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Exploring adaptive capacity to phosphorus challenges through two United Kingdom river catchments

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A B S T R A C T

Phosphorus (P) is a critical natural resource for food production, but one that is subject to global supply vulnerabilities. P is also responsible for endemic eutrophication in waterbodies due to poor stewardship in the food chain. Catchments are natural social-ecologically bounded systems for P use in agriculture and water management. Stakeholders, such as farmers, water and sewerage service companies, local authorities, and environmental organisations mediate catchment adaptive capacity to P supply risks and P pollution in waterbodies. Adaptive capacity at this level has been insufficiently explored in addressing the P challenge, yet is essential to it. We address this gap by exploring through a qualitative study of stakeholders in two United Kingdom catchments. Our results suggest that the awareness and relevance of P-supply challenges is low in catchments, but the problem of waterbody vulnerability to excess P is of greater concern. Our findings highlight the roles in adaptive capacity of entrenched practices; knowledge and training activities and organisations; stakeholder cooperation and synergy; funding, infrastructure, and technology; the governance environment; and time needed to draw down P. We find that farmers and water companies are especially important to adaptive capacity as they directly interact with P flows. We therefore suggest that catchment adaptive capacity would be significantly improved through a well-supported, and expanded package of existing efforts such as providing scientific evidence of catchment P dynamics; training; payments; more empowered local governance. This effort would support catchment stakeholders to adopt effective P-stewardship practices within a multi-decade integrated catchment management strategy.

1. Introduction

Phosphorus (P) is an essential element for life and a critical nutrient in agri-food systems. It is also a major pollutant in waterbodies due to excess agricultural and urban run-off and wastewater pollution, leading to eutrophication and impacts on food and potable water systems and livelihoods (Jarvie et al., 2015). Phosphorus pollution is now sufficiently widespread that it is recognised to have crossed a crucial planetary boundary (Li et al., 2019; Steffen et al., 2015). Furthermore, global supplies of phosphate rock come from only a few exporting countries, chiefly Morocco, Moroccan controlled Western Sahara, and Russia, resulting in uncertain supply and price vulnerabilities (Cordell and Neset, 2014; Nanda et al., 2019). These supply and pollution issues, compounded by a 'chaotic' lack of governance, pose difficult challenges for national, regional, and local food production and water quality (Withers et al., 2020).

Despite these challenges, considerable quantities of P exist as a potential bioresource within soils and plant, animal, and human waste, and together with emerging nutrient recovery and management technologies, suggest the potential for a much more resilient, sustainable phosphorus-food-water system (Jarvie et al., 2015; Le Noë et al., 2020). As with other natural resources, management of P is conditioned by

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national and transnational legal agreements and government policies, local environments, and the motivations and diversity of system stakeholders (Barquet et al., 2020; Jacobs and Brown, 2012; Lyon et al., 2020).

Proposals for creating a sustainable system of P stewardship draw on principles of circularity, such as the 5 R stewardship approach, which stresses technical measures (Re-align P inputs, Reduce P losses, Recycle P in bioresources, Recover P in wastes, and Redefine P in food systems) based on divesting from phosphate rock imports in favour of more efficient use of organic resources in ways that limit water pollution and maintain agricultural production (Withers et al., 2015). Stakeholders -as the actors whose knowledge, perspectives, and resources ultimately determine P use - are critical to enabling such a transition toward sustainable P stewardship (Jacobs et al., 2017; Lyon et al., 2020; Martin-Ortega et al., 2022; Withers et al., 2020).

While definitions vary somewhat (Siders, 2019), adaptive capacity is generally understood as the preconditions that allow “systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences” to general or specific shocks and stresses (Brown et al., 2010; IPCC, 2014, p. 118; Mortreux and Barnett, 2017; Siders, 2019; Thonicke et al., 2020). The catchment, as both a natural and social boundary for water management, is an appropriate scale to explore adaptive capacity. However, adaptive capacity research on catchment P stewardship is limited (Doody et al., 2016). Yet, adaptation is generally recognised to be shaped by local contexts (e.g. however defined, e.g. national, catchment, community) (Naylor et al., 2020), and catchment stakeholders (Garau et al., 2021), such as farmers, water companies,[1] and local environmental managers have the most direct ‘hands-on’ relationship to P management, with emerging research now beginning to explore their capacities for addressing P challenges (Bragina et al., 2019; Micha et al., 2018; Okumah et al., 2021). We contribute further theoretical, empirical, and methodological work to this research through a novel, in-depth, qualitative study of two UK catchments. Reflecting the international context (Withers et al., 2020), the UK is a political region without a clear and integrated governance structure for P management, reliant on P imports, and with significant catchment level P pollution due to agricultural run-off and wastewater (Environment Agency, 2019a), and thus provides an excellent setting to explore these challenges at the catchment scale.

2. Catchments and adaptive capacity to phosphorus

2.1. Catchments

Catchments are usually defined in hydrological terms, referring to the given area of land in which the inputs of rainwater and snow-melt are stored and released through streams, lakes, and evapotranspiration (Bales, 2015). A catchment is also a social-ecological system (SES) where human activity changes the input, output, and quality of water (Adger et al., 2021). For example, agricultural practices change the way soils and vegetation hold and release water; and dams, cities, and water treatment infrastructure change water storage, flows, and quality as these activities may introduce pollutants such as P (Jilbert et al., 2020; Maavara et al., 2020). Therefore, catchments are often used as statutory administrative units for decentralised water management (e.g. EU Water Framework Directive, South Africa’s National Water Act) (Meissner et al., 2017; Voulvoulis et al., 2017).

Catchment stakeholders, in the form of different groups and organisations who most directly govern the use and treatment of P include farmers, water companies, local government and agri-extension services, and fertiliser companies (Jacobs et al., 2017; Macintosh et al., 2019). Farmers and catchment communities, often with strong place and vocational attachment, are particularly vulnerable to ecological and economic disruptions to their livelihoods, and may struggle to adapt to rapidly changing contexts (Adger et al., 2021; Dixon et al., 2014; Marshall et al., 2012; Mitra et al., 2009; Peck et al., 2002).

