Charting water quality improvements and practice reversion with pesticide interventions at catchment scale

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Charting water quality improvements and practice reversion with pesticide interventions at catchment scale

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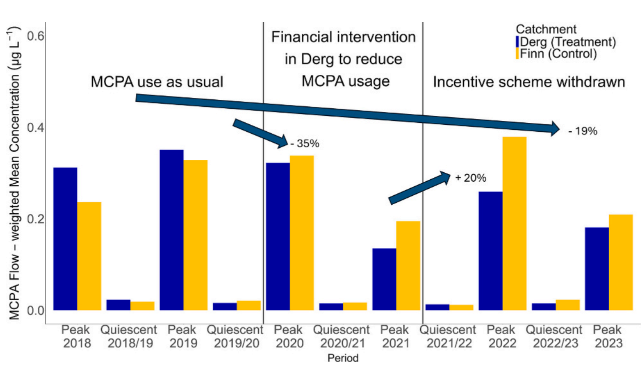
HIGHLIGHTS

- 10,000 water samples, a questionnaire and two workshops tracked pesticide dynamics.
- Catchment scheme reduced Drinking Water Directive breaches by up to 15.2 %.
- MCPA flow-weighted mean concentration reduced 35 % during scheme but rose 20 % after.
- Survey and workshops found strong status-quo bias in favour of MCPA over glyphosate.
- Sustained investment and training essential to effect long-term behavioural change.

GRAPHICAL ABSTRACT



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ABSTRACT

Freshwater quality, and the impacts of farming practice on drinking water supplies, are of concern in many countries and time-limited catchment management interventions are commonly used to improve water quality. However, ending such schemes may result in practice reversion. This study adopts an interdisciplinary approach combining evidence from water quality monitoring data with a behavioural study of farmers to explore changes in land use practice with reference to the pesticide MCPA (2-methyl-4-chlorophenoxyacetic acid) following a catchment-based management scheme delivered in the cross-border Derg catchment in Northern Ireland/Ireland between 2018 and 2021. Analysis of over 10,000 water samples demonstrated that, compared to the Finn (Control), the scheme achieved a 15.2 % and a 5.5 % reduction in the frequency with which MCPA concentrations in the Derg (Treatment) exceeded the total (0.5 μg L^{-1}) and individual (0.1 μg L^{-1}) EU Drinking Water Directive limits for treated drinking water respectively. The post-intervention flow-weighted mean concentration (FWMC) of MCPA for Peak usage season (April–October) was 19 % lower than pre-intervention in the Derg when compared to the Finn, although the during-intervention Peak season FWMC was lower in the Derg than post-intervention, suggesting practice reversion. The farmer survey and workshops provided further evidence of changes in pesticide usage, but also subsequent practice reversion due to a strong status quo bias for MCPA and other, mainly financial, barriers inhibiting a shift to the alternative pesticide, glyphosate. This study concludes

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that catchment approaches can be successful, but sustained investment in catchment measures is essential to effect meaningful long-term behavioural change.

1. Introduction

The state of freshwater quality is a concern globally (Berthet et al., 2021), with impacts linked to drinking water supplies (Ndehedehe, 2023), biodiversity (Albert et al., 2021), fisheries (Ribeiro et al., 2022) and recreational use (Schafft et al., 2024). The catchment-wide causes of reductions in freshwater quality are pressures arising from agriculture, forestry, urbanisation, industry, and infrastructure (Grzybowski and Glińska-Lewczuk, 2019; van Rees et al., 2021), with many also associated with processes linked to changing hydrometeorological patterns (Dupas et al., 2015). These processes include influences from hydrological pathways and extreme events such as droughts and floods (Mellander and Jordan, 2021).

To counter this, catchment management interventions to improve water quality are used throughout the world in various combinations of regulation and voluntary schemes (Musacchio et al., 2020; Paulus et al., 2022). Improvement objectives may include reductions in nutrient and pesticide chemical concentrations and the fluxes of these in and to water bodies (Jones et al., 2017; Cassidy et al., 2022), improvements in biological conditions (Poole et al., 2013) and general habitat and ecosystem services quality (Boetzl et al., 2021). However, interventions can take many years to manifest into improvements in environmental quality (Melland et al., 2018), if at all in some cases (Ait Sidhoum et al., 2023). Moreover, when voluntary schemes are delivered, these can be time-limited where monetary incentives diminish and so there is a risk of practice reversion (Burton et al., 2008; Riley, 2016). In recent years, catchment management approaches to water quality have grown in popularity (Berthet et al., 2021). These schemes are widely viewed as an attractive alternative to capital-intensive approaches to water quality issues which deal with the consequences instead of tackling them at source. In the UK, recent schemes targeting pesticide losses include weed-wiper trials (targeting MCPA) in Wales (Okumah et al., 2021) and Severn Trent Waters "Farming for Water" scheme which aimed to reduce metaldehyde concentrations in abstracted water (Cooke et al., 2020). However, evaluations of lasting effectiveness (i.e., for a period of time after the final intervention measure has ceased) are rare.

In both the Republic of Ireland and Northern Ireland the herbicide MCPA (2-methyl-4-chlorophenoxyacetic acid) is primarily used to reduce rush (*Juncus* spp.) cover in areas of rough grazing and pasture. During the period of this study, farmers in both countries were required to comply with Good Agricultural and Environmental Conditions (GAECs) in order to receive financial support under the Basic Payment Scheme (BPS). Where rushes were deemed to not be actively controlled, a breach of GAECs could be noted and may result in a reduction in payments from the BPS.

MCPA is the most widely detected herbicide in raw (i.e., untreated) water supplies across the island of Ireland making it an issue of significant concern (NI Water, 2022; Environmental Protection Agency, 2024). This is particularly the case in the cross-border Derg catchment as there have been several regulatory breaches in recent years at the Derg Water Treatment Works, which treats drinking water for approximately 40,000 people (NI Water, 2022).

The aim of this paper was to explore pesticide usage practice changes in a case study following a catchment-based management scheme that was delivered between 2018 and 2021 in the Derg catchment. The main priority of the Land Incentive Scheme (LIS) was to tackle the prevalence of MCPA in the catchment's rivers.

1.1. Background to case study

The LIS awarded €1.16 million in grants to farmers to adopt sustainable land management practices to protect drinking water sources in the Derg Catchment and was active between July 2018 and October 2021. Alongside a focus on changing MCPA usage, other measures were directed at soil and sediment conservation. Farmers who expressed an interest in the scheme were visited by project officers, who worked with them to develop Water Environment Management Plans (WEMPs). These were bespoke plans outlining any issues noted on the farm that could impact water quality and recommending measures to target them. In total, 223 WEMPs were produced and 118 of these were translated into measures actioned on farms.

General Data Protection Regulation (GDPR) issues at the time meant that the LIS team relied on media (radio, newspapers, posters in community centres) to advertise the LIS. This, in conjunction with COVID-19, caused delays in promoting the LIS. Therefore, on-the-ground measures (as opposed to expressions of interest, WEMPs or applications) were deemed to have begun in April 2020.

The promoted best management practice for MCPA was to replace the broadcast-spraying of MCPA (DT_{50}: 7–60 days (soil) and 14 days (water)) (Thorstensen and Lode, 2001; Morton et al., 2019), K_{oc} range (soil organic carbon to water partitioning coefficient) of 54–118 L kg^{-1}) (Mackay et al., 2006) with selective application of the less mobile glyphosate (K_{oc} = 884–50,660 L kg^{-1} (Thorstensen and Lode, 2001; Lewis et al., 2016), DT_{50}: 6.45 days (soil) and 9.9 days (water) (Lewis et al., 2016)) using weed-wiping equipment, which was funded as a contractor-supplied service. Weed-wipers, which consist of a rotating brush onto which glyphosate is sprayed, are effective against target species, such as rush (*Juncus* spp.) in pasture because the target plants stand taller than the surrounding grasses. As the weed-wiper moves across the area, the brush wipes against the leaves of the target plant, transferring glyphosate, while minimising drips onto non-target plants. MCPA is not licenced for use in weed-wipers. Of those actively participating in the scheme, 73 farms made use of weed-wiping services in 2020 and 32 in 2021, resulting in a cumulative area of 9.7 km^2 being weed-wiped. Five rush control knowledge-exchange events were also held to demonstrate the effectiveness of glyphosate as an alternative to MCPA for the treatment of rush. Additionally, the LIS provided 76 pesticide container storage units to reduce spillage potential.

