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An integrated connectivity risk ranking for phosphorus and nitrogen along agricultural open ditches to inform targeted and specific mitigation management.

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Abstract

On dairy farms with poorly drained soils and high rainfall, open ditches receive nutrients from different sources along different pathways which are delivered to surface water. Recently, open ditches were ranked in terms of their hydrologic connectivity phosphorus (P) along the open ditch network. However, the connectivity risk for nitrogen (N) was not considered in that analysis, and remains a knowledge gap. In addition, the P connectivity classification system assumes all source-pathway interactions within open ditches are active, but this may not be the case for N. The objective of the current study, conducted across seven dairy farms, was to create an integrated connectivity risk ranking for P and N simultaneously, to better inform where and which potential mitigation management strategies could be considered. First, a conceptual figure of known N open ditch source-pathway connections, developed using both the literature and observations in the field, was used to identify water grab sampling locations on the farms. During field work, all open ditch networks were digitally mapped, divided into ditch sections, and classified in terms of the existing P connectivity classification system. Sampling was conducted during the hydrologically-active period to ensure maximum connectivity of source-pathways and open ditches. The results from these water samples enabled a qualitative validation of N source-pathway presence or absence for each ditch category. The results showed that not all source-pathways were present across ditch categories for all species of N. This information was used to develop an improved open ditch connectivity classification system. Results showed that farmyard connection ditches were the riskiest for potential point source losses and outlet ditches had the highest connectivity risk among the other ditches associated with diffuse sources. Tailored mitigation options for P and N speciation were identified for these locations to intercept nutrients before reaching receiving waters. Furthermore, in ditches associated with diffuse sources, nitrate was introduced by subsurface sources (i.e., in-field drains and groundwater interactions from springs seepage and upwelling) and ammonium was introduced through surface connectivity pathways (i.e., runoff from internal roadways). In-field drains dominated connectivity pathways in open ditches. On dairy farms where open ditches are prevalent, the integrated classification system and mapping procedure presented herein will enable a targeted and nutrient-specific mitigation plan to be developed.

Keywords: Agricultural ditches; water quality; nutrient loss; grassland; drainage management; connectivity pathways; North Atlantic Europe.

1 Introduction

Open ditch networks, also referred to as “surface ditch networks”, are installed in poorly-drained soils to remove excess water, control the water table, and aid with grass production and utilisation (Tuohy et al., 2016; Hertzberger et al., 2019). These networks comprise a series of connected and unconnected sections that receive nutrients from a variety of surface and subsurface pathways, all of which can then be transported to other sections or associated water bodies (Kröger et al., 2007; Herzon & Helenius, 2008; Moloney et al., 2020). Connectivity is defined as the transfer of energy and matter across two landscape zones, whereas disconnectivity is the isolation of these zones (Chorley and Kennedy, 1971). Identifying the connectivity of these systems enables mitigation strategies to be implemented at optimal locations where nutrients can be reduced or restrained (e.g., breaking the connectivity, intercepting the pathway, removing some of the nutrients in the water) to minimise the impact on the receiving water body (Fenton et al., 2021). Research continues to help farmers to optimise farm management practices (baseline) and engineering solutions (above baseline) (Carstensen et al., 2020; Moore et al., 2010; Schoumans et al., 2014). Many open ditch studies have focused on nutrient dynamics (Sukias et al., 2003), sediment attenuation capacity (Ezzati et al., 2020; Mattila & Ezzati, 2022), nutrient loss attenuation potential by vegetation (Soana et al., 2017; Zhang et al., 2020), dissolved organic carbon dynamics (Tiemeyer & Kahle, 2014), organic matter composition (Hunting et al., 2016), ditch management (Dollinger et al., 2015; Hertzberger et al., 2019), and indirect greenhouse gas emissions (Hyvönen et al., 2013; Clagnan et al., 2019). However, few studies have investigated the role that open ditch connectivity plays in the transfer of nutrients from source to receptor. Such studies may provide vital information to ascertain the positioning of an engineered ditch mitigation option and the dominant nutrient species it is required to target. Moreover, there is a poor understanding of processes leading to the immobilisation and transformation of nutrients within soil and drainage systems along the hydrological pathways into ditches (Deelstra et al., 2014). For efficient mitigation of nutrient loss from open ditch networks, a conceptual understanding of how nutrient sources and their pathways connect to the open ditch system must be established.

The general trend and pathways of agricultural pollutants have been well documented and are summarised in Figure 1. In summary, nutrient entry into ditches is predominantly from diffuse sources, and often through complex surface and subsurface pathways determined by soil type, climate, landscape position, farm management, and nutrient input sources (manure, fertiliser type) (Granger et al., 2010; Monaghan et al., 2016; Gramlich et al., 2018). These factors regulate the hydrology, the primary driver of nutrient transfer, and the terrestrial and aquatic biogeochemistry that defines the type and form/species of nutrients entering open ditches and subsequently discharging to associated water bodies (Sukias et al., 2003). Conceptually, phosphorus (P), either as particulate P (PP) or dissolved reactive phosphorus (DRP), and nitrogen (N), as ammonium (NH_4^+) or nitrate (NO_3^-), are transported from fields or hard surfaces like roadways through surface flow pathways into open ditches (Figure 1).

In Figure 1, any groundwater-to-open ditch water connection represents a subsurface interaction distinct from in-field drain connections. In this scenario, typically P is in the form of DRP and NO_3^- represents mineralised N that has become mobilised due to infiltrating water. This N is primarily lost from diffuse sources in fields due to fertilisation and grazing of animals. Clagnan et al. (2018) have shown N conversion to NH_4^+ in poorly drained soils, which can be discharged in waters from in-field drains within the groundwater-to-open ditch water connections (Needleman et al., 2007; Valbuena-Parralejo et al., 2019). The presence of NO_3^- in open ditch networks suggests more permeable connectivity pathways that eventually seep into open ditches along seepage faces or upwell as the water table rises, whereas NH_4^+ suggests less permeable routes before discharge occurs. Groundwater springs represent a distinct groundwater storage component that protrudes onto fields, which are often drained by the installation of an intersecting pipe into an open ditch below the spring. This creates a direct discharge point within the open ditch (Figure 1). The presence of this discharge may change during dry periods, as the water level falls below the base of the open ditch.

Moloney et al. (2020) used this concept to rank connectivity risk (from highest to lowest) for P along agricultural open ditches. The riskiest open ditches were those directly connected to farmyards (farmyard connection ditches) and watercourses (outlet ditches), while the least risky open ditches included secondary and outflow ditches (disconnected ditches did not pose any risk of connectivity). The system devised by Moloney et al. (2020) conceptualised P sources and pathways with the aim of disconnecting P losses before discharge to associated water bodies. The current study takes the same approach but creates an integrated connectivity risk ranking that considers both N, which discharges into the open ditch network via surface and subsurface pathways (Figure 1), and P. Such integration necessitates a thorough understanding of N and P biogeochemical cycles and an understanding of how sources are connected along different surface and subsurface pathways to the open ditch network, and how this network is connected and delivered to the adjoining aquatic system e.g. river. Accounting for attenuation along the pathway and within the open ditch network is a constraint within the current conceptual framework. Therefore, there is a need to integrate N into the connectivity risk ranking, so that a more holistic mitigation management strategy may be designed (i.e., source protection on the farm and “right measure, right place” in the open ditch).

