Re-focusing Phosphorus use in the Wye Catchment

RePhOKUs

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Contents

1. Overview

This report presents the results of research work on elemental phosphorus (P) inputs and outputs in the Wye catchment, links to river water quality and stakeholder responses to the challenges of maintaining future food and water security in the region. This work was carried out as part of the RePhoKUs project which investigated how P use in the UK food system could become more efficient, sustainable and resilient at catchment, regional and national scales (Section 2). Although an essential nutrient for crop and animal production, rock phosphate is a finite resource which should not be wasted, and leakage of food system P into water is causing widespread damage to the quality and biodiversity of inland and coastal waters in the UK and globally.

The Wye catchment is one of three study catchments within the RePhoKUs project examining how P is used and the drivers of P efficiency, surplus and loss at the catchment scale, local vulnerability to market failures in P supply and the consequences for catchment water quality. The River Wye is a nationally important river with ongoing river P pollution that is compromising the natural capital, provision of ecosystem services and economic development of the region (see Section 2). Previous government and industry research (1994-2008) has shown the Wye landscape has a high risk of P loss in land runoff due to the nature of the soils and topography, the patterns of farming and the local climate. However, a better understanding of the cycling of P in the wider food system in the Wye catchment is needed to drive the potential system change that is required to meet the river's water quality targets for eutrophication control.

RePhoKUs has built on this previous work by (a) providing a better understanding of the annual P input pressure exerted on the Wye catchment and the fate this P pressure within the food system using a well-established Substance Flow Analysis (SFA) methodology (Section 3), (b) investigating the links between P input pressure and river P concentrations and fluxes at different scales (Section 4), (c) analysing the distribution of soil P fertility levels in the Wye catchment and how long they can sustain crop yields in the absence of P inputs (section 5) and (d) assessing stakeholder adaptive capacity to enact system change. In the final section (Section 7), the collective findings and recommendations from the RePhoKUs work are discussed in the context of our current understanding of strategies for sustainable P management in the catchment.

The aim of the report is to provide catchment stakeholders with a better evidence base for driving policy and administrative change that is required to improve the ecological functioning of the River Wye and its provision of ecosystem services.

Note on Terminology

RePhoKUs research uses elemental P (not phosphate P) for all food system stores and flows, and recognises three forms of river P concentrations: soluble reactive P (SRP), total dissolved P (TDP) and total P (TP). Regulatory agencies set river P concentrations as orthophosphate P and refer to phosphate-P. Elemental P is synonymous with TP, and SRP is considered synonymous with orthophosphate-P.

Photo courtesy of Shane Rothwell

2. The RePhoKUs Project: Re-Focusing Phosphorus Use within the UK Food System

RePhoKUs project team

PROJECT AIM:

The aim of RePhoKUs is to enhance the resilience and sustainability of the UK food system by developing and prioritising adaptive strategies that reduce the vulnerability of UK farming to future P scarcity at multiple scales, and that enhance the balanced delivery of multiple ecosystem systems for future food and water security.

WHY:

There is an important gap in knowledge as to the current state of P use within UK agriculture, the wider food system, its impact on the natural environment and vulnerability to a future disruption in P supply. The UK has no known deposits of rock phosphate (RP) and so is completely dependent on imports of manufactured inorganic P from other countries (including Russia) to support food production. The recent sharp rise in the cost of fertilisers and livestock feeds and the war in Ukraine has exposed this UK vulnerability. In addition, eutrophication caused by food system P leaking into our waterbodies is very costly to society and devalues many ecosystem services linked to water quality including, biodiversity, recreation and quantity for drinking. Therefore, improving the efficiency and sustainability of P use in food systems contributes to two objectives simultaneously – (1) increasing resilience to sudden or extreme changes in the global supply and price of P, and, (2) reducing water pollution caused by a build-up and poor management of P in the landscape beyond what is needed for immediate food production and the subsequent negative impacts on the natural environment.

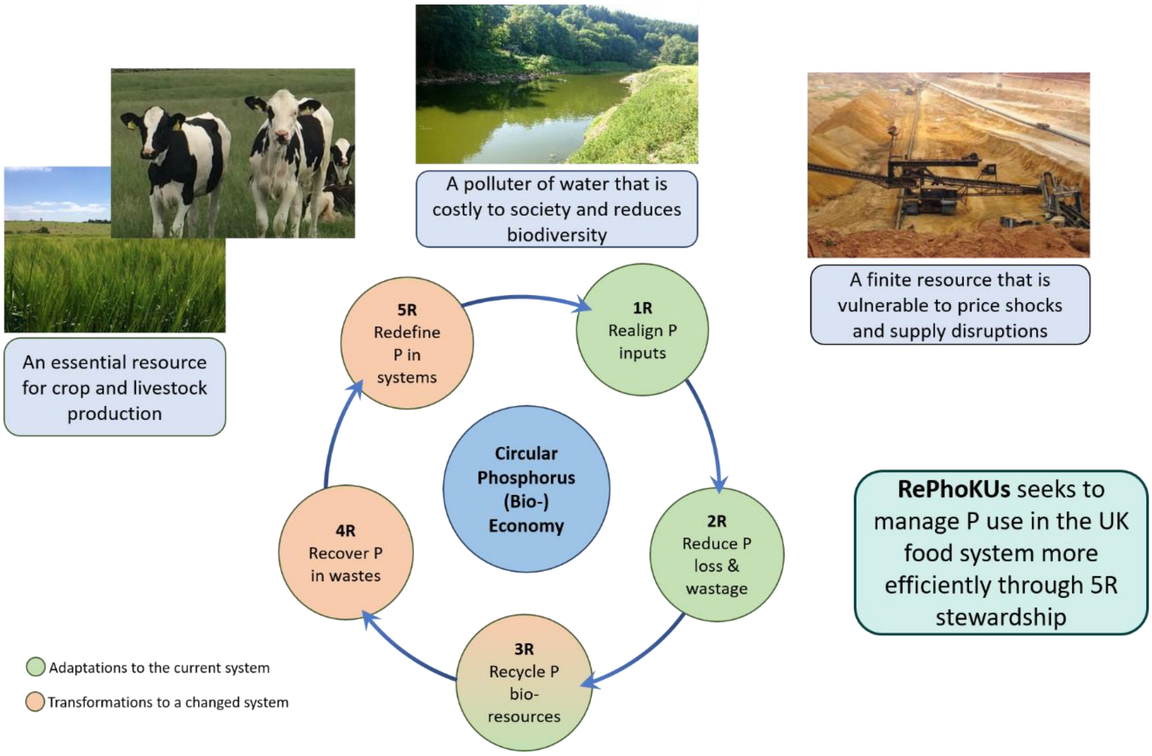
WHAT:

The RePhoKUs project combines different biophysical, social and economic approaches to examine the synergies and conflicts arising from how P is currently distributed within the food system to stimulate discussion and provide evidence for potential policy approaches to more sustainable P use, such as 5R P stewardship (Withers et al., 2015). The project involves an extensive stakeholder engagement process at farm, catchment and national scale.

Key outputs from the project include (1) a national strategy to reduce the vulnerability of the food system to shocks and stress due to P supply disruptions or price fluctuations. (2) a roadmap of the use and cycling of P in the UK food system and the regional imbalance between P demand and supply, (3) assessment of catchments for their vulnerability to P loss to water and options for more sustainable P management, (4) the residual agronomic value of soil legacy soil P reserves and how long they might last without affecting crop production, (5) stakeholder responses to the need and capacity for change at national, regional and catchment scales.

WHO:

The project is a collaboration between Lancaster University; Agri-Food and Biosciences Institute, Belfast;, University of Leeds; University of Technology, Sydney; and the UK Centre for Ecology and Hydrology and is funded by the Global Food Security's 'Resilience of the UK Food System Programme' with the UK's Biotechnology and Biological Science Re- search Council (BBSRC), the Economic and Social Research Council (ESRC), the Natural Environment Research Council (NERC) and the Scottish Government. More information at: http://wp.lancs.ac.uk/rephokus/.



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3. The Wye Catchment

3.1 Introduction

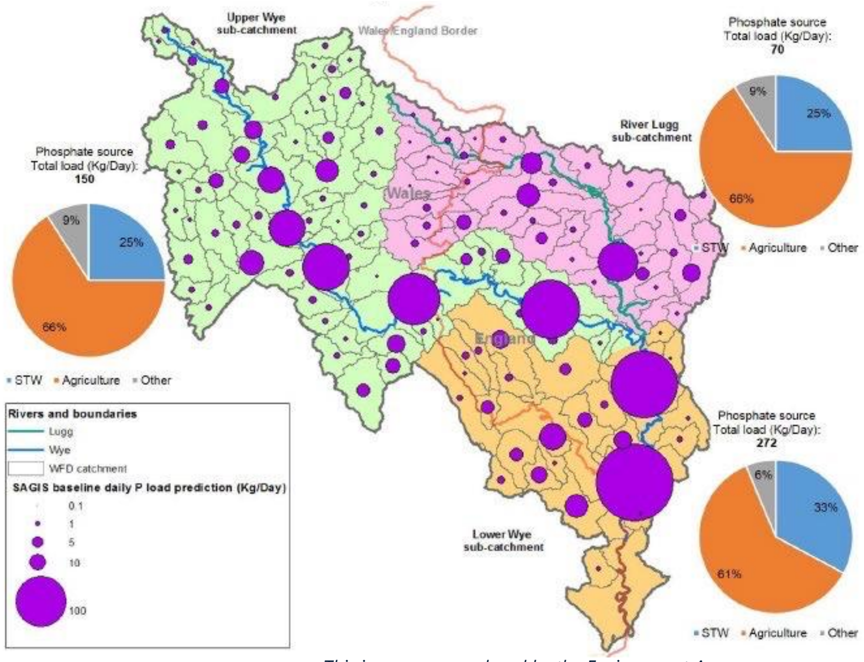
The River Wye is a nationally important UK river; it rises in the Plynlimon mountains in Wales and flows ca. 215 km in a broadly south-easterly direction to the Severn Estuary in England. Mean annual rainfall varies from 2450 mm in the upland north-west to 717mm in the lowland east. The River Wye and its main tributary the River Lugg is a Site of Special Scientific Interest (SSSI) and Special Area of Conservation (SAC) with a nationally significant rod fishery and a thriving regional tourist industry. The catchment (4017 km^2) includes 47 waterbodies all with high recreational value.

