal rules combined with trajectory analysis to minimize classification errors in satellite imagery.

Zhou et al. (2008) used multi-temporal remotely sensed imagery to derive land cover change trajectories. Wang et al. (2012, 2013) proposed a more advanced approach for spatio-temporal analysis of LULC change by using GIS and satellite imagery. Wang et al. (2012) used LULC trajectories for a large area (Xihe watershed, China) to detect the variability of landscape patterns and their changes. However, they considered only six main LULC classes. Wang et al. (2013) used the same approach and high resolution remote sensing imagery in smaller scale valleys (two sub-watersheds of Xihe watershed, China), considering the full trajectories to compare the spatio-temporal dynamic change characteristics. The above mentioned studies focused on the relationship between change patterns and natural geographic factors, role of human activities in the environmental changes, and assessed the impact of change trajectories in water and soil conservation. However, to our knowledge, no previous study has used full spatio-temporal trajectories to correct the overestimation errors and interpretation inconsistencies in existing land cover maps (i.e. CORINE) in relation to assessing the impact of LULC change on groundwater systems.

In this context the present study aims: (1) to assess the impact of land use data uncertainty on hydrological impact analysis, i.e. estimate how the error in the land cover mapping propagates in the hydrological model (recharge) results; (2) to improve the accuracy of CORINE land cover maps using change trajectory analysis; (3) to identify the spatio-temporal LULC change trajectories; and (4) to quantify effect of the LULC change on groundwater recharge by coupling hydrological models with spatio-temporal LULC change trajectories. The Flanders-Brussels area is taken as an example. It is a highly urbanized region and groundwater is an important resource for drinking water. Therefore quantifying LULC changes is essential for sustainable management of water resources in Flanders.

2 Methodology

The methodology consists of two parts. The first part contains two steps. First the change trajectory analysis is performed for the CORINE land cover maps for Flanders for 1999, 2000, 2006 (CLC 1990, 2000, 2006) and the most recent and detailed land use reference map of Flanders for 2013 (Poelmans et al., 2014). Secondly, the CORINE land cover maps are corrected according to pre-defined rational change rules. In the second part, the corrected land cover maps are integrated in the spatially distributed hydrological model WetSpass to calculate the seasonal and annual evapotranspiration, surface runoff and groundwater recharge.

2.1 Study area and data

The Flanders and Brussels region extends in northwestern Europe with a surface area of 13,700 km^2, constituting a nearly flat region. It is one of the most densely populated areas in Europe with a total population of 6.4 Million (Economie, 2014). Groundwater accounts for approximately 60% of public water supply (Dassargues and Walraevens, 2014). Flanders has three major river catchments: the Scheldt, Meuse and Yser, these consist of 11 regional catchments and 103 sub-catchment (Fig. 1).

The mean annual long-term precipitation varies spatially between 675 and 995 mm/yr, while the average yearly long-term potential open water evaporation varies between 662 and 675 mm/yr (Batelaan et al., 2007). The summer potential evaporation typically constitutes about 85% of the total yearly amount. The northern part of Flanders has mainly sand (26%) and loamy sand soils (18%), while in the south silty loam (18%) and sandy loam (13%) dominate.

The coastal area is characterized by the presence of clay, while the polders are characterized by heavy clay. The main land use types are built-up area (24%), meadow (22%), agriculture (30%), forest (11%), and lakes and rivers (2%) (Poelmans et al., 2014).

Data

CORINE Land Cover is a project co-financed by the European Environment Agency (EEA) to produce freely available land cover maps for most of Europe. The land cover of 1990 was constructed based on the satellite images of 1989 and 1990 (Landsat 4 and 5 MSS/TM) and the land cover types were grouped in 44 standard classes (Table A1). The map was created in GIS ARC/INFO format, at an original scale of 1:100,000. The land cover of 2000 was classified and delineated at the same scale based on physiognomic attributes manifested on satellite images of 2000 (Landsat 7ETM) (EEA, 1995). The 2006 land cover map contains land cover for most of Europe ($5.8\ 10^6\ km^2$) based on good quality multi-temporal satellite imagery of 2006 (Spot 4/5 and IRS P6 LISS III), and adequate reference data (Büttner et al., 2012).

The "change-mapping first" visual photo-interpretation technology, GIS and image processing were applied to produce the CORINE Land Cover change 2000-2006 database. The mapping unit and the thematic accuracy is 25 hectare and ≥ 85% respectively for the three land cover maps. The geometric accuracy for 1999 is ≤ 50 m, while it is ≤ 25 m for 2000 and 2006 (Büttner et al., 2012).

The Flanders land use map of 2013 (Poelmans et al., 2014) has a resolution of 10 meter by 10 meter and is a modified updated version of the land use map of Flanders and Brussels of 2005 (Gobin et al., 2009). This more detailed land use map is used as the final map in the land use change trajectory analysis applied to the three CORINE land cover maps.

The Flanders land use map 2013 (Poelmans, 2014) is classified into three levels; the first level contains the major land use types: urban, agriculture, water and different types of natural classes, while level 2 and level 3 contain the detailed land use classes (e.g. urban land use class includes: city center, built-up areas, infrastructure, sea harbor, and open built-up area).

We used level 2 land use classes and converted them to WetSpass land use classes in order to simulate the groundwater recharge for Flanders for 2013 (Schneiders et al., 2014). The same procedure is used for CORINE land cover maps, where the 44 classes were converted to WetSpass land use classification codes (Table A1).

2.2 Trajectory analysis

LULC trajectory analysis is a recently developed methodology, it is based on time series of each pixel (Mena, 2008; Lu et al., 2012). Rather than searching for single change events between remote sensed imageries of two dates, the idea is to search for idealized signatures in the entire temporal trajectories of spectral values (Wang et al., 2012). Previous studies have been mostly limited to forest-related land use change analysis (Mertens and Lambin, 2000; Vågen, 2006; Carmona and Nahuelhual, 2012; Wang et al., 2012). More recently trajectory analyses have been used for urban applications as well (Powell et al., 2008; Wang et al., 2012;

Verbeiren et al., 2013). In this study, trajectory analysis will take into account all LULC changes instead of focusing on one particular land use type.

2.2.1 LULC classification

To assess the effects of land use change on groundwater recharge in Flanders, three CORINE land cover maps (CLC, 1990, 2000, 2006) were resampled from 100 m to 50 m resolution using nearest neighbor method in ARCGIS. The maps include 44 classes of LULC features, which were primarily classified by visual image interpretation rather than automated classification procedures (Bach et al., 2006).

The land use map for Flanders of 2013 (Poelmans et al., 2014) has a resolution of 10 by 10 meter, its legend includes 114 detailed land use classes, which were structured hierarchically. This map was aggregated using a majority resampling technique to 50 by 50 m. In a majority resampling the new class of the cell is based on the most popular class within a filter window. The majority resampling method will find corresponding 4 by 4 cells in the input space that are closest to the center of the output cell and use the majority of the 4 by 4 neighbors (ESRI, 2013). For the map of 2013 the second level of land use classes were converted to WetSpass land use classification codes (Schneiders et al., 2014). Based on the WetSpass classification scheme (Table A1), the classes of the CORINE land cover and the Flanders land use map of 2013 were thematically aggregated and reclassified to nine general LULC classes for trajectory analysis (Table 1) in order to reduce the number of possible LULC trajectory combinations.

