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Quantifying faecal indicator organism hydrological transfer pathways and phases in agricultural catchments

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HIGHLIGHTS

- *E. coli* transfers are correlated with nutrient (P) transfers in two catchments.
- *E. coli* loads are aligned with specific nutrient pathways.
- Transport limitation dominates *E. coli* loads in specific pathways.
- Low flow *E. coli* loads in one catchment are indicative of chronic pollution.

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ABSTRACT

Faecal indicator organisms (FIOs) can impact on water quality and pose a health and environmental risk. The transfer of FIOs, such as *Escherichia coli* (*E. coli*), from land to water is driven by hydrological connectivity and may follow the same flowpaths as nutrients, from agricultural and human sources. This study investigated *E. coli* transfer in two catchment areas with high source and transport pressures. These pressures were: organic phosphorus (P) loading; human settlement; conduits and fissures in a grassland karst area; and clay rich and impermeable soils in a mixed arable area. The occurrence of *E. coli* and its transport pathways, along with the pathways of nutrients, were studied using a combination of targeted FIO sampling, during different hydrological phases and events, and high resolution nutrient analysis. The quick flow component in both catchments was found to be a more potent vector for *E. coli*, and was coincident with the total P flowpaths using a P Loadograph Recession Analysis (LRA). The karst grassland catchment was found to be a transport limited system and the mixed arable catchment a source limited system. Hence, despite the grassland catchment being a potentially higher FIO source, the *E. coli* loads leaving the catchment were low compared to the mixed arable catchment. *E. coli* load whole-event comparisons also indicated that the grassland karst transfers tended to be much lower on falling phases of runoff, while the arable catchment, over greywacke and mudstone geology, showed little change between the phases. Furthermore, the arable catchment showed asymptotic decline of sustained *E. coli* loads towards low flows, which may be indicative of chronic point sources. These results indicate the dominance of transport mechanisms over source mechanisms for mass *E. coli* loads and also chronic loads during low flow. These will be important considerations for risk assessment and mitigation.

1. Introduction

Faecal pollution of freshwaters and drinking water can arise from various waste water and agricultural sources, negatively affecting the quality of the water and potentially impacting on human health (Allevi et al., 2013; Frey et al., 2013; Marti et al., 2013; Walters et al., 2013). The World Health Organisation (WHO) states that approximately 780 million people in the world drink unsafe water (WHO and UNICEF, 2012), which in the context of inadequate sanitation and poor hygiene, causes diarrhoeal disease cases leading to 1.2 million deaths annually (Mattioli et al., 2012). *Escherichia coli* (*E. coli*), which is found in high numbers (10^9 g^{-1}) in the faeces of warm blooded animals, is a highly prevalent etiological agent of diarrhoea in the developing world (Edberg et al., 2000; Levine et al., 2012). Faecal indicator organisms (FIOs), such as *E. coli*, are used to confirm and monitor this contamination from exogenic sources (i.e. originating from catchments). While incidences of serious disease outbreaks due to faecal contamination of water are low in developed countries, there is enough concern for strict

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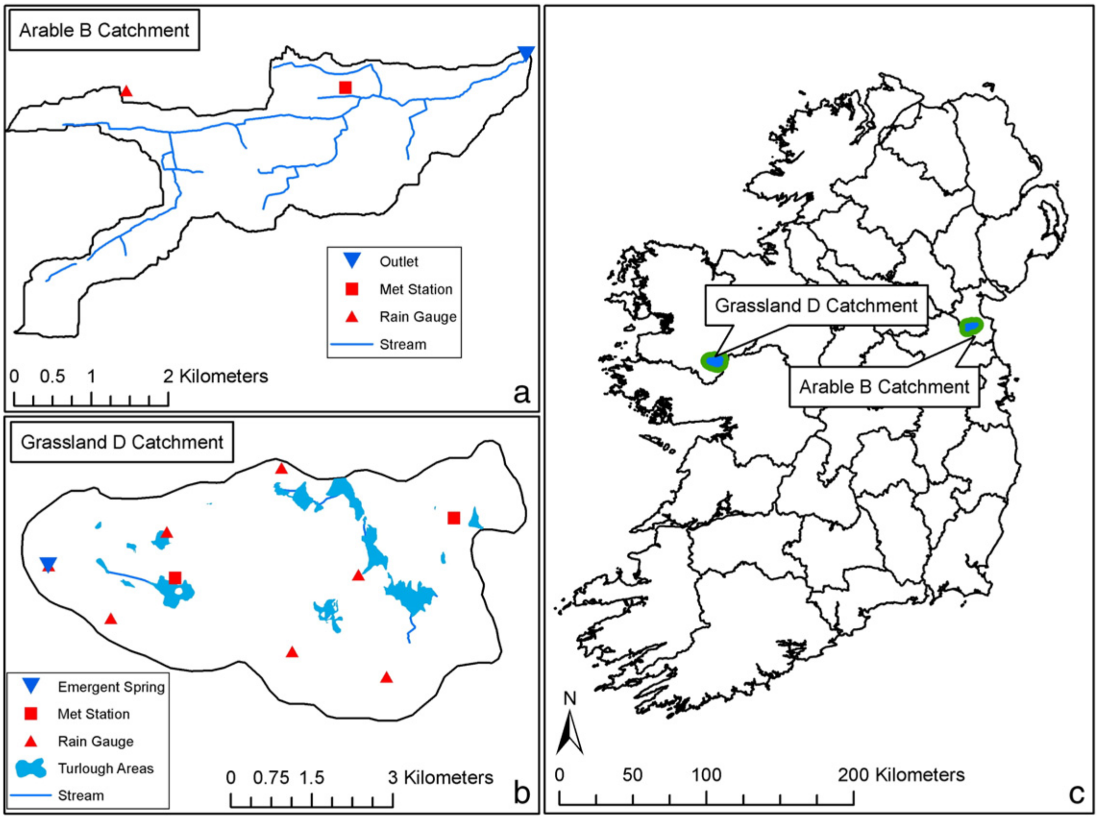

