CHARACTERIZING THE GROUNDWATER CONTRIBUTION TO ECOLOGICALLY VALUEBLE LOWLAND STREAMS USING TRAVEL TIME DISTRIBUTIONS

V.P. KAANDORP
Subsurface and Groundwater Systems, Deltares, Princetonlaan 6-8
Geochemistry, Utrecht University, Budapestlaan 4
Utrecht, The Netherlands

P.G.B. DE LOUW
Subsurface and Groundwater Systems, Deltares, Princetonlaan 6-8
Utrecht, The Netherlands

M.J.M. KUIJPER
Subsurface and Groundwater Systems, Deltares, Princetonlaan 6-8
Utrecht, The Netherlands

Y. VAN DER VELDE
Earth and Life Sciences, VU University Amsterdam, De Boelelaan 1085
Amsterdam, The Netherlands

H.P. BROERS
TNO Geological Survey, Princetonlaan 6
Utrecht, The Netherlands

Groundwater is the main source of stream flow for many lowland streams and therefore affecting the abiotic habitat conditions of aquatic ecosystems. The groundwater contribution to streams influences (1) river discharge, (2) water quality, (3) temperature and (4) the riparian zone. The input of groundwater provides streams with a stable base flow, good quality water and a steady temperature. However, the groundwater contribution to streams is often not characterized in detail. The current research addresses the groundwater input and its importance for aquatic ecology in lowland streams and aims to characterize it in a more sophisticated way using dynamic Travel Time Distributions.

A 3D groundwater flow model (MODFLOW) was used to characterize daily Travel Time Distributions in the Dinkel lowland catchment in The Netherlands. This revealed varying contributions of groundwater flow paths with different travel times. Longer and shorter flow paths differ in amount and timing of flow, hydrochemistry and temperature. Results can be used to study the effect of stresses on the groundwater component of stream flow, and the aquatic ecosystems and habitats present in the stream.

1 INTRODUCTION

Groundwater is the main source of water in many lowland streams and thus affects the abiotic habitat conditions of aquatic ecology. The amount and quality of groundwater discharging on the surface is temporally and spatially variable and controlled by the groundwater's flow paths and travel time [2, 9]. The input of groundwater provides streams with a stable base flow, good quality water and a steady temperature, which are important parameters for aquatic ecosystems. However, the contribution of groundwater to streams is frequently not characterized in detail.

The distribution of groundwater travel times is a fundamental catchment characteristic [2, 4, 11]. Travel Time Distributions (TTDs) based on actual groundwater flow dynamics can be calculated using particle tracking software. Most research has focussed on steady state situations and thus did not cover the differences in flow paths and residence times, spatial differences and changing in groundwater contribution to the stream throughout the year.

Recently, attempts have been made to fill this knowledge gap. For instance, Morgenstern *et al*. [5] calculated mean transit times for multiple base flow condition in a catchment in New Zealand, and demonstrated that the age of water in the stream varied with the amount of discharge. In addition, Rinaldo *et al*. [8] and Birkel *et al*. [1] also showed differences in mean transit times in stream flow between different seasons and wetness conditions.

The present research aims to go a step further by specifying the input of groundwater to lowland streams in more detail by making a distinction in the travel time of discharging groundwater throughout the year. The time-varying groundwater contribution to streams is characterized using dynamic Travel Time Distributions which are calculated using a MODFLOW-MODPATH combination. Dynamic TTDs for three lowland catchments in The Netherlands are computed and then compared with each other in order to gain more understanding of the functioning of these systems.

2 METHODS

2.1 Study Area

Calculations were done in three sub-catchments of the Dutch part of the catchment of the Dinkel river in the east of The Netherlands. These sub-catchments are the Springendalse Beek, Voltherbeek and Elsbeek. The watersheds are approximately 4 km^2 for the Springendalse Beek, 11 km^2 for the Elsbeek and 12 km^2 for the Voltherbeek. The area has a temperate marine climate, with a mean temperature of about 9.5 °C, a mean annual precipitation of about 800 mm and a mean annual evaporation of 560 mm.

