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Using an innovative Catchment Nutrient Balancing (CNB) approach to improve river water quality: A case study from rural sub catchment in Cumbria, United Kingdom

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Abstract

Nutrient pollution in river catchments is of significant concern in the UK, particularly from excessive phosphorus, and meeting water quality objectives requires addressing multiple sources of pollution. This study aimed at piloting Catchment Nutrient Balancing (CNB) approach in the Calthwaite Beck rural catchment, to achieve the water company's Water Framework Directive (WFD) objectives for phosphorus reduction. CNB is an innovative flexible permitting approach, enabling water companies to reduce fair share loads associated with their wastewater treatment works (WwTW), by working with other sectors to integrate WwTW and catchment solutions, balancing phosphorus load reductions across these solutions, to achieve regulatory requirements and wider benefits. It promotes collaboration, innovation and systems-thinking, rather than siloed approaches. This study was the first example in the UK, and is still one of the few, using CNB to meet regulatory phosphorus targets. It involved combining innovative treatment (Polonite®) at Calthwaite WwTW with farming interventions in the catchment to reduce phosphorus. The study successfully demonstrated the effectiveness of an integrated approach at achieving water quality objectives: over a three-year period, phosphorus reduction levels in the catchment achieved an annual average of over 65%, surpassing the 9% annual reduction target, with Calthwaite Beck's ecological status improving from "poor" to "moderate". The findings highlight the importance of collaborative engagement, particularly with regulators, farmers and catchment partners, to improve water quality and deliver wider benefits.

Key words: Water Quality, Phosphorus Pollution, Wastewater, Agriculture, Catchment Nutrient Balancing

1. Introduction

Declining water quality is a key concern across the UK and globally, with issues arising from multiple sources of pollution across catchments (Nguyen et al., 2023). In the UK, water quality improvements have been driven by the Water Framework Directive's (WFD) requirements since 2003, incentivising integrated practices such as catchment-based approach and river basin management, to achieve objectives. However, despite integrated approaches targeting different diffuse and point pollution sources related to urban and rural environments (Liu et al., 2022), only 16% of rivers and canals in England are achieving WFD "good" ecological status (Giakoumis and Voulvoulis, 2019). After physical modifications, the main reasons preventing waterbodies from achieving "good" are diffuse pollution from agricultural sources and urban runoffs (roads, cities), and point source discharges from centralised wastewater management systems, although smaller decentralised systems like septic tanks have been highlighted as an often-underestimated source of water pollution in rural areas (Dudley and May, 2007).
Contributing factors vary, depending on catchment characteristics and waterbodies, with wastewater and diffuse pollution likely to be main pollutants in urban areas, and agricultural practices in rural areas (Environmental Audit Committee, 2022). A recent review comparing

current and past river conditions in England, concluded that the picture is mixed – whilst water quality in urban rivers seems to have improved, it has declined in rural rivers (Whelan et al., 2022). Nevertheless, excess phosphorus (P) remains one of the most significant reasons for waterbodies failing to achieve "good" ecological status (Environment Agency, 2019; Nikolaidis et al., 2022; Withers et al., 2024).

To achieve phosphorus reduction required under WFD objectives, and more recently the Environment Act 2021, wastewater treatment works (WwTW) permit limits are becoming increasingly stringent in England and the UK. However, traditional, and emerging advanced P removal technologies are designed to address larger, urbanised WwTWs, whereas tighter permits in smaller, rural WwTWs can make P removal practically challenging and expensive. Furthermore, in 58% of waterbodies across England and Wales, the main source of nutrient pollution derives from agricultural and land management practices (Zhang, 2014). Hence, tackling small WwTWs discharges alone will not yield the desired improvements. And, with intensive agriculture, river quality in rural areas is likely to persist at levels worse than before the 1960s (Whelan et al. 2022). Therefore, the challenge of meeting regulatory objectives often goes beyond water company activities, thereby providing opportunities to take a wider integrated catchment approach to significantly address nutrient-related issues.

Similar to UK and Europe, integrated catchment management strategies have been employed across the world to tackle the impact of nutrients like phosphorus on water quality (Table 1). Additionally, there is growing interest in adopting partnerships at landscape and catchment levels (Sayer et al., 2013), for integrated water management and nature-based solutions (Malekpour et al., 2021). Multi-stakeholder collaboration, including with regulators, can help deliver water quality, quantity and ecological benefits in a joined-up way, although its effectiveness relies on clear governance, engagement and coordination across different policies, regulation and interests (Waylen et al., 2023).

In England, the environmental regulator, Environment Agency (EA), introduced innovative permitting approaches such as Catchment Nutrient Balancing (CNB), as a more flexible alternative to conventional permitting. CNB enables water companies to balance and offset some, or all, of their load reductions at a wastewater treatment works, with wider catchment interventions, by coordinating efforts with other sectors such as agriculture, to achieve bigger nutrient reductions from multiple sources in a catchment, beyond their regulatory obligations alone.

It should be noted that, although CNB and nutrient offsetting can be similar in mitigating nutrient pollution, they differ in execution. CNB is place-based, focusing on reducing nutrient inputs and balancing load reductions across a number of combined interventions within the affected catchment, whereas offsetting often involves compensatory actions that may occur outside the contributing source and immediate catchment area (Table 1), allowing polluters to offset emissions through mechanisms like nutrient trading (Jones et al., 2010; Lu et al., 2023) and off-site mitigations, which is the case for example, with nutrient neutrality (Natural England, 2022).
By balancing multiple nutrient pollution sources within the catchment, CNB enables the delivery of solutions that consider catchment-specific characteristics, providing the flexibility to combine integrated management approaches to create long-term water quality

improvements. It encourages local stakeholder engagement between water companies, catchment partners, farmers and regulatory agencies, unlocking the potential for collaboration (Sayer et al., 2013; Malekpour et al., 2021; Waylen et al., 2023), innovation, risk sharing, cost efficiencies and wider ecological benefits.

However, challenges must be considered, as implementing CNB requires effective coordination and relationship management among stakeholders, and a thorough understanding of catchment nutrient dynamics. It may also necessitate changes in land management and continuous monitoring to assess effectiveness of interventions. Therefore, careful consideration must be taken so that the inherent complexity of integrated approaches is not exacerbated (Waylen et al., 2023).

This paper reports on a case study delivered in a tributary of the River Petteril, Calthwaite Beck, in Cumbria, UK, where the CNB permitting approach was first piloted, bringing together local stakeholders to improve the health of the river through integrated catchment management.

Table 1: integrated catchment management approaches proposed across the world to improve water quality related to nutrient management

Approach	Key points	Countries	Key references
Nutrient management plans	Aim to optimise fertiliser use and reduce phosphorus runoff in agricultural land, incorporating practices like soil testing, precision agriculture, and best management practices. A study targeting 40% phosphorus reduction in the Gippsland Lakes to improve water quality, highlighted challenges and strategies of P management in rural catchments, recommending a framework for achieving environmental outcomes within budget constraints and trade-offs to mitigate diffuse-related nutrient pollution.	Australia	Roberts et al., 2012
Adaptive and innovative land management technologies	In certain areas intensive agricultural production has led to large amounts of nutrients exceeding crop and forage needs, increasing phosphorus loss. This has driven the need for targeted, collaborative and adaptive management strategies to address agricultural phosphorus pollution and protect water quality, such as emerging technologies to recycle phosphorus from water back to land as fertiliser.	USA and China	Sharpley et al., 2014
Adoption of "Integrated Water Resources Management"	A comprehensive cross-sectoral policy approach to water resource planning and management within watersheds, including controlling agricultural diffuse pollution and overcoming barriers to green infrastructure.	USA	Strifling, 2018
Coordinated urban-rural strategies for catchment management	Liu et al. (2022) studied how integrated catchment management strategies could sustainably improve water quality in the Cherwell Catchment, UK, using the CatchWat water management model. They evaluated model simulations against observed river flow and pollutants like phosphorus, testing scenarios of reduced fertiliser use and enhanced wastewater treatment, both separately and combined. Results showed that agricultural activities impact river quality in wet periods, while urban pollution is more significant in dry periods. The study recommended that, coordinated strategies which account for these mechanisms, are necessary for efficient and sustainable river water quality management.	UK	Liu et al., 2022

Nutrient offsetting and nutrient trading	Nutrient offsetting enables polluters to compensate for nutrient pollution caused by their actions through improvements that can reduce equivalent loads elsewhere, from alternative offsite point or diffuse sources. Nutrient trading is a market or non-market-based mechanism used to achieve nutrient offsetting objectives, whereby credits can be generated and sold through nutrient reduction actions and then purchased by polluters as an offset to meet their nutrient reduction obligations. This creates economic incentives to nutrient pollution management and can be an effective tool for improving water quality in agricultural watersheds. However, global adoption of these approaches has been limited; knowledge gaps act as barriers to widespread implementation of nutrient offset initiatives, and further research has been recommended to address gaps.	Australia and New Zealand, China, Canada and USA, China, European countries, including UK	Corrales et al., 2014; Lu et al., 2023

2. Material and Methods

2.1 Catchment Nutrient Balancing (CNB) methodology

The CNB approach was piloted in the Calthwaite area of the Petteril catchment from 2019 to 2023. It was co-developed and tested by United Utilities (UU), the water company of the North West of England, with the environmental regulator (the Environment Agency) and other key catchment stakeholders, as a new flexible permitting approach to achieving phosphorus reduction targets for a water company, based on the contribution from their wastewater discharges to phosphorus pollution in the river (their "fair share"), as required by the WFD. It aims to promote a catchment-scale approach to addressing nutrient challenge in catchments, supporting multiple sectors to meet the load reductions required and go beyond their "fair share", delivering better overall outcomes for the catchment. This pilot was the first of its kind, and the developed methodology provides an evidence-led model for similar future schemes. Below are the proposed key steps and description of the CNB methodology (Fig. 1; Table 2).

