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Publication Date	2024-02-19
Publisher	Frontiers Media
Repository DOI	10.3389/fenvs.2024.1337857

1 Published as: Opoku, D.G., Healy, M.G., Fenton, O., Daly, K., Condon, T., Tuohy, P. 2024.
2 An integrated connectivity risk ranking for phosphorus and nitrogen along agricultural open
3 ditches to inform targeted and specific mitigation management. *Frontiers of Environmental*
4 *Science* 12: 1337857. doi: 10.3389/fenvs.2024.1337857

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

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15 **Keywords:** Agricultural ditches¹, water quality², nutrient loss³, grassland⁴, drainage
16 management⁵, connectivity pathways⁶, North Atlantic Europe⁷.

17

18 **Abstract**

19 On dairy farms with poorly drained soils and high rainfall, open ditches receive nutrients from
20 different sources along different pathways which are delivered to surface water. Recently, open
21 ditches were ranked in terms of their hydrologic connectivity phosphorus (P) along the open
22 ditch network. However, the connectivity risk for nitrogen (N) was not considered in that
23 analysis, and remains a knowledge gap. In addition, the P connectivity classification system
24 assumes all source-pathway interactions within open ditches are active, but this may not be the
25 case for N. The objective of the current study, conducted across seven dairy farms, was to
26 create an integrated connectivity risk ranking for P and N simultaneously, to better inform

27 where and which potential mitigation management strategies could be considered. First, a
28 conceptual figure of known N open ditch source-pathway connections, developed using both
29 the literature and observations in the field, was used to identify water grab sampling locations
30 on the farms. During field work, all open ditch networks were digitally mapped, divided into
31 ditch sections, and classified in terms of the existing P connectivity classification system.
32 Sampling was conducted during the hydrologically-active period to ensure maximum
33 connectivity of source-pathways and open ditches. The results from these water samples
34 enabled a qualitative validation of N source-pathway presence or absence for each ditch
35 category. The results showed that not all source-pathways were present across ditch categories
36 for all species of N. This information was used to develop an improved open ditch connectivity
37 classification system. Results showed that farmyard connection ditches were the riskiest for
38 potential point source losses and outlet ditches had the highest connectivity risk among the
39 other ditches associated with diffuse sources. Tailored mitigation options for P and N
40 speciation were identified for these locations to intercept nutrients before reaching receiving
41 waters. Furthermore, in ditches associated with diffuse sources, nitrate was introduced by
42 subsurface sources (i.e., in-field drains and groundwater interactions from springs seepage and
43 upwelling) and ammonium was introduced through surface connectivity pathways (i.e., runoff
44 from internal roadways). In-field drains dominated connectivity pathways in open ditches. On
45 dairy farms where open ditches are prevalent, the integrated classification system and mapping
46 procedure presented herein will enable a targeted and nutrient-specific mitigation plan to be
47 developed.

48

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

51

52 **1 Introduction**

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

77 drainage systems along the hydrological pathways into ditches (Deelstra et al., 2014). For
78 efficient mitigation of nutrient loss from open ditch networks, a conceptual understanding of
79 how nutrient sources and their pathways connect to the open ditch system must be established.
80

81 The general trend and pathways of agricultural pollutants have been well documented and are
82 summarised in Figure 1. In summary, nutrient entry into ditches is predominantly from diffuse
83 sources, and often through complex surface and subsurface pathways determined by soil type,
84 climate, landscape position, farm management, and nutrient input sources (manure, fertiliser
85 type) (Granger et al., 2010; Monaghan et al., 2016; Gramlich et al., 2018). These factors
86 regulate the hydrology, the primary driver of nutrient transfer, and the terrestrial and aquatic
87 biogeochemistry that defines the type and form/species of nutrients entering open ditches and
88 subsequently discharging to associated water bodies (Sukias et al., 2003). Conceptually,
89 phosphorus (P), either as particulate P (PP) or dissolved reactive phosphorus (DRP), and
90 nitrogen (N), as ammonium (NH_4^+) or nitrate (NO_3^-), are transported from fields or hard
91 surfaces like roadways through surface flow pathways into open ditches (Figure 1).
92

93 In Figure 1, any groundwater-to-open ditch water connection represents a subsurface
94 interaction distinct from in-field drain connections. In this scenario, typically P is in the form
95 of DRP and NO_3^- represents mineralised N that has become mobilised due to infiltrating water.
96 This N is primarily lost from diffuse sources in fields due to fertilisation and grazing of animals.
97 Clagnan et al. (2018) have shown N conversion to NH_4^+ in poorly drained soils, which can be
98 discharged in waters from in-field drains within the groundwater-to-open ditch water
99 connections (Needleman et al., 2007; Valbuena-Parralejo et al., 2019). The presence of NO_3^-
100 in open ditch networks suggests more permeable connectivity pathways that eventually seep
101 into open ditches along seepage faces or upwell as the water table rises, whereas NH_4^+ suggests

102 less permeable routes before discharge occurs. Groundwater springs represent a distinct
103 groundwater storage component that protrudes onto fields, which are often drained by the
104 installation of an intersecting pipe into an open ditch below the spring. This creates a direct
105 discharge point within the open ditch (Figure 1). The presence of this discharge may change
106 during dry periods, as the water level falls below the base of the open ditch.

