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## **Impact of P inputs on source-sink P dynamics of sediment along an agricultural ditch network**

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## Abstract

Phosphorus (P) loss from intensive dairy farms is a pressure on water quality in agricultural catchments. At farm scale, P sources can enter in-field drains and open ditches, resulting in transfer along ditch networks and delivery into nearby streams. Open ditches could be a potential location for P mitigation if the right location was identified, depending on P sources entering the ditch and the source-sink dynamics at the sediment-water interface. The objective of this study was to identify the right location along a ditch to mitigate P losses on an intensive dairy farm. High spatial resolution grab samples for water quality, along with sediment and bankside samples, were collected along an open ditch network to characterise the P dynamics within the ditch. Phosphorus inputs to the ditch adversely affected water quality, and a step change in P concentrations (increase in mean dissolved reactive phosphorus (DRP) from 0.054 to 0.228 mg L<sup>-1</sup>) midway along the section of the ditch sampled, signalled the influence of a point source entering the ditch. Phosphorus inputs altered sediment P sorption properties as P accumulated along the length of the ditch. Accumulation of bankside and sediment labile extractable P, Mehlich 3 P (M3P) (from 13 to 97 mg kg<sup>-1</sup>) resulted in a decrease in P binding energies (k) to < 1 L mg<sup>-1</sup> at downstream points and raised the equilibrium P concentrations (EPC<sub>0</sub>) from 0.07 to 4.61 mg L<sup>-1</sup> along the ditch. The increase in EPC<sub>0</sub> was in line with increasing dissolved and total P in water, demonstrating the role of sediment downstream in this ditch as a secondary source of P to water. Implementation of intervention measures are needed to both mitigate P loss and remediate sediment to restore the sink properties. Farm-scale measures will need to account for a physicochemical lag time before improvement can be observed.

**Keywords:** Drainage water, farm pollution, phosphorus, soil, agriculture, sediment

## **1. Introduction**

Diffuse and point-source nutrient pollution from agriculture results in degradation of water quality (Sutton et al., 2011), including loss of aquatic biodiversity (FAO, 2011) and ecosystem services (Schindler et al., 2010). Incidental and legacy phosphorus (P) losses from agriculture to water (Haygarth et al., 2005) are major sources which contribute to eutrophication (Verheyen et al., 2015). The European Union Water Framework Directives (EU, 2000) sets a target to achieve at least “good” status in all water bodies by 2020 and member states must implement “programmes of measures” to minimise point and diffuse P losses (Kronvang et al., 2007; Sharpley, 2016; Macintosh et al., 2018; Melland et al., 2018). For example, in Ireland the Nitrates Directive has been implemented as a baseline set of measures to protect water bodies from nutrient and sediment loss. However, legacy P stores which are stored over decades of excessive P applications are difficult to mitigate and therefore further measures are needed to tackle such losses (Sharpley et al., 2013; Vadas et al., 2005; Fiorellino et al., 2017). Typically, water infiltrates into soil and interacts with legacy P stores along the transfer continuum. This water often discharges to drainage ditches which may act as corridors for nutrient movement (Needelman et al., 2007). However, concentrations of dissolved P in these networks may change due to dilution, direct discharges from pipes connected with a source, or as a result of sediment chemistry.

Clagnan et al. (2019) examined the connectivity of surplus nutrients lost from intensive dairy systems to adjoining ditch networks and found elevated dissolved reactive phosphorus (DRP) at all sampling locations. Moloney et al. (pers. comm.) attributed the risk of P loss from on-farm

ditch networks to connectivity of the farm yards to ditches as well as legacy P stored in the sediment of the ditches. There is a constant interplay between dissolved P in water and bankside-sediment/sediment chemistry in which physiochemical properties such as aluminium (Al), iron (Fe), calcium carbonate, clay, pH and organic matter (OM), enable mobilisation or immobilisation of P along the transfer continuum (Thomas et al., 2016). Shore et al. (2016) classified drainage ditch networks based on physical and chemical attributes such as Fe, Al, and calcium (Ca) contents, and found that ditch maintenance, including both removal and retaining vegetated sections, aided P attenuation along ditch networks (Haggard et al., 2004; Smith et al., 2005). The challenge for catchment managers and water policy is where these measures should be carried out. In addition, a synoptic view of the role of bank side and soil-sediments in the retention and mobilisation of P along these networks has been shown that (Delgado and Berry, 2008; Dollinger et al., 2016; Daly et al., 2017; Fenton et al., 2017). Daly et al. (2017) found that subsurface horizons rich in Al could attenuate P or make it less soluble and concluded that a 'right measure, right place' approach to drainage measure implementation could be effective. According to Haggard et al. (2004), sediments are spatially heterogeneous and can act as temporary stores of P or a transient storage pool that may be released back into water depending on *in situ* conditions. Smith et al. (2004) investigated the transient nature of P stored in ditches and found that sediment physiochemical properties affect ditch capacity to become a source, sink or regulator of DRP in ditch water. Hence, characterisation of ditch networks and closer monitoring of mobilisation of P is important in terms of their influence on the potential for nutrient losses to water (Kurz et al., 2005) and ditch management e.g. cost effective installation of an in-ditch P sorbing structure requires demarcating hotspots of P loss whilst avoiding natural attenuation areas (Penn et al., 2007).

There is a lack of basic understanding of how a ditch network functions as a natural attenuation area both laterally and vertically, with no studies considering how this changes along the network. Therefore, the primary objective of the current study was to identify optimal locations for implementing mitigation measures along an agricultural ditch, by examining the source-sink dynamics for P along a ditch network. This was done by examining high resolution spatial trends of P retention and mobilisation in bankside sediment and ditch basal sediment along a ditch connected to an intensive dairy farm, and to couple this signature with spatial and temporal dissolved reactive P trends. The connectivity between surface (runoff) and subsurface (groundwater and artificial drainage system) flow pathways was established, and extensive field and laboratory work was conducted to elucidate bankside-sediment-sediment and water characteristics at key sampling locations along the ditch network. This was used to evaluate the potential of the ditch becoming a P source for drainage water. Finally, the equilibrium P concentration of the sediments was investigated to study their dynamics with water.

## **2. Materials and methods**

### *2.1. Site description and identification of sampling locations*

The Johnstown Castle catchment, delineated in Fig. 1, contains an intensive dairy farm (190.4 ha) located in SE Ireland in North Atlantic Europe (52°17'52" N and 06°29'48" W). The 30-year mean annual rainfall on this site is approximately 1000 mm, of which approximately half is drained at different rates into well to poorly drained soils (Fig 1). Due to its glaciated origins, soils at the site are heterogeneous, varying in drainage class from well to poorly drained soils (saturated hydraulic conductivity ranges from 0.0001 to 0.029 m d<sup>-1</sup> (Jahangir et al., 2013)). The

grassland areas of the site consists of poorly and imperfectly drained Gleys to well drained silty clay loam (topsoil) and dense gravels intermixed with clay at 0.6 to 10.0 m subsoil geology. In poorly drained areas, an artificial drainage system has been installed and in-field drains discharge to a ditch network with high connectivity to the surrounding landscape (Fig 2). A detailed description of the drainage network is provided in Clagnan et al. (2019). The total length of the drainage system within the catchment boundary is 10.25 km, comprising of 1.01 km of ditches with drains installed at approximately 1.2 to 2.9 m depth. The main ditch within the farm runs parallel to the farmyard and is 850 m in length. This ditch starts with shallow depth of 30 cm and gradually gets deeper to 270 cm, with 20 m above ordnance datum (AOD) change in elevation, and is the focus of this current study.

