

Investigation of the human impact on regional groundwater systems

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Abstract

The human impact on regional groundwater systems is investigated in the Dijle basin, situated east of Brussels, Belgium. The hydrological and hydrogeological settings are rather complex because the land-use is strongly affected by urbanisation, industrialisation and agriculture.

The effect of land-use on the groundwater recharge is simulated with the WetSpa model, which allows to estimate spatially distributed runoff, evapotranspiration, and recharge in function of land cover, soil type and topography. In order to quantify the impact of urban and agricultural land-use, the results are compared with the hypothetical situation in which all land cover is assumed to be forest. The results show a substantial reduction in groundwater recharge especially in urban areas.

1 Introduction

The role and importance of groundwater in the natural water cycle has become more pertinent in the last decades due to the increased use of groundwater for many human activities. As a consequence many aquifers are intensively exploited. Because of this, the protection and wise management of aquifers has become essential for the preservation of these resources and the aquatic ecosystems that depend on it. Therefore, more and more studies are dealing with the safe use and sustainability of groundwater reserves and in particular the effects caused by human actions. Due to the complexity of the hydrological processes and basin wide characteristics, physically based distributed models using GIS techniques are very powerful tools in this respect.

In this paper we present the results obtained with a physically based distributed hydrological model WetSpa, that uses detailed basin characteristics to predict regional patterns of groundwater recharge. These results form part of a

regional study on the groundwater reserves in the Dijle basin in Belgium [1]. The goal of the study was to evaluate changes in the groundwater systems that have been induced by human activities. One of the important issues in this study is the effect of present land-use on the groundwater recharge. Groundwater reserves are directly affected by decreasing recharge and the spatial variations in the recharge is an important boundary condition needed for accurate prediction of regional groundwater flow patterns and relationships between groundwater recharge and discharge areas.

2 Theory

WetSpass is an acronym for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State. It was built upon the foundations of the time dependent spatial distributed water balance model "WetSpa" (Batelaan *et al.* [2], Wang *et al.* [3]). De Smedt *et al.* [4] describe a version of WetSpa, aiming at peak discharge simulation based on distributed data. A detailed description of the WetSpass model is given by Batelaan & De Smedt [5] and in the manual [6], which together with the model is available upon request.

Here, we restrict ourselves to the most important concepts of the methodology. The total water balance for a raster cell is split into independent water balances for the vegetated, bare-soil, open-water and impervious parts of each cell. This allows accounting for the non-uniformity of the land-use, which is dependent on the resolution of the raster cell. The processes in each part of a cell are set in a cascading way. This means that an order of occurrence of the processes, after the precipitation event, is assumed. Defining such an order is a prerequisite for the seasonal time scale with which the processes will be quantified. A mixture of physical and empirical relationships is used to describe the processes.

The water balance for vegetated surfaces is given by

$$P = ET + S + R \quad (1)$$

where P is the average seasonal precipitation [LT^{-1}], ET is the total evapotranspiration including interception [LT^{-1}], S is the surface runoff [LT^{-1}], and R the groundwater recharge [LT^{-1}]. The surface runoff, S , is calculated as a coefficient times the net-precipitation, i.e. precipitation P minus interception I

$$S = C(P - I) \quad (2)$$

where C is a surface runoff coefficient depending upon vegetation type, soil type and slope.

The evapotranspiration is calculated as a fraction of potential evaporation

$$ET = fcE \quad (3)$$

where E is the potential evaporation of open water [LT^{-1}], calculated with the Penman equation, c is a vegetation coefficient [-] (Knapp [7]), and f a factor [-] taking into account the effect of soil moisture conditions, calculated according to Vandewiele *et al.* [8] as

$$f = 1 - \exp(-\lambda w/ET) \quad (4)$$

where λ is a calibrated parameter related to the soil type, and w is the available water for transpiration [LT^{-1}], given by

$$w = P + (\theta_{fc} - \theta_{wp})D \quad (5)$$

where D is the root depth, depending upon vegetation type, and θ_{wp} and θ_{fc} are the soil moisture contents at respectively wilting point and field capacity [L^3L^{-3}], which depend upon soil and vegetation type (Saxton *et al.* [9]).