1. Catchment baselining and modelling validation

Baseline assessment and validation of nutrient loads + sources in catchment area

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2. Partnership approach to opportunity identification and development

Collaboration with local stakeholders to identify, assess and develop feasible opportunities

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3. Environment Agency collaboration

Agreement of interventions with EA based on fair share requirements (OTA)

↓

4. Intervention delivery and maintenance

Delivery of combined solutions (catchment + WwTW) integrated in same geography

↓

5. Intervention performance monitoring

Assessment of performance of interventions against baseline

↓

6. Regulatory compliance reporting

Assessment and annual reporting of compliance against targets agreed in OTA

Figure 1: Overview of key steps in CNB methodology piloted at Calthwaite (United Utilities, 2022)

Table 2: Detailed description of key steps in CNB methodology

Steps	Description
1) **Catchment baselining and modelling validation**	This initial step assesses the nutrient loads and sources within the catchment area to set the baseline, source apportionment, fair share reductions, and the target load for offsetting. To assess the baseline performance of the catchment before improvements, monitoring is carried out to understand where the issues are, how it compares with the modelled data produced by the regulator (validation and calibration of the model), and therefore establish an accurate target load reduction to be offset by the water company. In the UK, catchment modelling is undertaken using the Environment Agency's SAGIS-SIMCAT modelling tool, which sets out the source apportionment for different sectors contributing to water quality issues in waterbodies. In addition to the validation of sampled data against SAGIS-SIMCAT, a spreadsheet tool from the EA (P Optimiser) is used to calculate the P load reductions required from point and diffuse pollution sources on a 'fair share' basis, depending on contributing sectors, to meet in-river targets. The Optimiser takes SAGIS-SIMCAT modelled outputs and assesses how much phosphorus load needs to be removed from the river to meet various WFD targets. When improving or preventing deterioration of the water environment in the UK, the Environment Agency considers the proportion each sector contributes to the problem, targeted on a 'fair share' basis for each sector, business, or individual, which involves cutting nutrient levels by a percentage of their contributions, rather

	than by a fixed amount, to ensure a proportional distribution of responsibility based on their impact. The Environment Agency uses the 'polluter pays principle' to determine the required percentage reductions from sectors like agriculture, water industry and urban runoff. This approach promotes fairness and encourages sustainable practices.
2) **Partnership approach to opportunity identification and development**	A key success step for CNB is partnerships, to provide local knowledge, joint decision-making and challenge and validate assumptions. Collaboration unlocks the potential for new ways of working, opportunities for integrated solutions, risk sharing, cost efficiencies, and the delivery of multiple benefits. Place-based key stakeholders can range from local businesses, farming communities, volunteers, non-government organisations (NGOs), academia, government bodies such as local authorities and regulators, etc. Partners can be mobilised to identify appropriate catchment opportunities, including farming interventions, and their likely benefit in terms of nutrient reductions, which can then be quantified by experts through modelling tools. The Farmscoper model is broadly used to quantify the impacts of various mitigation methods on pollutant losses to water (nitrate, phosphorus, and sediment), air (ammonia), and greenhouse gases (nitrous oxide and methane). Methods such as the adapted RB209 can also be used to quantify load reductions from measures that are not included in Farmscoper (more detail in section 2.3). It is important that the interventions identified are shown to achieve over and above agricultural fair share requirements, in order to ensure adherence to a number of regulatory obligations, such as Farming Rules for Water (FRFW), cross-compliance or Nitrate Vulnerable zone (NVZ) regulations, which must be delivered by farmers and cannot be funded by another regulated business such as water companies, unless farmers are already meeting their requirements. Farm visits, engagement and surveys are recommended to assess suitability for CNB schemes. Finally, the CNB approach can attract various partners across the catchment, by addressing a wider range of issues across the landscape and seeking to deliver integrated solutions that provide additional benefits beyond nutrient reductions for water quality, such as reduction of sediment and faecal indicator organisms (FIO). Besides water quality, a catchment-based approach can also deliver flood reduction benefits, carbon reduction and biodiversity improvements, as well as alignment with other partners in the delivery of multiple interventions across the catchment.
3) **Environment Agency collaboration**	In England, WwTW discharges are traditionally governed by the Environmental Permitting Regulations (2016), where each site is permitted to discharge wastewater to surface or ground water. When a WwTW uses alternative permitting such as CNB, the water company must agree measures with the Environment Agency through a bespoke 'Operating Techniques Agreement' (OTA), which must be firstly trialled over an agreed timescale (usually 3 years) and reviewed at the end of the trial. If this is successful, then the OTA is embedded in the site as a permanent permit, setting out how the measures in the WwTW and the catchment are to be managed to achieve the overall target nutrient reduction. It also includes the detailed baseline load calculation, the target P load reduction for the WwTW and for other sectors apportionment, and the date the target load will apply. The agreed monitoring regime, locations, start date and frequency details must also be included. It is advisable to include

	in the OTA a programme of work document for complex schemes, detailing interventions that are scheduled to take place at each site within the selected catchment to meet the requirements of the OTA.
4) **Intervention delivery and maintenance**	The catchment interventions take place in the same geographical location as the WwTW where the OTA applies, preferably, but not exclusively, upstream of the receptor WwTW, as agreed locally with the Environment Agency. Water companies can use a partnership approach with catchment partners, such as farmers and other third parties, to deliver interventions, ensuring that these are always beyond the fair share requirements of other sectors like agriculture. Once the OTA is agreed and signed off by the EA and the water company, the water company develops delivery and maintenance agreements with the relevant delivery partners, engaging closely with them to collate appropriate evidence of delivered interventions. The water company is responsible for the installation and maintenance of all the improvement measures agreed through the OTA.
5) **Intervention performance monitoring**	The water company should agree an appropriate monitoring regime with the Environment Agency to assess how the delivered interventions are performing against the required target load reductions and the initial baseline. The sampling regime could be a combination of monitoring at WwTW, waterbody and catchment/farm level. • WwTW: following delivery of treatment interventions, the WwTW's final effluent should be sampled in line with ongoing operational sampling of the site, although additional sampling may be required by the EA. • Waterbody: the watercourse should be sampled downstream of the WwTW's discharge, at the same frequency and on the same days as the final effluent sampling. The default location for the sampling of the watercourse will be the regulatory compliance monitoring point for the waterbody, which should be safely accessible and comparable to the Environment Agency's WFD compliance sampling, although alternative locations can be agreed where necessary. • Catchment/farm level sampling – trend monitoring points should be identified for catchment or farm levels interventions, to demonstrate that these are successful. These are typically on small streams or drainage ditches.
6) **Regulatory compliance reporting**	At the end of each calendar year, the water company should report sampling results and compliance against the target catchment annual total nutrient load reduction (kg/year) agreed within OTA. The report should calculate the total catchment load reduction from the WwTW and catchment interventions, comparing these with the target catchment annual load reduction. The water company is compliant with its OTA if the target catchment annual total nutrient load reduction (kg/year) is achieved for the preceding calendar year. The analysis of compliance can be carried out by several tools, through sampled and photographic evidence of changes before and after delivery of interventions, which can then be confirmed through statistical analysis (using ANOVA, CAPATIN toolbox, C-Q plots) to assess significance of change, as well as independently verified by a third party, such as an academic institution. If compliance is not achieved, the operator must investigate the reasons why either the WwTW, or the catchment interventions, or both, did not achieve their reduction targets and report these to the Environment Agency within 28 days of the end of the reporting period. If the reduction target is not achieved because of third-party

	action, the water company should report these to the Environment Agency and explain how the third party has affected the reduction target. If the target is not achieved altogether during the trial, the operator has three years to improve the performance, and if performance does not improve over that period, then a revision of the Operating Techniques Agreement will be required.

2.2 Piloting CNB methodology in the Calthwaite area

2.2.1 Study site

Calthwaite Beck is a tributary of the River Petteril in the Eden catchment of Cumbria, in North West England (Fig. 2). The Petteril catchment, including Calthwaite Beck, faces complex water quality issues particularly due to phosphorus, which required simultaneously addressing multiple pollution sources to deliver significant reductions to improve ecological status. Therefore, United Utilities worked with the Environment Agency and other partners to establish a true baseline for the catchment and develop a holistic approach to address these issues.

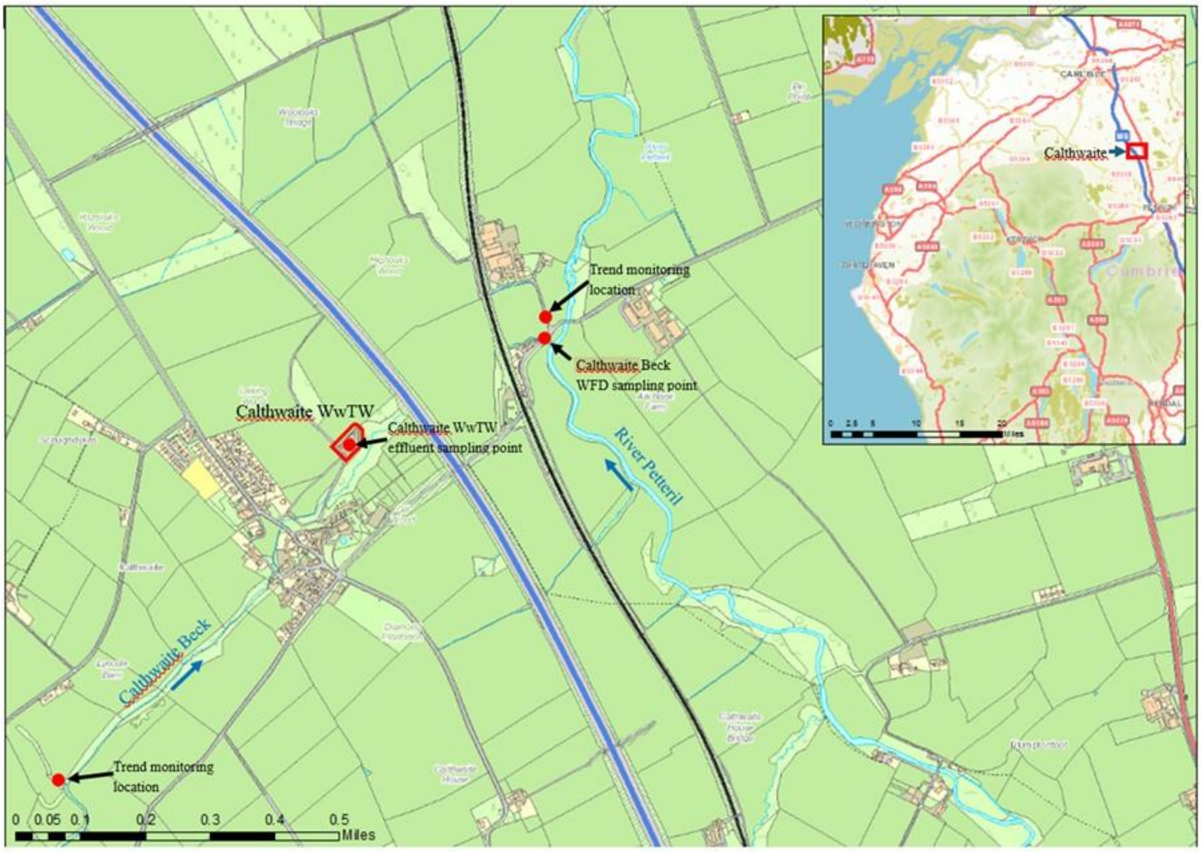


Figure 2: Map of the study site, Calthwaite Beck area, pointing out key catchment sampling locations, including the waterbody's and the WwTW's key details as follows:

Calthwaite Beck characterisation: it is mainly an agricultural area, predominated by livestock farms, with mean annual precipitation of 2000mm and 8°C temperature average. Several environmental pressures impact the local ecology, mainly nutrient inputs (phosphorus and nitrates), with phosphorus being the main reason for not achieving "good" ecological status under the Water Framework Directive ("Poor" status in 2015). Key sources of P include discharges from local wastewater treatment works, Calthwaite WwTW, agricultural pollution, other catchment pressures.