Despite a vast amount of catchment-based SES research including adaptive capacity (Crossman et al., 2016; Walker et al., 2009), examination of the influence of catchment P dynamics on it remains rare (Doody et al., 2016) providing an apt context for exploring new possibilities for P management.

2.2. Adaptive capacity

Recent work identifies two approaches to adaptive capacity (Mortreux and Barnett, 2017). The first, “asset-based” approach attempts to measure “generic” adaptive capacity based on assessments of five capitals (natural, physical, financial, social, and human) (Mortreux and Barnett, 2017). Emerging from livelihoods research, this approach is criticised for its difficulty in factoring stakeholders’ willingness or ability to (effectively) use their assets or capacities (Mortreux et al., 2020; Mortreux and Barnett, 2017). Thus, Mortreux and Barnett (2017) identify a second-generation of psycho-social mobilisation-based approaches and stress indicators that reveal if and how any assets may be used. They suggest a prospective indicator list (for household and community research) that includes perceptions of “risk probability and severity”, “personal experience”, “trust and expectations of authorities”, “place attachment”, “competing concerns”, and “household composition and dynamics” aligned with this second generation of adaptive capacity assessment.

An important feature of second-generation adaptive capacity thinking is recognising what is already working or could be introduced. Qualities such as ‘household dynamics’, ‘entrepreneurship’, ‘collaboration’, and ‘vision and strategy’ relate to the dynamics and agency for adaptation (e.g. Jacobs and Brown, 2014). Finally, despite being a popular approach to environmental management problems, adaptive capacity studies tend to produce highly specific indicators that may not easily lend themselves to transfer or generalisation (Siders, 2019).

2.3. Adaptive capacity for phosphorus dynamics

We define adaptive capacity for P dynamics as the capacity of catchment P stakeholders to address harmful P exports to aquatic systems or disruption to P supply. The 5-Rs for P stewardship, if adopted should mitigate both water quality and supply challenges, meaning these problems share common solutions, making this ‘circular P-stewardship’ the aspirational adaptive state (Withers, 2019; Withers et al., 2015). Cordell and Neset (2014) identify 26 asset-based potential stressors and corresponding indicators of adaptive capacity for P dynamics at national scales, identifying relevant catchment-level stakeholders, such as “farmers, extension officers, and sanitation providers (water utilities)”, and indicators such as “farmer household income”, “commodity price forecasts’, ”physical barriers to infrastructure”, “P load on aquatic environment”, and soil test results (Cordell and Neset, 2014, pp. 115–117). Such broad markers overlook the specifics of context. Therefore, an opportunity exists to fill this gap in sustainable P management by examining the adaptive capacity of catchment level stakeholders through the adoption of a second-generation adaptive capacity approach.

3. Research context and methods

3.1. Context

As of 2021 the UK formally left the EU and is transitioning away from EU agri-environmental jurisdiction and related changes in agri-food

[1] Water treatment and provision services are privatised in our cases, but non-UK jurisdictions may have other arrangements such as publicly-owned service provision.

trade. It thus faces heightened challenges from global risk of P price or supply shocks (Cordell and Neset, 2014; Geissler et al., 2019) and the uncertain transition to new governance arrangements for water resources (Environment Agency, 2019a). In England, in addition to general guidance on Codes of Good Agricultural Practice and P application, the 25-year Environment Plan (Defra, 2018) incorporates a set of farming rules[2] to control P pollution, an Environmental Land Management Scheme (ELMS) seeking new management plans for farms derived from a mix of advice, results-based payments (present in existing schemes[3]), self-assessment, and suitable technologies and payment mechanisms, which together with new legislation will shape the future of UK agri-environmental policy for P. Similarly, the Welsh Government's proposed Sustainable Farming Scheme intends to reward farmers for improved soil and water quality.

The Catchment Sensitive Farming (CSF) (Natural England, 2014)[4] initiative also provides training and farm-level advice in England on manure, nutrient, soil, pesticide, water, nitrate and infrastructure management and payment scheme compliance. CSFs cover 34% of English agricultural land have produced "moderate" improvements in water quality, including P reductions (Davey et al., 2020; Environment Agency, 2019b, 2019b; Thomas et al., 2020). Complementary to CSF, the Defra-supported Catchment Based Approach (CaBA)[5] involves stakeholder organisations (i.e. Rivers Trusts) in England and Wales that bring together environmental groups, businesses, water utilities, local and national government and agencies, and civil society groups to address water quality, habitat, and flood risk challenges (Collins et al., 2020). CSF and CaBA are not integrated and considerable inequity exists between the capacities and activities of the different catchment schemes, meaning that success is mixed (Collins et al., 2020). A need exists to better understand the constraints and enablers for success. Additionally, at the time of writing, the UK agri-food sector and supply chains are impacted by the Covid-19 pandemic,[6] which together with Brexit, contributes to increased sectoral vulnerability and uncertainty (Garnett et al., 2020; Power et al., 2020). The transitional context of which, reflects an urgent need and opportunity to assess the adaptive capacity of catchments and identify improvements.

3.2. Method

3.2.1. Study catchments

We examine the Wye and Upper Welland[7] river catchments (Fig. 1), which were selected for the presence of P management challenges, diverse agricultural systems, and participant accessibility for interview. Like most of the UK, neither catchment in this study has achieved the Environment Agency's 'good' water quality status (Defra Press Office, 2020), with waterbodies sensitive to P pollution. The Upper Welland covers 460 km^2, is predominantly rural and characterised by mixed arable and livestock farming on clay and calcareous soils. Recent monitoring in this catchment (2011–2013) showed that 90% of the waterbodies had ecologically damaging levels of nitrogen and phosphorus with 75% of P pollution resulting from discharge and leakage from wastewater treatment works (Biggs et al., 2016). The Wye catchment is larger (4017 km^2) with overlapping regulatory bodies, local authorities, considerable amenity value, and supports livestock, arable farming, and horticulture on mostly silty and sandy soils. However, as of 2020, it continues to miss P compliance targets for good ecological status due mainly to agricultural and rural pollution.