The immediate impact of the LIS on the flow-weighted mean concentration of MCPA in the Derg (compared to the neighbouring control catchment, the Finn) was a 21 % reduction (Cassidy et al., 2022). A cost-benefit analysis (CBA) of the LIS was conducted in 2021–22 to assess value for money and establish under what circumstances LIS catchment measures could successfully compete with traditional, capital-based solutions to improve water quality. Assuming long-term LIS investment, the CBA found that LIS benefits, in the form of water treatment cost savings, would cover implementation costs three times over (Glass and Burgess, 2022). Almost all the cost savings would be in capital and operational expenditure on drinking water treatment processes that would otherwise be necessary to prevent the regulatory breaches in MCPA. However, a process evaluation (see HM Treasury (2020)) of the LIS, undertaken to identify lessons learned and to inform the CBA, highlighted that, without sustained investment in catchment measures, farmers were likely to revert to MCPA use and some or all of the LIS gains would be lost (Glass et al., 2022). More specifically, the process evaluation concluded that a strong status quo bias in favour of MCPA would make farmers reluctant to switch to glyphosate unless actively supported over time to do so.

1.2. Study aims

Given that the LIS closed in 2021, this current study assessed the change in MCPA export levels as a result of the implementation and subsequent withdrawal of the LIS and its impact on farmer behaviour. Two data sources were used:

➢ **Water monitoring programme**: For temporal data, pre-, during and post-LIS periods were covered in both the Derg and a neighbouring control catchment (Finn). To check for pollution swapping of MCPA for glyphosate, the latter was also monitored in both catchments. For spatial data during the main April to June pesticide application period, a 2018 MCPA survey of eleven sites in the Derg catchment (Morton et al., 2021) was repeated in 2023.
➢ **Behavioural study**: This involved a postal survey of farmers in the LIS eligibility area followed up by farmer workshops providing a mixture of quantitative and qualitative data.

This study brings scientific data from the water monitoring programme and social data from the farmer survey and workshops together in a mixed-data approach as proposed by Okumah et al. (2021). There has been a growing interest in this type of interdisciplinary approach with researchers arguing that the two data streams are "both vital, mutually complementing information sources that can underpin the development of feasible and effective policies and management interventions" (Richter et al., 2022). In this study, the main objective of the scientific data analysis was to provide evidence of change in pesticide-use practice through reduced MCPA concentrations in surface waters, while the objective of the social data analysis was to understand the behavioural drivers behind these changes.

2. Materials and methods

2.1. Study area

The predominantly rural Derg (treatment) and Finn (control) catchments lie within the cross-border Foyle River basin in the north-west of the island of Ireland (Fig. 1). The catchments have previously been described comprehensively in Morton et al. (2021) and Cassidy et al. (2022) and are summarised in Table 1.

Until 31st December 2020 the UK was part of the European Union and subsequent to this date the UK withdrawal agreement ("BREXIT") and the Northern Ireland protocol allowed that the Water Framework Directive (Council of the European Commission, 1998) continued to apply in Northern Ireland throughout the remaining period of the study. As such, the respective 0.1 and 0.5 μg L^{-1} limits for individual and total

Table 1
Main characteristics summary for the Derg (treatment) and Finn (control) catchments. The sample point grid references denote the main temporal sampling points in Fig. 1 (yellow triangles).

	Derg (treatment)	Finn (control)
Sample point grid reference	54.722° N, 7.497° W	54.795° N, 7.686° W
Catchment area	384 km^2	386 km^2
Land use[a], %		
Marginal land and bog	44.0	62.0
Grassland	35.4	26.0
Woodland and forestry	17.6	11.2
Soil types	Cambisol, Umbrisol, alluvium, peat	Cambisol, Umbrisol, Gleysol, alluvium, peat
Annual river flow, mm	1490[b]	1904[c]
Q5:Q95 ratio	41.0[d]	39.6[e]

[a] CORINE (© European Union Copernicus Land Monitoring Service, 2018).
[b] National River Flow Archive (2024) 2017 to 2023.
[c] OPW (2024) 2017 to 2023.
[d] Department for Infrastructure (2024) 2003 to 2023.
[e] OPW (2024) 2003 to 2023.

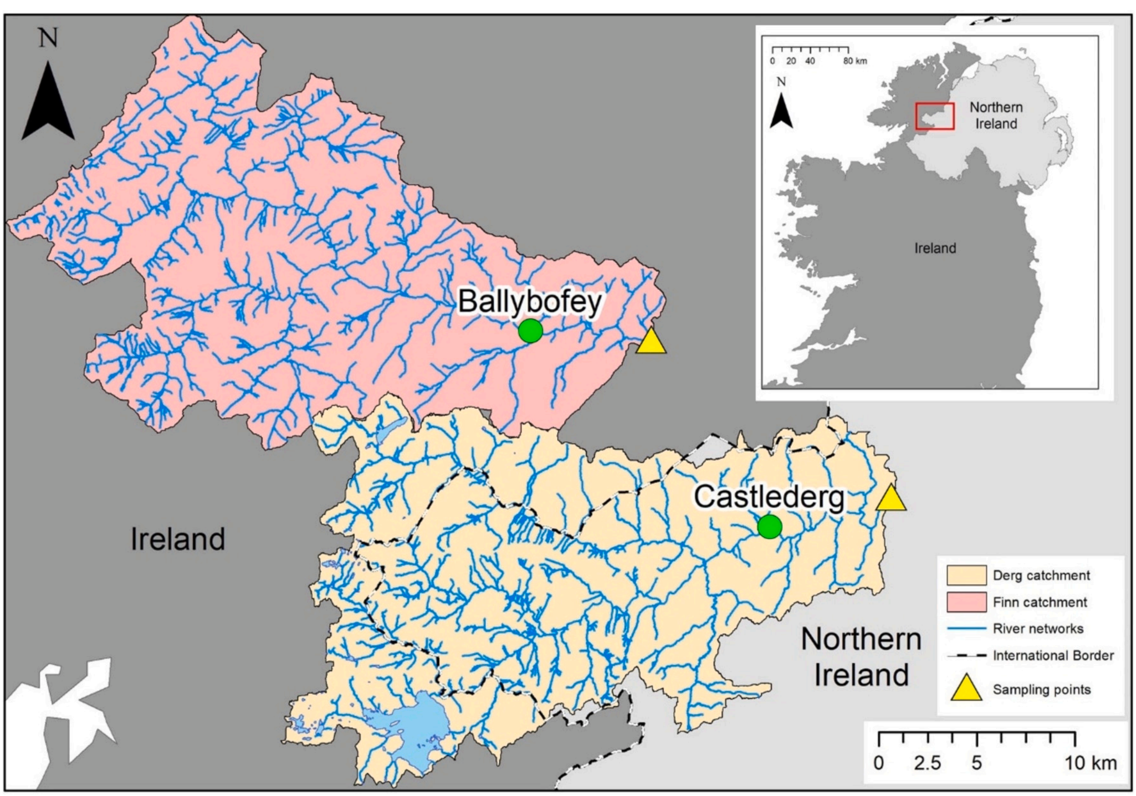

Fig. 1. Map showing the river networks of the Derg and Finn catchments. Also shown are the temporal sampling locations for each river. Inset shows the location of the two catchments on the island of Ireland.

pesticide concentrations permitted in treated drinking water remained in effect throughout the project. Directive 2009/128/EC (Safe Use of Pesticides) (Council of the European Comission, 2009) also remained in effect.

2.2. River Finn as the control catchment

The River Finn was selected as the control catchment after a review of several catchments of similar size across the north of the island of Ireland (see Supplementary Material in Cassidy et al. (2022) for details. Briefly, comparison of long-term flow duration curve (FDC) records showed the Finn to be the most appropriate choice given the similar rainfall-runoff patterns over the discharge range. Land use patterns in both catchments were also similar (Table 1).

