Aged streams: Time lags of nitrate, chloride and tritium assessed by Dynamic Groundwater Flow Tracking in a lowland landscape

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Abstract. Surface waters are under pressure of diffuse pollution from agricultural activities and groundwater is known to be a connection between the agricultural fields and streams. This paper is one of the first to calculate long-term in-stream concentrations of tritium, chloride and nitrate using dynamic groundwater travel time distributions (TTDs) derived from a distributed, transient 3D groundwater flow model using forward particle tracking. We tested our approach in the Springendalse Beek catchment, a lowland stream in the east of the Netherlands, for which we collected long time series of chloride and nitrate (1969-2018). These measurements showed that the trend reversal in solute concentrations following legislations in the 1980s occurred after a limited time lag. By combining calculated TTDs with solute input curves, we found that the variable contribution of different groundwater flow paths to stream water quality reasonably explained the majority of long-term and seasonal variation in the measured stream nitrate concentrations. An exploration of the model behaviour under different scenarios was done to study the time lag in the breakthrough of agricultural nitrate and it was found that this time lag mainly depends on 1) the travel time in the unsaturated zone, including slow release of organic N, 2) the combination of Mean Travel Time (MTT) and the rate of the solute input reduction, and 3) the spatial setting of agricultural fields, (bio)chemical processes and the drainage network. In absence of these processes, the effect of input reduction measures can generally be expected instantly, which is an important conclusion for water managers. By making the connection between dynamic groundwater travel time distributions and in-stream concentration measurements, we provide a method for validating the travel time approach and make the step towards application in water quality modelling and management.

1 Introduction

Diffuse pollution with nutrients is one of the main pressures on Europe's surface- and groundwaters (EEA, 2018). Intensive agricultural land-use and the accompanying use of manure and fertilizers have significantly increased the amount of nitrate in the hydrological system in the period after 1950 (Aquilina et al., 2012; Broers and van der Grift, 2004; Hansen et al., 2011;

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Worrall et al., 2015). Nitrate leaches to the groundwater (Boumans et al., 2008; Wang et al., 2012) from where it is transported towards surface waters through fast and slow flow paths, creating a stress on surface water quality (Howden et al., 2011b; Kaandorp et al., 2018b; van der Velde et al., 2010).

Flow paths are the routes that water particles travel through the subsoil, crossing different geological formations and reaching certain depths, which takes a certain travel time from infiltration to exfiltration (Broers and van Geer, 2005; van der Velde et al., 2010). The nitrate concentration in groundwater and streams depends on these groundwater flow paths and travel times, as well as on land-use (for instance use of manure and fertilizer). Both the flow route and travel time influence hydrochemical processes, as they determine which mediums are passed and the time that is allowed for (biogeo)chemical reactions. Nitrate concentrations may for instance decrease by denitrification when passing organic or pyrite-rich layers (e.g. Zhang et al., 2013).

Land-use determines the timing and quantity of nitrate input as well as its spatial distribution (Boumans et al., 2008). Thus, all water particles may carry different nitrate concentrations depending on their place and time of infiltration, their flow paths and their travel times along their flow paths. For example, the input of nutrients is higher on fertilized agricultural fields than in forested areas. In catchments, groundwater flow paths provide the hydrologic connection between infiltration areas and seepage zones in streams (e.g. Ali et al., 2014; Birkel et al., 2015; McGuire and McDonnell, 2010). Because groundwater flow paths are variable in time, the delivery of nitrate from groundwater to surface waters also varies in time (Rozemeijer and Broers, 2007).

In a recent paper, Kaandorp et al. (2018a) presented dynamic travel time distributions (TTDs) for lowland catchments in the Netherlands. They showed how groundwater flow paths in these catchments vary in time and discussed differences in mixing processes between young and old groundwater in the streams with time. Connecting this hydrologic approach with solute transport would enable validation of calculated travel times using stream concentration data and would highlight the potential of using TTDs for non-point source transport modelling. Therefore, we combine in this follow-up paper these dynamic travel time distributions with input curves for tritium, chloride and nitrate to reconstruct the concentrations in a Dutch stream from 1969 until present, while including the dynamic nature of catchments both in time and space. Our aims are twofold: first to validate the results of the TTD method by comparing them to measurements of solutes, and second to explore the effect of different processes and parameters on the breakthrough patterns and time lags of groundwater derived solutes as a way forward in a) model calibration and b) management of (ground)watersheds. This work extends on recent advances in research onf the groundwater contribution to streams (e.g. Engdahl et al., 2016; McDonnell et al., 2010; Morgenstern et al., 2010; Solomon et al., 2015; van der Velde et al., 2012), and is one of the first to couple measurement data of water quality and isotopes to dynamic TTDs calculated using a forward particle tracking model. Even though many recent papers suggest that this method holds a lot of potential (e.g. Hrachowitz et al., 2016), the papers which have attempted to do so are still scarce due to a lack of

long-term solute input in the range of 5-50 years and discharge concentration data. The data availability within our study catchment provides a unique opportunity to explore the application of dynamic TTD's for solute transport calculation.

In our study, tritium and chloride were included as water tracers. Tritium is part of the actual water molecule, while chloride was considered to be a conservative tracer of manure and fertilizers when it passes through the aquifer, and nitrate reactive. Convolutions of the solute input curves with the modelled TTDs were compared with observed stream concentrations of tritium, chloride and nitrate, which opens the possibility of validation of the model-derived TTDs. We used the model to assess whether the fluctuation in flow paths and contributing areas explain the variability of stream water quality, as has been found in other studies (Musolff et al., 2016; Rozemeijer and Broers, 2007), and ran an exploration of the model behaviour under different scenarios to analyse the parameters that determine lag times between recharge of the solutes and discharge in the stream, such as unsaturated zone delay, the distance between fields and the stream and the mean travel time of the system. Lastly, we explored the effects of input scenarios on the breakthrough of agricultural nitrate.

2. Methods

2.1. Study area

A lowland stream in the east of the Netherlands, the Springendalse Beek (Figure 1), was selected for this study because of its high nitrate concentrations and differences in land-use and discharge characteristics between upstream and downstream parts of the catchment (Kaandorp et al., 2018b). The catchment has a temperate marine climate with a mean temperature of 9.6 °C and mean annual precipitation and evaporation of around 850 and 560 mm respectively. The size of the catchment is 4 km2 and the average discharge downstream is 0.043 m3/s with a baseflow index of 0.8 (Gustard et al., 1992).

The catchment is located on the flank of an ice-pushed ridge that was formed during the Saalien glaciation and has a maximum elevation of 75 m above sea level. Recent hydrogeological inventories suggest a complex ice-pushed structure, composed of a series of tilted slabs of Tertiary clays (Formation of Breda and older) intercalated with Pleistocene moderately coarse, organic poor sands and some gravel that were deposited by a braided river (Formation of Appelscha). These slabs roughly have a N-S strike direction, perpendicular to the receiving Springendalse Beek stream (pers. comm. Harting and Bakker, TNO Geological Survey of the Netherlands) and can hardly be passed by groundwater flow, leading to relatively high groundwater tables compared to more sandy ice-pushed ridges in the Netherlands. In general, the average depth of the water table is around 0.5 m below the surface in the downstream part of the catchment and up to about 3.0 meter below the surface in the highest parts of the upstream catchment, presumably concentrated at outcrops of the Pleistocene sands. The streambed of the stream is sandy with some occasional gravel, which represents material from the tilted Appelscha Formation.

The upstream part (2 km^2) of the Springendalse Beek catchment has several spring areas and is mostly forested with some agricultural fields, while farmland is more abundant in the downstream part (2 km^2) of the catchment. Many of these farmlands are artificially drained by a system of tile drains and ditches, especially in the downstream part of the catchment due to the flatter topography and more shallow groundwater tables compared to the upstream part of the catchment. Available data indicates that the drainage density is around 20-30% lower in the upstream part of the catchment than in the downstream part. Due to its constant flow and permanent springs, the stream is known to have a high ecological value (e.g. Nijboer et al., 2003; Verdonschot et al., 2002).

2.2. Collecting water quality measurements of surface water

Surface water quality measurements were collected from various sources (Table 1), with a focus on the availability of data on chloride and nitrate. First, historical data from 1969 onwards of chloride and nitrate concentrations was obtained from earlier studies (Dam et al., 1993; Higler et al., 1981; Hoek, 1992; van der Aa et al., 1999; Verdonschot and Loeb, 2008). This dataset was complemented with a 1985-present time series of chloride and nitrate that was collected by the monitoring program of the local Waterboard Vechtstromen. In addition, we started sampling for 3H in 2016 because we anticipated that tritium could give an independent validation of our transient TTD model. In total 10 samples were taken over the period 2016 to 2018. These were stored in 1L plastic containers and measured at the Bremen mass spectrometric facility by degassing followed by analysis of ^{3}He with a Sectorfield mass-spectrometer (MAP 215-50) (Sültenfuß et al., 2009).

2.3. Groundwater Model and TTDs

Travel Time Distributions describe the distribution of ages of the water that contributes to discharge in a catchment. Dynamic TTDs do this in a time-variable way and include for instance seasonality in the contribution of older and younger water. Dynamic TTDs for the Springendalse Beek catchment were calculated using forward particle tracking on a high-resolution spatially distributed groundwater flow model following the method described by Kaandorp et al. (2018a). Groundwater flow was calculated using an existing finite-difference groundwater flow model (MODFLOW, Harbaugh, 2005) created and calibrated on groundwater heads and validated with both groundwater heads and river discharge in earlier studies (Hendriks et al., 2014; Kuijper et al., 2012). Groundwater flow was simulated with a monthly time step on a regional scale (total modelled area 58 by 45 km) with cells of 25*25 m. The top of the model followed the surface elevation and the model consisted of seven layers of variable thickness, based on the Dutch Geohydrological Information System (REGIS II, 2005). Figure 1 gives a 2D cross-section through the model's hydrogeological schematization of the subsurface, which is a gross simplification typical in regional groundwater flow models. Mean aquifer thickness in the model was approximately 18 m, but varied between 0.5 and 30 m. Transmissivity in the aquifers was approximately 40 m^2/day, porosity was assumed to be 0.3 and some anisotropy was added in the ice pushed ridges (Kuijper et al., 2012). The entire drainage system in the catchment was modelled using the DRN

and RIV MODFLOW packages (Harbaugh, 2005). Flow through the unsaturated zone was modelled using the MetaSWAP

130 model for a seasonal representation of the groundwater recharge based on land-use (De Lange et al., 2014; van Walsum and Groenendijk, 2008; van Walsum and Veldhuizen, 2011). To allow for the calculation of long groundwater flow paths the model was run for the period of 1700-2017, repeating climate data from the period 1965-2017 (see Kaandorp et al., 2018a).