2.2.2 Change trajectory analysis

A change trajectory of a time series can be expressed by trajectory codes in all kinds of forms (e.g. in values or letters) for every pixel in the raster image (Wang et al., 2012). We used the land use class number ranging from 1 to 9 as trajectory codes in order to detect the change for every pixel through the four temporal slices 1990, 2000, 2006 and 2013. Codes like 1111, 2222, and so on, with the same code for each time slice, stand for trajectories with no land use/cover change, while others like 4411, 5222 and 6622, indicate a change in land cover in a specific time period, e.g. 4422 indicate the change from agricultural land (4) to open built up area (2) between 2000 and 2006. We used attribute calculation in ArcGIS to determine the full spatio-temporal trajectories map for the study area.

A set of rational rules were assigned and adapted as proposed by Liu and Zhou (2004) to assess the rationality of changes and to correct the LULC trajectories. We have performed the change trajectory analysis in two steps:

1: Compute change trajectories on the basis of the four time slices using the ARCGIS raster calculator to produce a time series trajectory map.

2: Assess and correct all trajectories according to the following predefined rational rules (Table A2):

Rule I: no change (i.e. 1111, 2222); if a pixel is classified as the same land cover type throughout the four monitoring periods then it is assumed to be 'correctly' classified.

Rule II: urban expansion (i.e. 4422, 5553): if a pixel is classified as agriculture, forest, other vegetation or pasture throughout one or more of the first three times slices and consequently classified as urban, open built up or infrastructure, the pixel is assumed to be 'correctly' classified and considered as a pixel with urban expansion.

For the remaining trajectories pixels where rule I and II are not applicable, the following rule is used for correction:

Rule III: 2013 reference map priority: if a pixel is classified as the same land cover type through the first two or three time slices but classified differently at the fourth time slice (i.e. 1112, 4662, and 7112), it is considered to be 'incorrectly' classified and it will be reclassified according to the class of the most recent land use map (2013) since that one is considered to be the most reliable and accurate map.

2.3 Correcting CORINE land cover maps

Using the reclassification methodology, three corrected CORINE maps with the nine trajectory classes (Table 1) were produced. For example, the pixels with trajectory code 4333, will be assigned as agriculture (4) in 1990 and infrastructure (3) in 2000 and 2006. To this end we used attribute calculation and a lookup tool to correct the CORINE land cover map for the three time slices 1990, 2000, and 2006 according to the land use classification codes described in Table A1. Hence, after the change trajectory correction, we obtained a spatio-temporal consistent set of LULC maps of the study area.

To assess the accuracy of the corrected CORINE land cover maps we performed kappa statistics (cell-by-cell map comparison) using the map comparison kit (Visser and De Nijs, 2006) to measure the difference between independent reference maps (pasture, forest, and urban) of Flanders and the corrected CORINE 2000 land use map. Kappa is based on the percentage of agreement between two maps, corrected for the fraction of agreement that can be expected by pure chance (Visser and De Nijs, 2006). In the map comparison kit kappa is defined as the product of 'kappa location' and 'kappa histogram'. 'Kappa location' is a measure of the similarity of the spatial allocation of categories of the two compared maps, while 'kappa histogram' is a measure of the quantitative similarity of the two compared maps.

2.4 Recharge simulation

The WetSpass model (Batelaan and De Smedt, 2007) was used to estimate the long-term average groundwater recharge for LULC conditions of 1990, 2000, and 2006. The simulated WetSpass water balance results for the LULC of 2013 were taken from Zomlot et al. (2015). The WetSpass model simulates the seasonal and the annual spatial patterns of surface runoff, actual evapotranspiration and groundwater recharge. The model has especially proven its value in estimating the impacts of land cover change on the components of the water budget (Dams et al., 2008; Poelmans et al., 2010).

The model takes into account the spatial distribution (raster cells) of the land use, soil, slope, groundwater depth, and the meteorological characteristics (precipitation, potential evapotranspiration, wind speed, and temperature). Every raster cell is further sub-divided into four fractions (vegetated, bare soil, open water, and impervious surface) where a seasonal water balance is simulated for each fraction as follow:

$$PPT = RO + ET + RE \quad \text{Eq. 1}$$

Where PPT is the precipitation [LT^{-1}], RO the surface runoff [LT^{-1}], ET the actual evapotranspiration [LT^{-1}], RE the groundwater recharge [LT^{-1}].

Then the water balance of each grid cell can be calculated by summing up the independent water balances for the different fractions per raster cell. Interception is parameterized as a constant fraction of precipitation depending on the vegetation type. The actual evapotranspiration is simulated as a function of the potential evapotranspiration, a vegetation coefficient and water availability in the root zone (Batelaan and De Smedt, 2007). Surface runoff is a function of the amount and intensity of the rainfall, interception and soil infiltration capacity, which is controlled by the land use type, soil texture and slope of the grid cell. Finally, groundwater recharge is calculated as the residual term from the water balance.

Hence, the water balance model approach for estimating recharge has as limitation that unsaturated zone processes are highly simplified. However, the water balance approach allows 'checks and balances' on the recharge estimate via measurements and calibration of evapotranspiration, total discharge and baseflow at catchment level. The model is a fully spatially explicit approach in the sense that it takes all combinations of soil, land use, slope and meteorological conditions into account and therefore it is very suitable for estimating the impact of detailed LULC changes over larger areas. The study area has as main climatological characteristic a strong seasonal difference in the evapotranspiration and recharge. The model allows the built-up of soil water storage in the winter and its usage in the summer for evapotranspiration. The WetSpass, spatially explicit, water balance recharge estimation with its seasonal time scale has proven, based on comparison with other recharge estimates, to be appropriate for the study area (Batelaan and De Smedt, 2007).

Interpolated shallow long-term average groundwater depth data of Batelaan et al., (2007) were used in this study as input to the WetSpass model to fulfill the groundwater depth data requirement. Besides the groundwater depth layer, also land use, soil, and seasonal precipitation, potential evapotranspiration, wind speed map layers are required for spatial estimation of groundwater recharge. Land use and soil parameters are stored in attribute tables, where different parameters are used for winter and summer seasons.

We simulated the groundwater recharge for the years 1990, 2000, and 2006 by introducing the three corrected rescaled CORINE land cover maps. The remaining required input maps with a resolution of 50 m by 50 m were kept constant, assuming invariant soil and slope conditions and long-term average meteorological conditions as provided by Batelaan et al. (2007). The calibration and the parameter uncertainty was evaluated by Batelaan and De Smedt (2007).

2.5 LULC impact analysis

The impact of LULC changes on groundwater recharge was assessed by comparing the WetSpass simulated annual average groundwater recharge maps for the LULC conditions of 1990, 2000, 2006 and 2013. We compared the annual maps at three different scales: catchment, sub-catchment and pixel. We also modelled the recharge for the three time slices with the original CORINE land cover maps to detect the effect of misclassification and overestimation of land use classes on the simulated recharge.

3 Results and Discussion

3.1 Change trajectories

We identified all spatio-temporal trajectories for four land use maps (1990, 2000, 2006, and 2013) of Flanders (Table A2). In total only 57.4% of the pixels were consistent, from which 8% covered urban area. The remaining 42.6% pixels were classified as inconsistent. Main reason for the high number of inconsistent trajectories is over-estimation of urban and built-up areas; and the misclassification between pasture and agriculture classes in CORINE land use maps (Fig. 3). However, by applying the predefined change trajectory rules described in section 2.3, 99% of the trajectories could be evaluated, while 1% of the trajectories remains uncertain. 42.6% of the trajectories were corrected and made consistent.