2.3. The MCPA monitoring programme

2.3.1. Spatial monitoring

Weekly water samples were collected from 11 locations across the Derg catchment (Fig. 2) between 4th April and 27th June 2023 in a repeat of the sampling undertaken in 2018 (Morton et al., 2021). In summary, samples were taken using 750 mL HDPE bottles attached to TeleScoop Sample Dippas (bottle-holders on extendable poles; Bürkle GmbH, Bad Bellingen, Germany). Water was then decanted into 1 L amber glass bottles and stored in cool boxes for return to the laboratory. Morton et al. (2021) had noted a strong correlation between the proportion of improved grassland downstream of sample locations D2 and D3 (Fig. 2) and the higher magnitudes of MCPA concentration in the main tributaries coincident with the application period prior to the LIS. The purpose of the repeat survey was to determine whether this seasonal-spatial pattern had changed in the years following the withdrawal of the LIS.

2.3.2. Temporal monitoring

The experimental setup previously described in Morton et al. (2021) and Atcheson et al. (2022) continued to be used. In brief, refrigerated automated ISCO 6712R water samplers located at the temporal sampling points (Fig. 1) took water samples every 7 h between late March and mid-December each year. Samples were collected daily (at 14:00 GMT) during the remainder of each year. The 7-hourly sampling method follows the "Plynlimon" approach (Halliday et al., 2012) previously evaluated by Jordan and Cassidy (2011). Sampling began on 27th April 2018 in the Derg and 22nd May 2018 in the Finn and ended in both catchments on 31st October 2023.

2.3.3. Sample analysis

The concentration of MCPA in all samples was determined as described in Morton et al. (2021). Briefly, all samples were refrigerated within 8 h of collection and were analysed within 3 days. Unfiltered aliquots were extracted and concentrated before analysis by LC-MS/MS, following Gervais et al. (2008) and McManus et al. (2014). The limit of detection (LOD) was 0.0005 μg L^{-1}.

Each week, an equal volume of water was taken from each temporal sample and composited to form a weekly sample that was analysed for glyphosate concentrations between 9th July 2019 and 31st October 2023 by Northern Ireland Water using Off-Line FMOC-CL derivatisation, followed by direct injection LC-MS. The LOD, which varied through the period of the study as a result of changes in the supply of analytical laboratory services, ranged between 0.06 and 0.03 μg L^{-1}.

2.3.4. Data analysis

MCPA and glyphosate concentration values below the LOD were

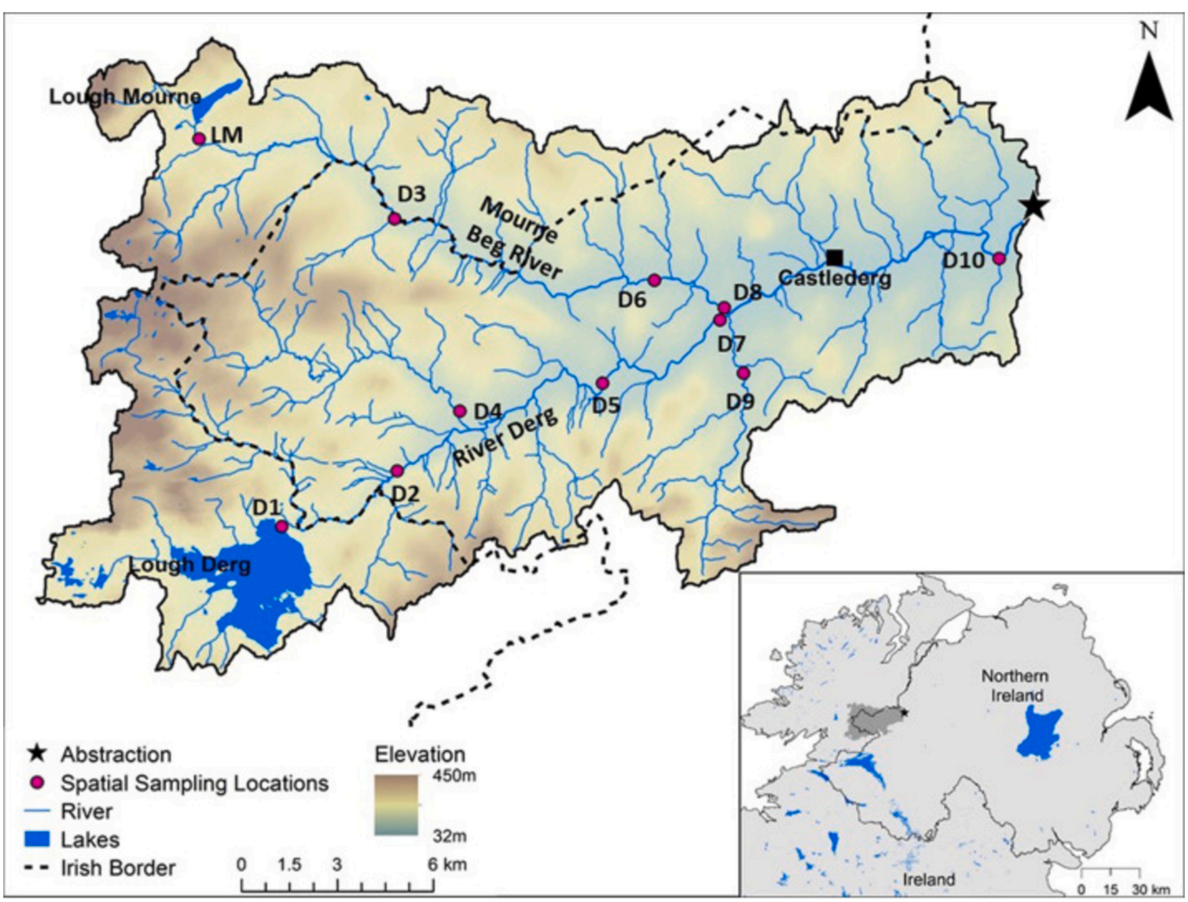

Fig. 2. Location of the spatial sampling water quality locations across the Derg Catchment.

changed to half the LOD for statistical analysis. However, this was not necessary for the temporal MCPA concentrations.

The median MCPA concentration for each spatial data sampling location was calculated for both the 2018 and 2023 sampling seasons and a line of best fit was added. A two-tailed *t*-test was used to determine if the slope of this line was significantly different from a 1:1 slope.

Analysis of the temporal data required division of the study into periods when pesticide application was expected to have occurred ("Peak"; 1st April–31st October) and when it was not ("Quiescent"; 1st November–31st March), as well as whether the data were collected before the LIS on-the-ground measures began ("Pre-LIS"; April 2018–March 2020), during the LIS ("During-LIS"; April 2020–October 2021) or after the LIS ended ("Post-LIS"; November 2021–October 2023).

Pesticide loads were determined on a weekly basis in each river according to Eq. 1:

$$Load = \sum_{1}^{n} c_i t_i q_i \tag{1}$$

Where:

c_i is the instantaneous pesticide concentration in the *i*th sample (μg L^{-1})

t_i is the time period represented by the sample (s)

q_i is the flow in the *i*th sample period (interpolated from hourly data) (m^3)

n is the total number of samples in the data set.