3.2.2. Data collection and analysis

Primary data were collected through qualitative semi-structured interviews, workshops, and an online questionnaire with catchment stakeholders. Qualitative case-study research with these methods (Marshall and Rossman, 2011; Moon et al., 2016; O'Keeffe et al., 2016) is well established, and is particularly suited to research where "practical (context-dependent)" knowledge is sought over prediction-minded theory or models (Flyvbjerg, 2006, p. 224). Thus, our intent to capture the views of a particular cohort of (catchment-based) stakeholders around a specific issue (P) to elicit practical information about their knowledge of, and adaptive capacity to, P challenges is appropriate to a qualitative case-study method.

Participants (N = 66, total unique participants between the interviews and workshops) were purposefully sampled and recruited initially through prior contact with well-networked catchment gatekeepers known to the research team. We included as many known organisations operating in the catchment as possible within contact, consent, time, and study budget limits. Though it is not possible to know if we captured all views present in the catchment, the pool of voluntarily consenting participants consisted of people from organisations with an active interest in the P issue, suggesting a strong representation from the available relevant stakeholders.

3.2.3. Participant categories

The distribution of participants and respondents differed by catchment but was categorically consistent across the interviews, workshops, and questionnaire in each location (Table A.1). In the predominantly rural and smaller Upper Welland catchment, most participants identified as farmers. In contrast, the larger Wye catchment saw government and catchment management organisations, farmer member groups, and service providers and a minority of farmers define study participation. Fertiliser companies are one stakeholder group missing from the final consenting pool at the catchment level yet provide farmers with the fertilisers that contribute to catchment P issues. However, they may feature more among national or global scale stakeholders given their relevance to global supply chains and agri-business.

3.2.4. Semi-structured interviews

Twenty-two semi-structured interviews of n = 24 (Upper Welland n = 14, Wye n = 10) participants[8] lasting about one hour were conducted in person by one or two project team members in May and June 2019. Questions (Appendix B, Table 1) were broad in scope and developed through discussion across the research team, covering participant organisational role, short- and long-term risks and challenges, P issue awareness, catchment social/community life, farm type and P practice, and idealised food or agriculture system transformation. Interview data were coded using the NVivo software for broad themes related to the

[2] The Farming Rules for Water is a set of eight rules introduced in 2018 "to prevent diffuse pollution from manure, fertiliser and soils from getting into watercourses". Essentially these rules describe when, how, and where farmers can store or use fertiliser, manage livestock, and soil test. However, it is too early to assess the effectiveness of these rules on nutrient pollution at the time of writing in early 2021. https://www.gov.uk/guidance/rules-for-farmers-and-land-managers-to-prevent-water-pollution

[3] The RPA administers several payment and grant schemes for farmers and land managers to encourage pro-environmental practices (Basic Payments Scheme, Countryside Stewardship Scheme, and Environmental Stewardship). To receive payments, applicants must meet 'cross compliance' standards for human, plant and animal health and welfare, including livestock, and climate change. https://www.gov.uk/government/collections/rural-payments-and-grants

[4] https://www.gov.uk/guidance/catchment-sensitive-farming-reduce-agricultural-water-pollution

[5] https://catchmentbasedapproach.org/about/

[6] Interview data were collected in 2019, before Covid-19 emerged and impacted the UK.

[7] The 'Lower' Welland catchment, beginning at the town of Stamford is a lower-lying area terminating in tidal marshland, geographically and administratively distinct from the Upper Welland and outside the scope of this research. References to 'Welland' used this paper refer to the Upper Welland catchment only.

[8] One interview consisted of three people.

Fig. 1. Locations of Wye and Upper Welland catchments in the United Kingdom (colour shaded areas).

adaptive capacity to the two P challenges as reflected in the interview guide.

Data coding was iterative, wide-ranging, and ongoing to refine and combine the initial nodes and codes that were useful for organising the findings for this and other outputs from this work. Some initial codes were determined beforehand, whilst others emerged during the research. Of particular relevance were data revealing participant awareness or actions around specific P challenges. Nodes such as 'farmer decision-making' produced emergent codes for data on influences like 'agronomist, 'peer-learning', 'organisation to farmer engagement', 'soil-testing'. 'Fertiliser' produced the range of fertilisers (P sources) used as 'compost fertiliser', 'farmyard manure', 'MAP', or 'biosolids'. The node,

Table 1
Interview question themes.

Interview question themes *Co-designed by research team*	Purpose
Participant organisation type and role (Lyon et al., 2020)	To understand current and potential stakeholder roles in the catchment system
Adaptation, Transformation, and Resilience	To understand stakeholder potential response to or influence on others in response to P-related disturbances or changes
Sustainability/phosphorus	To understand views and involvement in (P) sustainability issues
Specific organisation/farm P views and use information	P related technical information to assess knowledge and use of P
Most impactful action	Open question to elicit what participants saw as ideal action or scenario for P management beyond any current constraints

'resilience and vulnerability', produced emergent codes such as 'lack of knowledge', 'regulation enforcement', 'unstable funding', 'planning', 'local infrastructure', and 'reluctance', which point toward adaptive capacity. Such data established the level of knowledge (a human capital asset) held by stakeholders about P issues and provided an initial sense of the major adaptive capacity issues within the catchment that serve as a precondition for approaches that could be pursued by stakeholders, depending on enabling and supporting interventions (second-generation adaptive capacity). Analysis of interview data was used to inform the workshops and questionnaire design to draw out more focused adaptive capacity questions.

3.2.5. *Workshops and questionnaire*

Two online stakeholder workshops,[9] one per catchment, were held in November 2020. The Upper Welland workshop had 18 participants and the Wye workshop had 37 participants (N = 55). Six of the Upper Welland workshop participants and five of the Wye participants were also interviewed. We totalled N = 66 unique participants between workshops and interviews across both catchments, including overlap and new participants (all interviewees were invited to the workshops, but some declined and others were no longer available).