The objective of this study was to derive a farm-scale integrated open ditch risk ranking for both P and N loss risk based on connectivity, to inform future mitigation management on heavy textured, grassland dairy farms. To fulfil this objective, seven farms were selected with open ditch networks on heavy textured soils. A conceptual figure illustrating trends and pathways of agricultural pollutants for an open ditch is presented. The open ditch networks were mapped during a ground survey, and a qualitative water sampling campaign was conducted (based on the conceptual figure) to validate the presence or absence of pathways for N and P. This enabled an integrated classification of an open ditch network ranking to be developed. Mitigation options for each ditch class are presented.

2. Materials and methods

2.1 Site selection and characteristics

Seven grassland dairy farms on poorly drained soils geographically located across the SW and NE of Ireland were selected to represent a variety of agronomic dairy production systems and bio-physical settings (Table 1). As per the EPA soils and subsoils maps (Fealy and Green, 2009), the soil types on these farms varied from organic to mineral soils. The majority of these farm fields were imperfectly or poorly drained, necessitating an ad-hoc network of artificial drainage installations on the farms. The grazing area of each farm ranged from 28 to 45 ha. Intensive dairy farm management practices were observed on all farms. Morgan’s extractable soil P test (Morgan, 1941) was used to determine the agronomic excesses and deficiencies in plant available P for fields of each farm. Farms in this study were located in high rainfall areas with an average of 1092.5 mm. The average farm slope was measured on all seven farms, as it could influence open ditch connectivity.

2.2 Ground survey and mapping connectivity pathways for N into P connectivity risk ditch categories

A ground survey was carried out on all the farms during winter (November 2021 to March, 2022) to characterise the field boundaries, surface and subsurface networks on each farm. This period was selected following multiple field visits carried out across all seasons in the previous year. This period was identified as the best hydrological period when connectivity pathways were active for grab sampling. Drainage network features such as open ditches connected to the farmyard, and the proximity of the open ditch to water bodies were noted on each farm during the ground survey. Also, the connectivity pathways for N into open ditches from in-field drains, farm roadways, groundwater springs, seepage and upwelling as per the conceptual figure (Figure 1) throughout the drainage network were noted during this time. During the ground survey, all drainage network data such as drain locations, flows and connections, and sampling locations, were recorded using an electronic device with ESRI ArcGIS Field Maps mobile software (ESRI, 2024)

Open ditches were identified as man-made open drains usually sited along the field edges to carry excess water from the field and farm. Surface water bodies (1st and 2nd order streams) in and around each farm, defined as those appearing on the national ordnance survey maps (6-inch maps) (osi.ie), were mapped onto each farm map before each ground survey.

Information from the ground survey observations and qualitative interviews with farmers on drainage networks were used to digitise and map farm and field boundaries, and the open ditch network (open ditches, sub-surface in-field drains and drainage outlets) and associated connectivity pathways for N (Figure 2). For the open ditch network within each farm, each ditch was assigned a ditch category using their connection to a farmyard, watercourse, neighbouring farm, other ditches on the same farm and also their non-connection to any other part of the open ditch network after Moloney et al. (2020) (Table 2). These categories are: (1)

farmyard connection ditch (2) outlet ditch (3) outflow ditch (4) secondary ditch, and (5) disconnected ditch (Figure 2) using ArcMap GIS software (version 10.5).

On each assigned ditch category, the connectivity pathways for N (Table 3), where present, were mapped within this open ditch network using the conceptual figure (Figure 1) as a guide during fieldwork to integrate N connectivity pathway risk into the P connectivity risk open ditch categories. To identify the connectivity pathways, landscape position was taken into account, especially for assessing groundwater interaction with an open ditch section. Groundwater seeping through open ditch bank sides and groundwater uprising through the base of the open ditch were identified as groundwater seepage and upwelling, respectively (Table 3), and were classified together as one connectivity pathway. Roadways were identified as a connectivity pathway when there were site observations of water flow and eroded/gully surface (due to continuous past water flows) from the farm roads into a nearby open ditch. Groundwater springs were identified as high-flow groundwater purging out into open ditches either over the surface or through pipes. Subsurface in-field drains were all piped drains directed into ditches but were differentiated from piped springs with their low and intermittent flows into the open ditches.

The length of the open ditches, and farm and field boundaries were measured in ArcGIS and compared for each farm in Table 4. In addition, the occurrence of a particular N connectivity pathway was calculated as a percentage of the total number of N connectivity pathways observed for each farm, and for each open ditch category.

2.3 Grab water sampling campaign to assess integrated nutrient connectivity pathways

Water quality parameters change over time, depending on the local climatic conditions and farming practices (Huebsch et al., 2013). In the present study, the objective was to establish a link or connection (see Figure 1) between the source and pathway to the open ditch network. Therefore, “snapshot” sampling in spring (March) presented a good opportunity to collect qualitative data.

In spring (March) 2022, a total of 210 water samples were collected directly from 105 sampling sites in open ditches throughout the drainage network across all farms during a one-time sampling event following the procedure of Moloney et al. (2020). These sampling sites reflected connectivity pathways presented in Figure 1. March was selected for sampling because the period is hydrologically-active in Ireland and all pathways interact with the open ditch network (e.g. groundwater upwelling, seepage and springs) as observed from the previous year's field visits. As this study aimed to validate established connectivity risk (water and the presence or absence of N and P) between open ditch types and adjoining surface waterbodies, and did not aim to elucidate the load or impact of this connection, a temporal water sampling survey was not required. It is acknowledged that the connectivity level at the time of sampling water is influenced by the precipitation level (both antecedent and current). Therefore, sampling was undertaken when both surface and subsurface pathways were most active, and such data were used to validate source and hydrologic connectivity with the open ditch network.

The number of samples collected was dictated mainly by the observations of connectivity pathways on open ditches during the initial fieldwork campaign. As such, open ditches that had surface or subsurface connectivity pathways (Table 3) noted in the earlier survey were prioritised for sampling. These observations were used to validate surface, subsurface and groundwater flows that entered open ditches on the case study farms. However, some sampling points had no N connectivity pathways. Therefore, only four ditch categories from Table 2 (farmyard connection, outlet, outflow, and secondary ditches) were sampled for water across the seven case study farms. Shallow disconnected ditches (category 5 in Table 2) were dry, which indicated no N connectivity with perched or true water tables at the time of sampling. These acted as storage and recharge areas for groundwater during rainfall periods. At each water sample location, two 50 ml samples (filtered on-site using 0.45 µm filter paper and unfiltered) were collected for dissolved and total P analyses, respectively. Grab sampling was carried out in the mapped ditch categories on each farm, provided water was present in the open ditch. The grab water sampling taken directly from an open ditch was conducted within 1 m downstream of in-field drain outlets, farm roadways, groundwater springs, and groundwater seepage/upwelling, where present, in the open ditch categories. All water samples were kept in an ice-box during sampling and transportation and then tested within one day of sample collection.

Filtered water samples were analysed for DRP and total dissolved phosphorus (TDP) using a Gallery discrete analyser (Gallery reference manual, 2016) and a Hach Ganimede P analyser, respectively. Total dissolved phosphorus (TDP) was measured by acid persulphate oxidation, under high temperature and pressure. The unfiltered water samples were analysed for nitrite (NO_2-N), NH_4-N, total oxidised nitrogen (TON), and total reactive phosphorus (TRP) using the Gallery analyser. Total phosphorus (TP) was analysed using the Ganimede P analyser. Phosphorus was measured colourimetrically by the ascorbic acid reduction method (Askew and Smith, 2005), where the 12-molybdophosphoric acid complex is formed by the reaction of orthophosphate ion with ammonium molybdate and antimony potassium tartrate (catalyst) and reduced ascorbic acid. All samples, reagent blanks, and check standards were analysed at

Teagasc Johnstown laboratory following the Standard Methods (APHA, 2005). All quality control (QC) samples/check standards are made from certified stock standards from a different source than calibration standards. Quality control samples were analysed at the beginning and end of every batch, and every 10 samples within a batch, and if the QC fell outside limits, samples were repeated back to the last correct QC. Blanks were included in every batch and approximately 10 % of samples were repeated. Tolerances range up to a maximum of ±7.5% of nominal value. All instruments used were calibrated in line with manufacturers' recommendations. Nitrate-N was calculated by subtracting NO_2-N from TON, particulate phosphorus (PP) was the difference between TP and TDP, and dissolved unreactive phosphorus (DUP) was the difference between TDP and DRP.

