Enhanced Drainage Ditch Management

Annex A

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Foreword

This report annex was commissioned by Natural England to build knowledge and understanding on a range of nature-based solutions which could be used to reduce nutrients. Greenshank Environmental Limited were commissioned by Natural England to develop a process through which a novel methodology, Enhanced Drainage Ditch Management, could be used to manage agricultural drainage ditches and small watercourses in rural areas. This report presents a framework for how future proposed schemes, when adhering to the framework, can deliver nutrient reductions in perpetuity and be used as mitigation for new developments needing to achieve nutrient neutrality.

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Executive summary

This report is an annex to the report titled *Enhanced Drainage Ditch Management: A framework approach for nutrient neutrality*. The Enhanced Drainage Ditch Management Framework was developed in response to a requirement for approaches to environmental management that can be shown to reduce nutrient inputs to sensitive Habitats Sites. The Framework is based on the outputs from a literature review that is presented in this annex. The literature review sets the theoretical basis for the use of three 'best management practices' (BMPs), namely two-stage channel cross-sections, low-grade weirs and allowing ditches to be vegetated, for the purposes of nutrient management. These BMPs come from American catchment management toolboxes.

Methodology

The literature review first used a number of search terms in an academic literature search engine to obtain all relevant studies on drainage ditch BMPs for nutrient management. These studies were then analysed to obtain supporting information on processes that drive nutrient reductions due to the use of BMPs, and to extract quantitative data on the percentage nutrient reduction efficiency of different BMPs, as well as metadata on each study that may help to determine why some ditches performed better than others. Data were analysed statistically to determine average and precautionary estimates of nutrient reductions due to the use of BMPs in drainage ditches and small watercourses.

The theory behind using drainage ditch BMPs for nutrient mitigation

The literature analysis found that nutrient reductions due to ditch BMPs were predominantly due to chemical process that, especially for nitrogen, can be mediated by bacteria. Nitrogen is cycled by bacteria and removed from a ditch system by emission to the atmosphere as a nitrogen gas. Phosphorus cannot be removed by a 'degassing' process and is instead bound to particles retained in soils and sediments. Nutrient retention by vegetation is an important secondary mechanism of retention for both nitrogen and phosphorus, but it is a temporary nutrient store as nutrients can be re-released when vegetation dies and degrades. Physical processes can also help to store nutrients within a ditch, with sediment-bound phosphorus and nitrogen being deposited as ditch BMPs reduce flow velocities and increase the time water is stored within a ditch. The processes that are promoted by ditch BMPs are the same as those processes active in wetlands that have been shown to reduce onward nutrient transport, and many authors of studies on drainage ditch BMPs note that they help to create what are essentially linear wetland features.

Analysis of nutrient reduction efficiencies

The literature review extracted data on nutrient reduction efficiencies for further analysis. The analysis focused on total nitrogen and total phosphorus load removal in order to match the outputs from development nutrient budget calculations. It was found that average total nitrogen and total phosphorus removal efficiencies were both of the order of

50%, but that there were a relatively small number of studies that were > 1 year in duration which added uncertainty to the averages as they may not have captured seasonal variation. As such, a precautionary approach was used to select a lower bound estimate of nutrient reduction efficiency and round this down to two significant figures. This resulted in a precautionary nutrient reduction efficiency of 28% for both nitrogen and phosphorus. It was also found that this efficiency accorded well with the limited number of studies that reported results for control vs treatment ditches, suggesting that the use of ditch BMPs will result in additional nutrient reductions above that which may be happening due to natural process already active in ditches or watercourses pre-management.

Key design considerations

The literature review also assessed studies for key design factors that could be used to make recommendations of ditch BMP design principles that are likely to maximise nutrient reduction potential. Guidance on how to specify the geometry of a two-stage ditch was also used to inform a process by which a ditch or small watercourse can be reengineered to increase its water retention capacity and thus increase the contact time of nutrient enriched water with soils, sediments and vegetation. The review also makes recommendations about low-grade weir heights and spacing, as well as providing considerations around maintenance. Ditch BMP maintenance regimes should strike a balance between removing vegetation and sediment to reduce the risk from dead, degrading vegetation and excess sediment build up resulting in nutrient remobilisation, while also not impacting the ability of the ditch to slow water flow.

Contents

Introduction 8
Types of drainage ditch best management practices 9
Methodology 12
Literature search and screening 12
Data and metadata extraction 13
Data analysis 16
Mechanisms and factors influencing nutrient removal 17
Nutrient retention and removal by biogeochemical and physicochemical processes 17
Nutrient retention by vegetation assimilation 19
Nutrient retention by physical processes 20
Nutrient reduction efficiencies 21
Efficiency of nitrogen reduction through drainage ditch management 21
Efficiency of phosphorus reduction through drainage ditch management 26
Evidence for existing N and P retention and removal in drainage ditches 31
Drainage ditch design considerations 36
Recommendations re. minimum ditch length 36
Recommendations re. low-grade weir heights and spacing 37
Recommendations re. two-stage ditch design 38
Recommendations re. hydraulic loading rates and hydraulic residence times 43
Considerations re. maintenance 43
Conclusion 44
References 46
Glossary 51
Appendices 52
Appendix 1 52

Introduction

The requirement for new development in affected areas of the UK to achieve Nutrient Neutrality (NN) as part of Habitat Regulations Assessments (HRAs) has renewed focus on requirements to manage nutrient pollution to aquatic environments. Inputs of nitrogen (N) and phosphorus (P) pollution to waterbodies can come from various sources, with the majority coming from treated sewage and agriculture. Agricultural pollution has long been recognised as a key source of N and P to water environments globally (Västilä et al., 2021; Wade et al., 2022; Withers et al., 2014; Withers & Lord, 2002). Managing agricultural sources of N and P presents an opportunity for providing mitigation to help new development achieve NN. However, at present there are limited solutions available for reducing fluxes of N and P from agricultural environments that will pass the requirements of an HRA.

Agricultural drainage ditch networks are conduits for nutrient transport to rivers, lakes and coastal ecosystems. They are designed to move agricultural runoff rapidly into river channels for onward transport. This runoff often has high levels of N and P and ditches tend to allow little time for natural processes to attenuate and remove these nutrients. There is a growing body of literature on the potential for managing drainage ditches to promote natural N and P removal processes, with most studies conducted in North America and China. North American studies refer to drainage ditch 'Best Management Practices (BMPs)' (Faust et al., 2018; Hodaj et al., 2017; Kröger et al., 2011) and various authors have suggested that ditches applying BMPs can promote nutrient removal processes in a similar manner to constructed wetlands (Rizzo et al., 2023; Sharpley et al., 2007; Vymazal & Březinová, 2018). Wetlands are being widely adopted as a key mitigation method for use in response to NN (e.g., Johnson et al., 2022).

There are three main types of BMP that have been widely studied in literature on drainage ditch management for nutrient removal: low-grade weirs, two-stage ditches, and vegetated ditches. Some studies combine BMPs, often combining vegetation with one of the other BMPs. Further details on each BMP are provided below. There are very limited examples of drainage ditch BMP studies in Europe. A recent study in Finland highlighted the potential for two-stage ditches to retain P (Västilä et al., 2021), while a recent review has suggested good N and P reduction efficiencies can be achieved by vegetated ditches (Rizzo et al., 2023). This review did not find any studies of drainage ditch BMPs in the UK, however the results from international studies highlight the potential of this approach to provide nutrient mitigation. Given the ubiquity of drainage ditches in UK agricultural landscapes, BMPs present a large opportunity to develop nutrient mitigation schemes.

This review has collated studies on N and P reductions achieved using ditch BMPs and analysed them in the context of the requirements for mitigation schemes to support nutrient neutral development. Specifically, mitigation schemes need to have an ability to quantify TN and TP load reductions in units of kg/year, in order to align with nutrient budgets for new developments. The aim of this review was thus to compile an evidence base that highlights the potential N and P reductions that drainage ditch BMPs can achieve. This evidence base was used to summarise the processes of N and P removal and retention that are active in ditches applying BMPs. Studies were also analysed determine whether the available evidence was sufficient to set precautionary N and P reduction efficiencies for drainage ditch BMPs.

To increase the likelihood of achieving N and P reductions, this review also assessed key design considerations for drainage ditch management schemes. These considerations were used to make recommendations on various design factors for ditch management schemes. Design factors incorporate geometric parameters that will influence the hydraulics of a ditch to attenuate water flow and increase the probability of nutrient retention and cycling.

The synthesis of previous research within this review was used to establish the evidence base and a set of design principles for reengineering drainage ditches and small watercourses to generate nutrient mitigation. These have been combined in the associated Enhanced Drainage Ditch Management Framework report to which this review has been annexed. The Framework is provided as a separate document that is supported by this annex.

Types of drainage ditch best management practices

Two-stage ditches

Conventional drainage ditches have a trapezoidal cross-section and are often dredged to maintain this cross-sectional profile and assist with flow conveyance (Mahl et al., 2015). Two-stage ditches have been proposed as a nature-based solution that mimics the natural geometry of lowland streams that have narrow main channels and frequently inundated floodplain benches (Figure 1; Västilä et al., 2021). The two-stage ditch design allows for low-flow conveyance in the main channel with the floodplain benches becoming inundated during high flow events. Inundation of floodplain benches decreases discharge rates and allows more contact of ditch flows with soils. This has in turn been associated with increases in N and P removal through processes such as denitrification, P sorption to sediments and sediment deposition (Hodaj et al., 2017). As two-stage ditches have greater flow conveyance capacity, they can also provide additional benefits for natural flood management (Västilä et al., 2021).

Low-grade weirs

Low-grade weirs are a BMP that has mainly been applied in North American studies. Installing weirs in drainage ditches is often referred to as a ‘controlled drainage’ strategy that aims to reduce outflow rates from drainage ditches by storing more water within the ditch network, which can also help to retain nutrients (Kröger et al., 2012). Weirs are installed in drainage ditches to a height below the top of the banks of a ditch (Figure 2), which reduces flow velocities within the ditch (Faust et al., 2018). Weirs can be spatially distributed throughout a ditch system to retain certain volumes of water within the drainage without decreasing the overall capacity of the drainage ditch to convey high flows (Kröger et al., 2011). It has been suggested that positioning low-grade weirs in series so that they are able to retain around 5-10% of a drainage ditch's bankfull volume would be sufficient to help promote natural processes of nutrient removal (Kröger et al., 2011). Littlejohn et al. (2014) suggest that weirs could be constructed as an earthen dam covered with a geotextile for stabilisation and covered with a layer of rip-rap to secure the geotextile. Other designs could utilise wooden boards or Perspex sheeting to create a weir structure at the required height. Retention of water within drainage ditch networks using low-grade weirs may also have benefits for natural flood management.

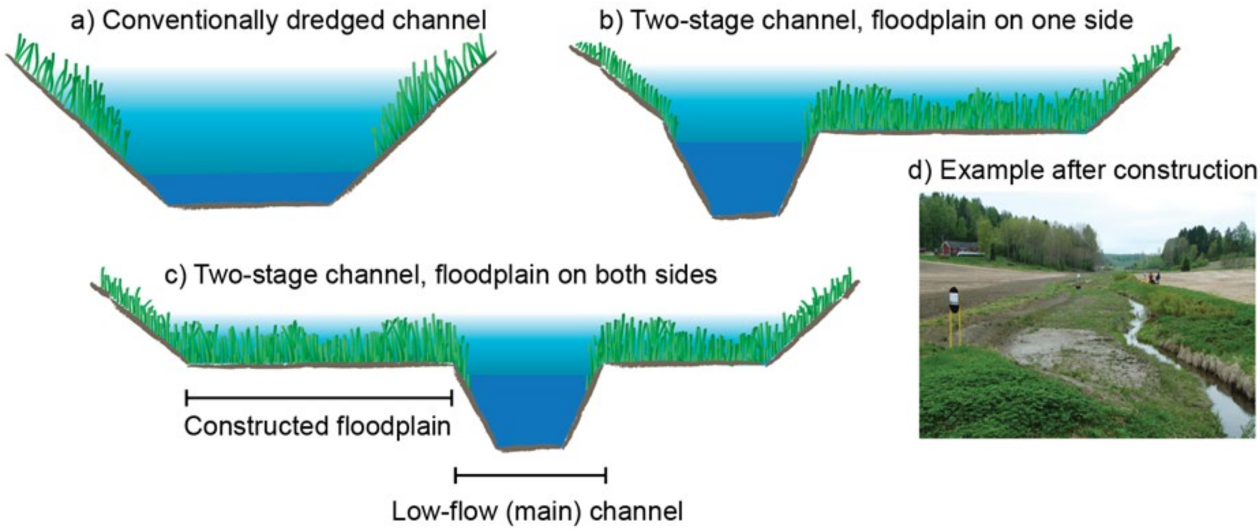

Figure 1: Schematic representation of typical cross-sections of a) conventional trapezoidal drainage ditches; b) and c) two-stage ditch designs; and d) an example of a two-stage ditch in Ritobäcken, Finland (Source: Västilä et al., 2021)**.**

Figure 2: Example of a low-grade weir installed in a drainage ditch in Mississippi, USA. It is noted that the drainage ditch in this image considerably larger than drainage ditches typically seen in the UK. (Source: Kröger et al., 2011)

Vegetated ditches

Drainage ditches tend to have vegetation removed in order to improve flow conveyance. Allowing vegetation to colonise drainage ditches (e.g., Figure 3) is a simple BMP that has been linked to higher rates of N and P removal and transformation (Vymazal & Březinová, 2018). Some studies of vegetation ditches have assessed the nutrient removal potential of this BMP in ditches that vegetated naturally (Lizotte & Locke, 2018), while other studies have used planting in drainage ditches to help promote nutrient removal processes (Nsenga Kumwimba et al., 2021). It has been suggested that vegetated drainage ditches colonised with hydrophytes may act essentially as linear wetlands, as well as providing habitat improvements that can benefit biodiversity (Nifong & Taylor, 2021). As with the other BMPs studied in this review, increasing vegetation density in drainage ditches will reduce flow velocities and increase hydraulic residence times (HRTs), with a potential additional benefit for natural flood management.