107

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

124

125 The objective of this study was to derive a farm-scale integrated open ditch risk ranking for
126 both P and N loss risk based on connectivity, to inform future mitigation management on heavy

127 textured, grassland dairy farms. To fulfil this objective, seven farms were selected with open
128 ditch networks on heavy textured soils. A conceptual figure illustrating trends and pathways of
129 agricultural pollutants for an open ditch is presented. The open ditch networks were mapped
130 during a ground survey, and a qualitative water sampling campaign was conducted (based on
131 the conceptual figure) to validate the presence or absence of pathways for N and P. This enabled
132 an integrated classification of an open ditch network ranking to be developed. Mitigation
133 options for each ditch class are presented.

134

135 **2. Materials and methods**

136 2.1 Site selection and characteristics

137 Seven grassland dairy farms on poorly drained soils geographically located across the SW and
138 NE of Ireland were selected to represent a variety of agronomic dairy production systems and
139 bio-physical settings (Table 1). As per the EPA soils and subsoils maps (Fealy and Green,
140 2009), the soil types on these farms varied from organic to mineral soils. The majority of these
141 farm fields were imperfectly or poorly drained, necessitating an ad-hoc network of artificial
142 drainage installations on the farms. The grazing area of each farm ranged from 28 to 45 ha.
143 Intensive dairy farm management practices were observed on all farms. Morgan's extractable
144 soil P test (Morgan, 1941) was used to determine the agronomic excesses and deficiencies in
145 plant available P for fields of each farm. Farms in this study were located in high rainfall areas
146 with an average of 1092.5 mm. The average farm slope was measured on all seven farms, as it
147 could influence open ditch connectivity.

148

149

150 2.2 Ground survey and mapping connectivity pathways for N into P connectivity risk ditch
151 categories

152 A ground survey was carried out on all the farms during winter (November 2021 to March,
153 2022) to characterise the field boundaries, surface and subsurface networks on each farm. This
154 period was selected following multiple field visits carried out across all seasons in the previous
155 year. This period was identified as the best hydrological period when connectivity pathways
156 were active for grab sampling. Drainage network features such as open ditches connected to
157 the farmyard, and the proximity of the open ditch to water bodies were noted on each farm
158 during the ground survey. Also, the connectivity pathways for N into open ditches from in-
159 field drains, farm roadways, groundwater springs, seepage and upwelling as per the conceptual
160 figure (Figure 1) throughout the drainage network were noted during this time. During the
161 ground survey, all drainage network data such as drain locations, flows and connections, and
162 sampling locations, were recorded using an electronic device with ESRI ArcGIS Field Maps
163 mobile software (ESRI, 2024)

164

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

169

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

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

179

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

194

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

199

200 2.3 Grab water sampling campaign to assess integrated nutrient connectivity pathways

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

206

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

221

222 The number of samples collected was dictated mainly by the observations of connectivity
223 pathways on open ditches during the initial fieldwork campaign. As such, open ditches that had
224 surface or subsurface connectivity pathways (Table 3) noted in the earlier survey were
225 prioritised for sampling. These observations were used to validate surface, subsurface and

226 groundwater flows that entered open ditches on the case study farms. However, some sampling
227 points had no N connectivity pathways. Therefore, only four ditch categories from Table 2
228 (farmyard connection, outlet, outflow, and secondary ditches) were sampled for water across
229 the seven case study farms. Shallow disconnected ditches (category 5 in Table 2) were dry,
230 which indicated no N connectivity with perched or true water tables at the time of sampling.
231 These acted as storage and recharge areas for groundwater during rainfall periods. At each
232 water sample location, two 50 ml samples (filtered on-site using 0.45 μm filter paper and
233 unfiltered) were collected for dissolved and total P analyses, respectively. Grab sampling was
234 carried out in the mapped ditch categories on each farm, provided water was present in the
235 open ditch. The grab water sampling taken directly from an open ditch was conducted within
236 1 m downstream of in-field drain outlets, farm roadways, groundwater springs, and
237 groundwater seepage/upwelling, where present, in the open ditch categories. All water samples
238 were kept in an ice-box during sampling and transportation and then tested within one day of
239 sample collection.