2.4 Data Analysis

To validate the link between the conceptualised connectivity sources-pathways and their introduction of N and P into the open ditch system, data from the spring season synoptic survey were analysed statistically to differentiate the nutrient concentrations for the various open ditch categories and also for the various connectivity to ascertain if they varied from each other. As the data for each water quality parameter were not normally distributed, Kruskal Wallis analysis was undertaken to find out the significant differences between farmyard connection, outlet, outflow and secondary ditch categories as treatment levels, and also between the conceptualised N connectivity pathways (in-field drains, internal roadways, springs, and seepage/upwelling) within and across the outlet, outflow and secondary ditch categories treatment levels for all the water quality parameters (NH_4-N, NO_3-N, TN, DRP, DUP, TP and PP). Data were analysed using R studio software version 4.0.2 (2020). Where significant differences were observed using alpha level of 0.05 (95 % confidence level), the pairwise Wilcoxon Rank Sum test was further used to find the differences between the means of the pairs. Microsoft Excel software version 16.0 (2016) was used to find a correlation between the number of occurrences of in-field drains and the percentage of drained fields on poorly draining soil farms.

3. Results

3.1 Analysis of the open ditch networks

All five ditch categories, classified by Moloney et al. (2020), were identified using the criteria outlined in that work. Expressed as an average percentage of the total ditch network in all farms, 17.1 %, 25.6 %, 12.7 %, 39.5 %, and 5.1% were farmyard connection, outlet, outflow, secondary, and disconnected ditches, respectively (Table 4). Farm 2 contained the fewest drainage categories (3 out of 5).

3.2 Observations relating to conceptualised N connections within the open ditch networks

Based on the criteria for identifying N connectivity pathways (Table 3), 52 % of all the open ditch network sampling points were observed to have N connectivity pathways interacting with them. The N connectivity pathways to open ditches considered in this study were mainly connected to secondary ditches, followed by farmyard connection, outflow, and outlet ditches, with no N connectivity pathway to disconnected ditches (Table S1). For each ditch category (Table 2) sampled in this study, the percentages of the different N connectivity pathways occurrence are shown in Figure 3. Among these N connectivity pathways across all ditch categories, in-field drains were the most common (representing 64 %), followed by groundwater springs, internal roadways, and groundwater upwelling/seepage, respectively, representing 20%, 11%, and 5% of the sampling points (Table S1). The occurrence of observed in-field drains was positively correlated to the percentage of drained fields on case study farms (R^2=0.35).

Farms 2 and 4, which had the lowest percentage of in-field drained fields (Table 1), had relatively high connectivity of groundwater springs to open ditches (Table S1). Aside from farm roadway connectivity pathways to open ditches on Farm 2, roadway connectivity pathway to open ditches was highest on farms with a flat topography, particularly Farms 3 and 5. Groundwater upwelling/seepage connectivity to ditches was uncommon. There was an absence of groundwater upwelling and seepage connectivity pathways on outflow and farmyard connection ditches, and roadway connectivity pathways on outlet ditches across all farms. In addition, there was evidence of multiple N connectivity pathways to individual ditches on some farms.

3.3 Validation of N connectivity pathway using synoptic survey

The average TN and TP concentrations were significantly higher in farmyard connection ditches (Figure 4) than in outlet, outflow and secondary ditches ($P < 0.01$). Across the outlet, outflow and secondary ditch categories, NO_3-N was the dominant N species, contributing on average to 44.7 % of TN at sampling points near N connectivity. Only 10.6 % of TN comprised NH_4-N within these ditch categories. The highest average NO_3-N across these ditch categories was observed in groundwater springs (1.90 mg L^{-1}), followed by in-field drains (0.75 mg L^{-1}), groundwater upwelling (0.65 mg L^{-1}), and roadways (0.17 mg L^{-1}) (Table S1). In addition, NO_3-N at groundwater springs were dissimilar ($P < 0.05$) to NO_3-N at roadways and in-field drains (Figure 5a). High concentrations of NO_3-N were also measured on roadways, where NH_4-N is conceptualised as being dominant (Figure 1) on secondary ditches. However, NH_4-N dominated TN across these ditches at sample points near roadways, with 25.3 % composition as opposed to 6.9 % of NO_3-N. Ammonium-N concentrations across these ditch categories were not statistically significant ($P > 0.05$).

No consistent trends in species of TP were observed across the outlet, outflow and secondary ditch categories. Among these ditch categories, TP concentrations were relatively high in secondary ditches, in which PP was predominant (Figure 5b). Across the outlet, outflow and secondary ditch categories, PP was statistically significant ($P > 0.05$), particularly between in-field drain and roadway connectivity pathways, and DRP was statistically significant ($P > 0.01$), particularly between roadways and groundwater springs. Comparing P species for each N connectivity pathway, average PP concentrations were highest in groundwater upwelling/seepage (0.24 mg L^{-1}), followed by roadways (0.12 mg L^{-1}), groundwater springs (0.04 mg L^{-1}), and in-field drains (0.02 mg L^{-1}) connectivity pathways, whereas average DRP concentrations were highest in roadways (0.19 mg L^{-1}), followed by groundwater upwelling/seepage (0.04 mg L^{-1}), in-field drains (0.03 mg L^{-1}), and groundwater springs (0.01 mg L^{-1}).

4. Discussion

4.1 Observations on ditch categories and associated N connectivity pathways

Of the seven farms surveyed, disconnected and secondary ditches comprised the lowest and highest average percentage of the total ditch length, respectively. This result is consistent with Moloney et al. (2020), who recorded similarly low and high average percentages for total ditch length on varying soil grasslands in Ireland. Disconnected ditches are ineffective for excess field water removal within the drainage system, and exist either as blocked normal ditches or as created disconnecting ditches that remove field runoff or precipitation water by infiltration or evaporation. Disconnected ditches, when wet, may hold water with vegetation and potentially provide denitrification or create pollution swapping by the release of nitrous oxide (N_2O) or nitric oxide (NO) greenhouse gases.

Secondary ditches, as the most prevalent connectivity pathway, had multiple N connectivity pathways of which in-field drains were the most prevalent (Figure 3). Secondary ditches connect to other ditch categories from the central farm fields, and due to farm slopes, frequently have a shallow water table (Clagnan et al., 2018). As the majority of the farms in this study contained poorly drained soils (Table 1), a positive, albeit weak, correlation (R^2=0.35) between the number of occurrences of in-field drains (Table S1) and the percentage of drained fields (Table 1) on poorly draining soil farms was observed. Both the number of occurrences of in-field drains and the percentage of drained fields help in regulating water table levels and supporting grass growth functionality, so they were positively correlated.