Figure 3: A vegetated drainage ditch in the Czech Republic (Source: Vymazal and Březinová, 2018)

Methodology

The literature review was focussed on peer reviewed studies published in academic journals. The geographical scope of the review was effectively global, but with a spatial hierarchy. A preference was given to any UK-based studies, followed by studies conducted in Continental Europe, then the USA and other countries at similar latitudes in Northern and Southern hemispheres. In keeping with other recent reviews of nature-based solutions for nutrient removal (Rizzo et al., 2023), this largely restricted studies included in this review to regions with temperate and subtropical climates. It was recognised that while subtropical climates often have rainfall ranges that overlap with the rainfall ranges seen in the UK, air temperatures are likely to be higher, which can have an impact on nutrient removal rates. The potential impacts of climate on nutrient removal were considered as part of this review.

Literature search and screening

A literature search was conducted using search terms in the academic literature search engine Web of Science. The first search term used was “drainage ditch nutrients”, which returned 427 results. Abstracts from these studies were reviewed for references to ditch management for nutrient removal. Studies referencing ditch management generally referred to three BMPs: low-grade weirs, vegetated drainage ditches and two-stage ditches. The search terms were refined as follows, returning a number of results per term:

- "Vegetated drainage ditch nutrients" – returned 56 results.
- "Two stage drainage ditch nutrients" – returned 21 results.
- "Low-grade weir drainage ditch nutrients" – returned 22 results.

For results returned under each search term, an abstract review was used to select studies that referred to BMPs promoting natural processes of nutrient removal. Following the abstract review, 50 studies were retained. Further screening of these studies was conducted through a rapid assessment of the results in each study. Studies where not taken forward for data extraction where they did not report data in a manner that could be used to determine percentage nutrient reduction efficiencies for drainage ditch BMPs. Following literature screening, 23 studies were retained for detailed review and data extraction.

The review focussed on research articles, review papers and conferences proceedings to provide general information on nutrient removal processes in drainage ditches. Only research articles and reviews were used for data extraction as conferences proceedings are not always peer reviewed.

Data and metadata extraction

For each study retained for detailed review, data on N and P removal were extracted along with metadata on elements of study design. With the exception of one mesocosm study that was conducted within an agricultural field drainage ditch (Castaldelli et al., 2018), all studies used an upstream-downstream study design to assess the impact of drainage ditch BMPs relative to an upstream reference reach. All studies reported sampling techniques, sample handling and laboratory protocol methods that indicated robust data collection procedures. In studies that reported both nutrient concentration and load reductions, a preference was made for capturing data on N and P load reductions. This is due to the requirement of nutrient mitigation for Nutrient Neutrality to be specified in kg/year of N and P, in line with the outputs of nutrient budget calculations for new development. Where data on N and/or P loads were not reported, data on concentrations were extracted instead.

In keeping with mitigation requirements specified in nutrient budgets, there was also a preference for extracting data on total nitrogen (TN) and total phosphorus (TP) reductions through drainage ditch BMPs. Where studies did not report data on TN and/or TP, data on total inorganic nitrogen (TIN) / total oxidised nitrogen (TON) and total inorganic phosphorus (TIP) were preferred over data on nitrate (NO_3) and orthophosphate / soluble reactive phosphorus (SRP), as TIN / TON and TIP represent greater fractions of TN and TP, respectively.

Metadata describing key aspects of study locations were also extracted for each study (Table 1). Data on soils were extracted where available, however too few studies provided information on soil types either within a ditch or in the area around the ditch to allow a meaningful comparison on the potential impacts of soil type on nutrient removal. Data were also captured on the source of water to the ditches in each study (Table 1). Studies with "simulated runoff" were conducted in experimental drainage ditches within research facilities and fed with influent water spiked with nutrients to simulate the impact of an agricultural runoff event. Data on the climate zone of the study location were captured, along with data on study durations (Table 1). Information on study duration was important for ascertaining whether a study captured potential seasonal change in N and P removal (i.e., the study was > 1-year in length). The type of BMP applied to the ditches in each study was recorded. Where a single study reported results for multiple ditches, each ditch was treated as a separate data point for extraction. From each study, the average nutrient reduction efficiency was extracted as a percentage. Where a study did not report the percentage nutrient reduction efficiency, it was calculated from the difference between nutrient concentrations or loads at the upstream reference sampling point and the downstream impact sampling point. Data extraction resulted in a total sample of n = 72 for analysis.

Table 1: Metadata showing key characteristics of studies that were used for data extraction. Some cells are left blank.

		Number of studies or measurements
Country	China	7
	Czech Republic	1
	Italy	1
	USA	14
Climate	Subtropical	11
	Temperate	10
	Temperate Mediterranean	1
	Not reported	1
Water source	Agriculture	14

		Number of studies or measurements
	Aquaculture	1
	Simulated runoff	4
	Wastewater treatment	4
Study duration	> 1 year	14
	< 1 year	12
	Not reported	3
BMP type	Vegetation	34
	Two-stage ditch	7
	Low-grade weir	14
	Multiple BMPs	17

Of the 72 extracted results, 37 reported N reduction efficiencies and 35 reported P reduction efficiencies. Table 2 shows the division of results between studies reporting data on N and P concentration or load.

Table 2: Breakdown of the number of observations of nitrogen and phosphorus reduction efficiencies were reported as load or concentration. Some cells are left blank.

Nutrient	Load or concentration	Number of observations	References
Nitrogen	Concentration	17	Flora and Kröger, 2014; Davis et al., 2015; Mahl et al., 2015; Iseyemi et al., 2016; Kumwimba, Zhu and Muyembe, 2017; Nsenga Kumwimba et al., 2017, 2021; Castaldelli et al., 2018; Vymazal and Březinová, 2018; Wang, Zhu and Zhou, 2019

Nutrient	Load or concentration	Number of observations	References
Nitrogen	Load	20	Kröger et al., 2011, 2012; Fu et al., 2014; Littlejohn et al., 2014; Baker et al., 2016; Hodaj et al., 2017; Faust et al., 2018; Lizotte and Locke, 2018; Cui et al., 2020; Zhang et al., 2020; Nifong and Taylor, 2021
Phosphorus	Concentration	17	Flora and Kröger, 2014; Davis et al., 2015; Mahl et al., 2015; Iseyemi et al., 2016; Kumwimba, Zhu and Muyembe, 2017; Nsenga Kumwimba et al., 2017; Vymazal and Březinová, 2018; Kindervater and Steinman, 2019; Wang, Zhu and Zhou, 2019
Phosphorus	Load	18	Kröger et al., 2011; Fu et al., 2014; Littlejohn et al., 2014; Baker et al., 2016; Hodaj et al., 2017; Faust et al., 2018; Lizotte and Locke, 2018; Cui et al., 2020; Nifong and Taylor, 2021

Data analysis

Data analysis divided the observations of reduction efficiencies as either concentrations or loads into specific types of N and P, e.g., TP, TN, TIN, TIP etc. It is important to differentiate between types of N and P, in order to reduce the risk of conflating removal processes that are relevant to specific types of nutrients, which would reduce the accuracy of analysis. For the reasons highlighted above, more detailed analysis focussed on studies reporting TN and TP load removal. Data on other types of N and P and on concentration reduction efficiencies were used for additional context and to inform wider considerations around processes of N and P removal. Data were first analysed for all observations of N and P reductions for a specific type of N or P load / concentration. Subsets of the data were then reanalysed for only studies > 1 year in duration. Due to a limited number of studies > 1 year in duration, TN and TP load reduction efficiencies were reanalysed for subsets of the full dataset (i.e., study lengths of any duration) to assess the potential impact of climate and type of BMP.

The limited sample sizes for data categorised as studies > 1 year, by climate and by BMP type. Limited the ability to conduct detailed statistical analysis across these different categorisations. Statistical analysis was thus carried out on the full datasets for TN and TP load reduction efficiencies, with outputs from analysis of data subsets being used to contextualise results from analysis of the full dataset for each variable. TN and TP load data were tested for normality of distributions using Q-Q plots and Shapiro-Wilk tests. Where data were normally distributed, means were tested for statistical significance using *t*-tests. 95% confidence intervals were used to determine a precautionary removal efficiency for TP and TN using drainage ditch BMPs.

Mechanisms and factors influencing nutrient removal

Studies of N and P removal in ditches generally report three key mechanisms: biogeochemical and physicochemical processes (e.g., Castaldelli et al., 2018; Sharpley et al., 2007; Taylor et al., 2015); vegetation assimilation (e.g., Kumwimba et al., 2017; Soana et al., 2017; Tyler et al., 2012; Wang et al., 2019); and physical process that impact hydraulics and sediment transport (e.g., Hodaj et al., 2017; Rizzo et al., 2023). The following sections provide a synthesis of studies that report the impacts of these mechanisms on nutrient removal in studies of drainage ditches managed using BMPs, and the factors that may influence them. As N and P are subject to differing biogeochemical and physicochemical removal processes, they are treated separately for each nutrient. There are greater similarities between N and P removal through vegetation assimilation and physical processes and thus these removal mechanisms are treated together for each nutrient.

Nutrient retention and removal by biogeochemical and physicochemical processes

Nitrogen removal

Although N cycling can also involve other processes (e.g., anaerobic ammonia oxidation) that cycle forms of organic and inorganic N through to dinitrogen gas (N_2), studies of N removal in drainage ditches focus on denitrification as the key biogeochemical process of N removal. Denitrification is also cited as the key N removal process for all types of drainage ditch BMP assessed in this review (e.g., Faust et al., 2018; Hodaj et al., 2017; Kröger et al., 2015). In the absence of other limiting factors, denitrification rates tend to increase with increasing water temperature (Wang et al., 2019). However, a number of other factors are often cited as causing rate limitation on denitrification in drainage ditches. Baker et al. (2015) note the importance of variable dissolved oxygen conditions and carbon (C) availability. Denitrification requires cycling of organic N and/or inorganic ammonium through processes of nitrification to nitrite and NO_3 under oxic conditions before denitrification to N_2 gas under anoxic conditions. The final denitrification process is bacterially mediated, using organic C as an electron donor as part of the microbial respiration process that consumes NO_3 and converts it to N_2, thus removing N from a drainage ditch system (Roley et al., 2012).

Due to the role of organic C in denitrification, studies have found biogeochemical N removal by denitrification is generally higher in the presence of more organic C in ditch soils. It is well-established that a lack of organic C in ditch soils can limit denitrification and studies have generally reported increased denitrification rates in the presence of increased organic matter (Faust et al., 2018; Roley et al., 2012). Organic C is also provided by root exudates and degradation of senescent vegetation, and thus ditch management that incorporates vegetation has been linked to higher rates of denitrification (Kröger et al., 2012; Taylor et al., 2015).

Vegetation in ditches also has a hydraulic impact on flow in ditches, decreasing flow velocities due to increased surface roughness (Bai & Zeng, 2019; Zhao et al., 2017). Decreased flow velocity and associated changes in discharge rates have been shown to impact denitrification within managed drainage ditches. Studying the impact of low-grade weirs on N removal, Baker et al. (2016) found that ditches managed with weirs had a more limited impact on mean TIN removal rates when compared with a control ditch. However, median TIN removal was higher in ditches with low-grade weirs. They suggested that because high flows during storm events transport most of the N load within the studied drainage ditches, the weirs were not able to retain high flows for long enough to have a marked impact on N removal by denitrification. Under low flow conditions, Baker et al. (2016) reported that ditches with weirs were consistently more effective at TIN removal than the control ditch. These findings were supported by Castaldelli et al. (2018), who used a mesocosm study in a vegetated ditch to assess the impact of vegetation on N removal at low flows. This study showed that at low flow, increases in flow rate and associated increases in the rate of NO_3 delivery to sediments increased denitrification rates and N removal. However, Castaldelli et al. (2018) suggested that that there is likely an upper flow threshold above which NO_3 delivery by diffusion to benthic microbes is reduced and denitrification rates decrease. Studies have shown >70% of N in agricultural environments is transported during high flow events (Davis et al., 2015), highlighting the need for drainage ditch BMPs to have hydraulic impacts that slow flow in ditches as much as possible, which can in turn increase N removal efficacy.