Backward groundwater travel times (TTs), that represent the age of the water that contributes to streamflow (Benettin et al.,

135 2015; Harman, 2015; van der Velde et al., 2012), were calculated using a combination of forward particle tracking and volume "book keeping" (Kaandorp et al., 2018a). Using the flow velocities calculated by the groundwater flow model, particle tracking software MODPATH version 3 (Pollock, 1994) was used to calculate transient flow paths and TTs. Particles were released monthly at the water table at the center of each model cell and represented the volume equal to the total groundwater recharge of that month. Particles were released for the total model period spanning 317 years yielding a total of 3,804 particle tracking

140 runs, with around 14 thousand particles each. Particles were stopped at strong sinks or at weak sinks if the fraction of discharge to the sink was larger than 50% of the total inflow to the cell (Kaandorp et al., 2018a). To construct monthly TTDs, particles were collected on a monthly time scale at their end points in an area of interest (whole catchment or part of catchment). As we started the particles at the water table, we effectively neglected the travel time through the unsaturated zone (e.g. Green et al., 2018; Sprenger et al., 2016; Wang et al., 2012), but this layer was generally thin in the study area (mostly <1 m) and is partly

145 bypassed by preferential flow. Also, our focus was on the groundwater TTs and time scales. Chemical processes in the unsaturated zone concerning nitrate were included in constructing the solute input curves. By adding input curves of tritium, chloride and nitrate to the calculated flow paths it is possible to calculate the water quality of the catchment's streams.

2.4. Tritium input curve

150 Principally, a series of tritium measurements in streams can be used to derive (ground)water age distributions (Broers and van Vliet, 2018a; Cartwright and Morgenstern, 2015; Duvert et al., 2016; Gusyev et al., 2014; Morgenstern et al., 2010; Solomon et al., 2015; Stewart et al., 2016). Here, we intend to use ^{3}H in an opposite approach; validating our dynamic groundwater model TTDs using a short series of ^{3}H measurements in the gaining stream (as e.g. Rodriguez et al., 2020). For the ^{3}H input into our model, we combined the monthly measurements of tritium in precipitation of the closest measurement stations

155 Groningen (1970-2010) and Emmerich (1978-2016) (distance from the catchment to these stations is 80 to 90 km), taken from the GNIP Database of tritium activity in precipitation (IAEA/WMO, 2018). For months that both stations had measurements, we used the average concentration, as our study area is located approximately halfway between these two measurement stations. For months that measurements from both stations were not available, we adjusted the available data using a factor based on the average difference between the stations, following an approach similar to Meinardi (1994). Because the relation

160 between the values measured at the two stations seemed to differ before and after 1997, we use two factors: before 1997, we

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used Emmerich = Groningen * 1.49. From 1997 onwards, we used Emmerich = Groningen * 1.03. For the period before 1970 we used adjusted measurements from Vienna and Ottawa, roughly following Meinardi (1994).

2.5. Land-use and chemical input curve

165   Two types of land-use were distinguished: farmlands and natural vegetation, which includes forests and heather (Figure 1). Concentrations of solutes reaching the water table below natural areas were assumed to be constant in time: 15 mg/L for chloride and 5 mg/L for nitrate, which are conservative estimates based on Kros et al. (2004) and Van Beek et al. (1994). Although these concentrations of solutes have not been constant during the last decades (e.g. Boumans et al., 2013), we feel this assumption is acceptable as the concentration changes due to atmospheric deposition are much smaller than those due to

170   agricultural inputs. For agricultural fields, a solute input curve was constructed on an annual basis. For the period 2000 to 2017, we used the data from the Dutch sandy areas of the Dutch Minerals Policy Monitoring Programme (LMM), which includes monitored concentrations in the uppermost first meter below the water table at agricultural fields since 1991 (see e.g. Boumans et al., 2005; Fraters et al., 2015). For the period 1950 to 2000, we used the nitrogen (N) and chloride surplus that was derived from historical bookkeeping records of minerals applied to farmlands and corrected for crop uptake (Broers and

175   van der Grift, 2004; van den Brink et al., 2008; Visser et al., 2007). We combined this data with the 2000-2017 LMM data by fitting the overlap between 1991-2000 by adjusting the older data to correspond to a groundwater recharge of 0.35 m/year and a nitrate transformation factor of 0.85 in the unsaturated zone, which corresponds with Dutch data for soils with average water tables around 1 m depth (Steenvoorden et al., 1997; van den Brink et al., 2008). Land use change was considered for two agricultural fields: a large field in the upstream part of the catchment which has been in use only since approximately 1985,

180   and an agricultural field of approximately 7.5 ha that was converted to natural vegetation in 1998. What was not considered is that small parts of the catchment changed from nature in agriculture and vice versa. This does not have a large effect on the downstream surface water concentrations.

2.6. Water quality modeling

185   The dynamic TTD was combined with the solute input curves by assigning tritium, chloride and nitrate to the particles based on their starting time and location (natural/agricultural). Figure 1 shows the areas where the constructed agricultural input curve was used as input for the model, the other parts of the catchments were given the constant concentration of natural vegetation. For each month the particles that contributed to stream discharge were combined, and their concentrations weighted based on their volumes to simulate the concentrations in the stream. The input concentrations of chloride and nitrate were

190   assumed constant over a specific year, whereas monthly ^{3}H measurements were directly assigned to the particles in the start month. The model keeps trace of particles that are lost through evapotranspiration within the months after their initial start, thus effectively removing water and ^{3}H in periods of a precipitation deficit. For chloride and nitrate the solute input is constant

over the year and based on concentrations in the uppermost groundwater, thus there is no need to further account for evaporation for these solutes.

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2.7. Exploration of the model behaviour under different scenarios

The initial run of the water quality model was based on the calibrated groundwater flow model and constructed solute input curves, and is not further calibrated for solute transport. We did not intend to add further local details to improve the model performance; instead we aimed at understanding the catchment mechanisms relevant for solute transport which is also useful

200   outside our study catchment. Therefore, we explored the model behaviour under different scenarios. In this model exercise, we explored the effect of the following processes on the breakthrough of solutes in the upstream part of the catchment: 1a) unsaturated zone hydrological delay, 1b) unsaturated zone N species delay, 2) increased saturated zone travel times, 3) different temporal input of solutes, 4) spatial differences in solute input, and 5) denitrification in the saturated zone (Table 2). The initial run of the model used the land-use maps of the catchment of the year 2007 (Figure 1) where the agricultural fields received

205   chloride and nitrate following the constructed solute input curves and the TTDs remain unchanged. Nitrate transformation processes in the unsaturated zone are (partly) captured in the solute input curves, by using a nitrate transformation factor of 0.85 (Steenvoorden et al., 1997; van den Brink et al., 2008).

Set 1a, unsaturated zone hydrological delay

210   The initial model neglected hydrological transport time in the unsaturated zone, while it takes time for water to flow from the surface to the groundwater table. This creates a time delay in the order of months to multiple years (Green et al., 2018; Sprenger et al., 2016) and even decades (Wang et al., 2012), depending on the depth of the water table and soil characteristics. In our model exploration we applied a time delay of 5 years for all particles in our model, assuming that piston flow occurs through an unsaturated zone with an equal thickness everywhere in the catchment area. In reality, flow through the unsaturated zone is

215   much more complicated due to e.g. macropores, but this was outside of the scope of the current study.

Set 1b, unsaturated zone N species delay

N added to agricultural fields as organic manure consist of directly available N and persistent N. Whereas the directly available N is quickly taken up by crops or leached towards the groundwater, the mineralization of organic N takes more time (e.g.

220   Ehrhardt et al., 2019). We explore the effect of this distinction by creating a time delay of 10 years in 50% of the nitrate that is added to the TTD model.

Set 2, increased saturated zone travel times

Next, we explored the effect of saturated zone travel time uncertainty by applying a multiplication factor of 5 on all the

225   calculated travel times of all flow paths. Increasing the ages of groundwater implies an increase in mean travel time (MTT),

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which could result from a different aquifer thickness, porosity, groundwater recharge or a change in drainage density (Broers, 2004; Duffy and Lee, 1992; Raats, 1978; van Ommen, 1986).

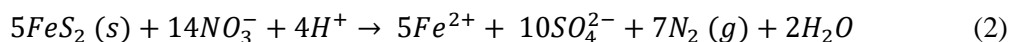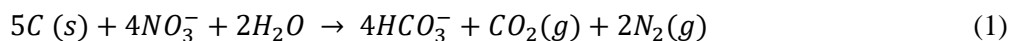*Set 3, different temporal input of solutes*

230 The solute input curve for chloride and nitrate was created on a regional scale and has been successfully used at a local scale in earlier studies (van den Brink et al., 2008; Visser et al., 2007). We explored the effect of a more delayed decrease in the solute input curve after 1985, which could for instance be caused by slightly different local farming practices compared to the regional input curves. In addition, we explored the effect of a sharp decrease in the input by removing all agricultural application of N after the year 1985. In both scenarios the peak of the agricultural input curve for chloride and nitrate was kept

235 at 1985, as this timing of the peak has been found all over the Netherlands (e.g. van den Brink et al., 2008; Visser et al., 2007; Zhang et al., 2013). This input trend reversal results from the EU milk quota legislations in 1984 and EU and Dutch manure laws (Dutch Manure Law, 1986; EU Nitrates Directive, 1991).

Set 4, spatial differences in solute input

240 We explored the effect of different land-use configurations by moving the agricultural fields either away from the stream (towards longer travel times) or towards the stream (shorter travel times). A buffer zone of 200 m around the stream was used and two scenarios were tested. First the buffer zone was turned into an agricultural area, while all fields outside the buffer zone were turned into natural areas. Second, the reverse was done: the buffer zone was turned into natural areas with agricultural fields outside of the buffer zone. A ratio of 50% agriculture and 50% natural vegetation was used for the agricultural areas in

245 these scenarios to prevent excessive nitrate concentrations and to keep the total input in the system approximately equal as based on the land-use maps.