In terms of runoff and sub-surface drainage, an area of 94 ha (Kurz et al. 2005) – delineated up-gradient (24 ha) and down-gradient (70 ha) in Fig 1 – contributes to discharge which enters the ditch through concrete pipes at No 1 & 2 (Fig 2). The down-gradient contribution area enters the ditch at No 2 and is represented by the sampling point A. The up-gradient area (Fig 1) enters the ditch at No 1. Other sources of water into the ditch stem are from direct rainfall or groundwater. A groundwater well between the ditch and the farmyard (Fig 2, Well 2 total depth of ~ 5 below ground level (bgl)) had an average water table height of < 1 m bgl with a hydraulic gradient of 0.5, indicating discharge to the ditch through the bankside subsoil horizons and through the base of the ditch. Fig. 2 shows the groundwater elevation in the area of the ditch showing movement through the farmyard area towards the ditch. This places the water-table at 1 m below the farmyard which interacts with the depth of the concrete slurry storage facilities. On the opposite side of the ditch poorly drained soils have not been artificially drained and are presently out of production. Based on their connectivity and landscape position, Moloney et al. (2019) identified

agricultural ditches as being high risk areas of P loss on Irish farms. At the Johnstown Castle site, water quality and P dynamics of bankside and sediment samples along the length of the ditch were collected to provide a detailed appraisal of the impacts of sources entering the ditch. Seven sediment and water sampling points (Sites A, B, C, D, E, F, G in Fig 2) along the ditch network were selected for sample collection.

## *2.2 Bankside and sediment sampling and analysis*

Sediment samples from the bankside and base locations of the ditch were collected in October 2017. Grass and plants were removed and the bankside profile was sampled at depth intervals of 30 cm from top to base. The number of samples collected at each site varied as the depth of the ditch varied along its length and are listed as follows: A: 1; B: 3; C: 4; D: 4; E: 8; F: 10; G: 9. Figures besides Location-Code represents the depth interval number (e.g. A1). Similarly, sediments from the base of the ditch were collected, at the same location as bankside samples.

### *2.2.1 Soil Chemistry analysis*

All sediment samples were oven dried (40 °C) and sieved (2 mm) to remove stones and debris, and were stored at room temperature prior to analysis. Sediment pH was analysed on 2:1 soil-water ratio paste and OM was measured based on loss-on-ignition of 4 g of samples at 500 °C (Schulte, 1995). The modified Mehlich 3-P (M3P) method (Mehlich, 1984) was used to determine labile extractable P, Al, Fe, Ca using a soil solution ratio of 1:10 in Mehlich 3 reagent (0.2M CH<sub>3</sub>COOH + 0.25MNH<sub>4</sub>NO<sub>3</sub>+ 0.015M NH<sub>4</sub>F + 0.13M HNO<sub>3</sub>+0.001M EDTA). Two



gram samples were shaken on a reciprocating shaker for 5 min and the supernatant was filtered to determine concentrations of labile extractable P, Al, Fe and Ca.

### *2.2.2 Phosphorus sorption isotherm and equilibrium P concentration*

The P sorption properties of the bankside and sediment samples were described by a P sorption isotherm derived for all locations and depths along the ditch. Sediment samples from the bankside and base locations were equilibrated with six solutions with concentrations of 0, 5, 10, 15, 20 and 25 mg P L<sup>-1</sup>. Analyses were carried out in duplicate by adding 30 ml of P solutions to 2 g sediment in 50 ml centrifuge tubes. The tubes were shaken in an end-over-end shaker at room temperature for 24 h, centrifuged and filtered, and the final concentration of P in solution was measured colorimetrically. ~~The difference between initial concentration and final equilibrium P concentration was calculated as P sorbed to the soil (Paulter and Sims, 2000).~~ The linear form of the Langmuir isotherm equation ( $C/S = 1/S_{\max} * k + C/S_{\max}$ ) was fitted to the sorption data and was used to derive the maximum sorption capacity ( $S_{\max}$ ; mg kg<sup>-1</sup>) and  $k$  (L mg<sup>-1</sup>), the constants related to the P binding energy in sediment.

The P sink/source dynamics of bankside and sediment samples was determined by the equilibrium P concentration ( $EPC_0$ ), which represents a solution P concentration at the sediment-water interface where P is neither sorbed nor released. This parameter is often used to describe the role of sediment in freshwater systems in regulating P concentrations where sediment will adsorb/desorb P in order to reach a target P concentration at equilibrium, or  $EPC_0$ . If the sediment  $EPC_0$  is higher than freshwater DRP, the sediment will release P to the water column in order to attain that equilibrium solution P concentration. If the sediment  $EPC_0$  is lower than the

freshwater DRP, there will be net P adsorption from the water to the sediment in an effort to maintain a lower P concentration in solution at equilibrium (McDowell et al., 2015). The EPCo in bankside and sediment samples collected along the ditch was measured using 1 g sediment equilibrated with 20 ml of solution P concentrations of 0, 0.1, 0.25, 0.5, 1 mg L<sup>-1</sup> and shaken at room temperature for 24 h, centrifuged and filtered through 0.45 µm filters to measure the concentration of P in solution (Murphy and Riley, 1962). The EPCo was calculated from the slope of the linear plot of P sorbed on the solid phase against final solution P concentration.

### *2.3 Ditch water sampling and analysis*

Grab water samples from sampling points A to G (Fig 2) were collected from Jan 2017 to July 2018. Filtered (0.45 µm) water samples were collected in 50 ml tubes and analysed for DRP using colorimetric analysis (Aquachem600 Labmedics Analytics, Thermo Clinical Labsystems, Finland) and digested with acid persulphate to determine total dissolved P (TDP). Unfiltered samples were analysed for total reactive P (TRP) using colorimetry (Aquachem) and particulate P (PP) was calculated by subtracting TDP from TP. Additionally, ditch water at each location was pumped to a flow cell connected with an *in-situ* Multiparameter Probe (In Situ Inc. Ltd., USA) to measure temperature, electrical conductivity (EC), rugged dissolved oxygen (RDO), and pH under steady-state conditions.