Finally, the groundwater recharge can be calculated as the residual term of the water balance

$$R = P - ET - S \quad (6)$$

The methodology described here results in the estimation of spatially distributed recharge as a function of vegetation, soil type, slope, precipitation and potential evaporation. Procedures similar to that for vegetated surfaces are applied to the bare-soil, open-water and impervious surfaces and the total water balance per raster cell is obtained by combining the balance components for vegetated, bare-soil, open-water and impervious parts of a raster cell.

3 Application

The modelling procedure is applied to the 691 km² large Dijle basin, situated east of Brussels, Belgium. The basin is characterised by a large diversity of soil types and especially land-use. The topography was digitised from 1/10,000 maps, and soil types were obtained from the physical system map of Flanders (Vlaamse Landmaatschappij). The land-use was derived from the digital land-use map of Flanders, based on remotely sensed data of 1995 (Ondersteunend Centrum GIS-Vlaanderen). About 30 land-use classes are shown on this map, of which 18 appear in the Dijle basin. Table 1 presents an overview of these land-use classes and their respective areas. The different land-uses can be grouped in major categories, as agricultural land (48.6%), forests (25.3%), urbanised areas (24.9%), and open water (1.2%).

The WetSpa model is applied to the study area using grid cells of 20 by 20 m. Figure 1 shows the obtained recharge values that results from the different slope, soil type and land-use class combinations. The influence of the urbanisation is evident, as roads and urban centres can easily be identified.

Tabel 1: Land-use types in the study area, with area of occurrence.

| Land-use | Area | |
|--------------------|--------------------|-------|
| | (km ²) | (%) |
| Open water | 8.0 | 1.2 |
| High way | 1.1 | 0.2 |
| Roads | 4.6 | 0.7 |
| Airport | 2.3 | 0.3 |
| Infrastructure | 36.4 | 5.3 |
| Heather | 11.0 | 1.6 |
| Mixed forest | 24.0 | 3.5 |
| Pine forest | 21.1 | 3.0 |
| Leaf forest | 119.0 | 17.2 |
| Industrial areas | 6.9 | 1.0 |
| Orchards | 0.0 | 0.0 |
| Wetlands | 14.2 | 2.1 |
| Maize | 115.2 | 16.7 |
| Meadows | 91.8 | 13.3 |
| Arable land | 115.1 | 16.6 |
| Closed urban areas | 43.5 | 6.3 |
| Open urban areas | 67.3 | 9.7 |
| Urban centres | 10.0 | 1.5 |
| Total | 691.4 | 100.0 |

In order to analyse the influence of the different land-use classes, the average recharge was determined together with the standard deviation for all land-use classes. These results are shown in Fig. 2, classified from high to low. From this figure it becomes evident that groundwater recharge is very strongly depending upon land-use. The mean annual precipitation varies between 734 and 808 mm, with an areal average of 764 mm, and the mean potential evaporation between 662 and 671 mm with an areal average of 667 mm. The resulting groundwater recharge for the present land-use ranges from about 250 mm/y to zero, with an average value of 166 mm/y, which is about 22% of the total precipitation. However, all urban land-use classes yield lower recharge rates, ranging between 100 mm/y and zero. For arable land the average recharge is 152 mm/y, which is slightly less than the total average. In view of the abundance of urban and arable land-use, one would be inclined to conclude that the recharge is substantially lower than what would be obtained under natural conditions. However, meadows yield the highest recharge, i.e. 259 mm/y on the average, which is substantially larger than forests. Because there are also a lot of meadows in the basin, it remains unclear whether the total effect of the present land-use on the groundwater recharge is negative or positive.

