Phosphorus and Water Quality in the Cleddau Catchment

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Executive Summary

The Cleddau catchment is an important area for Welsh agriculture, fisheries, recreation and tourism. The majority of the catchment, and the estuary into which its two main rivers (Western and Eastern Cleddau) flow, is an important Special Area of Conservation (SAC) which is currently in an unfavourable condition due to anthropogenic nutrient enrichment with phosphorus (P) and nitrogen (N). Over 70% of the waterbodies in the catchment are failing the orthophosphate-P target concentrations required for favourable condition of the SAC. Action is needed to reduce the catchment P loading into the Cleddau river network to meet these targets and to provide a clean and healthy water environment for both people and wildlife.

This report summarises research to better understand the sector P input pressures impacting on water quality within the Cleddau catchment in support of a Nutrient Management Plan (NMP) to mitigate P pollution of its waterways and restore favourable condition to the SAC. The study reports on a detailed analysis of sector P use within the Western and Eastern Cleddau catchments to where they join the estuary, assesses the potential impact of sector P input pressure on river P concentrations and flux in different sub-catchments, and the implications for sector P management.

A P Substance Flow Analysis (P-SFA) of the Western and Eastern Cleddau catchments based on agricultural and population census data for 2021 showed that current efficiencies of P use in both the agriculture and wastewater sectors of the catchment food systems is ≤50%. Inefficiencies in P use in the agriculture sector associated with livestock farming generated a high annual agricultural P surplus of unused P of ca. 8.5 kg/ha averaged over the farmed area (excluding rough grazing) in both catchments. Inefficiencies in P recovery in the wastewater sector resulted in effluent P discharges equivalent to ca. 0.23 and 0.09 kg/ha averaged over the catchment areas of the Western and Eastern Cleddau, respectively.

The distribution of agricultural P surpluses and wastewater discharges represent the annual P input pressure on the catchment waterbodies, and will vary more widely in sub-catchments depending on farm type, P inputs, and the location of Wastewater Treatment Works (WwTW). The combined annual P input pressure from both sectors on the whole Cleddau river network (Western and Eastern) amounted to ca. 385 tonnes of P, with the majority (>95%) originating from agriculture. The surplus P input pressure from agriculture was relatively consistent across the sub-catchments in the Western Cleddau catchment at 8-10 kg P/ha, but varied more widely from 6-17 kg P/ha in the Eastern Cleddau sub-catchments. This agricultural P input pressure is variably buffered by the catchment soils.

An analysis of river orthophosphate-P concentrations (assumed to be synonymous with soluble reactive P (SRP)) included both the routine monitoring by National Resources Wales (NRW) since 2000, and more consistent monitoring by the Citizen Science Project (C-CAP) since 2024. Detailed analysis of river P concentration (C) and flow (Q) over a stable 2010-2023 monitoring period found that the majority (>80%) of the river SRP signal at most monitoring stations was associated with diffuse agricultural P inputs during periods of higher flow. Only at three monitoring stations was the river SRP signal dominated by wastewater P inputs.

At monitoring stations dominated by diffuse P inflows from agriculture, annual average river SRP concentrations ranged from 0.04 - 0.07 mg/L in the sub-catchments of the Western Cleddau and from 0.004 - 0.04 mg/L in Eastern Cleddau sub-catchments. Corresponding annual SRP flux (i.e. total river P load) at these diffuse stations ranged from 0.3-0.6 kg P/ha in Western Cleddau and from 0.05-0.5 kg/ha in Eastern Cleddau. The much larger variation in the diffuse P concentration and flux in the Eastern Cleddau river network reflects the contribution from cleaner waters flowing from upland environments with less intensive farming and high river flows. This was responsible for a two-fold difference in mean SRP concentrations between the main Western Cleddau river (0.04 mg/L) and Eastern Cleddau (0.02 mg/L) river over the monitoring period. At monitoring stations dominated by wastewater P inputs, annual average SRP concentrations ranged up to 0.11 mg/L with annual SRP flux of up to 1.0 kg/ha and therefore become more important as pollution sources locally.