## **3. Results and discussion**

### *3.1 Trends in water quality along an open ditch*

Table 1 presents summary statistics of DRP, TP, PP, and TRP across sampling points for the sample period January 2017 to July 2018. The distribution of these data is shown as boxplots in Figure 3. Values of DRP and TP at sample points A to C were lower in comparison to values measured further downstream from D to G. Average DRP and TP values between A and C were 0.042 and 0.168 mg L<sup>-1</sup>, respectively, and increased to 0.237 mg DRP L<sup>-1</sup> and 0.48 mg TP L<sup>-1</sup> between D and G. A step change in P concentrations was observed at sample point D, indicating a point source contribution possibly due to inputs from the farmyard (Fig 2), which was located between sampling points D and E. Fieldwork during the current study identified several pipes directly discharging (odorous) into the ditch from the farmyard area, and these were also tested when running water discharged from the pipes (red straight lines between farmyard and ditch in Figure 2). The results at point E are indicative of direct discharges from the farmyard as evidenced by maximum DRP and TP concentrations of 2.976 mg L<sup>-1</sup> and 4.89 mg L<sup>-1</sup>, respectively. Downstream from D, these parameters remained high and increased along the length of the ditch, with highest mean DRP at F (0.434 mg L<sup>-1</sup>) almost 10 times higher than A and twice that recorded at E. Max DRP concentrations recorded at F of 1.258 mg L<sup>-1</sup> suggested that high P inputs are not attenuated by bankside and sediment along the ditch but continued to increase downstream at G, where the maximum DRP concentration was almost twice that of F. Highest concentrations at G are likely due to the direct discharges into the ditch from the yard (positioned at 37m AOD) and potentially the diffuse inputs coming from surrounding fields including a dairy lagoon, which are accumulated down slope (33 m AOD). A step-change in TP values was also observed at D. Maximum TP of between 0.11 and 0.33 mg L<sup>-1</sup> between A and C, rose to between 1.32 and 4.89 mg L<sup>-1</sup> from D to G, which were consistent with previously reported TP values in agricultural ditches with a direct connection to a farmyard (Harrison et al.,

2019; Moloney et al., 2019). At catchment scale, Harrison et al. (2019) reported mean TP values  $>1.5 \text{ mg L}^{-1}$  in a riparian survey of ditches connected to farmyards and Moloney et al. (2019) have identified this type of ditch as highest risk for P loss, if its landscape position allows for a direct connection into watercourses, compared to disconnected and secondary ditches.

Over the length of the ditch, average PP values were similar at all sample points except D, where a sharp increase to  $0.135 \text{ mg L}^{-1}$  was observed, coinciding with potential point source inputs from the farmyard. However, mean PP values further downstream fell back to within the range observed at upstream points, indicating some attenuation of the particulate fraction from this point onward. Point source inputs to the ditch were evident at sample point D, as soluble P remained high along the length of the ditch. However, the sharp increase in PP reverted to lower concentrations, indicating some ability to attenuate particulate fractions downstream.

### *3.2 Bankside and sediment characteristics*

The biogeochemical properties of bankside and sediment samples for each depth interval are represented by Mehlich extractable Al, Fe, Ca, % OM and pH, and are presented in Table 2. Sediment and bankside pH ranged from 5.38 to 7.9, with high pH values coinciding with highest values of Ca at sample points E, F and G. In general, most of the bankside and sediment samples had a neutral pH and moderately low Al and Fe values compared to those recorded in previous studies on Irish soils and sediments (Daly et al., 2015; Daly et al., 2017). High extractable Ca was evident at sample points E, F and G, perhaps as a consequence of a change in soil characteristics or soil type along this reach of the ditch as illustrated in Figure 2. The % OM ranged from 1.8 to 21.3% from point A to G, demonstrating the variability in soil types and drainage classes on surrounding fields at the site, with highest values recorded at surface

bankside samples on imperfectly drained soils and lowest values along the length of the ditch dominated by well drained soils (Fig. 2).

The extractable metals, Al, Fe and Ca, have been reported to have a high affinity for P in both soils and sediment (Gächter and Müller, 2003; Mellander et al., 2012; Daly et al., 2017). However, the bankside/sediment analysis of our study showed low level of Al (range of 355 mg kg<sup>-1</sup> between bankside of all sites) and Fe (range of 351 mg kg<sup>-1</sup> between all sites except C4, which was 781 mg kg<sup>-1</sup>), with moderate to high M3Ca values (range of 4223 mg kg<sup>-1</sup> with lowest values recorded at D and highest at G in the imperfectly drained area of the farm).

### 3.2 Trends in *Bankside and sediment P dynamics along the ditch network*

Mehlich3 extractable P varied along the length and depth of the ditch network, with values exceeding the agronomic optimum of 50 mg kg<sup>-1</sup> recorded at all sample points, except A and C (Table 3). There were higher M3P values at E which continued downstream reaching highest M3P values recorded at the surface bankside samples at G of 101 to 108 mg kg<sup>-1</sup> at depth of 90 cm. The step change in water quality P values recorded at D (Table 1), signalling point source inputs, was also observed in bankside and sediment P data; however, this occurred at the next downstream sample point (E). Welch's t-test results showed significant differences in M3P and EPC<sub>0</sub> values from D to E (p-value <0.05) and D and G (p-value of 0.0084), and significant differences in EPC<sub>0</sub> values between B and G (p-value=0.009). This implies that whilst point source P impacted water quality at D, these inputs may be mobilised downstream where they start to accumulate as M3P in sediment, starting at E. At upstream points between A and C, M3P values were generally low; however, accumulation of extractable P is evidenced by increasing

M3P values from E, downstream to G and likely due to P deposition by water draining the site. Box plots in Figure 4 illustrate the shift upwards in extractable P along the length of the ditch.

Phosphorus sorption isotherm parameters  $S_{\max}$  and  $k$ , representing sorption capacity and P binding energies, are presented in Table 3 and Figure 4. Values of  $k$  ranged from 0.3 to 2.9 L mg<sup>-1</sup> with lowest values recorded at sample point G, coinciding with high M3P values at this point. This parameter, representing P binding and affinity, decreased along the length of the ditch, from point E onward, and coincided with the upward shift in extractable P in bankside and sediment samples from E to G. Bankside and sediment locations downstream were characterised by loosely bound P and high extractable P, thereby increasing the likelihood of P loss to the overlying water. The  $EPC_0$  parameter in this study was measured along the length and depth of the ditch to identify whether this ditch acts as a source or sink at bankside and sediment locations along its reach. However,  $EPC_0$  illustrated in Figure 4 and tabulated in Table 3 highlighted the variability in  $EPC_0$  with highest values recorded at surface bankside locations and a trend toward increasing values from A to G along the length of the ditch. Highest  $EPC_0$  and M3P values at G indicate accumulation and deposition of P, which are a source of P to the overlying water in the ditch. At all bankside depths at G,  $k$  values were low (<1 mg L<sup>-1</sup>) and  $EPC_0$  values ranged from 0.24 to 4.61 mg L<sup>-1</sup>. The P dynamics at this point on the ditch indicate that deposition of P from upstream sources and water draining the site has altered the sediment P sorption characteristics towards net release of P to water.

The relationship between  $k$  and  $EPC_0$  in bankside and sediment samples is illustrated in Fig 5 (a), showing the influence of binding energies on potential P release. Bankside and sediment  $k$  values

accounted for 40 % of the variation in  $EPC_0$  values. Moloney et al. (2019) found a similar regression coefficient between  $k$  and  $EPC_0$  measured in ditch sediment across 10 farms and also reported the influence of accumulated labile P in ditch sediment on  $EPC_0$  values. A similar relationship between M3P and  $EPC_0$  is plotted in Fig 5 (b), demonstrating the positive relationship between accumulated labile P (M3P) and  $EPC_0$  values, therefore supporting the hypothesis that P deposition in ditches can act as a source of P to overlying water.

