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Evaluating the critical source area concept of phosphorus loss from soils to water-bodies in agricultural catchments

M. Shore [a,c,*], P. Jordan [b], P.-E. Mellander [a], M. Kelly-Quinn [c], D.P. Wall [d], P.N.C. Murphy [e], A.R. Melland [f]

[a] Agricultural Catchments Programme, Teagasc, Wexford, Ireland
[b] School of Environmental Sciences, University of Ulster, Coleraine, N. Ireland, United Kingdom
[c] School of Environmental & Biological Sciences, University College Dublin, Dublin, Ireland
[d] Environmental Research Centre, Teagasc, Wexford, Ireland
[e] School of Agriculture and Food Science, University College Dublin, Dublin, Ireland
[f] National Centre for Engineering in Agriculture, University of Southern Queensland, Toowoomba, Australia

HIGHLIGHTS

- Critical source area controls on storm phosphorus (P) losses were investigated in six agricultural basins.
- Relative P losses between basins did not reflect trends in predicted critical source area risk.
- Relative P losses between hydrologically *contrasting* basins were primarily hydrologically controlled.
- Relative P losses between hydrologically *contrasting* basins could be predicted using static transport metrics.
- Relative P losses between hydrologically *similar* basins were highly variable.

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ABSTRACT

Using data collected from six basins located across two hydrologically contrasting agricultural catchments, this study investigated whether transport metrics alone provide better estimates of storm phosphorus (P) loss from basins than critical source area (CSA) metrics which combine source factors as well. Concentrations and loads of P in quickflow (QF) were measured at basin outlets during four storm events and were compared with dynamic (QF magnitude) and static (extent of highly-connected, poorly-drained soils) transport metrics and a CSA metric (extent of highly-connected, poorly-drained soils with excess plant-available P).

Pairwise comparisons between basins with similar CSA risks but contrasting QF magnitudes showed that QF flow-weighted mean TRP (total molybdate-reactive P) concentrations and loads were frequently (at least 11 of 14 comparisons) more than 40% higher in basins with the highest QF magnitudes. Furthermore, static transport metrics reliably discerned relative QF magnitudes between these basins. However, particulate P (PP) concentrations were often (6 of 14 comparisons) higher in basins with the lowest QF magnitudes, most likely due to soil-management activities (e.g. ploughing), in these predominantly arable basins at these times. Pairwise comparisons between basins with contrasting CSA risks and similar QF magnitudes showed that TRP and PP concentrations and loads did not reflect trends in CSA risk or QF magnitude. Static transport metrics did not discern relative QF magnitudes between these basins.

In basins with contrasting transport risks, storm TRP concentrations and loads were well differentiated by dynamic or static transport metrics alone, regardless of differences in soil P. In basins with similar transport risks, dynamic transport metrics and P source information additional to soil P may be required to predict relative storm TRP concentrations and loads. Regardless of differences in transport risk, information on land use and management, may be required to predict relative differences in storm PP concentrations between these agricultural basins.

1. Introduction

The European Union (EU) Nitrates Directive (OJEC, 1991) provides a legislative framework for reducing the environmental risk of nutrient losses from agricultural sources to water-bodies. This framework has been ratified into national legislation in EU countries via National Action

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* Corresponding author at: Teagasc, Environmental Research Centre, Johnstown Castle, Co. Wexford, Ireland. Tel.: +353 5391 71200.
E-mail addresses: mairead.shore@teagasc.ie (M. Shore), P.Jordan@ulster.ac.uk (P. Jordan), per-erik.mellander@teagasc.ie (P.-E. Mellander), mary.kelly-quinn@ucd.ie (M. Kelly-Quinn), david.wall@teagasc.ie (D.P. Wall), paul.murphy@ucd.ie (P.N.C. Murphy), alice.melland@usq.edu.au (A.R. Melland).

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Programmes (NAPs) and mostly consists of measures to reduce the risk of nitrogen (N) transfers. However, in some countries, such as Ireland, parts of the U.K. and Sweden, where phosphorus (P) has also been identified in the eutrophication process (Ulén et al., 2007), the NAPs also focus on limiting the source risk of diffuse P loss by, inter alia, restricting plant-available soil P to an agronomic optimum range (SI 610, 2010; DARD, 2006; Swedish Board of Agriculture, 2002). Some NAPs include measures designed to limit the transport risk of P loss, for example by imposing stormy weather, season (approximately 15th October–12th January in Ireland) and saturated ground restrictions for land application of nutrients (S1 610, 2010). However, none of the NAPs account for the spatial variability in surface hydrological connectivity, i.e. the propensity for a saturated area to be connected by surface flow to the drainage network, which is an important driver of P loss in agricultural catchments (Lane et al., 2004; Doody et al., 2012). Furthermore, the assumption of a geographically uniform distribution of surface connectivity prevents the identification of critical source areas (CSAs), i.e. where high-P sources have a high propensity for connection to receiving water-bodies via effective transport pathways (Osmond et al., 2012; Strauss et al., 2007; White et al., 2009).

