WetSpass: a flexible, GIS based, distributed recharge methodology for regional groundwater modelling

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Abstract Regional groundwater models used for analysing groundwater systems (infiltration–discharge relations) are often quasi-steady state and therefore need long-term average recharge input. On the other hand, the spatial variation in the recharge due to distributed land-use, soil type, slope, groundwater level, meteorological conditions, etc. can be significant and should be accounted for. Hence, WetSpass was built as a physically based methodology for estimation of the long-term average spatial patterns of surface runoff, actual evapotranspiration and groundwater recharge. The model is especially suitable for studying long-term effects of land-use changes on the water regime in a basin. The computer model was integrated in the GIS ArcView. Its set-up is extremely flexible; it allows easy new definition of natural or man-made land-use types. This paper describes the concept of the model and gives an example of a calibrated WetSpass recharge map.

Key words Belgium; distributed model; GIS; recharge estimation; water balance; WetSpass

INTRODUCTION

The definition of recharge in this framework is taken from Freeze (1969): "recharge is the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone". Regional groundwater models used for analysing groundwater systems (infiltration–discharge relations) are often quasi-steady state and therefore need long-term average recharge input. On the other hand, the spatial variation in the recharge due to distributed land-use, soil type, slope, etc. can be significant and should be accounted for in these regional groundwater models. Stream flow recession analysis clearly shows this spatial variability of recharge (Chapman, 1999). Hence, WetSpass was built as a physically based methodology for estimation of the long-term average, spatially varying, water balance components: surface runoff, actual evapotranspiration and groundwater recharge.

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*., 1996; Wang *et al*., 1997). De Smedt *et al*. (2000) describes a 1-h based version of WetSpa, aiming at peak discharge simulation based on distributed data.

MODEL DESCRIPTION

The total water balance for a raster cell (Fig. 1) is split into independent water balances for the vegetated, bare-soil, open-water and impervious parts of each cell. This allows one to account for the non-uniformity of the land-use per cell, 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 timescale with which the processes will be quantified. A mixture of physical and empirical relationships is used to describe the processes. The quantity determined for each process is consequently limited by a number of constraints.

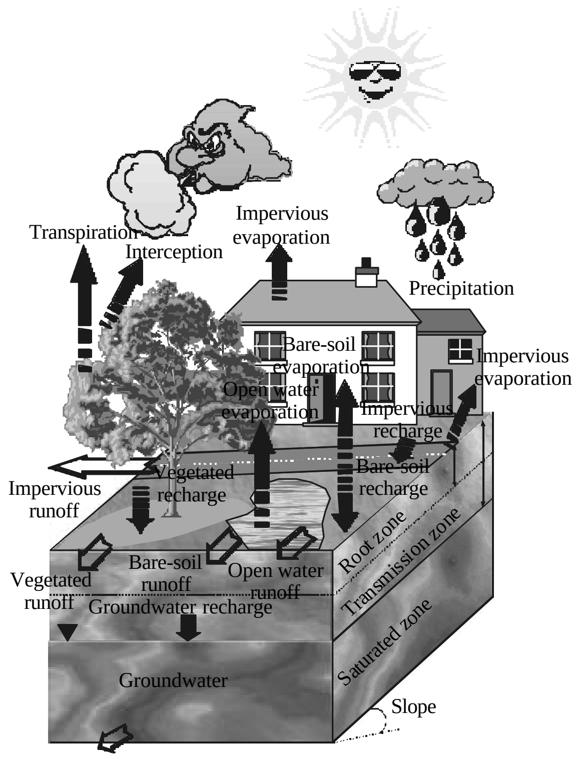

Fig. 1 Schematic water balance of a hypothetical raster cell.