Set 5, denitrification in the saturated zone

Denitrification is known to remove nitrate from the groundwater, partly by oxidation of organic C (Equation 1) or pyrite

250 (Equation 2):

$$5C\ (s) + 4NO_3^- + 2H_2O\ \rightarrow\ 4HCO_3^- + CO_2(g) + 2N_2(g) \tag{1}$$

$$5FeS_2\ (s) + 14NO_3^- + 4H^+ \rightarrow 5Fe^{2+} +\ 10SO_4^{2-} + 7N_2\ (g) + 2H_2O \tag{2}$$

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To see the possible effects of different conceptualizations, denitrification was modelled in two ways. First, it was simulated as a kinetic zero order reaction following $NO_3[output] = NO_3[input] - rate * travel\ time$. We used 10 mg NO3/L/year as the rate of denitrification, which is in the range of values reported by Van Beek et al. (1994) for the Netherlands. Second, denitrification was based on the occurrence of a pyrite layer at a certain depth, similar to the model of Zhang et al. (2013).

260 Oxidation of pyrite has been found to be the main nitrate reducing process in several studies (e.g. Broers and van der Grift,

2004; Postma et al., 1991; Prommer and Stuyfzand, 2005; Tesoriero et al., 2000; Visser et al., 2007; Zhang et al., 2009). In this model scenario, all nitrate passing through the denitrifying pyrite layers was instantaneously removed.

3. Results

3.1 Input curves of Chloride, nitrate and tritium

Figure 2 shows the constructed solute input curve that indicates the historic input of tritium, nitrate and chloride towards the groundwater. Tritium in precipitation increased in the 1950s and 1960s following hydrogen bomb testing and has been returning to natural values since the 1980s (Figure 2). The monthly ^{3}H concentration in precipitation was fed directly into the modelled groundwater recharge, as tritium is part of the actual water molecule. Chloride and nitrate increased from the 1950s until around 1985 due to intensification of agriculture (Figure 2). From 1985 concentrations from agricultural fields decreased as a result of national and European legislations (Dutch Manure Law, 1986; EU Nitrates Directive, 1991), that contain rules for the reduction of N applications in farming.

3.2. Water quality measurements of surface water

Tritium concentrations measured in the upstream catchment in 2016 and 2017 were between 4.8 and 6.0 TU with no clear seasonality (Figure 4a). For chloride and nitrate the measurements show some seasonality, with higher concentrations in winter than in summer. This variability seems larger for the total catchment than for the upstream part of the catchment (Figure 4). The long-term chloride concentrations varied between 20 and 40 mg/L with slightly lower values in the upstream than in the downstream catchment. Nitrate concentrations varied between approximately 30 and 50 mg/L during the last few decades. Both the chloride and nitrate measurements show a clear trend reversal in the 1990s (Figure 4c-f) that resembles the trend reversal in the solute input curves (Figure 2) due to legislations. Chloride concentrations in the upstream part of the catchment increase from about 20 mg/L in the 1970s to up to 30 mg/L between 1990 and 1994 (Figure 4c), which is about 5 to 10 years after the peak in the input (Figure 2). In the same period, the chloride concentrations measured at the outlet of the total catchment peak at a concentration up to about 42 mg/L (Figure 4d). After 1994, the chloride concentrations decrease both up- and downstream and have been approximately stable between 20 and 25 mg/L since the year 2000, similar to the trend in the chloride concentrations in the uppermost groundwater. The measured timing of nitrate at the outlet of the catchment (Figure 4f) is similar to chloride (figure 4d) with an increase up to 1994 when the maximum of 50 mg/L is reached. After that, nitrate concentrations have decreased but at a slower rate than chloride. What is especially noticeable is that for the upstream part of the catchment, the timing of the chloride and nitrate peaks in the measurements do not coincide. While chloride peaks around 1990 and quickly drops after that, nitrate concentrations only start decreasing after approximately 2000.

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3.3. Groundwater TTDs

The model indicated that about 20% of discharge in the Springendalse Beek is water with a travel time less than 1 year, while about 15% of discharge has a travel time of more than 25 years (Figure 3a and b). The discharge in the Springendalse Beek thus consists mainly of medium aged water (1 – 25 years) and the mean travel time is approximately 11 years and median travel time around 4 years. Based on the land-use map (Figure 1) and the particle tracking, we found that in the upstream part of the catchment between 15 and 25% of discharge infiltrated under agricultural fields (Figure 3c). For the total catchment this is slightly higher at about 25 to 35% (Figure 3d), because a slightly larger part of the streams capture zone in the downstream part of the catchment is used for agriculture. In the modelling results, the discharge contribution from agricultural fields shows a seasonal pattern especially for the total catchment (Figure 3d), with a higher contribution to discharge of water that was infiltrated under agricultural fields during the wet winter.

3.4. Water quality modelling

The initial combination of the TTD results and solute input curves was based on the land-use and solute input curves described in paragraph 2.5 and included no further processes or changes to the original flow model. The initial model run showed higher chloride and nitrate concentrations in winter than in summer, and this seasonal variation was larger for the total catchment than the upstream catchment. This agrees with the measurements and conclusion of Kaandorp et al. (2018a) that the contribution of different flow paths differ between the two parts of the catchment.

The modelled chloride concentrations confirmed the observed long-term trends (Figure 4c and d), although the modelled concentrations were too low for the period between 1990 and 1995 (underestimation of 5-15 mg/L) and the chloride peak was simulated around 1985 instead of 1990. For tritium, the model overestimates the measured concentrations by approximately 0.5 TU (Figure 4a), which could indicate either an underestimation of the mean age of water in the catchment (allowing for more decay) or an underestimation of the amount of younger water (contributing water with low tritium concentrations). While the measurements showed the nitrate peak around 1994 and 1997 for the total catchment and upstream respectively, the initial model run showed the nitrate peak around 1987 for both the total and upstream catchment. This may suggest that travel times were underestimated in the model, which is supported by the tritium measurements.

3.5. Exploration of model behaviour: Effects on the breakthrough of tritium, chloride and nitrate

Overall, the simulated tritium, chloride and nitrate concentrations in the stream did not completely match the measurements, both in concentration and in the arrival in time of the agricultural peak (Figure 4). Instead of attempting to further adapt and calibrate the groundwater flow model, we explored the model behavior under different scenarios, exploring the parameters

that might determine the apparent mismatch with the measured concentrations; thereby increasing our understanding of the flow and transport system in catchments in general.

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Set 1a, unsaturated zone hydrological delay

An unsaturated zone was added to the upstream catchment model with a travel time of 5 years, as a separate piston flow component superposed on the groundwater system that was modelled. This delay shifted the tritium peak in time and led to a decrease in the tritium concentrations because decay takes place while travelling through the unsaturated zone (Figure 5a).

330 Because chloride and nitrate were not reactive, the unsaturated zone merely added a certain amount of time to the whole travel time distribution, simply shifting the chloride and nitrate output curves in time (Figure 5b and c).

Set 1b, unsaturated zone N species delay

The lag time created in the unsaturated zone by the slower release of persistent N was simulated by putting a delay of 10 years

335 on 50% of the nitrate input. Because the input of nitrate is spread out over a longer period, this resulted in a lower peak value but extended the period with high nitrate levels (Figure 5c).

Set 2, increased saturated zone travel times

The application of a factor 5 on the mean travel times decreased the overall tritium concentrations due to the extra time for

340 decay (Figure 5a). The input of solutes was distributed more in time which lowered the chloride and nitrate peak and increased the tail of the peak (Figure 5b and c). This scenario thus has a similar effect on the shape of the breakthrough curve of nitrate as scenario 1b (Figure 5c). When all travel times were increased a 5-fold the chloride and nitrate peaks shifted approximately 10 years.

345 *Set 3, different temporal input of solutes*

We modelled two alternative solute input curves of agricultural fields. First, we used a solute input curve in which the rate of the decrease of nitrate after the 1985 peak is lowered (Figure 6a, red line). This slower decrease in the agricultural input resulted in an increase of nitrate during a longer period, remarkably also extending also into the period when the input is already decreasing, followed by a slower decrease after that (Figure 6b, red line). In the second scenario, we removed all agricultural

350 input after the 1985 nitrate peak (Figure 6a, green line). This instantly lowered the stream nitrate concentrations from 1986 onwards, as the stream consists of a large amount of young water and after removal of agriculture is only affected by nitrate from older flow paths that started before 1986 (Figure 6b, green line).

Set 4, spatial differences in solute input

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The effect of spatial changes of the input was modelled in two scenarios: one scenario where only the zone of 200 m around the stream was used for agriculture, and one scenario where agricultural input only took place outside of the same 200 m zone. With the agricultural fields directly around the stream (Buffer scenario 1) the nitrate peak shifted to 1985 (Figure 6c), which is the year of maximum input (Figure 2). With the agricultural fields in the more upstream parts of the catchment (Buffer scenario 2), representing e.g. a natural buffer strip, the nitrate peak shifted towards later in time and became flatter with a much slower decrease over time (Figure 6d). This results from the fact that the fields further away are connected with the stream by longer flow paths with longer travel times. When fields are further away, the agricultural input is distributed more over time resulting in a lower peak but a longer tail with higher concentrations.

Set 5, denitrification in the saturated zone

Two denitrification scenarios were modelled, using different conceptualizations. Zero order denitrification with a rate of 10 mg/L per year resulted in continuously lower nitrate concentrations without a shift in time (Figure 7). In the other scenario, denitrification was modelled based on the depth that the particles flowed through, for which nitrate was removed from all particles travelling through deeper layers (> model layer 2, >0.5-15 m below surface). This also resulted in decreased nitrate concentrations, but with higher values in the concentration tail than in the zero order scenario (Figure 7).

4. Discussion

Aim of this study is to test whether the use of dynamic TTDs as derived from a groundwater flow model helps us to understand the observed breakthrough pattern of solutes in a lowland stream. We collected long time series of chloride and nitrate which showed a clear trend reversal in the 1990 following national and European legislations restricting the use of manure and fertilizers. By combining the TTDs with input curves for solutes, we were able to calculate stream concentrations which we could compare with the long time series of chloride and nitrate. This base model, which did not include time delays due to the unsaturated zone or chemical processes (except a simple correction for nitrate in the unsaturated zone), was able to reasonably capture the long-term trends of chloride and nitrate. In addition to the trend reversal in the 1990s, both the measurements and model indicated seasonality in the in-stream concentrations, with higher concentrations in winter and lower concentrations in summer.