4.2 Hydrochemistry across P ditch categories and consideration of N connectivity pathways

Higher TN and TP average concentrations were measured in farmyard connection ditches relative to the other ditch categories, which was similar to the findings of Moloney et al. (2020), Harrison et al. (2019) and Ezzati et al. (2020). In the farmyard connection ditches, the TN and TP concentrations were nearly three times higher than the TN standard limits of 2.5 mg L^{-1} in the European Union for estuarine waters (Wuijts et al., 2022) and fifteen times higher for TP standards such as 0.1 mg L^{-1} as proposed by Wetzel (2001). While both Edwards et al. (2008) and Mockler et al. (2017) identified farmyards as point sources for high nutrient loss, the former argued runoff from farmyards has been overlooked and not duly considered as a major nutrient loss hotspot. Such runoff may lead to high nutrient-concentrated fields near the farmyard relative to fields further away (Fu et al., 2010), and these potentially may enter open ditches near the farmyard to create major downstream water quality problems. Unlike ditches (associated with point sources), the lower TP and TN concentrations in outlet, outflow and secondary ditch categories may be associated with diffuse nutrient sources. Studies have shown diffuse sources, relative to point sources, have lower TN and TP concentrations (Edwards & Withers, 2008; Pieterse et al., 2003). Management of some of these diffuse sources is problematic as they are difficult to locate in a landscape (Harrison et al., 2019). However, their impact on the deterioration of receiving water bodies is substantial and therefore needs to be managed (Andersen et al., 2014; Bradley et al., 2015). Diffuse sources depend on landscape and other management factors, which influence diffuse N and P mobilisation, transformation and delivery into the ditches (Granger et al., 2010; Schoumans et al., 2014). However, notable among these factors are the hydrological conditions, on which diffuse nutrient release strongly depends (Edwards & Withers, 2008; Chen et al., 2013). This, coupled with biogeochemical factors, which may vary within a landscape, influences the spatial and temporal distribution patterns of diffuse N and P, including the pathways by which they enter and leave farms (Clagnan et al., 2019; Grenon et al., 2021). Nutrient losses from the diffuse sources are delivered into open ditches along surface and subsurface pathways, creating hotspots of nutrient loss in certain open ditch categories, which need to be characterised and potentially mitigated. Climatic, landscape and management factors all have a role to play in when and where impacts occur. These could have contributed to the higher TN concentrations in water samples that were measured near N connectivity pathways than at locations with no N connectivity pathways within the outlet, outflow and secondary ditch categories, and also for TP in the outflow ditch category. This observation aligns with the reported works of Ibrahim et al. (2013) and Valbuena-Parralejo et al. (2019) on in-field drains, Fenton et al. (2021) and Rice et al. (2022) on roadways, Soana et al. (2017) on groundwater springs, and O'Callaghan et al. (2018) on groundwater upwelling/seepage.

Nitrate was the dominating N species in in-field drains, groundwater springs, and upwelling connectivity pathways in outlet, outflow and secondary ditch categories (Figure 5a). This may be attributed to their connection to a subsurface N source, which comprises leached N from animal excreta and fertiliser that may have been nitrified to NO_3-N (Necpalova et al., 2012). In poorly drained grasslands, nitrification may have been elevated by the high in-field drainage density (Table 1), which enhanced N preferential flow (Van Der Grift et al., 2016) and limited potential N attenuation (Clagnan et al., 2019; Valbuena-Parralejo et al., 2019). The average NO_3-N concentration was highest in groundwater springs and in-field drains. Factors such as the presence of these N connectivity pathways within the shallow subsurface region, nearness to the soil surface (where farm management mostly occurs), and exposure to N sources at the groundwater-ground surface intersection spots (particularly for groundwater springs; Infusino et al., 2022), could have contributed to the high NO_3-N concentrations in these locations. In contrast, NH_4-N was the most dominating N species measured for roadway connectivity pathways across the outlet, outflow and secondary ditch categories, especially where physical animal excreta were observed. This observation aligns with Fenton et al. (2021), who observed that roadways draw surface nutrient sources, high in NH_4-N, as runoff from soil-bound and animal excreta into nearby ditches and streams. Although important, redox reactions were not considered in the present study.

For TP concentrations across outlet, outflow and secondary ditch categories, P concentrations were relatively low compared to the farmyard connection ditch category. However, such TP concentrations in the outlet, outflow and secondary ditch categories were still high enough to cause eutrophication downstream if undiluted. High TP concentrations measured in secondary ditches may be related to the impacts of farm management activities including grazing and farm machinery movement, which is intense within the central fields of most farms where secondary ditches lie as connecting ditch links. These contribute to the erosion of ditch sides and associated deposition of soils in the secondary ditches, as reflected in the higher PP concentrations observed. High TP concentrations measured near roadways on outflow ditches may be due to animal excreta, run-on deposits from farmyards, fields, and poached surfaces as a result of animal and machinery movement (Fenton et al., 2021). Both PP and DRP can trigger eutrophication in waterbodies and may pose risk to downstream water bodies. However, this depends on their closeness, connection, and mitigation along the pathway to water sources within agricultural landscapes.

Such information from the study provides additional insight into the source, connection and presence (and transformation process) of N in ditch categories from a previous study by Moloney et al. (2020), who observed high NH_4^+ and NO_3^- concentrations in all ditch categories except for the outlet ditch, where high NO_3^- and low NH_4^+ were measured, and disconnected ditches where NO_3^- dominated. The risk ranking of connectivity along the open ditch for N and P does not determine the impact of the nutrients being lost to the associated water body; it simply establishes the N connectivity pathway if it is present.

4.3 Deriving a connectivity risk for N into P agricultural open ditch categories

The evidence of N concentrations in the ditch water chemistry from Moloney et al. (2020) and the current study informs an improved ditch connectivity risk category system (Table 5). This is a valuable information tool for environmental sustainability officers to enhance water quality management and mitigation options for N and P losses on dairy grassland farms with heavy textured soils in high rainfall areas. It considers both the connectivity pathways, through which N can be introduced to a ditch network, and their associated N species.

In the current study, all of the conceptualised N connectivity pathways (Figure 1) established from the literature were present, but not in all of the sampled P risk ditch categories developed by Moloney et al. (2020) (Table S1). For instance, the established general trends and connectivity pathways of groundwater seepage and upwelling were not present on farmyard connection and outflow ditches. Moreover, the grab water data results validated all the conceptualised N connectivity pathways present in ditches (Figure 5a), except groundwater seepage and upwelling. The dominance of high NO_3-N concentrations at in-field drains and springs, and high NH_4-N concentrations at roadways within farmyard connection ditches, indicated a point pollution source arising from their connection to the farmyard aside from the hydrology-induced N concentrations. Farmyards pose the greatest nutrient loss risk on farms due to high nutrient concentration within discharges (Vedder, 2020) and like other point sources, they are independent of hydrology (Edwards & Withers, 2008). As such, primarily managing the farmyard wastewater before discharge into connecting ditches for mitigating nutrient connectivity to water sources is essential (NFGWS, 2020) before deployment along/within ditches interventions.

For the other sampled outlet, outflow and secondary ditch categories, all N conceptualised pathways were observed, except for internal farm roadway on outlet ditches, and groundwater seepage and upwelling on outflow ditches (Table S1). In outlet, outflow and secondary ditch categories, the ditch water synoptic data validated the conceptualised NO_3-N and NH_4-N for all the observed N connectivity pathways, except farm roadway connection on secondary ditches (which was invalid with NO_3-N dominance over conceptualised NH_4-N from hard field surface flow pathways). Nitrate dominated in-field drains, groundwater springs, upwelling and seepage connectivity pathways, and NH_4-N-dominated farm roadways across the outlet, outflow and secondary ditch categories, as conceptualised in Figure 1.