We identified 36 trajectories in total and the spatio-temporal trajectory map of Flanders for 1990 to 2013 is presented in Fig. 4. There are 27 different trajectories, which all represent urban expansion amounting to 10.8% of the study area, whereas the remaining nine trajectories are trajectories without land use changes. The major change is from agricultural land to built-up area and open built-up area, while minor changes occur for other land use classes (forest, pasture, other vegetation). Major urban sprawl (8.5%) is observed between 2006 and 2013, 1.4% between 2000 and 2006, while only 0.9% of urban sprawl is identified between 1990 and 2000.

3.2 Correcting CORINE land cover maps

CORINE land cover maps provide relatively coarse spatial information (100x100 metres), but it is the only land cover database available for the whole European territory that allows analysis of land cover over a period of 16 years. However, CORINE maps tend to overestimate urban areas and misclassify vegetation land use classes compared to the most detailed land use map of 2013.

This overestimation is mainly caused by the level of spatial and thematic generalisation of the land cover data in the CORINE dataset. The minimum mapping unit is 25 ha and under this threshold landscape units are not identified on the land cover map and will be merged in surrounding categories (Gallego et al., 2000). For example, patches of grassland located in the middle of urban built-up area will be included in the urban built-up area polygon, which could considerably affect hydrological impact analysis.

Using the consistent spatio-temporal trajectory map, the three CORINE land use maps of 1990, 2000, and 2006 were corrected at a scale of 50 by 50 meter according to the WetSpass land use classification (Fig. 3). For example, the built-up areas (urban area, infrastructure, and open built-up area) covered 27.2% of the total study area in the 2000 map, but after correction this fraction is reduced to 19.7%. The original CORINE maps also overestimated the agricultural land in favour of pasture land use classes. For example, in 1990, the agricultural land was estimated to cover 53.7% of the study area while pasture covers 9.4% only. After correction, the agricultural land reduced to 38.3% and the pasture land use was increased to 24.6%.

To estimate the accuracy of the corrected land use maps, we conducted three different comparisons of original CORINE and corrected CORINE land cover maps with independent reference land cover maps (Fig. 5). Comparisons were made for percentage and spatial pattern of pasture, forest and urban land use classes (urban, open built up area, and infrastructure).

The reference agriculture map of AGIV (2008) was used to compare the percentage and the spatial pattern of pasture land use class with those of the CORINE land cover map of 2006.

AGIV (2008) created the reference agriculture map 2008 via an on-screen digitalisation of the agricultural use of land for each individual farmer, based on data of agricultural parcel use of the previous year. The map was verified by detailed photo-interpretation, with the possibility of verification / survey of the area in the field. Finally, the resulting polygon map is subjected to a quality assessment developed by the European Research Centre JRC (Joint Research Centre).

The percentage of pasture in the CORINE land use map was 9.2% for 2006 and was corrected to 24.4%, while the coverage percentage of the reference agricultural map of 2008 was 18.3%. The overall kappa between the CORINE pasture land use map and the reference map was 0.2 and it improved to 0.7 after correction (Table 2).

The percentage and spatial pattern of forest land use was compared with a reference forest land use map (AGIV, 2000). The forest reference map 2000 is an actualisation of the 1990 forest reference map of the Department of Forest and Green, AMINAL, LIN, Ministry of the Flemish Community. The 1990 forest reference map was created by Eurosense Technologies on the basis of the interpretation of high-resolution color-infrared orthophotos (scale 1/5000), acquired in the period 1978-1992. The map was verified by quality assessment and field surveys.

The percentage of forest in the CORINE land use map was 7.4% in 2000 and was corrected to 11.9%. This result is in accordance with the percentage of 11.3% coverage in the reference map. The overall kappa between the CORINE forest land use map and the reference map was 0.6 and it improved to 0.8 after correction (Table 2).

The percentage of built-up areas was compared to the study of Poelmans et al. (2010) (Table 2). They used an urban expansion model to project the spatial pattern of urban expansion up to 2050 based on Landsat ETM+ images of 1978, 1988, and 2000 and performed a verification by a random sample of 250 control points. As shown in Fig. 5, the corrected percentage of built-up area (19.7%) was in accordance with the results of 2000 (18.3%). The 1.5% difference can be explained by the fact that the accuracy of the 2000 land use map was 81% (Poelmans et al., 2010) and that 1% of the pixels in the original CORINE map was not corrected. The overall kappa between the CORINE 2000 urban land use map and the reference map was 0.5 and it improved to 0.6 after correction (Table 2).

As shown from the results of this study, LULC trajectory analysis is a powerful method to correct existing land use maps. 99% of all pixels were considered, but there is still some uncertainty associated with the methodology. The predefined rules form a drawback in detecting the dynamic urban sprawl. For example, the trajectories 1442, 5442, and 3442 were corrected to 4442 according to urban expansion priority rule. This means that the pixels were assigned as agricultural for the first three time slices and open built up area in the last year 2013. However, there is a chance that these pixels were wrongly classified and the urban expansion started from 1990 or 2000. For such a case historical NDVI maps or/and referenced urban mask maps could be used to support the decision of correcting these trajectories. A more advanced automated approach could be implemented to include such kind of maps together with the predefined rules to correct these trajectories.

3.3 Recharge simulation

The yearly and seasonal water balances for Flanders for 1990 are presented in Fig. 6. Groundwater recharge comprises 32% of the total yearly precipitation (756 mm/yr) in 1990, it mainly occurs during the winter, while evapotranspiration represents 60% of the total yearly water balance in Flanders and occurs mainly in summer. Surface runoff is the smallest water balance component which represents 8%. This finding confirms the study of Poelmans et al. (2010), showing that the average yearly recharge amounted to 31.3% of the total water balance in Flanders for 1990 using a land use map based on Landsat-ETM+ images of 1988.

Forest and agricultural land use types have the highest groundwater recharge in Flanders, while urban areas and infrastructure have the lowest groundwater recharge. Hence, deforestation and urbanization will have a significant negative impact on groundwater recharge in Flanders. Urban areas, infrastructure, and open built-up areas have the highest surface runoff, except for open water areas. The highest values for evapotranspiration are found for open water, followed by the vegetation land use classes.

The total groundwater recharge and surface runoff do not change much between 1990 and 2006 at the scale of Flanders, as the mean difference is in the order of 0.1 percent. However, at pixel level the differences increase ranging from 4% to 18% for recharge and from 5% to 37% for runoff (Fig. 7). A significant change in groundwater recharge and surface runoff occurs between 2006 and 2013, which amounts on average to -0.8% and 1.1% respectively at the scale of Flanders. These differences increase up to maximum -35 % for recharge and maximum 45% for runoff at the level of individual pixels. This decrease in groundwater recharge is due to a major urban expansion in this period, which leads to an increase in the impervious fraction of the land cover. Hence, surface runoff increased and water is prevented from infiltrating. The decrease of average yearly evapotranspiration between 1990 and 2013 was relatively small, 0.5% at scale of Flanders and ranges from 5% to 15% at the level of individual pixels. Which is mainly caused by increasing the impervious fraction of the soil by urban expansion.