Interestingly, a time lag seems to exist between the reduction of the solute input and the following trend reversal observed in the long time series. This time lag, defined as the time between the peak in solute application and the observed peak in the stream, was further studied using the model. For this, we did an exploration of the model behaviour under different scenarios, to get more understanding of the effect of different processes on the long-term breakthrough of the solutes.

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In the discussion we will first focus on the effect of different processes on the breakthrough of solutes, based on the exploration of the model behaviour under different scenarios. We will evaluate how unsaturated zone processes, advective saturated flow, the spatial source zones and temporal patterns of solute inputs and transformation processes such as denitrification will influence time lags in the receiving water body. Using our dynamic TTD model, we will then introduce 'contributing areas' to discuss the spatial and temporal effects of land-use and groundwater flow paths. We will subsequently discuss the measurements and model results of the study area and take another look at the observed breakthroughs and time lags of the different solutes. Lastly, we will discuss the implications of our findings for catchment management.

4.1. The effect of processes on modelled breakthroughs

Multiplication of the TTD lowered the nitrate peak because the larger age of the discharging groundwater resulted in a larger contribution of pre-1950 water, which has been less influenced by agricultural activities. Because the ages of the younger flow paths were increased, the agricultural peak from the 80s is distributed over a larger amount of time, resulting in a shift in arrival of the peak and a slower decrease of concentrations after the maximum stream concentration has been reached (Figure 5; Table 3). The factor 5 we multiplied the MTT with in our results clearly shows the effect on the breakthrough but is a very extreme case. It would represent a system with an aquifer that is also 5 times as thick (or with an unrealistic porosity 5 times higher) given the same groundwater recharge rate (van Ommen, 1986; Vogel, 1967).

Changing the shape of the solute input curve led to a change in stream concentrations similar to that applied to the input. In the case we presented, this was a slower decrease in concentrations after the concentration peak (Figure 6a). We did not shift the time of the peak in the input because we have strong indications that the peak in Dutch agriculture occurred during the same year in all of the Netherlands, due to the strict measures taken around 1985 (van den Brink et al., 2008; Visser et al., 2007). It seems obvious that the solute input curve and its uncertainty have a large effect on the stream concentrations (Howden et al., 2011a). In the scenario where all agriculture was removed from the year 1986, nitrate concentrations in the stream instantly decreased following the removal of input. This follows from the relatively large amount of young water discharges by our catchment and is in line with the quick response observed for other catchments in the Netherlands (e.g. Rozemeijer et al., 2014). Van Ommen (1986) used a conceptual case to illustrate the same fast reaction: in catchments with an exponential TTD (or in our case close to exponential TTD; Kaandorp et al., 2018a), a change in the input directly affects stream concentrations for all MTTs. This is however not always the case when the reduction in inputs is more gradual: the scenario where the solute input curve was changed to have a slower decrease of NO3 resulted in a time lag of the peak observed in the surface water. Thus, the time for a change in input to show in stream concentrations seems to depend also on the reduction rates of the input.

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To further study this observation, we combined exponential TTDs with varying MTTs with different conceptual input scenarios and no other processes. Results show that a time lag in the arrival of the peak is possible when the MTT is rather long or the input decreases slowly or a combination of those (Table 4). Figure 8 illustrates three input scenarios for a conceptual catchment with an exponential Travel Time distribution with a Mean Travel Time (MTT) of 5. The three input scenarios are a direct stop, a slow decrease of the input and a fast decrease of the input, all following a block input of '100' between time=0 and time=10. The direct stop leads to a direct decrease in output concentrations, showing an 'inverse' exponential distribution which represents the new unpolluted front travelling through the groundwater system. The other two scenarios on the contrary do not show a direct decrease: the scenario with the fast decrease of the input shows a concentration increase for one extra time step (1 month) before decreasing, and this decrease is much slower than the scenario with the direct input stop as a result from the extra input after t=10. The scenario with a slowly decreasing input shows the same behaviour but more extreme: an increase in output concentration until t=16, even with a decreasing input in that period.

The time lag until peak output concentration following a decrease in the input is thus controlled by both the MTT of the exponential travel time distribution and the speed of the input change (Table 4). Figure 9 shows the time to peak for different MTTs and input decreases. The time lag increases with increasing MTTs and with slower input decreases. This behaviour is only the result of the hydrology of the groundwater system and is related to the net result of mass loading through groundwater recharge and mass removal at the outflow point. Concentrations at the outflow only start decreasing once the net input is smaller than the net output (Broers and van Geer, 2005). This analysis shows that in the general case of a catchment with an exponential TTD the effect of measures on the solute input can be expected to show directly, but that a lag time can be introduced by certain combinations of MTTs and solute input reduction rates.

The unsaturated zone was considered in a simplified way in the model by 1) coupling the groundwater model with an unsaturated zone model (MetaSWAP, see also Kaandorp et al., 2018a) to provide a realistic groundwater recharge based on e.g. recharge and by 2) including part of the unsaturated zone processes in the solute input curves by using a nitrate transformation factor of 0.85 on the data before 2000 and using the concentrations of shallow groundwater from 2000 onwards. Although in this way many unsaturated zone processes were accounted for, it did not include potential delays caused on the breakthrough of solutes. The model exploration showed that unsaturated zones lead to a shift in time of the breakthrough of the nitrate curve due to the time it takes for water to percolate from the surface towards the groundwater (Figure 5; Table 3). This is purely a hydrological effect (Set 1a). In catchments with thick unsaturated zones, the lag time due to unsaturated zones has been calculated to be up to decades such as for aquifers in the U.K. (Wang et al., 2012). The time lag introduced by the unsaturated zone is often averaged on a catchment scale, due to spatial variation in its thickness, although it can lead to long tails in the nitrate concentrations. On the other hand, longer residence times in the unsaturated zone will promote the uptake efficiency by crops and potential denitrification in saturated parts of the unsaturated zone. Other biochemical processes in the unsaturated zone can also create time lags in the breakthrough of nitrate (Set 1b). N applied on agricultural fields comes partly

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in the form of directly available N and partly in the form of persistent organic N. While the directly available N is rapidly leached towards the groundwater, persistent N is only slowly transformed into nitrate and leaches towards the groundwater over a time scale of decades (e.g. Ehrhardt et al., 2019). This not only lowers the height of the nitrate peak, but also leads to a time lag in the output with elevated nitrate levels over a longer period of time.

Denitrification removes (part of) the nitrate and thus lowers concentrations. When applied as zero order denitrification this does not change the timing of the peak (Table 3), as the denitrification takes place equally along all flow paths. When this is not the case denitrification does affect the shape and timing of the breakthrough of nitrate, for instance when denitrification takes place only at certain depths (Figure 7). Zhang et al. (2013) and more recently Kolbe et al. (2019) showed that varying denitrification with depth has a major influence on nitrate delivered to streams via groundwater. Our scenarios were relatively simple with equal denitrification rates and depths throughout the catchment. It is however known that there is a large variability in the reactivity of for instance organic matters (e.g. Hartog et al., 2004; Middelburg, 1989; Postma et al., 1991), which could lead to spatial or temporal differences in denitrification and therefore a change in the nitrate breakthrough. If denitrification for instance occurs predominantly in the stream valley close to the stream, where conditions are wet and organic matter is abundant, denitrification removes nitrate mostly from younger flow paths, thus shifting the nitrate peak due to the delivery of nitrate mostly by older flow paths, which generally originate from a larger distance from the stream (e.g. Modica et al., 1998). This effect was shown by the model scenario in which a buffer without agriculture was introduced around surface waters (Figure 6c and d) and is a result of the difference in travel time of the flow paths from the fields close to the stream and the fields more upstream (e.g. Musolff et al., 2017).

The location of agricultural fields in relation to the catchments' drainage network, and more precisely the location of high loading is thus an important factor that largely governs the travel times of the agricultural solutes. Both seasonal and long-term concentration-discharge relationships strongly depend on spatial source patterns (e.g. Musolff et al., 2017) and spatial differences in reactivity (e.g. Kolbe et al., 2019) can further cause spatial variability between solute concentrations of water in different flow paths. It can therefore be argued that in modelling not only the location of fields must be known but also more information about leaching towards the groundwater at every field, as there can be a significant difference in the use of manure and fertilizers due to for instance differences in crops. However, for our catchment, national and EU regulations put strong constraints on the application of nitrogen, thus levelling differences in inputs to farmlands (e.g. Oenema et al., 1998; Schroder et al., 2007). Effectively, soil properties and groundwater levels determine the areas with strongest leaching towards the groundwater as those factors determine the potential for unsaturated zone denitrification.

Summarizing the observations from the model exploration, a time lag of the breakthrough of a trend reversal can be caused by: 1) travel time of the unsaturated zone, including slow release of (part of the) N, 2) the combination of MTT and solutes

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input reduction, 3) spatial setting between solute input, (bio)chemical processes and the drainage network (e.g. locations of agricultural fields and denitrification).

4.2. Contributing area of streams

490 In the previous paragraph, we have seen that the spatial distribution of inputs and processes is an important factor in the breakthrough of agricultural solutes. Recently Barlow et al. (2018) restated the definition of the 'contributing area' as "the two-dimensional areal extent of that portion of a capture zone that intersects the water table and surface-water features where water entering the groundwater-flow system is discharged". They did this for groundwater wells, but streams also have a contributing area, which is variable in time and not the same as the catchment. The catchment of a stream is the area in which

495 all discharging water finally ends up in the stream. The contributing area of streams is also not to be confused by the 'contributing area' or 'upslope area' used in many distributed hydrologic modes by catchment scientists, which is the runoff-generating area, i.e. the parts of the catchment where seepage and discharge towards the surface water occur (e.g. Ambroise, 2004; Beven and Wood, 1983; Beven and Kirkby, 1979; Mcglynn and Seibert, 2003; Yang et al., 2018). To avoid further confusion, we introduce the terms 'groundwater contributing area' and 'runoff contributing area'. The groundwater

500 contributing area (GCA) is defined as the area where the water that is actively contributing to streamflow at a certain moment of time through active flow paths entered the coupled groundwater-surface water system as precipitation (recharge area). The runoff contributing area (RCA) is defined as the area where at a certain moment in time water is discharged from the catchment storage as seepage or overland flow, and thus is the area where runoff is generated (Figure 10). Areas that are neither groundwater- or runoff contributing areas do not actively contribute to streamflow at that specific moment in time. In our

505 particle tracking method, the GCA is the starting point and the RCA is the ending point of a particle (Figure 11).