Studies linking P concentrations and loads in runoff primarily to source factors e.g. soil P, organic P loadings (Kurz et al., 2005; Pote et al., 1999), supported the rationale for focusing NAP measures on soil P availability alone. However, these studies, referred to here as 'Type 1', have mostly been focused at laboratory and field scales where hydrological variability was either removed or was relatively small. Studies linking P concentrations and loads in runoff or stream flow primarily to CSAs are much more common (Osmond et al., 2012; Strauss et al., 2007; Melland et al., 2008). These studies, referred to as 'Type 2', have supported the use of a CSA approach to P loss mitigation in the U.S.A. and elsewhere (Buczko and Kuchenbuch, 2007). Studies linking P concentrations and loads in runoff or stream flow primarily to transport factors e.g. surface runoff, erosion (Daly et al., 2002; Buda et al., 2009; Jordan et al., 2012) are still emerging. These studies, referred to as 'Type 3', highlight the complexity of hydrological processes across landscapes, scales and storms and the associated uncertainty for predicting the role of hydrology in diffuse P pollution.

Due to the increasing dominance of hydrological controls with increasing scale (Haygarth et al., 2012; Jordan et al., 2005), catchment scale studies generally fall into types 2 and 3. Recognising the importance of hydrological controls on P concentrations and loads at catchment scales is important for achieving water-quality objectives which are now focused on river basin scales (E.C. Directive, 2000/60/EC). Although water-quality objectives for river catchments in Europe are primarily focused on P concentrations (WFD — OJEC, 2000), total P loads leaving river catchments also need to be considered for the trophic status and health of downstream standing water bodies (Hilton et al., 2006; Stamm et al., 2013). Recent catchment scale studies in Ireland have demonstrated that hydrological factors were more important than source factors in determining P concentrations (Daly et al., 2002) and loads (Jordan et al., 2005, 2012) at particular sites, supporting type 3 studies. However, these studies did not investigate the relationship between P concentrations and loads and CSAs (type 2 studies) and did not investigate changes in hydrological control at nested small basin scales. More information is therefore needed on whether transport metrics alone provide better estimates of P concentrations and loads in catchments than CSA metrics which combine source factors as well, particularly across different landscapes and at different catchment scales. This is important as a growing body of literature suggests that a CSA approach, using sophisticated source assessments and hydrological routing models, might be an appropriate policy tool to manage diffuse P pollution in Europe (e.g. Doody et al., 2012; Reaney et al., 2011; Thompson et al., 2012; Heathwaite et al., 2005).

Even with the knowledge that hydrological controls can be a major factor in determining P losses from a particular site, a major obstacle to the incorporation of P transport indicators into current NAP measures is the lack of a suitable metric for describing hydrological variability at land management scales. Metrics such as the Q5:Q95 ratio and hydrograph separation of quickflow (QF) have been used to characterise the P transport risk in gauged catchments (Jordan et al., 2005; Mellander et al., 2012) and may also be good indicators of relative P loads between catchments where these loads are primarily hydrologically controlled (Jordan et al., 2012). However, the requirement for gauged basins limits application of these metrics at national scales. The Network Index of Lane et al. (2004) is a recently developed modification of the Topographic Wetness Index (Beven and Kirkby, 1979) which describes the spatial distribution of wet and connected parts of the landscape and can be applied to un-gauged basins where high-resolution DEMs are available. This may be a valuable tool as high-resolution DEMs are becoming increasingly available and at increasingly higher resolution through the use of sub-metre light detection and ranging (LiDAR) technology. Soil drainage class (i.e. well-drained or poorly-drained) is another potentially useful measure of surface transport risk which can be used in un-gauged basins. Recently, Shore et al. (2013) demonstrated that both the Network Index and soil drainage class were good predictors of surface hydrological connectivity, measured as the density of channels (stream and ditch) in small basins (ca. 130 ha), in hydrologically contrasting agricultural catchments. However, the ability of the Network Index and soil drainage class to predict relative QF magnitudes (which is a more direct measure of P transport risk) and P concentrations and loads between basins, is unknown and was investigated in this study.

This study used sub-hourly measurements of quickflow (QF) P concentrations and loads, measured in stream flow in two hydrologically contrasting catchments and at different nested scales, to investigate whether transport metrics provide better estimates of storm P losses from agricultural basins than combined transport and P source (CSA) metrics which combine source factors as well.

2. Materials and methods

2.1. Study catchments

Two agricultural catchments with contrasting dominant drainage pathways located in south-east Ireland (Fig. 1) were selected for this study. These catchments were previously termed Grassland B and Arable A by Wall et al. (2011) but for this study will be referred to as the Grassland and Arable catchments. The area has a temperate maritime climate and receives on average 1060 mm yr^{-1} (1981–2010 mean, Johnstown Castle, Met Èireann).

The Arable catchment is approximately 1102 ha (Fig. 1a). Ninety three percent of the land area is agricultural, with 54% in arable land use and the remainder under grassland. Typical management of spring barley crops in this catchment involves ploughing from January to February with sowing from late February to early April and harvesting from August to early September. Mineral P fertiliser is typically applied at sowing time and tilled into the soil. Fertiliser application is prohibited from 15 September to 12 January, termed the 'closed period'. Eighty percent of the catchment has well drained, Brown Earth soils (Cambisols) with the remainder consisting of poorly-drained Groundwater Gleys located near the stream network. Four percent of the catchment has slopes of <1% and 18% has slopes of >5%. The majority of storm flow reaches the stream via near-surface hydrological flow pathways but with a significant delayed flow component (Mellander et al., 2012). The Grassland catchment is approximately 1200 ha (Fig. 1b). Ninety seven percent of the land area was in agriculture, with 77% under grassland and the remainder in arable land use. For grassland fields, mineral P is typically applied in early spring and slurry is spread throughout the remainder of the growing season, particularly after the first cut of silage in May/June. Fertiliser application is also prohibited during the 'closed period' in this catchment. Seventy-four percent of the catchment has poorly drained Surface-water