240

241 Filtered water samples were analysed for DRP and total dissolved phosphorus (TDP) using a
242 Gallery discrete analyser (Gallery reference manual, 2016) and a Hach Ganimede P analyser,
243 respectively. Total dissolved phosphorus (TDP) was measured by acid persulphate oxidation,
244 under high temperature and pressure. The unfiltered water samples were analysed for nitrite
245 ($\text{NO}_2\text{-N}$), $\text{NH}_4\text{-N}$, total oxidised nitrogen (TON), and total reactive phosphorus (TRP) using
246 the Gallery analyser. Total phosphorus (TP) was analysed using the Ganimede P analyser.
247 Phosphorus was measured colourimetrically by the ascorbic acid reduction method (Askew
248 and Smith, 2005), where the 12-molybdophosphoric acid complex is formed by the reaction of
249 orthophosphate ion with ammonium molybdate and antimony potassium tartrate (catalyst) and
250 reduced ascorbic acid. All samples, reagent blanks, and check standards were analysed at

251 Teagasc Johnstown laboratory following the Standard Methods (APHA, 2005). All quality
252 control (QC) samples/check standards are made from certified stock standards from a different
253 source than calibration standards. Quality control samples were analysed at the beginning and
254 end of every batch, and every 10 samples within a batch, and if the QC fell outside limits,
255 samples were repeated back to the last correct QC. Blanks were included in every batch and
256 approximately 10 % of samples were repeated. Tolerances range up to a maximum of $\pm 7.5\%$
257 of nominal value. All instruments used were calibrated in line with manufacturers'
258 recommendations. Nitrate-N was calculated by subtracting $\text{NO}_2\text{-N}$ from TON, particulate
259 phosphorus (PP) was the difference between TP and TDP, and dissolved unreactive phosphorus
260 (DUP) was the difference between TDP and DRP.

261

262 2.4 Data Analysis

263 To validate the link between the conceptualised connectivity sources-pathways and their
264 introduction of N and P into the open ditch system, data from the spring season synoptic survey
265 were analysed statistically to differentiate the nutrient concentrations for the various open ditch
266 categories and also for the various connectivity to ascertain if they varied from each other. As
267 the data for each water quality parameter were not normally distributed, Kruskal Wallis analysis
268 was undertaken to find out the significant differences between farmyard connection, outlet,
269 outflow and secondary ditch categories as treatment levels, and also between the
270 conceptualised N connectivity pathways (in-field drains, internal roadways, springs, and
271 seepage/upwelling) within and across the outlet, outflow and secondary ditch categories
272 treatment levels for all the water quality parameters ($\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, TN, DRP, DUP, TP and
273 PP). Data were analysed using R studio software version 4.0.2 (2020). Where significant
274 differences were observed using alpha level of 0.05 (95 % confidence level), the pairwise
275 Wilcoxon Rank Sum test was further used to find the differences between the means of the

276 pairs. Microsoft Excel software version 16.0 (2016) was used to find a correlation between the
277 number of occurrences of in-field drains and the percentage of drained fields on poorly draining
278 soil farms.

279

280 **3. Results**

281 3.1 Analysis of the open ditch networks

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

287

288 3.2 Observations relating to conceptualised N connections within the open ditch networks

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

301

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

311

312 3.3 Validation of N connectivity pathway using synoptic survey

313 The average TN and TP concentrations were significantly higher in farmyard connection
314 ditches (Figure 4) than in outlet, outflow and secondary ditches ($P < 0.01$). Across the outlet,
315 outflow and secondary ditch categories, $\text{NO}_3\text{-N}$ was the dominant N species, contributing on
316 average to 44.7 % of TN at sampling points near N connectivity. Only 10.6 % of TN comprised
317 $\text{NH}_4\text{-N}$ within these ditch categories. The highest average $\text{NO}_3\text{-N}$ across these ditch categories
318 was observed in groundwater springs (1.90 mg L^{-1}), followed by in-field drains (0.75 mg L^{-1}),
319 groundwater upwelling (0.65 mg L^{-1}), and roadways (0.17 mg L^{-1}) (Table S1). In addition, $\text{NO}_3\text{-N}$
320 N at groundwater springs were dissimilar ($P < 0.05$) to $\text{NO}_3\text{-N}$ at roadways and in-field drains
321 (Figure 5a). High concentrations of $\text{NO}_3\text{-N}$ were also measured on roadways, where $\text{NH}_4\text{-N}$ is
322 conceptualised as being dominant (Figure 1) on secondary ditches. However, $\text{NH}_4\text{-N}$
323 dominated TN across these ditches at sample points near roadways, with 25.3 % composition
324 as opposed to 6.9 % of $\text{NO}_3\text{-N}$. Ammonium-N concentrations across these ditch categories
325 were not statistically significant ($P > 0.05$).

326

327 No consistent trends in species of TP were observed across the outlet, outflow and secondary
328 ditch categories. Among these ditch categories, TP concentrations were relatively high in
329 secondary ditches, in which PP was predominant (Figure 5b). Across the outlet, outflow and
330 secondary ditch categories, PP was statistically significant ($P > 0.05$), particularly between in-
331 field drain and roadway connectivity pathways, and DRP was statistically significant ($P >$
332 0.01), particularly between roadways and groundwater springs. Comparing P species for each
333 N connectivity pathway, average PP concentrations were highest in groundwater
334 upwelling/seepage (0.24 mg L^{-1}), followed by roadways (0.12 mg L^{-1}), groundwater springs
335 (0.04 mg L^{-1}), and in-field drains (0.02 mg L^{-1}) connectivity pathways, whereas average DRP
336 concentrations were highest in roadways (0.19 mg L^{-1}), followed by groundwater
337 upwelling/seepage (0.04 mg L^{-1}), in-field drains (0.03 mg L^{-1}), and groundwater springs (0.01
338 mg L^{-1}).