The workshops and subsequent questionnaire aimed to elicit the participants' insights into catchment adaptive capacity when they were presented with preliminary results from ongoing research on their specific catchment P dynamics and the interviews. The workshops began with presentations from the research team on our preliminary results on P concentration and discharge (C-Q), Substance Flow Analysis (SFA), and legacy soil P experiments, and from the earlier interviews.

Following the presentation, the Wye workshop permitted a 45-minute participatory scenario exercise centred on three scenarios for reducing catchment P-flows from different sources based on our SFA results as well as propositional scenarios in which sources of P (fertilisers, livestock) were varyingly reduced. Scenarios were presented as discussion pieces intended to provoke creative thinking about possibilities (Oteros-Rozas et al., 2015) for reducing P-import dependency and soil and water concentrations (Martin-Ortega et al., 2022). In this way, locally tailored evidence informed discussion and allowed participants to discuss catchment adaptive capacity to the P challenges (Doody et al., 2020). Participant time constraints did not permit the scenario exercise in the Upper Welland workshop. However, this workshop included an interactive discussion in which participants validated, corrected, or asked questions of our results. The outcome of this workshop and follow-on engagement with participants produced a further list of 37 questions for the research team, written answers to which were provided and circulated with participants. Recognising differences between catchments allowed us to tailor our workshop activities to meaningfully engage participants in both catchments in ways that constructively verified our findings, provided further opportunity for participant engagement and learning, and focussed data collection on adaptive capacity.

Participants then completed an online questionnaire centred on second-generation adaptative capacity mobilisation questions (Appendix C). This activity sought participant views on constraints and enablers as well as potential actions to support enhancement of adaptive capacity for P. The response rates for the questionnaire were 74% in the Upper Welland and 35% in the Wye catchments (Welland, n = 14, Wye, n = 14). Whilst it was not immediately clear why these questionnaire response rates differed, we note that the catchments contrasted in geographical area, population, the relative diversity of stakeholders (i.e., Upper Welland smaller, farmer focused; Wye, larger, more diverse), and only one was amenable to a scenario exercise. While there was some overlap with the participants interviewed, the workshops also saw many new participants, and prompted strong participation in the questionnaire.

The aim of a workshop is to cocreate a collective output, meaning that is impossible to disaggregate one person's greater or lesser contribution to the whole as data are collectively produced through the workshop dialogues between participants and participants and researchers (Galafassi et al., 2018; Martin-Ortega et al., 2022). Thus, while we note the participation rate in the questionnaire and workshop, we also cannot know whether or how a respondent's answer was influenced by the workshop discussions that included people who did not respond to the questionnaire.

The results from each distinct method were then integrated to produce the overall narrative for our findings of adaptive capacity.

4. Results

4.1. *Catchment vulnerability to P supply shocks and water-quality stresses*

4.1.1. *P supply shock vulnerability*

Despite the risk of disruptions to phosphate rock supply (Cordell and Neset, 2014; Elser et al., 2014) catchment stakeholders differed in their perception of this risk. Arable farmers are objectively vulnerable through the use of imported fertilisers and the complex and under-researched role of soil P reserves (Condron et al., 2013), whereas livestock farmers would see vulnerabilities through the impact on animal feed prices where imported P is a direct or indirect (through feed crops) input to production (Withers et al., 2020). Prior to being interviewed and without information about potential future P shocks, farmers and agricultural organisation stakeholders from both catchments were largely unaware of and unconcerned about, the P supply risk, including having only a limited sense of where P imports originated. For example, farmers stated, "I'm thinking South America. No, I don't know" (Farm 6), and "Well, I didn't know that it was rock mined in Morocco…" (Farm 8). Despite a relatively major temporary price increase in 2008, farmers were also generally unaware of this event or only vaguely so: "I'm pretty bad at checking year on year what the prices are and even if it went up dramatically…" (Farm 5), or "yeah, went up to £ 600 a ton or something…" (Farm 4). Several farmers appeared to rely mostly on imported P resources, such as "bagged phosphate" (Farm 10), "DAP" (Farm 4, 8), "MAP" (Farm 5), "TSP" (Farm 5, Agricultural organisation) ,[10] or a mix of imported and organic P "we use chemical fertiliser, as well, to balance it up" (Farm 12). However, farmers across the study also drew on a range of secondary P products, including biosolids from treated sewage (Farm 4, 6), livestock slurries and manures (Farm 1, 2, 4, 5, 10, 12), anaerobic digestate (AD) from organic waste materials plants (Farm 1, 6), as well as branded processed liquid or granular

[9] These workshops occurred online due to Covid-19 restrictions on in-person events.

[10] DAP, diammonium phosphate; MAP, monoammonium phosphate; TSP, triplesuperphosphate are forms of rock-derived phosphate fertiliser.

organic fertilisers (Farm 6). Importantly, when asked about their responses to a price or supply shock, they did not see this as a great challenge:

> "If DAP is £ 400 a tonne – ballpark, I don't know where it is today. If it got to £ 600 a tonne, I don't think we'd buy it…[and]…would not be surprised at all to see, very quickly, new replacement products that would claim to or deliver the similar attributes of P". (Farm 8)

One participant observed a slow price increase, but had this to say when asked about their response:

> "Oh we've seen the price of…[branded] superphosphate double, even triple, haven't we, in the last ten years…" Interviewer: What have you done in response to that? "Not used any." Interviewer: Has that impacted on anything in terms of your farm productivity? "No." (Farm 5)

This awareness-practice gap and lack of concern suggests the exposure of catchment farmers to P supply disruptions or price increases is mediated by their experience, knowledge, or practices such that this risk is not a major feature of their farm planning.