Slowing flow within a ditch and increasing the time for diffusion of NO_3 into sediments also increases the opportunities for nitrate-rich water to encounter the anoxic microsites where denitrification takes place (Roley et al., 2012). This study of N removal in two-stage ditches noted the importance of two-stage ditch design to ensure floodplain benches are inundated frequently enough to allow for ditch flows to interact with the floodplain. They observed lower denitrification rates within ditch channels when compared with the denitrification rates in floodplain sediments, which was attributed to floodplain sediments containing more anoxic microsites that stimulated denitrification.

Phosphorus retention

Physicochemical P retention processes are primarily driven by sorption of P onto sediments as ditch flows interact with shallow saturated zones. Capacity for P sorption in sediment is largely dictated by the equilibrium P concentration (EPC_0) in sediments and the concentration of P in the water column (Collins et al., 2016; Sharpley et al., 2007).

Where EPC_0 in sediments is higher than the P concentration in the water column, P will desorb from sediments and be released into overlying water. Conversely, when the P concentration in ditch flow increases above the EPC_0 of ditch sediments, P can sorb to and be retained by sediment. Kindervater and Steinman (2019) reported lower EPC_0 in ditch sediments of two-stages ditches vs a reference reach, meaning the two-stage ditch sediments were more likely to adsorb dissolved P from the water column. This was ascribed to differences in soil and sediment TP concentrations and organic matter availability, including an increase in the amount of available clay particles. These finer sediments lower EPC_0 and increase P retention capacity.

P sorption capacity in soils is also heavily impacted by the presence of aluminium and iron oxides and hydroxides, which can increase the P sorption capacity by providing more binding sites for P within a sediment matrix (Smith et al., 2006). Redox sensitivity of sediments and the switch from oxidizing to reducing conditions has also been observed to impact P retention in ditch sediments. Reduction of ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}) under anaerobic conditions has been associated with the dissolution of P from Fe-bound P minerals (Sharpley et al., 2007). In a study on the impact of low-grade weirs on nutrient removal, Littlejohn et al. (2014) note that as ditches tend towards more perennial flow regimes, as opposed to flowing intermittently during rainfall events, the amount of dissolved phase P reduces. This highlights the need for drainage ditch BMPs to strike a balance between hydraulic retention times (HRTs) that allow for contact of water with sediments to allow for sorption processes to occur and retention of water in ditches to the point of stagnation which can result in desorption of sediment-bound P.

Nutrient retention by vegetation assimilation

In vegetated drainage ditches, both N and P fluxes can be attenuated through assimilation of N and P in vegetation biomass. Numerous studies reporting the impacts of BMPs on N and P reduction in drainage ditches have highlighted the role of vegetation assimilation (Kumwimba et al., 2017; Nifong & Taylor, 2021; Nsenga Kumwimba et al., 2021; Shen et al., 2021; Zhang et al., 2020). Assimilation of N and P by vegetation is a temporary removal process, with N and P released when vegetation senesces and subsequently decomposes. N and P assimilation is a seasonal process that increases during vegetation growing seasons. It has also been observed that the amount of N and P that is assimilated into vegetation biomass within drainage ditches can be significantly affected by the type of vegetation growing in the ditch. While generally less well described direct assimilation of N and P by periphyton has also been noted to be an important store of nutrients within microbial communities in ditch sediments (Kindervater & Steinman, 2019; Kröger et al., 2012).

In studies of ditch management BMPs that used vegetation, total N and P removal by vegetation assimilation was generally less important than other processes such as denitrification, P sorption and sediment deposition (Nsenga Kumwimba et al., 2017; Wang et al., 2019). Vymazal and Březinová (2018) reported that the standing stock of vegetation in a drainage ditch in the Czech Republic accounted for 26.3% of TN removal and 13.6%

of the TP removal over a two-year period. This study also reported that of the dominant plant species in the studied drainage ditch, *Typha latifolia* assimilated consistently more N and P when compared to *Phragmites australis* and *Glyceria maxima*. *P. australis* was also observed to assimilate notably more N and slightly more P than *G. maxima* (Vymazal & Březinová, 2018). Similar findings highlighting a greater importance of certain plant species for N retention were reported in Taylor et al. (2015) and suggest that BMPs for nutrient removal in drainage ditches can be optimised by selecting native vegetation that has a greater capacity for N and P assimilation.

Assimilation of N and P in plant biomass is a temporary nutrient store. The time N and P will remain stored in vegetation depends on plant lifecycles, with plants that dieback annually resulting in more short-term attenuation of nutrient fluxes due to assimilation. Seasonal impacts on N and P removal due to vegetation growth and dieback have been reported for studies of vegetated drainage ditches in the USA and China (Kindervater & Steinman, 2019; Wang et al., 2019). Nutrient assimilation tends to peak at the height of the vegetation growth season. Although release of nutrients following vegetation dieback and decay may result in smaller impacts on annually averaged nutrient removal efficiencies, larger seasonal reductions in nutrient loads transported via drainage ditches to sensitive environmental receptors may help to ameliorate the risks associated with elevated nutrient concentrations during algal growth seasons. Furthermore, a recent Chinese study on N removal in a vegetated drainage ditch during cold weather found that the impacts of *Myriophyllum aquaticum* on N removal remained significant throughout winter (Zhang et al., 2020). This suggests that some nutrient removal processes that are facilitated by vegetation may not reduce markedly during winter in all cases.

Nutrient retention by physical processes

Drainage ditch BMP studies tend to cite factors influencing flow hydraulics as the key control on physical N and P removal processes. The main physical process of N and P removal is sedimentation (Bai & Zeng, 2019; Zhang et al., 2020), however as described above, the impact of BMPs on ditch hydraulics have been suggested as a key controlling factor on various removal process. All of the BMPs discussed in this review should have an impact on hydraulic roughness in a drainage ditch, slowing flow rates and increasing HRTs. This in turn decreases sediment transport capacity and encourages sediment deposition, helping to attenuate the particulate loads of N and P carried in ditch flows. While deposition of sediment-bound N and P was rarely found to be the main mechanism of N and P removal in ditches applying BMPs, N and P removal due to increased HRTs and associated sediment trapping have been reported for studies of low-grade weirs (Kröger et al., 2015), two-stage ditches (Hodaj et al., 2017) and vegetated ditches (Kumwimba et al., 2017). N and P removal by sediment deposition is also predominantly associated with particulate fractions of N and P, which generally manifests as reductions in TN and TP without having significant impacts on dissolved N and P fractions.

Increasing HRT within a drainage ditch can theoretically impact dissolved P fractions through sedimentation if P is chemically precipitated. In P enriched waters, dissolved P precipitation can occur in the presence of Ai or Fe oxides, or through binding with calcium (Ca) compounds (Sibrell et al., 2009). The former requires high Ai or Fe concentrations, with the latter process requiring high pH. These conditions are rarely met in agricultural drainage ditches and as such, P precipitation is rarely mentioned as P removal process in drainage ditch BMP studies.

Finally, it has been shown that hydraulic loading rates to drainage ditches can have complex interactions with nutrient removal. A study of a vegetated drainage ditch in China observed decreased TN and TP load removal efficiencies under higher hydraulic loads while absolute TN and TP load removal was greatest at the highest recorded hydraulic loads to the ditch (Wang et al., 2019). This suggests that while biogeochemical and physicochemical removal processes can see rate limitation at high input rates of N and P, this is not sufficient to reduce the overall nutrient removal potential of drainage ditch BMPs when flow rates increase. Studies where increased hydraulic loading rates have been cited as a factor in reduced N and P removal efficacy (e.g., Baker et al., 2016) point to the importance of designing drainage ditch BMPs to maximise HRTs under a wide array of flow conditions, thus providing the greatest probability of higher nutrient removal efficiencies and load reductions.

Nutrient reduction efficiencies

Efficiency of nitrogen reduction through drainage ditch management

Initial analysis of the 35 observations of N removal efficiencies collated for this review treated all observations together for concentration and load, respectively, of different types of N. For both concentration and load, the range of N removal efficiencies was contingent on the type of N reported in each study (Figure 4). It should be noted that only four measurements of TIN were found, while between 7 to 10 results were found for the other types of N shown in Figure 4. Small sample sizes mean that the range of values shown by the boxplots should be treated with caution, but Figure 4 shows a pattern of high variability in both concentration and load reduction efficiencies for N fractions dominated by dissolved forms of N, i.e., NO_3 and TIN, and more consistent reduction efficiencies for TN. The negative load reduction efficiencies for mean TIN load reductions are all from a single study on the impact of low-grade weirs in Mississippi (Baker et al., 2016). The authors attribute the TIN source behaviour of the ditches to high flow events that limited HRT and TIN removal potential, skewing the mean. This study reported positive median removal efficiencies for TIN, showing that the ditches were effective at TIN removal at lower flows. Three studies reported TN load reduction efficiencies greater than the median (57%), with each of these studies using vegetation as the BMP (Cui et al., 2020; Faust et al., 2018; Zhang et al., 2020). They largely attribute the high N removal performance in these ditches to high rates of denitrification linked to greater HRTs and the presence of microbial communities associated with plant root zones. Biomass assimilation of N and P by plants was reported as an important secondary mechanism of N and P removal.

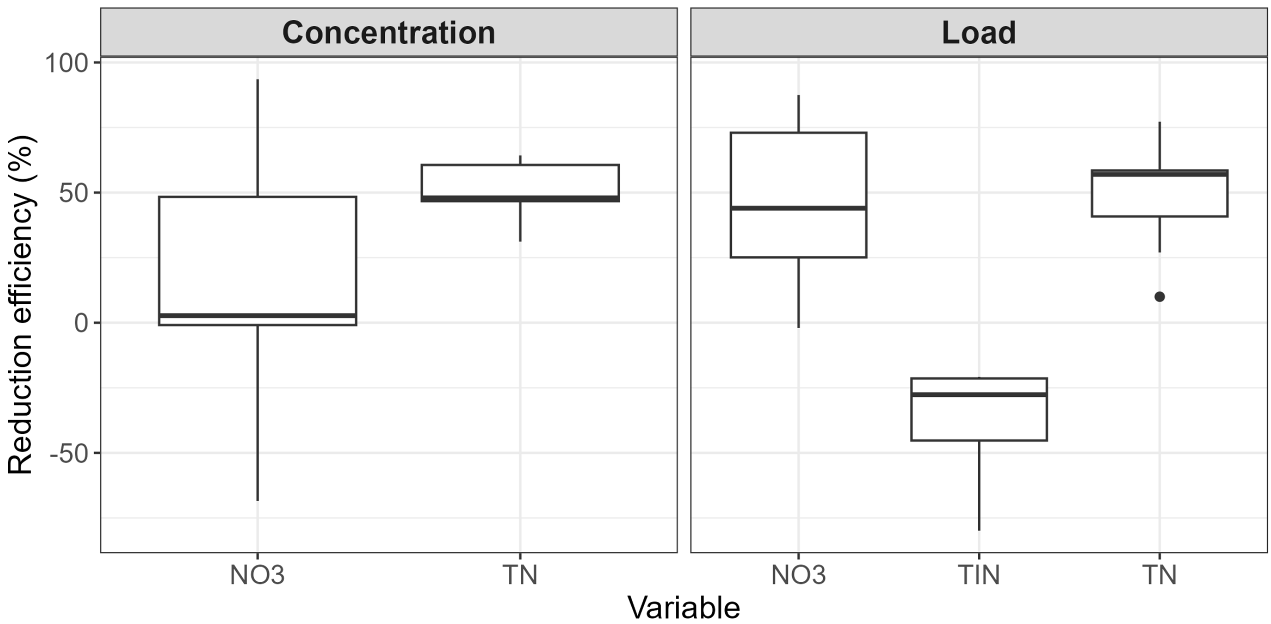

Figure 4: Boxplots showing the range of reduction efficiencies for different types of N reported in drainage ditch BMP studies. NO3 = nitrate, TN = total nitrogen, TIN = total inorganic nitrogen. Lines in boxes show the median; boxes show the 1st and 3rd quartiles and the interquartile range (IQR); whiskers show 1.5*IQR; and points show outliers > 1.5*IQR.

Mean reduction efficiencies were calculated for N concentration and load data published in all studies, combining data from studies of different BMPs, of any duration and in different climate zones (Figure 5). As noted above, the negative TIN load reduction efficiencies are all from the same study (Baker et al., 2016). Note that the mean (± SE) reduction efficiencies for TN concentrations (51.2% ± 4.4) and load (49.0% ± 8.6) were similar, with relatively low standard error suggesting low variation around these mean efficiencies across the reviewed studies. There was more variation seen for NO_3, although the mean NO_3 load reduction of 44.6% ± 11.1 was still quite high.