Because flow paths change based on wetness conditions (e.g. Kaandorp et al., 2018a; Rozemeijer and Broers, 2007; Yang et al., 2018) the groundwater contributing area also shifts through the seasons. This includes the inactivation of flow through shallow flow paths towards e.g. drainage pipes and ditches in dry periods, which leads to a non-linear reaction of the dynamic

510 TTD to discharge. When wetness conditions decrease, groundwater levels decrease, and drainage units fall dry. Consequently, the water that was flowing towards these drainage units suddenly stays in the aquifer and/or flows towards another drainage unit. When wetness conditions increase again, groundwater levels first have to rise to the point that they can activate these flow paths again. This also (at least partly) explains why concentration-discharge relationships vary with the wetness of catchments. In our results, the discharge originating from agricultural fields changes in time as a result of this variation in the

515 GCA (Figure 3 and 9), and this seasonal variation in flow paths lead to fluctuations in the concentrations of nitrate in the stream (e.g. Figure 4). Figure 10 illustrates how the groundwater contributing area may shift based on wetness conditions: in the wet period all flow paths are active while during the dry period only the older flow paths are active, and flow through shallow short flow paths has ceased. Therefore, in this example the groundwater contribution of the field close to the stream

stops in the dry period and removing this field thus only affects stream nitrate concentrations during the wet period. This concept extents on the ideas presented by Rozemeijer and Broers (2007), by adding the spatial dimension and groundwater contributing area to their concept of variation in the contribution of flow paths with depth.

4.3. Understanding nitrate in the Springendalse Beek catchment

The previous paragraphs discussed more generally the important processes that affect the breakthrough of agricultural solutes, which we will use in this paragraph to discuss the observations from both the measurements and TTD model in the study area. Overall the model was able to describe the trend reversal that was observed in the measurements of the Springendalse Beek catchment. The time series of discharge and solutes showed that the upstream area has less seasonal variation in discharge than the downstream catchment, as well as less variation in the contribution from agricultural fields and in the stream concentrations of chloride and nitrate (Figures 3 and 4). Our groundwater-based model was able to simulate this difference between up- and downstream which indicates that this variation can largely be explained by variations in the contribution of different groundwater flow paths originating from different locations in the catchment, as was also concluded by e.g. Martin et al. (2004); Musolff et al. (2016); Rozemeijer and Broers (2007) and van der Velde et al. (2010a). High chloride and nitrate concentrations from agricultural activities are mostly present in the shallower layers (0-5m below surface) (e.g. Bohlke and Denver, 1995; Broers and van der Grift, 2004; Rozemeijer and Broers, 2007; van der Velde et al., 2009; Zhang et al., 2013) and especially in the downstream part of the catchment, with its larger drainage density from the many (shallow) agricultural tile drains and ditches, these shallow flow paths contribute more water of a young age in the wet period with high groundwater tables than in the dry period (Kaandorp et al., 2018a). This increase in relative old water contribution during dry periods has been found in several studies and is called the 'inverse storage effect' (e.g. Benettin et al., 2017; Harman, 2015). Similar to our model, van der Velde et al. (2010) and Wriedt et al. (2007) were able to model seasonality of in-stream nitrate concentrations using only groundwater dynamics and concluded it to be an important process that is further superposed by denitrification and variability in loading. We conclude that the upstream part of the Springendalse Beek catchment with its stable year-round discharge compared to the downstream part of the catchment, provides the lower limit of the nitrate concentrations, while the drained downstream part of the catchment mainly causes the seasonal variation in stream concentrations.

The fact that most of the discharge has travel times larger than one year might explain that no seasonality was observed in the tritium measurements. The model overestimated all observed tritium concentrations in the initial model run, by approximately 0.5 TU on average (Figure 4a). This could indicate the uncertainty in the measured concentrations but based on experience in other catchments (Broers and van Vliet, 2018a; Morgenstern et al., 2010; Stolp et al., 2010) this might be caused by the model underestimating the mean age of water in our catchment, for instance due to an overestimation of the recharge. On the other hand, an overestimation of the mean water age by the model could also cause higher modelled tritium concentrations, as more

recently infiltrated water has lower tritium concentrations (Figure 2). Unfortunately, no earlier measurements of tritium are available for the Springendalse Beek to draw further conclusions using tritium.

555 Denitrification does not seem to occur substantially in the upstream part of the study area as the modelled nitrate concentrations are generally already lower than the measurements. This is confirmed by the oxic nature of the sandy sediments that the groundwater discharges from (Kaandorp et al., 2019), the presence of oxygen and lack of iron in the discharge water (data not shown). Although the upstream part of the catchment contains less agriculture than the downstream part (Figure 3), the nitrate concentrations in the stream are comparable. This may be an indication of denitrification in the downstream part of the 560 catchment where water levels are close to the root zone, promoting shallow denitrification, which could be a reason for the overestimation of nitrate as well as the fact that the model overestimates the seasonal variation in the downstream catchment (Figure 4f). Another important aspect is uptake of nitrate and denitrification within the surface water system. This is currently not accounted for and probably limited in winter (high flow velocities and low temperatures), but may be causing lower nitrate concentrations in summer.

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Measurements of chloride and nitrate showed a time lag between the trend reversal in the solute input and in the discharge. In the lowland groundwater-driven study catchment, unsaturated zones are relatively thin in the downstream part of the catchment (maximum a few meters, but mostly <1 m) and slightly thicker in the upstream part (up to 3 meters), and thus only a maximum time lag of a few years would be realistic. Due to the complex hydrogeology of the ice pushed ridge, especially in the upstream 570 part of the catchment, there is quite some uncertainty in the exact depths and volumes of the aquifers that are present within the ice-pushed ridge. In the regional groundwater flow model, this complex geology was highly simplified based on the version of the hydrogeological schematization of REGIS (REGIS II, 2005) that was available when building the flow model. The complex geological structure of the ice-pushed ridge makes it difficult to exactly pinpoint the position of the tilted Pleistocene sand layers that probably form the main pathways to the stream, as the tilted slabs of Tertiary clays form hydraulic barriers for 575 groundwater flow (pers. comm. Harting, TNO Geological Survey of the Netherlands). Given the approximate N-S strike direction of the sandy intercalations, this may have influence on the distinct farmlands that contribute to the nitrate concentrations in the stream, that may be positioned further away than the modelled schematization might allow in the regional groundwater flow model. It might also affect the mean travel times in the groundwater system as a larger aquifer volume would result in overall longer travel times (Vogel, 1967; van Ommen, 1986). The observation that the time lag is larger for nitrate 580 than for chloride, especially in the downstream catchment, can be explained by processes that only affect nitrate and not the more conservative chloride, such as a difference in residence time of different N species or spatial differences in denitrification. The difference could also indicate that the ratio between chloride and nitrate has changed in the fertilizers used.

Although a time lag was observed, the measurements showed that legislations in the 1980s were effective in lowering the 585 concentrations of agricultural solutes in the stream. The model was reasonably able to simulate the long-term trends, but could

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be improved by adding more detail based on the lessons learned from the model exploration. However, these lessons on the breakthrough of solutes are already applicable in other catchments and will be further discussed in the next paragraph.

4.4. Management implications

590 The exploration of the model behaviour indicated that removing the source of diffuse pollution leads to an immediate decrease of in-stream concentrations (Figure 6b), due to the large fraction of younger water in the TTD. Therefore, contrary to what is often thought, the response of measures through the groundwater system is instant in the general case that the TTD is (close to) exponential and thus managing the input of agricultural pollutants is a good management option with direct benefits. We showed however that this direct impact does not occur when decreases are very slow or the MTT is very large. After the 595 immediate decrease, the legacy from older groundwater flow paths leads to a slow further decrease in time.

According to scenarios modelled by Tufford et al. (1998) the management of stream water quality is most effectively done at riparian and adjacent lands. Our results show that the location of agricultural fields indeed has a large effect on stream concentrations. Not only does the location of the fields affect the time lag and shape of the breakthrough curve of stream 600 concentrations, longer flow paths from the fields further away from the stream also have more time for processes such as denitrification. The scenario with the 200 m agricultural-free zone around the stream can be compared with a (natural) riparian zone, on which much research has been done (e.g. Anderson et al., 2014; Feld et al., 2018; Hefting and Klein, 1998; Hill, 1996; Ranalli and Macalady, 2010). These studies show that riparian zones positively affect stream water quality because of their high rate of denitrification. Johnes and Heathwaite (1997) even suggested to move agricultural fields to the locations with the 605 highest potential for nutrient retention.

Our results show that in addition to the denitrification potential of a riparian buffer zone, the longer length of the groundwater flow paths lags the arrival of and dampens the nitrate peak. In fact, as denitrification rates are highly variable (e.g. Tesoriero and Puckett, 2011; Van Beek et al., 1994) and riparian zones can be by-passed by deeper groundwater flows (Bohlke and 610 Denver, 1995; Flewelling et al., 2012; Hill, 1996; O'Toole et al., 2018; Ranalli and Macalady, 2010), the longer distance and thus distribution of solutes in time is at some locations and/or moments arguable the more important effect of riparian buffer zones. Therefore, creating a (significant) riparian buffer zone lags and dampens the effect of agricultural pollution on surface water quality and riparian buffers have a positive effect even when it is bypassed or when denitrification is low. Although overall positively affecting water quality of the stream by decreasing concentrations, the longer travel times of agricultural 615 solutes will also lead to a longer tail and thus invoke a longer lasting effect of agricultural solutes on stream concentrations.

The modelling approach using Travel Time Distributions is a valuable approach for water quality management. While often (ground)water models focus on representing groundwater heads and discharges, a better representation of travel times and flow

paths is essential to correctly simulate non-point source solute transport. Using TTDs therefore delivers more realistic
620 scenario's predicting future concentration trends and/or the effects of mitigation options.