It is clear from these results that the tested methodology allow spatial and temporal estimation of the water balance components and that these reveal patterns of importance for hydrological or groundwater modelling and/or management. As a consequence of land use change, mainly urbanisation, important reductions in recharge fluxes are identified especially at the local scale.

3.3.1 Impact of land use uncertainty

To illustrate the impact of land use uncertainty on assessing groundwater recharge, we have simulated the long-term average recharge with the original CORINE land cover map for the year 1990. The spatial pattern of the long-term average difference in groundwater recharge between the results based on the original and the corrected CORINE land cover map for the year 1990 is shown in Fig. 8. The misinterpretation of different vegetation classes (agriculture, meadow, and forest) lowered the recharge by 10% to 20%, and shows clear spatial differences. In areas where built-up land is overestimated the recharge is decreased by 20% to 30%, and vice versa. Open water classes were mainly classified as forest on the original CORINE land cover map and represent the highest negative change percentage in groundwater recharge (30 to 40 %), explained by the fact that the WetSpass model assigns a zero recharge to open water classes (Batelaan and De Smedt, 2007).

Uncertainty is an important aspect in recharge estimation and models. As shown here, misclassification of LULC leads to wrong parameterization of land use parameters and hence wrong estimation of groundwater recharge and consequently groundwater fluxes. It also has an impact on estimating the surface runoff which leads possibly to failures to predict flood hazards.

LULC maps are also important inputs to a wide variety of studies and many of them are based on CORINE land cover maps, often ignoring their inconsistencies and uncertainty, which may cause models to provide unreliable predictions (Fang et al., 2006). For example Janssen (2008) estimated a change in the agricultural sector (which was overestimated and misclassified) to estimate the impact of LULC on bio-productive capacity of Belgium. Cazaux et al. (2007) evaluated the challenges for agricultural diversification in a peri-urban region based on the CORINE data base. Therefore, an accurate estimation of land use map uncertainty is of critical importance for modelling LULC impact on the environment, agriculture, and land management.

3.3.2 Impact of LULC change on groundwater recharge

Fig. 9 shows the spatial distribution of the long-term annual groundwater recharge difference between the annual recharge maps of 1990 and 2013 at three scale levels: the catchment, sub-catchment and the pixel scale. It clearly shows that the change in groundwater recharge is largely determined by the land cover change. In general recharge is decreasing with increasing built-up area during the period 1990 to 2013. The mean average decrease in groundwater recharge for the whole of Flanders for the period 1990 to 2013 is ranging from

5% to 35% at the level of individual pixels. While the mean average increase in surface runoff is ranging from 5% to 45%.

The change in groundwater recharge is highly controlled by the scale of analysis. In general, the percentage of simulated difference in long-term average of groundwater recharge increased with increasing spatial resolution (Fig. 9). This results in recharge differences of up to 35% at the level of individual pixels of 50 m by 50 m, decreasing up to maximum 1.9% at sub-catchment level and maximum 1.2% at catchment level. At the scale of Flanders, the recharge differences are relatively limited to less than 1%. Therefore, spatial detail should be taken into account to avoid local underestimation of impacts of LULC change on groundwater recharge and surface runoff.

4 Conclusion

This study demonstrated a change trajectory methodology to improve the accuracy of land use maps, identify spatio-temporal land use/land cover (LULC) change trajectories and investigate the impact of land use change on groundwater recharge in Flanders, Belgium. Additionally, it is shown that even the availability of one high resolution LULC reference map allowed additional improvement and downscaling of the different land use maps.

Due to their availability and relative uniformity over the entire European territory, CORINE land cover maps are often used for LULC change analysis and identification of impact(s) on the environment. Although several studies have shown the uncertainties and inconsistencies of these maps, still many studies ignore it causing unreliable predictions. In this study, we were able to significantly improve the spatio-temporal patterns of CORINE maps for the three time slices 1990, 2000, and 2006 by using change trajectory analysis. The overall kappa between the forest class in the CORINE land cover map and a reference forest map was improved from 0.6 to 0.8, while for pasture and urban land use classes the overall kappa was improved from 0.2 to 0.7 and from 0.5 to 0.6 respectively.

Change trajectory analysis was performed considering a timeseries of three CORINE maps of 1990, 2000, and 2006 combined with the more detailed land use map of 2013 for Flanders (10 m resolution) to identify spatio-temporal LULC trajectories. Considering 99% of all pixels 36 trajectories were identified in Flanders. 27 of the trajectories represent urban expansion which covers 10.8% of the study area, while the remaining nine trajectories represent unchanged LULC. The major change occurred from agriculture land to built-up and open built-up area, while minor changes occurred for other land use classes (forest, pasture, other vegetation).

The most significant change in groundwater recharge and surface runoff occurred in the period 2006 till 2013. Surface runoff was more sensitive to LULC impact with 1.1% average increase for the whole of Flanders (including the many unchanged pixels), while recharge decreased by 0.8%. This decrease in groundwater recharge is due to major urban expansion in this period, leading to an increase of impervious fractions, hence surface runoff increased and water was prevented from infiltration. These results indicate that LULC has a significant impact on groundwater recharge and should be taken into account in water resources management. The change in groundwater recharge is also highly controlled by the scale of analysis; it increases significantly with increasing spatial resolution.

The impact of land use uncertainty on groundwater recharge estimation was identified by comparing the spatial pattern of the long-term average groundwater recharge difference between the original and the corrected CORINE land cover map for the year 1990. Misinterpretation of different vegetation classes resulted in a 10% to 20% difference of the estimated groundwater recharge at pixel scale, while overestimation of built-up areas resulted in a 20% to 30% reduction.

LULC change trajectory analysis is considered a powerful method to improve the accuracy of land use maps and timeseries, but there is still some uncertainty associated with this method. Therefore, it is recommended that future studies should be conducted in such a way that more reliable historical reference data are incorporated, and a more advanced automated approach could be implemented to support the definition of decision rules to correct the LULC change trajectories. Further research is also needed to explore the driving forces and constraints of LULC in Flanders and its impact on groundwater recharge.

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Fig. 8: Spatial patterns of the simulated difference (recharge map of 1990 minus recharge map of 2013) in long-term annual groundwater recharge at: (A) pixel scale; (B) sub-catchment scale; and (c) catchment scale. Recharge differences clearly increase with increasing spatial resolution.

Table 1: Trajectory codes of LULC classes.

Land cover type	Code
Urban areas	1
Open built up areas	2
Infrastructure	3
Agriculture	4
Pasture	5
Forest	6
Other vegetation	7
Open water	8
Beach/dune/salt march	9

Table 2: Kappa statistics for pasture, forest and urban land use classes. Change trajectory analysis improved the accuracy of CORINE land cover maps.