Water balance components

The water balance for vegetated surfaces is given by:

$$P = I + S_v + T_v + R_v \tag{1}$$

where P is the average seasonal precipitation [LT^{-1}], I is the interception by vegetation [LT^{-1}], S_v is runoff over land surface beneath vegetation [LT^{-1}], T_v is the actual transpiration [LT^{-1}] and R_v is groundwater recharge [LT^{-1}]. The term actual evapotranspiration, ET_v, is used here for the sum of the transpiration, T_v, and the evaporation from the bare soil between the vegetation, E_s. ET_{tot}, the total actual evapotranspiration is the sum of the evaporation of water intercepted by vegetation, I, and the actual evapotranspiration, ET_v.

The interception fraction has been shown to be reasonably constant at a given annual precipitation value and exhibits a consistent decrease with increasing annual rainfall total (Roberts, 1983). Therefore, the intercepted value is parameterized as a constant percentage from precipitation, dependent on the vegetation type (Calder, 1979; Nonhebel, 1987).

The surface runoff, S_v, is calculated in two stages. In the first the potential surface runoff (S_{v-pot}) is calculated as a coefficient times the precipitation minus the interception:

$$S_{v-pot} = C_{Sv}\,(P - I) \tag{2}$$

where C_{Sv} is a surface runoff coefficient for vegetated infiltration areas, based on the rational formula (Smedema & Rycroft, 1988; Pilgrim & Cordery, 1992; Chow *et al.*, 1988). C_{Sv} is a function of vegetation type, soil type and slope. In groundwater discharge areas, saturated surface runoff is occurring. Here, the surface runoff coefficient is very high and assumed to be constant, due to its reduced dependency on soil and vegetation type and the generally near to river position of the runoff producing areas. In the second stage, the potential surface runoff is actualized by taking into account differences in precipitation intensities in relation to soil infiltration capacities. Rubin (1966) showed that in this case Hortonian overland flow is rare.

$$S_v = C_{Hor}\, S_{v-pot} \tag{3}$$

C_{Hor} is a coefficient that parameterizes the part of the seasonal precipitation which is actually contributing to the (Hortonian) surface runoff. In groundwater discharge areas all intensities of precipitation contribute to surface runoff, i.e. C_{Hor} is 1. In infiltration areas only high intensity storms will generate surface runoff. For the precipitation station Ukkel (Belgium) an analysis has been made of 10-min precipitation data for the period 1948–1998. For each season the cumulative precipitation falling with an intensity greater than 1, 2, 3 mm h^{-1} etc. is determined. It is clear that the cumulative high intensity precipitation amount is much bigger in summer than in winter. For each soil class the infiltration rate (Rawls *et al.*, 1992; Saxton *et al.*, 1986) has been related to the precipitation intensity. The Hortonian surface runoff, can now be determined as the fraction of the seasonal precipitation with an intensity higher than the infiltration capacity.

In order to obtain a seasonal distributed evapotranspiration value, WetSpass proposes to convert the open-water evaporation value, as commonly available from the Penman equation, to a reference transpiration (Federer, 1979) value based on a vegetation coefficient:

$$T_{rv} = c\,E_o \tag{4}$$

where T_{rv} is the reference transpiration of a vegetated surface [LT^{-1}], E_o is the potential evaporation of open water [LT^{-1}] and c is the vegetation coefficient [–]. The vegetation coefficient can be determined as the quotient of the reference vegetation transpiration, as given by the Penman-Monteith equation, and the potential open-water evaporation, as given by the Penman equation, resulting in:

$$c = \frac{1 + \gamma/\Delta}{1 + \gamma/\Delta\left(1 + r_c/r_a\right)} \tag{5}$$

where the proportionality constant Ä is the slope of the first derivative of the saturated vapour pressure curve [$ML^{-1}T^{-2}C^{-1}$], ã is the psychrometric constant [$ML^{-1}T^{-2}C^{-1}$], r_c is the canopy resistance [TL^{-1}] and r_a is the aerodynamic resistance [TL^{-1}]. Dingman (1994) derived an equation similar to equation (5) but included the soil moisture dependent canopy resistance function from Stewart (1988).

