Modelling of unsaturated and saturated zone time lag at the hillslope scale

S.E. Vero[1,2], O. Fenton[1], P-E Mellander[1], K.G. Richards[1], C.E. Coxon[3], R. Creamer[1], T. Henry[4], M.G. Healy[2], and E. McAleer[1,3]

[1]Teagasc, Johnstown Castle, Environment Research Centre, Wexford, Rep. of Ireland. [2]Civil Engineering, National University of Ireland, Galway, Rep. of Ireland. [3]Geology Department, School of Natural Sciences, Trinity College Dublin. [4]Earth and Ocean Sciences, National University of Ireland, Galway, Rep. of Ireland.

INTRODUCTION

The European Union Water Framework Directive (EU-WFD) necessitates evidence-based quantification of the efficacy of mitigation measures (e.g. the Nitrates Directive). Hence, elucidation of catchment-specific time lags in response to such measures is essential. Time lag (t_T) consists of two components: unsaturated (t_U) and saturated (t_S) (Fig. 1), or for simplicity "soil" and "groundwater". Initial estimates, assuming fully saturated conditions, proved that achievement of good status in all water bodies by 2015 was not possible (Fenton *et al*., 2011). Trends, indicating the initial response to programmes of measures (POM), are required under EU-WFD guidelines, in order to assess efficacy in the short term. The present paper combines results from two PhD studies and presents hillslope-scale estimates of time lag in a grassland catchment.

METHODOLOGY

- The catchment consists of loamy, moderate-well drained topsoil and permeable subsoil over Devonian old red sandstone geology, dominated by fracture flow. Thickness of the unsaturated zone ranges between 0.5 -10 m (near-stream to upslope).

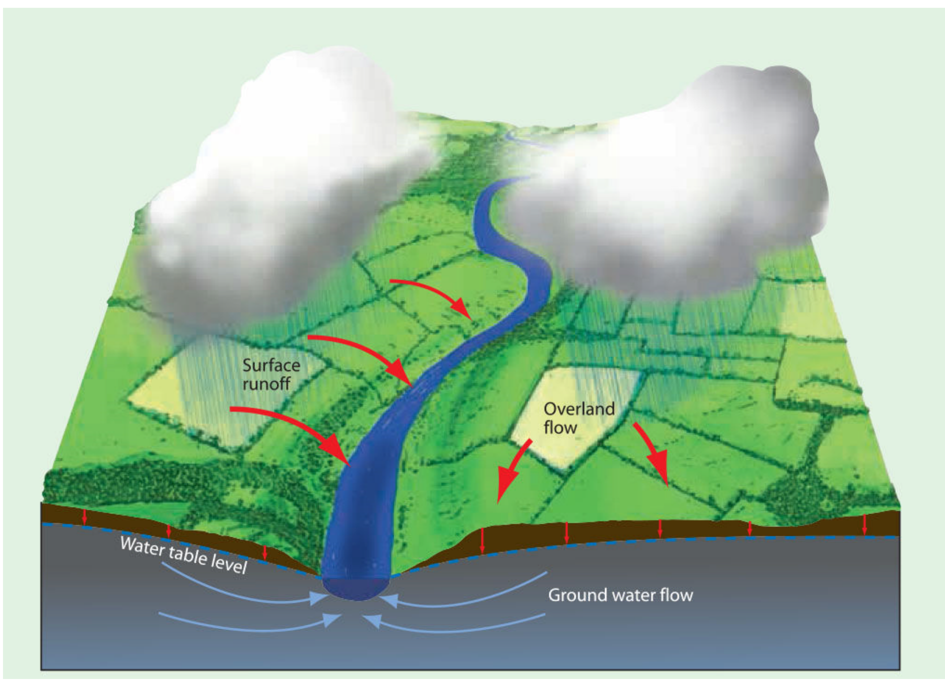

***Fig. 1*: Soil and groundwater time lag in a catchment.**

- Soil profiles were excavated (2014) *(Fig. 2)* and multi-level borehole transects (2010) were installed to obtain soil/subsoil and aquifer hydraulic parameters/water table elevations, respectively. Groundwater quality monitoring was initiated thereafter.
- The Hydrus 1D numerical model (*Fig. 2*) was used in accordance with Vero *et al*. (2014) to determine t_U. Resulting breakthrough curves at the base of the profiles were used to identify initial breakthrough (IBT) of the solute to the groundwater monitoring network, indicating trend response to POM, and solute exit, by which the contaminant is totally flushed from the profile, indicating long-term t_u.