5. Conclusions

This paper is among the first to attempt to couple decades long time series of water quality to dynamic travel time distributions based on a high-resolution spatially distributed groundwater flow model. We collected a unique dataset of solute measurements
625 for the period 1969-2018 for the Springendalse Beek, a Dutch lowland stream. We combined calculated TTDs with input curves for tritium, chloride and nitrate spanning the period 1950 to 2018. This way, we calculate solute concentrations in the Springendalse Beek between 1969 and 2018. By making this connection between dynamic groundwater travel time distributions and long-term in-stream concentration measurements, we were able to show that the seasonal and long-term fluctuations of in-stream solute concentrations were mainly caused by the dynamic contribution of different groundwater flow
630 paths.

Both the measurements and model showed a trend reversal in concentrations which followed legislations on the solute input in the 1980s. Because we observed a time lag between the time of the peak solute input and the peak concentrations in the stream, we ran an exploration of the model behaviour under different scenarios to understand the important transport factors.
635 We found that a time lag in the arrival of the trend reversal of nitrate can be caused by: 1) travel times in the unsaturated zone, both due to slow percolation as (bio)chemical processes such as the slow mineralisation of organic N; 2) the combination of MTT and input reduction, caused by combination of a slow decrease of the input with a relatively long MTT; and 3) the spatial setting between input, (bio)chemical processes and the drainage network (e.g. locations of agricultural fields and denitrification). To describe the spatial effect of processes and land-use on the breakthrough of solutes, we introduced the
640 'groundwater contributing area' of a stream, which is the catchment area where the discharging water infiltrated, increases and shrinks based on wetness conditions.

The results of this study are interesting for water managers of catchments with diffuse pollution from agriculture, as it provides an insight into the possible parameters to steer on. We show that for most catchments, which have a (close to) exponential
645 TTD, a direct reaction of stream nitrate concentrations can be expected to reductions in the nitrogen inputs, even if mean travel times are high, which is contrary to what is often expected. However, we also showed the different processes that can cause a time lag. Furthermore, we show that creating riparian buffer zones is a good management option, due to the importance of the spatial distribution (distance) of agricultural fields and the reactivity of the subsurface on the breakthrough patterns of diffuse pollutants.

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A limited amount of stream tritium measurements proved to be a valuable indication of the performance of the model. The method presented in this paper can be used to validate calculated TTDs and provides an opportunity to validate groundwater models not only on celerities, but also on water velocities. Further research could be aimed on application of the same method in other catchments and focus on gathering further knowledge on dynamic contributing areas in other hydrogeochemical and
655   topographical settings.

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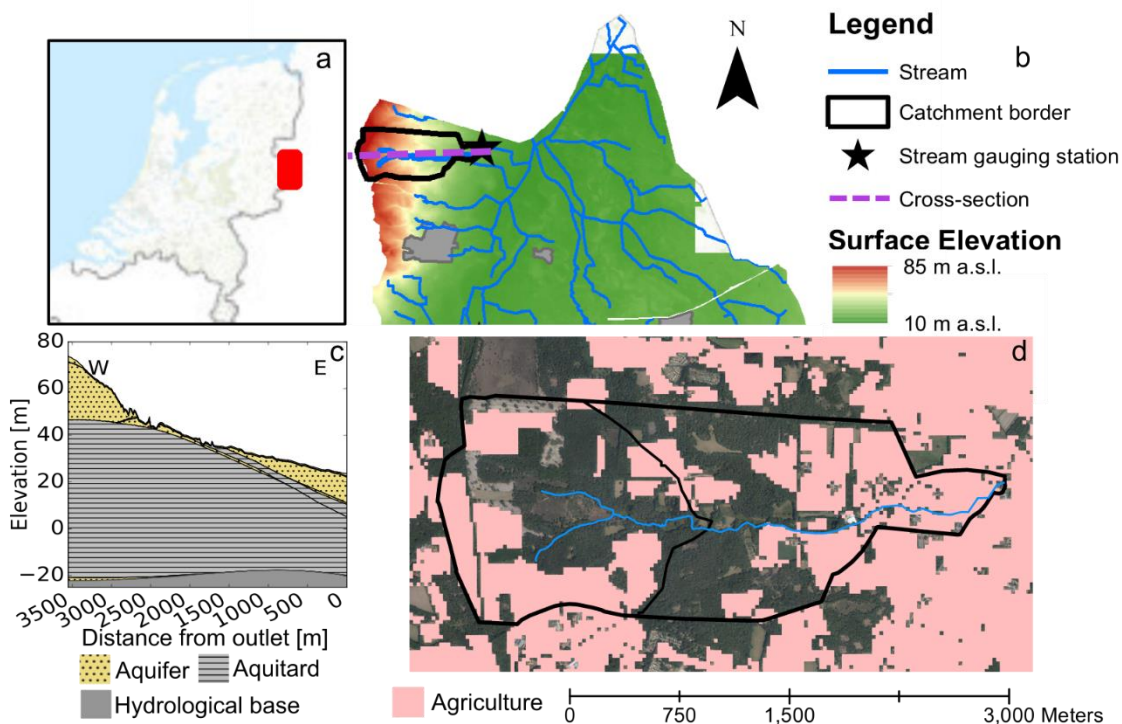
Figure 1: Location of the study area (a, b), model conceptualization (c), and the location of agricultural fields in the year 2019 (d). *Background maps and DEM from PDOK (PDOK.nl/datasets).*
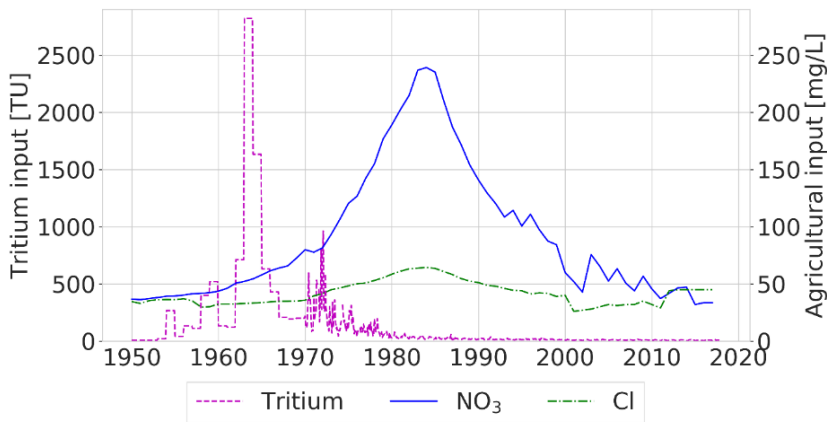
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Figure 2. Input curves for tritium (left axis) and the estimated concentrations of nitrate and chloride under farmland (right axis). The tritium input curve is based on precipitation measurements at stations Vienna and Ottawa (before 1970) and Groningen and Emmerich (from 1970). The 1985 peak in chloride and nitrate coincides with the start of the legislations from the Dutch Manure Law that placed restrictions on the applications of N in agriculture.
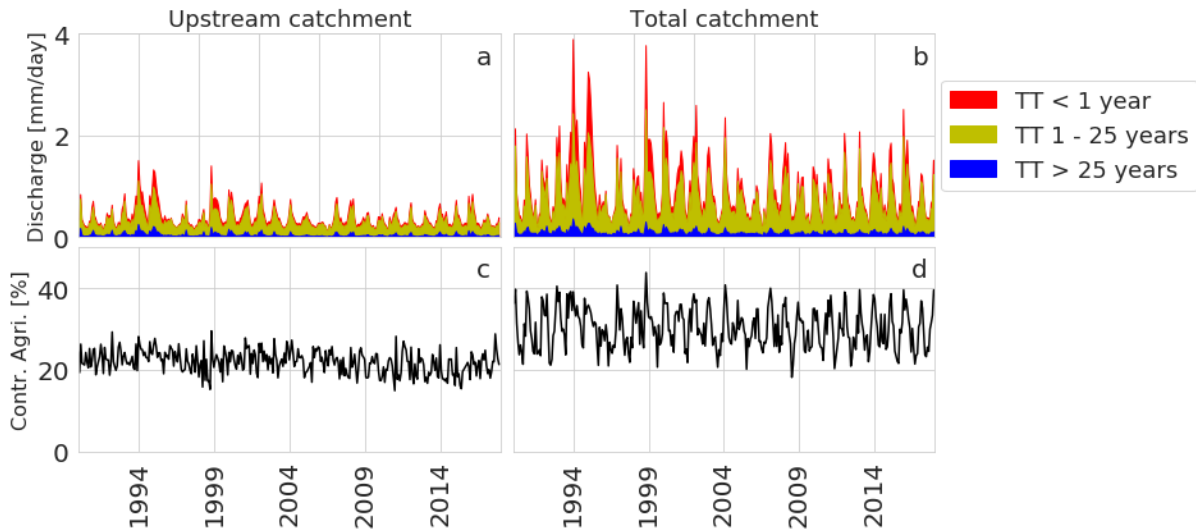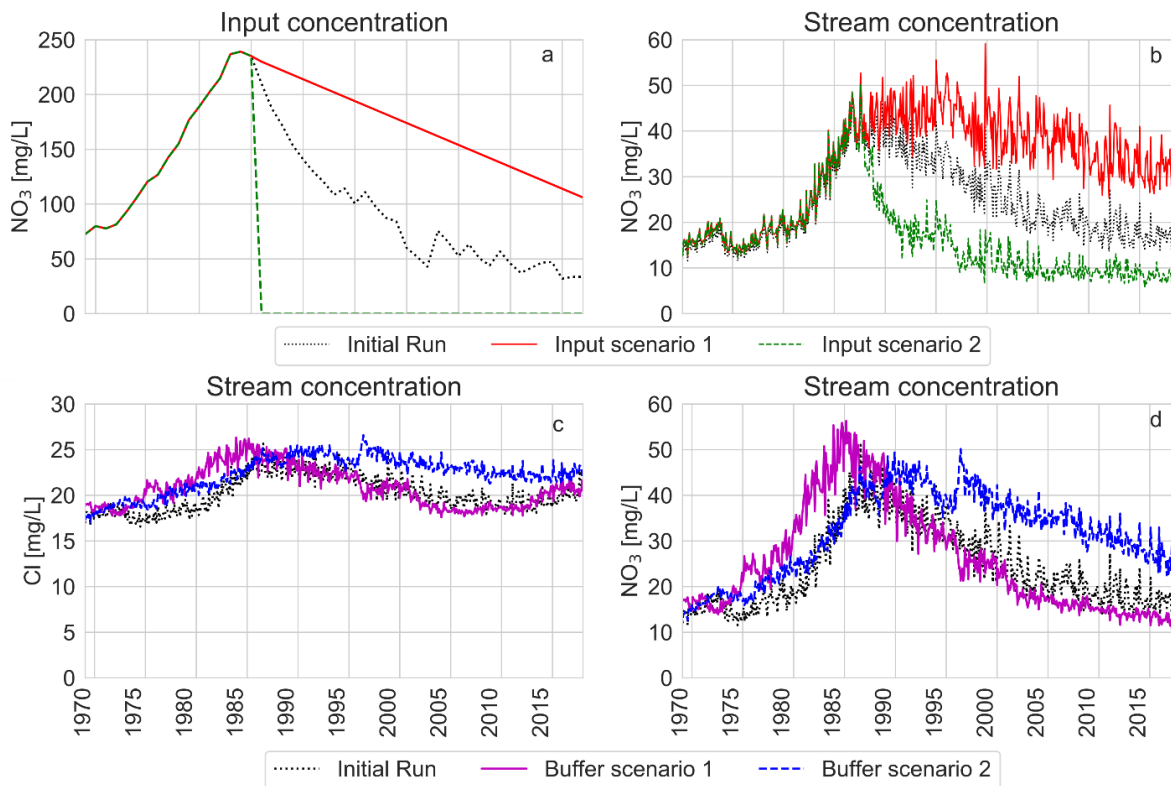