### *3.5. Impacts on water quality and source-sink properties of ditch sediments*

The water quality and bankside-sediment data are both indicative of diffuse and point sources of P coming into the ditch network. A step change in water quality was observed at D, due to point source inputs from the yard, but the effect on sediment P dynamics and deposition occurred further downstream at E. These data signal the influence of the farm yard on water quality and sediment P deposition in agricultural ditches. These inputs acted as a direct point source of P into the ditch and a source of P accumulation in sediment, causing deterioration in water quality and altered P sorption dynamics of the bankside and sediment. Changes in sediment P were characterised by higher extractable P (M3P) and lower P binding energies. Furthermore, P inputs into the ditch altered the  $EPC_0$ , reducing the attenuation capacity of bankside and sediments in the ditch. This is also evidenced by the positive correlation between M3P and  $EPC_0$ , highlighting the influence of P inputs on the ability of the sediment to attenuate P.

The accumulated P in surface layers of E, coupled with lower  $k$  values, and consistently high DRP and TP concentrations in the overlying water, show the release of P from bankside sediment. This is similar to some deeper intervals of F and all intervals of G, which were

saturated with P. This resulted in greater releases of accumulated P into the water and thus higher DRP concentrations. This observation is also supported by the relationship between mean bankside and sediment  $EPC_0$  at each sampling point along the ditch plotted against mean DRP values at each point (Fig 6). The plot include the 1:1 line of equality between  $EPC_0$  and DRP values, where points below the line indicate the sediment acts as a P source and points above the line indicate a P sink (Smith et al., 2004). In Fig. 6 most of the  $EPC_0$  values along this ditch, with the exception of values recorded at A and B, acted as source of P.

It is also necessary to implement mitigation interventions (McDowell and Nash, 2012) to clean ditch water before it leaves the farm (King et al., 2015). This study identified the location for successful installation of an in-ditch nutrient interceptor between points D and E, the locations at which the nutrient concentrations start to elevate and before they accumulate at point G. Using the ditch network and maximising the natural attenuation capacity by implementing in-ditch engineered structures filled with media with nutrient adsorption/remediation capacity (Ezzati et al., 2019) will retain P before entering into surface water. Here again, we should consider the high legacy P in deeper soil layers of the bankside which will continue releasing P into the water. Therefore, there will not be an immediate impact of water quality even after removing the source pollution.

#### **4. Conclusion and recommendations**

This study examined hydrochemistry and sediment P trends along the length and depth of an agricultural ditch network on an intensive dairy farm. High spatial resolution grab samples of



ditch water were collected over 18 months alongside measurements of bankside and sediment P chemistry at depth intervals at points along the ditch.

The results demonstrated that such P inputs have altered the physico-chemical characteristics of the ditch sediment, which highlights the need to remediate sediment to restore its natural P attenuation capacity and reverse its role as a secondary source of P to water. Water quality policy design will need to account for physico-chemical the lag phases in sediment remediation before any improvements are observed. Preventing further point source inputs to the ditch requires substantial restructuring in the farm yard, such as redirecting yard runoff entering ditches, directly or indirectly, by for example, blocking the pipes and collecting runoff for water treatment.

## Figure Captions

Figure 1. Johnstown Castle Intensive Dairy farm showing the up-gradient and down-gradient surface/subsurface drainage system and runoff areas and their entry point into the open ditch system, soil drainage class, and sampling points across the farm documented by Kurz et al. (2005) and Clagnan et al. (2019). ☒ No.1 ; ⊕ No.2

Figure 2. In ditch grab water and soil-subsoil-sediment sampling points (Sites A-G). Position of farmyard, entry points of up-gradient and down-gradient discharge to the ditch (☒ No.1; ⊕ No.2), position of pipes discharging directly into the ditch and water table height (m AOD) around the ditch network. Groundwater flow is perpendicular to groundwater contours i.e. into ditch.

Figure 3. Boxplots showing distribution of water quality data: DRP, TP, PP, and TRP (mg/l) at sampling locations A-G. The midline represents the median.

Figure 4. Boxplots showing the distribution of S<sub>max</sub>, EPC<sub>0</sub>, k, and M3P values in all bankside and sediments at sampling locations A-G. The midline represents the median.

Figure 5. Scatter plot showing (a) regression line between log EPC<sub>0</sub> and log K and (b) regression line between log EPC<sub>0</sub> and log M3P in all bankside and sediment samples.

Figure 6. Mean DRP values collected at sampling points as a function of average EPC<sub>0</sub> at bankside and EPC<sub>0</sub> of sediment.

Close circle: Average  $EPC_0$  from bankside ( $\text{mg L}^{-1}$ ), Open circle:  $EPC_0$  ( $\text{mg L}^{-1}$ ) values from sediment. Values below 1:1 line indicate that the point act as a potential source of P.

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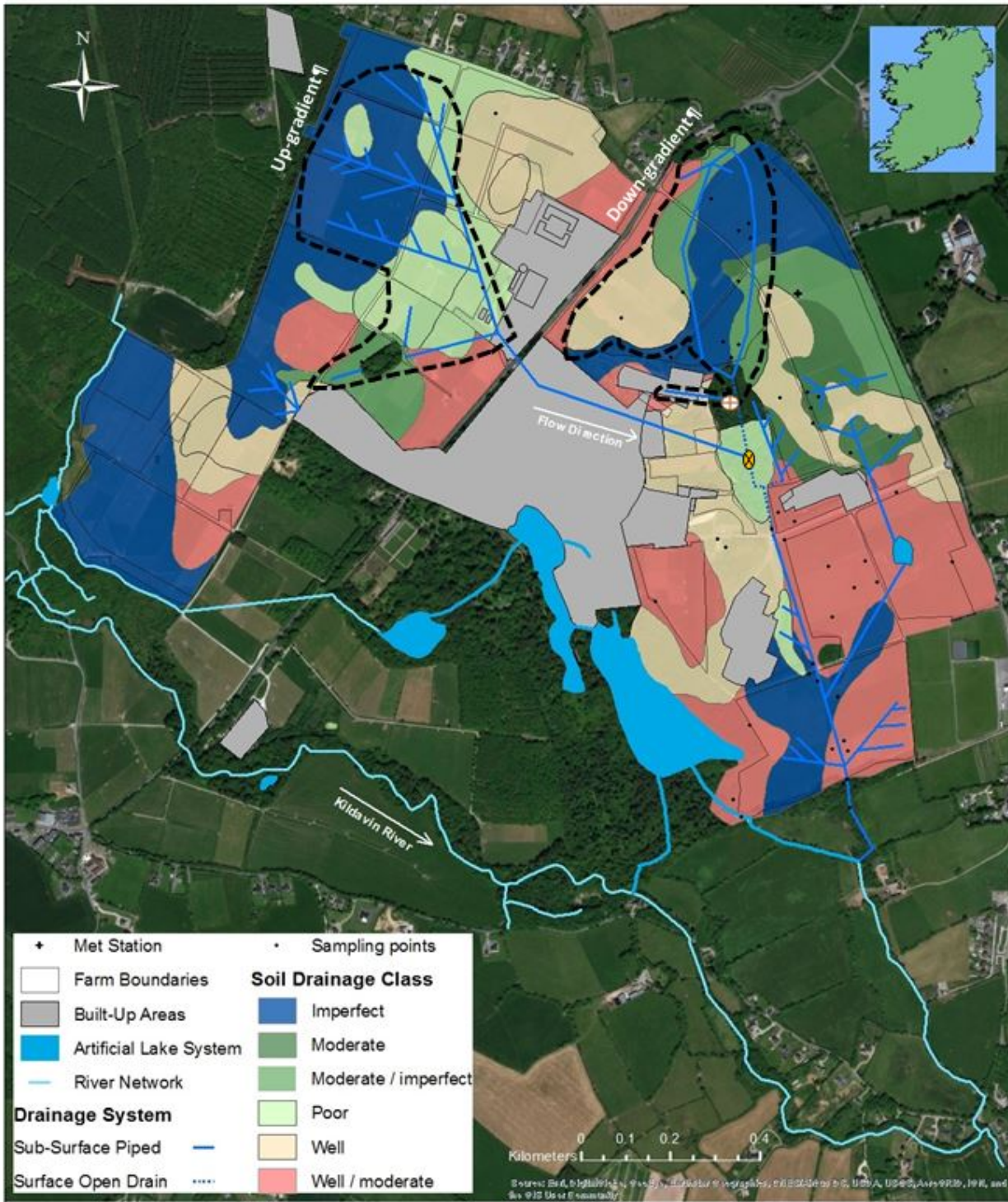