Assessment of N connectivity pathway within ditch category 5 could not be included in the study due to the unavailability of water samples in this ditch for validating conceptualised N connectivity pathways. Moloney et al. (2020) showed that disconnected ditches were the least risky ditch class for nutrient loss and therefore merit less focus during nutrient loss mitigation for surface water. However, such low nutrient concentrations could be leached into groundwater and therefore may require mitigation interventions to prevent leaching.

To apply this research in practice, once open ditches are investigated and mapped, a category should be assigned for an individual open ditch, after which the available N connections for that ditch are noted. All of these connections in combination will aid in the future mitigation management strategy. It is unlikely, for example, that more than one mitigation option will be installed in a single open ditch. Therefore, the information gathered from Table 5 can be used to ensure that the correct nutrients and their speciation are targeted for mitigation in the open ditch. Mitigation options may be a combination of those that limit diffuse and point sources. For example, with respect to diffuse sources, strict adherence to action programmes to reduce losses is important (e.g., Good Agricultural Practice Regulations, in line with the Nitrates Directive (91/676/EEC)). With respect to roadway runoff, NH_4^+ mitigation options are available and have been outlined in Fenton et al. (2021) and Rice et al. (2022) (e.g., diversion bars to move runoff to a buffer area of at least 1.5 m, cambering farm roadways, and directing flow onto adjacent fields). Adopting a two-stage ditch design may reduce high PP concentrations (Faust et al., 2018; Hodaj et al., 2017; King et al., 2015). With respect to the subsurface N connectivity pathways (in-field drains, groundwater springs, upwelling and seepage), in-ditch management practices may control the flow and the nutrient content leaving the open ditch. These may include sediment traps (Wilkinson et al., 2014), vegetated ditches (Faust et al., 2018; Kröger et al., 2008; Soana et al., 2017) or in-ditch filters or bioreactors (Goeller et al., 2020; King et al., 2015; Liu et al., 2020). Nutrient filtering through vegetation (Moeder et al., 2017) or use of media (Ezzati et al., 2020) can only aim to mitigate a small amount of overall nutrients leaving the ditch due to hydraulic retention times needed and by-pass flow during high storm events. Furthermore, mitigation practices including the construction of wetlands (Tanner et al., 2005), vegetated buffer zones (Faust et al., 2018) and low-grade weirs (Baker et al., 2016; Kröger et al., 2012; Littlejohn et al., 2014) that may be placed at the end of ditches after the connectivity pathways, especially for farmyard connection and outlet ditch categories, would help to limit nutrient loss from these farms. Therefore, all measures need to be considered as a package and not in isolation when trying to minimise nutrient and sediment loads leaving an open ditch system. It is worth noting that co-operation at the local level is needed to prevent other mitigation-related problems (such as the polluter pays principle regarding outflow ditches between neighbouring farmers) to ensure mitigation occurs before waters are impacted.

5. Conclusion

Distinctly different from a P-only classification system, the integrated connectivity risk classification system for N and P showed that not all source-pathway interactions within open ditches are active. This is a valuable information tool that enables a much more specific and targeted nutrient-specific mitigation approach to be implemented on open ditches in heavy textured grassland dairy farm in high rainfall areas. The new system avoids the pitfalls of a P-only classification system (i.e. mitigating for P but allowing N to affect water quality unabated). The findings of this study are limited to these field sites, and may (or may not) differ in other geographic areas with different soils, climates, agricultural practices, etc. However, the same methodology may be applied to other areas to develop a bespoke integrated connectivity risk ranking for P and N along agricultural open ditches to inform targeted and specific mitigation management on those farms. Further assessment of the temporal and spatial variability of soil, weather, drainage system, and general hydrogeochemistry, which influences nutrient connectivity, may be needed to rank the N and P risk in each ditch category.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contribution

D.G. Opoku: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Roles/Writing – original draft, Writing – review & editing; M.G. Healy: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Software, Validation, Visualization, Writing – review & editing; O. Fenton: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Validation, Software, Visualization, Writing – review & editing; K. Daly: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – review & editing; T. Condon: Funding acquisition, Methodology; P. Tuohy: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Software, Validation, Visualization, Writing – review & editing.

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Table 1 Summary of agronomic and soil data and associated in-field drainage percentages across case study farms.

Farm #	Farm size	NUE[1]	% of number of fields with high P index[2]	Soil OM[3] (%)	Annual rainfall (mm)	Farm topography slope angle range (º)	Dominant Soil type	Drainage classes[4] (%)				Major soil type[4] (%)			% Fields with in-field drains[5]
	(ha)	(kg N /ha)						Poor	Imperfect	Moderate	Well	Mineral	Humic	Organic	
1	43	27	16.3	16.2	1086.3	2-3	Humic Surface Water Gley	30.9	52.9	16.2	0	69.1	30.9	0	48.4
2	40	23	40.0	16.7	1283.7	3-11	Humic Surface Water Gley	8.8	39.7	35.1	16.4	68.4	31.6	0	34.1
3	45	24	19.6	30.6	1002.4	0	Groundwater Gley	50.1	38.5	11.4	0	46.2	31.0	22.8	72.5
4	37	32	10.3	18.0	1320.2	4-8	Humic Brown Podzolic	45.1	0.9	54	0	58.4	41.6	0	13.6
5	41	35	59.4	8.4	900.0	0.6-0.9	Surface Water Gley	57.5	17.2	2.1	23.1	88.2	11.8	0	78.4
6	39	45	21.5	14.8	1035.6	1-8	Typical Surface Water Gley	42.1	3.5	25.1	29.3	84.3	10.9	4.9	25.2
7	28	42	41.7	12.1	1019.6	5-7	Typical Surface Water Gley	50.2	5.1	42.5	2.2	97.1	1.7	1.2	69.6

[1] Nitrogen use efficiency [2] High P index (Index 4) fields have soils with excess P concentration (above 8 mg L^{-1}, measured as Morgan's P, on grassland) [3] OM, organic matter (Corbett et al. 2022[a]; Corbett et al. 2022[b]) [4] Data from Tuohy et al. (2018, 2021) [5] % Field with in-field drain = (size of drained field / total farm size) × 100 %

Table 2. Definition and description of open ditch categories for the P classification system of Moloney et al. (2020).

Ditch category	Description
1. Farmyard	A ditch/pipe that connects a farmyard to the drainage connection network or directly to a surface water body.
2. Outlet	A ditch that connects the drainage network to a surface water body.
3. Outflow/transfer	A ditch that carries drainage water across the farm boundary onto neighbouring land.
4. Secondary	A ditch that typically flows perpendicular to the slope of the land connecting two larger open ditches, or running through a field for excess water removal.
5. Disconnected	A ditch that is not connected to the overall drainage network but may have groundwater connectivity potential.

Table 3. Criteria for identifying N connectivity pathways on open ditch categories and associated source of connection.

N connectivity pathway	Source of connection	Criteria description[1]
In-field drains	Subsurface	Evidence of in-field pipe drains connecting into ditch, usually with less water flow.
Farm roadway	Surface	Evidence of farm roadway and hard surface runoff connectivity with the open ditch network (directly during rainfall or indirect signs such as established rills and breakthrough points).
Groundwater springs	Subsurface	Evidence of natural springs or pipe springs (with high water flow) connecting into ditch.
Groundwater upwelling or seepage	Subsurface	Evidence of groundwater seeping from either base or side of ditch into the ditch.