Calthwaite WwTW: Owned by United Utilities, serves a population of less than 300. The treated effluent discharged into Calthwaite Beck. The site had permit obligations under WFD objectives to remove phosphorus to 1.0mg/l (2015-2020). CNB approach was firstly piloted in this catchment to achieve target load reductions associated with this site's permit obligations.

2.2.2 Catchment baselining and modelling validations

To establish a baseline for the Petteril catchment, including Calthwaite Beck, United Utilities collaborated with the Environment Agency (EA), Eden Rivers Trust, Lancaster University, Cumbria County Council and others, to deliver an intensive 17-week monitoring programme (August 2016-January 2017). This involved deploying monitoring equipment (auto-samplers) across various locations, including:

- Sampling at 10 river and tributary points, with samples collected twice a week
- One monitoring station measuring river flows
- Six WwTWs, including Calthwaite WwTW, were also monitored, with single 24-hour composite samples of crude and final effluents taken weekly
- Determinants analysed: total phosphate and orthophosphate

The data collected was used to validate the EA's SAGIS-SIMCAT model assumptions (Fig. 3). This model is used to establish the source apportionment contribution from different sectors to water quality issues, or "fair share".

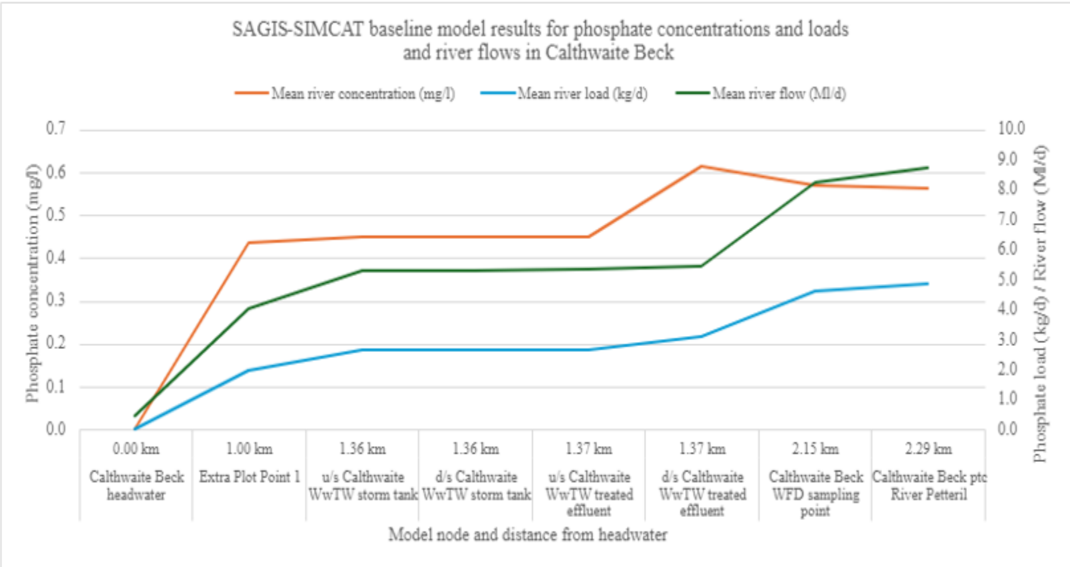


Figure 3: SAGIS-SIMCAT baseline model for phosphorus concentrations, loads and river flow covering the length from Calthwaite Beck headwater to the main River Petteril, based on sampled data which was then used to validate the model shown in this figure.

Furthermore, the sampled data showed that Calthwaite WwTW contributed only 10-15% of the phosphorus load onto Calthwaite Beck, which was significantly lower than the originally modelled 92% contribution. With the baseline data suggesting multiple phosphorus sources contributing to the water quality problem, it highlighted the need for a more holistic phosphorus management approach, paving the way for flexible CNB permitting. Because Calthwaite

WwTW required a new phosphorus reduction permit (1.0 mg/l) sooner than the other WwTWs in the catchment, it was firstly chosen to pilot CNB before rolling it out across the Petteril catchment.

2.2.3 Partnership approach to opportunity identification and development

To agree consistent monitoring and identify interventions, the Petteril steering group was formed, consisting of United Utilities, Environment Agency, Eden Rivers Trust (a local environmental charity that hosts the catchment-based approach in this part of Cumbria) and its volunteers, Lancaster University, British Geological Survey, Nestle UK, Carlisle City Council, Cumbria County Council, Natural England, local farmers and National Farmers Union. They worked collaboratively to make decisions and challenge assumptions, co-created the Calthwaite trial, conducted community-based surveys, delivered monitoring and identified interventions to improve catchment water quality.

2.2.3.1 Assessment of farm intervention opportunities

Guided by the steering group, farm visits and assessments were conducted by catchment partners, led by the Eden Rivers Trust. They identified potential farms in the Calthwaite area, through local engagement and farm walkovers, that could significantly reduce phosphorus to help offset the water company's requirement at Calthwaite WwTW. The assessment focused on baseline data and fair share requirements for the agricultural sector, to identify additional interventions that could improve nutrient management on selected farms and reduce phosphorus pollution, to achieve benefits beyond agricultural fair share and regulatory requirements. To understand the potential phosphorus reduction from selected local farms, the Farmscoper model, developed by ADAS and recommended by the regulator, was used. For interventions not included in Farmscoper, United Utilities and the steering group developed an alternative model adapted from the Nutrient Management Guide RB209. These methods are further described in Table 6.

2.2.3.2 Development of an innovative technology to treat P at Calthwaite WwTW

The CNB flexible approach allowed United Utilities to explore innovative alternatives for P removal at Calthwaite WwTW. Conventional P treatment methods using chemical dosing with iron or aluminium salts are cost-effective in larger WwWTs, becoming more costly, on a per capita basis, in small WwTWs (Fig. 4). Chemical dosing also presents concerns in terms of health and safety and carbon impact. Therefore, United Utilities was interested in finding more sustainable alternatives for small, rural WwTWs.

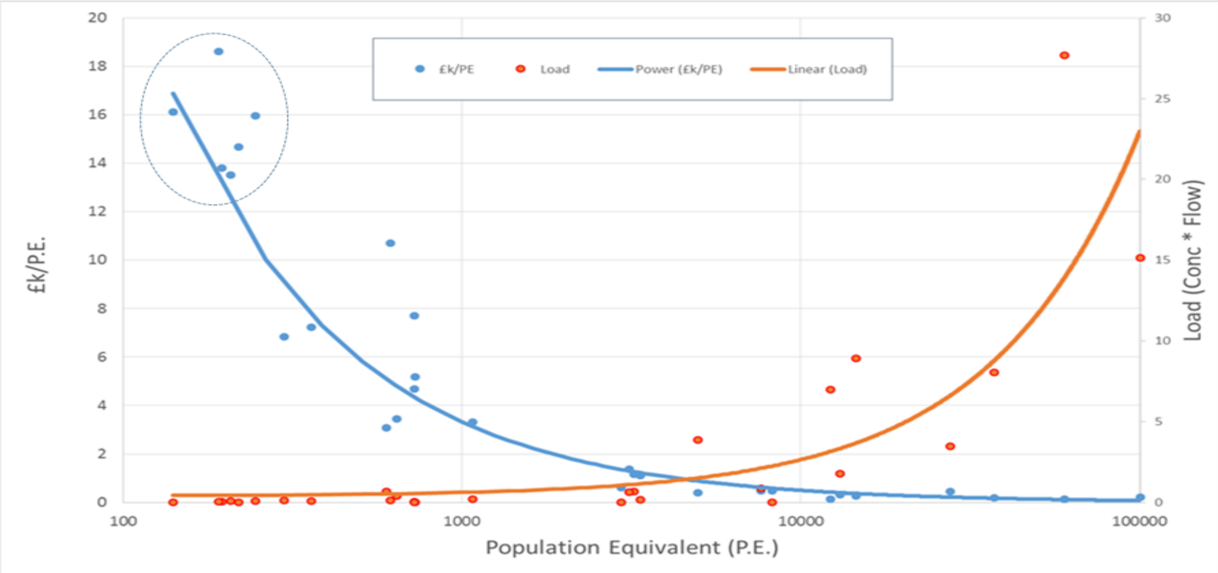


Figure 4: Low P permits at small works deliver small load reductions at high cost per population equivalent (PE). Blue trend shows the cost per capita (£/PE). Orange trend shows load increasing with PE. This assessment was carried out by United Utilities, based on their wastewater treatment works with P permits, and the cost of conventional treatment using chemical dosing to remove P loads (market costs based on 2016-2017).

Reactive media for P removal is being applied in various forms. Polonite® is one such example, successfully used in Sweden and Poland in small wastewater filtration systems, that shows good scale-up potential (Renman, 2008; Cucarella et al, 2009). This technology is attractive because it can align with existing treatment processes, is not energy intensive, does not require frequent chemical deliveries or interventions to optimise performance. However, unlike chemical dosing, reactive media requires a dynamic approach to target removal rates, which is only feasible with the flexibility provided by CNB permitting. Following a series of pilot-scale trials testing P removal capacity on several reactive media, carried out by United Utilities and Lancaster University, supported by the Petteril steering group, Polonite® was found to be the most effective, and therefore chosen to proceed as a full-scale solution at Calthwaite WwTW.

2.2.4 Environment Agency collaboration

The Environment Agency played a crucial role as a regulator in the Calthwaite CNB trial. They helped establish the steering group and identify nutrient issues in the catchment, supporting delivery of the CNB programme from the baseline assessment to development of the Operating Techniques Agreement (OTA) which sets out the details required by the water company to achieve their regulatory compliance under CNB permits, as well as assisting with intervention identification, assessment and selection, by reviewing outputs from Farmscoper and the adapted RB209. They also supported United Utilities and the Petteril steering group in setting up the ongoing monitoring programme, as well as in the assessment of the CNB trial performance through annual compliance reporting.

2.2.5 Intervention delivery and maintenance

United Utilities was responsible for the installation and maintenance of all the improvement measures agreed through the OTA. The CNB trial in Calthwaite marked a step change towards more integrated catchment management, by allowing United Utilities to explore sustainable phosphorus removal technology like Polonite® and combine it with catchment interventions, therefore taking a hybrid approach to achieve greater phosphorus reduction and additional benefits such as nitrate and sediment reduction and biodiversity improvements.

2.2.5.1 Catchment improvements – delivering farm interventions

As part of the CNB guidelines, the Environment Agency provided a list of farm interventions that water companies were allowed to fund to reduce nutrient pollution from agricultural sources (United Utilities, 2022), which was used to initially identify and assess potential interventions at each farm. Through discussions with farmers and catchment partners, the list was refined to ensure practical and feasible measures. Table 3 shows the farm-based interventions deployed in two farms in the Calthwaite catchment for the CNB pilot.