Agriculture is the major land use with pastoral farming (sheep and beef) in the uplands, and more intensive arable/mixed farming (cereals, potatoes, hops, soft fruit, dairy, and poultry) on the fertile and highly productive soils in the lowlands. Poultry farming, in particular, has expanded rapidly in the region in recent years along with important cash crops such as maize and potatoes. A mixed geology gives rise to sandy and very silty soils which are prone to erosion. Heavier silty soils are widely underdrained.

3.2 Water Quality

Sections of the main river and its tributaries are failing to achieve the statuatory eutrophication control targets for good or high ecological status due to P pollution (Natural Resources Wales, Environment Agency and Natural England, 2021). Comparison of mean annual orthophosphate concentrations (rolling three year average) against current targets of 0.03-0.05 mg L^{-1} shows phosphate (note not total P) limits are already being exceeded at 31 points in the river catchment, with further failures likely in the future.

Multiple sources of P including sewage effluent discharges from wastewater treatment centres and rural septic tank systems, light industrial discharges, and surface and sub-surface runoff from agricultural land, farmyards and urban areas all contribute to the phosphate loading to the rivers. With advanced P-stripping now implemented at the wastewater treatment centres serving major population centres, source apportionment modelling suggests that 60-70% of the total phosphate load now comes from agriculture (Figure 1).



This image was produced by the Environment Agency

Figure 1 Distribution of phosphate-P loads to the Upper Wye, Lugg and Lower Wye operational sub-catchments and their apportionment from wastewater, agriculture and other sources as modelled by the regulatory agencies (taken from Nautral Resources Wales, Envrionment Agency and Natural England report "*River Wye SAC Nutrient Management Plan Phosphate Action Plan*" 2021) .

3.3 Need for Action

Although the Wye is a Catchment Sensitive Farming (CSF) high priority catchment and has had high levels of investment over the last 14 years to encourage farmers to voluntarily adopt management practices to mitigate diffuse transfer of pollutants from agricultural land, the river water quality remains poor and appears to getting worse. In 2020, a thick algal bloom extended for over 140 miles of the river (Figure 2).

Following a recent Dutch case law ruling, local county councils have placed restrictions on all planning applications that will lead to an increase in P loading to sensitive sections of the river and have recommended designation as a statuatory Water Protection Zone.

Political tensions in the catchment are consequently high due to conflicting stakeholder priorities, and different administrations spanning the Wales-England border are responsible for policy development, regulation and advice. Stakeholder activity is coordinated through the Wye Catchment Partnership supported by the local rivers trust (Wye and Usk Foundation) along with additional citizen science monitoring projects.

A Phosphate Action Plan has been prepared to restore the ecological functioning of the River Wye by reducing river phosphate concentrations to below set limits (Natural Resources Wales, Environment Agency and Natural England, 2021). A strong evidence base is needed to support this strategic mitigation plan.


Photo courtesy of the Wye and Usk Foundation

Figure 2: Algal bloom on the lower Wye in June 2020.

3.4 Key Messages:

- The River Wye is a **nationally important river** with a variety of important habitats of high scientific and conservation value and supporting recreational value for a thriving tourist industry.
- **Highly fertile productive soils** support a wide range of intensively farmed crops and livestock, with recent rapid expansion of the poultry industry, maize and potatoes.
- **Water quality in many areas of the catchment continues to fail** current eutrophication control standards due to high phosphate concentrations in the rivers.
- **A strong evidence base is needed to drive a catchment Phosphate Action Plan**.

4. Phosphorus Substance Flow Analyses for the Wye Catchment

A Substance Flow Analysis (SFA) was undertaken to quantify the stocks and flows of elemental P within the Wye catchment. The SFA maps all significant materials associated with different sectors of the food system and that are entering, leaving or circulating within the catchment, and is a useful mass balance model for identifying significant inefficiencies, losses and accumulations of P in the landscape. The SFA uses publicly available regional and national statistics, industry data, previous scientific studies and local expert opinion. Further details of the SFA methodology are given in Rothwell et al. (2020, 2022).

For the Wye catchment, the model used established coefficients for crop yields and agricultural P offtake (AHDB, 2022), livestock P excretion coefficients from Defra (pers. comm.) and human P use coefficients from Rothwell et al. (2022). Regional fertiliser application rates were taken from the British Survey of Fertiliser Practice (Defra, 2019) and crop areas in the catchment were determined from UKCEH land cover data (Rowland et al. 2017; 2020).

Cattle populations were taken from the Cattle Tracing System and Agricultural Survey geo-located population data (provided by the APHA under license, APHA, 2019), and sheep and pig populations were based on the last complete Defra detailed regional census in 2016 (both Defra Pers. Comm.). Poultry numbers were taken from local investigative work (https://cutcher.co.uk/linklog/2021/07/15/counting-chickens), and confirmed by expert opinion following discussion with the poultry industry. Losses to water from waste water treatment and agriculture were taken from the Separate model (Zhang et al., 2014). Quantities of P entering and leaving the waste management sector were not included due to lack of available catchment data. All data are mass of elemental P in tonnes per annum (t yr^{-1}).

4.1 Substance Flow Analysis Findings

The model output (Figure 3) shows that the Wye catchment imports a total of ca. 6500 t yr^{-1} of P and exports ca. 3100 t yr^{-1} giving an overall catchment P use efficiency of only 48%. The largest P import into the catchment is in livestock feed (ca. 5000 t P yr^{-1}) and the largest internal flow of P is in livestock manure (ca. 6100 t P yr^{-1}), signifying that the livestock sector dominates P use in the catchment. Fertiliser P imports are ca. 1150 t yr^{-1}.

Discussions with local stakeholders have identified that there are currently movements of poultry manure both into and out of the catchment, though these are difficult to quantify and for the purpose of this model are assumed to cancel each other out. Details of livestock sector P inputs, outputs and efficiencies are shown in Table 1.

Table 1: Details of estimated phosphorus flows and sector efficiency for different livestock types, all flow values are tonnes P per year.

	Cattle and sheep	Pigs	Poultry
Feed P	1017	119	4473
Grass P	2802	-	-
Manure P	3365	89	2579
Meat P*	325	30	1846
Milk P	122	-	-
Egg P	-	-	48
Efficiency %	16	25	42

*Liveweight

Annual soil P inputs in the catchment are ca. 7500 t P as manure (82%), fertiliser (15%) and biosolids (3%), and crop and grass P offtake is ca. 4200 t P giving a P uptake efficiency of 57% which is lower than the UK national average of 65%. The imbalance between agricultural P input (fertiliser, manure and biosolids) and offtake (grass and crops) means that around 3000 t of surplus P are accumulating in agricultural soils in the Wye catchment every year, a rate equivalent to 17 kg P ha^{-1}, which is considerably higher than the national average of 7 kg ha^{-1} (Rothwell et al., 2022).

The agricultural P surplus together with the net food P imports gives the total Net Anthropogenic P Input (NAPI) pressure on the catchment, amounting to 19 kg P ha^{-1} yr^{-1}. Losses to water were estimated as 83 t P yr^{-1} from wastewater treatment centres and 225 t yr^{-1} from agricultural land.

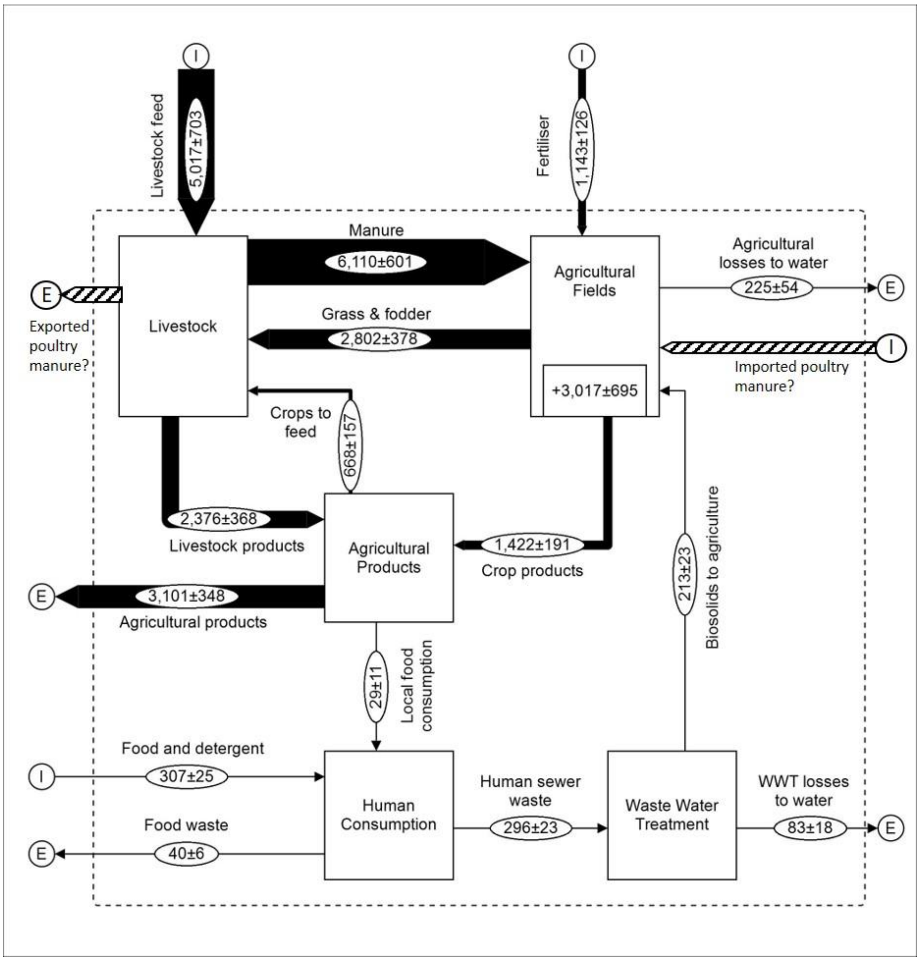


Figure 3: Phosphorus Substance Flow Analysis for the Wye catchment

4.2 Key Messages:

- The Wye catchment **imports a total of ca. 6500 t P yr^{-1}** as animal feed (78%), fertiliser (18%), food & detergents (5%).
- **Exports** of P from the Wye catchment in agricultural products are **ca. 3100 t P yr^{-1}**.
- **Soil P inputs** in the catchment are potentially **ca. 7500 t P yr^{-1}** as manure (82%), fertiliser (15%) and biosolids (3%).
- **Crop and Grass P offtake was ca. 4200 t P yr^{-1}**.
- When agricultural losses to water are accounted for, agricultural **soil surplus accumulation is therefore ca. 3000 t P yr^{-1} or 17 kg ha^{-1} yr^{-1}** over managed agricultural land (excluding rough grazing).