Non-farm stakeholders, however, recognised that the UK is "almost entirely dependent on imports of phosphorus…and that's obviously going to create some issues as far as food security's concerned" (Wye local government), or the "idea of peak phosphorus being reached at some point" (Water company 4). These comments reflect the view of an experienced government representative, aware of the issue, who stated, "I don't think it's well known where we are at with it…many people haven't heard about peak phosphate or phosphorus" (UK government agency).

Thus, a disconnect exists between farm and organisational stakeholders in the level of concern for P supply disruption. More research is needed as this has implications for how organisational stakeholders, especially at the national level, understand and respond to this vulnerability. Whether this is a risk for farmers likely depends on soil reserves and recycled secondary alternatives for P relative to the duration of any supply problem.

4.2. Barriers, enablers, support, and potential for adaptive capacity

Stakeholders, however, were aware of a gap between current perceptions and the need to develop and adopt practices to address both current and potential P vulnerability for water issues. In interviews, workshops, and the questionnaire participants identified barriers, enablers, and supporting actions for developing adaptive capacity. They also made judgements on the feasibility of actions to enhance adaptive capacity in their catchments. We organise these results into thematic headings structured around specific issues identified by participants (Appendix Table D.2).

4.2.1. Readiness to change and established practices

Among the barriers to adaptive capacity, participants expressed doubts about the relative readiness to change, characterised by individual attitudes and practices and structural inertia. For example, in interviews and workshop, responses raised concerns that some stakeholders are too wedded to established practices (e.g. fertiliser-intensive farming methods) to change. Another concern involved farmers subverting regulations to avoid regulatory scrutiny, such as permit applications for "a poultry unit that is just under the threshold for environmental permitting regulations so they can bypass a lot of the restrictions that might be placed on them" (Local government representative). Comments also suggested that current policy and regulations support the maintenance of the status quo, such as poorly-sited or managed maize, livestock, or anaerobic digestion operations. However, we consider this situation may change in the coming years depending on the final post-Brexit changes in national agriculture and environmental legislation and policy such as ELMS and SFS. Similar concerns include a vested interest in maintenance of the status quo that extended beyond the catchment, such as the well-resourced agricultural industry.

Overcoming confidence barriers to farming at lower soil P-test scores was suggested to be initially challenging for some farmers who are more comfortable at higher soil test P scores. Other farmers were less concerned about soil P-test scores. For example, a change to zero-till practices, meant "put(ting) very little phosphate on", relying instead on phosphorus reserves in the soil (Farm 8). Another took a more informal approach, stating, "I don't know, I've not studied the chemistry enough…I just do what seems right" (Farm 10).

However, because of the high profile of poor water quality (to the degree of disrupting regional planning from one local authority), participants felt changes were beginning to occur. These changes included more interest in better soil and farm management practices to reduce P-losses, increased public awareness, interest in evidence-based farming, and less adherence to 'grandfathered' methods. "Deeply committed individuals", active members or leaders of different catchment organisations aligned with improving P management (Lyon et al., 2020), were also highlighted as enablers of change through their communication and convening power.

Participants also identified actions that would support behaviour change, including aligning P with larger environmental issues such as "climate change and the ecological emergency", raising the profile of P as an urgent issue, and providing "tangible benefit" to improved P stewardship. Other comments included awareness and promotion campaigns for P, supply-chain wide buy-in, and related industry engagement with the "grassroots" (i.e., farmers), as well as "neutral advisors". The point about supply-chain wide buy-in is particularly notable as it links to the need to maintain or improve stakeholder livelihoods as part of adaptive capacity, with which knowledge and training can help.

4.2.2. Knowledge and training for P-stewardship

Participants placed emphasis on the lack of, and thus need for, better knowledge and training about farm and catchment P dynamics, as barriers to P management. For example,

> "You can't just paint everything with the same project. I think there needs to be more people with boots on the ground talking with farmers and landowners and helping them, and just saying, you know, "We know you've got a problem. We're not here to judge, we're here to help you and improve water quality for everybody." (Environmental organisation, see also the 'Knowledge and training' section in Appendix Table D.2).

Existing efforts to do this are small scale and voluntary, and include knowledge, free training and advice (for farmers, agronomists, and catchment managers), such as the CSF, CaBA, and payment schemes (RPA) described earlier. A water company also provided scientific research presentations and free soil testing for metaldehyde for slug control in an effort to encourage farmers to change practices (Water company 3).

However, there was evidence that experimentation with some 5-R P stewardship practices was already occurring in the catchment (Withers et al., 2015), and indicated a capacity that could be developed with expanded knowledge and training efforts. Table 2 shows the kinds of 5-R efforts mentioned by interview participants.

Participants also mentioned that if stable support, such as long-term funding for training and mentoring for farmers existed, catchments might have the potential to move toward responsible P stewardship. Evidence from other research suggests that such hands-on training efforts, "the right information through the right channels" as one participant put it, are successful in promoting learning and behaviour change among farmers (Okumah et al., 2021; Rust et al., 2022; Thomas et al., 2020).

Notably, at least some farmers were experimenting with P-friendly practices based more on their own judgements rather than advice and

Table 2
Examples of 5-R stewardship efforts in the study catchments.