Table 3: Delivered farm interventions and location details

Farm improvement measures	Location
410 metres of fencing	Along both sides of the tributary of Calthwaite Beck to the southwest of farm A
Settlement pond	At the end of the tributary of Calthwaite Beck to the southwest of farm A
100 metres of fencing	Along the north side of Calthwaite Beck in the field to the south of farm
Fencing along the whole length of the farm drain	In the field to the south of farm B
Curb stone apron around slurry store reception pit at farm B	Around the slurry store reception pit at farm B
Repair to weeping wall	At the slurry store at farm B
Covering the feeding yard	At farm B
Concrete over the open yard	At farm B

2.2.5.2 Delivery of an innovative solution at Calthwaite WwTW

As endorsed by the steering group, Polonite® was installed at Calthwaite WwTW in 2019, as a full-scale treatment to meet the required P standards agreed by Operating Techniques Agreement. Calthwaite WwTW became the first site in the UK to deploy a full-scale plant using reactive media to treat phosphorus to regulated standards.

2.2.6 Intervention performance monitoring

The water company is responsible under the OTA to ensure that the measures put in place are fit-for-purpose and adequately maintained by farmers and catchment partners (Figure 5).

5a)

5b)

Figure 5: Examples of catchment interventions delivered in Calthwaite area:
5a) Farm improvements: fencing(A); settlement pond (B); covered feeding yard (C); yard cross drain (D)
5b) Bankside improvements on a tributary of Calthwaite Beck before and after delivery of farm interventions

To ensure effectiveness of the interventions, an ongoing monitoring programme was agreed with the Environment Agency to provide evidence of improvements against initial baseline. Monitoring was conducted for a year (2019-2020) at both Calthwaite WwTW and Calthwaite Beck area (including farm sites) to establish total phosphorus and orthophosphate levels before delivery of interventions. Monitoring continued post-implementation, throughout the pilot period (2020–2023), to assess “before” and “after impact of delivered interventions on total phosphorus and orthophosphate levels in the catchment (Table 4).

Table 4: Monitoring regime carried out in the CNB study site area of Calthwaite

Location	Sampling method	Sampling Frequency	Sampling Duration	Parameters	Data usage

WwTW	Daily spot samples	24 per annum	4 years	Total phosphate orthophosphate	To assess impact of Polonite® reactive media at WwTW
Catchment: Calthwaite Beck WFD sampling point	Spot water quality samples	24 per annum	4 years	Total phosphate orthophosphate	To assess impact of combined measures in the catchment WwTW+ farm interventions)
Catchment: Farm trend points at farms A and B	Spot water quality samples	24 per annum	4 years	Total phosphate orthophosphate	To assess impact of farming interventions at each farm

Water quality samples were collected manually (twice a month) and sent to a UKAS accredited laboratory for analysis. Orthophosphate levels were measured using SAN++ Air Segmented Analysers, which involve adding reagents to develop coloured complexes and measuring their absorbance spectrophotometrically. For total phosphorus, samples were acidified with nitric acid, digested at 80°C for at least 18 hours, and then analysed using an Inductively Coupled Plasma (ICP) instrument. This process involves dispersing the sample into an aerosol, transporting it to high-temperature plasma, and measuring the emitted radiation to detect multiple elements simultaneously.

Furthermore, prior to the start and during the CNB trial (2016-2023), Calthwaite WwTW final effluent and Calthwaite Beck WFD were annually monitored (12 per annum minimum) for operational purposes. The operational data was then used to compare the changes in total phosphate and orthophosphate concentrations, pre- and post-CNB pilot.

2.2.7 Regulatory compliance reporting

The final step in the CNB trialled at Calthwaite was compliance reporting. At the end of each calendar year, United Utilities needed to report sampling results and compliance against the target catchment annual total nutrient load reduction (kg/year) agreed within the “Operating Techniques Agreement” as shown in table 5.

Table 5: Target P load reduction from Calthwaite WwTW and catchment solutions

Year ending	**Ortho P load in Calthwaite Beck at WQ 88006374 (kg/yr)**	**Ortho P load contribution from Calthwaite WwTW (kg/year)**	**Ortho P load contribution from other sectors (kg/yr)**	**UU Target catchment annual ortho P load reduction (kg/year)**
Baseline	1683	164	1519	Not Applicable
31-Dec-19	1670	164	1506	13
31-Dec-20	1533	27	1506	150

The annual report outlined the calculated reductions in total phosphorus load from both the WwTW and catchment-based interventions and compared it with the initial baseline and previous years' data.

Calculation of annual orthophosphate P loads

As agreed in the 'Operating Techniques Agreement', the annual orthophosphate load discharged to Calthwaite Beck was calculated as follows:

WwTW load

- Orthophosphate concentration from spot samples was multiplied by the mean flow over the same 24-hour period to get the mean daily load.
- Each daily loads for the calendar year were added together and then divided by the number of sampling days to obtain the mean daily load for the WwTW.
- The mean daily load was multiplied by 365 to obtain the mean annual load (kg/year).

Total catchment load reduction

Calculated as follows:

- Baseline load minus the annual orthophosphate load at the WFD sample point.
- The baseline load was 1,683kg/year, which is the orthophosphate load from the SAGIS-SIMCAT model at the WFD sample point.
- The annual orthophosphate load at the WFD sample point was calculated using the mean annual orthophosphate concentration multiplied by the mean flow from the SAGIS-SIMCAT model (8,250m^3/d).

2.2.7.1 Additional analysis of collected data

To assure that the data collected in the trial and reported for compliance was significant in terms of the observed changes, further statistical analysis by |United Utilities and a modelled assessment by Lancaster University were carried out, to validate the findings.

Statistical analysis

To assess the statistical significance of the mean total and orthophosphate concentrations in the WwTW final effluent and Calthwaite Beck, t-tests were employed. These tests help determine if there are significant differences in the mean concentrations of total and orthophosphate before and after the CNB pilot. Additionally, Analysis of Variance (ANOVA) was used to evaluate the statistical significance of the annual mean orthophosphate levels at Calthwaite Beck, to understand if there were significant differences in the mean orthophosphate levels across different years, providing insights into the effectiveness of the interventions over time.

Observed change in concentration where stream discharge is used as a reference

Lancaster University applied an alternative way of studying CNB benefits by using the SAGIS-SIMCAT model to simulate changes in orthophosphate (or phosphate) concentration. The alternative approach used as a 'reference' of the stream discharge measured for the same date as each water quality sample (Stevens and Smith, 1978). Douglas et al. (1999) used this approach of examining concentration-discharge relations to study year-to-year changes in suspended sediment concentration resulting from forestry operations in Malaysia.

Lancaster University (LU) had installed a discharge gauging station further upstream on Calthwaite Beck in January 2019 (NGR NY 46257 39584) as part of a research project to quantify the effects of nature-based solutions for flood mitigation (e.g., Mindham et al., 2023; Beven and Chappell, 2024). The gauging station comprised of a 430-L/s trapezoidal flume (Genesis Composites Ltd., Glenrothes, UK) pre-calibrated for discharge. Water level was monitored at a tapping point installed within the throat of the flume using a SLS-A-DC-A010-BV-0250G-00 pressure transmitter (Stork Solutions Ltd., Basingstoke, UK). This was undertaken every 1 minute, then integrated over 5 minutes and transmitted to a data server via an RX3000 telemetry unit (Onset Computer Corporation, Bourne, MA, USA).

Two rain gauges, located within 10km of the LU flume (at NGR NY 43590 36078 and NY 49406 30831) recorded rainfall during the pre-intervention period of 2016, and post-intervention period of 2019-2023. Two simple linear models between the average rainfall from these two rain gauges and the observed flume discharge for the period 2019-2023 were developed:

- For drier parts of the year: Qmodel = 0.0003R
- For wetter parts of the year: Qmodel = 0.0037R

Where Qmodel is the simulated daily discharge (m^3/s average per day), R is the observed daily rainfall (mm/d) and overall $r^2 = 0.413$.

This simple model was then used to estimate the daily discharge time-series for the 2016 period (i.e., prior to installation of the flume). For 2016, some 22 water samples were available for comparison with these derived discharge reference values (specifically in the period 30 August to 20 December 2016). For the period post-CNB interventions, when direct discharge values were available as the reference, some 84 observed concentration values were available (specifically covering the period 12 March 2019 to 17 November 2023). To ensure that deriving the discharge for 2016 did not give a biased estimate when compared with directly observed discharge records for 2019-2023, the concentration to natural log of discharge (C-lnQ) relation for the 2019-2023 period was evaluated for SI-derived and observed discharge data.

2.3 Modelling tools applied in the CNBS methodology in Calthwaite

Table 6 details all the modelling tools applied in the Calthwaite CNB trial.

Table 6: Modelling tools applied in the Calthwaite CNB trial

Modelling tool	Description	Application
SAGIS-SIMCAT Model	In the UK, catchment modelling is conducted using the Environment Agency's SAGIS-SIMCAT tool. This tool, developed collaboratively by United Kingdom Water Industry Research (UKWIR), the Environment Agency, and Scottish Environment Protection Agency (SEPA) (UKWIR, 2018) provides: • River Basin Management: assisting regulators in planning and quantifying chemical sources to achieve Good Chemical Status under the Water Framework Directive (WFD).	This model was used to establish a true baseline of the Calthwaite catchment and validated through the baseline monitored data.

	• Water Industry Planning: helping the water industry identify cost-effective asset management strategies to meet water quality objectives. The SAGIS-SIMCAT model is a stochastic deterministic model that predicts the impact of discharges on river quality through mass-balance calculations (Warn and Brew, 1980). It accounts for various inputs, including industrial discharges, agriculture, urban runoff, and septic tanks. The SIMCAT models are calibrated against actual data, and SAGIS provides a user interface for modifying inputs and displaying outputs in GIS. The model produces statistical results of river flow and quality in the river network, along with source apportionment of the point and diffuse sources of pollution and of all modelled discharges into the rivers. In SAGIS-SIMCAT, livestock and arable sectors are generally considered as rural diffuse, and highways and urban runoff are urban diffuse. Point sources refer to pollution contribution from WwTWs, intermittent discharges, and industry discharges. Decentralised small wastewater treatment like septic tanks and package plants in rural areas are also considered rural point sources. SAGIS-SIMCAT is the Environment Agency approved tool for catchment modelling in England.	
P Optimiser tool	The Environment Agency's Phosphorus Optimiser is a Microsoft Excel-based tool that uses output files from the SAGIS-SIMCAT model to calculate the necessary phosphorus load reductions required from point and diffuse sources depending on contributing sectors, on a "fair share" basis, at any point in a river network, to meet in-river WFD targets. The 2019 version of the Optimiser tool was used in the Calthwaite study. This is the approved tool for catchment modelling in England by Environment Agency.	This tool was used to find the optimal solution for phosphorus reduction from the Calthwaite WwTW and upstream of the Calthwaite Beck WFD compliance point.
Farmscoper tool	The ADAS Farmscoper tool (FARM SCale Optimisation of Pollutant Emission Reductions) is designed to assess the impact of various mitigation methods on pollutant losses to water, air, and greenhouse gases. It uses a multi-objective approach to optimise the selection of mitigation methods without prioritising pollutants. The tool is user-friendly and helps policymakers in England and Wales evaluate mitigation methods for action and management plans. It also guides catchment officers in providing funding and advice to farmers to address diffuse pollution (Gooday et al, (2014; ADAS, 2021). The tool includes over 100 mitigation methods and can be customised and to reflect different farming conditions. It consists of two key workbooks: Farmscoper-Create, which helps create a farm profile and determine pollutant loads, and Farmscoper-Evaluate, which selects and assesses the cost and impact of mitigation methods. Assessments are performed by Farmscoper experts with support from catchment partners and farmers. Farm visits are recommended to evaluate current management practices and infrastructure. Farmscoper is the standard method used by the water sector in the UK and accepted by regulators, to quantify and assess phosphorus savings that could be made by changing traditional farming practices and interventions	The tool was used in the Calthwaite catchment to quantify potential phosphorus savings and improve nutrient performance beyond fair share obligations. The tool was customised and validated by visits to each farm.