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Figure 3. Three age classes of the travel time distributions of the discharge in the Springendalse Beek for the upstream part of the catchment (a) and the total catchment (b). The lower panels show the percentage of discharge originating from agricultural fields for the upstream part of the catchment (c) and the total catchment (d).
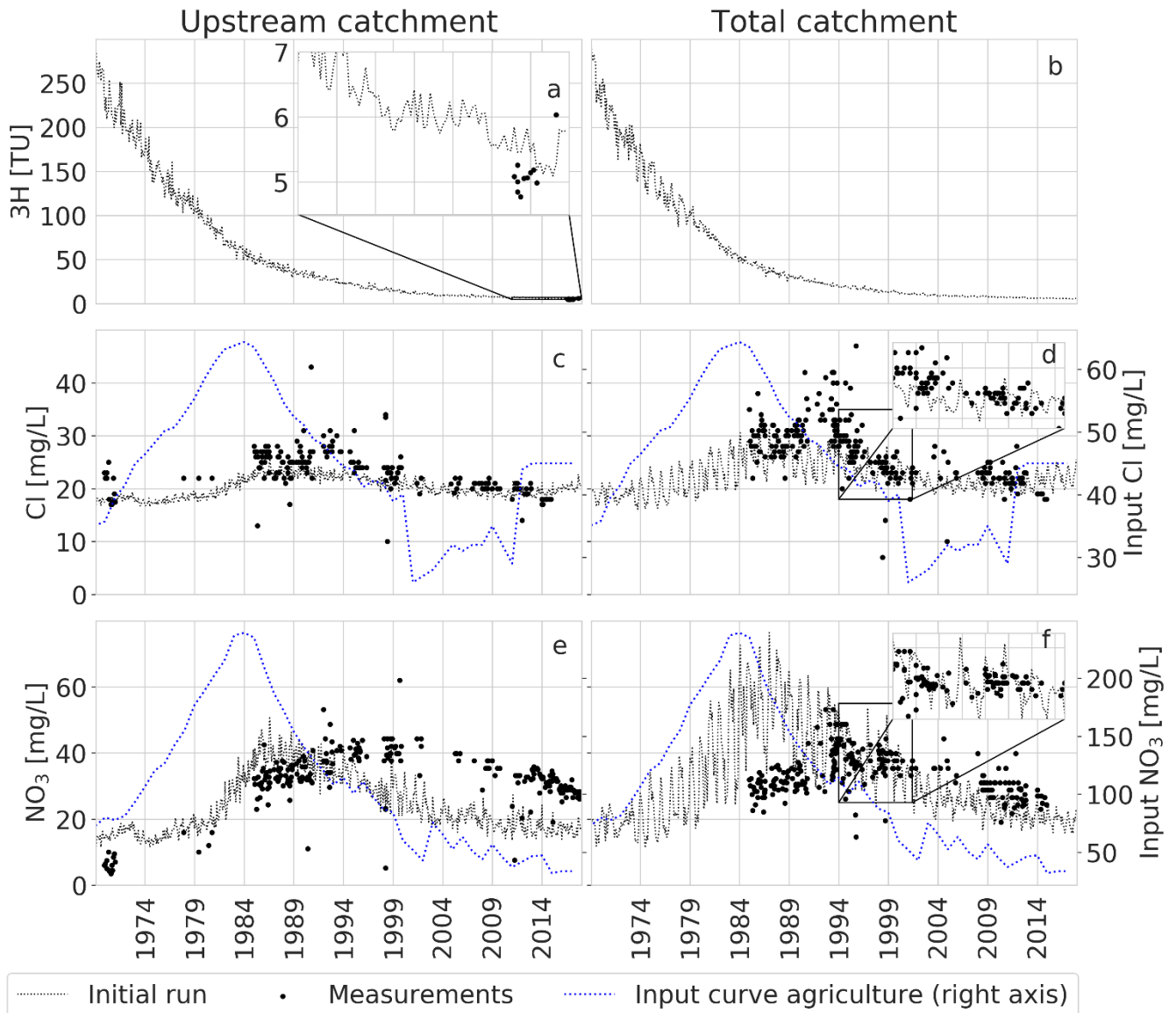
Figure 4. Measurements, agricultural input curves and initial model results based on the TTDs from Kaandorp, et al. (2018) and the solute input curves in Figure 2. No further processes were added. Note that tritium samples were only available for the upstream part of the catchment (panel a).

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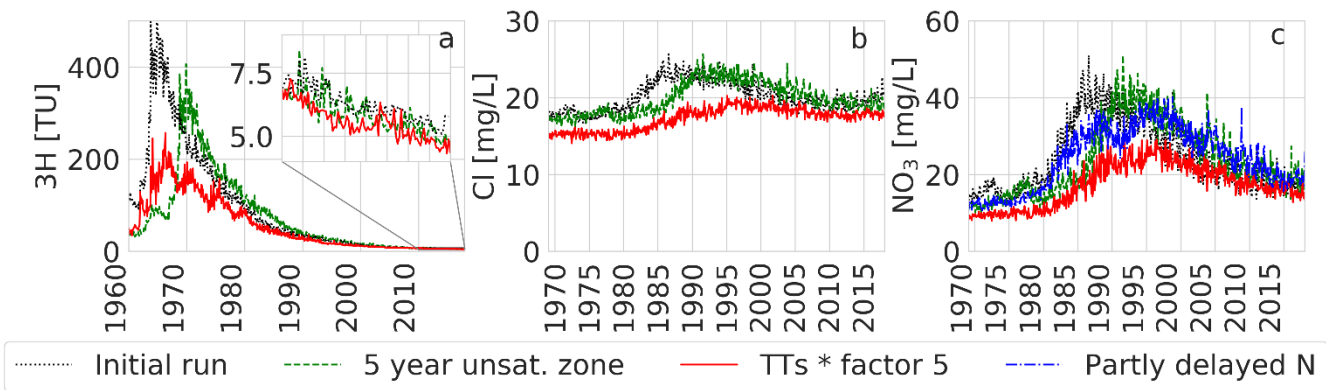
Figure 5. The effect on tritium (a), chloride (b) and nitrate (c) of a scenario with a 5-year delay due to an unsaturated zone and a scenario where all travel times where increased by a factor 5.


Figure 6. Panel a and b show the effect of two scenarios with changes in the nitrate input curve. Note the difference in scale of the x-axis between the left and right panels. Panels c and d show the effect of spatial changes in land-use on both chloride (c) and nitrate (d): only agriculture inside of a 200 m strip around the stream (Buffer scenario 1), and only agriculture outside of the same buffer strip (Buffer scenario 2). In both scenarios agricultural parts have 50% agriculture and 50% nature, so that the total amount of fields is approximately equal to that in the real catchment.
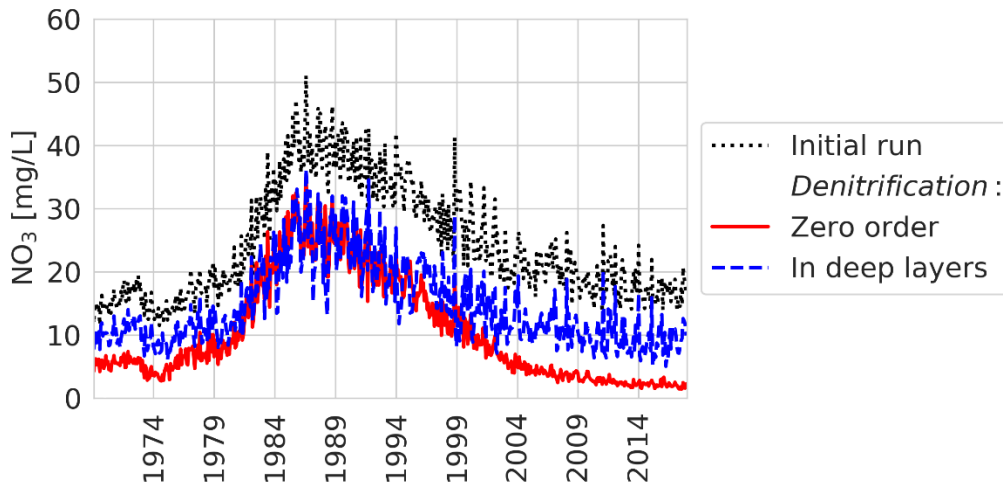
**Figure 7. Effect of denitrification for the upstream part of the catchment using different conceptualizations: zero order denitrification and denitrification in deep layers.**
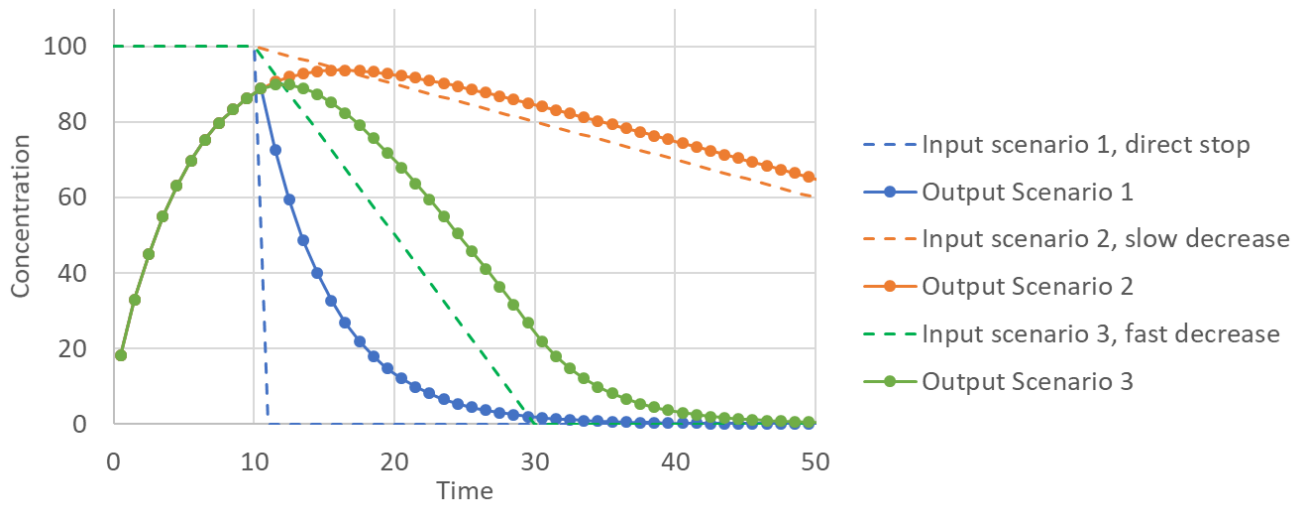