Figure 1. Johnstown Castle Intensive Dairy farm showing the up-gradient and down-gradient surface/subsurface drainage system and runoff areas and their entry point into the open ditch system, soil drainage class, and sampling points across the farm documented by Kurz et al. (2005) and Clagnan et al. (2019). ⊗ No.1 ; ⊕ No.2



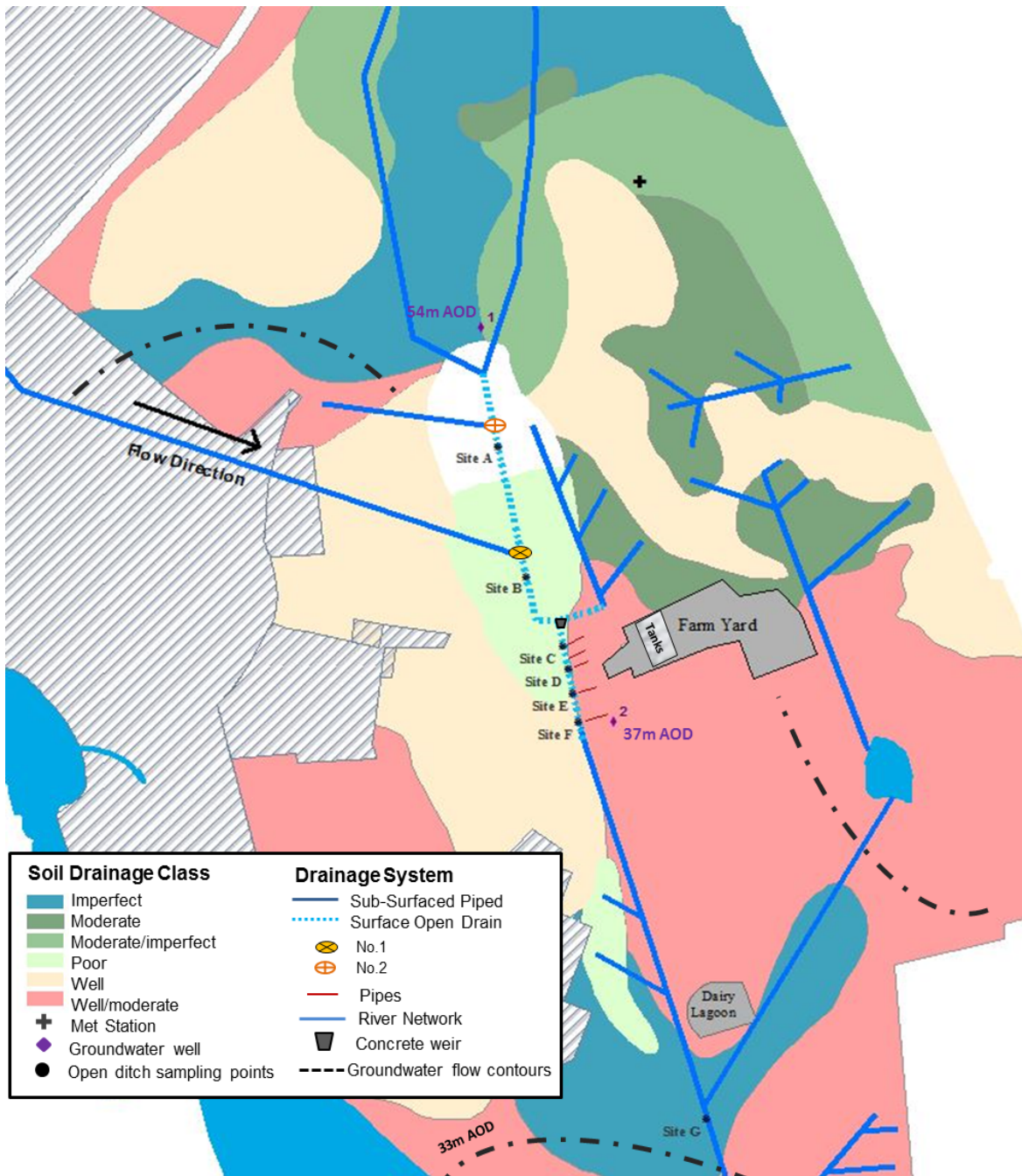


Figure 2. In ditch grab water and soil-subsoil-sediment sampling points (Sites A-G). Position of farmyard, entry points of up-gradient and down-gradient discharge to the ditch (⊗ No.1; ⊕ No.2), position of pipes discharging directly into the ditch and water table height (m AOD) around the ditch network. Groundwater flow is perpendicular to groundwater contours i.e. into ditch.