Obviously, in vegetated groundwater discharge areas, the actual transpiration, T_v, is equal to the reference transpiration, since soil water availability is not limiting:

$$T_v = T_{rv} \quad \text{if} \quad (G_d - h_t) <= R_d \tag{6}$$

where, G_d, is the groundwater depth [L], h_t is the tension saturated height [L] and R_d is the rooting depth [L]. The actual transpiration for vegetated areas where the groundwater level is below the root zone is calculated as:

$$T_v = f(\theta) T_{rv} \quad \text{if} \quad (G_d - h_t) > R_d \tag{7}$$

where $f(\theta)$ is a function of the water content. In WetSpass, for a time invariant situation; the methodology developed by Vandewiele *et al.* (1991) is used for defining $f(\theta)$:

$$f(\theta) = 1 - a_1^{\frac{w}{T_{rv}}} \quad \text{with} \quad w = P + (\theta_{fc} - \theta_{pwp}) R_d \tag{8}$$

where a_1 is a calibrated parameter related to the sand content of a soil type (Van der Beken & Huybrechts, 1990), w is the available water for transpiration [LT^{-1}], and $\theta_{fc} - \theta_{pwp}$ is the plant available water content.

Groundwater recharge can be calculated as a residual term, from the water balance:

$$R_v = P - S_v - ET_v - E_s - I \tag{9}$$

The methodology described here will result in the estimation of spatially distributed recharge as a function of vegetation, soil type, slope, groundwater depth, precipitation regime and other climatic variables. Even in groundwater discharge areas some recharge will be calculated, in agreement with the conceptual picture that a thin unsaturated zone is also present in discharge areas, allowing some recharge. However, in summer the calculated recharge in discharge areas will be often negative as a result of the potential transpiration of the vegetation. High winter recharge will in some cases compensate the negative recharge.

Change in storage is brought into the model, on a seasonal basis, in two ways. First, it is possible to have different groundwater levels for the winter and summer situation. Secondly, it is assumed that during winter the plant available soil moisture reservoir is filled up and that during summer this reservoir can be depleted.

A procedure similar to that for vegetated surfaces is applied to the bare-soil, open-water and impervious surfaces.

Water balance per raster cell

The total water balance, per raster cell and season, can now be calculated using the previously described water balance components for vegetated, bare-soil, open-water and impervious parts of a raster cell.

$$ET_{raster} = a_v ET_v + a_s E_s + a_o E_o + a_i E_i \tag{10}$$

$$S_{raster} = a_v S_v + a_s S_s + a_o S_o + a_i S_i \tag{11}$$

$$R_{raster} = a_v R_v + a_s R_s + a_i R_i \tag{12}$$

where ET_{raster}, S_{raster}, R_{raster} are respectively, the total evapotranspiration, surface runoff and recharge in a raster cell. a_v, a_s, a_o and a_i are respectively the vegetated, bare-soil, open-water and impervious area fractions of a raster cell.

GIS IMPLEMENTATION

WetSpass was completely integrated in the GIS ArcView as a raster model, coded in Avenue. Parameters, such as land-use and related soil type, are connected to the model as attribute tables of the land-use and soil raster maps. This allows for easy definition of new land-use or soil types, as well as changes to the parameter values. The soil classification used for the WetSpass model is based on the US Department of Agriculture (Soil Survey Staff, 1951) classification. For the land-use type a land cover map for Flanders is used, which is based on a Landsat 5 classified image, resampled to a 50 by 50 m resolution.

Using the distributed recharge from WetSpass in a steady-state groundwater model will improve the prediction of the simulated groundwater level, discharge and recharge areas. However the groundwater level is input to the WetSpass simulation. Therefore, the groundwater and WetSpass models have to be performed one after the other, while exchanging recharge and groundwater depth (Fig. 2). This will lead to a stable solution for the groundwater level and discharge areas after a few iterations.