5. Linking Phosphorus Surplus to Water Quality Impacts

A full analysis of river P concentrations and loads at existing routine water quality monitoring sites in the Wye catchment was outside the scope of the RePhoKUs study, but such data was generally difficult to access. A previous analysis of Environment Agency (EA) gauged sites by Jarvie et al. (2003) covering the six-year period from 1995-2000 found river annual total P (TP) loads ranging from <0.05 – 0.93 kg ha^{-1}, with 29-72% (mean 50%) in orthophosphate form. Highest P loads and flow-weighted concentrations were in the Frome, Lugg and Monnow sub-catchments.

Some more recent, limited river P data was available but was not useable to investigate the link between catchment P input pressure and river total P (TP) concentrations and/or loads over time and in space due to a lack of data resolution and quality. Likewise, appropriate high resolution data for fertiliser and manure inputs, and crop yields were unavailable. Some historic higher resolution river P data was available from previous Defra research projects NT1027, PE0116 (PARIS) and PE0202 (PSYCHIC) spanning 1994-2008. These projects measured annual TP loads varying from 0.16-2.96 kg ha^{-1}, with 29-82% (mean 60%) in orthophosphate form, but it should be noted that these data do not reflect the current wastewater and farming sources operating in the Wye catchment.

5.1 Wider Regional and Catchment Analysis

The RePhoKUs project did investigate the relationship between P input pressure (NAPI) and river TP loads at both the regional scale and catchment scale as part of a wider analysis. NAPI is calculated as the sum of P applied as fertiliser, manure P, and P from humans (dietary, detergent, and plumbosolvency), minus the total amount of P harvested in crops and grass (Sobota et al., 2011). The same data sources for the SFA model were used to calculate the NAPI values. For the regional analysis, NAPI values were calculated for the year 2010 to match availability of latest river P load data from Harmonised Monitoring Scheme (provided by UKCEH). Total P load was estimated by summing the most downstream HMS monitoring points from each region and expressed as kg ha^{-1}.

The catchment analysis included data from 69 large catchments spanning the 1990s-2010s. Three consecutive years of NAPI data with corresponding high resolution river TP loads were calculated for each catchment, averaged to give single NAPI and river TP load values and expressed as kg ha^{-1}.

Regional scale*:* a highly significant positive relationship between NAPI and river TP loads indicates that as P pressure increases the impact on water quality is likely to increase (Figure 4). At this scale, both the agricultural P surplus and human P pressure, unless P stripping at wastewater treatment centres is widely used (South East is an outlier on Figure 4C due to prevelance of P removal technology at waste water treatment works), drive P losses to water.

Catchment scale: a significant positive relationship between NAPI and riverine TP load is also apparent ($P<0.05$), although there is clearly much greater variability. This difference can be attributed to (a) issues of data resolution required to calculate NAPI values accurately at smaller scales and (b) catchment characteristics other than the P input pressure influence river TP loads; for example reflecting P losses from the way P inputs or the land surface is managed leading to direct P loss during application or large erosion events.

5.2 Source Contributions

Relationships between concentration (C) and flow (Q) can be used as indicators of biological and hydrological functioning, and provide information on catchment nutrient sources and their delivery mechanisms. Historic research project catchments with high resolution flow and P concentration (SRP and TP) data were used to examine CQ relationships in the Wye catchment. The CQ relationship is log-transformed, and b is a unitless exponent respresenting the slope of the relationship (Moatar et al., 2017). The relationship can be analysed across all river flows, or can be split at the median flow to distinguish different behaviours at high (b50+) or low (b50-) flows. Chemodynamic concentration (b>0.1) or "up" patterns (Figure 5) are attributed to enhanced mobilisation of dissolved and particulate P during high flows, due to reconnection of pollution sources via surface or subsurface routes (Moatar et al, 2017). This pattern of P delivery is transport limited, since delivery to the stream is controlled by connection pathways rather than the abundance of a source.

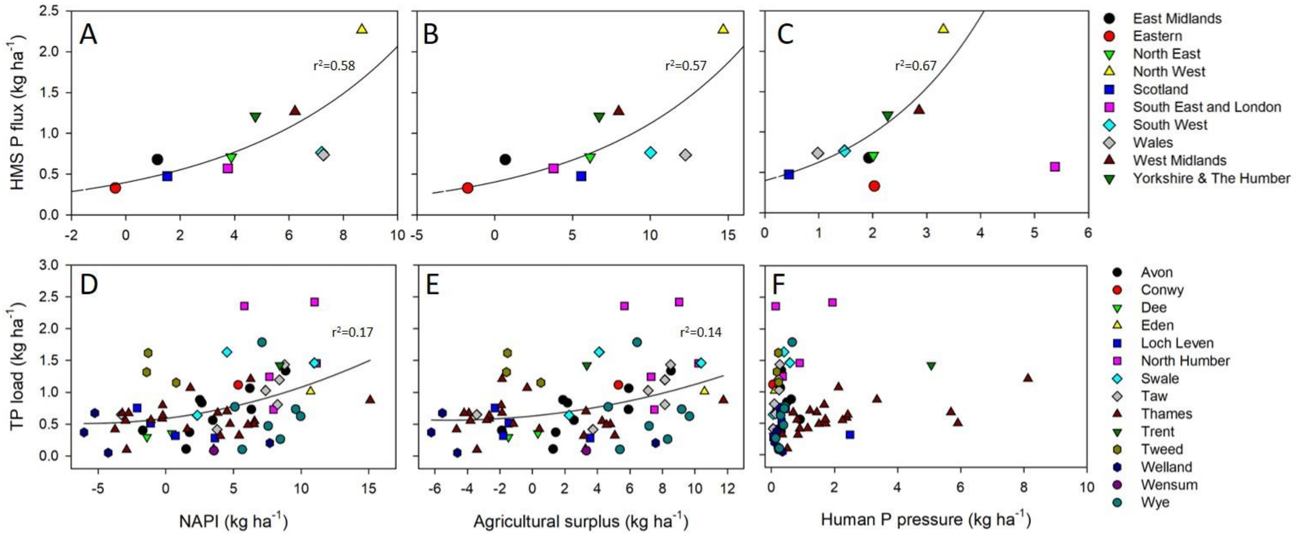


Figure 4: The relationship between Net Anthropogenic Phosphorus Inputs (NAPI); Agricultural surplus; human P pressure and riverine TP load (kg ha^{-1}). Panels A, B and C depict the UK NUTS1 regions, and D, E and F depict different UK sub-catchments within 14 river catchments.

Chemostatic (b>-0.1<0.1) or "flat" behaviour implies a homogenous distribution of a P source, which may be small as in upland catchments or large as in intensively farmed catchments. In this type of P behaviour, changes in hydrological connectivity do not affect solute concentrations, or that flow pathways are stable across time.

Chemodynamic dilution (b <0.1) or "down" relationships are attributed to dilution of solutes during high flows. This pattern of P delivery is source limited, since delivery is determined by P source abundance or rate of release, rather than transport capacity.

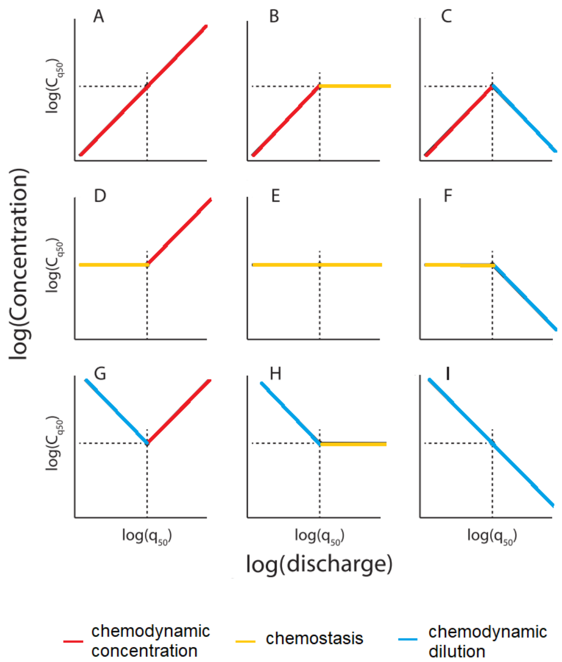


Figure 5: Conceptual schematic of the nine possible concentration (C) flow (Q) relationships when the hydrograph is segmented at the median flow. Edited from Moatar et al. (2017).

Typically, chemodynamic concentration patterns of P delivery are associated with diffuse source P losses from agriculture during storm events or river bank erosion, whereas chemodynamic dilution patterns of delivery are associated with more continuously discharged P losses from point sources in the catchment, such as wastewater treatment centres, industrial units, septic tanks and farmyards.