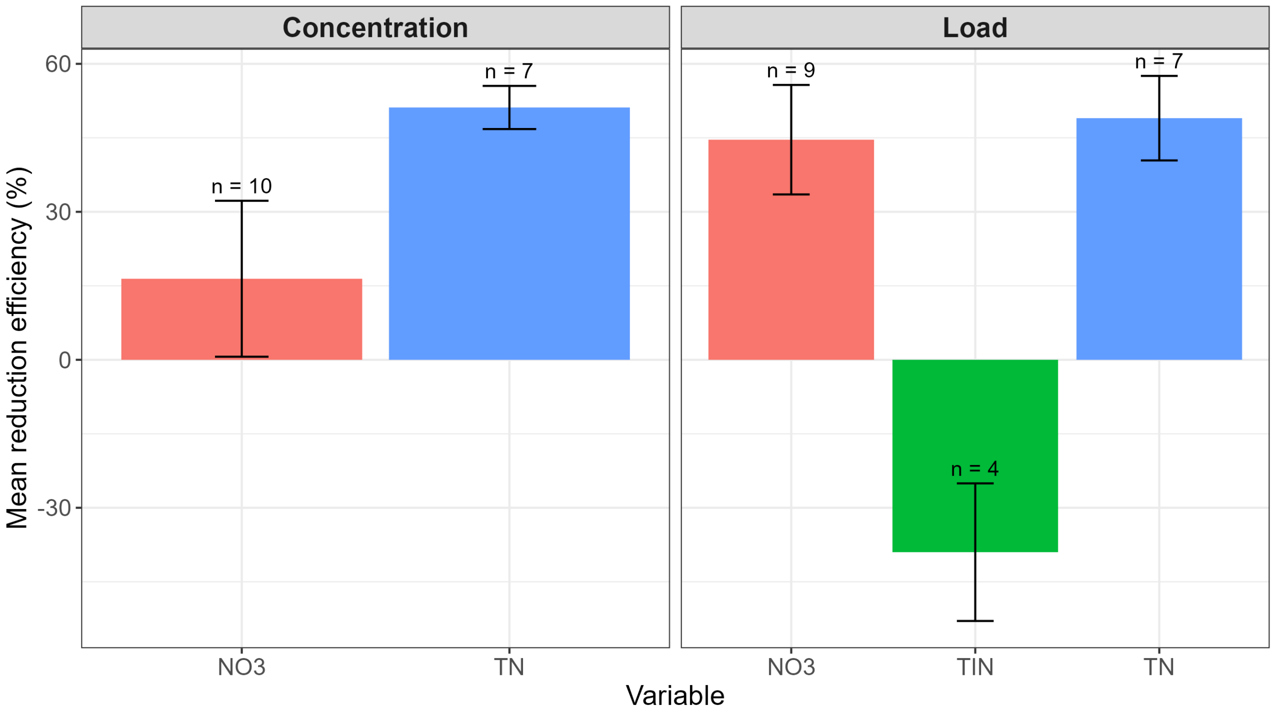

Figure 5: Mean concentration and load reduction efficiencies from studies of N removal using drainage ditch BMPs. Error bars show standard error. NO3 = nitrate, TN = total nitrogen, TIN = total inorganic nitrogen. Each mean was calculated from n observations, as shown above the error bars.

Data were reanalysed with removal of studies < 1 year in duration to assess the potential impact of short sampling periods missing seasonal variation in N removal (Figure 6). Again, data were combined across BMPs and climate zones. All studies reporting concentration reductions for TN in the studied ditches were > 1 year in duration and thus the mean concentration reduction efficiency is as above. Only one study of TN load reduction was > 1 year in duration, however the reduction efficiency reported this study (54.7% in a study of a vegetated drainage ditch in the USA; Lizotte & Locke, 2018) is similar to the mean efficiency reported above from the full dataset. Longer studies suggest a lower reduction efficiency for NO_3 concentration and load, but NO_3 load reductions were, on average, still positive (11.6% ± 13.6), albeit based on a very limited sample size.

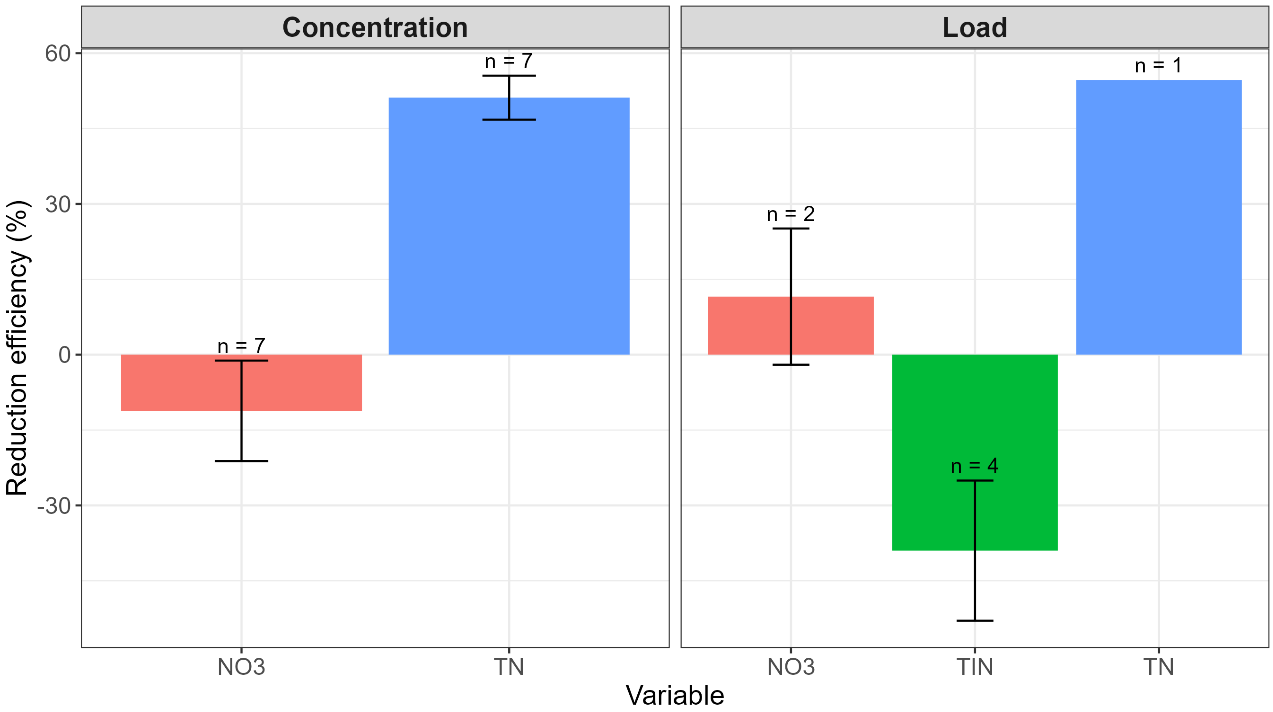

Figure 6: Mean concentration and load reduction efficiencies for studies of N removal using drainage ditch BMPs over periods > 1 year. Error bars show standard error where n > 1. NO3 = nitrate, TN = total nitrogen, TIN = total inorganic nitrogen. Each mean was calculated from n observations, as shown on each bar. Where n = 1, the value of this single result is shown.

Focussing on TN load reductions as the key variable of interest in the context of NN, data were also analysed to assess the impact of climate zone and BMP type on TN removal in managed drainage ditches. Due to the limited number of samples in each climate category, there is limited certainty in terms of the impact of climate on TN load reductions. However, the available data suggests that TN reduction efficiency does not vary markedly between observations in subtropical and temperate climates (Table 3).

Table 3: TN reduction efficiencies for drainage ditches managed with BMPs across different climate types. Some cells are left blank

Variable	Climate zone	*n*	Reduction efficiency (%; mean ± SE shown where *n* > 1)
TN load	Not reported	1	27
	Subtropical	5	52.2 ± 11.2
	Temperate	1	54.7

As with data on climate, there are a limited number of studies from which to extract data on TN load reductions in ditches managed with differing BMPs (Table 4). However, the available data suggests that vegetated ditches and ditches including multiple BMPs (the single study in Table 4 applying multiple BMPs used vegetation and low-grade weirs; Nsenga Kumwimba et al., 2021) can result in nutrient reductions of the order of the mean percentage reduction efficiency for all studies (49% ± 8.6). The single study (Faust et al., 2018) reporting TN load reductions for a ditch managed with low-grade weirs suggests this BMP in isolation will still deliver TN reductions, but these may be less effective than vegetated ditches or ditches applying multiple BMPs. Again, these findings should be treated with caution due to the limited number of available studies, however they represent the best available evidence on the impact of differing drainage ditch BMPs on TN reductions.

Table 4: TN reduction efficiencies for drainage ditches managed with different types of BMPs. Some cells are left blank.

Variable	Best management practices	*n*	Reduction efficiency (%; mean ± SE shown where *n* > 1)
TN load	LGW	1	10
	Multiple	1	57
	Vegetation	5	55.2 ± 8.1

The TN load reductions reported by subsets of studies of drainage ditch BMPs for study lengths > 1 year (Figure 6), different climates (Table 3) and for different BMPs (Table 4) suggest that the mean TN reduction derived from the full set of studies analysed in this review is a good representation of the TN reduction potential of drainage ditch BMPs. The full TN load reduction efficiency dataset was thus tested to determine whether the mean reduction efficiency was statistically significant. Q-Q plot analysis and a Shapiro-Wilk test ($p > 0.05$) showed that the data were normally distributed. The mean was tested with a *t*-test that found the mean TN load reduction efficiency of drainage ditch BMPs (49% ± 8.6) to be statistically significant ($df = 6$, $p < 0.01$). This mean efficiency is in line with values reported in recent reviews of the combined efficiency of vegetated drainage ditches and free water surface wetlands (Rizzo et al., 2023), and drainage ditches and ponds (Shen et al., 2021). These studies reported average removal efficiencies of 35% and 39%, respectively.

It is recognised that the mean TN load removal efficiency for drainage ditches found in this review is slightly higher than those reported in similar recent reviews (Rizzo et al., 2023; Shen et al., 2021). The mean TN load removal efficiency in this review is derived from five studies reporting results from seven separate drainage ditches managed with BMPs. Four of the ditches were in China, while three were in the USA. Only Lizotte & Locke (2018) conducted a study over one-year in length (this study ran for four years). As such, there will be uncertainty associated with the potential TN removal efficiency of drainage ditch BMPs applied to deliver N mitigation within UK agricultural landscapes. In keeping with the

Precautionary Principle, it is recommended that for the purposes of specifying nutrient mitigation schemes using drainage ditch BMPs, a lower bound estimate of TN load removal efficiency is used. For this purpose, 95% confidence intervals (CI) around the mean TN load removal efficiency were calculated. The lower 95% CI is 28.1%. To simplify the use of the TN load removal efficiency attributed to drainage ditch management schemes and provide additional precaution, it is suggested that calculated efficiency is rounded down to two significant figures, resulting in a TN load removal efficiency of 28% for drainage ditch BMPs that is based on best available evidence while recognising uncertainties within the evidence base.

Efficiency of phosphorus reduction through drainage ditch management

Figure 7 shows the range of P reduction efficiencies reported in all studies of drainage ditch BMPs. Some types of P have small sample sizes so boxplots, particularly for SRP and TIP loads, should be treated with caution. Dissolved forms of P (SRP and TIP) tend to have more variable reduction efficiencies for concentration and load when compared with TP (Figure 7). As with N, negative TIP reduction efficiencies were all reported in Baker et al. (2016) and attributed to low HRTs during storm events in ditches installed with low-grade weirs. Negative SRP concentration reduction efficiencies were only recorded in one two-stage ditch site in a study that assessed the nutrient removal potential of six two-stage ditches in the USA (Mahl et al., 2015). This study found that when averaged across the six sites, SRP concentrations were 23% lower at the end of two-stage ditches compared with reference sites, which was attributed to differences in substrate composition and higher vegetation densities in two-stage ditches compared with reference reaches.