The flow-weighted mean concentration (FWMC), which weights pesticide concentration at each time step by both the duration of the observation and the river flow at that time, is considered more representative of river systems where there is a high dependency of concentration on flow (Schäfer et al., 2008; Bundschuh et al., 2014). The FWMCs were also calculated for each river for each week and separately for each Peak and Quiescent season, according to Eq. 2:

$$FWMC = \frac{\sum_{1}^{n} c_i t_i q_i}{\sum_{1}^{n} t_i q_i} \tag{2}$$

Linear mixed effects models were run to determine whether the interventions decreased MCPA concentrations, loads and FWMCs in the Derg catchment compared to the Finn and, if so, whether this effect continued after the LIS ended. Baseline regression models, which included the catchment (Derg and Finn), the time period (Pre-LIS, During-LIS and Post-LIS) and the interaction between the two as fixed factors, were separately fitted to the MCPA concentrations, loads, and weekly MCPA FWMCs using the "gls" function from the nlme package in R (Pinheiro et al., 2023). Peak and Quiescent seasons, and their interactions with the other fixed factors, were also included in the FWMC models. These factors were assessed using linear mixed effects models (using the "lme" function in the nlme package), following the protocol outlined in Zuur et al. (2009). The random effects tested were the year and week (carousel cycle) and, for concentrations and loads, the day of sampling and the time the sample was taken. Models with different random effects were tested against one another using a restricted maximum likelihood function, with the Akaike Information Criterion (AIC) value used to determine the model with the best fit. The fixed effects were similarly evaluated against one another once the random structure was chosen using a maximum likelihood function. The model with the lowest AIC of two models with a single difference in fixed effects was chosen and progressed. This process continued stepwise by removing a single variable until the AIC indicated that a better model was not available. The "lmer" function in the lmerTest package was used to obtain *p*-values using Satterthwaite's method for unbalanced designs and Type III ANOVA tables (Kuznetsova et al., 2017). The "glht" function with the "Tukey" option from the "multcomp" package (Hothorn et al., 2008) was used as a post-hoc test to determine between which interaction-term categories significant differences occurred. Following Cassidy et al. (2022), a statistical significance level was set at $\alpha = 0.05$ and a (non-significant) tendency at $\alpha = 0.05$–0.10.

2.4. The behavioural study

The behavioural study involved two elements: a farmer survey and farmer workshops. A list of farmer contacts was obtained from DAERA (Department of Agriculture, Environment and Rural Affairs), Northern Ireland. The questionnaire (see Supplementary information) was developed through multiple iterations, designed in Canva, professionally printed in A4 full colour and mailed with a freepost return envelope to 415 farmers located in the Derg catchment in October 2023. An online version, produced on Snap Surveys, was made available to farmers via QR code on the paper questionnaire. Farmers were also invited to complete the questionnaire by telephone with a researcher, though no farmers chose this option. To enhance response rates, a reminder with replacement questionnaire was mailed out several weeks later and all recipients were offered free entry into a prize draw for one of five £100 gift vouchers on completion of the questionnaire. The survey responses contained a mixture of quantitative and qualitative data with the latter analysed via manifest content analysis in which direct quotations are used to convey respondents' opinions and perceptions (Kleinheksel et al., 2020).

Farmers who completed the survey were asked to indicate their willingness to participate in future workshops to discuss water quality in the catchment and how farmers could be supported to protect it. This was to scrutinise responses obtained via the survey and to promote discussion about possible solutions to the MCPA challenge in a dynamic group setting. Two workshops followed in February 2024 which were audio-recorded and professionally transcribed. Again, manifest content analysis was used to evaluate the transcriptions.

3. Results

3.1. Spatial MCPA re-survey

In both 2018 and 2023, 143 grab samples were collected from the 11 sampling locations. The highest MCPA concentration recorded in 2018 was 8.97 μg L^{-1} at D9, whereas it was 31.89 μg L^{-1} at D8 in 2023 (Fig. 3.a). It should be noted that the largest 2023 concentration was recorded after a 22 day dry spell and two small rainfall events (1.2 mm on 13th June (Met Office, 2024)) and that five other sites experienced their highest MCPA concentrations for 2023 on the same date. The next largest MCPA concentration at D8 in 2023 was 0.52 μg L^{-1}. While there was a considerable increase in median concentration at one site, D4 (where the LIS had proved less popular), between 2018 and 2023 (Fig. 3b), the median MCPA concentrations decreased for seven sites, and the remaining three sites showed little change. The regression comparing 2018 and 2023 median concentrations of MCPA had a significantly shallower slope than the 1:1 line ($t(9) = 2.97$, $p = 0.02$) indicating that, overall, MCPA concentrations across the river network in the Derg catchment were lower in 2023 than 2018. Apart from D4, this decrease in concentration was in the critical downstream zone where Morton et al. (2021) had noted higher land use pressures and MCPA concentrations in 2018.

3.2. Temporal MCPA pre-, during- and post-LIS

There were 4998 samples (92 %) successfully collected simultaneously from both sites during the six years of the study. In individual rivers, the successful sample rates were higher, with only 1.1 % (61) of samples not being collected in the Derg and 7.0 % (378) of samples not being collected in the Finn.

MCPA concentrations ranged between 0.0015 and 10.7 μg L^{-1} in the Derg (Treatment) and 0.0020 and 7.45 μg L^{-1} in the Finn (Control), but in both rivers the frequency with which concentrations were in excess of

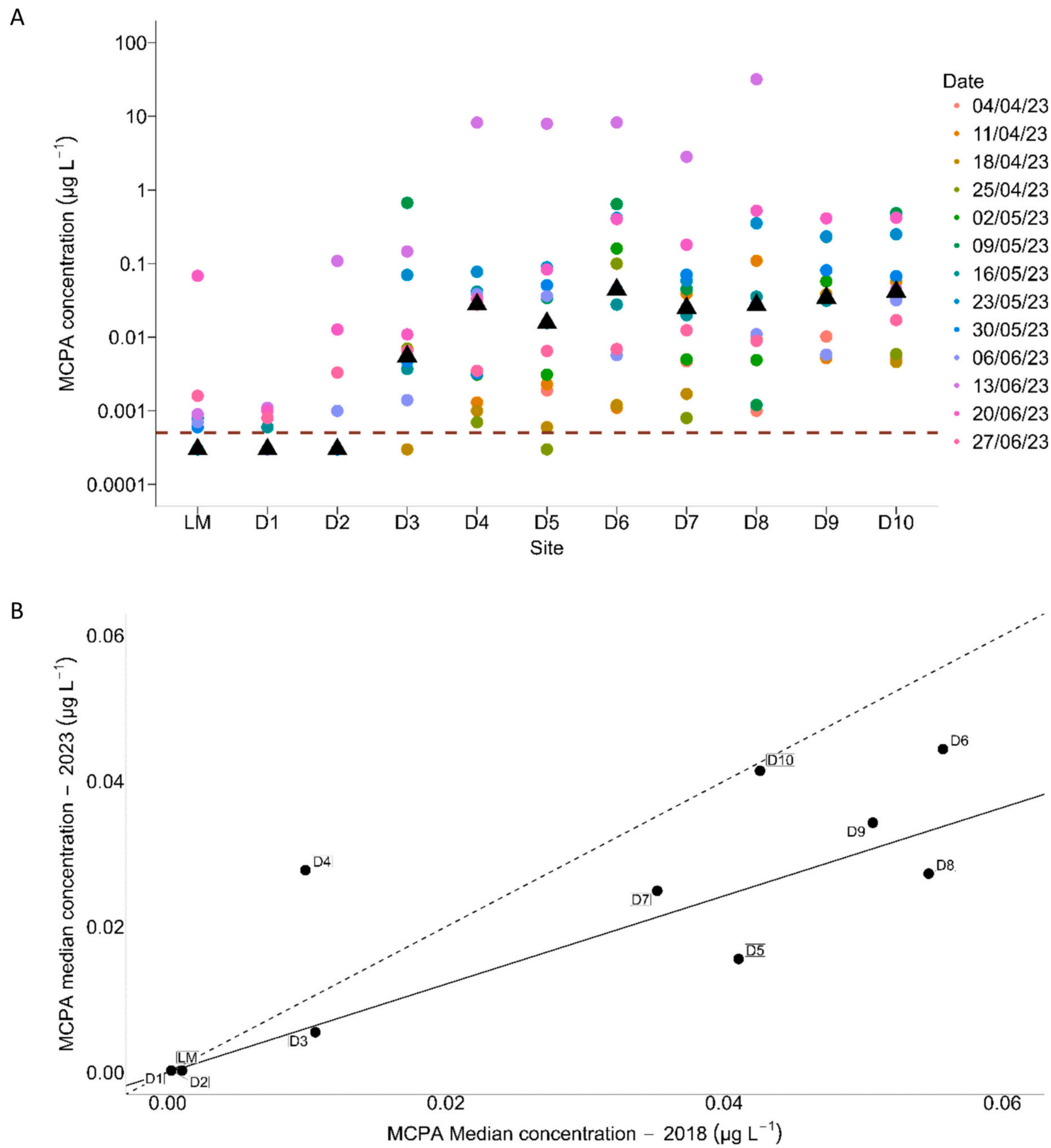

Fig. 3. A) MCPA concentrations recorded at all sites during the spatial sampling exercise in 2023 (circles) and the weekly median pesticide concentration (black triangles) and B) median values of MCPA concentrations at each sampling location in 2018 vs 2023. All concentrations that were below the limit of detection (LOD) were assigned the value of half LOD.