Adapted RB209 tool	A manual calculation methodology based on RB209 (nutrient management guide developed by the Agriculture and Horticulture Development Board, UK) was developed by United Utilities and agreed with Environment Agency to quantify the P saving from interventions delivered beyond Farmscoper model (United Utilities, 2022).	This was used to quantify the P savings from the "cover feeding yard" interventions
C-lnQ	C-Q plots (Concentration-Discharge plots) are graphical representations used to analyse the relationship between the concentration of an element like P in a river and the river discharge (flow rate). These plots help to understand how the concentration of an element changes with varying flow conditions. This information is valuable for water quality management and understanding the impact of different land use practices or interventions on rivers/water bodies. This is widely used tool for catchment modelling (see section 2.2.7.1 for details).	Lancaster university used this method to independently assess pre- and post-pilot P changes at the Calthwaite Beck

3. Results

3.1 Total phosphorus and orthophosphate results at Calthwaite WwTW

Table 7 shows the mean total phosphorus and orthophosphate concentration at Calthwaite WwTW before and after Polonite® installation. The result evidenced that both total phosphorus and orthophosphate concentrations had significantly reduced ($p<0.05$) at Calthwaite WwTW final effluent following the installation of Polonite® reactive media to remove P.

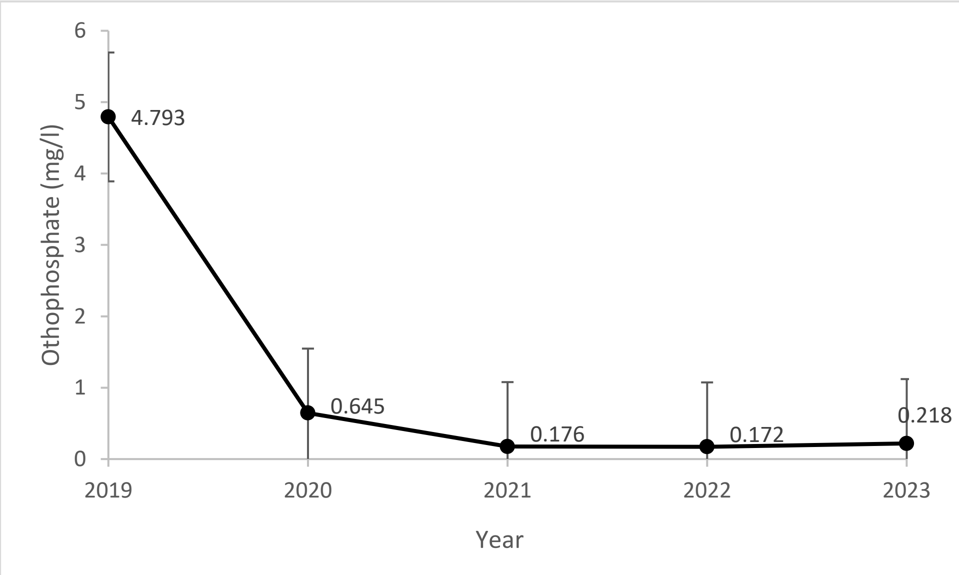
Table 7: Total phosphorus and orthophosphate concentrations (mean) at Calthwaite WwTW's final effluent before and after Polonite® reactive media installation. Different letter in row indicates significant differences at P< 0.05 *(t-test, n=279 before and n=233 after Polonite® installation respectively)*

Parameter	Before Polonite® delivery (2016-2019)	After Polonite reactive media delivery (2020-2023)
Mean total phosphorus (mg/l)	5.01^{a}	0.402^{b}
Mean orthophosphate (mg/l)	4.816^{a}	0.415^{b}

Figure 6a demonstrates the mean orthophosphate results at Calthwaite WwTW during the CNB pilot (2019-2023). Over this period, the final effluent orthophosphate concentration was shown to be significantly reduced. This improved performance at Calthwaite WwTW was consistently maintained following installation of Polonite® reactive media and recorded less than 0.25mg/l for the last three years, which is much lower than the stretch target of 1.0mg/l, for which Polonite® was designed to achieve at the treatment works.

Figure 6b shows the mean orthophosphate results at Calthwaite Beck during the CNB pilot period, which were significantly reduced ($p< 0.05$ ANOVA, n=20) from the baseline year (2019), and consistently sustained over the last three years post-interventions. There has also been an improvement in the WFD status of Calthwaite Beck, from "poor" to "moderate".

a)



b)

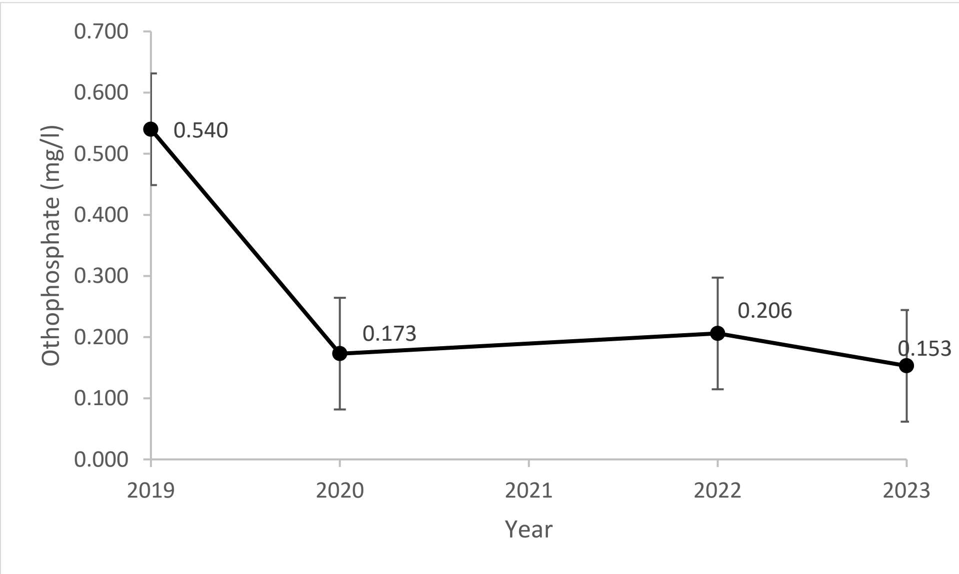


Figure 6: Mean (± SE) Orthophosphate concentration changes during the CNB pilot period of 2019 to 2023. **Fig 6a)** shows ortho-P concentration at Calthwaite WwTW while **Fig 6b**) shows ortho-P concentration at Calthwaite Beck.

Based on mean effluent flow and mean effluent concentration, annual orthophosphate load reduction (kg/year) achieved at Calthwaite WwTW was calculated for the CNB pilot period and results are summarised in table 8.

Table 8: Orthophosphate (OP) load reductions achieved at Calthwaite WwTW

Year	Mean effluent flow (Ml/year)	Mean effluent concentration (mg/l OP)	Mean effluent load (kg/year)	Annual load reduction compared to baseline (kg/year)
Baseline (2017)			164	0
2019	25.562	4.793	123	41
2020	33.649	0.645	22	142
2021	25.384	0.176	4	160
2022	21.590	0.172	4	160
2023	28.048	0.218	6	158

3.2 Total phosphorus and orthophosphate in the catchment

Table 9 shows the mean total phosphorus and orthophosphate concentrations at Calthwaite Beck before and after catchment interventions were delivered (using a WFD sampling point downstream from where both the WwTW and the catchment improvements were delivered). Before delivery of interventions for CNB, the mean total phosphorus and orthophosphate concentrations were recorded as 0.546mg/l and 0.495mg/l respectively. After installation of Polonite at the WwTW and delivery of farm interventions, concentrations dropped to 0.185mg/l and 0.181mg/l for total phosphorus and orthophosphate respectively. This represents a significant reduction ($p<0.05$) at Calthwaite Beck, following delivery of interventions at both Calthwaite WwTW and the wider catchment.

Table 9: Total phosphorus and orthophosphate mean concentrations at Calthwaite Beck before and after CNB interventions. Different letter in a row indicates significant differences at p<0.05 ***(t-test, n=46 before and n=68 after CNB interventions respectively)***

Parameter	Before CNB intervention (2016 -2019)	After CNB intervention (2020-2023)
Mean total phosphorus (mg/l)	0.546a	0.185b
Mean orthophosphate (mg/l)	0.495a	0.181b

Table 10 shows the catchment orthophosphate load targets year-on-year, during the CNB pilot period, and the actual load at Calthwaite Beck (calculated using the methodology described in section 2.2.7. It should be noted that catchments are dynamic, impacted by many sources of nutrient pollution, such as WwWT discharges, farm activities (e.g., fertiliser, slurry application, ploughing), rainfall, etc. Therefore, 2 samples per month may not entirely reflect on daily changes. These uncertainties have been considered when developing interventions.

Table 10: Catchment load target against baseline vs actual achieved at Calthwaite Beck

Year	Catchment orthophosphate target load against the baseline (kg/year)	Measured orthophosphate load achieved (kg/year)
Baseline (2017)	1683	N/A
2019	1670	1626
2020	1533	521
2022	1533	621
2023	1533	461

Based on the data summarised in table 8 and 10, orthophosphate load reductions achieved from WwTW and wider catchment against the baseline had been calculated and summarised in table 11. The catchment orthophosphate load reductions target was 150kg/year. In 2020, the orthophosphate load reduction achieved at Calthwaite Beck was 1162kg/year, with 142kg reduction from WwTW improvements and 1020kg reduction from the wider catchment interventions. Between 2022 and 2023 the catchment orthophosphate load reductions maintained similar levels, both at the WwTW and in the wider catchment.