Reduction efficiencies for TP load and concentration were more consistent and were positive in all studies (Figure 7). As TP measures both dissolved and particulate forms of P, physical processes of P removal related to sedimentation and assimilation by plants tend to be more consistent where ditch BMPs increase HRTs (Cui et al., 2020; Faust et al., 2018; Hodaj et al., 2017). Three studies reported four results for ditches that had TP load reduction efficiencies higher than the median efficiency shown in Figure 7. Three of these ditches were vegetated and one had low-grade weirs installed. Sediment deposition was suggested as key mechanism for TP reductions in the ditch installed with low-grade weirs (Faust et al., 2018). Microbial communities associated with vegetation, assimilation of P by plants and increased HRTs due to increased ditch roughness were indicated as common mechanisms for TP removal in vegetated ditches with high TP removal rates (Cui et al., 2020; Faust et al., 2018; Lizotte & Locke, 2018)

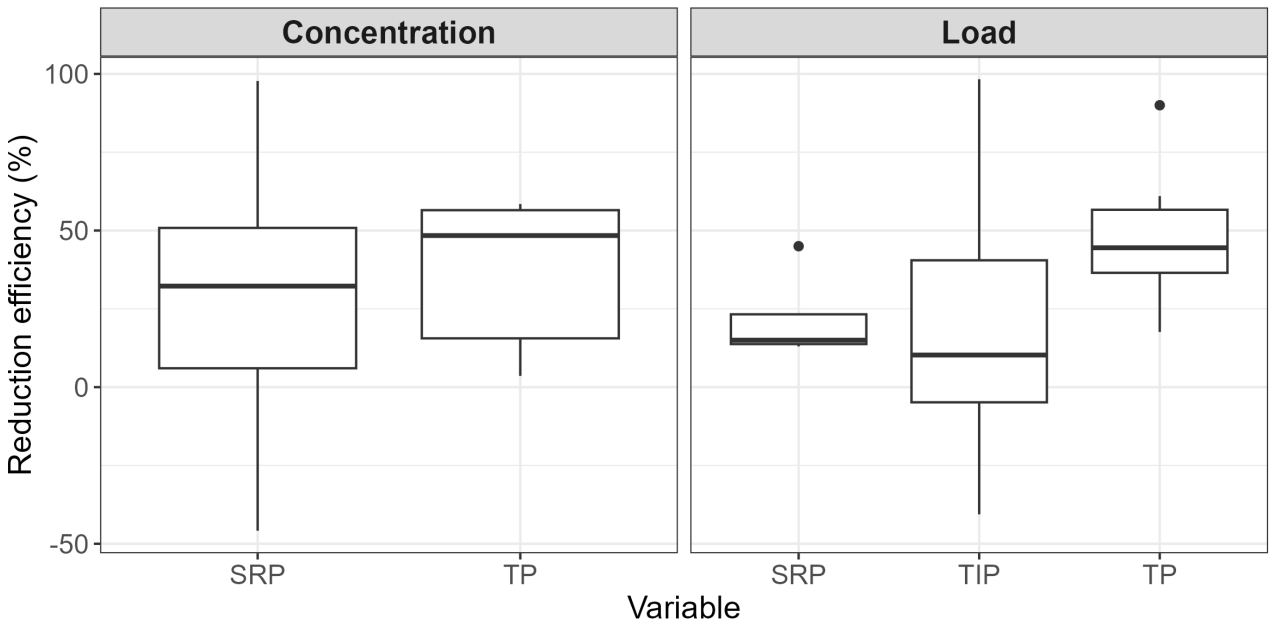

Figure 7: Boxplots showing the range of reduction efficiencies for different types of P reported in drainage ditch BMP studies. SRP = soluble reactive phosphorus, TP = total phosphorus, TIP = total inorganic phosphorus. Lines in boxes show the median; boxes show the 1st and 3rd quartiles and the interquartile range (IQR); whiskers show 1.5*IQR; and points show outliers > 1.5*IQR.

Mean concentration and load reduction efficiencies were calculated for data extracted from all studies of P removal due to drainage ditch BMPs (Figure 8). Mean reduction efficiencies were similar for SRP concentration (28.3% ± 17.1) and load (22% ± 7.7), however the higher standard error highlights more variation around the mean for SRP concentration reductions, highlighting more variable SRP concentration reduction efficiencies. The large standard error for TIP is again driven by the negative TIP load reduction efficiencies reported in Baker et al. (2016). The mean reduction efficiency for TP concentration (37.4% ± 7.1) was lower than for TP load (47.3% ± 7.9), with relatively low standard error suggesting a lower variation of TP reductions efficiencies around the mean when compared with studies reporting data on dissolved forms of P.

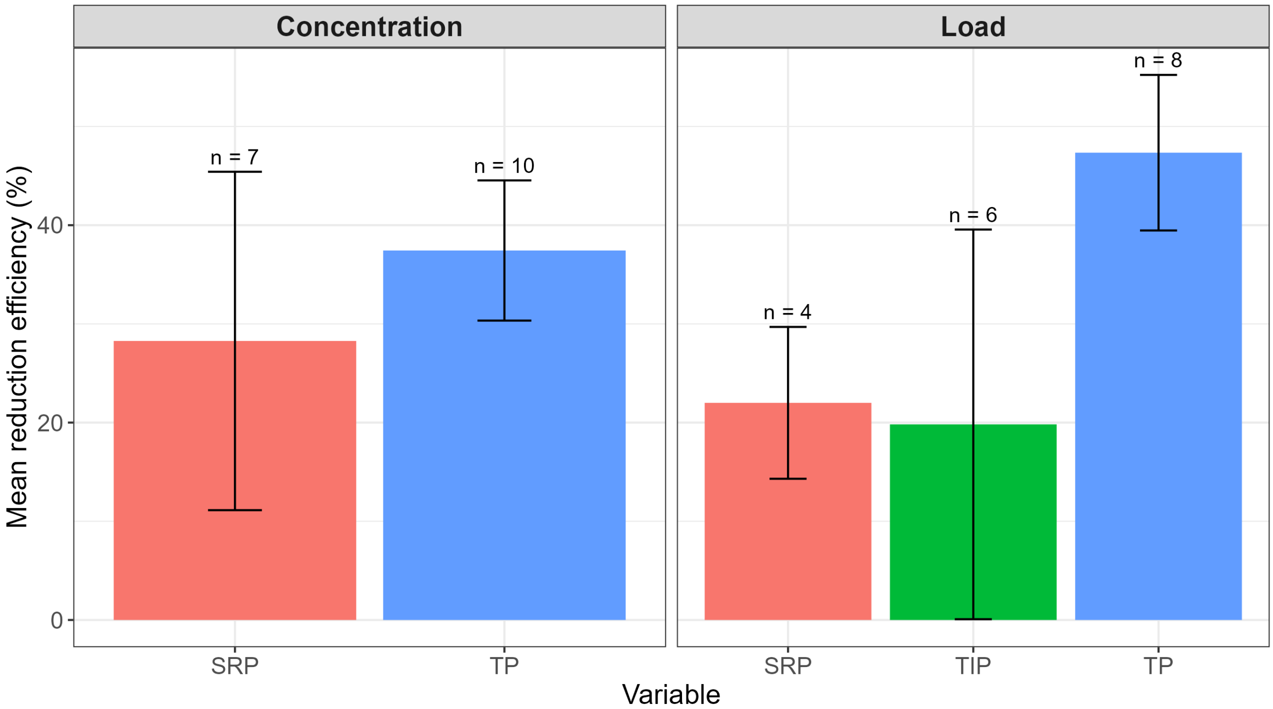

Figure 8: Mean concentration and load reduction efficiencies in from studies of P removal using drainage ditch BMPs. Error bars show standard error. SRP = soluble reactive phosphorus, TP = total phosphorus, TIP = total inorganic phosphorus. Each mean was calculated from n observations, as shown above the error bars.

Reanalysis of data on P reduction with studies < 1 year in duration removed showed a similar pattern to data on N removal (Figure 9). Mean reduction efficiencies of dissolved forms of P were reduced both for SRP concentrations and TIP loads (noting that no studies > 1 year in duration reported data on SRP loads). The higher negative TIP load reduction efficiencies reported in Baker et al. (2016) were offset by a 1.5-year study of low-grade weirs for P removal in the USA which reported average TIP load removals of 45.9% (Littlejohn et al., 2014). As with N, mean TP concentration and load reduction efficiencies were very similar between studies > 1 year in length and mean efficiencies calculated with studies of any length. Indeed, the mean TP concentration reduction (44% ± 7.9) was higher when analysing only longer duration studies. This suggests that drainage ditch BMPs can result in TP reduction efficiencies that will remain consistent over longer time periods.

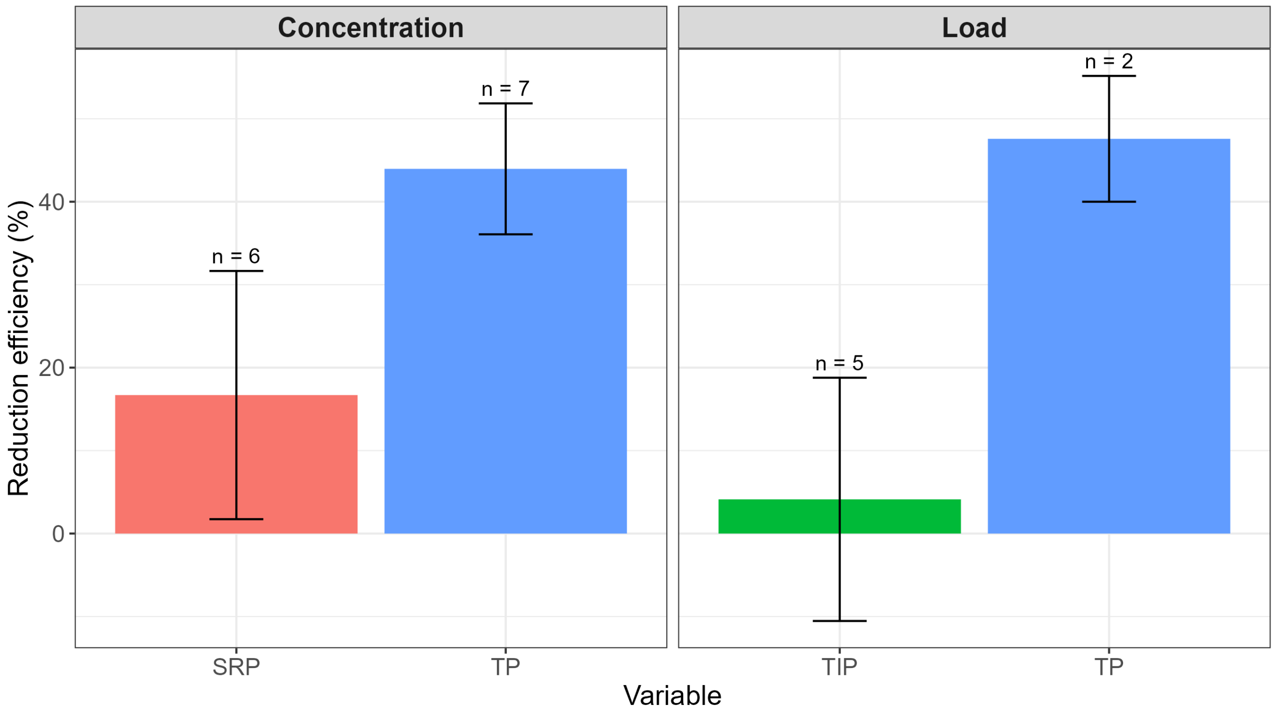

Figure 9: Mean concentration and load reduction efficiencies for studies of P removal using drainage ditch BMPs over periods > 1 year. Error bars show standard error where n > 1. SRP = soluble reactive phosphorus, TP = total phosphorus, TIP = total inorganic phosphorus. Each mean was calculated from n observations, as shown on each bar.

As TP load is the key variable in the context of NN, further analysis of TP load reduction efficiencies was conducted to assess the impact of climate zone and BMP type. As with TN, there was little difference in TP reduction efficiencies between studies in locations with subtropical and temperate climates (Table 5). It is noted that, especially for studies in temperate climates, the available data were limited and that this analysis of climate impacts on TP reduction efficiencies should be treated with caution.

Table 5: TP reduction efficiencies for drainage ditches managed with BMPs across different climate types. Some cells are left blank.

Variable	Climate zone	*n*	Reduction efficiency (%; mean ± SE shown where *n* > 1)
TP load	Not reported	1	26
	Subtropical	5	51.5 ± 11.9
	Temperate	2	47.6 ± 7.6

Analysis of TP load reduction efficiencies in ditches managed with differing BMPs also suffers from limited samples of studies applying individual BMPs. However, it was found that reduction efficiencies were similar across studies applying low-grade weirs, vegetation and multiple BMPs together (). The lower mean reduction efficiency for two-stage ditches is due to one study (Faust et al., 2018) reporting average TP load reductions of 17.6%. The other two-stage ditch study assessed in this review reported higher TP load reductions of 40% (Hodaj et al., 2017). The limited number of studies applying each BMP limits the reliability of conclusions on the true differences between TP load reductions due to different BMPs, however the available data suggests that all types of BMPs assessed in this review can facilitate TP load reductions within drainage ditches.

Table 6: TP reduction efficiencies for drainage ditches managed with different types of BMPs. Some cells are left blank.

Variable	Best management practices	*n*	Reduction efficiency (%; mean ± SE shown where *n* > 1)
TP load	LGW	1	45
	Multiple	1	61
	Two-stage ditch	2	28.8 ± 11.2
	Vegetation	4	53.8 ± 13.5

Analysis of subsets of studies of drainage ditch BMPs for study lengths > 1 year (Figure 9), different climate zones (Table 5) and for different BMPs (Table 6) show limited variation between the mean TP reduction derived from the full set of studies analysed in this review and subsets representing key aspects of study design or environment that may impact TP load reductions. Thus, the mean TP load reduction from all studies is likely to be a good overall representation of the TP reduction potential of drainage ditch BMPs. Following the same approach as detailed above for TN, the mean TP load reduction efficiency was tested for statistical significance. The data were normally distributed based on Q-Q plot analysis and a Shapiro-Wilk test ($p > 0.05$). A *t*-test found the mean TP load reduction efficiency of drainage ditch BMPs (47.3% ± 7.9) to be statistically significant ($df = 7$, $p < 0.001$). This mean efficiency is also in line with the review of Rizzo et al. (2023), who reported median TP removal efficiencies of 37% from a combined dataset of studies from both vegetated drainage ditches and free water surface wetlands.

