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A framework for determining unsaturated zone water quality time lags at catchment scale

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ABSTRACT

The responses of waterbodies to agricultural programmes of measures are frequently delayed by hydrological time lags through the unsaturated zone and groundwater. Time lag may therefore, impede the achievement of remediation deadlines such as those described in the EU Water Framework Directive (WFD). Omitting time lag from catchment characterisation renders evaluation of management practices impossible. Time lag aside, regulators at national scale can only manage the expectations of policy-makers at larger scales (e.g. European Union) by demonstrating positive nutrient trajectories in catchments failing to achieve at least 'good' status. Presently, a flexible tool for developing spatial and temporal estimates of trends in water quality/nutrient transport and time lags is not available. The objectives of the present study were first to develop such a flexible, parsimonious framework incorporating existing soil maps, meteorological data and a structured modelling approach, and to secondly, to demonstrate its use in a grassland and an arable catchment ($\sim$10 km^2) in Ireland, assuming full implementation of measures in 2012. Data pertaining to solute transport (meteorology, soil hydraulics, depth of profile and boundary conditions) were collected for both catchments. Low complexity textural data alone gave comparable estimates of nutrient trajectories and time lags but with no spatial or soil series information. Taking a high complexity approach, coupling high resolution soil mapping (1:10,000) with national scale (1:25,000) representative profile datasets to $<$5 m depth, indicated trends in nutrient transport of 10–12 months and 13–17 months throughout the grassland and arable catchments, respectively. For the same conditions, regulators relying on data from groundwater sampling to test the efficacy of the present measures would be delayed by 61–76 months and 46–79 months, respectively. Variation in meteorological datasets enabled temporal analysis of the trends in nutrient transport and time lag estimates. Such a tool could help catchment scientists to better characterise and manage catchments, determine locations for monitoring or mitigation, assess the efficacy of current measures, and ultimately, advise policy makers and regulators.

1. Introduction

The European Union Water Framework Directive (WFD) (WFD; 2000/60/EC, Official Journal of the European Communities, 2000) requires that all waterbodies attain 'good' chemical qualitative status (amongst other stipulations) within set reporting periods (e.g. 2015, 2021, 2027). Attainment of this status is attempted through implementation of programmes of measures (POM), such as those described by the Nitrates Directive (European Commission, 1991), which remediate pollution from agricultural sources via land and fertiliser management strategies. Quality status is determined via environmental monitoring implemented by the Environmental Protection Agency (EPA) in accordance with Annex II of the WFD. In Ireland, POM include the implementation of buffer zones, timing of fertiliser application, and prescribed application rates – derogation to which is critical for attainment of national production goals (Food Harvest 2020 (Dept. of Agriculture, Food and the Marine, 2010) and Food Wise 2025 (Dept. of Agriculture,

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Food and the Marine, 2015)). However, the inherent delay or 'time lag' (Sousa et al., 2013) that surplus nutrients (or other potential contaminants such as heavy metals or pesticides) encounter through subsurface pathways renders correlation between POM efficacy and waterbody status challenging (Cook et al., 2003; Schulte et al., 2006; Bechman et al., 2008; Fenton et al., 2011a,b; Huebsch et al., 2013; Van Meter and Basu, 2015). Total time lag (t_T), not including the attenuation of nutrients or other pollutants during transport (Huebsch et al., 2013; Jahangir et al., 2013), may be subdivided into unsaturated (t_u) and saturated (t_s) zone components (Fig. 1) (Fenton et al., 2011a,b; Sousa et al., 2013). As the unsaturated zone offers an early indication of trends in water quality concentration and POM efficacy, it is a critical zone to monitor in order to guide the expectations of policymakers and stakeholders (Kronvang et al., 2008; Dworak et al., 2005; Wahlin and Grimvall, 2008; Huebsch et al., 2013). Transport of water and solutes through this region may occur relatively slowly through the soil matrix or rapidly as a result of preferential transport through macropores (Richards et al., 2005; Keim et al., 2012; Kramers et al., 2012). Matrix flow may present the greatest impediment to the achievement of deadlines, as it indicates the slowest rate of solute flushing from the catchment. Hence, it may contribute to prolonged elevation of solute concentration at an abstraction point or surface waterbody, as opposed to rapidly observed peaks resulting from preferential flow (Mellander et al., 2016). Both pathways can and do occur concurrently within a catchment, but the focus of the current paper is on the matrix component, and where t_u is mentioned hereafter, it is this portion which is referred to. Although the effects of soil properties on t_u are acknowledged as a potential impediment to applied POM (EPA, 2015), no framework exists to assess these limitations and associated timeframes in catchments and sub-catchment areas which are vulnerable to nutrient loss through the soil and groundwater pathway. While biogeochemical attenuation factors are also important (Jahangir et al., 2013; Van Meter and Basu, 2015), the current paper addresses the hydrological component of t_u, which may be differentiated into the following stages: initial breakthrough or trends (IBT/Trend), peak breakthrough (Peak), centre of mass (COM – indicating the bulk effect of POM), and complete exit of the solute from the profile (Exit) (Vero et al., 2014; Fenton et al., 2015). The IBT/Trend is particularly critical as it represents the first instance in which conservative nutrients transported by water may be observed at the base of the soil profile subsequent to implementation, and thereby indicates the general direction of water quality response. IBT/Trend reflects initial effects of POM, as might be ascertained from monitoring networks in the unsaturated zone or shallow groundwater.