Table 11: Orthophosphate load reductions achieved in the Calthwaite study area against the baseline

Year	Catchment orthophosphate load reduction target (kg/year)	Orthophosphate load reduction achieved at Calthwaite Beck (kg/year) (A)	Orthophosphate load reduction achieved from WwTW improvements (B)	Orthophosphate load reduction achieved from the wider catchment = (A – B)
Baseline (2017)	0	0	0	0
2019	13	57	41	16
2020	150	1162	142	1020
2022	150	1062	160	902
2023	150	1222	158	1064

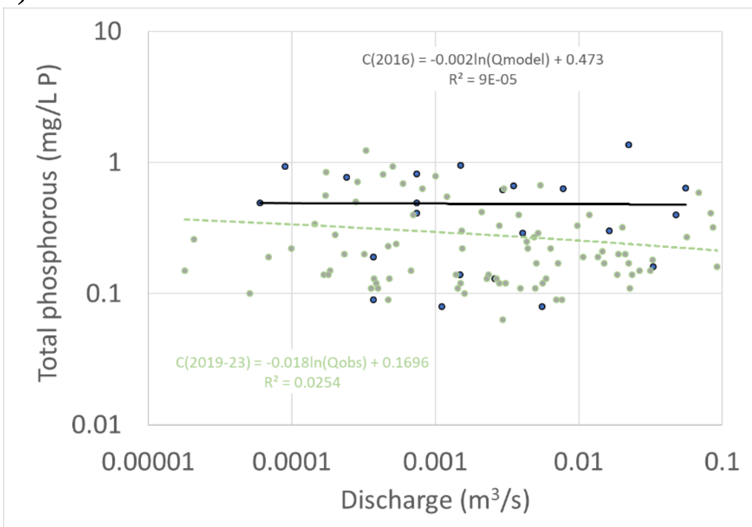
The results suggest that the reactive media treatment at Calthwaite WwTW have had a considerable impact on the overall orthophosphate load reduction but, by comparison, improvements in the wider catchment have had five to seven times greater impact on overall annual orthophosphate load reduction, as measured at the Calthwaite Beck monitoring point. This additional load reduction across the catchment was consistently sustained over three years.

3.2.1 Evidence of CNB-related reductions in phosphorus concentrations in Calthwaite Beck from a comparison of C-*ln*Q relations

Figure 7a shows the C-*ln*Q relations for total phosphorus (mg/l) for 2016 and for 2019-2023. The trend line in the C-*ln*Q linear regression relation for total phosphorus is consistently lower (over the range of discharge observed) for the 2019-2023 period (broken green line) following the start of interventions on farms, compared to the 2016 period prior to the interventions (solid black line). Figure 7b, which relates to the independently determined orthophosphate concentrations, shows the same finding. Namely, the trend line in orthophosphate C-*ln*Q linear relation is consistently lower for the 2019-2023 period (broken green line) compared to the 2016 period (solid black line). The variance in points around the trend lines are large. For example, the sum of the squared error (SS_E) in the offset for the 2016 period of 2.474 (derived by the LINEST function) is large compared to the offset value of 0.473 (Figure 9). However, the observation that the post-intervention trend lines are lower within both the total phosphorus and orthophosphate data, gives some indication that an underlying change may have occurred.

It is important to check that differences in the offset in the C-*ln*Q trend lines is not an artefact of using *observed* discharges for the 2019-2023 period but *modelled* discharge of the 2016 period. Thus Figure 8 (ab) is included, showing both the observed discharge for 2019-2023 and the values for the same period derived by the same rainfall-driven SI-model used for the 2016 period. A similarly lower trend line in concentration for 2019-2023 is seen whether directly observed discharges ('Qobs') or SI-model derived discharges ('Qmodel') are used for this CNB trial period. This gives some assurance that the lower concentrations per discharge reference (pre- versus post-intervention) are not an artefact of the methodology to extend the discharge record.

a)



b)

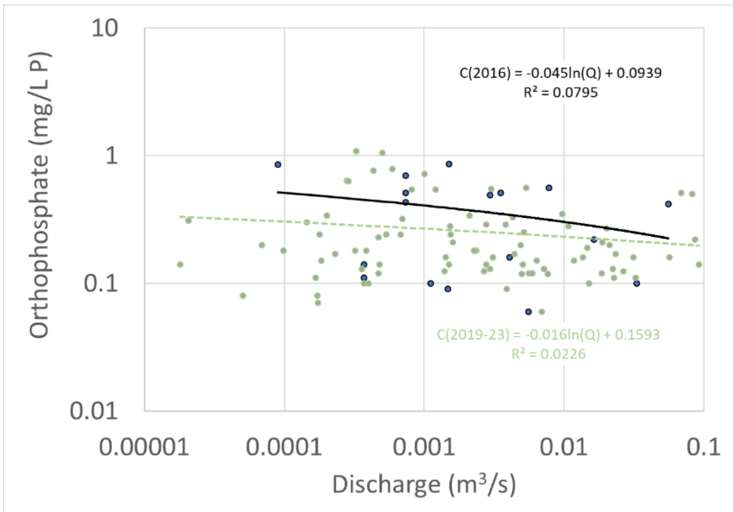
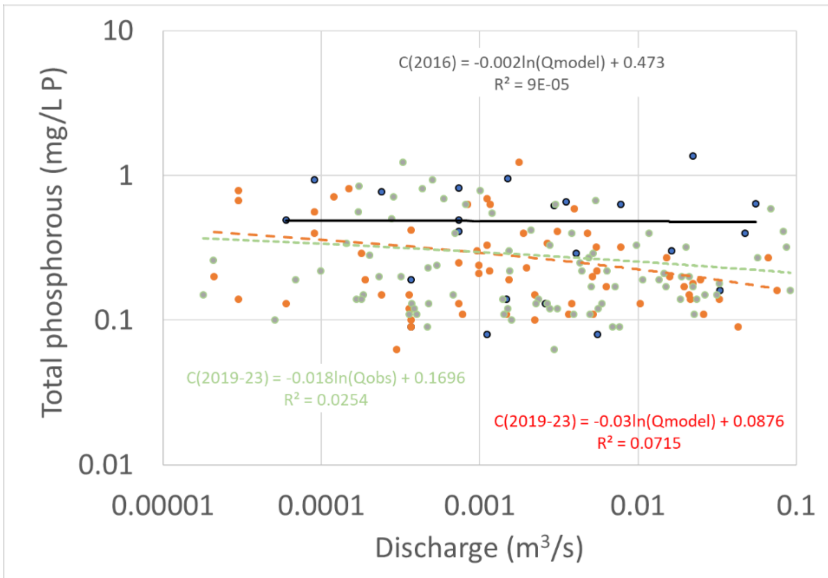


Figure 7: Values of P concentration measured for Calthwaite Beck plotted against the daily discharge for the 1.2 km^2 Calthwaite Beck sub-catchment. **Fig. 7a)** shows the total phosphorus (mg/l) concentrations, while **Fig. 7b** shows the orthophosphate (mg/l P). The blue-black markers and black regression line are for C-*ln*Q pairs in 2016 prior to the CNB interventions. The green markers and broken regression line are for C-*ln*Q pairs in 2019-23 following introduction of CNB interventions

a



b

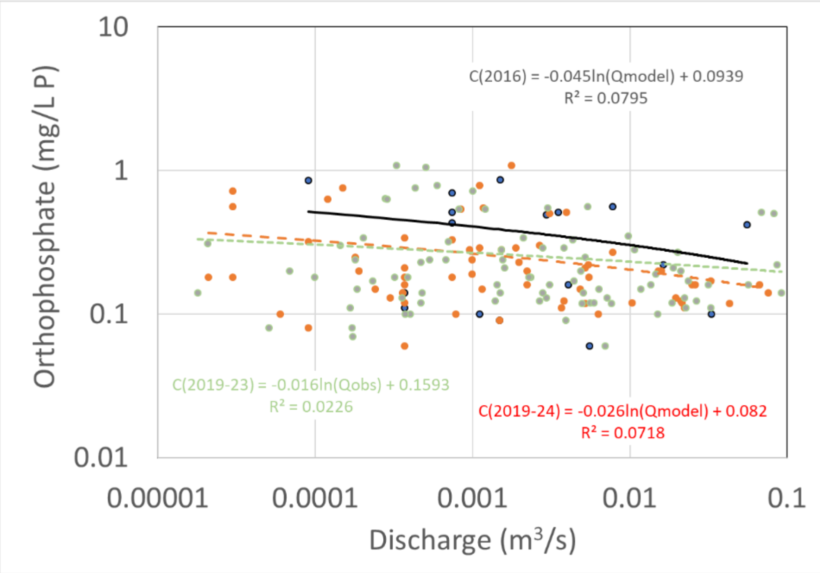


Figure 8: Values of concentration measured for Calthwaite Beck plotted against the daily discharge for the 1.2 km^2 Calthwaite Beck sub-catchment. **Fig 8a**) shows the total phosphorus (mg/l) concentrations, while **Fig 8b**) shows the orthophosphate (mg/l P) concentrations. The blue-black markers and black regression line are for modelled discharge values (Qmodel) in 2016 prior to the farm interventions delivered during the CNB pilot. The green markers and broken regression line are for observed discharge values (Qobs) in 2019-23 following introduction of the farm interventions delivered for CNB, while the red markers and broken regression line are for modelled discharge values (Qmodel) in 2019-23.

The large variance in the values around the trend lines is likely to be partly attributable to factors other than hydrological processes affecting the total phosphorus and orthophosphate concentrations, for example biogeochemical processes (Heathwaite and Bieroza, 2021). The small number of water samples collected (at an unknown time in the day) and analysed for total phosphorus and orthophosphate concentration is, however, likely to be a further factor. Others have demonstrated that phosphorus and orthophosphate concentrations within small streams are highly dynamic at sub-daily timescales (Jordan et al. 2007; Dupas et al., 2024). Where only daily (or less frequent) sampling has been undertaken in such circumstances, biased datasets result from a phenomenon known as temporal aliasing (Chappell et al., 2017). Such aliasing may introduce large errors in estimates of the magnitude of change or may hide the presence of real trends or temporal shifts within environmental time-series. This may be overcome by increasing the sampling rate sufficient to capture the dominant modes of temporal change in the concentration, by using chemical analysers running continuously in the field, as presented in Jordan et al. (2007) and Heathwaite and Bieroza (2021). Such high frequency (near-)continuous data also then permit time-series analyses with more sophisticated System Identification tools (e.g. Heathwaite and Bieroza, 2021; Chappell et al., 2017), and therefore more robust identification of temporal change. The temporally sparse concentration time-series available for this study (i.e., 22 samples in 2019, and an average of 16.8 samples/year over the 2019-2023 period) provide insufficient data resolution to justify the use of sophisticated System Identification tools. Unsophisticated C-*ln*Q analyses can, however, utilise data-pairs that are sampled very sparsely, hence their use in this preliminary study.

Further, the monitoring programme was also scheduled to collect samples from two trend points at farm level (Table 4). However, selected points (small streams and ditches) were dry during the summer months, and the data therefore could not be used to assess direct impact of P reduction at farm level.