5-R principle	Results	Interview data examples
Re-align P inputs	Switching from mineral to organic P, and experimenting with reducing P input, taking into account soil test results, or drawing on legacy P, but again varied widely in their level of adoption and nature of such measures.	"You have to have the phosphorus and other nutrients at the right levels so we're regularly soil testing…We don't buy very much fertiliser, just a little bit to go in the maize. Everything we use is just digestate" (Farm 6)
Reduce P losses	Biological controls such as constructed wetlands and cover-cropping.	"…quite natural-looking wetland area [to] restrict the flow of water through that to ensure or.floating reed beds on that where the roots will go down into the water and the water will be pumped through quite slowly, to the point of which it's being treated by the time it comes out at the other end." (Environmental charity). "We aim to keep the soil covered even if it's not got something actually growing in it over winter so that it's protecting the soil [with cover-crop] from rain splash." (Farm 11)
Recycle P in bioresources	Farmers using straw ash, sewage cake, compost, and manures (livestock) from both agricultural and food supply chain waste, but with caveats	"I'm trying to reduce legacy phosphate…but just looking at the indices that I've got on the spreadsheet, actually they're going up so we're still putting on too much poultry litter or too much straw." (Farm 2) Costs associated drying manure were seen as an initial obstacle, as this would reduce the weight and volume thus costs of application (Farm 4).
Recover P in waste	Investment in anaerobic digestion (AD) plants in the catchments but caveated	"So there's things like more maize being grown specifically to feed AD plants and that has issues with land use, soil condition, runoff…" (Government agency)
Redesign P systems	Resources and funding, more face-to-face trust building with stakeholders, enforcing existing regulations, quality assurance schemes, payment schemes for farmers, smart/precision farming, complete circularity, rewilding, linking to health and social services, economic localisation	"more people with boots on the ground talking with farmers and landowners" (Environmental organisation)"knowledge transfer to agriculture" (Farm 5)"computer…will quickly diagnose the challenges being phosphate" (Farm 8) "rewilding" (Local government)"we have had initiatives to try and look at local procurement" (Sustainability organisation)

training. For example, one farmer indicated a change to zero-till practices, meant "put(ting) very little phosphate on", relying instead on legacy soil phosphorus (Farm 8). Another was sceptical of the UK's official nutrient management guidance (the AHDB 'RB209' guide[11]) and reduced their P application.

> "…when you look at RB209…it takes relatively little consideration of how much volume of soil you've got on your farm. It sounds really simple, and it might be completely wrong.So, we stopped putting phosphate on and. our yields haven't changed yet." (Farm 10)

Further, the current system of scattered and limited knowledge and training efforts are in farm-level packages of information and practices and not part of a strategic long-term effort to reduce P vulnerabilities at farm or catchment level. For example, the many follow-up questions and invitations to speak to specific stakeholder groups on our locally-based evidence on catchment P dynamics at the workshops is testimony to the importance for stakeholders to have locally-relevant scientific knowledge, and also the lack of central coordination. A well-designed and appropriately scaled training programme for catchment farmers and other stakeholders is a pathway to strengthening adaptative capacity and effective stewardship for P.

4.3. Stakeholder synergy

Although the stakeholder compositions were different in each catchment (Upper Welland, majority farmer vs. Wye, majority organisations), in both cases the capacity of stakeholders for collective action appeared to be a critical feature of their adaptive capacity. Catchment farmer training organisations, rural environmental charities, and water companies conducted outreach and extension learning with farmers. Such organisations used forms of bonding (farmer to farmer) and bridging (support organisation to farmer) social capital to establish rapport, influence, and networks (Hall and Pretty, 2008), through hands-on learning (Okumah et al., 2021) and outreach by water companies with financial incentives. These efforts were voluntary and resource limited,[12] leading to arguments for improvement.

> "If we had a massive expansion, which involved improved resources, equipment, staffing and the rest, I wouldn't want that to be at the expense of the collaboration that we do, because I like to think that we all benefit from that collaboration…" (Farming organisation)

Staff are also crucial to maintain close farmer engagement, without whom, trust-built collaboration with farmers would suffer. The capacity to adapt or change practices for improved farm-level P stewardship is centrally contingent on knowledge and training delivered in ways that maintain close face-to-face relationships. Evidence shows such efforts can aid farmers' adaptation to UK policy changes (Arnott et al., 2021).

This point is further stressed in the contrast between the farmer-centred Upper Welland, and the larger more organisationally-diverse Wye with its more visibly pressing P issues. The Wye catchment did not have the same social capital dynamics, with significant stakeholder tensions serving as a barrier to effective action. Workshop comments and questionnaire responses from stakeholders here suggested tensions where some catchment organisations were perceived to be 'attacking' farming or the agricultural community thus contributing to a harmful "tone" of the debate over P. Further tensions existed between local government and agriculture stakeholders over limits to new construction due to P-pollution concerns. However, the existence of a bridging organisation (CaBA) headed by deeply committed individuals served as a well-connected social hub or convenor that could host groups in tension, if not act as a catalyst for adaptive actions.

Stakeholders also cited as key enablers of action their shared commitment, expanded local Nutrient Management Board participation, and the activity of catchment organisations and partnership meetings, despite considerable uncertainty about what actions to take because of a lack of local evidence of catchment P dynamics (which our work was beginning to provide). For solutions, stakeholders suggested that catchment organisations could engage and work with farmers instead of confront them. This response, coupled with comments in the questionnaire, again suggests that an alignment of aims or at least more cooperative or synergistic stakeholder relationships would be beneficial.

[11] https://ahdb.org.uk/nutrient-management-guide-rb209

[12] Linking capital (e.g. hierarchical links to government or higher-level stakeholders) is an additional social capital indicator of agricultural behaviour change and stakeholder power imbalances (Hall and Pretty, 2008; Rust et al., 2020), but is unexamined here as it is beyond the scope of the catchment-level only focus of this research.

4.4. Funding, infrastructure, and technology

Adopting or adapting infrastructure or technologies for P stewardship was viewed as a significant financial undertaking and perceived risk by farmers and water companies. Catchment and farming infrastructure, which may take a significant investment in time and resources, are slow to change and are thus vulnerable to financial constraints. For example, although wastewater P removal technology (e.g. to produce struvite) exists, water companies suggested that such technology is not cost-effective for small or older water treatment facilities.

> "Putting P removal on small works is extremely expensive for the loads that you're going to be removing." (Water company 4)

> "Financially, we can't afford to put phosphate removal on every single one of those small works, we don't have the hundreds of millions that we would need…" (Water company 2)

Constraints also existed for a water company that worked closely with farmers in an advisory role, that found farmers were,

> "doing the correct things for the environment but actually to have the money there to go out and invest in a new pesticide handling area or take money to take areas out of production and not make any profit from, it is a big thing." (Water company 3)

This financial constraint was further compounded by uncertainty around the nature of changes in agricultural and environmental governance that meant "not knowing where rules and regulations are going and they don't know what to expect, a lot of moving goalposts" (Water company 3).