Splitting the hydrograph distinguished high concentrations of all forms of P at low flows ("down" behaviour), and high flows ("up" behaviour), in the different sub-catchments (Table 2). Patterns which implied high P concentrations at low flows (G, H and I) normally indicative of a point source signal made up 55% of the catchments. The D pattern of 'up' behaviour was the most common for all P forms (27% of catchments), and 64% of catchments have an "up" pattern (A, D and G) for TP at high flows (b50+). This implies that during high flows, P is mobilised from pollution sources as surface and subsurface hydrological connections are made, which is classical of an agricultural signal. B and E patterns were not detected.

This work highlights the difference in P pollution signals between high and low flows across multiple sub-catchments within the Wye, and therefore the need to understand and consequently mitigate catchment P pollution differently across space and time. For example, "up" behaviour at high flows implies the need to reduce source and transport pathways from land to water, whilst "down" behaviour at low flows implies the need to control point sources, such as septic tanks, farmyards, or discharges from waste water treatment works where discharge is not solely dependent on rainfall. It is the combination of source and transport controls that will have the most impact in reducing river P concentrations.

Table 2: The slopes of the split hydrograph at low flows (b50-) and high flows (b50+) for sub-catchments in the Wye for soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP) and total phosphorus (TP). "Down", "flat" and "up" behaviour are shaded blue, yellow, and red respectively.

Catchment	Size (km^2)	b50-			b50+		
		SRP	TDP	TP	SRP	TDP	TP
Frome	77.7	-0.149	-0.126	-0.116	-0.085	-0.093	0.046
Erwood	1282.1	-0.314	-0.222	-0.422	0.091	-0.004	0.182
Garren Brook	91	0.025	-0.017	-0.011	0.702	0.475	0.582
Redbrook	4010	-0.246	-0.327	-0.201	-0.123	-0.136	-0.004
Stretford Brook	55.9	-0.782	-0.730	-0.600	-0.223	-0.195	-0.121
Dore	41.4	0.240	0.043	0.098	-0.189	-0.222	-0.126
Worm Brook	73.4	0.138	0.048	0.001	0.430	0.419	0.482
Rosemaund	0.31	0.054	0.128	0.084	0.483	0.498	0.717
Whitchurch	6.46	0.034	-0.082	0.235	1.501	0.844	0.882
Dinedor	8.69	-0.146	-0.126	-0.184	0.689	0.785	1.143
Kivernoll	9.87	-0.505	-0.447	-0.438	0.133	0.191	0.485

5.3 Key Messages:

- Analysis of NAPI – river TP load relationships at both the regional and catchment scale suggest that **reducing the overall P input pressure/surplus** on the landscape **is critical in tackling river TP pollution.**
- CQ analysis for the Wye catchment shows a highly variable **combination of point source and diffuse source P signals** in different sub-catchments.
- **Both source and transport measures to mitigate P transfer** from land to water are required to improve water quality.
- Previous analysis of P concentrations and loads across the Wye catchment shows that the **dissolved P** (orthophosphate or soluble reactive P) signal **is at least 50% of total P loads.**

6. Legacy Soil P Reserves and their Agronomic Value

Annual surpluses of P beneficially build-up soil P fertility (typically measured as Olsen-P on farms) for optimising crop yields, but as soil P increases the risk of P loss in land runoff to adjacent waterbodies and consequently eutrophication risk also increases (Withers et al., 2017). A soil Olsen-P status of 16-25 mg L^{-1} (P Index 2) is considered the agronomic optimum for a wide range of crops (AHDB, 2021), and the levels and distribution of soil Olsen-P within a catchment can give an indication of the extent of 'legacy' soil P reserves that have accumulated from previous annual P surplus loading on catchment soils.

The potential trade-off between soil P fertility and runoff P loss risk in the Wye catchment was assessed by (a) collation of soil analysis results for Olsen-P for the 5-year period 2017-2021 in the Eastern part of the catchment where farming intensity is greatest, (b) a meta-analysis of previous research data on likely rates of Olsen-P accumulation in Wye soils with increases in surplus P loading, and (c) a laboratory study investigating the agronomic value of legacy soil P to crops and potential release of dissolved P into solution and potentially into land runoff. Soil analysis results were compiled by Cobb-Agri Ltd analysed at a common laboratory.

6.1 Soil P Fertility in the Wye Catchment

The collated 5-year soil analysis results (Cobb Agri typically sample 20% of farms each year) provide a database of 13000 field samples with which to assess catchment soil P fertility in intensively farmed areas. The results show that 55% of fields have more P than the recommended agronomic optimum (P Index 2) and that 15% of soils have very high soil P fertility (P Index 4 and 5+) (Figure 6A). This percentage of P-rich soils (> P Index 2) is well above the UK national average of 43% (PAAG, 2021). A limited sub-catchment analysis (data not shown) also suggested that areas with high soil P status had the highest livestock manure P production.

The meta-analysis of previous research on representative Wye soils suggest that Olsen-P will increase at a rate ca. 9 mg kg^{-1} (or mg L^{-1}) for every 100 kg P ha^{-1} of annual surplus P input (Figure 6B). This rate of increase (ca. 250 kg P_2O_5 ha^{-1} to raise soil Olsen-P by 10 mg L^{-1}) is similar to current nationally recommended guidelines (AHDB, 2021). The current annual surplus P loading of 17 kg P ha^{-1} to Wye soils would therefore be expected to increase Olsen-P by < 2 mg kg^{-1} y^{-1}. This clearly shows that long-term trends in soil analysis results are required to fully capture the cumulative impacts of annual surplus P accumulation in the catchment.

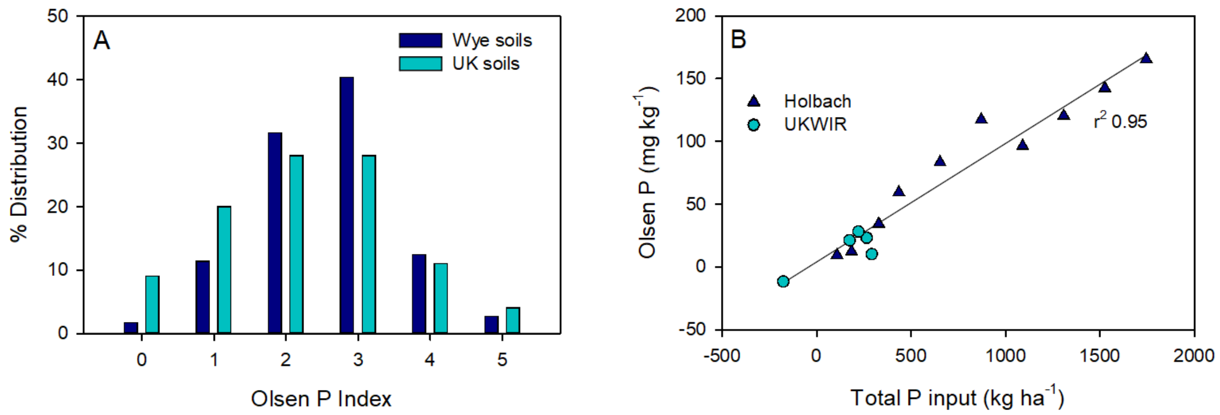


Figure 6: (A) Percentage distribution of Olsen-P indices for Wye soils compared to UK soils and (B) the relationship between surplus total P inputs (kg ha^{-1}) and Olsen-P concentrations (mg L^{-1}) at ADAS Rosemaund. Results are shown for two separate experiments: Holbach (arable) and UKWIR (grassland), testing fertiliser and/or manure treatments together with a common regression line.

6.2 Value of Legacy Soil P Reserves

Cumulative annual P surpluses over many years lead to a reservoir of ‘legacy’ soil P reserves. Two important questions for sustainable P management in catchments are: (a) could legacy soil P could be agronomically important i.e. could crops use this reservoir of P instead of applying inorganic P fertilisers and manures, and (b) does this reservoir of legacy P pose a long-term threat to water quality?

A trial was conducted at Lancaster University under controlled environmental conditions to try and answer these two questions. Soils were collected from the three RePhoKUs study catchments (Upper Bann, Upper Welland and the Wye), and their crop-available legacy P reserves were drawn down by repeated grass harvests (Figure 7A). Soil porewater samples were also taken to monitor soil dissolved P (SRP) release to the soil solution. Soils sampled from the Wye catchment were representative of the majority of the Eastern half of the catchments where farming is most intensive (Figure 7B).

The trial demonstrated that some legacy P could potentially be utilised in all of the catchment soils we tested. Using actual crop yield and soil P data from the farms we sampled, we estimate legacy P could supply anywhere between 2 and 20 years P without impacting on crop yield. The legacy P in the Wye soils, in particular, appeared to be crop available. For example, legacy P in a sandy loam soil typical of the lower part of the Wye catchment with a soil P of Index 4 might support a typical arable rotation for 10 years with no yield penalty.

The trial also found that Wye soils release high levels of SRP into their porewaters, especially when Olsen P levels are above the agronomic optimum, which was not observed in the other catchment soils (Figure 8A). The porewater SRP concentration at P Index 2 is also ca. 0.1 mg L^{-1} which is considerably greater than the current Wye river targets of 0.03-0.05 mg L^{-1} required for eutrophication control. This pattern of high P release is attributed to the particular physical and chemical properties of the Wye soils (high silt content) that mean they have a low ability to hold on to applied P (i.e. they have a low P buffering capacity).