339

340

341 **4. Discussion**

342 4.1 Observations on ditch categories and associated N connectivity pathways

343 Of the seven farms surveyed, disconnected and secondary ditches comprised the lowest and
344 highest average percentage of the total ditch length, respectively. This result is consistent with
345 Moloney et al. (2020), who recorded similarly low and high average percentages for total ditch
346 length on varying soil grasslands in Ireland. Disconnected ditches are ineffective for excess
347 field water removal within the drainage system, and exist either as blocked normal ditches or
348 as created disconnecting ditches that remove field runoff or precipitation water by infiltration
349 or evaporation. Disconnected ditches, when wet, may hold water with vegetation and

350 potentially provide denitrification or create pollution swapping by the release of nitrous oxide
351 (N_2O) or nitric oxide (NO) greenhouse gases.

352

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

362

363 4.2 Hydrochemistry across P ditch categories and consideration of N connectivity pathways

364 Higher TN and TP average concentrations were measured in farmyard connection ditches
365 relative to the other ditch categories, which was similar to the findings of Moloney et al. (2020),
366 Harrison et al. (2019) and Ezzati et al. (2020). In the farmyard connection ditches, the TN and
367 TP concentrations were nearly three times higher than the TN standard limits of 2.5 mg L^{-1} in
368 the European Union for estuarine waters (Wuijts et al., 2022) and fifteen times higher for TP
369 standards such as 0.1 mg L^{-1} as proposed by Wetzel (2001). While both Edwards et al. (2008)
370 and Mockler et al. (2017) identified farmyards as point sources for high nutrient loss, the former
371 argued runoff from farmyards has been overlooked and not duly considered as a major nutrient
372 loss hotspot. Such runoff may lead to high nutrient-concentrated fields near the farmyard
373 relative to fields further away (Fu et al., 2010), and these potentially may enter open ditches
374 near the farmyard to create major downstream water quality problems. Unlike ditches

375 (associated with point sources), the lower TP and TN concentrations in outlet, outflow and
376 secondary ditch categories may be associated with diffuse nutrient sources. Studies have shown
377 diffuse sources, relative to point sources, have lower TN and TP concentrations (Edwards &
378 Withers, 2008; Pieterse et al., 2003). Management of some of these diffuse sources is
379 problematic as they are difficult to locate in a landscape (Harrison et al., 2019). However, their
380 impact on the deterioration of receiving water bodies is substantial and therefore needs to be
381 managed (Andersen et al., 2014; Bradley et al., 2015). Diffuse sources depend on landscape
382 and other management factors, which influence diffuse N and P mobilisation, transformation
383 and delivery into the ditches (Granger et al., 2010; Schoumans et al., 2014). However, notable
384 among these factors are the hydrological conditions, on which diffuse nutrient release strongly
385 depends (Edwards & Withers, 2008; Chen et al., 2013). This, coupled with biogeochemical
386 factors, which may vary within a landscape, influences the spatial and temporal distribution
387 patterns of diffuse N and P, including the pathways by which they enter and leave farms
388 (Clagnan et al., 2019; Grenon et al., 2021). Nutrient losses from the diffuse sources are
389 delivered into open ditches along surface and subsurface pathways, creating hotspots of
390 nutrient loss in certain open ditch categories, which need to be characterised and potentially
391 mitigated. Climatic, landscape and management factors all have a role to play in when and
392 where impacts occur. These could have contributed to the higher TN concentrations in water
393 samples that were measured near N connectivity pathways than at locations with no N
394 connectivity pathways within the outlet, outflow and secondary ditch categories, and also for
395 TP in the outflow ditch category. This observation aligns with the reported works of Ibrahim
396 et al. (2013) and Valbuena-Parralejo et al. (2019) on in-field drains, Fenton et al. (2021) and
397 Rice et al. (2022) on roadways, Soana et al. (2017) on groundwater springs, and O’Callaghan
398 et al. (2018) on groundwater upwelling/seepage.

399

400 Nitrate was the dominating N species in in-field drains, groundwater springs, and upwelling
401 connectivity pathways in outlet, outflow and secondary ditch categories (Figure 5a). This may
402 be attributed to their connection to a subsurface N source, which comprises leached N from
403 animal excreta and fertiliser that may have been nitrified to $\text{NO}_3\text{-N}$ (Necpalova et al., 2012). In
404 poorly drained grasslands, nitrification may have been elevated by the high in-field drainage
405 density (Table 1), which enhanced N preferential flow (Van Der Grift et al., 2016) and limited
406 potential N attenuation (Clagnan et al., 2019; Valbuena-Parralejo et al., 2019). The average
407 $\text{NO}_3\text{-N}$ concentration was highest in groundwater springs and in-field drains. Factors such as
408 the presence of these N connectivity pathways within the shallow subsurface region, nearness
409 to the soil surface (where farm management mostly occurs), and exposure to N sources at the
410 groundwater-ground surface intersection spots (particularly for groundwater springs; Infusino
411 et al., 2022), could have contributed to the high $\text{NO}_3\text{-N}$ concentrations in these locations. In
412 contrast, $\text{NH}_4\text{-N}$ was the most dominating N species measured for roadway connectivity
413 pathways across the outlet, outflow and secondary ditch categories, especially where physical
414 animal excreta were observed. This observation aligns with Fenton et al. (2021), who observed
415 that roadways draw surface nutrient sources, high in $\text{NH}_4\text{-N}$, as runoff from soil-bound and
416 animal excreta into nearby ditches and streams. Although important, redox reactions were not
417 considered in the present study.