The mean TP load removal efficiency for drainage ditches found in this review is higher than the median reported in a similar recent review by Rizzo et al. (2023). The mean in the present review is derived from five studies reporting results from eight separate drainage ditches managed with BMPs. Five of the ditches were in the USA, while three were in China. Two of the studies (Hodaj et al., 2017; Lizotte & Locke, 2018) were over one-year in length. These studies ran for 2 years (Hodaj et al., 2017) and four years (Lizotte & Locke, 2018) and reported average TP load reduction efficiencies of 40% and 55.2% from a two-stage ditch and a vegetated ditch, respectively. It is recognised that the relatively small sample size and lack of UK studies means there will be uncertainty associated with the potential TP removal efficiency of drainage ditch BMPs applied to deliver P mitigation within UK agricultural landscapes. Following the approach detailed above for TN, the 95% CI of the mean TP reduction efficiency was calculated. The lower 95% CI was 28.7%. To simplify the use of the TP load removal efficiency attributed to drainage ditch management schemes and provide additional precaution, it is suggested that calculated efficiency is rounded down to two significant figures, resulting in a TP load removal efficiency of 28% for drainage ditch BMPs that is based on best available evidence while recognising uncertainties within the evidence base.

Evidence for existing N and P retention and removal in drainage ditches

Typical drainage ditches without BMPs will still result in hydraulic and soil-water interactions that may result in processes of nutrient retention and removal. This raises the question of whether the suggested percentage reduction efficiencies detailed above incorporate some N and P removal that is already happening within a ditch system? The literature on drainage ditch BMPs was therefore analysed to extract details on nutrient removal/retention in control ditches vs those managed with BMPs. A relatively small number of studies had designs that incorporated control sites. Table 7 shows the results from studies that reported comparisons between control and treatment ditches.

Table 7: Comparing nutrient reductions where studies reported results for control and treatment ditches. Some cells are left blank.

Reference	Control or treatment	Reduction in N transport (%)	Reduction in P transport (%)	Notes
Baker et al. (2016)	Control	-17	18.3	• Study of the impact of low-grade weirs on N and P reduction. • Nutrient reductions are median total inorganic nitrogen (TIN) and total inorganic phosphorus (TIP) load reductions. • This study was one of the few that reported consistent source behaviour for TIN and more limited source behaviour for TIP. • This was attributed to high flows during storm events limiting

Reference	Control or treatment	Reduction in N transport (%)	Reduction in P transport (%)	Notes
				residence times, thus limiting the available time for N and P reduction processes to act.
Baker et al. (2016)	Treatment	0.4	65.8	See above
Baker et al. (2016)	Treatment	-11.6	11.9	See above
Baker et al. (2016)	Treatment	-16.1	15.8	See above
Baker et al. (2016)	Treatment	-3.64	-1.5	See above
Castaldelli et al. (2018)	Control	9		• Mesocosm study that extracted vegetated and non-vegetated ditch sediments, analysing the impact of vegetation on N removal under lab conditions. • Study reported NO_3 concentration reductions.
Castaldelli et al. (2018)	Treatment	89		See above
Flora & Kröger (2014)	Vegetation control	63	47	• Study was assessing the TP and NO_3 load reductions in ditches fed by effluent from aquaculture ponds. • They did not have a true control with bare sediment but did compare a ditch with only vegetation vs. a ditch with vegetation and low-grade weirs as the treatment.

Reference	Control or treatment	Reduction in N transport (%)	Reduction in P transport (%)	Notes
				• The data for treatment were read from a graph and hence only a range of reduction efficiencies could be obtained.
Flora & Kröger (2014)	Treatment	90-100	53-81	See above
Fu et al. (2014)	Control	5	9	• Study reported TP and TN load reductions. • The control ditch was a standard agricultural drainage ditch. • The treatment ditch was planted with vegetation and had a gravel filter bed that helped to reduce flow and increase residence time.
Fu et al. (2014)	Treatment	27	26	See above
Hodaj et al. (2017)	Control	-4	-75	• Best study design of studies reporting controls. Sampling over three-years at a relatively high frequency. • Treatment was a two-stage ditch with vegetated floodplain benches. • Results for TP and NO_3 load.
Hodaj et al. (2017)	Treatment	-6	38	See above

Reference	Control or treatment	Reduction in N transport (%)	Reduction in P transport (%)	Notes
Kumwimba et al. (2017)	Control	4	3	• The treatment ditches were a vegetated ditch and a vegetated ditch with gravel filter bed. • The ditch with the gravel filter bed performed best. • Studied reported data on TN and TP concentration reduction.
Kumwimba et al. (2017)	Treatment	31	27	See above
Kumwimba et al. (2017)	Treatment	64	58	See above
Moore et al. (2010)	Control	77	95	• Study of a vegetated (treatment) and non-vegetated (control) drainage ditch with results for total Kjeldahl nitrogen (TKN) and TP load reductions. • Results generated from simulated storm events with the addition of nutrient slugs to discharge pumped into each ditch. • The authors noted an error in the nutrient amendments where the control ditch discharge had a TP concentration that was 60% higher than the treatment ditch.
Moore et al. (2010)	Treatment	92	86	See above

The majority of studies reporting data that allows for a comparison of N and/or P reductions in treatment and control ditches show that while some N and P reductions are generally observed in ditches not applying BMPs, ditches managed with BMPs tended to result in greater nutrient reductions. However, there were some exceptions to this pattern. Baker et al. (2016) reported results for TIP load reductions for four treatment ditches with low grade weirs where three of the treatment ditches had TIP reductions that were between 2.5% and 19.8% lower than the control ditch; one treatment ditch resulted in a TIP reduction that was 47.5% higher than the control ditch. This study noted that average nutrient reductions were depressed due to all drainage ditches being sources of nutrients during high flow events, with the authors highlighting the need to ensure that ditch BMP designs maximise hydraulic residence times (HRTs) to improve nutrient reduction potential.

Hodaj et al. (2017) reported similar levels of source behaviour for NO_3 loads in both a control and treatment two-stage ditch which was attributed to this being a perennially flowing ditch system in a gaining reach. Upwelling groundwater reduced the ability for NO_3 in the ditch flows to penetrate the hyporheic zone, in turn limiting contact of NO_3 enriched surface water with reducing conditions in the ditch sediments, with these reducing conditions required to promote higher rates of denitrification. This study reported comparatively very high TP reduction rates in the treatment ditch relative to the control, with the control ditch being a strong source of TP while the two-stage treatment ditch reduced TP loads by 38%.

Moore et al. (2010) studied the impacts of vegetation on TKN and TP removal in a non-vegetated control ditch and a vegetated treatment ditch, using simulated storm events with a discharge of water amended with nutrient slurries. They found the treatment ditch had 15% greater TKN load removal, while the TP reduction rate was reported as 11% higher in the control ditch compared with the treatment ditch. However, the TP results reported in this study should be treated with caution as an error in the mixing of the nutrient slurries resulted in a 60% higher nutrient concentration in the discharge to the control ditch compared with the treatment ditch. It is well established in studies of P dynamics in wetland systems that P reductions are positively correlated with P concentrations (e.g., Land et al., 2016) and thus the greater P removal in the control ditch may simply have been a function of the considerably higher P concentration of the influent.

To summarise the potential impact of existing N and P reductions in drainage ditches, the difference in reductions between control and treatments was calculated and averaged. This output is summarised as follows:

- Using all data to calculate a mean difference, treatment ditches removed on average 25% more N and 24% more P.
- Removing the likely erroneous result for P in Moore et al. (2010), the mean increase in P reduction in treatment ditches is 28%.
- Removing the data from Baker et al. (2016), where the authors recognise that the low-grade weirs installed did not increase HRTs sufficiently to have a large impact on nutrients, the mean increase in nutrient reductions in treatment ditches increases further to 33% for N and 46% for P.

The proposed efficiency value for a drainage ditch management scheme is 28% for both N and P. These values are very close to the mean difference between the treatment and control ditches detailed above, and lower than the mean difference between treatment and control ditches when removing data from studies where there were known reasons for lower nutrient reductions in treatment ditches.

Drainage ditch design considerations

The following sub-sections provide an analysis of key factors related to drainage ditch design for the purpose of nutrient mitigation. These factors are considered in the context of designing drainage ditches for nutrient management that will incorporate a two-stage channel geometry, vegetated floodplain benches and low-grade weirs. Based on the analysis presented above, this combination of BMPs is likely to result in the best chance of reducing nutrient loads in ditch flows.

Recommendations re. minimum ditch length

For studies reporting the length of drainage ditches, nutrient reduction efficiencies were compared against ditch lengths to assess whether there was a correlation between ditch length and nutrient reduction efficiencies (Figure 10). There was a lack of any pattern of increasing nutrient reduction efficiency with increasing ditch length. Indeed, some of the lowest reduction efficiencies for both N and P were observed in longer drainage ditches. Baker et al. (2016) studied four ditches ranging from 500 m to 1754 m long. The best nutrient reduction efficiencies in this study were observed in a 595 m long drainage ditch with two low-grade weirs. The worst efficiencies were observed in a 1081 m long drainage ditch with four low-grade weirs. Similarly, a study of two-stage ditches that ranged from 450 m to 800 m in length reported the best nutrient reduction performance in the 450 m and 600 m long ditches (Davis et al., 2015). This study suggested that the key factor influencing better nutrient reduction efficiencies was the height of floodplain benches in the two-stage ditch, with lower benches that were inundated more frequently and for longer resulting in better nutrient removal, especially for P.

It is apparent that ditch length is not a critical variable in the design of drainage ditch BMPs. Considering studies that showed low nutrient reduction efficiencies due to ditch BMPs, Baker et al. (2016) attributed the poor performance of the ditches to being overwhelmed by high flow events, while Davis et al. (2015) indicated floodplain bench heights and impacts on water retention as critical to better nutrient removal. This highlights that BMPs could be applied in a ditch of any length, as long as they are designed in manner that increases HRTs (see below).

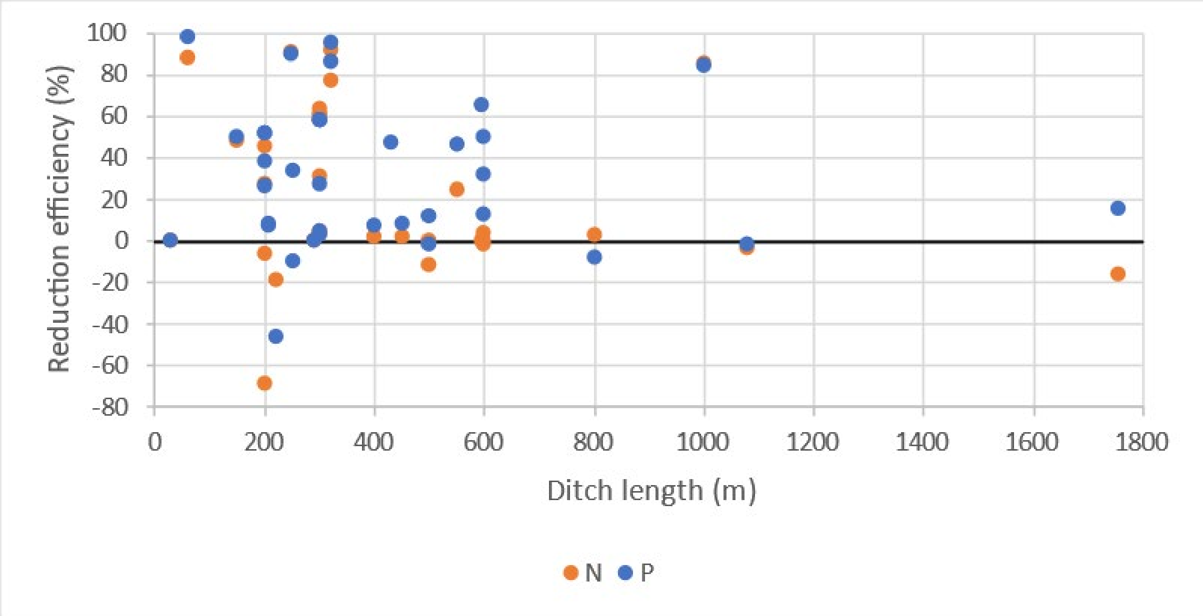

Figure 10: Nutrient reduction efficiencies plotted against ditch lengths, excluding control ditches without BMPs. The reference line shows 0% reduction efficiency, i.e., the ditch BMPs had no impact on N and/or P reduction. Negative reduction efficiencies show where ditches with BMPs were sources of N and/or P.

Recommendations re. low-grade weir heights and spacing

There is limited information specifying recommended weir spacing in terms linear distance along a drainage ditch. Recommendations are based on maintaining a grade fall within a ditch that does not adversely impact flow conveyance (Kröger et al., 2011). This study gave an example of a 400 m ditch with a 1.15 m fall and the positioning of two weirs to maintain a fall of around 0.6 m at two points along the ditch. To achieve this, it was suggested the weirs would be quite small, at between 5-10% of bankfull volume, with a more general suggestion that weir heights should be between 5-20% of bankfull depth (Kröger et al., 2011). The higher a weir, the greater the reduction in grade between weirs and thus the greater the impact on hydraulic retention. Low-grade weir design for nutrient mitigation should aim to maximise the height of weirs and/or install more smaller weirs to reduce ditch gradient and help to increase residence time of water within the ditch system.