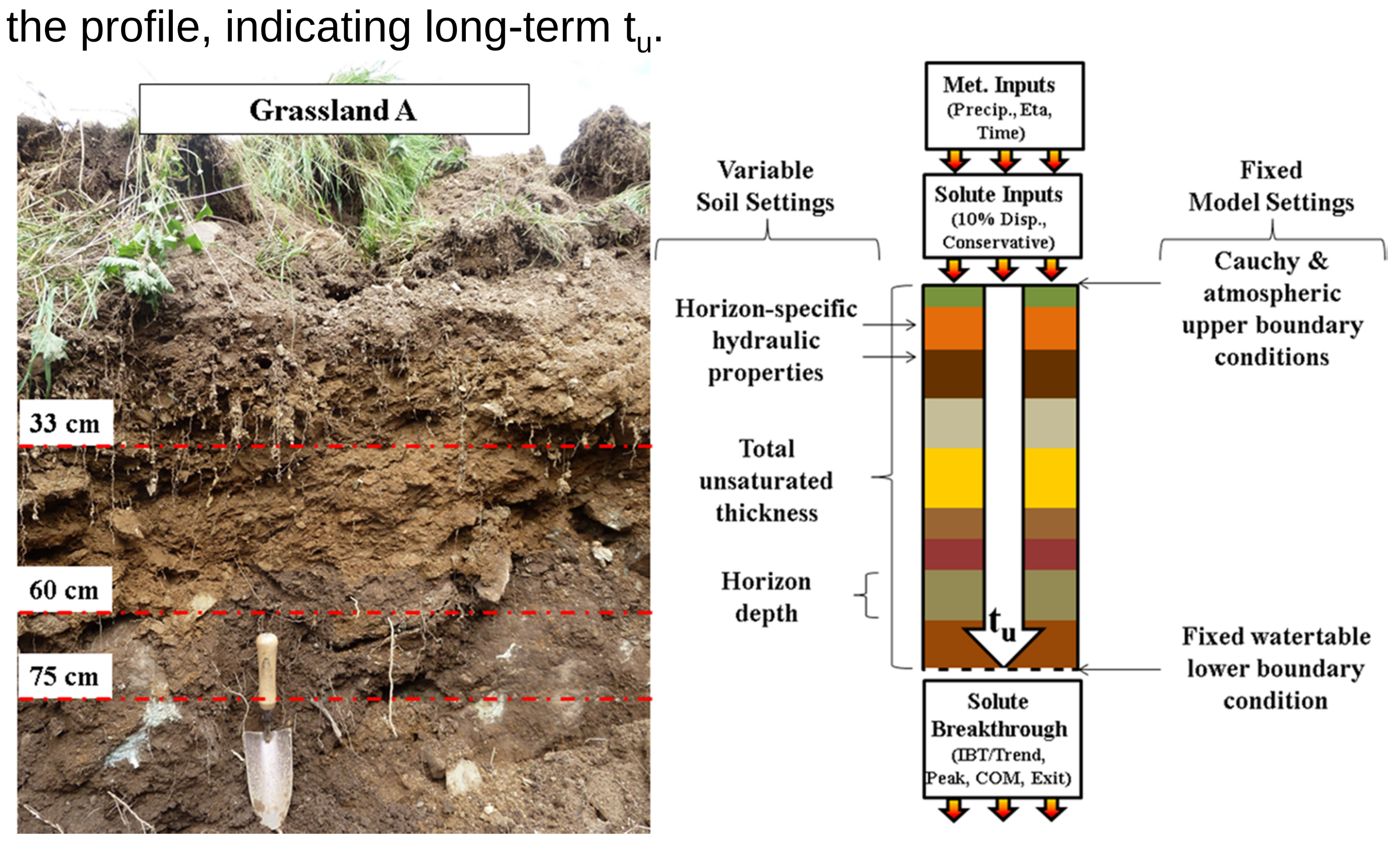

***Fig. 2*: Soil profile for Grassland A and Hydrus 1D conceptual model.**

- A finite difference GW flow model was created using aquifer hydraulic properties as inputs and measured water table elevations as calibration targets (*Fig.3*). A particle tracking approach quantified flow direction and cumulative travel time within each aquifer zone.