		Kappa	**K_{loc}**	**K_{histo}**
Pasture	CORINE	0.2	0.42	0.44
2006	Corrected CORINE	0.7	0.73	0.97
Forest	CORINE	0.6	0.76	0.78
2000	Corrected CORINE	0.8	0.78	0.97
Urban	CORINE	0.5	0.65	0.75
2000	Corrected CORINE	0.6	0.56	0.95

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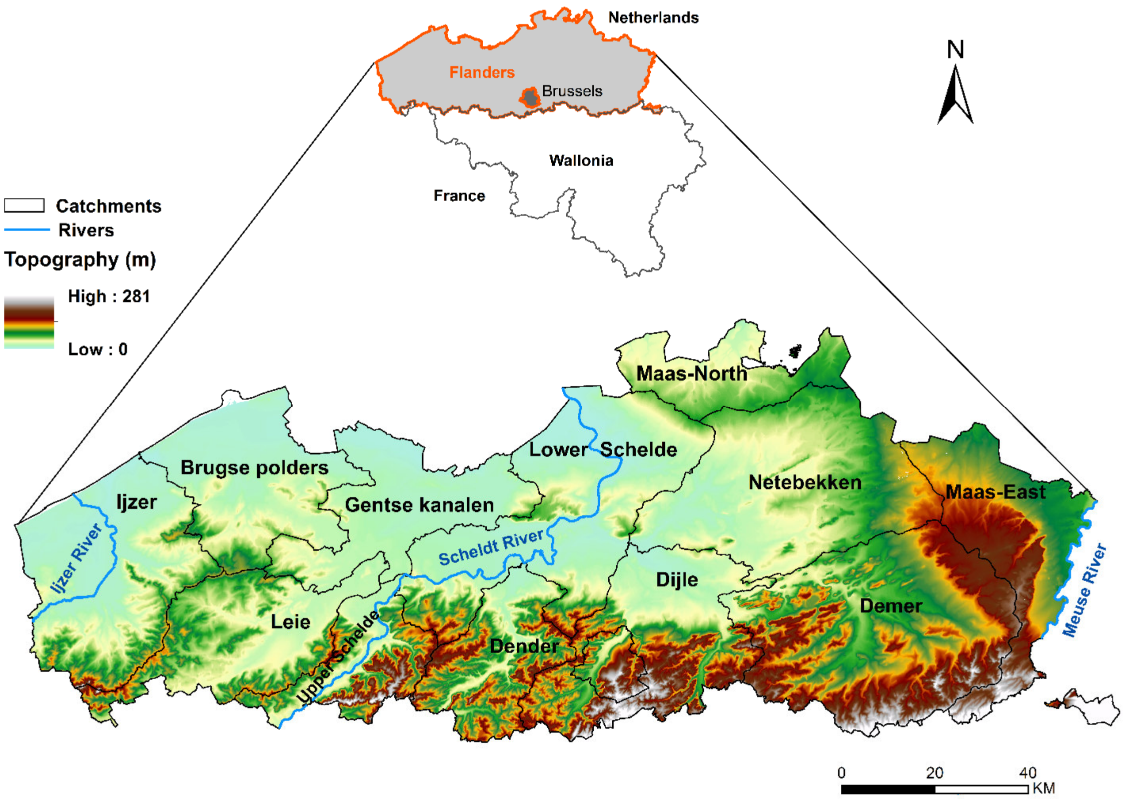

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831 Fig. 9: Topography, main rivers and catchment boundaries of Flanders, Belgium.

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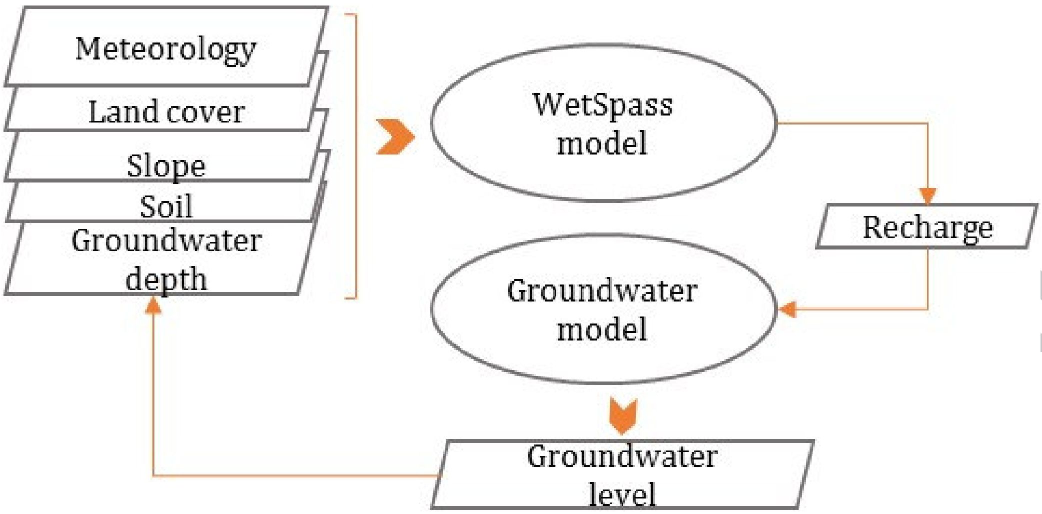

Fig 10: Schematic representation of input layers for WetSpass and the possible iterative link between WetSpass and a groundwater model (Batelaan and De Smedt, 2007).

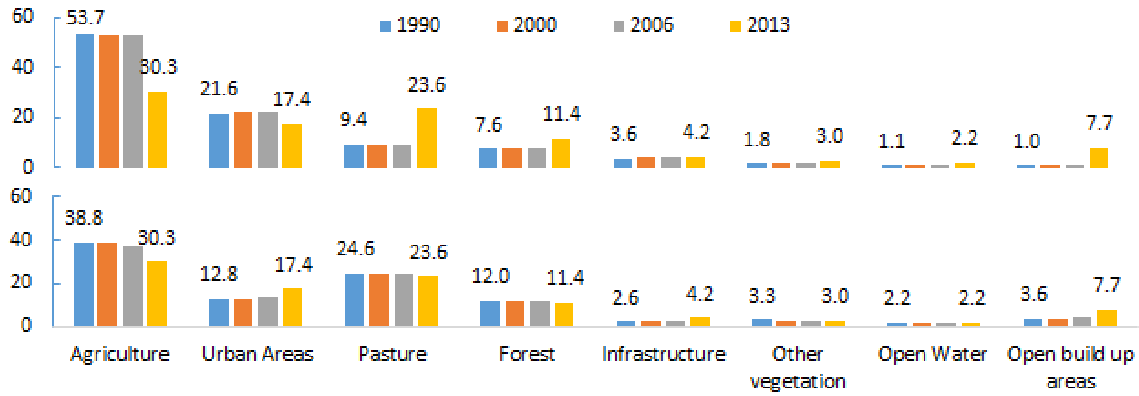

Fig. 11: Percentages of generalised LULC classes in Flanders for 1990, 2000, 2006, and 2013 in the (A) original and (B) corrected CORINE land cover maps. Change trajectory analysis corrected the interpretation inconsistencies and overestimation errors in CORINE land cover maps.