4. Discussion

Excess phosphorus (P) remains one of the main reasons for waterbodies failing to achieve "good ecological status" under the WFD (Environment Agency, 2019) in the UK. In rural areas, phosphorus pollution can be greater from diffuse sources such as agricultural practices, while smaller decentralised wastewater systems like septic tanks, may contribute to groundwater contamination and P loads in waterbodies, often needing effective management strategies to reduce impact (Gyimah et al., 2024). Furthermore, although rural centralised WwTWs contribute to the problem, they tend to be smaller in size and P reduction from these sites alone is often not enough to improve ecological status. To address specific catchment needs in a holistic way, the Environment Agency introduced innovative permitting approaches such as CNB in England, as a flexible alternative to conventional permitting. This provides an opportunity to combine WwTW solutions with catchment interventions to reduce P loads associated with a WwTW's fair share target reduction, supporting a more integrated catchment approach. CNB was firstly piloted at the Calthwaite Beck area, to see if it could effectively: 1) drive P reduction beyond Calthwaite WwTW's fair share targets; 2) lead to improved ecological status in the river (Calthwaite Beck was classified as "poor" at the start of the trial).

CNB enabled the combination of P reduction at Calthwaite WwTW with farm interventions, by offsetting some of the fair share load reduction from the treatment works into the wider catchment. The trial has successfully demonstrated that the integrated approach can be effective, resulting in an average annual P reduction of more than 65% against the original baseline load of 1,683kg, compared to the expected target load reduction of 9% (150kg/year). Furthermore, the data suggests that although the Polonite® treatment at Calthwaite WwTW has had a significant impact on overall P reduction, catchment-based interventions may have been the main contributing factor to the observed phosphorus reductions (six to seven times more when compared to P reductions at the WwTW alone). This is supported by the regression lines in Figures 7 and 8, which show a reduction in P following the delivery of farm interventions in the wider catchment.

The reduction in phosphorus load in the catchment is concurrent with a change in the ecological status of Calthwaite Beck, which improved from "poor" to "moderate", thus moving towards "good" ecological status. It is unlikely however, that all load reductions across the catchment have been solely delivered through the interventions deployed within two farms in Calthwaite Beck (Table 3). Other potential factors contributing to the observed improvements could include ongoing catchment schemes, fluctuating rainfall patterns, changes in land use (e.g., converting arable land to low-input maize farming) and farming practices (e.g., observed decline in chemical fertiliser use in the area).

However, the results support the view that an integrated catchment management approach i.e., addressing pollution sources in a combined, collaborative way, can be more beneficial than siloed ways of working. Integrated approaches such as taken in this study, take a systems-thinking view, attempting to blend the objectives of environmental protection, sustainable agriculture, and natural resource management within catchments, together with the principles of ecologically sustainable development (Riddiford, 2021). This requires multi-stakeholder collaborative decision-making, looking at different perspectives to maximise benefits through combined efforts. The last two decades have seen an increasing worldwide effort to address the often siloed and fragmented delivery of catchment interventions (Butterworth et al., 2010; Rollason et al., 2018) with more holistic approaches (Rollason et al., 2018; Riddiford, 2021), to enable the sharing of resources, knowledge, costs and risks, delivery of multiple benefits, and joined-up decision-making, particularly in relation to climate change resilience (Basuki et al., 2022), declining water quality, landscape recovery and biodiversity crisis.

Collaborative systems-thinking can be complex and difficult to implement (Ananda, 2013; Rollason et al., 2018), which may be why these initiatives are yet to transition to "business-as-usual" catchment management. Because water infrastructure can be heavily regulated, the level of evidence required by regulators makes it challenging for integrated interventions to be delivered, particularly for things like nutrient reduction, where policy drivers can be conflicting and create competing pressures (Macleod et al., 2007), and the scientific evidence of success remains limited. Therefore, regulators and policymakers have a key role to play in enabling the use of integrated catchment management by mitigating risks and complexities, such as through innovative permitting approaches like CNB.

This is why the Calthwaite CNB trial is important: it provides one of the few evidence-based studies in the UK that demonstrates both the benefits of delivering nutrient reduction through an integrated catchment approach, and equally important, shows the enabling role that regulatory mechanisms such as CNB can play in delivering catchment-wide benefits beyond expected targets, thereby contributing to much wider outcomes. To expand this approach further, the key elements to be considered are: 1) balancing load reductions by combining asset and catchment-based interventions; 2) collaboration across stakeholders; 3) incentivisation through enabling policy and regulation; 4) strong evidence base to inform measures and report on progress. These agree with success factors suggested elsewhere (Macleod et al., 2007; Butterworth et al., 2010; Riddiford, 2021). This is because an integrated approach addresses the complexity of scale and diversity of challenges in a catchment by considering all sources of pollution and issues therein, leveraging collaboration to identify and combine solutions to deliver regulatory targets as well as wider benefits.

By working in this way in Calthwaite, United Utilities has been able to harness activities by other stakeholders who are interested in these wider benefits, driving even greater benefits. Engaging with, and supporting agriculture and catchment partnerships, is likely to yield improved land use changes and agricultural performance, leading to better compliance (Mohammed Ibrahim et al., 2019). By working with farmers, water companies don't just get what they pay for but identify a host of other things that farmers can deliver themselves to support their own nutrient reduction targets, therefore facilitating better overall water quality. The benefits achieved in the Calthwaite case study successfully demonstrate how CNB permitting, combined with integrated catchment approaches, can lead to a paradigm shift, driving better ways of working and innovation to achieve outcomes beyond regulatory compliance.

However, despite the evidence-led benefits demonstrated in this trial, there are considerable challenges with rolling the approach beyond a small-scale study to make it "business-as-usual": CNB is new, and therefore subject to changes, as regulators are still establishing a methodology and ways of working, which can lead to uncertainty in how innovative permitting can become common practice (Environment Agency, 2022). The uncertainty is further compounded by recent changes in environmental regulation, such as the UK's exit from the European Union and the subsequent introduction of the Environment Act 2021. These regulatory changes can in turn hinder the uptake of integrated catchment approaches, when compared to the more transactional delivery of regulated activities through well-understood end-of-pipe solutions.

These challenges can widen the perception that integrated catchment are high risk alternatives to tried and tested traditional approaches, creating a bias towards the certainty of conventional carbon-intensive solutions; despite carbon lock-in constraining long-term resilience (Seto et al., 2016), especially with regulatory standards in wastewater treatment works becoming tighter and upgrades being needed. Furthermore, the implications of climate change need to be addressed, particularly when considering nature-based solutions, that tend to be more cost-effective and more resilient to climate change than engineered solutions (Lafortezza et al., 2018), and their value is maximised when optimised through a catchment-based approach (Liu et al., 2023).

Moreover, it is important that regulatory guidance is clear and avoids creating competing pressures, because, as seen at Calthwaite, even with the flexibility offered by CNB, there are considerable restrictions on the activities that can be co-funded by the water company, as they can only support interventions beyond the agriculture sector's regulated "fair share" reductions. This can make delivery of interventions and analysis of benefits and costs more complex, because rather than focusing on maximising achievable outcomes, it instead focuses on restricting what can and cannot be delivered, and opportunities can become siloed and limited.

Therefore, this period of legislative changes provides an opportunity for regulators and policymakers to work with the water sector and other stakeholders to consider how to best mobilise policy and regulation to promote the use of innovative approaches such as CNB, to incentivise the implementation of more resilient solutions such as integrated catchment management; as well as ensure that guidance is streamlined and supports integrated outcomes rather than siloed approaches. As shown in this case study, where flexibility exists and regulatory mechanisms incentivise collaboration and integrated approaches, wider benefits can be achieved beyond regulatory expectations.

5. Conclusion

This study piloted an innovative approach to flexible permitting, CNB, to effectively address wider phosphorus reduction challenges in the rural Calthwaite area of the Petteril catchment. The results show that the adoption of CNB, which enabled the delivery of integrated catchment approaches, led to a significant reduction in phosphorus loads, beyond regulatory requirements at Calthwaite WwTW, and an improvement in water quality in Calthwaite Beck from "poor" to "moderate" ecological status. The findings highlight the importance of collaborative engagement and taking a holistic approach to catchment management, to achieve visible results for regulatory performance and water quality compliance.

However, challenges remain around competing regulatory pressures, particularly during the period of adjustment following the European Union exit with its related uncertainties and understanding how to scale up this trial to a "business-as-usual" approach. Further studies should therefore be rolled out to other catchments to gauge the impact of CNB and emerging legislation in different scenarios, focusing on integrated catchment management. The following recommendations should also follow:

- Clear steer and guidance from regulators on how to deliver interventions that can meet requirements whilst maximising outcomes rather than restricting interventions.
- Assess how catchment monitoring, modelling and decision support tools can be used to broaden the scope of interventions and possibilities, and to quantify multiple benefits.
- Increase CNB awareness across different sectors and stakeholders to facilitate application across other catchments.
- Develop standardised approaches for cost-effective and robust catchment monitoring and how to report on performance.

Credit authorship contribution statement

Nalika S. Rajapaksha: Conceptualisation, Methodology, Resources, Writing – original draft, review & editing, **Amina Aboobakar**: Conceptualisation, writing – review & editing, **James Airton:** Conceptualisation, writing – review & editing, **Nick A. Chappell:** Formal analysis, Methodology, Software, writing – review & editing, **Nick Hibbert:** Data curation, Formal analysis, **David Mindham:** Software, Formal analysis, **Andy Dyer:** Project Administration, review & editing.

Declaration of competing interest

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

Acknowledgments

Calthwaite CNB pilot was funded and led by United Utilities, supported by Eden Rivers Trust and its volunteers, Carlisle City Council, Cumbria County Council, Natural England, National Farmers Union, the Environment Agency and The Rivers Trust. The Lancaster University-owned discharge gauging station at Calthwaite Beck was installed and maintained by the Q-NFM project funded by Natural Environment Research Council grant NE/R004722/1NE. Analysis of the C-Q data by Lancaster University's co-authors was funded by the EA CiFR project.

References

ADAS, 2021. Farmscoper, Version 5 – October 2021 Description, RSK ADAS Ltd, UK. Available at: https://www.adas.co.uk.

Ananda, J., Proctor, W., 2013. Collaborative approaches to water management and planning: An institutional perspective. Ecological Economics, 86, 97-106. https://doi.org/10.1016/j.ecolecon.2012.10.018.

Basuki, T.M., Nugroho, H.Y.S.H., Indrajaya, Y., Pramono, I.B., Nugroho, N.P., Supangat, A.B., Indrawati, D.R., Savitri, E., Wahyuningrum, N., Purwanto, Cahyono, S.A., Putra, P.B., Adi, R.N., Nugroho, A.W., Auliyani, D., Wuryanta, Riyanto, H.D., Harjadi, B., Yudilastyantoro, C., Hanindityasari, L., Nada, F.M.H., Simarmat, D.P., 2022. Improvement of Integrated Watershed Management in Indonesia for Mitigation and Adaptation to Climate Change: A Review. Sustainability, 14(16), p.9997. https://doi.org/10.3390/su14169997.

Butterworth, J., Warner, J., Moriarty, P., Smits, S., Batchelor, C., 2010. Finding practical approaches to integrated water resources management. Water Alternatives, 3, 68-81. Available at: https://edepot.wur.nl/144444.

Chappell, N.A., Jones, T.D., Tych, W., 2017. Sampling frequency for water quality variables in streams: systems analysis to quantify minimum monitoring rates. Water Research, 123, 49-57. https://doi.org/10.1016/j.watres.2017.06.047.