A B

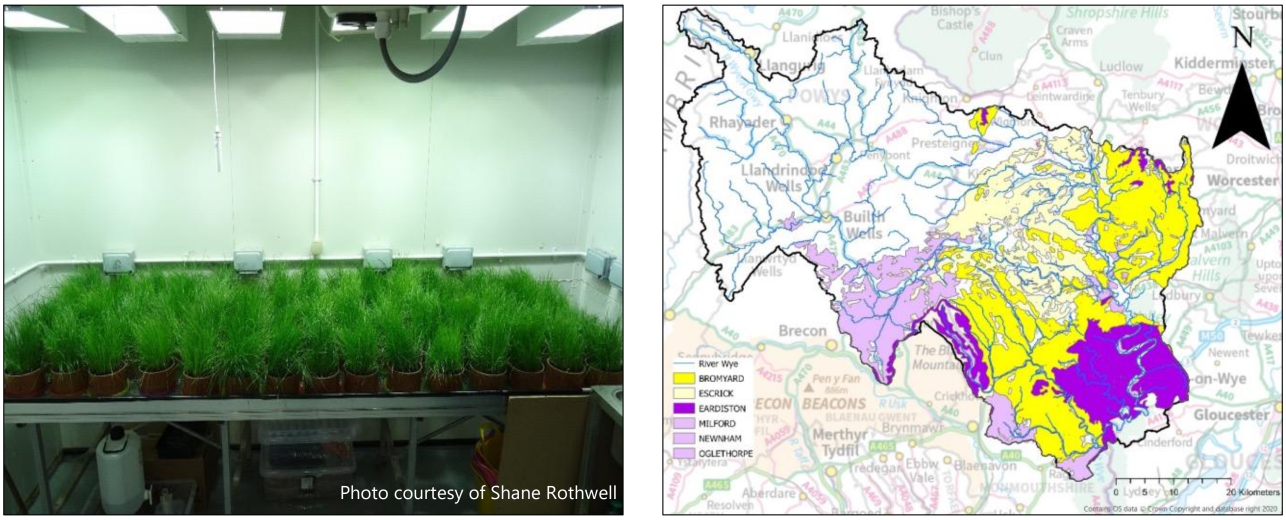


Figure 7: (A) Grass harvests draw down legacy P from catchment soils in a pot trial at Lancaster University, and (B) the distribution of the soils sampled from the Wye catchment used in the trial. Bromyard (yellow) and Eardiston (purple) were the two soils used, the other soil types shown in the lighter shades are from the same soil series and will likely exhibit similar properties of P behaviour.

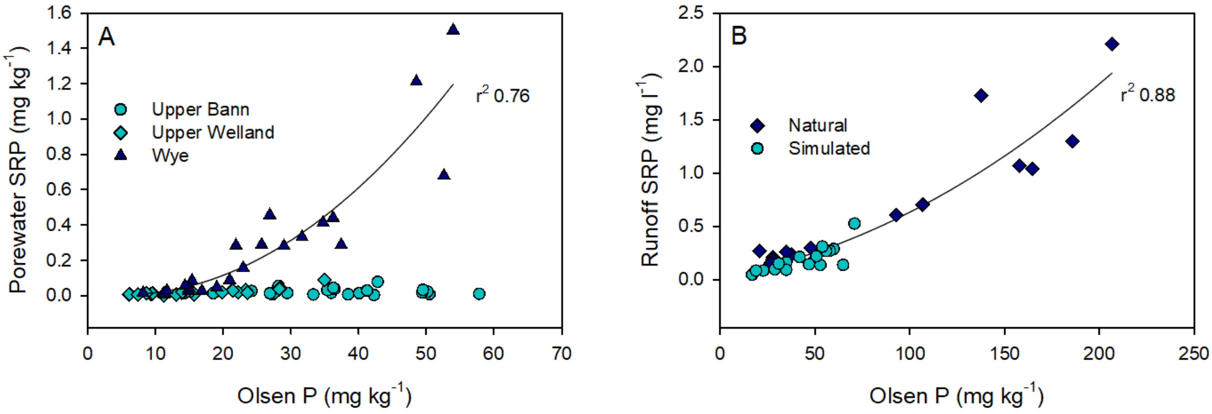


Figure 8: (A) Relationship between soil Olsen P status (mg kg^{-1}) and soluble reactive P (SRP) concentrations (mg L^{-1}) in the soil porewater in the legacy pot trial (Wye soils are highlighted in dark blue), and (B) SRP concentration (mg L^{-1}) in storm runoff increase as soil Olsen-P increases under either natural or simulated rainfall at ADAS Rosemaund (data are from Withers, unpublished).

While this low P buffering capacity explains why the legacy P reserves were particularly crop available in the Wye soils, this may also pose an increased diffuse P pollution risk because of the influence of soil Olsen-P on SRP release to runoff waters. (Withers et al., 2017). Previous experiments conducted at ADAS Rosemaund in the Wye catchment under both natural and simulated rainfall have similarly shown increasingly high rates of SRP release in runoff as soil Olsen-P concentrations increase (Figure 8b). Previous monitoring of field drains and streams in the Wye catchment also indicate high rates of SRP release even under best management. For example, the Foxbridge field drain draining soil P Index 2 land at ADAS Rosemand showed 3-year annual median and mean SRP concentrations in drainflow of 0.13 and 0.18 mg L^{-1}, respectively (Withers and Hodgkinson, 2009; Withers et al., 2009).

Drawing down soil P levels in Wye soils to at least the agronomic optimum (P Index 2) by continuing to offtake P in crops without any P input in needed to help mitigate this P loss risk. The pot experiment results suggest this could take up to a decade at typical crop P offtake rates. The RePhoKUs studies also confirm previous research on SRP release rates to land runoff, and suggests that farming at soil P Index 1 will be required to achieve current target SRP (orthophosphate) concentrations for Wye rivers.

6.3 Key Messages:

- **Soil P fertility levels** in the Eastern part of the catchment are already much **greater than the national UK average** and are indicative of a landscape receiving too much surplus P.
- **Wye soils are more P-leaky** than many other soils because of their poor ability to hold onto applied P in fertilisers and manures, and **pose a high risk of P loss to draining streams**.
- **Regular soil analysis surveys in the catchment are needed** to help (a) monitor the impact of land nutrient management change on soil Olsen-P concentrations, and (b) help establish relationships between surplus P loading, soil P status and river P concentrations.
- **Legacy soil P reserves can be safely drawn down** to the current agronomic optimum (Olsen-P Index 2) without risk of yield loss, but this may take many years.
- Concentrations of SRP from Wye soils, even at P Index 2, are likely to exceed current river SRP targets.
- Management options to farm at soil P Index 1 should be explored.

7. Stakeholder Responses in the Wye Catchment

7.1 Overview of Stakeholder Workshops

A series of interviews, interactive workshops, and an online questionnaire was conducted with stakeholders across the RePhoKUs study catchments to assess their adaptive capacity to make system and management change. Adaptive capacity refers to 'the capacity of catchment P stakeholders to address harmful P exports to aquatic systems or disruption to P supply' (Lyon et al., 2022).

The two key features of adaptive capacity are the assets or resources available to the catchment stakeholders and the ability of those stakeholders to effectively use those resources to sustainability manage P. A shortfall in either, or both capacities, means the catchment has low adaptive capacity and is vulnerable to P supply disruptions and/or water quality problems. On the other hand, strong assets and the willingness to use them would mean the catchment has high adaptive capacity and a good chance of sustainably managing P to avoid supply disruption risks and reduce P pollution to restore water bodies (Withers et al., 2015).

Catchment stakeholders included farmers, farming representatives from water companies, CSF organisations, agriculture and environmental groups such as rivers trusts, and government agencies (Figure 9).

The questions asked of stakeholders in these activities covered their:

- Occupation or roles;
- Knowledge of P and activities such as P use, training, and policies;
- Views on risks, challenges, and hinderances to more sustainable P management;
- Views on what is helping the movement toward sustainable P stewardship;
- Views on what is needed to improve P stewardship in the catchment.

Figure 9: Wye stakeholders debate adaptive capacity

7.2 Stakeholder Responses

Stakeholders, including farmers, were largely unconcerned with P supply issues such as price shocks, or aware of the origins of imported fertilisers or feed P supplements. They felt that any sharp price increase, or import restriction, would be temporary and/or reasonably easy to weather by using substitutes like livestock manures, or applying less or no P. Note that these responses were obtained before the recent sharp rise in the costs of fertilisers, and the future implications of the Ukraine war on P import supply. Currently Russia provides a large proportion of the fertiliser P imported into the UK.

Stakeholders considered water quality issues more challenging as these more directly involved agricultural P and land management practices and operational efficiency at wastewater treatment centres. Stakeholder responses are considered under a series of adaptive capacity indicators and summarised below and listed in Table 3.

Readiness to change practices: Most participants, including farmers and water companies, were willing to explore and adopt practices for better P stewardship. However, not all stakeholders were equally represented, especially farmers. Some responses also suggested that there was reluctance from some groups to change practices, or would game existing regulations, such as those for poultry unit capacity, to avoid regulatory requirements for pollution management.

Hands-on knowledge and training: The current knowledge and training offered by CSF, and Catchment Based Approach (CaBA), schemes were received well by the farmers and other stakeholders. However, responses indicated that these programmes lack predictable funding and resources, and operate at too small a scale to achieve the critical mass of mitigation actions required for water quality improvement.

A key finding was the value of hands-on face-to-face learning, especially for farmers. Such training provided knowledge uptake because it included building strong relationships and trust between stakeholders – 'the right information through the right channels' (comment from a catchment stakeholder).

Building strong stakeholder relationships (Stakeholder synergy): The presence of CSF groups, charities, water companies with extension services, and other citizen iniatives and activities meant that there was a high level of interaction between catchment stakeholders with an interest in P issues. Responses confirmed that this level of awareness and communication, despite some disagreements, is helpful for knowledge sharing for more widespread uptake and enacting behaviour changes by stakeholders, should more resources be made available.

Legislation, regulation, and resources: Responses indicated that upgrading wastewater P removal and water company infrastructure, training more farmers and other stakeholders, meeting costs associated with new practices, and other stakeholder initiatives required investment from government in the forms of improved regulation and financial resources. Water companies and farmers operate under regulations that could be strengthened for improved P stewardship or wastewater P removal. Such changes may be initially costly, but financial incentives such as those under the new Environmental Land Management Scheme (ELMS) could be made available to offset any expense risks.