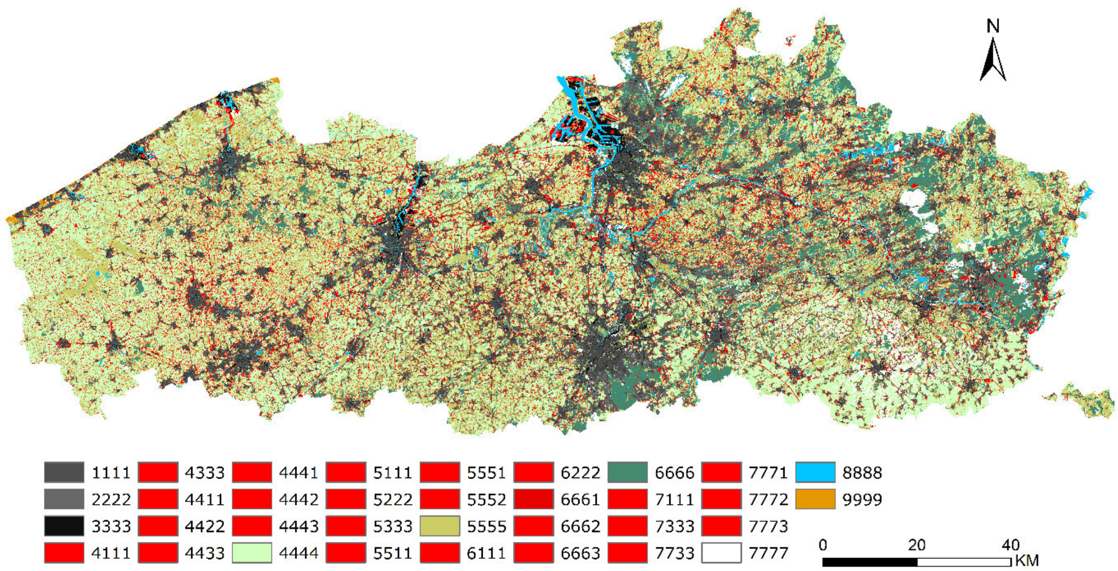

Fig. 12: Land use/Land cover change trajectory map of Flanders (1990-2013). The urban expansion trajectories (marked in red) represent 10.8% of the study area. The full meaning of the trajectory codes is given in Table A2.

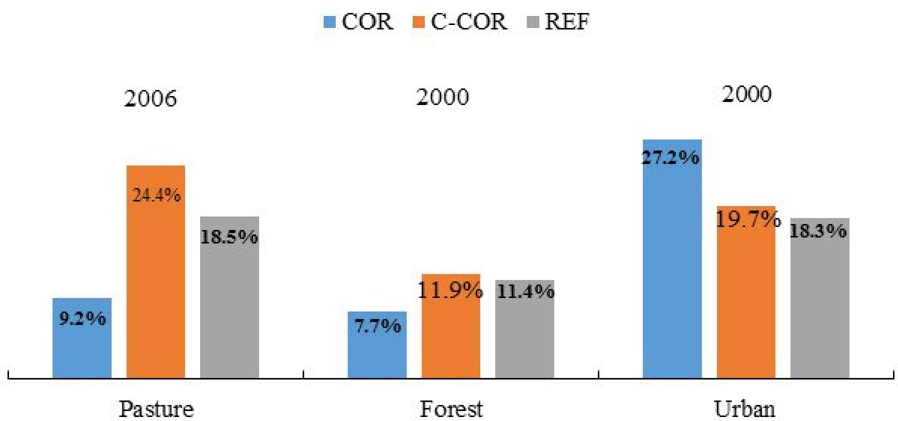

Fig. 13: Comparison of pasture (2006), forest (2000) and urban (2000) land use classes, between the original CORINE (COR), the corrected CORINE (C-COR) and reference (REF) land use maps (AGIV, 2008, 2000; Poelmans et al., 2010).

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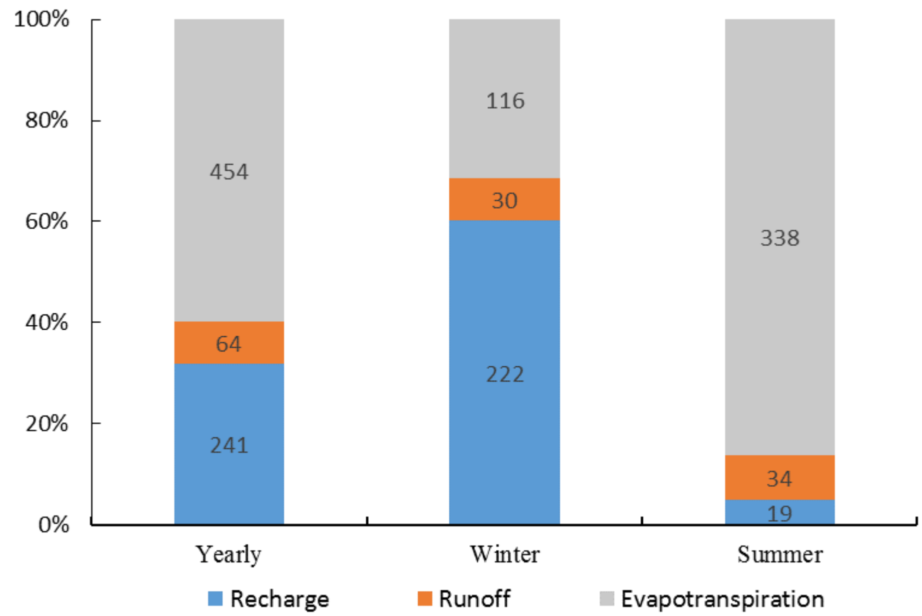

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869 Fig. 14: Average yearly, winter and summer water balances for Flanders for 1990 (values are
870 in mm/yr).

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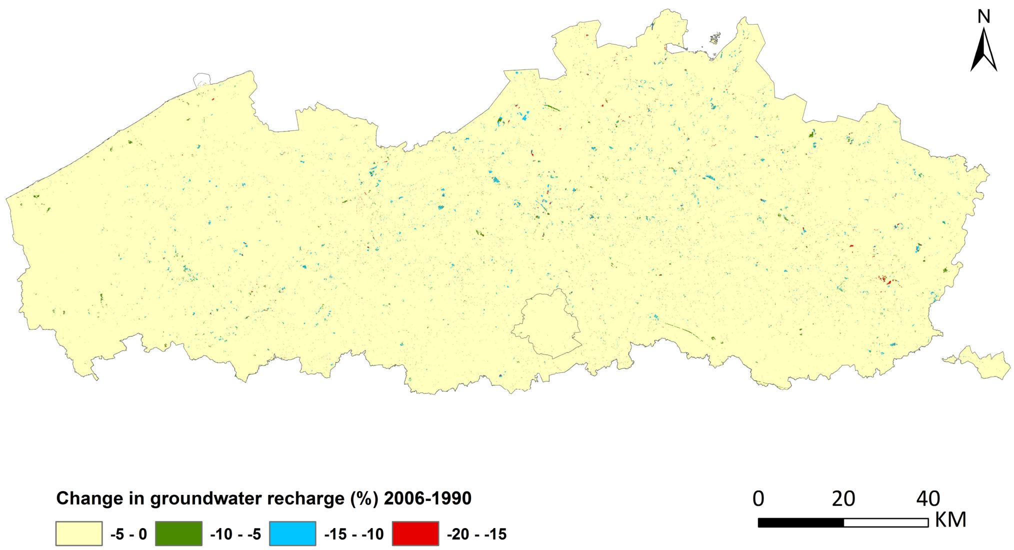