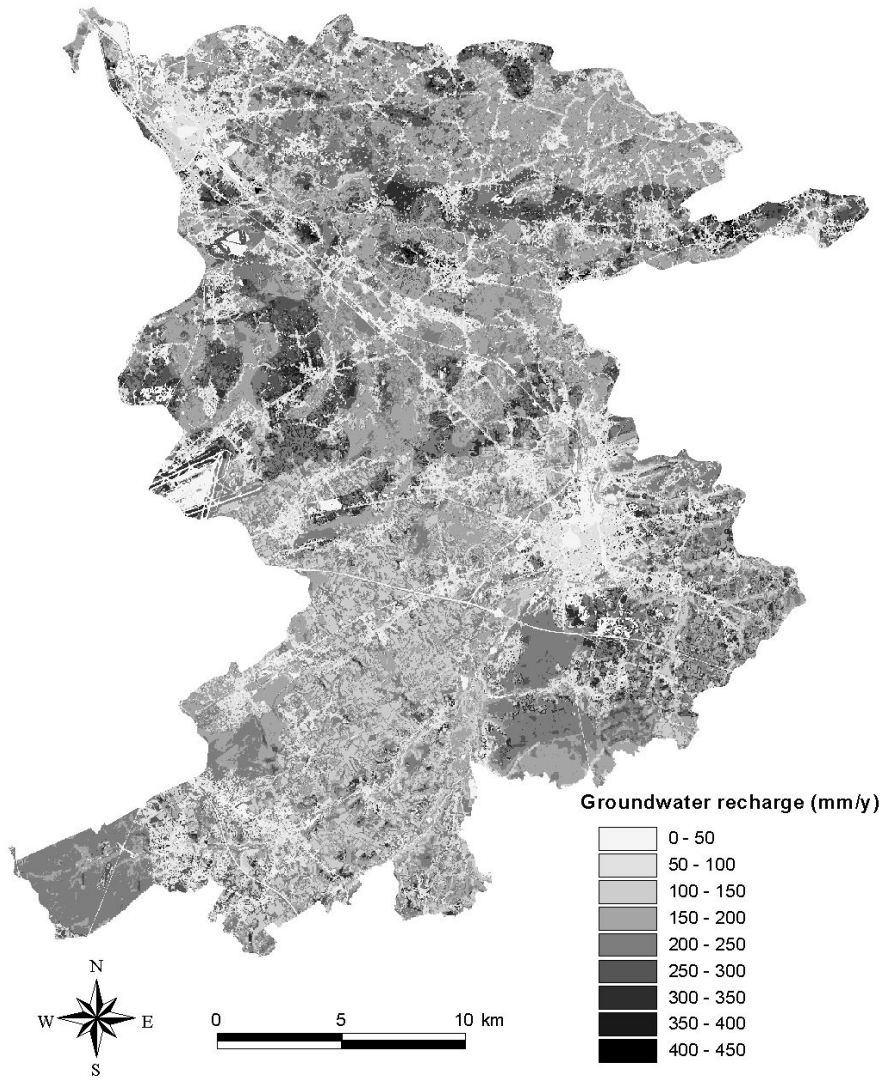


Figure 1: Simulated groundwater recharge with the WetSpass model for the Dijle basin, in function of land-use, soil type, and slope.