There are limited data available on weir spacing relative to nutrient reductions in drainage ditches. Baker et al. (2016) installed either two or four weirs in drainage ditches to achieve a fall of 0.03 m per 30.5 m of ditch. However, as detailed above this study reported poor nutrient reduction efficiencies so it suggests that their design was not sufficient to increase HRTs and drive significant nutrient reductions. The two- and four-weir ditches were around 500 m long and between 1000-1700 m long, respectively. The distance between weirs was not detailed, but a diagram suggests the weirs were spaced approximately equidistantly along each ditch. This suggests a weir spacing of between 160 m and 425 m. Other studies reporting good reduction efficiencies (50-100%) for ditches with low-grade weirs had two (Kröger et al., 2011) and three weirs (Flora & Kröger, 2014) in ditches of 59 m and 292 m long, respectively. Wang et al. (2019) reported reduction efficiencies of 48% for N and 50% for P in a 150 m long ditch with vegetation and weirs deployed at ~30 m intervals. In each of these studies, the most downstream weir was not at the end of each ditch, which suggests a spacing of somewhere between 20 m and < 100 m. These spacings are clearly significantly lower than those reported in Baker et al. (2016) and suggest that weir spacing should be minimised as much as possible within the constraints of maintaining adequate flow conveyance within a ditch.

Studies reporting weir heights (Flora & Kröger, 2014; Kröger et al., 2011) did not also report bankfull depths for their study ditches so it is difficult to infer recommendations on weir height from these studies. In a follow-up paper to Kröger et al. (2011), Kröger et al. (2012) showed that ditches with weirs more than doubled HRTs compared with control ditches without weirs and these studies make recommendations for weirs being deployed at 5-20% of bankfull depth. Given the goal to maximise HRTs in drainage ditches, it is suggested that ditch management designs for BMPs for nutrient mitigation should aim to minimise spacing between weirs and aim to deploy weirs with heights at potentially above 20% of the bankfull depth of a ditch. A trade-off between weir height and spacing should be possible such that more widely spaced weirs can be made higher in order to decrease the grade fall between weirs. There will be a requirement to allow for a ditch to continue functioning for flow conveyance. This consideration should be facilitated through ditch BMP designs that also incorporate a two-stage channel (see below). In this case, the weir designs should be made with consideration to the dimensions of the floodplain channel and the objective to promote lateral connectivity with floodplain benches.

Recommendations re. two-stage ditch design

As with low-grade weirs, design specifications are somewhat lacking in studies of two-stage ditches for nutrient reduction. However, there are more detailed descriptions of design processes for two-stage ditches provided in USDA (2007) and Powell et al. (2007). These references provide design specifications aimed at creating stable two-stage ditches that reach a geomorphic dynamic equilibrium whereby net change in sediment storage is close to zero and the ditch therefore neither aggrades nor degrades to a point where it requires significant maintenance. The ditches considered in these references are in a North American context and thus are significantly larger than agricultural drainage ditches typical of UK rural landscapes. In the US, drainage ditches are often more akin to low gradient alluvial channels and thus some of the design stages are not relevant to typical UK ditches which tend to be small, with ephemeral flow regimes and sediments that are generally homogenous and reflect local soil conditions. Furthermore, while USDA (2007) and Powell et al. (2007) provide guidance on how to design ditches that should achieve a geomorphic dynamic equilibrium, for the purposes of nutrient mitigation it would be more beneficial to specify ditch designs so that they are net aggradational. By enhancing sediment storage there will be a requirement for periodic sediment removal, however this will also enhance nutrient retention within the ditch catchment.

Figure 11 shows the conceptual design of a two-stage ditch. Below, a set of steps provide a suggested approach specifying two-stage ditch dimensions in small, trapezoidal UK agricultural drainage ditches, based on the guidance detailed in USDA (2007) and Powell et al. (2007). For ease of reference, these steps will refer to different parts of the two-stage ditch design by the names shown in Figure 11.

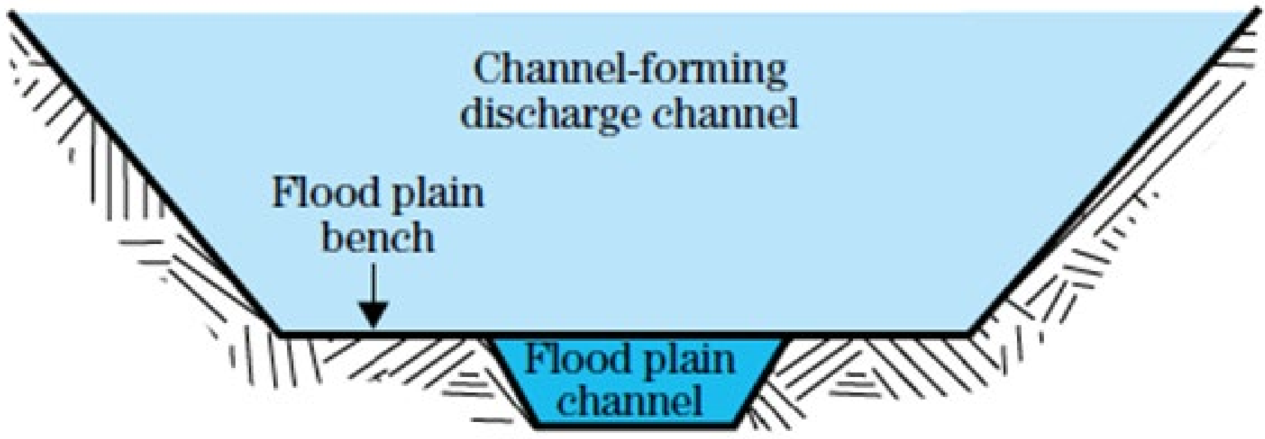

Figure 11: Conceptual design of a two-stage ditch. Source: USDA (2007).

The following steps are suggested to determine the design of a two-stage ditch:

1. Measure the existing dimensions of the trapezoidal ditch that is proposed for reengineering.

    a. The existing dimensions of the trapezoidal ditch can be used to provide a starting point for the two-stage ditch dimensions.

    b. The two-stage ditch should aim to incorporate these dimensions in the floodplain channel width and depth, the floodplain bench widths and the channel-forming discharge channel width and depth.

2. Determine a regional curve for the wider drainage basin in which the two-stage ditch is being deployed.

    a. A regional curve plots the dimensions of steam channels within the deployment drainage basin against the drainage area for each channel at the measurement point.

    b. By deriving a relationship between channel geometry, e.g., width, and drainage area, it is possible to predict the approximate width of a channel with a given drainage area.

    c. It should be noted that regional curves should ideally be determined using cross-sectional measurements of stream channels at multiple locations and in the above references they are generally taken from the cross-sections at gauging stations. Because the examples in the guidance are from US catchments, the drainage areas and channel geometries span multiple orders of magnitude, and the relationship is best described by a power law.

d. An example of a regional curve for the River Tone catchment in Somerset is shown in Figure 12. This regional curve was developed by measuring channel widths in satellite imagery and relating them to the drainage area at the point where the channel width was measured.

e. As the measurements at the scale of the Tone catchment only span an order of magnitude, the relationship between channel width and drainage area is better represented by a linear, rather than a power law relationship.

f. It is recognised that measurements of channel width taken from satellite imagery will be prone to error and the outputs from a regional curve generated in this way should be used as a guide to sizing two stage channel dimensions.

3. Calculate the drainage area for the ditch.

   a. Drainage areas for ditch systems can be calculated using topographic data and standard watershed delineation approaches.

4. Estimate the channel slope from topographic data.

5. The guidance documents do not provide recommendations on a critical slope beyond which increased stream power may cause erosion that would undermine the two-stage channel geometry.

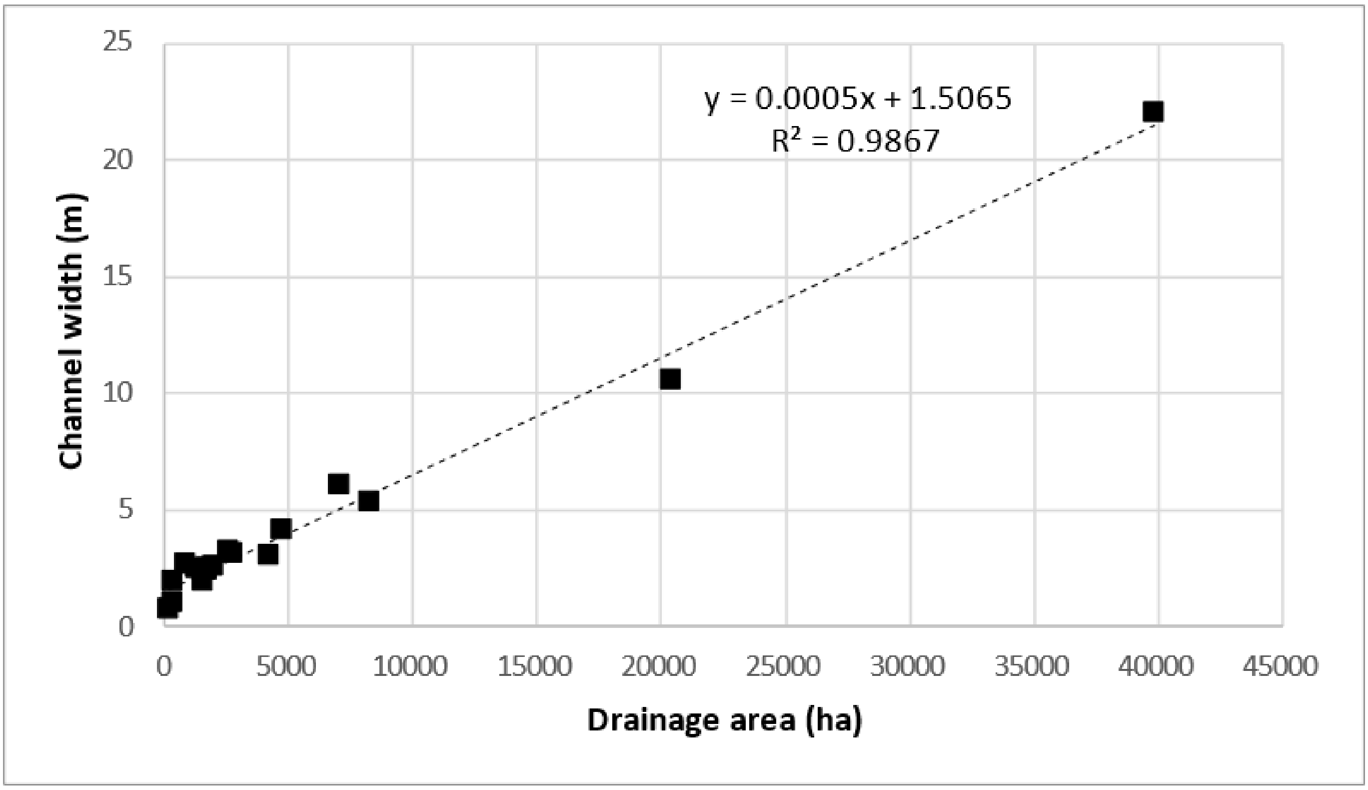

Figure 12: Regional curve for the River Tone catchment showing the relationship between channel width measured from satellite imagery and drainage area at the point of width measurement.

6. Determine a conceptual channel geometry.

   a. The data obtained from the above steps can be used to determine a conceptual two-stage channel geometry.

   b. Guidance suggests that as a rule of thumb, the width of the channel-forming discharge channel should be between three to five times the width of the floodplain channel (total floodplain bench widths are two to four times the floodplain channel width).

   c. This should reduce the risk of a narrower channel resulting in high shear stresses at high flow, with associated erosion and channel instability.

   d. Limiting channel-forming discharge channel width relative to floodplain channel width will reduce the risk of having overwide floodplain benches that may allow a meandering floodplain channel to evolve and cut into the ditch banks.

7. Estimate flow conveyance capacity of the two-stage ditch.

   a. This is an additional step not included in USDA (2007) or Powell et al. (2007).

b. As the two-stage geometry of a ditch is described by two trapezoidal ditches, it is possible to apply Manning's equation for open-channel flow to estimate the flow conveyance capacity of the two-stage ditch.

c. The equation has the form:

$$V = \frac{1}{n} R_h^{2/3} S^{1/2}$$

where V is the cross-sectional velocity (m/s), n is the Manning coefficient, R_h is the hydraulic radius (m), S is the stream slope (m/m). Calculation of V allows for an estimate of discharge using the velocity-area method:

$$Q = AV$$

where Q is discharge (l/s) and A is the cross-sectional area of the channel (m^2).