418 For TP concentrations across outlet, outflow and secondary ditch categories, P concentrations
419 were relatively low compared to the farmyard connection ditch category. However, such TP
420 concentrations in the outlet, outflow and secondary ditch categories were still high enough to
421 cause eutrophication downstream if undiluted. High TP concentrations measured in secondary
422 ditches may be related to the impacts of farm management activities including grazing and
423 farm machinery movement, which is intense within the central fields of most farms where
424 secondary ditches lie as connecting ditch links. These contribute to the erosion of ditch sides

425 and associated deposition of soils in the secondary ditches, as reflected in the higher PP
426 concentrations observed. High TP concentrations measured near roadways on outflow ditches
427 may be due to animal excreta, run-on deposits from farmyards, fields, and poached surfaces as
428 a result of animal and machinery movement (Fenton et al., 2021). Both PP and DRP can trigger
429 eutrophication in waterbodies and may pose risk to downstream water bodies. However, this
430 depends on their closeness, connection, and mitigation along the pathway to water sources
431 within agricultural landscapes.

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

439

440 4.3 Deriving a connectivity risk for N into P agricultural open ditch categories

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

447 In the current study, all of the conceptualised N connectivity pathways (Figure 1) established
448 from the literature were present, but not in all of the sampled P risk ditch categories developed

449 by Moloney et al. (2020) (Table S1). For instance, the established general trends and
450 connectivity pathways of groundwater seepage and upwelling were not present on farmyard
451 connection and outflow ditches. Moreover, the grab water data results validated all the
452 conceptualised N connectivity pathways present in ditches (Figure 5a), except groundwater
453 seepage and upwelling. The dominance of high $\text{NO}_3\text{-N}$ concentrations at in-field drains and
454 springs, and high $\text{NH}_4\text{-N}$ concentrations at roadways within farmyard connection ditches,
455 indicated a point pollution source arising from their connection to the farmyard aside from the
456 hydrology-induced N concentrations. Farmyards pose the greatest nutrient loss risk on farms
457 due to high nutrient concentration within discharges (Vedder, 2020) and like other point
458 sources, they are independent of hydrology (Edwards & Withers, 2008). As such, primarily
459 managing the farmyard wastewater before discharge into connecting ditches for mitigating
460 nutrient connectivity to water sources is essential (NFGWS, 2020) before deployment
461 along/within ditches interventions.

462 For the other sampled outlet, outflow and secondary ditch categories, all N conceptualised
463 pathways were observed, except for internal farm roadway on outlet ditches, and groundwater
464 seepage and upwelling on outflow ditches (Table S1). In outlet, outflow and secondary ditch
465 categories, the ditch water synoptic data validated the conceptualised $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ for
466 all the observed N connectivity pathways, except farm roadway connection on secondary
467 ditches (which was invalid with $\text{NO}_3\text{-N}$ dominance over conceptualised $\text{NH}_4\text{-N}$ from hard field
468 surface flow pathways). Nitrate dominated in-field drains, groundwater springs, upwelling and
469 seepage connectivity pathways, and $\text{NH}_4\text{-N}$ -dominated farm roadways across the outlet,
470 outflow and secondary ditch categories, as conceptualised in Figure 1.

471 Assessment of N connectivity pathway within ditch category 5 could not be included in the
472 study due to the unavailability of water samples in this ditch for validating conceptualised N
473 connectivity pathways. Moloney et al. (2020) showed that disconnected ditches were the least

474 risky ditch class for nutrient loss and therefore merit less focus during nutrient loss mitigation
475 for surface water. However, such low nutrient concentrations could be leached into
476 groundwater and therefore may require mitigation interventions to prevent leaching.