Topography in the Dutch part of the Dinkel catchment varies from 18 to 80 meter above sea level. The subsoil of the area is characterized by moraines which are clayey and form a hydrological barrier. Stream valleys are filled with more recent, sandy deposits. Springs are located on some hill edges, especially in the catchment of the Springendalse Beek. The streams have different discharge characteristics. For instance, the Springendalse Beek has an average annual discharge of about 1.4 10^6 m^3, the Voltherbeek 2.6 10^6 m^3 and the Elsbeek 3.3 10^6 m^3. They also differ in variation of discharge throughout the year: the Voltherbeek has the highest peaks while the Springendalse Beek has a fairly stable discharge in time (Figure 1). Main land use in the study area is agriculture, for which the catchments are intensively drained by ditches and pipe drainage. In addition, many streams have been straightened or deepened in order to improve drainage.

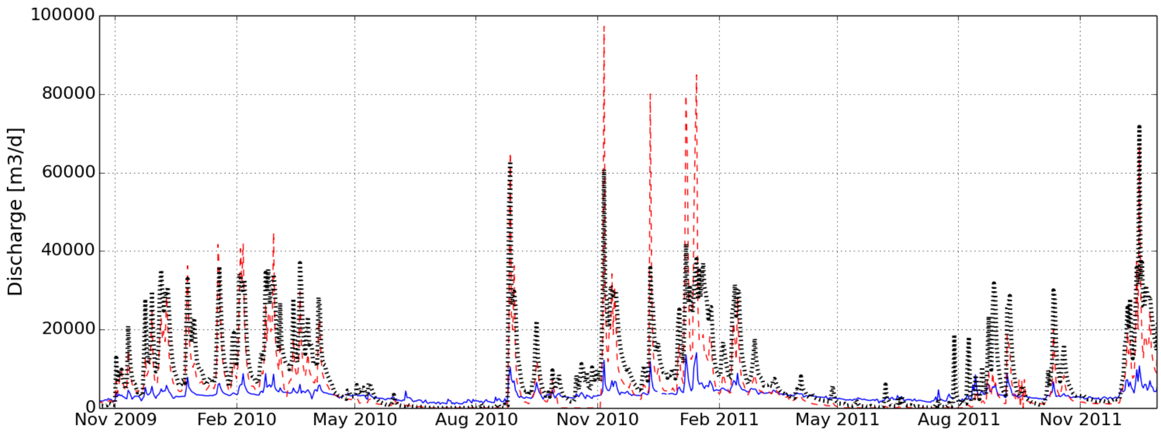

Figure 1. Measured discharge 2009-2011 of the Springendalse Beek (solid), Voltherbeek (dashed) and Elsbeek (dotted).

2.2 Groundwater flow model

A calibrated MODFLOW [3] groundwater flow model of the Dinkel catchment was used. The total modeled area comprised the three catchments and was divided into 25 by 25 meter cells. The top of the model followed the surface elevation and 7 layers with variable thicknesses were added in the vertical, based on the Dutch Geohydrological Information System [8]. The east side of the model was located on the water divide and as such modelled as a no-flow boundary, whereas the other boundaries were constituted as fixed head boundaries, as there was no clear water divide. The unsaturated zone was simulated using the MetaSWAP module [10], which was coupled with MODFLOW and provided the flux towards and from the saturated zone. From this model the three sub-catchments were clipped from the regional Dinkel-model and simulated for further analysis.

2.3 Particle tracking model

Next, travel times were calculated using the particle tracking software MODPATH [6]. Calculations were done for one year, using the fluxes of one representative year computed by the groundwater flow model. One particle was started on the groundwater level in the centre of each cell and symbolized the groundwater recharge at that point. Particles were started every day after which the particles were followed through the aquifer till their point of seepage.