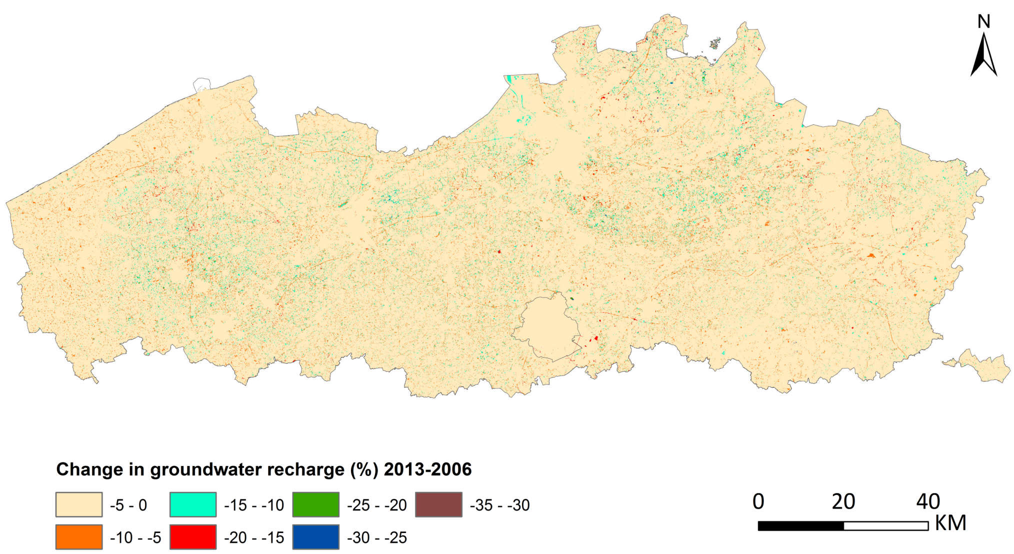


Fig 15: Spatial patterns of the simulated differences in long term annual groundwater recharge at pixel scale for Flanders for (A) recharge map of 2006 minus recharge map of 1990; (B) recharge map of 2013 minus recharge map of 2006.

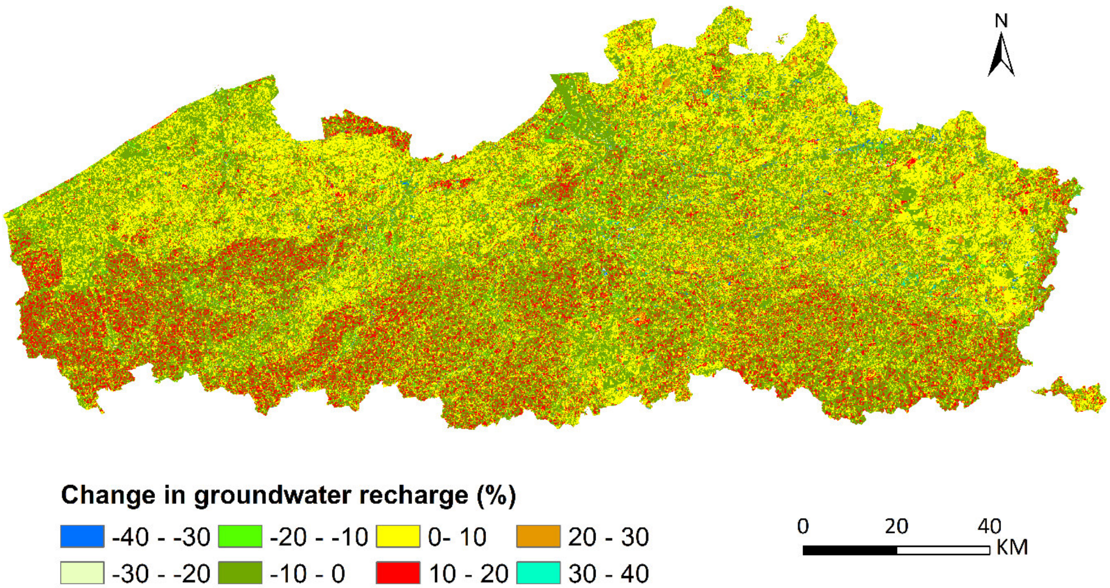
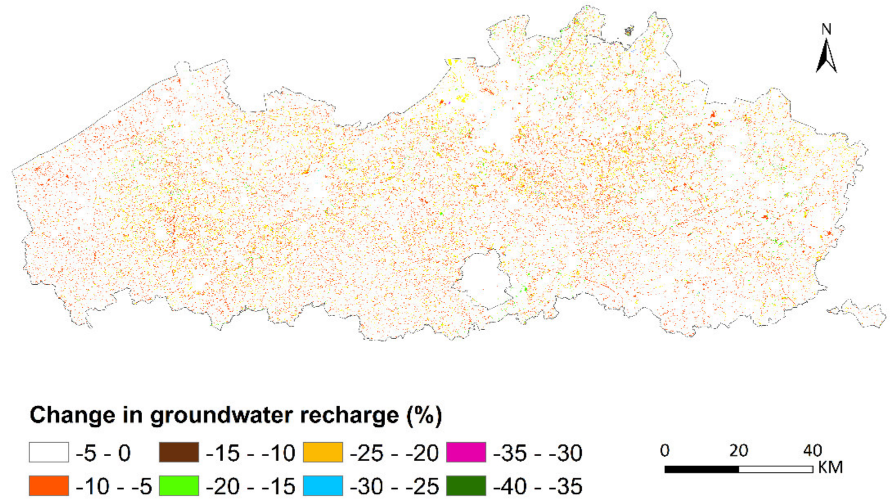
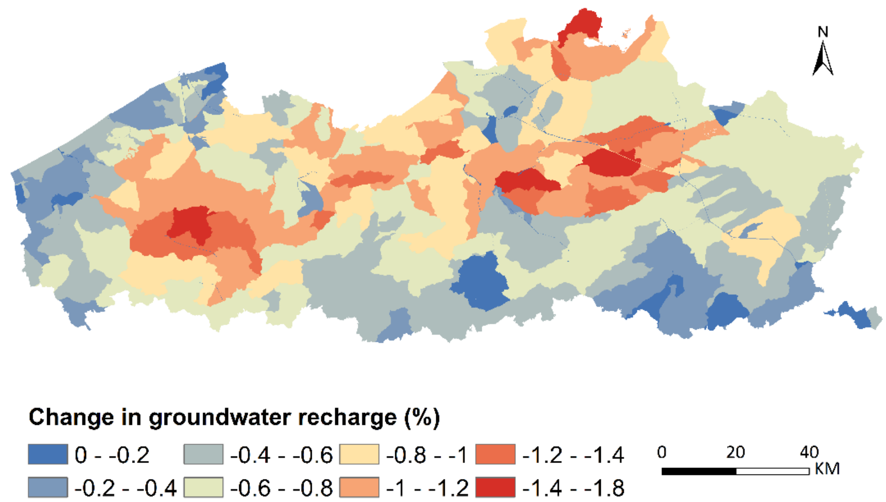


Fig. 16: Spatial distribution of the simulated difference (corrected minus original CORINE land use map) for long-term averaged groundwater recharge for the year 1990. Inconsistencies in the original CORINE map introduce uncertainty in groundwater recharge estimation in a range of 10 to 30%.