[1] Criteria description (Teagasc, 2022)

Table 4. Summary of open ditch data including the proportion of the open ditch network accounted for by different P open ditch categories for each case-study farm.

Farm Number	Field perimeter (m)	% perimeter as ditch	Total ditch length (m)	Proportion of total ditch length (%)				
				1.Farmyard connection	2. Outlet	3. Outflow	4. Secondary	5. Disconnected
1	16471.5	44.3	7290.4	10.7	0	18.4	70.2	0.7
2	21524.1	9.0	1935.1	6.8	59.4	33.8	0	0
3	19737.9	35.4	6990.7	5.7	22.6	9.4	62.4	0
4	16572.3	17.2	2847.4	28.4	23.3	4.6	10.5	33.2
5	13085.9	43.5	5692.4	25.5	39.5	0	34.3	0.7
6	16966.5	52.6	8916.3	8.5	22.4	7.2	60.9	0.9
7	9607.5	28.9	2773.3	34.2	11.7	15.8	38.3	0
Average				17.1	25.6	12.7	39.5	5.1

Table 5. An updated integrated ditch connectivity ranking that considers both phosphorus and nitrogen coupled with suggested strategies to reduce nutrients from ditches on dairy farms.

P Ditch Category	Description	Validated N Connection with Category	Associated Source	Future Mitigation Management
1.Farmyard Connection	A ditch/pipe that connects a farmyard to the drainage network or directly to a surface water body. These connections pose the highest risk and should be prioritised in terms of future management.	Subsurface interaction	In-field drains (pipes; moles; gravel moles; older variation) bring P and N from fields to the open ditch. All forms of P and N are potentially lost through this pathway to the ditch, with NO$_3^-$ and DRP dominating.	Management practices that disconnect sub-surface drainage system discharges into the open ditch: • These may include adherence to correct land drainage design, installation guidelines and maintenance. • Use of end-of-pipe land drainage mitigation options including low grade weirs (Baker et al., 2016), filter cells, cartridges, and structures (Goeller et al., 2020; King et al., 2015; Liu et al., 2020) (see discussion for details). Strict adherence to good farming practices to minimise diffuse losses and leaching of nutrients to sub-surface drainage system that are connected to the open ditch: • These may include in-ditch measures such as sediment traps, bioreactors, and filters to slow the flow and control nutrient loads (Fenton et al., 2020).
		Surface runoff	Farmyards and hard surfaces including farm internal roadways bring P and N forms, dominated by NH$_4^+$ and PP from raw organic waste, loss to the ditch	Management practices that disconnect the farmyard from the open drainage ditch and internal farm roadway network are needed specifically within 100 m of the farmyard in this category: • These may include measures that prevent roadway runoff from entering the open ditch using low-cost diversion bars or surface modifications (Fenton et al., 2020). There must be a buffer of at least 3 m (EPA Ireland, 2020) to reduce runoff impacts surface waters.
		Groundwater interaction	Natural springs bring shallow groundwater P and N, dominated by NO$_3^-$, into open ditches through piped drains.	Strict adherence to good farming practices to minimise diffuse losses: • These may include end-of-pipe mitigation measure where spring has been piped e.g. vegetated buffer spots (Faust et al., 2018) and filter cells, cartridges, and structures using various materials (Ibrahim et al., 2015; King et al., 2015; Penn et al. 2020) (see discussion for details). Full list of materials is reviewed in Ezzati et al. (2020).
2. Outlet		Subsurface interaction	In-field drains (pipes; moles; gravel moles; older variation) bring P and N	Management practices that disconnect sub-surface drainage system discharges into the open ditch:

	A ditch that connects the drainage network to a surface water body.		forms, dominated by NO_3^-, from fields to the open ditch.	• These may include adherence to correct land drainage design, installation guidelines and maintenance. • Use of end-of-pipe land drainage mitigation options such as constructed wetlands (King et al., 2015; Tanner et al., 2005) (see discussion for details) Strict adherence to good farming practices to minimise diffuse losses and leaching of nutrients to sub-surface drainage system that are connected to the open ditch: • These may include in-ditch measures such as sediment traps, bioreactors, and filters to slow the flow and control nutrient loads (Fenton et al., 2020).
		Groundwater interaction	Natural springs bring shallow groundwater, dominated by NO_3^- concentration, into ditches through piped drains.	Strict adherence to good farming practices to minimise diffuse losses: • These may include end-of-pipe mitigation measures where spring has been piped e.g. vegetated buffers (Faust et al., 2018) and filter cells, cartridges, and structures using various materials (Ibrahim et al., 2015; King et al., 2015; Penn et al., 2020) beneath piped springs location on ditch. Full list of materials is reviewed in Ezzati et al. (2020).
		Groundwater interaction	Seeping and upwelling deep groundwater, dominated by NO_3^-, enters into ditches.	Strict adherence to good farming practices to minimise diffuse losses: • In terms of groundwater up-welling or spring connectivity in-ditch intervention that slows the flow and mitigates nutrients using bioreactors, two-stage ditch, filters and vegetated ditches (Faust et al., 2018; King et al., 2015) may be introduced after spring connectivity and before the outlet to reduce dissolved and particulate nutrients entering waters.
3. Outflow/transfer	A ditch that carries drainage water across the farm boundary through neighbouring land.	Subsurface interaction	In-field drains (pipes; moles; gravel moles; older variation) bring P and N, dominated by NO_3^-, from fields to the open ditch.	This drainage water will pass to an adjoining farm and will be mitigated as another landowners Farm Management Plan. Some mitigation can occur in Outflow ditches using mitigation management practices provided for Farmyard Connection and Outlet ditches as appropriate, which may increase the efficacy of mitigation across the farm landscape.
		Surface runoff	Farm internal roadways introduce NH_4^+ and DRP-dominated hard surface water to the ditch	This drainage water will pass to an adjoining farm and will be mitigated as another landowners Farm Management Plan. Some mitigation can occur in Outflow ditches using mitigation management practices provided for Farmyard Connection and Outlet ditches as appropriate, which may increase the efficacy of mitigation across the farm landscape.
		Groundwater interaction	Natural springs connect shallow groundwater, dominated by NO_3^- concentration, into ditches	This drainage water will pass to an adjoining farm and will be mitigated as another landowners Farm Management Plan. Some mitigation can occur in Outflow ditches using mitigation management practices provided for Farmyard Connection and Outlet ditches as appropriate, which may increase the efficacy of mitigation across the farm landscape.
4. Secondary	A ditch that typically flows perpendicular to	Subsurface interaction	In-field drains (pipes; moles; gravel moles; older variation) bring P and N,	Mitigation is unlikely to occur in these open ditches as they do not discharge directly to waters but act as conduits. Some mitigation can occur