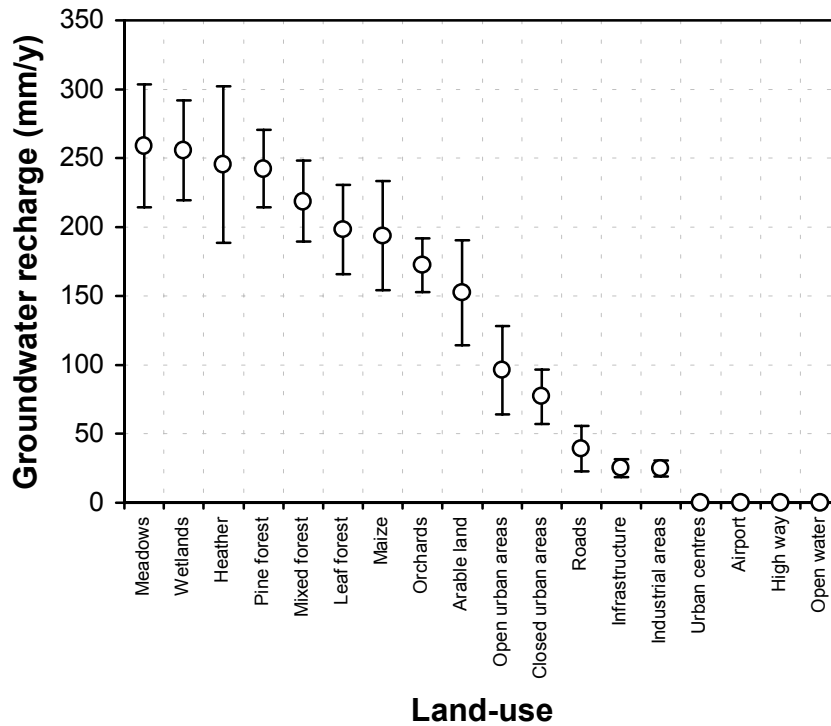


Figure 2: Simulated average groundwater recharge for the different land-use classes with the WetSpaas model; error bars give the average plus or minus the standard deviation; the land-use classes are classified from high to low and clearly show the effect of urbanisation.

In order to determine the impact of present land-use on the groundwater recharge, the WetSpaas was rerun with natural land-use conditions. For the latter, we assumed leaf forest to be present everywhere in the basin. For such conditions the model predicts an average groundwater recharge of 199 mm/y, or 26% of the total precipitation, which is 4% more than for the present conditions. The influence of the present land-use is obtained by taking the difference in recharge between the natural and present conditions. Figure 3 presents the average difference in recharge together with the standard deviation for all present land-use classes, classified from large to small. The difference in groundwater recharge ranges from about -220 to 70 mm/y, with an average value of -33 mm/y, or 20% of the present mean recharge, which for the Dijle basin amounts to 62.510 m³/d or almost the present total groundwater abstractions in the basin. Hence, the decline of groundwater recharge due to present land-use results in a loss for the groundwater reserves of the same magnitude as the present groundwater abstractions for industry and production of drinking water.