0.1 and 0.5 µg L^{-1} (Water Framework Directive (Council of the European Commission, 1998)) limits for individual and total pesticide concentrations allowed in treated drinking water, respectively) were lower at the end of the study than the beginning (Table 2). In the Derg, there was a 32 % reduction in the frequency of MCPA concentrations in excess of 0.5 µg L^{-1} During-LIS compared to Pre-LIS. However, in the Finn, there was a slight increase (1.4 %) in the number of samples containing >0.5 µg L^{-1} of MCPA over the same period. There was then a decrease in the frequency of 0.5 µg L^{-1} exceedances Post-LIS in both rivers (Derg: 18.4 %, Finn: 30.1 %) compared to During-LIS. The Post-LIS frequency of exceedance of 0.5 µg L^{-1} of MCPA in the Derg was 44.4 % lower than Pre-LIS, while the Finn only showed a 29.2 % reduction over the same period. The frequency with which samples exceeded 0.1 µg L^{-1} of MCPA in both rivers rose During-LIS compared to Pre-LIS (Derg: 3.7 %, Finn: 12.1 %), but was then followed by an almost-identical Post-LIS reduction of 33.0 % in the Derg and 32.9 % in the Finn. The Derg showed a 30.5 % reduction in exceedance frequency between Pre- and Post-LIS periods, while the Finn showed a 25.0 % reduction over the same period.

Table 2
The frequency with which MCPA concentrations in automated samples from both rivers were in excess of the Drinking Water Directive limits for treated water of 0.1 and 0.5 µg L^{-1}.

River	Samples >0.1 µg L^{-1} (%)			Samples >0.5 µg L^{-1} (%)		
	Pre LIS	During LIS	Post LIS	Pre LIS	During LIS	Post LIS
Derg	26.9	27.9	18.7	7.2	4.9	4.0
Finn	35.5	39.8	26.7	7.2	7.3	5.1

Average MCPA raw (i.e., not flow-weighted) concentrations increased in both rivers During-LIS and decreased slightly Post-LIS. The linear mixed effects model showed that there was a significant difference in the interaction between catchment and LIS-period for MCPA concentrations ($F_{2,8433}$ = 22.9, $p < 0.0001$), although the post-hoc test revealed that the Finn had higher concentrations than the Derg in each period including Pre-LIS ($p < 0.001$ for all).

MCPA loads showed distinct seasonal patterns in both the Derg and the Finn, with loss during Peak seasons being considerably larger than those in Quiescent seasons (Fig. 4). Loads in the Derg ranged between 19.5 kg and 84.6 kg across the Peak seasons and between 2.94 kg and 5.04 kg in the Quiescent seasons, while in the Finn they ranged between 42.9 kg and 85.9 kg (Peak) and 3.34 kg and 6.69 kg (Quiescent). Across Peak seasons, the Derg River load ranged between 44.4 % (Peak 2021) and 104 % (Peak 2019) of the Finn load with the lowest percentage occurring in the second Peak season During-LIS. The linear mixed effects model comparing MCPA loads between LIS periods showed a significant difference in the interaction between catchment and period ($F_{2,8282}$ = 38.2, $p < 0.0001$), but as with the raw MCPA concentrations, the post-hoc test showed that the Finn loads were higher than Derg loads in all three periods. However, there was high variation in river discharge (Fig. 4) and rainfall across years which is likely to have affected the amounts of MCPA transferred off land into the rivers: using the FWMCs accounts for that variability.

The MCPA FWMCs for each period also showed a clear Peak/Quiescent season pattern with the highest values in the Derg Pre-LIS (Fig. 5). However, FWMCs in the Finn Peak seasons were greater than those in the Derg Peak seasons both During-LIS and Post-LIS. There was no clear pattern of higher FWMCs for either river during the Quiescent seasons.

Linear mixed effect models, performed on weekly FWMCs, showed that there was not a significant interaction between catchment and period for FWMCs ($F_{2,279}$ = 1.23, p = 0.29). However, the weekly FWMC values did differ significantly between the Peak and Quiescent seasons ($F_{1,190}$ = 379, p < 0.0001) (Fig. 5). Therefore, given MCPA should only be sprayed during Peak seasons, the data were split and analysed separately. Perhaps unsurprisingly, weekly FWMCs were very low during Quiescent seasons (both Derg and Finn ranged between <0.01 and 0.15 μg L^{-1}) and there was no significant interaction between catchment and LIS-period for them ($F_{2,101}$ = 0.05, p = 0.95). However, Peak season weekly FWMCs were much higher (Derg: <0.01 to 1.52 μg L^{-1}, Finn: <0.01 to 1.91 μg L^{-1}) and showed a tendency towards significance between catchment and LIS-period ($F_{2,176}$ = 2.49, p = 0.085), with Pre-LIS weekly FWMCs being slightly higher in the Derg than the Finn (mean of FWMC weekly values: Derg: 0.31 μg L^{-1}, Finn: 0.25 μg L^{-1}), During-LIS the weekly FWMCs were higher in the Finn (0.24 μg L^{-1}) than the Derg (0.19 μg L^{-1}) and Post-LIS were slightly higher in the Finn (0.21 μg L^{-1}) than the Derg (0.21 μgL^{-1}). While the statistical significance of the differences in MCPA FWMCs between LIS-periods and catchments for the Peak season is borderline, this still translates into a Finn-corrected Peak season MCPA FWMC reduction of 35 % in the Derg catchment from Pre-LIS to During-LIS (calculated from a 38 % reduction in Derg FWMC and a 3 % decrease in Finn FWMC). There was a 20 % increase in the Finn-corrected Peak season MCPA FWMC in the Derg from During-LIS to Post-LIS (as the Derg FWMC increased by 9 % while the Finn FWMC reduced by 11 %) but the Derg still achieved an overall reduction in MCPA FWMC of 19 % from Pre-LIS to Post-LIS when differences in the Finn were accounted for (33 % reduction in Derg FWMC and 14 % reduction in Finn FWMC).

To see whether the LIS had a significant impact overall on MCPA concentrations (i.e., regardless of when it ceased as learnings and physical assets such as pesticide storage units from the scheme would still be current), the Peak FWMCs linear mixed effects model was rerun with all data in the During-LIS and Post-LIS as a single After-LIS time period: there was a significant interaction between catchment and period ($F_{1,178}$ = 5.01, p = 0.026), with there being no significant difference between catchments Pre-LIS (p = 0.64) but a tendency towards significance After-LIS (p = 0.072).