Noted in Table 2, an interview participant also cited the financial incentives created by the advent of profitable AD plants,[13] widely seen as having multiple environmental and economic benefits (Ackrill and Abdo, 2020; Akhiar et al., 2020), creates additional P run-off problems, again highlighting perverse or misaligned policies.

These constraints speak to the need for a well-designed integrated mix of financially incentivised technologies (e.g. waste-water removal, AD, and environmentally friendly farming, e.g. precision agriculture, legacy P uptake).

4.5. Legislation, regulation, and enforcement

Underlying all the adaptive capacity indicators is the governance environment, which is driven by more complex, high-level stakeholder capacities and priorities. Brexit also featured more in the interviews than in the workshops, which occurred before the UK formally left the EU. Interview participants expressed concerns that deep uncertainty was the prevailing sentiment on the ground. For example, participants frequently voiced views similar to the following:

> "Brexit, we have no idea. The right thing might be to plod on doing the same thing." (Farm 11) "We've got uncertainty around Brexit, we've no idea what's going on…which makes things difficult for farmers to plan with any sort of certainty." (Water company 2)

> "A big concern will be Brexit in terms of the amount of land that could potentially change hands as businesses fail if…basic payments are reduced." (Environmental charity 3)

Comments in the workshops and online questionnaire, however, centred on more practical concerns about the perceived lack of enforcement, inspections, and punitive powers of the Environment Agency, and thus the failure of the voluntary nature of compliance, including the subversion of regulations (see Appendix Table D.2). However, some stakeholders also suggested that the rules and payment schemes (described earlier) (Defra, 2021) were helpful for farmers in addressing P pollution problems.

More encouragingly, they also identified hard policy options to improve governance, such as legislation similar to that existing for nitrogen no-spread and no-plough zones, traceable poultry manure or by-products, ending subsidies for crops such as maize, financial penalties for non-compliance, or a P tax or ban (Appendix Table D.2). For soft policy options, participants suggested that "permission" not to use the sceptically-regarded RB209, and knowledge dissemination in the ELMS would be helpful. Workshop participants felt there was potential for improved P stewardship if the political will was present and practical steps were implemented such as strong P controls in the ELMS and Rural Payments Agency (RPA) cross-compliance rules for agriculture. These comments highlight the limits of catchment stakeholder adaptive capacity and need for an effective regulatory regime at the national scale.

4.6. Time needed to improve water quality

Finally, the perhaps underappreciated point about the time needed to improve water quality was mentioned by one participant.

> "We're trying to understand that if we address all of the yard issues and the sewage works does all of their P stripping, will the river actually get to good status or because of all of that…will it ever actually reach good status if it's going to take us 30 years to run down the P indices of 20% of the catchment?" (Environmental charity 3)

Understanding such decadal biogeochemical response times for P is a noted research gap (Hamilton, 2012; Jarvie et al., 2013) and mismatched P management policies that fail to account for these lags may result in mismatched nutrient ratios, such as nitrogen (N) and P in water systems, that impact ecology (Westphal et al., 2020) or compete with many future years of changing socio-economic pressures on agriculture or land-use.

5. Discussion: hands-on learning and stakeholder cooperation for catchment P stewardship

The global diversity of P policies and practice initiatives cover a range of mandatory and voluntary rules and schemes show mixed success, and point toward uncertain outcomes if the status quo is maintained (Kleinman et al., 2015; McDowell et al., 2016). Such efforts are well-established means of building adaptive capacity and creating lasting and impactful transformation (Brown et al., 2016; Johannessen et al., 2019; Johannessen and Hahn, 2013; Löf, 2010; Pahl-Wostl, 2009), including for nutrient pollution management on UK farms (Okumah et al., 2021), as they lead to the deep understanding necessary for enduring practice change (Hochachka, 2021; O'Brien, 2018). Such efforts show success in UK contexts (Davey et al., 2020; Thomas et al., 2020), including interim farmer feedback (September 2020) from ongoing trials of the ELMS (Defra, 2020), and different efforts in Northern Ireland (Okumah et al., 2021). Our results complement these efforts and provide a strong case for their expansion. The challenge, as described earlier, is creating effective hands-on learning programmes and regulation of sufficient scope to meaningfully improve P stewardship across UK catchments.

The New Zealand (NZ) Government faces a similar challenge. In a radical step change from the norm, it plans to introduce mandatory and enforced freshwater management plans for all farms, rooted in a new policy based on the Māori concept of *Te Mana o te Wai* (Stokes et al., 2021). Te Mana o te Wai,

> "refers to the fundamental importance of water and recognises that protecting the health of freshwater protects the health and well-

[13] AD processes process plant and animal material and wastes to produce burnable gas for clean energy production and 'digestate' that can be used as a fertiliser. Ideally, these plants use waste material but profitable economics may incentivise farmers to divert agricultural production to AD and apply digestate as fertiliser, which may not reduce P loadings.

being of the wider environment. It protects the mauri of the wai.[14] Te Mana o te Wai is about restoring and preserving the balance between the water, the wider environment, and the community." (Ministry for the Environment, 2020, p. 5)

What sets the NZ approach apart from efforts elsewhere is the prioritisation of the "health and well-being" of water resources ahead of and as a precursor to the health and well-being of people and community (Ministry for the Environment, 2020, p. 6; Stokes et al., 2021) and the intent to empower and compel local authorities to undertake "long-term" farm and "Freshwater Management Unit" (i.e., catchment level) visioning for water quality according to national standards and set these as regional policy objectives (Ministry for the Environment, 2020). Central to implementing farm-level efforts will be a large network of knowledgeable advisors who are able to engage with the tens of thousands of NZ farms (Fairweather, 2008; Stokes et al., 2021). This approach addresses key issues in our results, a realistic appraisal of the time needed to improve water quality and reduce P-import dependence, the usefulness of trusted and knowledgeable advisors and empowered convening and catalysing organisations (CaBA, CSF), backed by strong national government policy and regulation (ELMS).