Concentrations of TP were generally not routinely monitored except at the two gauging stations at Prendergast Mill and Canaston Bridge. Combining data for these two stations with older data (e.g. 2004-2010) suggested significant contributions of particulate and dissolved organic P in both catchments (TP:SRP ratios of 1.6-4.1), and especially in the Eastern Cleddau river. River TP flux ranged from 0.52-1.25 kg/ha across the Western Cleddau tributaries and main river and from 0.12-1.26 kg/ha across the Eastern Cleddau river network.

When combined with river SRP and TP flux from other livestock dominated catchments, there was a significant (P <0.001) positive non-linear relationship between the annual agricultural P surplus and river SRP flux (r^2 0.55 for Western Cleddau and r^2 0.73 for Eastern Cleddau) and TP flux (r^2 0.59) across sub-catchments. The relationship suggested that up to 5% of the annual agricultural P surplus was lost directly in storm runoff each year, and that up to 60% of the SRP and TP flux from diffuse sources was derived from legacy soil P reserves depending on the amount of the annual P surplus. At the average Cleddau catchment surplus of 8.5 kg P/ha, legacy P accounted for 0.4 kg P/ha of a TP flux of 0.77 kg P/ha.

Estimates of sector source apportionment using the SEPERATE model within the predominant SAC areas of the catchments also support a dominant contribution from agriculture of 83% in the Western Cleddau and 91% in the Eastern Cleddau catchment. This source apportionment is consistent with the results of the CQ analysis which highlighted the predominance of monitoring stations where 80% of the river P flux was derived from diffuse sources. These results highlight the need to reduce the agricultural P surplus in addition to the current programme of enhanced P removal at WwTW. Nutrient footprinting on farms is recommended to identify the range of management options required to redcue the agricultural P surplus.

Continued annual surplus P inputs from agriculture will not only lead to increased direct losses of P in runoff each year but also increase soil P content and P saturation and the loss of soil P in runoff. Climate change will likely exacerbate these losses and this research suggests that reductions in the agricultural P surplus are needed to enable SAC targets for favourable condition to be met. Removing the current average annual agricultural P surplus of ca. 8.5 kg P/ha was estimated to reduce river SRP and TP flux in the Western and Eastern Cleddau by between 40 and 60% over the long-term. These percentage reductions were equivalent to SRP concentration reductions in the agricultural P signal of ca. 0.02 mg/L and 0.01 mg/L in the Western Cleddau and Eastern Cleddau catchments, respectively.

Further research is recommended to:

(a) Undertake a SFA for nitrogen and a further iteration of the P-SFA based on stakeholder feedback in the catchment.
(b) Improve nutrient monitoring programmes across the catchment to better capture the temporal variation and forms of N and P exported in the rivers.
(c) Assess the amounts and distribution of legacy P in the catchment soils and their potential release rates in land runoff during storm events.

Crynodeb Gweithredol

Mae dalgylch y Cleddau yn ardal bwysig ar gyfer amaethyddiaeth, pysgodfeydd, hamdden a thwristiaeth yng Nghymru. Mae’r rhan fwyaf o’r dalgylch, a'r aber y mae dwy brif afon y dalgylch yn llifo iddo, sef y Cleddau Wen a’r Cleddau Ddu, yn Ardal Cadwraeth Arbennig (ACA) o bwys. Nid yw cyflwr yr ACA yn ffafriol ar hyn o bryd, gan fod gweithgaredd dynol (anthropogenig) yn golygu fod ffosfforws (P) a nitrogen (N) yn cyfoethogi maetholion. Nid yw 70% o'r cyrff dŵr yn y dalgylch yn cyrraedd y targed o ran crynodiadau orthoffosffad-P, sy'n ofynnol ar gyfer cyflwr ffafriol yn yr ACA. Er mwyn cyrraedd y targedau hyn ac er mwyn darparu amgylchedd dŵr glân ac iach i bobl a bywyd gwyllt, mae angen gweithredu i leihau’r llwyth P sy’n mynd i mewn i’r rhwydwaith afonydd yn nalgylch y Cleddau.