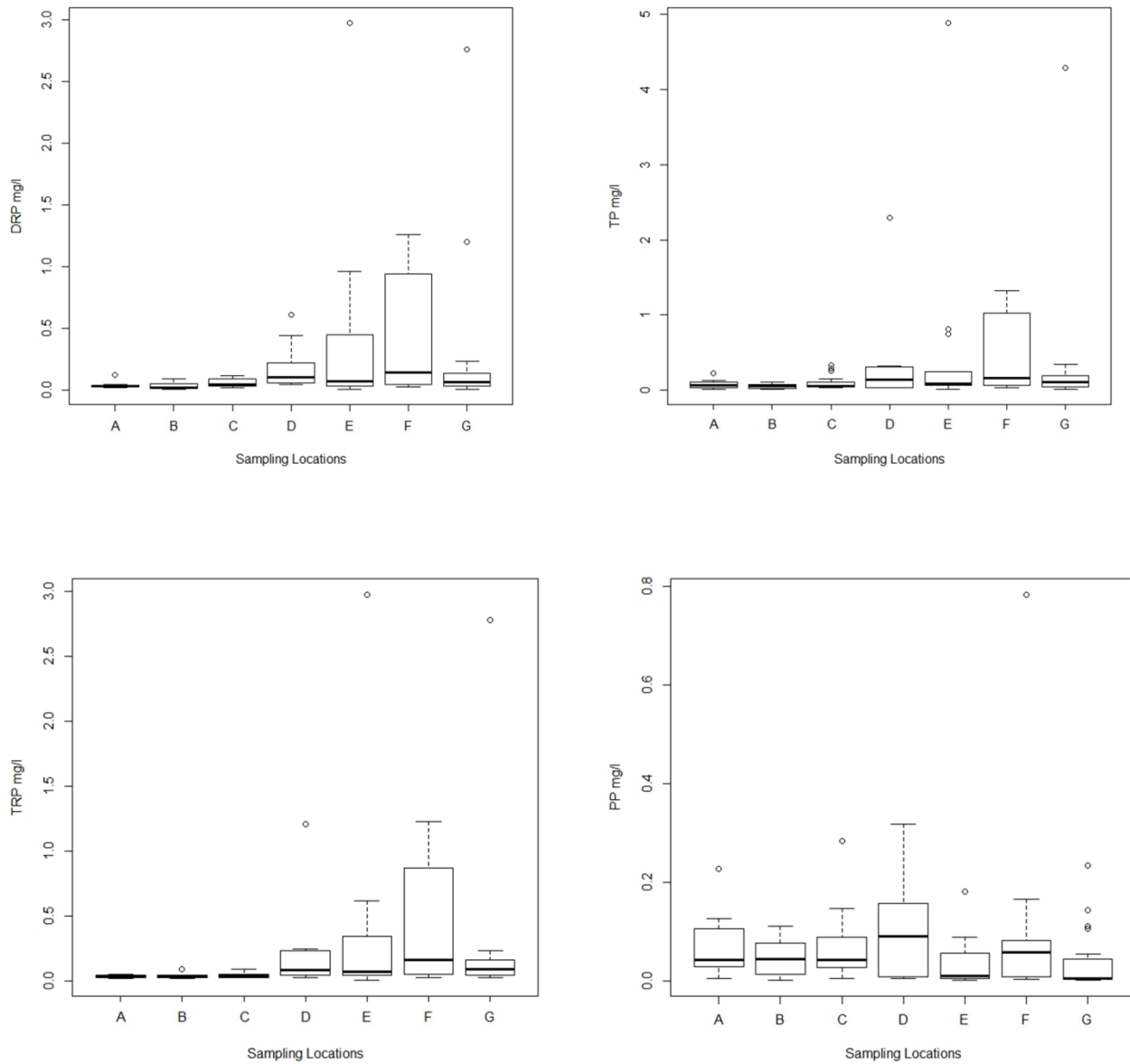


Figure 3. Boxplots showing distribution of water quality data: DRP, TP, PP, and TRP (mg/l) at sampling locations A-G. The midline represents the median.

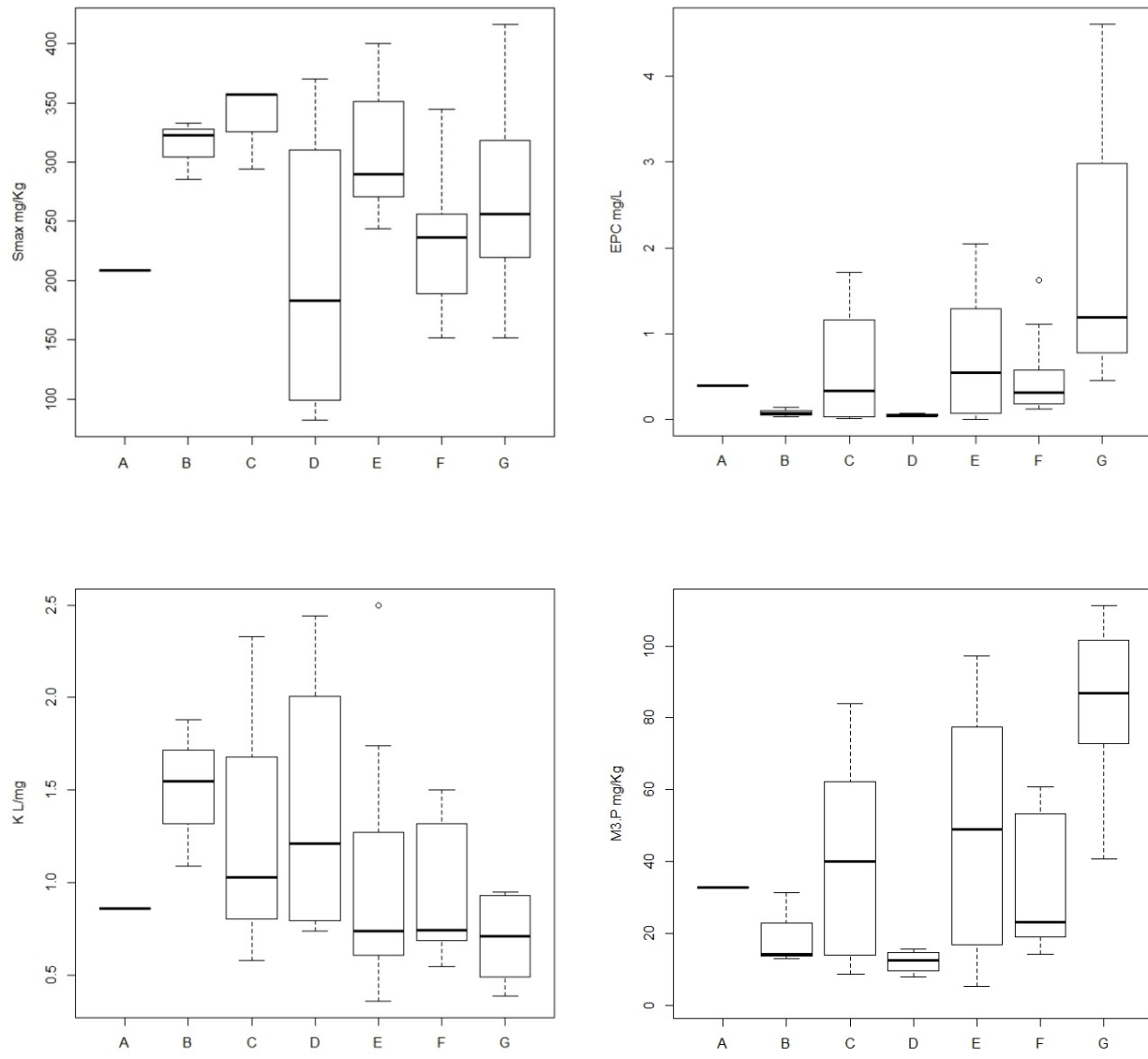


Figure 4. Boxplots showing the distribution of Smax, EPC<sub>0</sub>, k, and M3P values of bankside and sediments at sampling locations A-G. The midline represents the median.