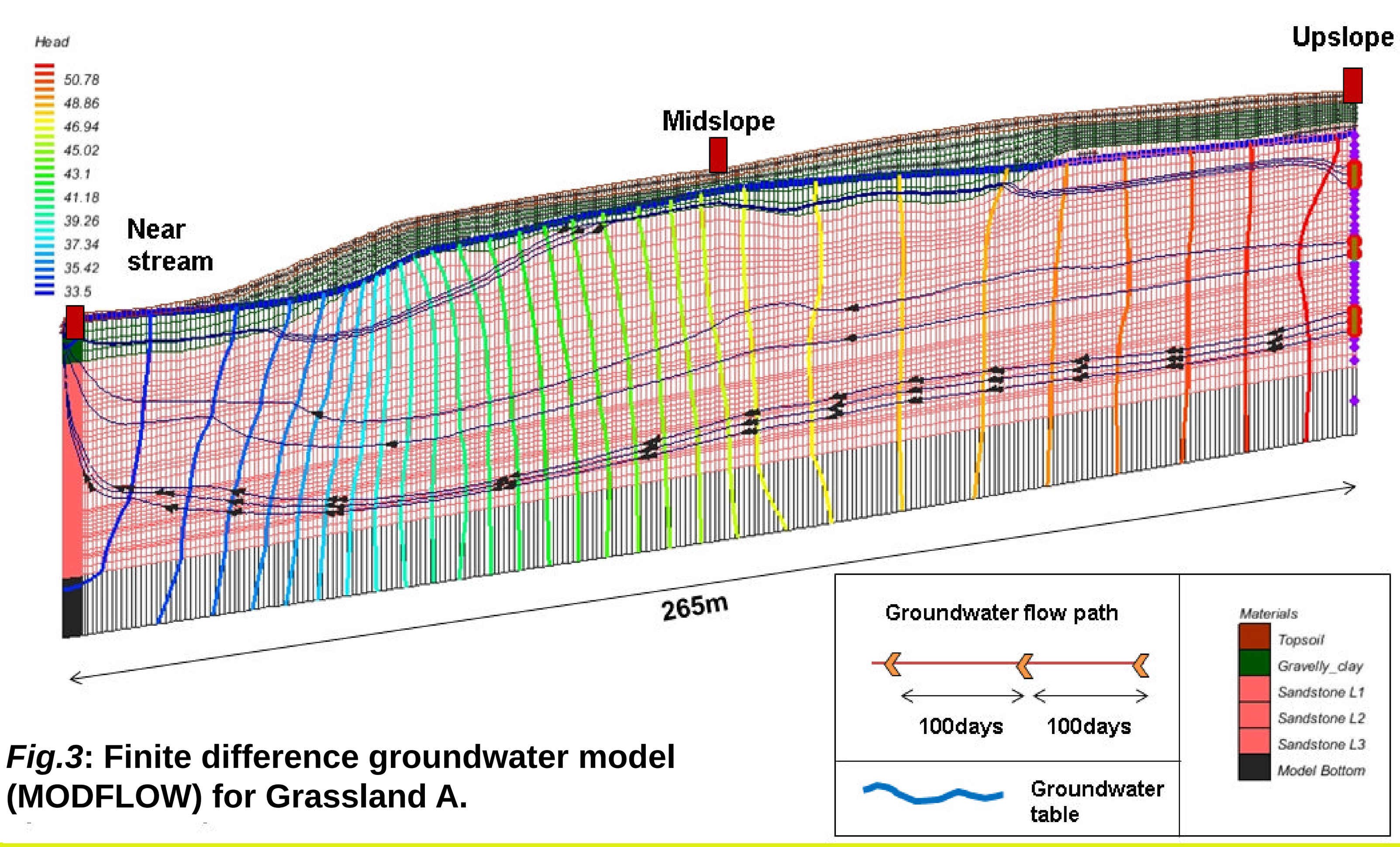

***Fig.3*: Finite difference groundwater model (MODFLOW) for Grassland A.**

- The percentage of t_T controlled by the soil zone is expressed as t_u/t_T, and indicates the relative importance of the soil component.

RESULTS

Table 1 presents the combined results of both unsaturated and saturated zone modelling in Grassland A. Where t_u indicates when trends may be first observed in groundwater for each site, and when the full effect of POM (indicated by solute exit from the profile) will occur, t_s indicates time lag through shallow, transitional and deep groundwater, and t_T indicates the total time lag from source to receptor.

***Table 1*: Soil and groundwater time lag across a hillslope.** Highlighted cells indicate the minimum and maximum t_T which may be observed at the transect scale.

Time Lag Ranges (months) (subsequent to implementation of POM in 2012)									
Grassland A									
	IBT/Unsaturated Zone (t_U) (months)		Saturated Zone (t_S) (Hillslope position to receptor - stream) (months)				Total time lag (t_T) = (t_U+t_S) (months)		
Hillslope Position	IBT/Trends observed	Solute Exit (long-term t_U)	Groundwater Zone	NS-Stream (2 m)	MS-Stream (146 m)	US-Stream (264 m)	Total time lag (t_T)	Min	Max
Near stream (NS)	1	12	Shallow GW	<1	3	5	NS - Stream	1	17
Mid-slope (MS)	8	22	Transition GW	<1	3	8	MS - Stream	1	45
Upslope (US)	9	>36	Deep GW	6	23	48	US - Stream	13	>84

The minimum travel times represent the fastest possible pathways where the source is adjacent to the receptor, the unsaturated zone is thin and t_S is through the shallow groundwater. The maximum values indicate the slowest pathway, where the source is distant from the receptor, the unsaturated zone is thick and the deep groundwater pathway is dominant.