Mae'r adroddiad gweithredol hwn yn crynhoi’r ymchwil er mwyn sicrhau gwell dealltwriaeth o bwysau’r mewnbwn ffosfforws o fewn y sector perthnasol, sy'n effeithio ar ansawdd y dŵr o fewn dalgylch y Cleddau. Mae’r adroddiad hefyd yn gefnogol i sicrhau Cynllun Rheoli Maetholion (NMP) i liniaru llygredd oherwydd presenoldeb P yn nyfrffyrdd y Cleddau, gan sicrhau fod cyflwr yr ACA yn ffafriol drachefn. O fewn yr astudiaeth, ceir dadansoddiad manwl o ddefnydd ffosfforws o fewn y sector yn nalgylchoedd y Cleddau Wen a’r Cleddau Ddu, hyd at y man lle maent yn ymuno ym Mhwynt Picton. Hefyd, mae’r astudiaeth yn adrodd ar yr effaith posibl gan bwysau mewnbwn P o fewn y sector ar y crynodiadau P a’r fflwcs P sydd yng ngwahanol is-ddalgylchoedd yr afonydd, a'r goblygiadau ar gyfer rheoli P o fewn y sector.

Yn 2021, dangosodd Dadansoddiad Llif Sylweddau (P-SFA) yn nalgylchoedd y Cleddau Wen a’r Cleddau Ddu, mai <50% oedd effeithlonrwydd cyfredol y defnydd o P yn systemau bwyd y dalgylch o fewn y sectorau amaethyddol a dŵr gwastraff. Roedd aneffeithlonrwydd yn y defnydd o P yn y sector amaethyddol sy'n gysylltiedig â ffermio da byw, yn cynhyrchu gormodedd o P amaethyddol bob blwyddyn. Roedd y swm uchel hwn o P nas defnyddiwyd tua 8.5 kg/ha ar gyfartaledd o fewn yr ardal ffermio (ac eithrio pori tir garw) yn y ddau ddalgylch. Roedd aneffeithlonrwydd o ran adfer y P yn y sector dŵr gwastraff yn arwain at ollyngiadau P mewn carthion sy'n cyfateb i tua 0.23 kg/ha ar gyfartaledd yn nalgylch y Cleddau Wen (Gorllewinol) ac i tua 0.09 kg/ha ar gyfartaledd yn nalgylch y Cleddau Ddu (Dwyreiniol).

Mae dosbarthiad y ffosfforws amaethyddol dros ben a gollyngiadau dŵr gwastraff yn cynrychioli'r pwysau mewnbwn P ar gyrff dŵr y dalgylch bob blwyddyn. Amrywia’r dosbarthiad hwn yn fawr yn yr is-ddalgylchoedd, yn dibynnu ar y math o fferm, mewnbynnau P, a lleoliad y Gwaith Trin Dŵr Gwastraff (WwTW). Roedd y pwysau mewnbwn P cyfunol blynyddol o'r ddau sector, ar rwydwaith afonydd y Cleddau, yn cyfateb i tua 385 tunnell o P, ac roedd y mwyafrif (>95%) yn deillio o amaethyddiaeth. Roedd pwysau’r mewnbwn P dros ben o amaethyddiaeth yn gymharol gyson ar draws yr is-ddalgylchoedd yn nalgylch y Cleddau Wen (Gorllewniol), sef 8-10 kg P/ha, ond roedd mwy o amrywiaeth yn is-ddalgylchoedd y Cleddau Ddu (Dwyreiniol), sef 6-17 kg P/ha. Mae'r pwysau sydd yn y mewnbwn P amaethyddol hwn yn cael ei glustogi gan briddoedd y dalgylch.

Roedd dadansoddiad o grynodiadau orthoffosffad-P mewn afonydd (y tybir eu bod yn gyfystyr â ffosfforws hydawdd adweithiol (SRP)) a fflwcs, yn cynnwys y monitro arferol gan Cyfoeth Naturiol Cymru (CNC) ers 2000, a monitro mwy cyson gan y Prosiect Gwyddoniaeth Dinasyddion (C-CAP) ers 2024. Canfu dadansoddiad manwl o grynodiad P yn yr afonydd (C) a llif (Q) dros gyfnod monitro sefydlog rhwng 2010 a 2023, fod y rhan fwyaf (>80%) o ffosfforws adweithiol hydawdd yr afon a welwyd yn y rhan fwyaf o orsafoedd monitro yn gysylltiedig â mewnbynnau P amaethyddol gwasgaredig yn ystod cyfnodau o lif dŵr uwch. Dim ond mewn tair gorsaf fonitro y gwelwyd mai mewnbynnau P dŵr gwastraff oedd y nodwedd amlycaf yn y ffosfforws adweithiol hydawdd. Ar sail y monitro C-CAP, nodwyd fod amrywiad amserol mwy sylweddol yn y crynodiadau ffosfforws adweithiol hydawdd mewn llednentydd, o'i gymharu â monitro gan Cyfoedd Naturiol Cymru mewn safleoedd sy'n gyffredin i'r ddwy raglen.

