Journal of Contaminant Hydrology 170 (2014) 53–67

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

Consequences of varied soil hydraulic and meteorological complexity on unsaturated zone time lag estimates

S.E. Vero [a,b,*], T.G. Ibrahim [c], R.E. Creamer [a], J. Grant [d], M.G. Healy [b], T. Henry [e], G. Kramers [a,f], K.G. Richards [a], O. Fenton [a]

[a] Crops, Environment and Land Use Program, Teagasc, Johnstown Castle, Co. Wexford, Ireland
[b] Civil Engineering, National University of Ireland, Galway, Co. Galway, Ireland
[c] Sustainable Land and Soils, Department for Environment, Food and Rural Affairs, London, United Kingdom
[d] Teagasc Research Operations Group, Statistics and Applied Physics Department, Ashtown, Dublin 15, Ireland
[e] Earth and Ocean Sciences, National University of Ireland, Galway, Co. Galway, Ireland
[f] School of Geosciences, University of the Witwatersrand, Private bag 3, PO Box Wits 2050, Johannesburg, South Africa

ARTICLE INFO

Article history:
Received 5 March 2014
Received in revised form 29 September 2014
Accepted 1 October 2014
Available online 13 October 2014

Keywords:
Time lag
Hydrus
Water quality
Unsaturated

ABSTRACT

The true efficacy of a programme of agricultural mitigation measures within a catchment to improve water quality can be determined only after a certain hydrologic time lag period (subsequent to implementation) has elapsed. As the biophysical response to policy is not synchronous, accurate estimates of total time lag (unsaturated and saturated) become critical to manage the expectations of policy makers. The estimation of the vertical unsaturated zone component of time lag is vital as it indicates early trends (initial breakthrough), bulk (centre of mass) and total (Exit) travel times. Typically, estimation of time lag through the unsaturated zone is poor, due to the lack of site specific soil physical data, or by assuming saturated conditions. Numerical models (e.g. Hydrus 1D) enable estimates of time lag with varied levels of input data. The current study examines the consequences of varied soil hydraulic and meteorological complexity on unsaturated zone time lag estimates using simulated and actual soil profiles. Results indicated that: greater temporal resolution (from daily to hourly) of meteorological data was more critical as the saturated hydraulic conductivity of the soil decreased; high clay content soils failed to converge reflecting prevalence of lateral component as a contaminant pathway; elucidation of soil hydraulic properties was influenced by the complexity of soil physical data employed (textural menu, ROSETTA, full and partial soil water characteristic curves), which consequently affected time lag ranges; as the importance of the unsaturated zone increases with respect to total travel times the requirements for high complexity/resolution input data become greater. The methodology presented herein demonstrates that decisions made regarding input data and landscape position will have consequences for the estimated range of vertical travel times. Insufficiencies or inaccuracies regarding such input data can therefore mislead policy makers regarding the achievability of water quality targets.

1. Introduction

The European Union Water Framework Directive (EU-WFD) (European Commission (EC), 2000) was enacted in December 2000. Its objective is to attain ‘good’ status for all surface and groundwater bodies by 2015, with the possibility to extend deadlines to the second reporting period in 2021 or beyond. The EU-WFD is enforced in member states through programmes of measures (POM) e.g. the Nitrates Directive in Ireland (EC, 1991), which aims to prevent water pollution by managing the use of fertiliser, manure and increasing nitrogen use efficiency (van Grinsven et al., 2012). In Ireland, the Agricultural Catchments

* Corresponding author at: Crops, Environment and Land Use Program, Teagasc, Johnstown Castle, Co. Wexford, Ireland. Tel.: +353 877576641.
E-mail address: sara.vero@teagasc.ie (S.E. Vero).

http://dx.doi.org/10.1016/j.jconhyd.2014.10.002
0169-7722/

Program (ACP) evaluates the environmental and economic effects of POM implemented under the Nitrates Directive (ACP, 2013). Despite prompt implementation of POMs throughout the EU in 2012, many catchments may not achieve good water quality status within the given timeframe, due to the time lag of nutrient transport from source to receptor via surface and subsurface hydrologic pathways. An appraisal of catchment time lag issues may offer a more realistic, scientifically-based timescale for expected water quality improvements in response to mitigation measures (Fenton et al., 2011; Jordan et al., 2005).

1.1. Time lag

Time lag (t_T), also referred to as time delay, retardation factor, residence time, or memory effect (Bechmann et al., 2008; Cook et al., 2003; Fenton et al., 2011), is defined in this paper as the inherent hydrologic delay in response to mitigation measures. It is often conceptualised as consisting of both a vertical component through the unsaturated zone (t_u) and a lateral component via the saturated zone (t_s) (Sophocleous, 2012). It is acknowledged that the unsaturated zone also will inevitably contain a lateral component (Forrer et al., 1999), but for the purposes of this study t_u is assumed to represent vertical transport through the unsaturated zone alone. Furthermore the soil profiles used herein represent profiles in which this pathway prevails.