Numerical models simulate water flow and solute transport in the unsaturated zone (Saxena and Jarvis, 1995; Pang et al., 2000; Pachepsky et al., 2004; Schoups et al., 2008; Konikow, 2011), and can therefore be used to assess t_u (Bouraoui and Grizzetti, 2014). Such models require input data pertaining to soil hydraulic properties (Durner and Lipsius, 2006; Vero et al., 2014; Fenton et al., 2014), temporal meteorological data (Mertens et al., 2002; Gladnyeva and Saifadeen, 2013; Vero et al., 2014) and boundary conditions (Jacques et al., 2008; Vereecken et al., 2010). Vero et al. (2014) examined the consequences of soil and meteorological input data complexity on t_u estimates produced using the Hydrus 1D model (Šimůnek et al., 2013). Results indicated that low-complexity soil data (textural properties and bulk density (ρ_d)) were sufficient to indicate trend response at the base of a soil profile to POM. Further soil hydraulic parameter evaluation (Fenton et al., 2015) indicated that three popular laboratory textural analyses methods (pipette, laser diffraction and hydrometer) perform equally well as sources of low-complexity data. Previously, Fenton et al. (2010) estimated ranges of t_u for Ireland using default values from the literature to simulate the unsaturated and saturated zones. Since then, more extensive soil datasets have become available via the Irish Soil Information System (SIS) (Creamer et al., 2014), and the Irish Agricultural Catchment Programme (ACP) (Wall et al., 2011) is currently testing the efficacy of agricultural POM implemented under the Nitrates Directive. Therefore, the primary objective of the current paper was to develop a parsimonious, readily implementable framework for the estimation of unsaturated soil time lag ranges in agricultural catchments. This framework will provide a mechanism by which catchment scientists can distinguish between various stages of t_u, and hence increase the detail included in projections of time lag trajectories. To fulfil this objective, the current study utilised onsite meteorological (from 2012 onwards to match implementation of POM) and soil data (from the Irish SIS) for two agricultural catchments, as inputs to the Hydrus 1D numerical model (Šimůnek et al., 2013). The secondary objective was to examine long-term t_u under future moderate rainfall scenarios, in order to comment on the achievability of subsequent WFD deadlines (e.g. 2021, 2027) within these catchments.

2. Materials and methods

In the development of the modelling framework, the following tasks were performed for both catchments: identification of catchment boundaries using GIS, collation of SIS soil and meteorological datasets, validation of the soil series via a soil survey and auguring campaign, numerical modelling using Hydrus

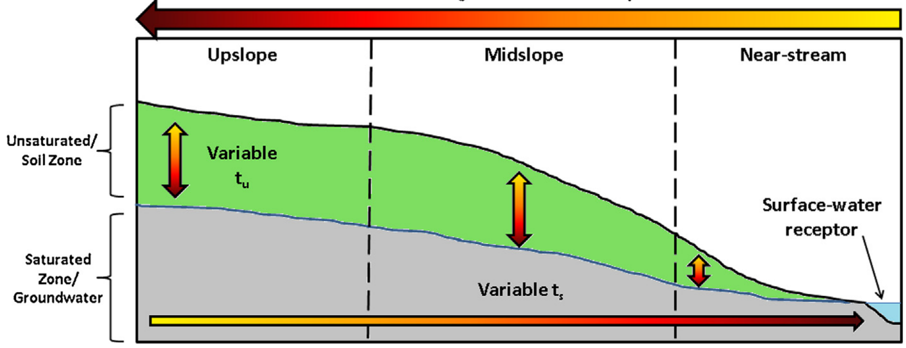

Fig. 1. Total time lag (t_T) from source to receptor, including the unsaturated soil pathway (t_u) and the saturated groundwater pathway (t_s). Arrows indicate the variable duration of t_u and t_s, depending on the depth of the soil profile and proximity to a receptor, respectively.