Despite a very active forum for stakeholder interaction and knowledge exchange, the overall adaptive capacity in the Wye catchment is considered low because there are insufficient resources to implement effective regulatory, training, incentive, technical and infrastructure support at the scales necessary to enable measurable improvements in water quality. More resources and expansion of existing schemes to encourage broader participation, sustained over many years are needed to meet the P challenge.

7.3 Key Messages:

- Stakeholders were generally not unduly concerned about future disruptions to P import supply, or cost, and considered the **challenge of addressing poor water quality more pressing** (N.B. This work was before the current price increases in P fertilisers and supply uncertainties of the Ukraine War).
- Nascent stakeholder capacity to adapt current practices to help improve water quality is high, but the **scale and levels of uptake of catchment mitigation measures is insufficient to show demonstrable benefit**.
- A **firmer evidence base and greater regulatory, training, incentive, technical and infrastructure support is needed** to make the incremental and transformative change required in different sectors for river water quality in the Wye to improve.
- Overall catchment **adaptive capacity is low**.

Table 3: Adaptive capacity thematic indicators from the online post-workshop questionnaire (from Lyon et al. 2022).

Adaptive capacity thematic indicators	*"What do you think is currently **hindering** the catchment organisations or farming community efforts to improve phosphorus stewardship?"*	*"What do you think is currently **helping** the catchment organisations or farming community to improve phosphorus stewardship?"*	*"What kinds of activities or **supports** would need to be put in place to help catchment organisations or the farming community improve phosphorus stewardship?"*	*"What do you think is the **potential** for this catchment to adopt measures to greatly improve phosphorus stewardship? "*
Readiness to change and established practices	– Reluctance to change, short-termism, excuse-making, cheating, self-interest – Farmers resistance to change Apparent resistance from farmer's union Vested interests in the status quo – Fear of the unknown – Overcoming inertia/dependency for farming types or practices Lock-in to farming types (e.g. poultry/livestock) – Continued permitting of P-loaded livestock and poultry – Focus on maize crops, – Continued permitting of large poultry units Agriculture as an industry is a powerful interest resistant to regulation and change – Subsidy-led farming history – Lack of soil health, heavy cultivation	– Renewed interest and impetus for in soil management or P-friendly practices – More interest in conservation agriculture – Soil management importance has shot up the agenda for many and potentially increased uptake of countryside stewardship – Buy-in from supply chain but overall not much – Public awareness – Already wide uptake of farm P-loss reduction measures – Uptake by "clusters" of farmers – Efforts of deeply committed individuals – Awareness and evidence-based farming is increasing, shifting farming away from grandfathered method	– Awareness raising – Supply-chain wide buy-in to P sustainability – Practical examples or demonstrations – Public awareness – Improved promotion and awareness campaigns – Industry engagement at grass roots with existing groups by industry recognised and technically competent advisors who do not have their own agenda – Payments for environmental practices – Approval for alternative uses for manures for livestock/poultry dependent farmers	– Possible - and should be aligned with the significant impetus that will be given to climate change and the ecological emergence – Possibly advise P-index 1, but may be risky and too soon – Get farmers on board – Yes, if it was high enough profile, encouraged farmer participation, with tangible benefit
Knowledge & training	– Lack of clarity in yield response to P – Getting the message across to overcome farmer hesitancy	– Greater/better scientific evidence and data of causes and solutions	– Dedicated advisors, bespoke website – Clarity on causes and reasons for P pollution	– There is always potential we just need to get the right information to

	– Lack of knowledge – Lack of information on how to best manage soil P – Poor communication of actual cost of P loss to a business – Knowledge gap – Mixed messaging, siloed advice rather than holistic approaches to soil and farm management – Lack of availability of science to support farming at P-index 1 – Access to affordable quality advice – Lack of understanding – Lack of knowledge or confidence that stakeholders are doing the right thing – Lack of knowledge of P-friendly farming, economic benefits, value of P – Lack of clear communication – Excessive amount and timing of P applications – Lack of catchment advisors, lack of clarity about practical steps, lack of joined-up approaches – Government project managers and advisors with little or no technical knowledge – Information overload for farmers	– Research like the researchers' project – Publicity, media attention, knowledge sharing – Consistent messages to the farming communities about the cost-effectiveness of effort by showing outcomes – Peer-to-peer learning and – CSF advice well received – Knowledge exchange and discussion groups for small groups of likeminded farmers to share ideas – Countryside Stewardship Scheme – Education, such as research project workshops – Education – Increased research	– Educate farmers, feed, and fertiliser suppliers on the costs of P pollution – 1:1 hands-on farm advice – Educating young farmers – Bespoke catchment P planning tools – Interactive fur video tutorials/animations to educate – Free advice on P and livestock diets for farmers – Better data on local P dynamics to target interventions – Nutrient Management Plans – Communication – More handholding, training, and demonstrations for farmers – Trusted sources of advice (CSF) – Research and knowledge on practical measures that can be implemented for farm businesses – Better yield response data – Peer to peer learning – Pilot in smaller subcatchment with farming unions support – Real examples: No-till farmers attending the workshop were an inspiration – Benchmarking among farmers within similar sections of agriculture	farmers through the right channels. I think Agronomists are a good way in! – Yes it is possible, easier with some soils than others possibly. Targeted use of countryside stewardship options could go a long way. – If demonstration farms are supported and benefits such as C-sequestration and NFM are made – Manure & nutrient management planning informed by increased soil sampling

			– Better for agronomists e.g. P-stewardship in BETA conservation training – Knowledge and practical demonstrations of low P farming More education – Practical demonstration of lower P-index farming over the mid to long term to show farmers and agronomists that the accepted norm of P-index2 is not the be all and end all of phosphate management – On farm demonstrations and accompanying data – More workshops like this – Funding for independent advisers and mentors to support farmers through transition to farming systems that don't import P in bag or manures.	
Stakeholder synergy	– Catchment organisations attacking agriculture industry inhibits partnerships – Alarmist headlines that damage relationships – Tone of debate (farming community under attack by environmental groups)	– Expanded NMB participation and strong leadership – Shared commitment across catchment organisations – Intergovernmental agreement on the P problem and measures to address it – Catchment partnership meetings – Activity of catchment organisations	– Catchment organisations engaging and working with farmers, not confronting them	– Courage to really push on this issue. – Different parties have different priorities; but need a common economically driven aim to overcome

Funding, technology, & infrastructure	– Village/small sewage treatment works are a major problem – Lack of Natural England/catchment sensitive farm practice training and the existence of funding infrastructure (e.g. concrete yards) that support livestock intensification rather than sustainable low-input profitable grass based solutions – Financial and planning constraints – Deep cuts to public sector resources – Lack of financial reward or discipline – Market forces/Brexit – Short-term funding inhibits developing strong local relationships with catchment organisations	– Water company P removal infrastructure – Technology gains – Cost-management – Public good for public money ethos	– Assistance with farm infrastructure for handling manure and slurry – Poultry manure processing facility (energy or other products, such as ash fertiliser) – Local economic development for manure export industry – New ways to profit from manure exports – Reworked post-Brexit subsidy system to hardwire efforts into the system – Long-term funding and commitment from government – Financial assistance (for farmers)	– New technology to access soil legacy P to reduce reliance on imports – Harder to achieve would be a move away from heavy farm machinery trafficking fields and reducing large amounts of soil disturbance. – If time and resources are made available
Legislation, regulation, & enforcement	– Lack of enforcement/inspections by EA; lack "boots on the ground" Failure of voluntary compliance Lack of statutory powers and prosecutions of those who flout rules – Planning regulations	– New regulations, Farming Rules for Water, which focus on nutrient/P management Increasing farming costs and capped returns – Adoption of Mid-tier Stewardship	– Compulsory non import, non-spread zones, no plough zones, audit trail out of the county for poultry manure or processed equivalent by products, digestate removal from county, stop RHI and greening subsidy for maize; payment schemes – Forceful solutions and penalties A united approach, with carrots and sticks, e.g. payments and fines	– Great potential possibly with ELMS – If they political will is there, and before irrevocable damage – The potential is good, but making farmers think about Phosphate applications and giving them the information to take it seriously will be a challenge particularly

			– Tax P, ban or tax users for non-compliance – Permission to move away from RB209 – Robust support for ELMS – Knowledge dissemination in ELMS targeting – Enforcement – Legislation for P was with NVZ restrictions	as there is already a great deal of rules and regulations to be aware of as well as getting the actual work done. The Rural Payments Agency would have to make Phosphate management part of cross compliance. – Consumer-side – stop externalising environmental costs for food

8. Improving Phosphorus Sustainability in the Wye Catchment

8.1 Reducing P Losses to Water

Achieving the reductions in river P concentrations required for good or high ecological status is generally confounded by the multiple wastewater, agricultural, industrial and urban sources contributing variable loads of dissolved and particulate P along different hydrological pathways, and variable rates of P retention and ecological response once in the water column (Withers and Jarvie, 2008). This is especially the case in the Wye catchment because the majority of the P load entering the river is from agriculture which is more difficult to mitigate because of its diffuse nature, and dependence not only on current P management but also the 'legacy' of P surpluses that have accumulated in the landscape over many years.

A combination of current and historic high annual P input pressure (NAPI) on the Wye landscape, poorly-buffered silty soils that release high concentrations of dissolved phosphorus into storm runoff, highly dispersible soils that erode easily and make rivers turn red, steep runoff-prone slopes and moderate to high rainfall provide the perfect storm for accelerated P loss in surface runoff and drainflow into the river.

Hence, although river P concentrations notably declined after the introduction of advanced P-stripping at wastewater treatment works serving major populations centres during the late 1990s (see Jarvie et al., 2003), river P concentrations maybe starting to increase again (Figure 10) in line with an increase in farming intensity and P input pressure in the catchment.