3.3. Temporal glyphosate pre-, during- and post-LIS

The glyphosate FWMCs showed less pronounced seasonal and inter-annual patterns compared to those of MCPA (Fig. 6), with values in the Derg ranging between 0.02 and 0.04 μg L^{-1} (Peak) and 0.01 and 0.03 μg

River discharge (mm)

Finn	746	927	880	1181	887	1138	746	999	853	973	942
Derg	488	814	728	1004	724	949	484	782	571	797	733

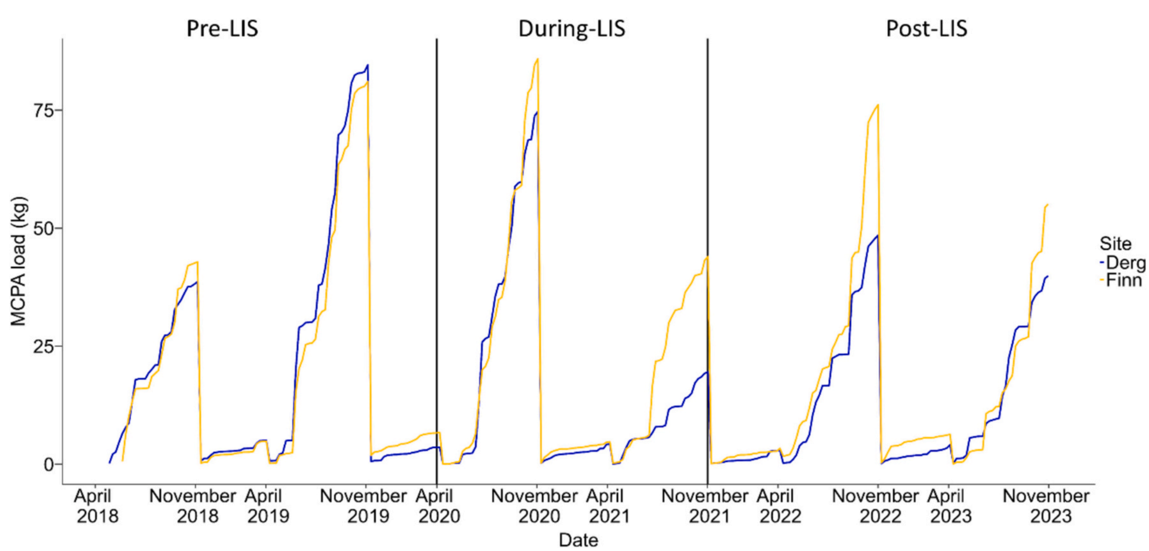

Fig. 4. The cumulative loads of MCPA calculated for each Peak and Quiescent season of the study. The inset table details the total cumulative discharge from each river for each corresponding Peak and Quiescent season. The vertical black lines indicate when the intervention period began and ended.

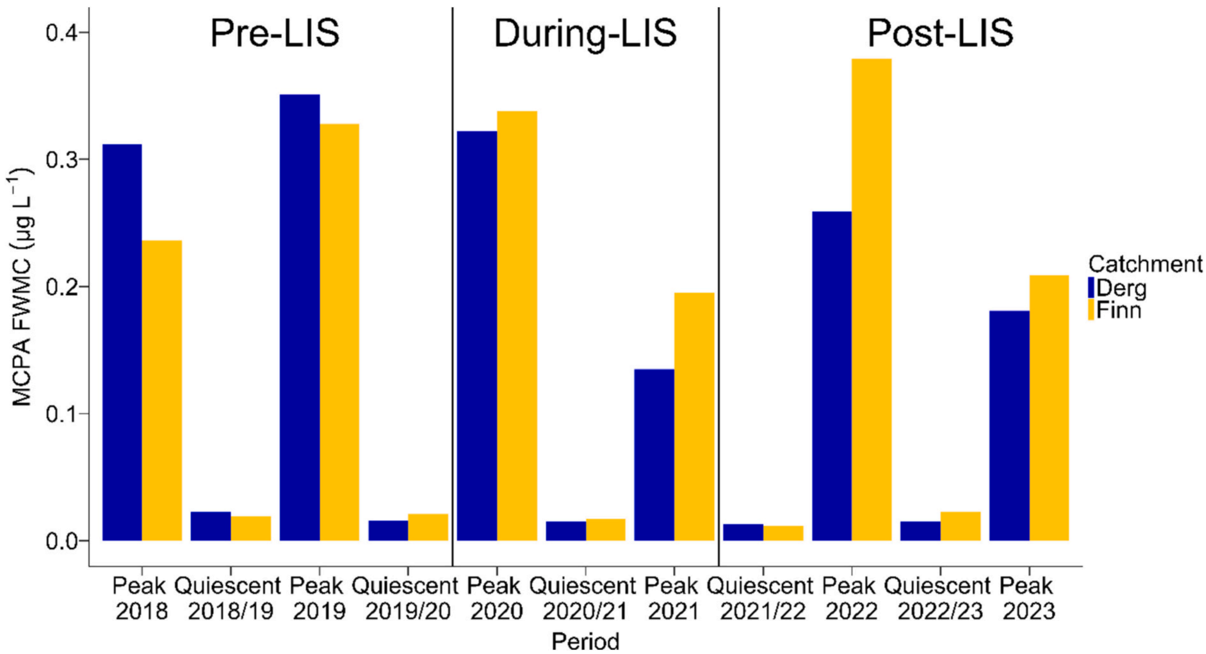

Fig. 5. The flow-weighted mean concentration (FWMC) of MCPA in the Rivers Derg and Finn throughout different stages of the Land Incentive Scheme (LIS) and spraying (Peak) and non-spraying (Quiescent) seasons. The vertical black lines indicate when the intervention period began and ended.

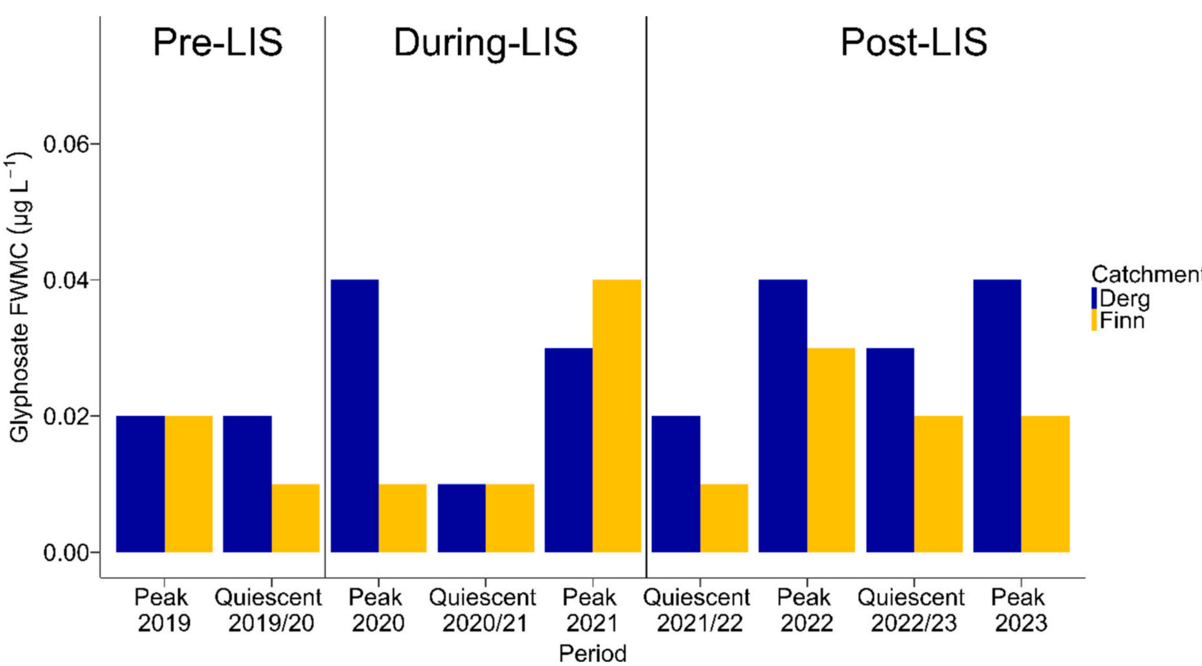

Fig. 6. The Flow-weighted Mean Concentration (FWMC) of glyphosate in the Rivers Derg and Finn throughout different stages of the Land Incentive Scheme (LIS) and spraying (Peak) and non-spraying (Quiescent) seasons. The vertical black lines indicate when the intervention period began and ended.

L^{-1} (Quiescent) and between 0.01 and 0.04 (Peak) and 0.01 and 0.02 µg L^{-1} (Quiescent) in the Finn.