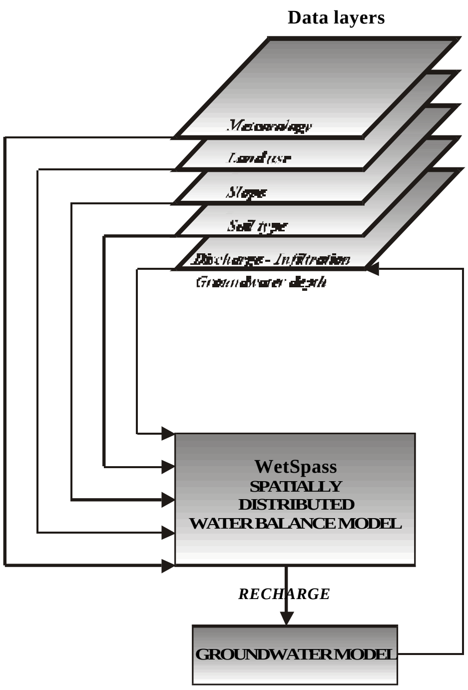

Fig. 2 Schematic representation of the iteration process in the WetSpass model.

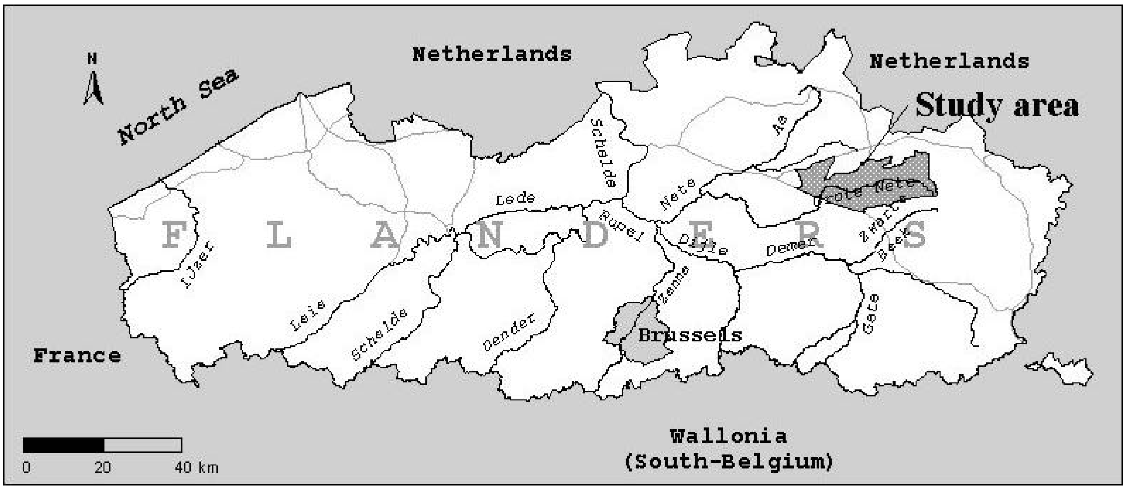

Fig. 3 Location of the study area.