Farming in the Wye catchment without contributing ecologically-damaging P concentrations to the draining rivers is therefore very challenging. The RePhoKUs comparisons between P input pressure and river P pollution across regions and different research catchments in the UK clearly show that the greater the P input pressure on a landscape, the greater the loads and concentrations of P in the rivers. Such relationships often break down within individual catchments (such as the Wye) because of greater uncertainty over NAPI values, poor availability and resolution of river P data and/or an overriding influence of other factors affecting P mobilisation and delivery to the river (e.g. extreme storm events).

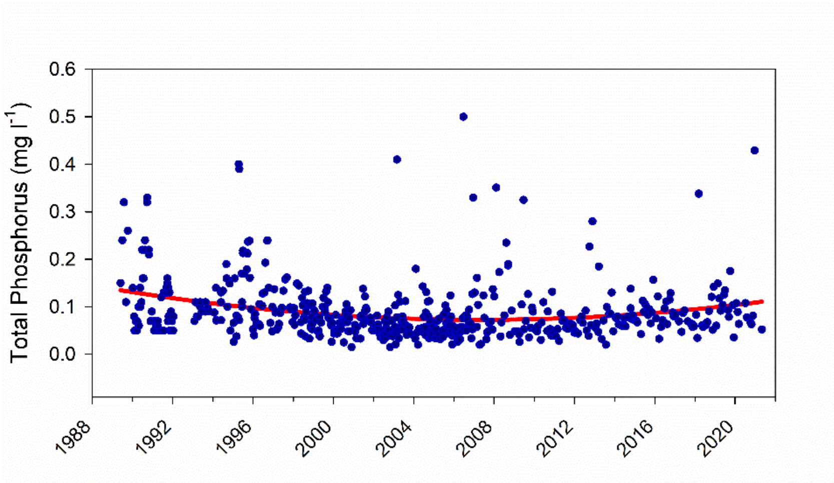


Figure 10: The concentration (mg L^{-1}) of total phosphorus (TP) at the outlet of the Wye (Redbrook) from 1989 to 2021 (data provided by Natural Resources Wales). An overall trend line is given. (NB. Data is based on low resolution and inconsistent sampling).

The RePhoKUs results suggest that water quality in the Wye catchment will not improve until the high annual P input pressure is reduced. Current CSF strategies to reduce P leakage to water are reliant on farm scale mitigation actions centred on sensitive land and nutrient management (e.g. reducing land runoff and erosion rates, fencing waterways and installing buffer strips, ponds and wetlands), but with little evidence to-date that they are having a marked impact (Davey et al., 2020).

There is currently no emphasis on the wider system level change that may be required to reduce the catchment annual P input pressure. However, achieving a catchment zero P surplus, or encouraging agriculture to draw down legacy P reserves, requires a level of governance that is beyond the responsibility of the individual farmer or industry. It is a collective catchment stakeholder responsibility.

8.2 Reducing P Input Pressure in the Wye Catchment

8.2.1 Drivers of the Wye Agricultural P Surplus

The very high P input pressure being exerted on the Wye catchment is driven by the large agricultural P surplus which is symptomatic of a livestock-dominated farming pattern with a low efficiency of P use (Rothwell et al., 2020): the efficiency with which imports of P in feed, fertiliser and food into the Wye catchment were converted into useful product for consumption or export was low at only 48%. This is very similar to the overall P use efficiency for the UK food system at 43% (Rothwell et al., 2022), but is higher than that found in the Northern Ireland food system (22%) which is more reliant on more P-inefficient ruminant production systems (Rothwell et al., 2020). Other countries with a high non-ruminant population have very similar P efficiencies: Belgium (59%), The Netherlands (66%) and Denmark (44%), (van Dijk et al., 2016). This low P inefficiency demonstrates the large amounts of unused P that is wasted or lost annually in the Wye catchment.

The main driver of the large annual P surplus is the quantities of livestock manure that are produced each year (over 6000 t P). Manure production has significantly increased in the last 5 years due to the rapid expansion of the poultry industry and poultry have now overtaken cattle as the main producer of manure P in the catchment (Table 1). Total manure P production alone exceeds the requirement for P by cropland and grassland in the catchment by 45%. Combined with the annual inorganic fertiliser use (still over 1100 t), this excess P is accumulating in catchment soils, and adding to the already substantial legacy soil P reserves in the catchment.

Whilst the soil analysis survey did not cover the whole catchment, the proportion of over-fertilised soils is already considerably greater than the UK national average, with some evidence that those areas the highest percentages of over-fertilised soils are those which have the greatest manure P loadings.

8.2.2 Addressing the Agricultural P Surplus

A reduction in the agricultural soil P surplus in the Wye catchment is dependent on addressing the catchments manure mountain. Optimising livestock dietary P intake to reduce rates of livestock P excretion will help, but additional and more fundamental solutions involving significant system level change will be needed to bring the catchment into P balance.

Figure 11 is a scenario SFA that demonstrates the scale of change required. In this example, fertiliser import into the catchment is reduced by 75%, and 80% of all pig and poultry manure P is exported out of the catchment to regions that require P fertiliser. This leaves the catchment with a near zero surplus of only 0.1 kg ha^{-1} yr^{-1}.

However, historic annual catchment P surpluses over many years mean large legacy P reserves have accumulated in the catchment soils, which also pose an environmental risk due to high vulnerability of Wye soils to leak dissolved P and erode particulate P in storm runoff. Reducing these legacy P reserves would actually require the catchment being in a negative P balance where more P is taken off in crops than is applied. Figure 12 shows another scenario SFA where again, fertiliser P is reduced by 75%, 80% of pig and poultry manure P is exported and additionally 50% of all cattle manure P is exported from the catchment. This would bring the catchment into a drawdown rate of -4 kg ha^{-1} yr^{-1}.

Addressing this legacy soil P now is a significant long-term challenge for agriculture. The RePhoKUs pot trial results suggest it could take a decade or more to reduce soil Olsen-P concentrations to the agronomic optimum, and also that Wye soils at the agronomic optimum may still generate runoff SRP concentrations well above current targets for good and high ecological status in rivers. Therefore, it is imperative that options are explored for managing soils below the current soil P agronomic optimum (i.e. farming at P Index 1) while maintaining farm profitability. Reducing the soil P concentration to the agronomic optimum level will also require careful management of these soils and the correct strategies for doing this, so as to balance agronomic and environmental targets.

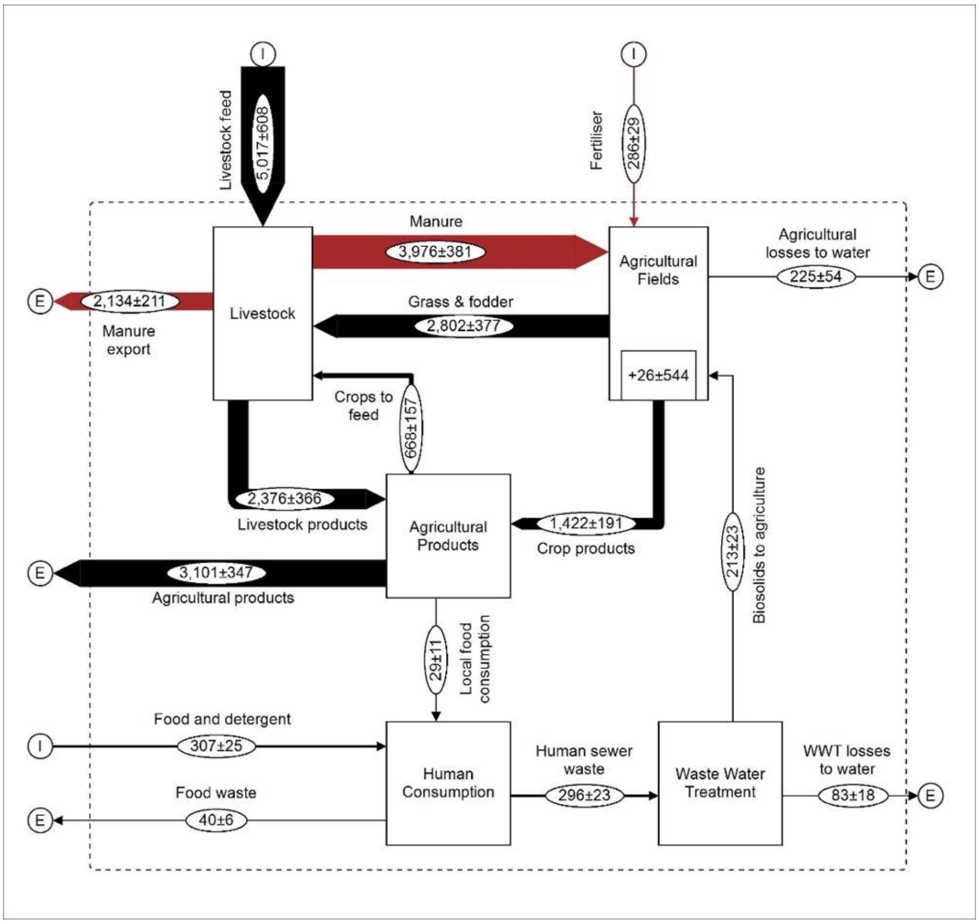


Figure 11: Catchment zero P balance scenario SFA for the Wye catchment area.