477 To apply this research in practice, once open ditches are investigated and mapped, a category
478 should be assigned for an individual open ditch, after which the available N connections for
479 that ditch are noted. All of these connections in combination will aid in the future mitigation
480 management strategy. It is unlikely, for example, that more than one mitigation option will be
481 installed in a single open ditch. Therefore, the information gathered from Table 5 can be used
482 to ensure that the correct nutrients and their speciation are targeted for mitigation in the open
483 ditch. Mitigation options may be a combination of those that limit diffuse and point sources.
484 For example, with respect to diffuse sources, strict adherence to action programmes to reduce
485 losses is important (e.g., Good Agricultural Practice Regulations, in line with the Nitrates
486 Directive (91/676/EEC)). With respect to roadway runoff, NH_4^+ mitigation options are
487 available and have been outlined in Fenton et al. (2021) and Rice et al. (2022) (e.g., diversion
488 bars to move runoff to a buffer area of at least 1.5 m, cambering farm roadways, and directing
489 flow onto adjacent fields). Adopting a two-stage ditch design may reduce high PP
490 concentrations (Faust et al., 2018; Hodaj et al., 2017; King et al., 2015). With respect to the
491 subsurface N connectivity pathways (in-field drains, groundwater springs, upwelling and
492 seepage), in-ditch management practices may control the flow and the nutrient content leaving
493 the open ditch. These may include sediment traps (Wilkinson et al., 2014), vegetated ditches
494 (Faust et al., 2018; Kröger et al., 2008; Soana et al., 2017) or in-ditch filters or bioreactors
495 (Goeller et al., 2020; King et al., 2015; Liu et al., 2020). Nutrient filtering through vegetation
496 (Moeder et al., 2017) or use of media (Ezzati et al., 2020) can only aim to mitigate a small
497 amount of overall nutrients leaving the ditch due to hydraulic retention times needed and by-
498 pass flow during high storm events. Furthermore, mitigation practices including the

499 construction of wetlands (Tanner et al., 2005), vegetated buffer zones (Faust et al., 2018) and
500 low-grade weirs (Baker et al., 2016; Kröger et al., 2012; Littlejohn et al., 2014) that may be
501 placed at the end of ditches after the connectivity pathways, especially for farmyard connection
502 and outlet ditch categories, would help to limit nutrient loss from these farms. Therefore, all
503 measures need to be considered as a package and not in isolation when trying to minimise
504 nutrient and sediment loads leaving an open ditch system. It is worth noting that co-operation
505 at the local level is needed to prevent other mitigation-related problems (such as the polluter
506 pays principle regarding outflow ditches between neighbouring farmers) to ensure mitigation
507 occurs before waters are impacted.

508

509 **5. Conclusion**

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

523

524 **Conflict of interest**

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

527

528

529 **Author contribution**

530 D.G. Opoku: Conceptualization, Data curation, Formal analysis, Investigation, Methodology,
531 Validation, Visualization, Roles/Writing – original draft, Writing – review & editing; M.G.
532 Healy: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision,
533 Software, Validation, Visualization, Writing – review & editing; O. Fenton: Conceptualization,

534 Funding acquisition, Investigation, Methodology, Supervision, Validation, Software,
535 Visualization, Writing – review & editing; K. Daly: Conceptualization, Investigation,
536 Methodology, Validation, Visualization, Writing – review & editing; T. Condon: Funding
537 acquisition, Methodology; P. Tuohy: Conceptualization, Funding acquisition, Investigation,
538 Methodology, Project administration, Resources, Supervision, Software, Validation,
539 Visualization, Writing – review & editing.

540

541 **Funding**

542 The authors are grateful to Teagasc for the award of a Walsh Scholarship to the first author
543 [grant number: RMIS-1381] to conduct this research.

544

545 **Acknowledgements**

546 The authors are grateful to Simon Leach, Asaf Shnel and Denis Brennan for GIS, fieldwork
547 and laboratory assistance provided.

548

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801 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 (°)	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

802 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
803 (Corbett et al. 2022^a; Corbett et al. 2022^b) ⁴Data from Tuohy et al. (2018, 2021) ⁵ % Field with in-field drain = (size of drained field / total farm size) × 100 %

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806 Table 2. Definition and description of open ditch categories for the P classification system of
807 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.

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811 Table 3. Criteria for identifying N connectivity pathways on open ditch categories and
 812 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.

813 ¹ Criteria description (Teagasc, 2022)

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815 Table 4. Summary of open ditch data including the proportion of the open ditch network
 816 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

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826 Table 5. An updated integrated ditch connectivity ranking that considers both phosphorus and nitrogen coupled with suggested strategies to reduce
 827 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.	<p>Management practices that disconnect sub-surface drainage system discharges into the open ditch:</p> <ul style="list-style-type: none"> • 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). <p>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:</p> <ul style="list-style-type: none"> • 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	<p>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:</p> <ul style="list-style-type: none"> • 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.	<p>Strict adherence to good farming practices to minimise diffuse losses:</p> <ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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) <p>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:</p> <ul style="list-style-type: none"> • 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.	<p>Strict adherence to good farming practices to minimise diffuse losses:</p> <ul style="list-style-type: none"> • 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.	<p>Strict adherence to good farming practices to minimise diffuse losses:</p> <ul style="list-style-type: none"> • 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.