Glyphosate composite concentrations were higher in the Derg than the Finn across all LIS-periods ($F_{1,181} = 68.0$, $p < 0.0001$). The interaction between site and period showed a tendency towards significance ($F_{2,181} = 2.42$, $p = 0.092$), with the difference between catchments in each period greater During-LIS than Pre-LIS or Post-LIS, potentially suggesting a slight but non-sustained increase in glyphosate use in the Derg catchment during the LIS. However, when concentrations were converted to loads, there was no significant interaction between catchment and period ($F_{2,182} = 1.98, p = 0.14$) meaning lower river flows may have concentrated the glyphosate more During-LIS than Pre-LIS or Post-LIS.

3.4. Behavioural factors influencing MCPA pollution control at source

Of the 415 questionnaires mailed to farmers, 115 were completed (14 % of these were online). This represents a response rate of 28 %. The two workshops were attended by 8 and 18 farmers, respectively.

3.4.1. Prevalence of rush

The survey found that 90 of the 115 farmers (78 %) who completed the survey had areas of rush on their farm, and all but one farmer used some method of rush control, with 46 % applying solely MCPA or MCPA in combination with topping and/or glyphosate.

3.4.2. Motivations behind rush control

Respondents indicated that the following reasons were either important or very important for rush control: Better silage (important 62 %/very important 22 %); Neat and tidy fields (52 %/38 %); Better grazing (49 %/45 %); To ensure GAEC (Good Agricultural and Environmental Condition) compliance (51 %/38 %). In the UK and EU, farmers are required to comply with GAECs to receive financial support under the Basic Payment Scheme (BPS). If rushes are not controlled, this may be regarded as a breach of GAECs and result in a reduction in the BPS payment.

For farmers who attended the workshops, avoiding loss of farm payments was very important. As one farmer remarked, "*The biggest reason most people are doing it is not to break the single farm payment* [i.e. the Basic Payment Scheme]". Another participant said pride was a big factor in rush control: "*Farmers with pride wouldn't want their neighbours seeing their ground all rushes… The nearer to town the tidier they're getting*"; "*Looks a lot neater; stops all the other farmers from chatting about them (lol)*" Other farmers also said they if they are not dealt with, they take over: "*I want rid of them, they just overgrow and take over everything…I think if you don't cut or spray or do anything, just makes it thicker*".

3.4.3. Attitudes to glyphosate as alternative to MCPA

Respondents were asked to describe any perceived advantages or disadvantages of glyphosate compared to MCPA. Of those who responded to this question, the main perceived advantage of glyphosate was that it is better for the environment because it is applied directly on to the rush so it will not harm wildflowers and other species and is better for water quality (30 % of respondents, $N = 47$). However, 15 % said that glyphosate does more sward damage because it can drip on to the grass and destroy it while 6 % indicated that it does less sward damage. In terms of effectiveness at rush extermination, 17 % of respondents felt that glyphosate was less effective than MCPA and 15 % felt the opposite. Reported sub-standard contractor performance during the LIS led some farmers to doubt the efficacy of glyphosate. This was confirmed in the workshops with one participant saying that it put some farmers off availing of a second year of free weed-wiping, "*I think that was putting people off the second time round, to see the job done and the rushes were still green*". However, one farmer in the workshops was willing to give it another go with a different contractor and was satisfied with the results: "*We've had it done since, we paid privately to have it done ourselves, that was a better job*". Other perceived advantages of glyphosate were that it was cheaper to use (13 %) or better for human/animal health because of cleaner drinking water (9 %). One farmer commented that it was easier to remove at the water treatment works so resulted in cost savings. Other perceived disadvantages of glyphosate given were that new machinery would need to be purchased to apply glyphosate (i.e. weed-wiper) and that it can be difficult to get a contractor.

3.4.4. Pesticide awareness

Respondents with rush on their farms were asked how they learned to control it. Sixty-nine per cent of respondents learned about rush control from family members but only 30 % of respondents learned it from a training course. Eighteen per cent of respondents learned from neighbours and 15 % from other sources including the LIS project officers (3 respondents), farming media, online research and their spraying contractor. The survey also found that farmers often spray in sub-optimal weather conditions with 38 % of respondents spraying MCPA or glyphosate if it is dry overhead and forecast to be dry for the rest of day, but with no reference to the next day's weather forecast.

3.5. Farmers' engagement with the LIS

Seventy-one per cent of survey respondents had heard about the LIS. While respondents often learned about it through multiple channels, the most common way of hearing about it was through other farmers (56 %), followed by roadshows or information events (35 %). Respondents learning about LIS through family/friends and leaflets/posters in shops or community centres was equal at 30 % each.

Twenty-eight per cent of respondents engaged with the LIS to the point of having measures actioned on their farms. Of those who didn't have any measures actioned, almost two-fifths had never heard about the scheme while 18 % said LIS funds were exhausted. A further 18 % did not proceed because there were no suitable options for their farm. Other reasons for non-participation included not having the time to apply (11 %), concern about future obligations (10 %) or the possibility of not being paid back (4 %).

Of the farmers who had measures actioned on their farm, 18 availed of free weed-wiping contractor hire. Eleven of these had never previously used weed-wiping with glyphosate before. When asked about future use, 5 out of 15 respondents intend to use only weed-wiping with glyphosate going forward, an increase from two respondents pre-LIS.

For farmers persisting with MCPA only following weed-wiping, reasons given were that it is cheaper than weed-wiper contractor hire and because they already had their own boom sprayer. Six respondents stated that they intended to use both MCPA and glyphosate going forward, whereas just two would have done so before the LIS. However, these farmers still appeared to have a strong preference for MCPA stating in one case: "*We have a boom sprayer. Trying to make an earlier investment worthwhile*", and in another: "*I find it hard to get a contractor to weed-wipe when you need it done to get best results.*".

3.6. Farmers' feedback on how to achieve permanent reductions in MCPA concentrations

In the survey and workshops, farmers were invited to give feedback on what measures should be offered in future schemes to support them in reducing MCPA. Several measures were important to farmers:

3.6.1. Support to switch to glyphosate

Given the status quo bias in favour of MCPA, farmers thought support to switch to glyphosate was important. The cost of buying a weed-wiper is estimated at around £3000–£5000 and may be considered prohibitively expensive, especially given that farmers may only need to treat rushes for a few days every year. Suggestions from respondents included: *"Funding to buy own weed-wipers for farmers that have land on the river"; "outright purchasing of equipment"; "Supply grants for purchase of weed-wipers"*. This was echoed by participants in the first workshop: *"Lots of farmers have their own sprayer, that's why they use MCPA."*.

In the second workshop, the farmers were keener on weed-wiper contractor hire noting that weed-wiping is time-consuming. It was confirmed by participants in both workshops that the weed-wiping contractors did a more thorough job in the locality of the second workshop over the first one.

3.6.2. Training and practical support

Several survey respondents indicated that training and practical support would be important for future schemes. Comments from survey respondents included: "*Farmer workshops, i.e., tell them how dangerous MCPA is and how careful they need to be with empty containers, and how far to stay from waterways."; "…training in use of weed-wiper and pesticide handling"; "Information sessions and courses held in the evenings and weekends"; "Workshops"; "Training and demonstrations"; "Pay for weed-wiping, pesticide and storage training*". The workshop participants also emphasised the importance of pesticide training; *"Why are people so relaxed about something so important?... Spilling it all over themselves…"; "Safety might come last"; "They shouldn't be doing it if they're not trained"*.

Pesticide disposal scheme/pesticide storage units.

The farmers in the workshop thought running pesticide disposal schemes regularly would help: "*there was a scheme… They … would pick up the chemicals… it keeps it out of the river*.. One farmer commented that people do not think about pesticides making their way to rivers: "*It will travel as well. People think because they throw it here and you're 500 yards away from the river, it'll not get to the river, but it gets there just the same*". Another farmer saw that the pesticide storage cabinet he received through the LIS would help reduce the likelihood of spillages: "*If I spill something in the cabinet, it stays in the bottom"*.