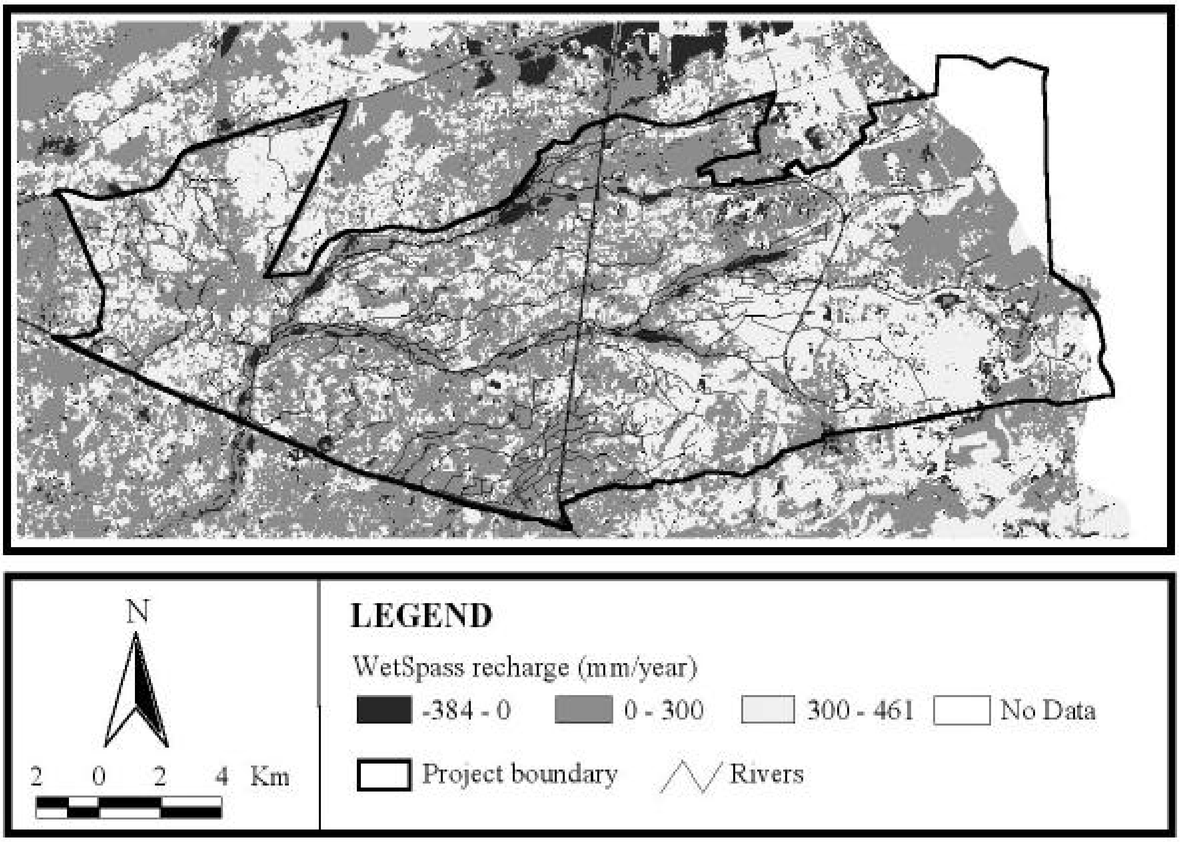

Fig. 4 WetSpass calculated recharge for the Grote Nete area.

APPLICATION

WetSpass was used for a land-planning project in the Grote Nete basin, Belgium (Fig. 3). In this study the effects of land-use changes on the groundwater discharge areas were analysed. A distributed recharge estimation was therefore essential. The WetSpass results are taken from a larger WetSpass model for the basins of the Dijle, Demer and Nete Rivers (Fig. 3). The model was calibrated for these basins on the basis of discharge measurements at 17 gauging stations, of which two are located in the Grote Nete basin. Total discharge, as well as surface runoff and baseflow, determined by two different discharge separation techniques, were used for the calibration of the WetSpass water balance components. A groundwater model, with recharge from WetSpass as input, was calibrated in conjunction with the WetSpass calibration. Groundwater discharge areas calculated by the groundwater model were also verified by field mapping of phreatophytes for the Grote Nete area.

Figure 4 shows the recharge map obtained for the Grote Nete land-planning project area for the present land-use. The results have been reclassified into three ranges. The recharge values range from –384 to 461 mm year^{-1}, with an average of 282 mm year^{-1}. Negative and low values, due to high evapotranspiration, are found in the river valleys and especially at locations of groundwater discharge. The highest values are found under bare soil on the interfluves.

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