8. Estimate the discharge in the channel for a range of return periods up to the 1-in-100-year runoff event, plus an allowance for climate change.

    e. The discharge conveyed by each ditch can be estimated using a greenfield runoff rate estimation tool[1].

    f. Relating the estimated discharge that would be conveyed by the ditch to the estimated maximum conveyance potential using Manning's equation provides a means to check whether a two-stage ditch geometry is likely to be able to retain low return period flow events and thus increase HRT for higher return period events.

9. Plan how to establish vegetation rapidly on floodplain benches.

    g. It is recommended that grasses are established rapidly on the floodplain benches and the banks of the channel-forming discharge channel.

    h. Grasses are recommended over woody vegetation as larger plants can shade the floodplain benches resulting in areas of bare soil that are more prone to erosion.

    i. There are limited recommendations on vegetation planting in studies of vegetated ditches for nutrient removal. Only Cui et al. (2020) provides details on planting density in a vegetated ditch, noting that their experimental ditch was planted with 50 seedlings/m^2 of *Vallisneria natans*, a

[1] For example, The HR Wallingford greenfield runoff rate estimation tool. Available from: https://www.uksuds.com/tools/greenfield-runoff-rate-estimation, accessed on: 14/11/2023.

subtropical submerged macrophyte. This study reported good rates of N and P removal but is less relevant to vegetation in two-stage ditches where grasses should be established at high density on floodplain benches, as opposed to using submerged macrophytes.

Recommendations re. hydraulic loading rates and hydraulic residence times

There is a general consensus among studies of drainage ditch BMPs that designing a drainage ditch to maximise HRTs is a key requirement for increasing nutrient reduction potential. However, as the drainage ditch studies included in this evidence review span an array of different sizes and settings, from experimental ditches with controlled influent inputs to large agricultural drainage ditches with catchments > 2000 ha, a comparison of hydraulic loading rates (HLRs) and HRTs between multiple studies is difficult.

In studies of agricultural drainage ditches with large catchments and natural hydrographs, it was generally only studies of two-stage ditches that provided some metric of HRT through the time floodplain benches were inundated. There was no clear pattern with respect to time floodplain benches were inundated, HLRs and nutrient reduction rates. Inundation events ranging from 3.3 days to 14.5 days were associated with similar levels of N and P reduction (Davis et al., 2015; Mahl et al., 2015). Average P reductions of 38% were reported for a two-stage ditch where floodplain benches were inundated for an average of 6-14 hours per flow event over a three-year period (Hodaj et al., 2017). It is therefore difficult to draw a clear inference on what a ‘good’ HRT is for ditches receiving natural runoff and as detailed above, ditch design should aim to maximise flow across floodplain benches to increase the probability of achieving higher nutrient reductions.

A number of studies reported results from experimental ditches where HLRs were controlled and HRTs were measured. Most of these studies show high N and P reduction efficiencies (> 50%) with HRTs ranging from 1.5 hours to 5.6 hours (Flora & Kröger, 2014; Kröger et al., 2011; Nsenga Kumwimba et al., 2017, 2021; Wang et al., 2019). These studies generally used low HLRs that were relative to the size of the experimental ditches, which were smaller when compared with studies of ditches in agricultural settings. However, they highlight that significant nutrient retention can occur with relatively short HRTs assuming ditches are sized to take the range of discharges that they are likely to receive. The design considerations detailed above in terms two-stage ditch geometries, and low-grade weir heights and spacing are intended to result in ditched that maximise HRTs and thus provide increase the probability of nutrient retention occurring within the ditch system.

Considerations re. maintenance

The majority of studies of drainage ditches for nutrient reductions do not provide detailed maintenance procedures required to improve the longevity of nutrient retention/removal. The following key maintenance considerations are suggested:

- Vegetation removal is not a requirement and should be considered primarily for maintaining the hydraulic performance of a ditch. Removal of too much vegetation may adversely affect the nutrient reduction capacity of a ditch (e.g., Iseyemi et al., 2016).

- Two-stage ditches, if well designed, should be geomorphically stable over long periods (D'Ambrosio et al., 2015) and should not require significant intervention to maintain a two-stage form.

- Sediment retention is a goal for drainage ditch BMPs for nutrient mitigation, so there should be a net increase in sediment within a ditch system over time. There is often a requirement for periodic sediment removal in trapezoidal drainage ditches and the additional volume of a two-stage ditch should reduce the frequency with which sediment needs to be removed. Sediment removal should be carried out when regular inspections show that the hydraulic capacity of the ditch may be being reduced by the presence of deposited sediments.

- Removed sediments should be spread within the catchment of the drainage ditch in locations which aim to minimise the risk of rapid remobilisation. This should result in a circular system where sediment and associated nutrients are mostly retained within the catchment of a drainage ditch.

- Regular inspection should check the integrity of low-grade weirs and repair any weirs that are starting to show signs of failure that may reduce their hydraulic impact.

Conclusion

There is an increasing body of evidence supporting the potential for drainage ditch BMPs to provide nutrient mitigation. While there are no studies of the impact of drainage ditch BMPs in UK settings, the processes that remove and retain nutrients within drainage ditches are the same regardless of the geographical location. This review has detailed the range of key nutrient processes that BMPs can facilitate within drainage ditches. These processes are largely the same as the processes that remove nutrients in constructed wetlands. As such, numerous studies have highlighted process similarities between drainage ditches utilising BMPs and constructed wetlands. Given the ubiquity of drainage ditches within UK agricultural landscapes and the problems associated with diffuse nutrient pollution from agricultural sources, drainage ditch BMPs present an opportunity to deploy simple and effective nutrient mitigation solutions at scale.

Studies from multiple countries have shown that drainage ditch BMPs can be effective for N and P removal. Data from these studies were extracted and analysed for different types of N and P. This analysis highlighted more variable reduction efficiencies for dissolved forms of N and P, while TP and TN saw higher and more consistent reduction efficiencies. Removal and retention of dissolved forms of N and P are contingent on biogeochemical and physicochemical processes that can become rate limited or, for P, reversed (i.e., resulting in the release of P) under certain environmental conditions. However, multiple studies reported reductions in dissolved forms of both N and P due to drainage ditch BMPs. TN and TP reduction efficiencies are potentially more consistent because the hydraulic impacts of BMPs and nutrient assimilation by vegetation are less affected by changing environmental conditions. Because both TN and TP include the particulate fractions of N and P carried in drainage ditch flows and BMPs tend to reduce the sediment transport capacity of a drainage ditch, enhanced sediment deposition was cited as a secondary but important factor in increased TN and TP removal in managed drainage ditches.

Analysis of subsets of data on TN and TP load reduction efficiencies for longer duration studies, studies in different climate zones and studies of different types of BMPs was hampered by small sample sizes for each subset. However, the available data suggested that TN and TP load reductions can be maintained over longer time periods and do not differ markedly between temperate and subtropical climate zones. Nutrient reduction efficiencies tended to be higher in ditches that included vegetation as one of their BMPs, though all types of BMPs analysed in this review had positive TN and TP load reduction efficiencies. Owing to the similarities in TN and TP load reductions reported for studies across BMP types, climate zones and study durations, data from all studies reporting data on TN and TP load reduction were analysed together to determine a reduction efficiency that could be applied to drainage ditch BMP nutrient mitigation schemes. It was suggested that the lower 95% CI of the mean TN and TP reduction efficiencies, rounded down to two significant figures, is a suitably precautionary estimate that could be used for drainage ditch BMP mitigation schemes deployed in the UK. **This resulted in an estimated retention of efficiency of 28% for both TN and TP.**

The studies analysed in this review cited various design considerations for drainage ditch BMPs that can help to increase the probability of achieving higher TN and TP reduction efficiencies. Designing BMPs to maximise HRTs was consistently cited as a key design factor that will help to facilitate all nutrient removal processes within a drainage ditch. Planting a ditch with vegetation or allowing it to naturally revegetate will also promote nutrient removal. Selecting native plants that do not dieback annually and that assimilate more N and P in biomass will also help to improve TN and TP reduction efficiencies. It has also been suggested by various studies (Faust et al., 2018; Kröger et al., 2015) that combining BMPs could help to maximise nutrient removal benefits through drainage ditch management. This review provides a range of recommendations for drainage ditch BMP design to maximise HRTs and increase the probability of achieving significant nutrient retention/removal. These recommendations include ditch designs that incorporate a two-stage geometry, vegetation planting and low-grade weirs.

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Glossary

Nutrient neutrality: Within the hydrological catchments of Habitats Sites that are failing conservation objectives due to elevated nutrient concentration, nutrient neutrality is a requirement for new developments, especially those increasing overnight stays, to show they will not increase nutrient inputs to the Habitats Site.

BMP: Best Management Practice – a term used to describe catchment management approaches that can have benefit for river management.

Denitrification: A biologically mediated process through which nitrogen is cycled through various forms before being converted to dinitrogen gas and transported to the atmosphere.

Sorption: A chemical process wherein a molecule, such as inorganic phosphate, is bound to another particle.

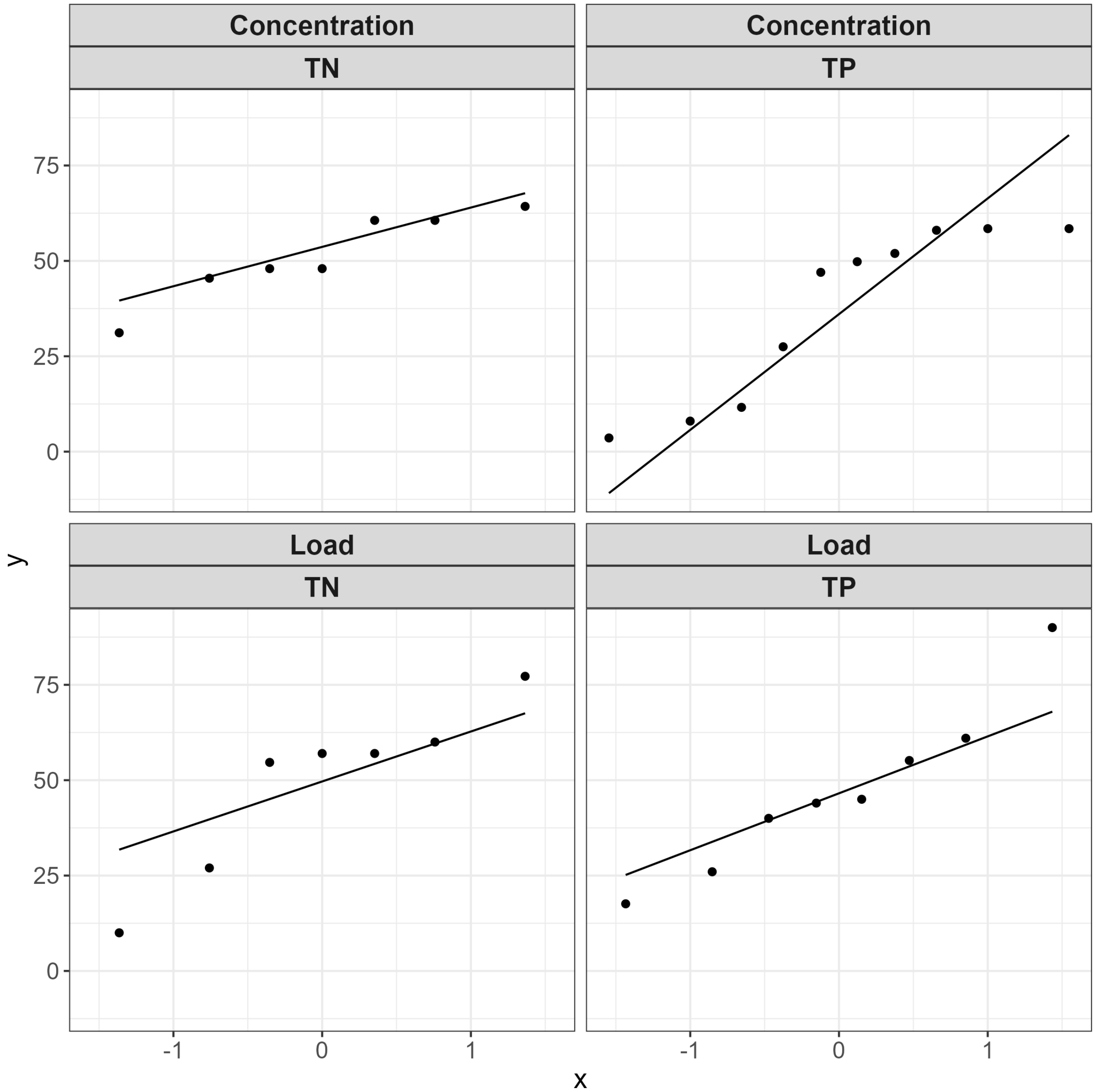
Hydraulic residence time: The time taken for water to flow through a section of drainage ditch or watercourse.

Precipitation: In the context of phosphorus retention, this is a process through which phosphorus binds with other molecules, creating chemical complexes that fall out of suspension in the water column.

Appendices

Appendix 1

Q-Q plots for TN and TP load and concentration data showing the normal distribution for TN and TP load data used to calculate mean reduction efficiencies and associated 95% confidence intervals.



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