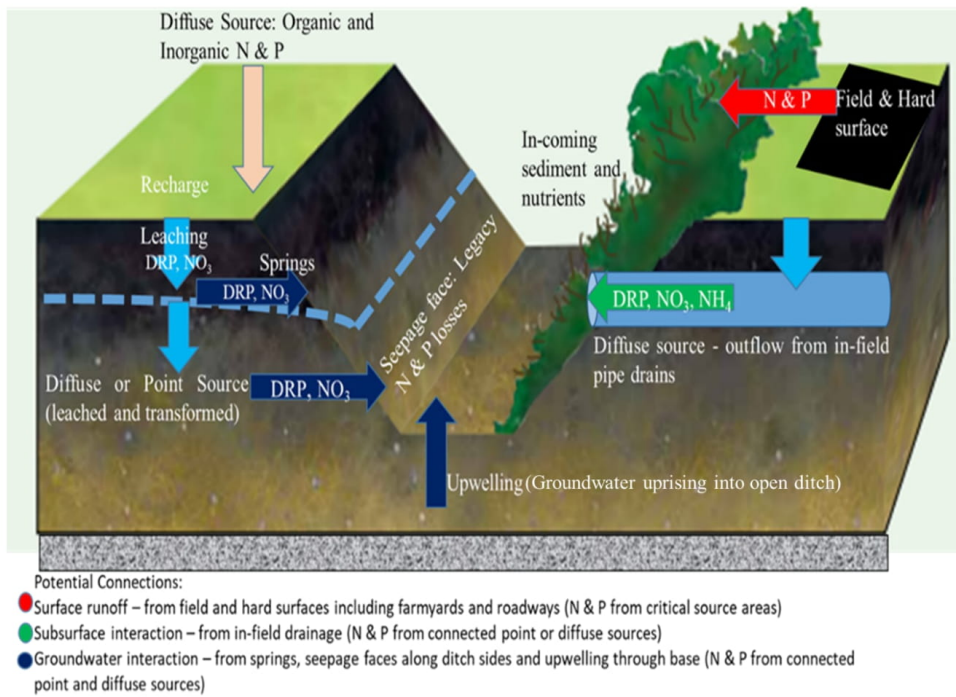


Figure 1: Conceptual figure of an open ditch showing all potential nitrogen and phosphorus sources (point and diffuse), pathways and discharge connections (modified from Teagasc (2022) and Simpson et al. (2011)).



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).

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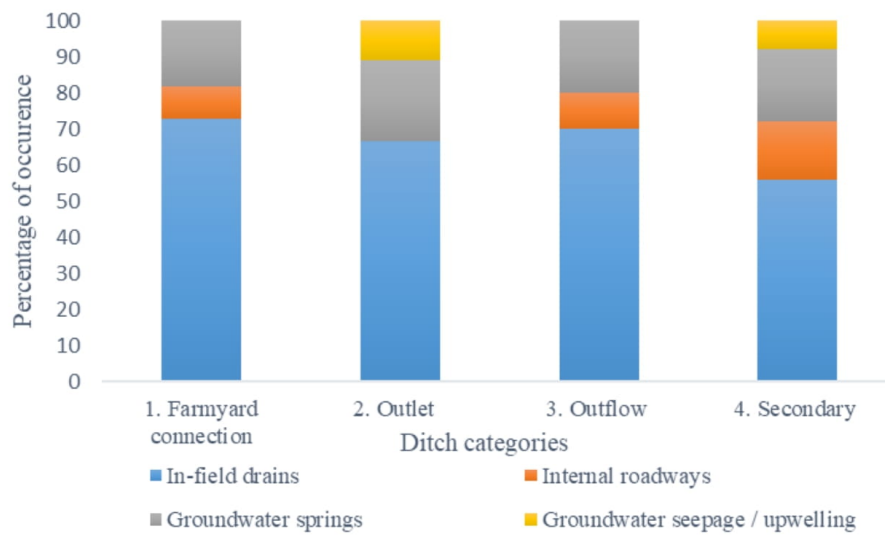


Figure 3. The percentages of the occurred N connectivity pathways for the ditch categories