2.4 Analysis

Before further analysis, the borders of the three sub-catchments were revised using the results of the particle tracking calculations in order to include the area draining towards the studied streams through the groundwater. After this, particles seeping up outside the studied catchments were removed. Particles were then given a volume, based on the groundwater recharge on the day and location their calculation started. Next, a correction for evaporation from groundwater was done by continuously decreasing the volume of the most recently started particle by the appropriate amount. Finally, the results of the 365 separate particle tracking runs were combined for which all particles contributing to the stream flow on a specific day were summed. The particle volumes were used to weight the contribution of the particles to the stream flow. The result of this procedure was a daily distribution of travel times in the stream flow. Additional analysis of these travel times was done by comparing the fluctuation of travel times throughout the year with water chemistry measurements.

3 RESULTS AND DISCUSSION

Results of the groundwater flow model included groundwater heads and discharge of the various streams. Figure 2 shows the modelled versus measured discharge of the Voltherbeek, and illustrates that the model was able to produce a good fit with the measurements. The model was not able to simulate the highest peaks though, these are probably not caused by groundwater input but for instance direct precipitation and as such, were not included in the model.

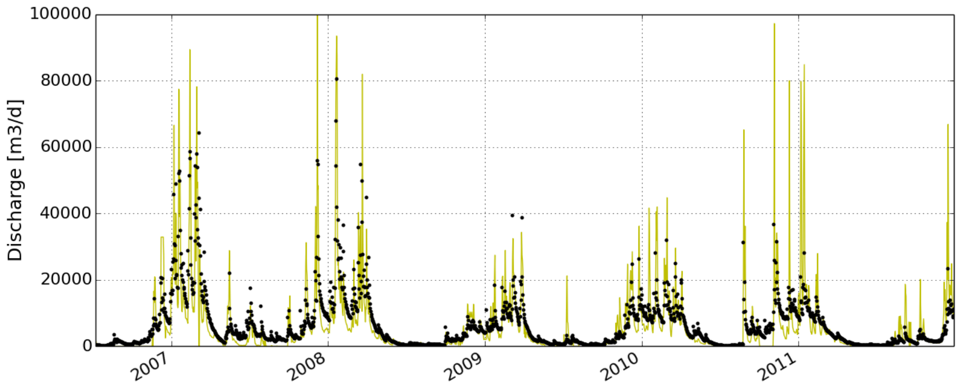

Figure 2. Measured (line) versus modelled (dots) discharge of the Voltherbeek.

Groundwater catchment borders were revised based on the particle tracking runs. This showed that the topographical surface water catchment did not coincide with the groundwater catchment. This is an important observation to keep in mind during further analysis and furthermore is important information to water managers. Apparently, water infiltrated outside the topographical catchment can still end up in the stream, and thus stream water is also influenced by measures or pollution from these areas.

Next, daily Transit Time Distributions were derived from the particle tracking calculations. From these, it is clear that the contribution of groundwater of different ages fluctuates throughout the year. For instance, while the quantity of water is smaller during summer, stream water contains a bigger fraction of water with a travel time of more than 10 years during summer than during winter, which is in accordance with earlier research (e.g. [5]). The contribution of different flow paths reacts to precipitation, with the biggest fluctuations in the youngest water, which produces the majority of the discharge peaks after precipitation events. It is interesting to compare the TTDs of the different studied catchments. The Springendalse Beek is clearly different from the other streams, in particular, the discharge has less peaks and is more stable throughout the year. The calculated Travel Time

Distribution shows that this is caused by a smaller contribution of young water. Additionally, the older water contributing to the Springendalse Beek is very stable in time.

4 CONCLUSIONS

This study began with the premise that it is needed to specify the groundwater input to streams in more detail and suggested that travel times would be a good parameter to use. Dynamic Travel Time Distributions were computed using particle tracking software which give more insight into stream functioning and the contribution of different groundwater flow paths throughout the year. Several small catchments were compared which revealed that TTDs can be very different on short distances due to i.e. geology and land use. The water of the various flow paths differ in chemical composition and temperature and as such, the distribution of their contribution to stream discharge in time and space control the abiotic conditions for aquatic ecosystems. Results can be used to study the effect of stresses on the groundwater component of stream flow, and the aquatic ecosystems and habitats present in the stream.

5 ACKNOWLEDGMENTS

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