Corrales, J., Naja, G.M., Bhat, M.G., Miralles-Wilhelm, F., 2014. Modeling a phosphorus credit trading program in an agricultural watershed. Journal of Environmental Management, 145, 1-11. https://doi.org/10.1016/j.jenvman.2014.04.01.

Cucarella, V., Mazurek, R., Zaleski, T., Kopeć, M., Renman, G., 2009. Effect of Polonite used for phosphorus removal from wastewater on soil properties and fertility of a mountain meadow. Environmental Pollution, 157(7), 2147-2152. https://doi.org/10.1016/j.envpol.2009.02.007.

Douglas, I., Bidin, K., Balamurugam, G., Chappell, N.A., Walsh, R.P.D., Greer, T., Sinun, W., 1999. The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah. Philosophical Transactions of the Royal Society B, 354, 1749-1761. https://doi.org/10.1098/rstb.1999.0518.

Dudley, B., May, L., 2007. Estimating the phosphorus load to waterbodies from septic tanks. NERC/Centre for Ecology and Hydrology, 45pp. (Unpublished). Available at: https://nerc.openresearcharchive.ac.uk.

Dupas, R., Faucheux, M., Senga Kiessé, T., Casanova, A., Brekenfeld, N., Fovet, O., 2024. High-intensity rainfall following drought triggers extreme nutrient concentrations in a small agricultural catchment. Water Research, 15, 264:122108. https://doi.org/10.1016/j.watres.2024.122108.

Environment Agency, 2019. Phosphorus and Freshwater Eutrophication Pressure Narrative. Environment Agency, England. Available at: https://consult.environment-agency.gov.uk.

Environment Agency, 2022. PR24 WINEP supporting guidance – Permitting of innovative solutions Final draft, Version 0.3. Environment Agency.

Environmental Audit Committee, 2022. Water quality in rivers, Fourth Report of Session 2021–22, HC74, House of Commons, UK. Available at: https://committees.parliament.uk.

Giakoumis, T., Voulvoulis, N., 2019. Water Framework Directive programmes of measures: Lessons from the 1st planning cycle of a catchment in England. Science of the Total Environment, 668, 903-916. https://doi.org/10.1016/j.scitotenv.2019.01.405.

Gyimah, R., Lebu, S., Owusu-Frimpong, I., et al., 2024. Effluents from septic systems and impact on groundwater contamination: a systematic review. Environmental Science and Pollution Research, 31, 62655–62675. https://doi.org/10.1007/s11356-024-35385-1.

Gooday, R.D., Anthony, S.G., Chadwick, D.R., Newell-Price, P., Harris, D., Duethmann, D., Fish, R., Collins, A.L., Winter, M., 2014. Modelling the cost-effectiveness of mitigation methods for multiple pollutants at farm scale. Science of the Total Environment, 468-469, 1198-1209. https://doi.org/10.1016/j.scitotenv.2013.04.078.

Heathwaite, L., & Bieroza, M., 2021. Fingerprinting hydrological and biogeochemical drivers of freshwater quality. Hydrological Processes, 35(1), e14012. https://doi.org/10.1002/hyp.14012.

Jordan, P., Arnscheidt, J., McGrogan, H., & McCormick, S., 2007. Characterising phosphorus transfers in rural catchments using a continuous bank-side analyser. Hydrology and Earth System Sciences, 11(1), 372-381. https://doi.org/10.5194/hess-11-372-2007

Jones, C., Branosky, E., Selman, M., Perez, M., 2010. How Nutrient Trading Could Help Restore the Chesapeake Bay. World Resources Institute, Washington DC. Available at: http://www.wri.org.

Lafortezza, R., Chen, J., Konijnendijk van den Bosch, C., Randrup, T.B., 2018. Nature-based solutions for resilient landscapes and cities. Environmental Research, 165, 431–441. https://doi.org/10.1016/j.envres.2017.11.038.

Liu, L., Dobson, B., Mijic, A., 2022. Hierarchical systems integration for coordinated urban-rural water quality management at a catchment scale. Science of the Total Environment, 806, 150642. https://doi.org/10.1016/j.scitotenv.2021.150642.

Liu, L., Dobson, B., Mijic, A., 2023. Optimisation of Urban-Rural Nature-Based Solutions for Integrated Catchment Water Management. Journal of Environmental Management, 329, 1 March 2023. https://doi.org/10.1016/j.jenvman.2022.117045.

Lu, J., Burton, J., Garzon-Garcia, A., Jackson, C., Newham, M., Bloesch, P., Ramsay, I., Rogers, J., Griffith, M., Saeck, E., Burford, M.A., 2023. Scientific challenges and biophysical knowledge gaps for implementing nutrient offset projects. Journal of Environmental Management, 339, 11790. https://doi.org/10.1016/j.jenvman.2023.117902.

Mindham, D., Beven, K., Chappell, N., 2023. Rainfall-streamflow response times for diverse upland UK micro-basins: quantifying hydrographs to identify the nonlinearity of storm response. Hydrology Research, 54(2), 233-244. https://doi.org/10.2166/nh.2023.115.

Macleod, C.J.A., Scholefield, D., Haygarth, P.M., 2007. Integration for sustainable catchment management. Science of the Total Environment, 373, 591–602. https://doi.org/10.1016/j.scitotenv.2006.12.029.

Malekpour, S., Tawfik, S., Chesterfield, C., 2021. Designing Collaborative Governance for Nature-Based Solutions. Urban Forestry & Urban Greening, 62, 127177. https://doi.org/10.1016/j.ufug.2021.127177.

Mohamad Ibrahim, I.H., Gilfoyle, L., Reynolds, R., Voulvoulis, N., 2019. Integrated catchment management for reducing pesticide levels in water: Engaging with stakeholders in East Anglia to tackle metaldehyde. Science of the Total Environment, 656, 1436–1447. https://doi.org/10.1016/j.scitotenv.2018.11.260.

Natural England, 2022. Nutrient Neutrality Principles. Natural England Technical Information Note TIN186. Available at: http://www.gov.uk/natural-england.

Nguyen, T.A., Le, D.C., Nguyen, T.N., Schmalz, B., Tran, L.L., 2023. Influences of key factors on river water quality in urban and rural areas: A review. Case Studies in Chemical and Environmental Engineering, 8, 100424. https://doi.org/10.1016/j.cscee.2023.100424.

Nikolaidis, N.P., Phillips, G., Poikane, S., Várbíró, G., Bouraoui, F., Malagó, A., Lilli, M.A., 2022. River and lake nutrient targets that support ecological status: European scale gap analysis and strategies for the implementation of the Water Framework Directive. Science of the Total Environment, 813, 151898. https://doi.org/10.1016/j.scitotenv.2021.151898.

Renman, A., 2008. On-site wastewater treatment – Polonite and other filter materials for removal of metals, nitrogen and phosphorus. Doctoral Thesis, Department of Land and Water Resources Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden. Available at: https://www.aquatron.se.

Riddiford, J., 2021. Chapter 9 - Current integrated catchment management policy and management settings in the Murray–Darling Basin. In: Murray-Darling Basin, Australia, Its Future Management, Volume 1 in Ecohydrology from Catchment to Coast, pp. 185-201. https://doi.org/10.1016/B978-0-12-818152-2.00009-7.

Roberts, A.M., Pannell, D.J., Doole, G., Vigiak, O., 2012. Agricultural land management strategies to reduce phosphorus loads in the Gippsland Lakes, Australia. Agricultural Systems, 106(1), 11-22. https://doi.org/10.1016/j.agsy.2011.10.007.

Rollason, E., Bracken, L.J., Hardy, R.J., Large, A.R.G., 2018. Evaluating the success of public participation in integrated catchment management. Journal of Environmental Management, 228, 267–278. https://doi.org/10.1016/j.jenvman.2018.09.024.

Sayer, J., Sunderland, T., Ghazoul, J., Pfund, J.-L., Sheil, D., Meijaard, E., et al., 2013. Ten Principles for a Landscape Approach to Reconciling Agriculture, Conservation, and Other Competing Land Uses. Proceedings of the National Academy of Sciences, 110(21), 8349-8356. https://doi.org/10.1073/pnas.1210595110.

Seto, K.C., Davis, S.J., Mitchell, R., Stokes, E.C., Unruh, G., Ürge-Vorsatz, D., 2016. Carbon lock-in: types, causes, and policy implications. Annual Review of Environmental Resources, 41, 425–452. https://doi.org/10.1146/annurev-environ-110615-085934.

Sharpley, A.N., Wang, X., 2014. Managing agricultural phosphorus for water quality: Lessons from the USA and China. Journal of Environmental Sciences, 26(9), 1770-1782. https://doi.org/10.1016/j.jes.2014.06.024.

Stevens, R. J., & Smith, R. V.,1978. Simulating the effects of land use on streamflow and water quality in the River Basin. Journal of Hydrology, 39(3-4), 321-339. https://doi.org/10.1016/0022-1694(78)90020-9.

Strifling, D., 2018. Integrated Water Resources Management and Effective Intergovernmental Cooperation on Watershed Issues. Mercer Law Review Forthcoming, Marquette Law School Legal Studies Paper No. 18-19. Available at: https://ssrn.com/abstract=3195354.

UKWIR, 2018. Extending and updating UKWIR's pollution source apportionment tool (18/WW/02/9). UKWIR, London, UK.

United Utilities, 2022. Catchment Nutrient Balancing (CNB) Approach: An example for the water industry. United Utilities Plc. Available at: https://www.unitedutilities.com.

Warn, A.E., Brew, J.S., 1980. Mass balance. Water Research, 14, 1427-1434.

Waylen, K.A., Blackstock, K.L., Marshall, K., Juarez-Bourke, A., 2023. Navigating or Adding to Complexity? Exploring the Role of Catchment Partnerships in Collaborative Governance. Sustainability Science, 18(1), 123-137. https://doi.org/10.1007/s11625-023-01387-0.

Whelan, M.J., Linstead, C., Worrall, F., Ormerod, S.G., Durance, I., Johnson, A.C., Johnson, D., Owen, M., Wiik, E., Howden, N.J.K., Burt, T.P., Boxall, A., Brown, C.D., Oliver, D.M., Tickner, D., 2022. Is water quality in British rivers "better than at any time since the end of the Industrial Revolution?" Science of the Total Environment, 843, 157014. https://doi.org/10.1016/j.scitotenv.2022.157014.

Withers, P.J.A., Rothwell, S.A., Ross, K.J., 2024. Managing phosphorus input pressures for improving water quality at the catchment scale. Journal of Environmental Management, 370, 122792. https://doi.org/10.1016/j.jenvman.2024.122792.

Zhang, Y., Collins, A.L., Murdoch, N., Lee, D., Naden, P.S., 2014. Cross-sector contributions to river pollution in England and Wales: Updating waterbody scale information to support policy delivery for the Water Framework Directive. Environmental Science & Policy, 42, 16-32. https://doi.org/10.1016/j.envsci.2014.04.010.