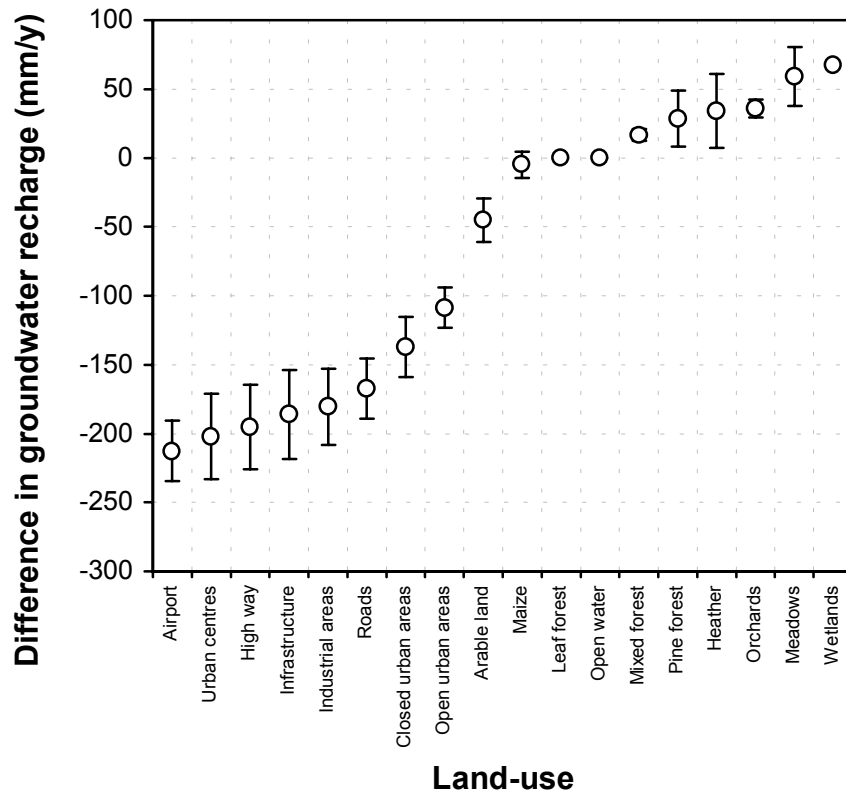


Figure 3: Simulated average difference in groundwater recharge for the different land-use classes with the WetSpaas model; error bars give the average plus or minus the standard deviation; the land-use classes are classified from high to low and clearly show the effect of urbanisation.

The reasons for this loss in recharge can be deduced from Fig. 3. In this figure one can notice that all urban land-use classes give rise to considerable losses in groundwater recharge, i.e. 100 to 220 mm per year. For agricultural land-use the results are mixed. For arable land the average loss in recharge is 45 mm/y, for maize this is only 5 mm/y, but for meadows there is a gain in groundwater recharge of 59 mm/y. Because arable land, maize and meadows are about equally abundant in the basin, the net effect of agricultural practices on the groundwater recharge turns out to be nearly zero. Also, mixed forest, pine forest, orchards, heather, and wetlands yield small gains in recharge, but because these do not occur very much in the basin, their effect is negligible. Hence, it turns out that urbanisation is the main cause of the reduction in groundwater recharge.

Taking into account the different types of urbanisation and their occurrence in the basin, as given in Table 1, we can conclude that the loss in groundwater recharge is mainly due to infrastructure, closed urban areas, and open urban areas, each of which account for about 30% of the total loss. The remaining 10% of the loss in recharge is due to urban centres. All of these land-use classes imply impervious soil cover and draining of precipitation run-off to sewers systems. The loss for the groundwater systems constitutes considerable amounts of water, which can be estimated as 20% of the present mean recharge. Because urbanised areas constitute about 25% of the land-use in the basin, the direct link is obvious, and the rule of thumb that the percentage of impervious areas in an area equals the percentage loss in recharge is quite reasonable.

4 Conclusions

The human impact on regional groundwater systems was investigated in the 691 km² Dijle basin in Belgium, where the land-use is very much affected by urbanisation, industrialisation and agriculture. An important issue in this respect is the effect of the land-use on the groundwater recharge, because decreasing recharge influences groundwater reserves and sustainability of groundwater use.

The effect of land-use on the groundwater recharge is simulated with the WetSpa model that uses detailed basin characteristics to predict regional patterns of groundwater recharge. The results are compared with the hypothetical situation in which all land cover is assumed to be forest.

The results show a substantial reduction in groundwater recharge especially in urban areas. The mean groundwater recharge for the present conditions is 166 mm/y, this is 20% of the precipitation, but all urban land-use classes yield much lower recharge rates, ranging between 100 mm/y and zero. In natural conditions, the model predicts an average ground water recharge of 199 mm/y, or 26% of the total precipitation.

All urban land-use classes give rise to considerable losses in groundwater recharge, i.e. 220 to 100 mm/y. For agricultural land-use the results are mixed, i.e. negative for arable land and positive for meadows, such that the net effect is zero. Other land-uses as mixed forest, pine forest, orchards, heather, and wetlands yield small gains in recharge, but because these are not abundant, their total effect is negligible. Hence, urbanisation is the main cause of the significant reduction in groundwater recharge. It can be concluded that the loss is mainly due to infrastructure, closed urban areas, and open urban areas, each of which account for about 30% of the decline in recharge, while the remaining 10% is due to urban centres.

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