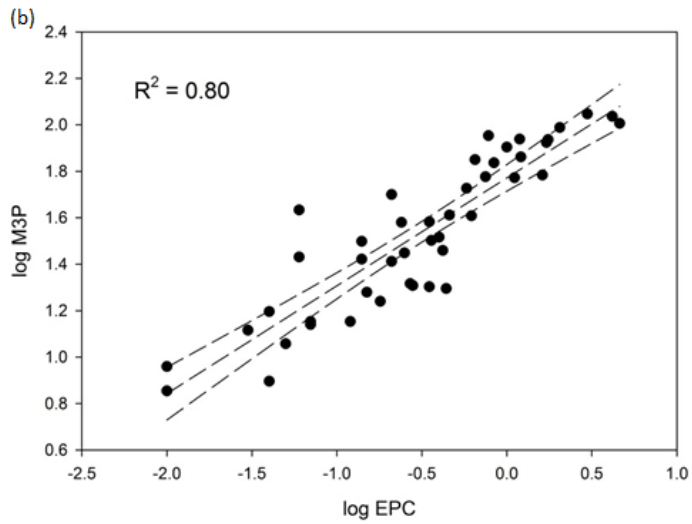
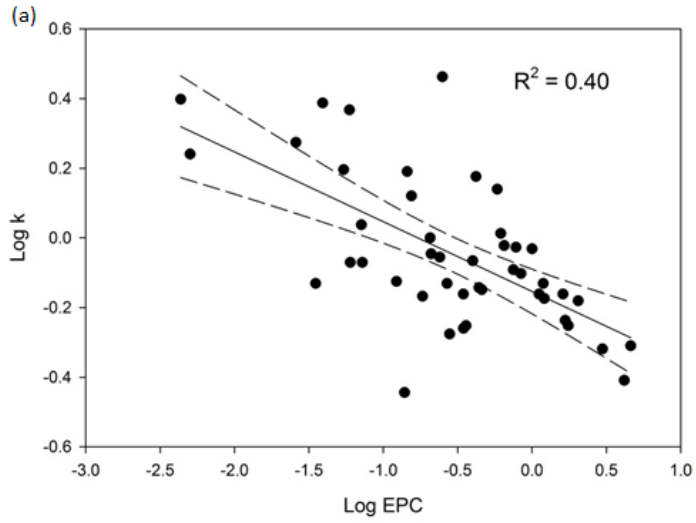


Figure 5. Scatter plot showing (a) regression line between  $\log EPC_0$  and  $\log K$  and (b) regression line between  $\log EPC_0$  and  $\log M3P$  in all bankside and sediment samples.

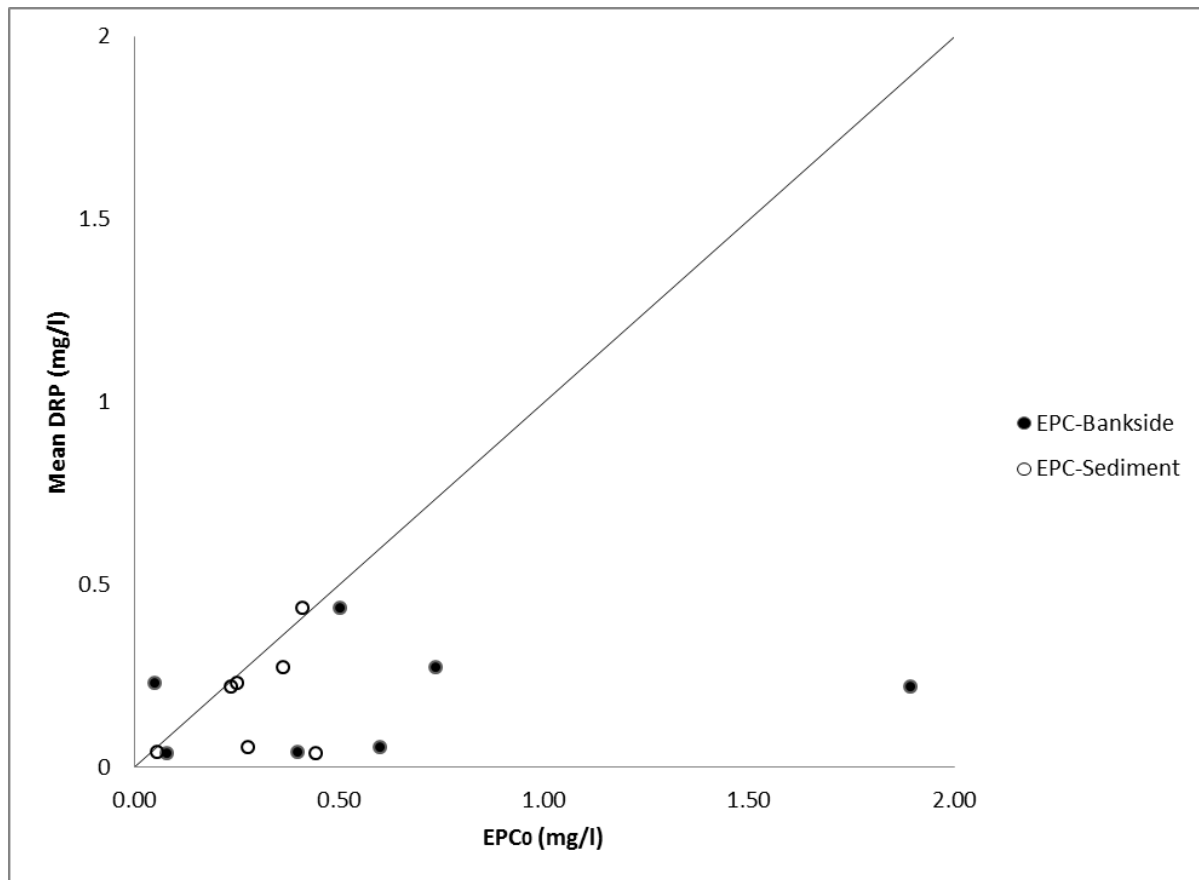


Figure 6. Mean DRP values collected at sampling points as a function of average EPC<sub>0</sub> at bankside and EPC<sub>0</sub> of sediment.

Close circle: Average EPC<sub>0</sub> from bankside (mg L<sup>-1</sup>), Open circle: EPC<sub>0</sub> (mg L<sup>-1</sup>) values from sediment. Values below 1:1 line indicate that the point act as a potential source of P.

Table 1. Summary statistics of phosphorus concentrations and biogeochemical data for sites A-G in the ditch during January 2017-July 2018.

Location	Sample size	DRP	TP	PP	TRP	pH	Temp.	EC	RDO
		mg L <sup>-1</sup>					°C	μS cm <sup>-1</sup>	mg L <sup>-1</sup>
<b>Site A</b>	10								
Max		0.120	0.227	0.227	0.052	8.44	12.9	471.1	10.67
Min		0.020	0.014	0.004	0.021	6.86	8.06	251.9	9.12
Mean		0.041	0.080	0.077	0.037	7.26	9.8	364.1	9.99
Median		0.030	0.053	0.042	0.038				
<b>Site B</b>	10								
Max		0.088	0.110	0.110	0.093	7.27	10.07	388.8	9.64
Min		0.008	0.009	0.009	0.019	5.95	9.03	366.9	8.93
Mean		0.036	0.051	0.031	0.043	6.82	9.3	375.3	9.24
Median		0.019	0.053	0.013	0.040				
<b>Site C</b>	18								
Max		0.114	0.330	0.284	0.090	8.2	12.5	426.7	12.56
Min		0.021	0.028	0.005	0.025	6.97	7.9	236.7	8.21
Mean		0.054	0.087	0.066	0.045	7.23	9.6	348.5	10.18
Median		0.043	0.055	0.040	0.039				
<b>Site D</b>	10								
Max		0.610	2.290	0.318	1.210	7.56	12.6	423.8	10.75
Min		0.047	0.031	0.005	0.048	6.9	9.1	342	8.98
Mean		0.228	0.536	0.135	0.363	7.18	11.3	392.9	9.86
Median		0.123	0.156	0.100	0.132				
<b>Site E</b>	16								
Max		2.976	4.890	0.180	2.980	8.6	14.9	720	11.7
Min		0.008	0.017	0.001	0.007	6.34	7.9	252	8.89
Mean		0.272	0.536	0.036	0.432	7.32	11.1	466.1	10.28
Median		0.031	0.086	0.010	0.071				
<b>Site F</b>	18								
Max		1.258	1.320	0.784	1.230	8.6	14.8	560.8	10.86
Min		0.027	0.034	0.003	0.025	7.05	9.1	346.2	9.98
Mean		0.434	0.537	0.096	0.451	7.56	11.5	423.2	10.56
Median		0.147	0.165	0.058	0.167				
<b>Site G</b>	18								
Max		2.759	4.290	0.234	2.781	9.24	12.6	632.1	11.9
Min		0.004	0.016	0.000	0.025	6.98	8.2	233.2	8.09
Mean		0.220	0.242	0.037	0.225	7.90	9.5	385	10.102
Median		0.062	0.105	0.005	0.094				