A



B



C

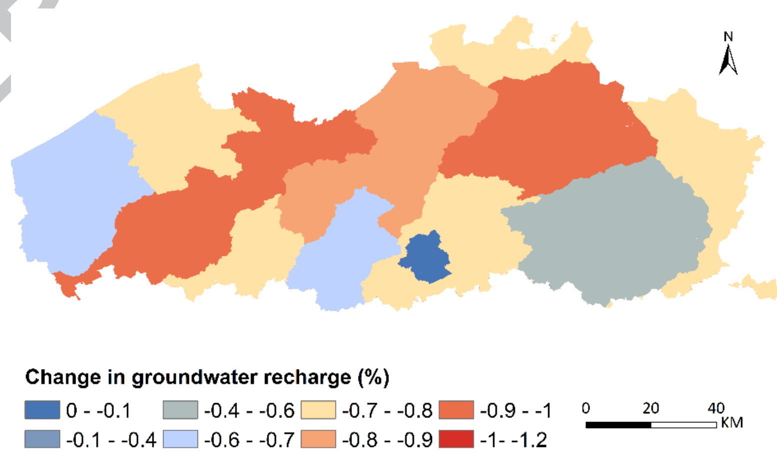


Fig. 17: Spatial patterns of the simulated difference (recharge map of 1990 minus recharge map of 2013) in long-term annual groundwater recharge at: (A) pixel scale; (B) sub-

catchment scale; and (c) catchment scale. Recharge differences clearly increase with increasing spatial resolution.

Supplementary martial

Table A1: CORINE land use classes with corresponding classes used for the WetSpass (WSS) model and LULC classes for the trajectory analysis.

CORINE class	WSS class	Trajectory classes	LULC Codes
Continuous urban fabric	City Center Built up	Urban Areas	1
Discontinuous urban fabric	Built up		
Green urban areas	Open built up	Open Built Up area	2
Sport and leisure facilities	Open built up		
Industrial or commercial units	Industry	Infrastructure	3
Road and rail networks and associated land	Highway		
Port areas	Sea harbor		
Airports	Airport		
Mineral extraction sites	Excavation		
Bare rocks	Excavation		
Sparsely vegetated areas	Excavation		
Burnt areas	Excavation		
Glaciers and perpetual snow	Excavation		
Dump sites	Infrastructure		
Construction sites	Infrastructure		
Non-irrigated arable land	Agriculture	Agriculture	4
Permanently irrigated land	Agriculture		
Rice fields	Agriculture		
Complex cultivation patterns	Agriculture		
Land principally occupied by agriculture	Agriculture		
Annual crops associated with permanent crops	Maize and tuberous		
Pastures	Meadow	Pasture	5
Natural grasslands	Meadow		
Inland marshes	Wet-meadow		
Peat bogs	Wet-meadow		
Agro-forestry areas	Mixed forest	Forest	6
Broad-leaved forest	Deciduous forest		
Coniferous forest	Coniferous forest		
Mixed forest	Mixed forest		
Vineyards	Orchard	Other Vegetation	7
Fruit trees and berry plantations	Orchard		
Olive groves	Orchard		

Moors and heathland	Heather		
Sclerophyllous vegetation	Shrub		
Transitional woodland-shrub	Shrub		
Water courses	Navigable river		
Water bodies	Lake		
Coastal lagoons	Estuary	Open Water	8
Estuaries	Estuary		
Sea and ocean	Sea		
Beaches, dunes, sands	Beach/dune		
Salt marshes	Mudflat/salt march	Beach/Dune/mudflat	9
Salines	Mudflat/salt march		
Intertidal flats	Mudflat/salt march		

Table A2: Original and corrected trajectories for the 4 years 1990, 2000, 2006, and 2013.

Original trajectories	Corrected	Description
1331, 3111, 3311, 1131, 1661, 1221, 1771, 3331, 2221, 8881.1411	1111	Consistent Urban
3332, 1332, 3372, 2112, 1222, 6332, 1112, 8882	2222	Consistent Open Built up area
8883, 1333, 3113, 3733, 3883, 6113, 3313, 1663, 1553, 1113, 2223, 1133	3333	Consistent Infrastructure
5554, 1114, 1444, 4114, 5444, 4554, 4664, 1144, 4414, 4334, 2224, 5114, 4774, 1554, 7444, 3444, 4144, 4434, 4454, 5664, 5544, 2444, 4224, 6664, 7774, 6444, 6644, 6554, 3334	4444	Consistent Agriculture
2225, 4445, 1115, 665, 1445, 3335, 4115, 5445, 4555, 7775, 6445, 4335, 4665, 4415, 1145, 5665, 6555, 3445, 4435, 3775, 3325, 4225, 6115, 1665, 4775, 6645, 7335, 4145, 5335, 7445, 5545, 1335, 4455, 4885, 5515, 5575, 2445, 1155, 5775, 8445, 7115, 1555, 5115, 8885, 7765	5555	Consistent Pasture
4446, 1116, 5556, 2226, 3336, 7776, 4666, 6446, 7666, 4116, 1446, 1666, 6116, 8886, 5666, 7766, 5446, 4556, 6556, 5566, 6676, 4336, 6776, 6336, 5576, 4466, 3666, 6646, 6226, 4416, 7336, 2666, 3446, 1166, 1226, 5116, 6616, 1146, 3776, 4776, 4226, 1556, 7446	6666	Consistent Forest
6667, 1117, 5557, 3337, 1447, 3777, 1447, 3777, 9997, 7667, 2227, 7447, 8887, 4337, 3377, 7117, 7337, 1777, 7767, 5777, 1147, 4667, 4557, 6447, 5577. 5447, 4117, 4447, 4777	7777	Consistent Other vegetation
2228, 4888, 3888, 7778, 3388, 7888, 8338, 6888, 8448, 8388, 4448, 6668,3338, 1118, 5558, 4338, 4118, 4488, 5578, 1448, 4388, 5448, 4558	8888	Consistent Open water
7779, 4449, 1119, 2229, 5559, 8889	9999	Consistent Beach/Dune/Salt March
5553, 1443, 3443, 5443, 6443, 4663	4443	Urban expansion(UE): agriculture to infrastructure
1442, 5442, 1142, 6442, 3442	4442	UE: agriculture to open built up
4112, 4412, 4332, 1412, 4432	4422	UE: agriculture to open built up
4111, 1411, 4431	4411	UE: agriculture
1441, 5441, 3441	4441	UE: agriculture
1551, 4551	5551	UE: pasture to urban

1552, 4552	5552	UE: pasture to open built up
1662, 4662	6662	UE: forest to open built up
7332, 7112	7222	UE: other vegetation to open built up
4413	4433	UE: agriculture to infrastructure
4553	5553	UE: pasture to infrastructure
7732	7722	UE: other vegetation to open built up
5113	5333	UE: pasture to infrastructure
4331	4111	UE: agriculture to urban
5112	5222	UE: pasture to open built up
4113	4333	UE: Agriculture
5512	5522	UE: pasture to open built up
3773	7773	UE: other vegetation to infrastructure
6331	6111	UE: forest to urban
6612	6622	UE: forest to open built up
6112	6222	UE: Forest to open built up
5331	5111	UE: pasture to urban
7331	7111	UE: other vegetation to urban

Highlights

- Change trajectory analysis improved the consistency of CORINE land-cover timeseries.
- LULC uncertainty has a great impact on hydrological impact analysis.
- The scale of hydrological analysis plays a major role in groundwater recharge estimation
- Up to 35% decrease in groundwater recharge due to urbanization in Flanders.