The CaBA and CSF, whose water-centred missions echo the water-first Te Mana o te Wai, are crucial to aligning stakeholders and reaching farmers but appear to be missing from the NZ approach. Integrating these initiatives with local authorities (whose planning is most impacted by P), resourced and standardised to mitigate unequal local capacities under suitably empowering legislation, may provide a more collaborative or cooperative catchment-level platform (Wynne-Jones, 2017) for local stakeholders to develop effective P-stewardship in ways that fundamentally support farmers through training and education.

Thus, there is an opportunity for significant progress in catchment adaptive capacity and stewardship for P in the form of proven packages of technologies and schemes to facilitate practice changes among farmers, tailored to individual catchments. Elements of such packages could include:

- The provision of comprehensive local data on catchment P-dynamics to meet knowledge gaps;
- Policy and practice instruments, such as expanded training, education, and payment incentives for farmers to meet skills gaps;
- Strong policy, regulatory empowerment, and integration of relevant local authorities and local offices of national environment or agriculture agencies;
- Support for infrastructure such as P removal technology for water treatment companies[15]; and,
- Stable long-term support for key catchment stakeholders (i.e. convening organisations) to facilitate, enhance and maintain stakeholder synergy (Arnott et al., 2021) in the resulting integrated management paradigm.

This paradigm must also consider the potentially lengthy lag times for reducing P loadings and restoring water quality.

Finally, addressing the P pollution issue through expanded farmer training and institutional integration and support does not directly address the P import vulnerability. However, the adoption of water- or catchment-friendly farming practices necessarily involves adopting measures of P-stewardship that aim to 'close the circle' of P use to limit the reliance on imported P (Withers, 2019; Withers et al., 2015). That said, the generally low level of knowledge or concern at the catchment level and the global-local linkage of P-imports for agriculture, may mean that the involvement of national and global-scale importers and fertiliser producers (not represented in the pool of catchment stakeholders and possibly disincentivised by advocacy for reduced fertiliser use) is needed here. This point is especially relevant for researchers and policy audiences for whom the supply challenge is viewed as important, albeit potentially contentious (Cordell and Neset, 2014; Geissler et al., 2019).

6. Conclusion

Drawing on data from a UK study, we find support for adoption of the catchment as a key scale for cultivating adaptive capacity to water quality vulnerabilities to P pollution. Our results show that while awareness and concern for phosphorus-related supply challenges are low among catchment stakeholders, they are present among government level participants, suggesting that P supply vulnerabilities may be better addressed at national or global scales of action, as well as through increasing awareness among farmers and other catchment stakeholders. Most visible in our cases is the awareness of water quality vulnerabilities for P, which was a major, and in one case, contentious issue for stakeholders in the study catchments. We find that adaptive capacity is limited by the inertia of established practices; availability and uptake of knowledge and training; stakeholder synergy; financial support linked to technology and infrastructure; the governance environment; and the lag time between action and waterbody recovery.

Importantly, our results confirm the pivotal role of farmers and water companies in catchment adaptive capacity. Farmers, in our study, benefitted from knowledge and training for better P-stewardship, but the limited opportunities to do this, transitional rules and regulations, the lack of infrastructure and technology to support practice change, and confrontation with other catchment stakeholders over P or other environmental issues were clear barriers to the widespread uptake of P-stewardship. Although water companies are mandated to remove P in wastewater, as private entities they lack resources and incentives to make this a clear priority beyond statutory compliance.

We suggest that developing and expanding the nascent institutional structure (CaBA, CSF, and ELMS) to support farmers and catchment stakeholders through knowledge and training schemes, will enhance adaptive capacity. Integration into a package of expanded scientific (i.e. localised P soil, water, and source data) and material support (i.e. stable funding, resources) will be a key element. Formal recognition of clear responsibilities, the need for strong national government policy intervention to strengthen and provide robust support for specific farmer duties of care (Shepheard, 2012), as in New Zealand, and to resource and regulate such support to ensure broad public benefit will be essential.

A note of caution is warranted to avoid tunnel vision in any efforts to strengthen integrated catchment P management. Catchments face multiple intersecting challenges including climate, biodiversity, and socio-economic changes and must reconcile any trade-offs, such as between P and climate (Forber et al., 2020), biodiversity (Montoya et al., 2020), and population and technological change (Fraser and Campbell, 2019; Stringer et al., 2020).

Lastly, this is a limited study of two agrarian UK river catchments involving only the set of stakeholders, institutions, and P challenges unique to these settings. The salience of our findings and indicators to other areas such as urban, lake, coastal, or non-temperate catchments and governance set-ups remain opportunities for future work. However, we believe our study is an important starting point for future research.

Compliance with ethical standards

The authors declare that they have no conflict of interest. This research was evaluated and approved by the Research Ethics Committee of the University of Leeds, number LTSEE-093.

[14] The *mauri of the wai* describes the *life force of water*, which in the Māori epistemology is harmed by events such as nutrient pollution from human activity (Hopkins, 2018).

[15] Or 'utilities' in jurisdictions where water treatment is publicly owned.

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CRediT authorship contribution statement

Christopher Lyon: Conceptualisation, Writing – original draft, Writing – review and editing, Data curation, Methodology, Investigation, Formal analysis. **Brent Jacobs:** Conceptualisation, Writing – review and editing, Methodology. **Julia Martin-Ortega:** Writing – review & editing, Methodology, Project administration, Supervision, Funding acquisition. **Shane A. Rothwell:** Writing – review & editing, Investigation. **Liz Davies:** Writing – review & editing, Resources. **Chris Stoate:** Writing – review and editing, Resources. **Kirsty J. Forber:** Writing – review and editing, Investigation, Visualisation. **Donnacha G. Doody:** Writing – review & editing, Funding acquisition. **Paul J.A. Withers:** Project lead, Investigation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.06.001.

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