	the slope of the land connecting two larger ditches. Can also occur as an open ditch running through a field to collect and remove large excesses of surface water		dominated by NO_3^- from fields to the open ditch.	in Secondary ditches using in-ditch mitigation management practices provided for Farmyard Connection and Outlet ditches as appropriate, which may increase the efficacy of mitigation across an individual farm.
		Surface runoff	Farm internal roadways introduce PP, DRP and NO_3^- dominated within the water from hard surface to the ditch	Mitigation is unlikely to occur in these open ditches as they do not discharge directly to waters but act as conduits. Some mitigation can occur in Secondary ditches using in-ditch mitigation management practices provided for Farmyard Connection and Outlet ditches as appropriate, which may increase the efficacy of mitigation across an individual farm.
		Groundwater interaction	Natural springs bring shallow groundwater, dominated by NO_3^- concentration, through piped drains over ditch sides to introduce both PP and NO_3^- into the ditch	Mitigation is unlikely to occur in these open ditches as they do not discharge directly to waters but act as conduits. Some mitigation can occur in Secondary ditches using in-ditch mitigation management practices provided for Farmyard Connection and Outlet ditches as appropriate, which may increase the efficacy of mitigation across an individual farm.
		Groundwater interaction	Deep groundwater, dominated by NO_3^-, seeps through ditch side surfaces and/or upwells through ditch base to introduce PP and NO_3^- into ditches	Mitigation is unlikely to occur in these open ditches as they do not discharge directly to waters but act as conduits. Some mitigation can occur in Secondary ditches using in-ditch mitigation management practices provided for Farmyard Connection and Outlet ditches as appropriate, which may increase the efficacy of mitigation across an individual farm.
5. Disconnected	A ditch that is not connected to the overall ditch network. May be connected with groundwater.	Surface and Groundwater interaction	Diffuse source of NO_3^- interacts with open ditch. Runoff may interact with the open ditch.	Connectivity is not present to surface water within the open network but there may be a groundwater connection which subsequently discharges to surface water. Precautionary practices should be taken at these locations to minimise recharge to groundwater by provision of a soil buffer.

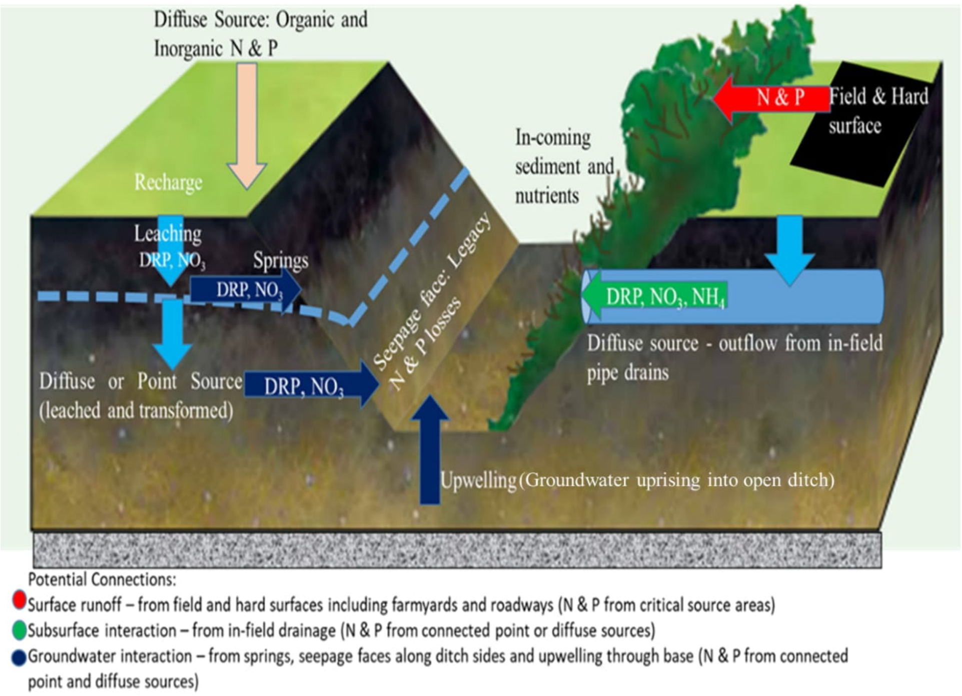


Figure 1: Conceptual figure of an open ditch showing all potential nitrogen and phosphorus sources (point and diffuse), pathways and discharge connections (modified from Teagasc (2022) and Simpson et al. (2011)).

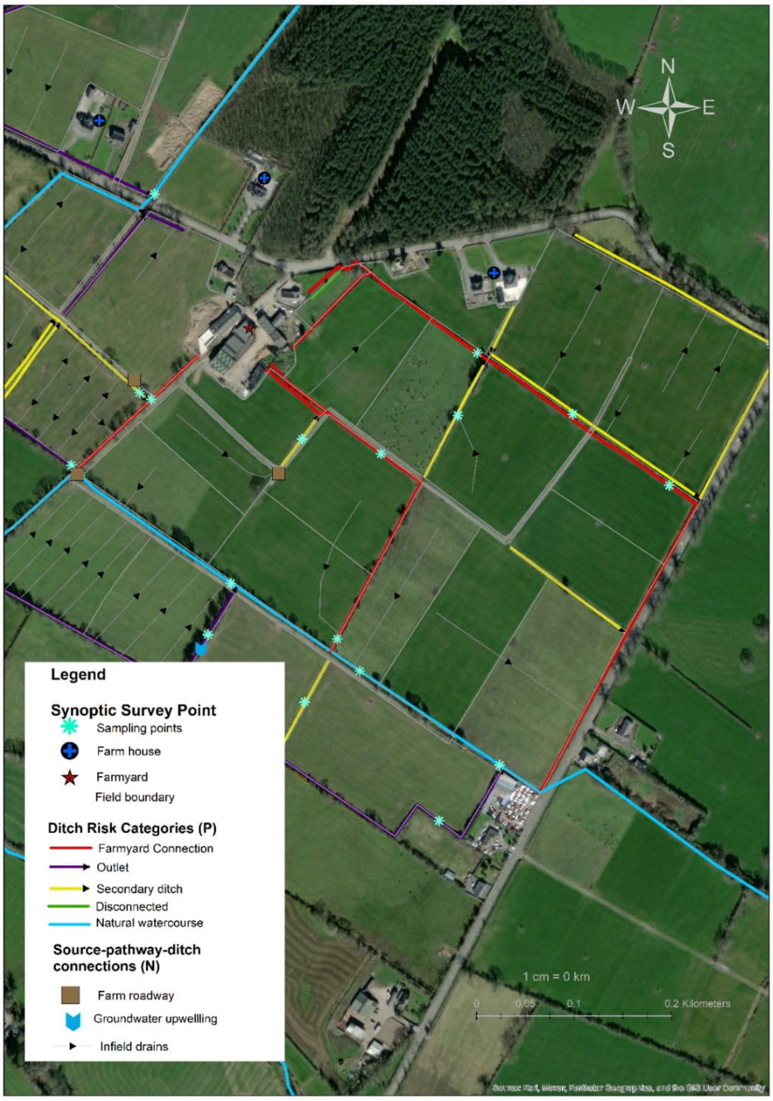


Figure 2: Example of a farm output map (for Farm 5) showing the ranked classification risk along the open ditch network for P (colour coded into categories of connectivity risk) and all conceptualised N open ditch connectivity pathways to individual open ditch sections. For in-field drains, arrows indicate fall and flow direction towards open ditch sections, with a particular P risk indicated by the existing colour coding scheme of Moloney et al. (2020).