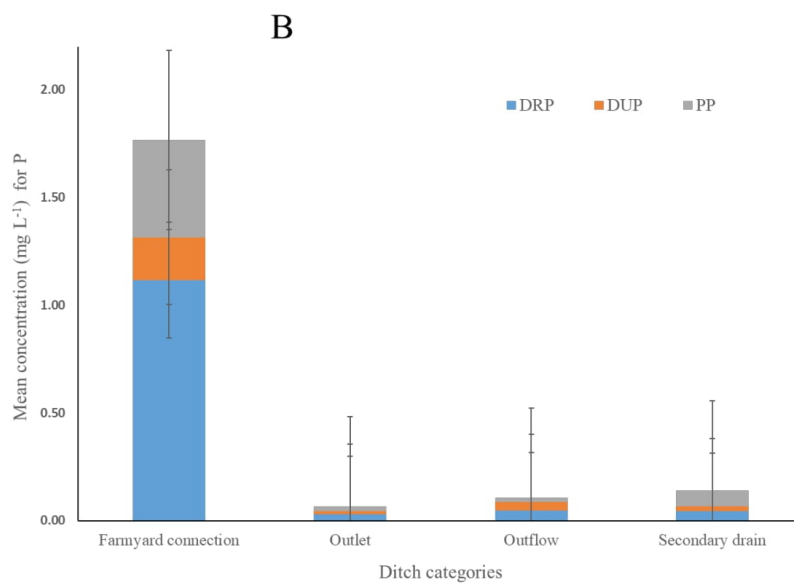
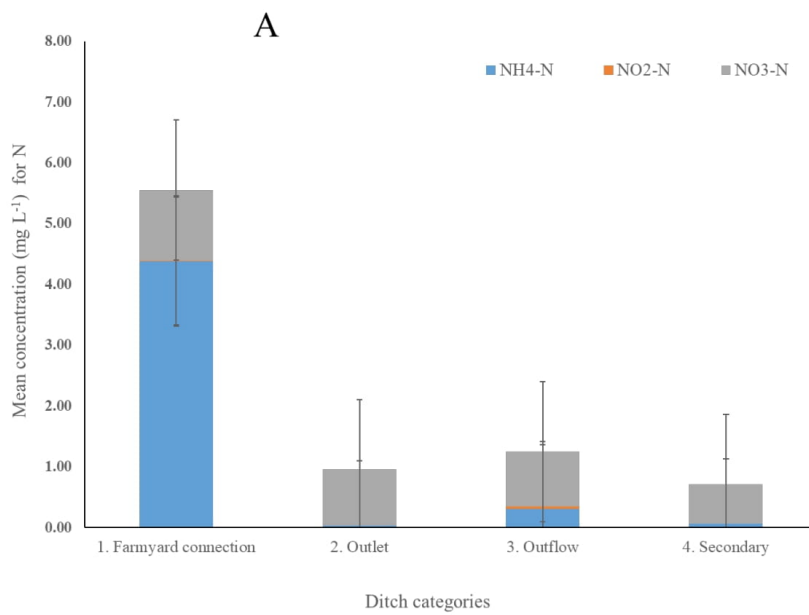


Figure 4 (A) Nitrogen (N) and (B) Phosphorus (P) mean + standard errors (SE) concentrations within the open ditch categories across case study farms.

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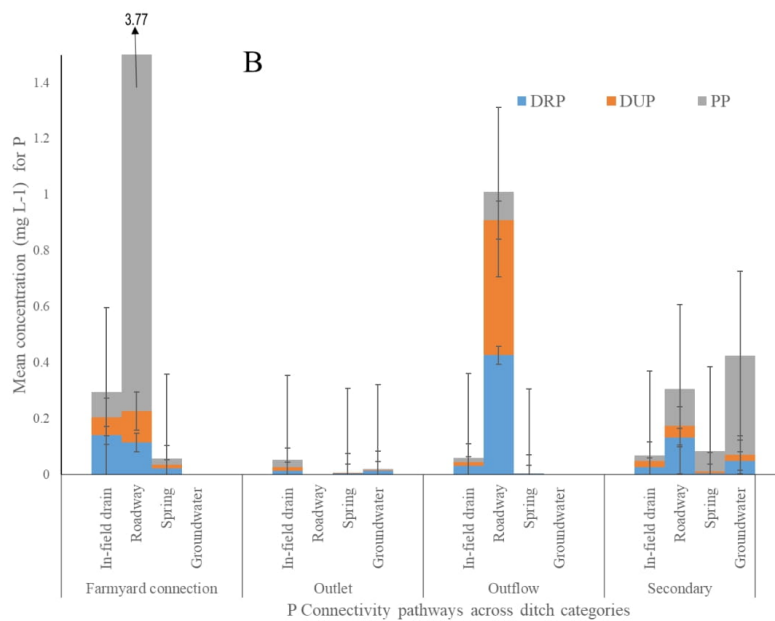
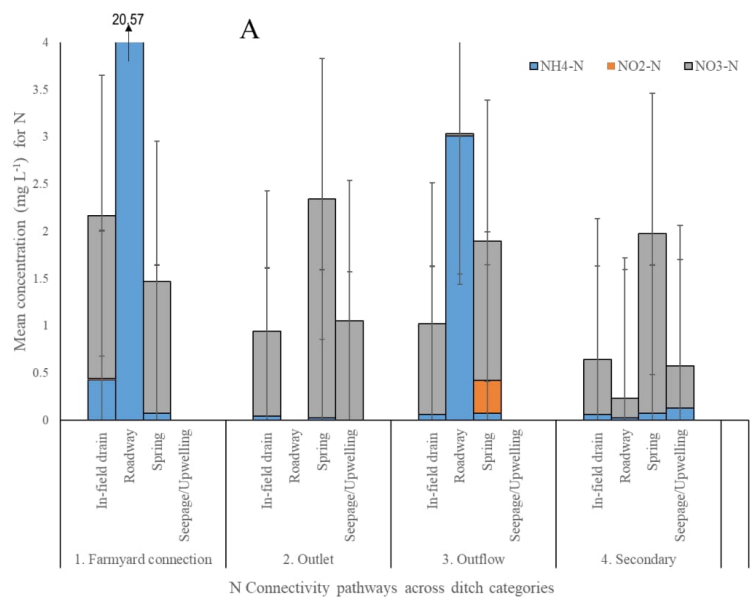


Figure 5. (A) Nitrogen (N) and (B) Phosphorus (P) mean + standard errors (SE) concentrations within associated connectivity pathways in sampled open ditch categories across case study farms.

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