Temp: Temperature; EC: Electric conductivity; RDO: Rugged dissolved oxygen.

Table 2. Bankside and sediment biogeochemical properties from each depth represented by Mehlich extractable Al, Fe, Ca, with % organic matter (OM) and pH.

Location		Depth	pH	OM	M3Ca	M3Al	M3Fe
		(cm)		(%)			
Site A	A1	0-30	6.9	3.2	12568	213	230
	Sediment		6.0	1.8	977	259	134
Site B	B1	0-30	5.38	8.0	12363	448	259
	B2	30-60	5.42	5.5	10592	511	308
	B3	60-100	5.66	5.0	1172	449	401
	Sediment		7.2	3.1	1530	173	26
Site C	C1	0-30	6.1	6.8	1811	338	284
	C2	30-60	6.2	4.8	15012	309	269
	C3	60-90	7.3	2.8	14563	234	418
	C4	90-110	7.5	5.2	34854	65	781
	Sediment		7.9	1.0	698	68	139
Site D	D1	0-30	6.5	5.2	1996	469	149
	D2	30-60	6.5	2.0	792	362	67
	D3	60-90	6.4	0.8	303	130	142
	D4	90-110	6.7	1.7	870	205	323
	Sediment		7.8	1.4	986	91.88	190
Site E	E1	0-30	7.1	5.6	25454	180	264
	E2	30-60	7.2	6.1	21864	200	276
	E3	60-90	7.4	5.0	22672	285	193
	E4	90-120	7.4	3.9	19943	373	215
	E5	120-150	7.5	2.9	13851	411	178
	E6	150-180	7.6	1.4	849	256	236
	E7	180-210	7.9	2.4	20217	369	146
	E8	210-240	7.9	1.0	20175	362	154
	Sediment		7.8	2.9	91	89.54	239
Site F	F1	0-30	6.8	4.6	19997	493	225
	F2	30-60	5.9	4.4	1397	399	230
	F3	60-90	6.0	3.9	12546	456	226
	F4	90-120	6.2	3.8	12148	277	164
	F5	120-150	6.0	3.8	11765	328	179
	F6	150-180	6.1	3.2	11054	191	157
	F7	180-210	6.4	5.7	17744	307	278
	F8	210-240	6.6	7.1	22538	343	245
	F9	240-270	6.7	7.4	26862	484	266
	F10	270-290	6.7	6.1	23473	476	191
	Sediment		7.2	3.3	1705	158.73	336
Site G	G1	0-30	6.3	21.3	45266	376	261
	G2	30-60	6.5	18.1	38003	312	226
	G3	60-90	6.6	17.7	42736	372	280
	G4	90-120	7.1	6.5	2728	399	275
	G5	120-150	6.7	10.1	25664	315	260
	G6	150-180	7.1	8.0	27634	251	225
	G7	180-210	7.1	5.4	19883	256	282
	G8	210-240	7.4	17.7	18495	244	266
	G9	240-270	7.8	1.3	15364	129	204
	Sediment		7.6	1.5	1015	143.4	266

1  
2

Table 3. Phosphorus sorption expressed by Langmuir  $S_{max}$ ,  $k$ ,  $EPC_0$ , and Mehlich-extractable-P from each interval depths of the bankside and sediments.

Location		Depth (cm)	Langmuir		$EPC_0$ (mg L <sup>-1</sup> )	M3P (mg kg <sup>-1</sup> )
			$S_{max}$ (mg kg <sup>-1</sup> )	$k$ (L mg <sup>-1</sup> )		
Site A	A1	0-30	208	0.85	0.40	32.8
	Sediment		200	0.728	0.06	42.9
Site B	B1	0-30	285	1.093	0.07	14.2
	B2	30-60	333	1.87	0.03	13
	B3	60-100	322	1.55	0.14	31.4
	Sediment		196	0.850	0.44	19.7
Site C	C1	0-30	357	0.58	1.71	83.9
	C2	30-60	294	1.03	0.62	40.5
	C3	60-90	357	2.33	0.06	26.9
	*C4	90-110	n/a	n/a	0.01	9.1
	Sediment		131	0.5278	0.28	20.3
Site D	D1	0-30	250	0.85	0.07	13.8
	D2	30-60	370	1.57	0.05	11.4
	D3	60-90	116	0.741	0.04	7.8
	D4	90-110	81	2.440	0.04	15.
	Sediment		163	2.902	0.25	28
Site E	E1	0-30	285	0.66	2.05	97.3
	E2	30-60	285	0.56	1.75	86.3
	E3	60-90	256	0.81	0.75	59.7
	E4	90-120	294	0.79	0.84	68.6
	E5	120-150	243	0.69	0.35	38.2
	E6	150-180	187	0.75	0.14	26.4
	E7	180-210	400	2.50	0.00	5.4
	E8	210-240	303	1.73	0.01	7.1
	Sediment		192	0.55	0.36	31.7
Site F	F1	0-30	256	1.0	0.21	25.8
	F2	30-60	217	0.75	0.12	14.2
	F3	60-90	222	1.32	0.15	19
	F4	90-120	185	0.675	0.18	17.3
	F5	120-150	188	0.73	0.27	20
	F6	150-180	151	0.55	0.35	20.08
	F7	180-210	250	0.68	1.62	60
	F8	210-240	250	0.68	1.11	59.1
	F9	240-270	344	1.38	0.58	53.2
	F10	270-290	333	1.50	0.42	28.7
Sediment		285	0.89	0.41	50	
Site G	G1	0-30	285	0.49	4.61	101.4
	G2	30-60	357	0.38	4.17	108.8
	G3	60-90	416	0.48	2.98	111.3
	G4	90-120	344	0.93	0.78	89.7
	G5	120-150	285	0.74	1.19	86.7



<b>G6</b>	150-180	303	0.67	1.21	72.7
<b>G7</b>	180-210	256	0.92	1.00	80.1
<b>G8</b>	210-240	250	0.95	0.65	70.7
<b>G9</b>	240-270	178	0.708	0.46	40.8
<b>Sediment</b>		227	0.88	0.24	38

3 \* Freundlich  $R^2$  was 0.4.

4