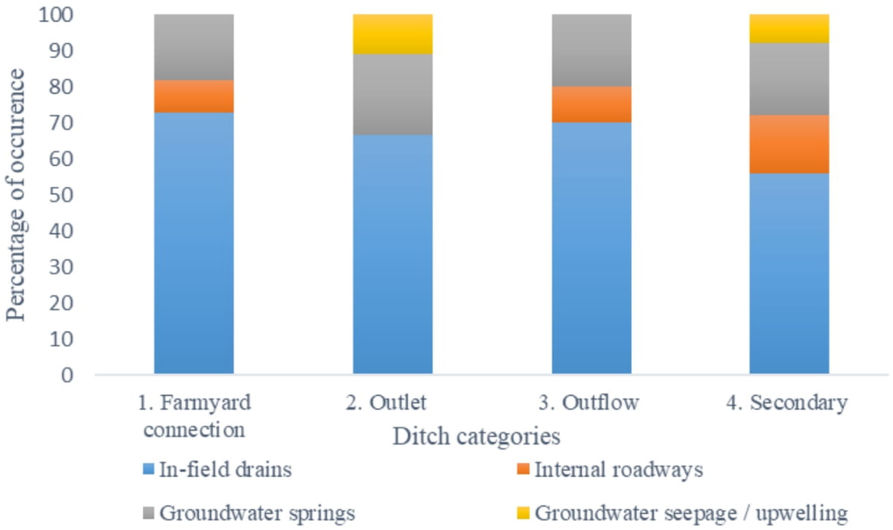
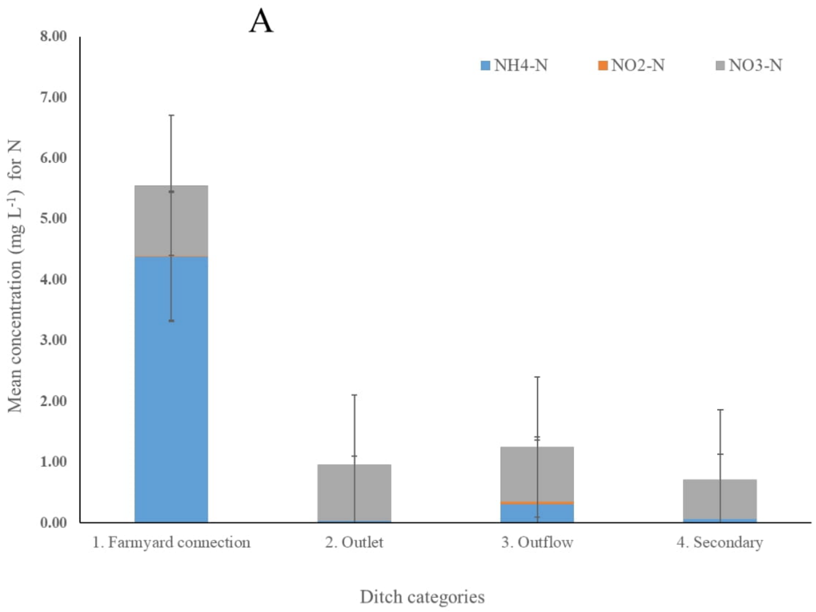


Figure 3. The percentages of the occurred N connectivity pathways for the ditch categories



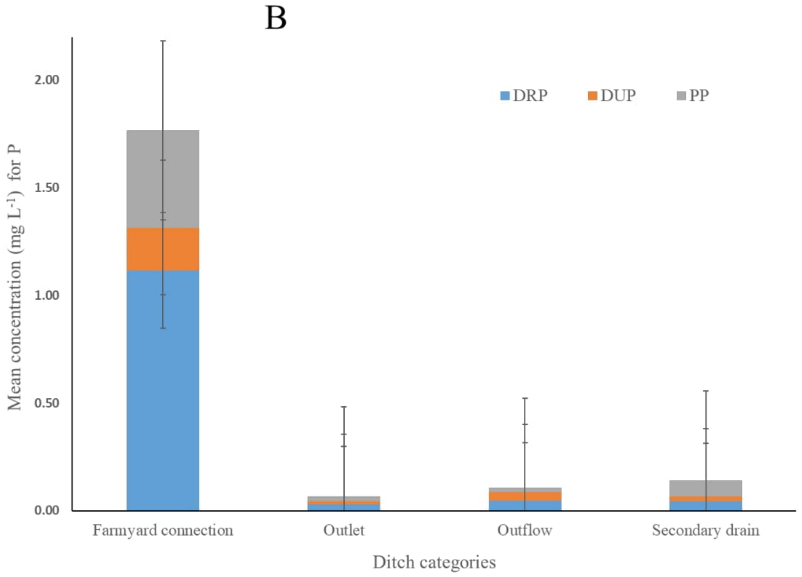


Figure 4 (A) Nitrogen (N) and (B) Phosphorus (P) mean + standard errors (SE) concentrations within the open ditch categories across case study farms.

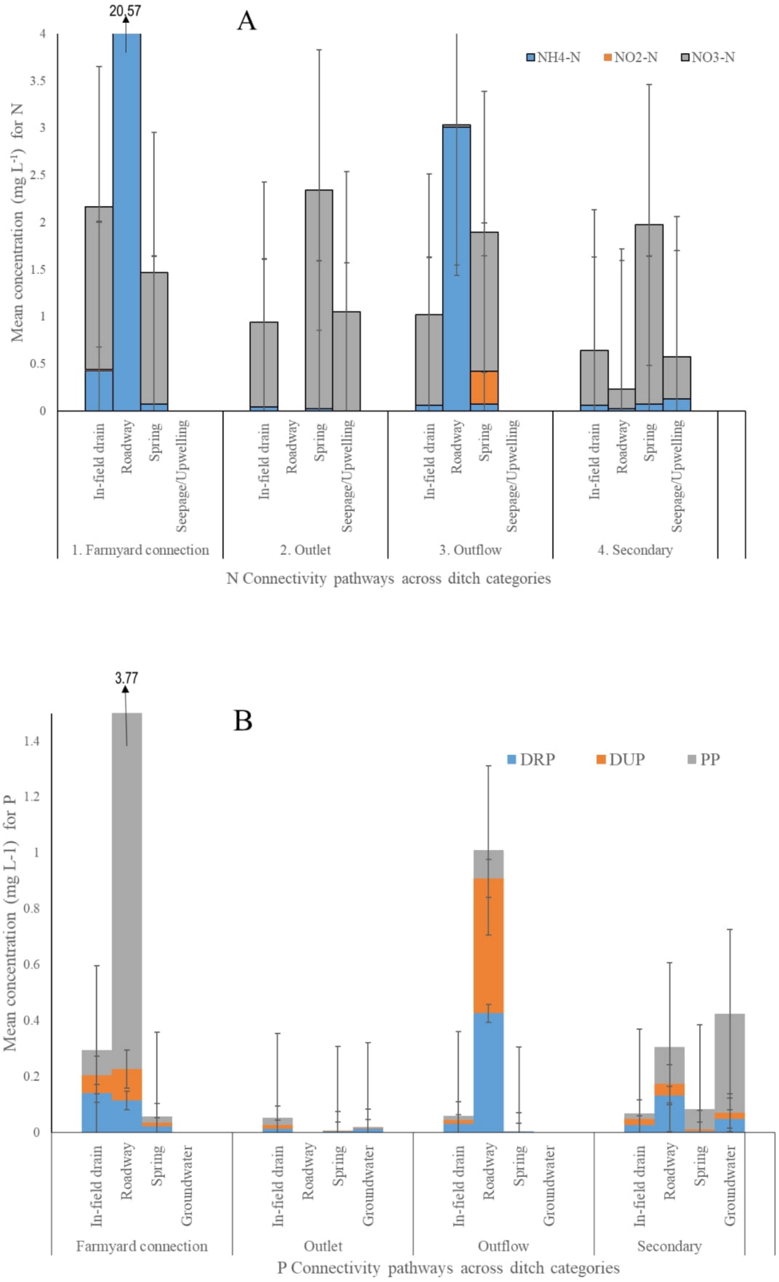


Figure 5. (A) Nitrogen (N) and (B) Phosphorus (P) mean + standard errors (SE) concentrations within associated connectivity pathways in sampled open ditch categories across case study farms.