The relative importance of t_u ranged between **43%** (NS-Stream) and **66%** (US-stream**)**, in the context of t_T, indicating an important role of the soil in nutrient transport in this catchment.

DISCUSSION

- The monitoring and modelling described herein, corresponds to key dates in the EU-WFD implementation timetable, enabling site-specific assessment of POM efficacy within the current reporting period, and provides insight into the subsequent reporting period (**2015-2021**).
- The combined effects of t_U and t_S preclude trend changes in surface water quality before a minimum time lag of **1 month** (where the source is directly adjacent to the receptor), to **13 months** (where the source is at a high slope-position, distant from the receptor).
- Long-term time lag may extend from **17 months** to over **84 months (7 yrs)**, before the contaminant is totally flushed from the soil and groundwater.
- The full effects of POM are unlikely to be observed in less than **7 years** within the catchment.

CONCLUSIONS

- These results indicate that within these catchments, the 2015 reporting period represents an unrealistic timeframe in which to expect changes to ground- and surface water quality in response to POM (Nitrates Directive) applied in 2012.The 2021 period presents as a more feasible response timescale.
- IBT/Trend and t_T indicate when groundwater and surface-water sampling should be initiated by monitoring agencies, respectively.
- This methodology presents a low-cost, rapid means by which the trend response to POMs may be assessed in a variety of agricultural catchments. Longer meteorological datasets may also be applied, in order to comment on later reporting periods.

Acknowledgements

Thanks to the Teagasc Walsh Fellowship Scheme, the Dept. of Agriculture, Food and the Marine, and the Agricultural Catchments Program.

References

Fenton et al., 2011. Environmental Science and Policy
Vero et al., 2014. Journal of Contaminant Hydrology