There is also evidence of time lag at larger national scales (e.g. Granlund et al., 2005 (Finland); Kronvang et al., 2008 (Denmark); van Grinsven et al., 2013 (EU)). Fenton et al. (2011), using saturated assumptions to various depths (maximum 10 m), demonstrated that t_T is likely to inhibit the capacity of many Irish catchments to achieve WFD targets within the designated reporting periods, and consequently, deadlines have been extended (Daly, 2011). However, site specific analyses incorporating variably saturated solute transport parameters would better account for the national diversity of soil and landscape conditions. Although it is often purported as a "generic excuse" (Scheure and Naus, 2010) to overcome more stringent policy measures, elucidation of time lag is fundamental in order to better predict the response of water bodies to a change in agricultural management practices (Meals et al., 2010; Mellander et al., 2012). In addition, catchments with the lowest time lags (high vulnerability) display a rapid response to POMs (e.g. free draining soils underlain by high permeability karst bedrock) (Huebsch et al., 2013) and offer an opportunity to test such POMs within specified reporting periods. Conversely, catchments with longer time lags (e.g. due to lower soil and aquifer permeability (Wang et al., 2012)), display slower responses limiting the potential to assess POM efficacy within the same reporting periods.

Numerous studies have highlighted the crucial role of the unsaturated zone within the hydrologic cycle, and the need for realistic quantification of t_u within hydrological models (Hooper, 2009; Torres et al., 1998; Vereecken et al., 2008). Sousa et al. (2013) described a methodology to assess the importance of t_u within the context of t_T (the sum of unsaturated and saturated time lags: $t_T = t_u + t_s$) and advocated the use of measured rather than generic data collection to more accurately account for t_T. While it is typical within a catchment study for more investment and information to be readily available on t_s little thought is often given to estimating t_u, despite the influence it exerts on solute transport timelines.

The focus of this paper is t_u, which is mainly controlled by soil/subsoil/bedrock type (Bejat et al., 2000; Helliwell, 2011), unsaturated thickness (Hillel, 2004), its variably saturated nature (Nielsen et al., 1986), interactions between the solute and the soil matrix (Leij and van Genuchten, 2011) and climatic factors (Diamond and Shanley, 2003; Stark and Richards, 2008). In addition, the spatial (Gumiere et al., 2013; Peck et al., 1977) and temporal variability (Mapa et al., 1986; Sousa et al., 2013) of weather and soil data and the proximity of a particular landscape position relative to ground and surface water receptors (Fenton et al., 2009, 2011; Jordan et al., 2005; Schulte et al., 2006; Sousa et al., 2013) are significant when determining the importance of t_u. Numerous studies (Baily et al., 2011; Fenton et al., 2011; Fousssereau et al., 2001; Gladnyeva and Saifadeen, 2013; Huebsch et al., 2013; Premrov et al., 2014) have identified the critical influence exerted by meteorological patterns on t_u. Direct recharge (sometimes called effective drainage — Fenton et al. (2011)) to groundwater (and hence contaminant transport and t_u) is implicitly linked with rainfall amount and soil/subsoil/bedrock permeability (Fitzsimons and Misstear, 2006).

1.2. Theoretical framework

1.2.1. Unsaturated zone numerical modelling

Accounting for vertical transport presents a challenge due to the nonlinearity of unsaturated flow (Russo, 1991). A simple approach is to assume constant saturation (Fenton et al., 2011) (Eq. (1)). However, this is likely to underestimate t_u, as it fails to reflect the variably saturated nature of field conditions.

$$t_u = \frac{d}{ER/(n_e/100)} \tag{1}$$

where d (m) is depth of the soil profile, ER (m) is effective rainfall calculated after Schulte et al. (2005), and n_e is effective porosity (%). Fenton et al. (2011) demonstrated that for Ireland, t_T would exceed current EU-WFD reporting periods and, moreover, in some cases, t_u alone would be outside such periods. Sousa et al. (2013) represented the % of travel time spent in the unsaturated zone (t_r) within the context of t_T (Eq. (2)).

$$t_r = \frac{t_u}{t_T}. \tag{2}$$

In recent years, numerical models (free-licence and proprietary) capable of describing transport in the unsaturated zone have been developed (see reviews by Arheimer and Olsson, 2003; Jackson et al., 2006; Sousa et al., 2013). These models incorporate the Richards' equation for unsaturated flow and so better reflect field conditions than the saturated approach. Model selection must be based not only upon which best describes the process/problem in question, but also upon the data available and accuracy required (Konikow, 2011; Wagener et al., 2001). Models may simulate conservative solutes or include more complex solute transformation equations, such as in the UNSATCHEM module incorporated in the Hydrus series (Šimůnek et al., 1996).