Figure 8. Output concentrations for a hypothetical catchment with an exponential TTD with a MTT of 5, following three input scenarios: a direct stop of the input, a slow decrease in the input and a fast decrease of the input.
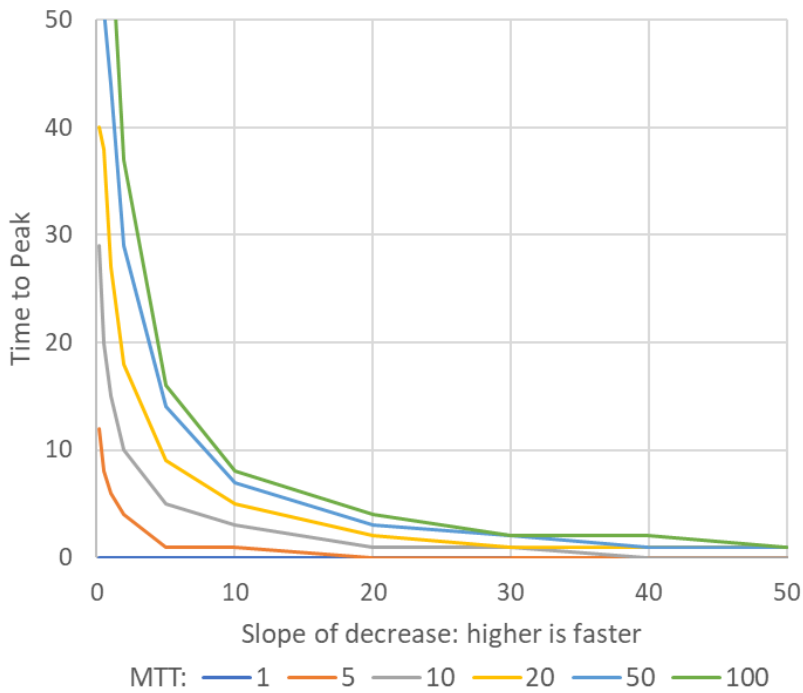
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Figure 9. Graphical representation of Table 4 showing the time lag in output concentration (time to peak) on changes in the input for an exponential TTD. The time lag is based on both the MTT and the speed of decrease of the input, a direct stop in the input always results in a direct response in the output. Figure 8 shows some of the scenarios used to construct this Figure.

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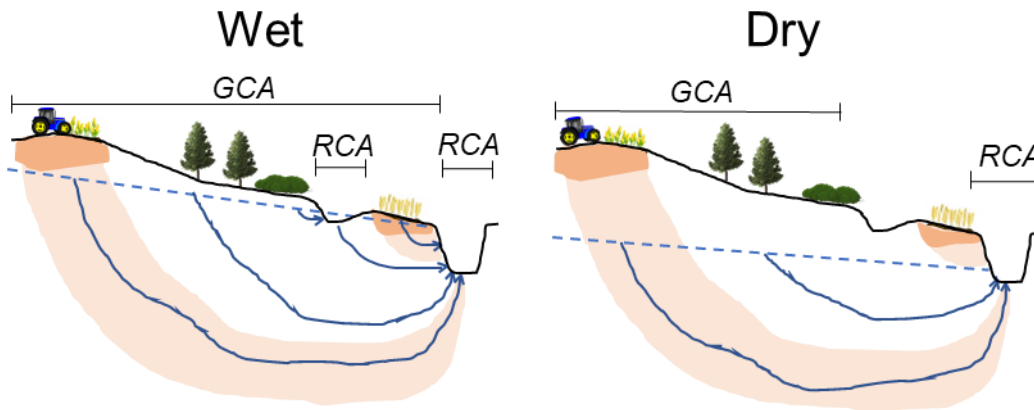
Figure 10. Contributing areas fluctuate with wetness conditions due to changing flow paths. GCA is the Groundwater Contributing Area which is where discharge was infiltrated and RCA is the Runoff Contributing Area which is where discharge is generated. Areas between the two different contributing areas are 'inactive' and do not actively influence stream discharge.
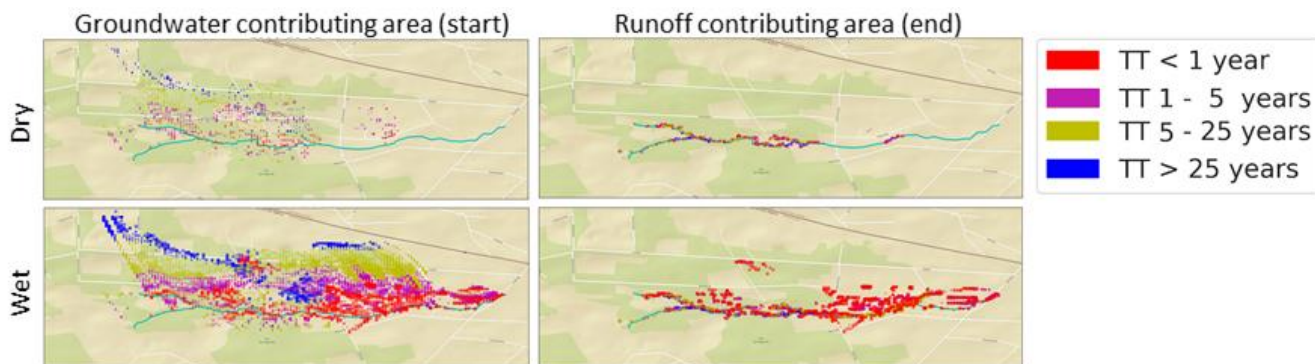
Figure 11. Contributing area in the model for a dry (top; summer 2006) and a wet (bottom; winter 2006/2007) period. Colors represent the travel time towards the stream with blue TT >25 year and red TT < 1 year (similar to Figure 3). Notice the large increase in the runoff contributing area in the downstream part of the catchment during wet periods which results from the extensive agricultural drainage system. *Background map ESRI_StreetMap_World_2D, Sources: Esri, DeLorme, NAVTEQ, USGS, NRCAN, METI, iPC, TomTom, http://services.arcgisonline.com/ArcGIS/rest/services/ESRI_StreetMap_World_2D/MapServer.*

Table 1. Overview of the collected chloride and nitrate measurements.

Location	Parameters	Period	Source	Total amount of samples
Upstream	Cl, NO$_3$	1969 - 1981	Higler et al., 1981	15
Upstream	Cl, NO$_3$	1992	Hoek, 1992	1
Upstream	NO$_3$	1980 - 1990	Dam et al., 1993	2
Upstream	Cl, NO$_3$	1998	Van der Aa et al., 1999	1
Upstream	Cl, NO$_3$	2004 - 2005	Verdonschot en Loeb, 2008	2
Upstream	Cl, NO$_3$	1985 - 2018	Waterboard Vechtstromen	245
Downstream	Cl, NO$_3$	1992	Hoek, 1992	1
Downstream	Cl, NO$_3$	1985 - 2018	Waterboard Vechtstromen	282

Table 2. Exploration of the model behaviour under different scenarios.

Set		Parameter
-	Base case. Variable input, no denitrification	
1a	Unsaturated zone hydrological delay	Travel Time
1b	Unsaturated zone N species delay	Travel Time only part of N
2	Increased saturated zone travel times	Mean Travel Time
3	Different temporal input of solutes	Input
4	Spatial differences in solute input	Input

Table 3. Summarized results of the exploration of the model behaviour.

		Peak concentration change [mg/L]		Time to peak change [years]		Conc. in 2016 change [TU]
Set		Cl	NO$_3$	Cl	NO$_3$	Tritium
1a	Unsaturated zone, delay 5 years	0	0	+5	+5	-0.29
1b	Unsaturated zone, delay 10 years on 50% of N	0	-11	0	+10	0
2	Increased sat. zone travel times, factor 5	-5	-20	+10	+10	-0.63
3	Different temporal input 1: direct stop N	0	0	0	0	0
	Different temporal input 2: slower reduction N	0	+2	0	+10	0
4	Spatial differences in solute input 1	+1	+5	-1	-1	0
	Spatial differences in solute input 2	0	-1	+7	+4	0
5	Denitrification saturated zone zero order	0	-15	0	0	0
	Denitrification saturated zone deep layers	0	-15	0	0	0

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Table 4. Time to peak [years] of the output concentrations following a change in the input for different rates of changes and MTTs.

Slope of decrease [fraction of max / step]		*Young*	Mean Travel Time (MTT)			*Old*	
		1	5	10	20	50	100
Slower decrease	0.2	0	12	29	40	55	90
	0.5	0	8	20	38	51	76
	1	0	6	15	27	44	58
	2	0	4	10	18	29	37
	5	0	1	5	9	14	16
	10	0	1	3	5	7	8
	20	0	0	1	2	3	4
	30	0	0	1	1	2	2
Faster decrease	40	0	0	0	1	1	2
	50	0	0	0	1	1	1

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