3.6.3. Address perverse incentives

It is clear that one of the main reasons for spraying rush is to ensure compliance with GAECs. As one survey respondent said, high MCPA is "*a side effect of area-based payments for farmland. MCPA is used so farmers can say land is actively farmed. Just pay them to let rushes grow and MCPA usage will greatly reduce*". During the LIS, the project officers became aware of over-spraying to ensure GAEC compliance. In the Republic of Ireland, the government recognised this as a problem and issued guidance that suppression of rushes where this is not feasible, or desirable because of location and farm profitability factors, is not mandatory (Department of Agriculture Food and the Marine, 2020). There are plans to address these unintended consequences in Northern Ireland also.

3.6.4. Wider education and more rigid controls at point of purchase

The workshop participants felt that wider education was needed as this is not just a farmer issue: "*I would think gardeners, people with their back gardens and sprays… I would reckon they wouldn't have a clue about the stuff that's left over…I think you need to be educating more than farmers, that's my opinion*". Two participants were concerned at how easy it is for people to buy pesticide and dispose of any leftovers down the drain: "*just go the garden centre and buy whatever you want…there's a bit left over, it's washed out, threw away*". In hardware or agri-food stores where higher concentrations are available, one farmer said, "…*the thing of it is anybody can walk in off the street into a hardware store, buy whatever you want*".

4. Discussion

In recent years, catchment management approaches to ameliorate water quality have grown in prominence as an alternative to capital-intensive approaches to solve water quality issues, which deal with the consequences instead of tackling them at source (Environment Agency, 2011; Berthet et al., 2021; Okumah et al., 2021). Cassidy et al. (2022) showed that significant progress in reducing problem pesticides in a catchment is achievable in a short space of time if farmers are given the right support and understand their role both in the problem and in the solution, which is in agreement with the findings of others working elsewhere (Blackstock et al., 2010; Okumah et al., 2021; Bjørnåvold et al., 2022). However, the results from this project's monitoring programme have shown a partial erosion of LIS gains. This is consistent with the findings from the behavioural study which found that although a small number of farmers made the switch to glyphosate use only and others are tentatively moving in that direction, a continuation of support is clearly needed to convince the majority to fully commit.

Although the survey and workshop results demonstrate that farmers are supportive of improving water quality, especially given that the Derg is a drinking water catchment, there remain barriers to overcome, and it is important to ensure that the gains and setbacks are recognised and understood. For example, point source losses are often the cause of significant spikes in pesticide concentrations, but many are relatively easy to address through best practice in bottle storage and machinery washing. Based on the comments from the farmer workshops, it seems reasonable to suggest that much of the drop in frequency of 0.5 $\mu g\ L^{-1}$ MCPA exceedances During-LIS were due to improvements in these habits. This is a positive story that can be used to encourage further farmer engagement, as well as a useful metric by which to quantify the impact of the LIS for funders or for future schemes. On the other hand, diffuse pollution is challenging to explain and manage because there are no clear sources, and it must be recognised that there is the potential for best practice behaviours to, on occasion, still lead to significant pollution events. MCPA sorbs poorly to organic matter, but is moderately persistent, meaning that the herbicide will remain available to be flushed into surface waterbodies at the first rainfall event (Morton et al., 2019). Consequently, the first rainfall event after a prolonged period of dry weather has the potential to lead to significant spikes in pesticide concentrations (Chow et al., 2020; Halbach et al., 2021). The spike in MCPA concentrations observed in the Derg spatial sampling on 13th June 2023 (Fig. 3a) occurred after 22 days without rain. Given the time of year, it would be reasonable to expect a considerable mass of MCPA had been sprayed across a number of the sub-catchments, including in D8 which has a high proportion of improved grassland (Morton et al., 2021), during these dry days. It is important to ensure that farmers are aware of the potential for this to happen, and not to take this as a sign that their efforts are ineffective.

Farmers in the Derg also exhibit a strong status quo bias for MCPA and would need considerable support to switch to glyphosate. Many already own boom sprayers and have decades of experience with MCPA, meaning that the transition would take time—a finding that is also transferrable. Efforts are also needed to overcome misconceptions about the efficacy of glyphosate after sub-optimal contractor weed-wiping. Studies have found that information on the benefits of recommended measures is needed to address negative attitudes that may at times be based on false or incomplete information. For example, Zhang et al. (2016) found that a 20 % rise in farmer awareness of the fact that not applying fertiliser before a storm event or in autumn/winter would result in reduced phosphorus run-off risk from farm fields would lead to a 35–48 % increase in the likelihood of individuals adopting best practice. More weed-wiping demonstrations, which co-occurred with the LIS implementation, could help to address this.

However, it is important to note that encouraging a long-term shift from MCPA to glyphosate may introduce other problems. The first is the potential for pollution-swapping: although not evident in this study (Fig. 6), it should motivate scheme designers to develop a holistic approach with a strong emphasis on minimising pesticide use wherever possible. The second danger is the possibility of a glyphosate ban. In the EU, its approval has recently been extended for a further 10 years. However, member countries are free to apply different rules at national level and several countries have introduced significant restrictions on its use (Finger et al., 2023). Given that a partial ban on glyphosate could increase MCPA use, again this highlights the need to develop a holistic approach. Pesticide training is essential to effect positive, long-term land-use practice, as is the need to eliminate all unnecessary spraying. The behavioural study showed that policies to address over-spraying to be GAEC-compliant will be positive for MCPA reductions.

Awareness-building among the general public is important given pesticide use in gardens and on driveways. A survey of 2000 people across Wales found that 30 % of people thought that weedkiller should be applied liberally over a weed to exterminate it, ignoring the recommended usage advice on the product label, and 6 % of respondents wrongly thought that pouring the product down the sink with boiling water was the correct disposal method (Welsh Water, 2021), while Gerecke et al. (2002) showed that wastewater treatment works can be viewed as point sources for pesticides because they are located at the end of urban drainage networks. More education would help to address this deficit and, judging by some of the comments from the farmers' workshops, could increase farmer engagement by reassuring them that they have not been singled out as the only source of the pesticide problem. There is also a need to engage with the amenity sector, i.e. hotels, golf courses, sports grounds, as these can contribute to the overall pesticide load across the catchment.

5. Conclusions

Catchment management approaches have the potential to address water quality issues, but the implementation time allowed must be suited to the goals of the scheme. The number of occasions in which the 0.5 μg L^{-1} drinking water pesticide limit was exceeded declined both during and after the LIS implementation period in the Derg (treatment) catchment, while MCPA FWMCs were reduced to a greater extent during the LIS than after, when compared with Pre-LIS FWMCs. This highlights the need to consider the extent of behavioural change required in setting the timeframe for a scheme. Equally, the importance of effectively engaging with the whole catchment was emphasised by the spatial results, where those sub-catchments that were more fully engaged showed a reduction in median MCPA values in 2023, relative to 2018. Some adjustments, such as storing pesticide containers in bunded storage tanks or washing down machinery in a different part of the farmyard are easy and (moderately) convenient to adopt and could be implemented as part of a short-duration LIS. However, changing pesticides and pesticide application method requires an understanding of new methodologies, may require capital investment in new machinery and comes with an increased risk (or perceived risk) of adverse effects on farm functioning while making the transition. This requires a longer-term LIS that comes with a sustained advisory system to maintain the knowledge exchange required for behavioural change. Unfortunately, however, catchment schemes are often grant-funded and suffer from restrictive, short-term funding schedules. This prevents them from capitalising on the trust- and relationship-building with farmers to identify and remove barriers to long-term behavioural change. This study demonstrates that gains are possible but can be quickly eroded, making it necessary to resort to costly end-of-pipe solutions to resolve water quality issues. Instead, efforts should be maintained long-term to deliver lasting land use change to safeguard water.

CRediT authorship contribution statement

Luke Farrow: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Catherine Glass:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Phoebe Alice Morton:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **W. Colin McRoberts:** Writing – review & editing, Methodology. **Stewart Floyd:** Writing – review & editing, Methodology, Investigation. **Diane Burgess:** Methodology. **Philip Jordan:** Writing – review & editing, Funding acquisition, Conceptualization. **Rachel Cassidy:** Writing – review & editing, Funding acquisition, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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