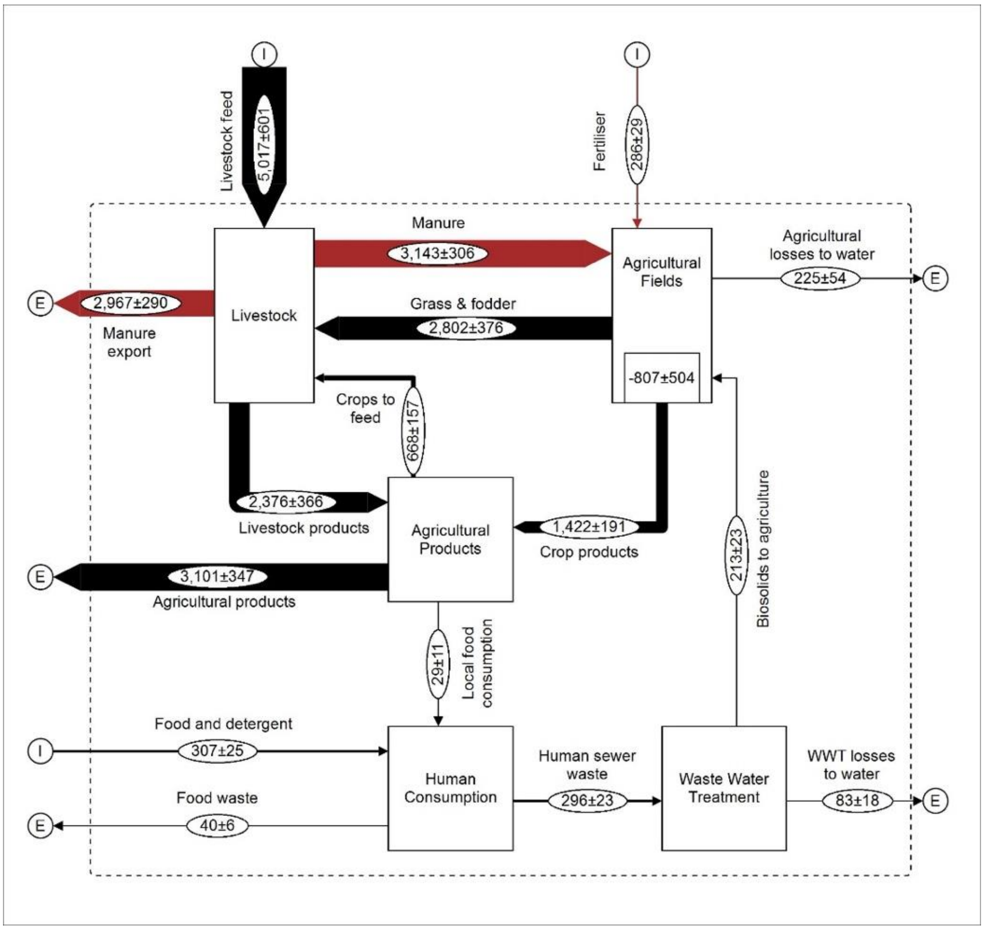


Figure 12: Catchment P drawdown scenario SFA for the Wye catchment area.

8.2.3 Achieving a Sustainable P Balance

Sustainable food systems use P resources efficiently (i.e. more production with less P inputs), maximise recycling of residue P (i.e. re-use P), and minimise P surplus, wastage and loss. These are the guiding principles of 5R P stewardship and a circular nutrient economy which seeks to balance P use in food production with the protection of our water environment (Withers et al., 2015), and are applicable to the food system in the Wye catchment as in any other region. This essentially means operating at least a zero P surplus at the catchment scale.

Reducing P inputs into the catchment might be achieved by lowering P demand (for example by destocking or through human dietary change), by recovering P from manures to substitute for imports of fertilisers and feed supplements, by utilising legacy soil P reserves instead of applying fresh P, or a combination of these. The National Food Strategy (National Food Strategy, 2021) recommends cutting meat consumption by 30% over the next decade but this requires national policy development, and reducing livestock numbers without clear alternatives may also impact on rural livelihoods and the economy.

The potential for increasing recycling (P circularity) within the Wye catchment is limited because most livestock manures, which represent the largest internal P flow, and wastewater biosolids recycled back to land. There is insufficient data on which to quantify the amounts of P flowing into the waste management sector (e.g. from livestock carcases) in the Wye catchment, but quantities of P lost in food waste are relatively small (40 t). Recovery of P from the waste sector, or further improvements in the efficiency of P removal at wastewater treatment centres would also only add to the P loading pressure on the catchment. There is simply too much residue (manure) P already recirculating within the Wye catchment, and alternative solutions need to be developed.

Hence options to recycle P sustainably must consider the wider national food system by exporting excess manure P out of the catchment. The value of organic manures for maintaining soil organic matter can still be realised where their application can meet crop P requirements, but when applied in excess they become an environmental hazard and must be exported. Given the costs and impracticalities of regularly transporting bulky livestock manures long distances, this means that technological solutions are needed to either make livestock manures more transportable (e.g. by dewatering dairy slurry (Lyons et al., 2021), or recover inorganic P from manures and biosolids in a fertiliser-grade form (e.g. as struvite or calcium phosphate, Tonini et al., 2019). Recovered P can then potentially directly substitute for imported inorganic P fertilisers into the catchment, or be exported out of the catchment to other areas of the country with a P deficit, such as in Eastern England.

Research is needed to help develop reliable cost-effective technological solutions for manure treatment, and to confirm the effectiveness and safety of recovered P fertilisers for use on a wide range of crops.

However, achieving a zero surplus at the catchment scale will not address the loss of P in storm runoff from soils that already have far more P than they need for agricultural production. Given the unnecessarily high levels of crop-available Olsen-P in Wye soils, the catchment will need to operate a negative P surplus in the future in order to draw-down soil P fertility to at least the agronomic optimum. Soil P drawdown is clearly a long-term strategy, and CSF measures designed to reduce the mobilisation of soil and applied P in land runoff, and the delivery of any mobilised P to the watercourse, consequently become particularly important for mitigating agriculture’s impact on water quality.

More field-based research is needed to confirm the results of the legacy pot trial that annual P inputs in fertilisers and manures can be withhold for a number of years without any risk of yield loss.

Improvements in the ecological functioning of the Wye river therefore rely on a combination of catchment-scale measures to reduce the annual P input pressure on the landscape, industry measures to reduce point source effluent discharges and sewage overflows, and farm-scale measures to effectively utilise legacy soil P reserves and minimise the loss of P in runoff and erosion.

In turn this requires better governance of P at the catchment scale and a collective stakeholder responsibility to enact the level of system change required to mitigate river P pollution. The Wye Catchment Partnership, the Wye and Usk Foundation, Wye Agri-Food Partnership and the Friends of the Wye are examples of the active stakeholder forums that exist in the Wye to facilitate such change. Investment in higher resolution and targeted routine water quality monitoring programmes is needed to monitor progress, and WUF and citizen science is already helping in this regard.

The RePhoKUs project has helped provide the evidence base to allow stakeholders to take the innovative actions and management changes required to maintain the high ecological biodiversity and recreation status that the Wye river is famous for.

8.3 Key Recommendations for Action:

- Policies to mitigate river P pollution from agriculture should change emphasis and seek to **reduce the P input pressure on catchments in addition to the current emphasis on mitigating transport and delivery of P** from land to water. Catchments cannot continue to absorb annual agricultural P surpluses without risk of long-term endemic P loss to water.
- **Better enforce and support existing regulation** (e.g impending Water targets and existing Farming Rules for Water) with policies, tools and governance towards achieving at least net zero P surplus at catchment and regional scale.
- **Reduce livestock manure P loading through a reduction in animal numbers and by processing manure to produce renewable fertilisers** to replace imported fertiliser, and by exporting manure to other regions. Research is needed to support technological development of safe and effective recovered P fertilisers and feed supplements.
- Provide **incentives to draw-down areas of high-risk P-rich soils** to at least the agronomic optimum. Research is also needed to explore farming at soil P Index 1.
- **River monitoring data generally needs to be made more accessible, consistent and at a higher resolution** to be able to make robust comparisons to catchment nutrient loading pressures and soil P build-up and monitor progress of the P Action Plan.
- **Substantially scale-up and provide for stable resourcing and long-term funding of local catchment officers, complementary land stewardship schemes and permanent knowledge sharing and coordination platforms to build stakeholder trust and understanding of P issues**, and support uptake of both incremental and more transformative structural changes in practice.
- **High resolution crop census data, and fertiliser and manure input data needs to be made more widely available** to allow accurate quantification of P cycling within the catchment.

9. Summary of Key Findings

- The Wye catchment has a high risk of agricultural P loss due to high P input pressure, poorly-buffered and highly dispersible P-rich soils, steep slops and moderate to high rainfall.

- Farming generates an annual P surplus (i.e. unused P) of ca. 3000 t (17 kg P ha^{-1}) in the Wye catchment, which is accumulating in the agricultural soils. This P surplus is nearly 60% greater than the national average, and is driven by the large amounts of livestock manure produced in the catchment.

- The risk of P loss in land runoff due to accumulation of soil P is greater in the Wye catchment than in other UK soils due to poor soil P buffering capacity and high dispersibility during storm events.

- Analysis of long-term river P concentration data for the Wye catchment outlet at Redbrook suggests river P pollution may be gradually rising again, but more consistent and higher frequency water quality monitoring is required to confirm.

- Clear evidence of positive links between annual P input pressure (and P surplus) and river P concentrations and loads exists at regional and catchment scales and this should drive a greater emphasis on redcuing the P input pressure in the Wye catchment.

- EA/NRW water quality monitoring programmes are not considered adequate to capture river quality impacts of short-term or small area changes in agricultural practice. Similarly, the general provision of up-to-date census data is not at a sufficiently fine resolution to accurately quantify spatially distributed P input pressure in catchments. These are both generic problems confounding provision of robust evidence of cause and effect.

- Water quality in the Wye catchment, and many other livestock-dominated catchments, will not greatly improve without reducing the agricultural P surplus and drawing-down P-rich soils to at least the agronomic optimum. This will take many years.

- A combination of reducing the number of livestock and processing of livestock manures to recover renewable fertilisers that can substitute for imported P products is needed to effectively reduce the P surplus.

- Catchment stakeholders have a nascent capacity to change practice but require a firmer evidence base and on-the-ground support to implement both incremental and transformative change in practices to improve river water quality. Experience in Northern Ireland suggests support schemes have a measurable impact on behavioural change.

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