Fig. 1. Map of Arable B catchment (a) showing outlet (inverted triangle), Met station (square), rain gauge (triangle); map of Grassland D catchment (b) showing emergent spring (inverted triangle), Met station (square), rain gauge (triangle); map of Ireland showing where each of the two catchments is located (c). (Printed under license number 6155 from the Ordnance Survey Ireland).

management protocols for protection of drinking water and bathing water resources to be implemented (Kallis and Butler, 2001; Bartram and Cairncross, 2010).

Agricultural sources of FIOs include incidental point discharges from, for example, farmyards, milking parlours and slurry/manure storage facilities, where faecal matter is not retained within the managed facility (Collins and Rutherford, 2004; Edwards et al., 2008). Faecal runoff from fields, where manure has been applied, is considered a diffuse incidental source, where the loss to water is via convergent, hydrological flowpaths following heavy rainfall (Preedy et al., 2001). Furthermore, if farm animals graze close to water courses, water quality can be impacted due to direct defecation (Fisher et al., 2000; Eyles et al., 2003). As sheep and cattle produce more FIOs per head and can be present in larger numbers than humans in rural areas, the potential for point and diffuse incidental losses from land to water and direct defecation of faecal matter is higher than losses from the human population (Kay et al., 2007). Unsewered rural houses with rudimentary, or improperly sited, septic tank systems can also, however, make a contribution to FIO loading of streams and groundwater (Arnscheidt et al., 2007; Crowther et al., 2002; Rodgers et al., 2003).

Point and diffuse sources of faecal pollution can also transfer nutrients, such as phosphorus (P) and nitrogen (N), a surplus of which can cause euthrophication when transferred from land to water in surface and sub-surface runoff (Bowes et al., 2003; Gburek et al., 2005; Mellander et al., 2012a). Septic tank systems can cause low level, but continuous, P as well as FIO contributions in agricultural catchments (Brownlie et al., 2014; Withers et al., 2014). A high proportion of such P inputs can be in a dissolved and highly bioavailable form (Edwards et al., 2000; Withers and Jarvie, 2008; Withers et al., 2011).

Hydrological connectivity plays an important role in the movement of incidental FIOs from the land into water. Studies in the UK and New Zealand on high river flows, for example, showed an order of magnitude increase in both volume of flow and FIO concentration, which caused a two order of magnitude increase in FIO delivery to waterbodies, when compared to low flow periods (Muirhead et al., 2004; Kay et al., 2010). Other studies have, however, shown that in-channel sources can occasionally produce FIO concentration peaks that resemble FIO peaks seen during rainfall-runoff events, due to entrainment of organisms from the streambed sediments (McDonald and Kay, 1981; Jenkins et al., 1984; Wilkinson et al., 1995). Catchment FIO fluxes commonly peak in summer when livestock are in the fields and not being housed, and when slurry amendments coincide with summer rainfall, although the rate of bacterial die-off is generally higher in summer than in winter because of increased UV light and higher temperatures (Rodgers et al., 2003). There are fewer studies of winter FIO flux dynamics and how they impact contamination rates (Kay et al., 2008; Tetzlaff et al., 2012). Moreover, the specific flowpath dynamics of FIOs during different runoff phases and flow regimes in rivers has received little attention. This omission is important as flowpath vectors of catchment sourced pollution are relevant to FIO monitoring in general and to the specific type of mitigation measures that might be effective (e.g. Mellander et al., 2012a).

Hydrograph separation (Dingman, 2002) has been used to determine hydrological runoff pathways. These pathway sources have been measured further by End Member Mixing Analysis (EMMA), which links observed hillslope water chemistry to observed stream water chemistry (Hooper et al., 1990; Soulsby et al., 2003). Using EMMA, research conducted in a catchment in the UK, for example, showed that the hydrograph was usually dominated volumetrically by subsurface flow from agricultural drains; field surfaces were contributing to the overland flow that generally dominated the hydrograph peak and baseflows were dominated by groundwater which contributed more to the hydrograph