Mewn gorsafoedd monitro lle mae arwyddion bod ffosfforws amaethyddol gwasgaredig yn dominyddu, roedd y crynodiadau ffosfforws adweithiol hydawdd ar gyfartaledd bob blwyddyn yn yr afonydd yn amrywio o 0.04 -0.07 mg/L yn is-ddalgylchoedd y Cleddau Wen (Gorllewinol) ac yn amrywio o 0.004 -0.04 mg/L yn is-ddalgylchoedd y Cleddau Ddu (Dwyreiniol). Roedd fflwcs y ffosfforws adweithiol hydawdd ar gyfartaledd bob blwyddyn mewn gorsafoedd gwasgaredig yn amrywio o 0.3-0.6 kg P/ha ar y Cleddau Wen (Gorllewinol) ac o 0.05-0.5 kg/ha ar y Cleddau Ddu (Dwyreiniol). Mae'r amrywiad llawer mwy sydd yn y fflwcs ffosfforws gwasgaredig yn rhwydwaith afonydd y Cleddau Ddu (Dwyreiniol) yn adlewyrchiad o gyfraniad y dyfroedd mwy pur sy'n llifo o amgylcheddau amaethu llai dwys ar yr ucheldir, a lle mae llif uwch yn yr afonydd. Roedd hyn yn gyfrifol am ddyblu'r gwahaniaeth yn y crynodiadau ffosfforws adweithiol hydawdd cymedrig rhwng prif afon y Cleddau Wen (Gorllewinol) (0.04 mg/L) a'r Cleddau Ddu (Dwyreiniol) (0.02 mg/L). Mewn gorsafoedd monitro, lle mae mewnbynnau P yn dominyddu yn y dŵr gwastraff, roedd cyfartaledd y crynodiadau ffosfforws adweithiol hydawdd bob blwyddyn yn amrywio hyd at 0.11 mg/L ac roedd cofnodion fflwcs y ffosfforws adweithiol hydawdd bob blwyddyn yn amrywio hyd at 1.0 kg/ha, ac felly mae eu pwysigrwydd fel ffynonellau llygredd ar gynnydd yn lleol.

Yn gyffredinol, ni chafodd crynodiadau o gyfanswm y ffosfforws (TP) eu monitro'n rheolaidd ac eithrio yn y ddwy orsaf fedryddu ym Melin Prendergast a Phont Canaston. Yn dilyn cyfuno data ar gyfer y ddwy orsaf hyn â data hŷn (e.e. 2004-2010), canfuwyd fod cyfraniadau P sylweddol ar ffurf gronynnau a ffosfforws tawdd organig yn y ddau ddalgylch (cymhareb TP:SRP o 1.6-4.1), ac yn enwedig yn afon y Cleddau Ddu (Dwyreiniol). Roedd y fflwcs yng nghyfanswm y ffosfforws yn yr afon yn amrywio o 0.52-1.25 ledled llednentydd a phrif afon y Cleddau Wen (Gorllewinol), ac roedd yn amrywio o 0.12-1.26 ledled rhwydwaith afon y Cleddau Ddu (Dwyreiniol).

Pan gânt eu cyfuno â'r ffosfforws hydawdd adweithiol yn yr afonydd a'r fflwcs yng nghyfanswm y ffosfforws o ddalgylchoedd eraill a ddominyddir gan dda byw, roedd perthynas gadarnhaol arwyddocaol ($P < 0.001$) rhwng y P amaethyddol oedd dros ben bob blwyddyn a fflwcs y ffosfforws hydawdd adweithiol yn yr afonydd (r^2 0.55 ar gyfer y Cleddau Wen ac r^2 0.73 ar gyfer y Cleddau Ddu) â fflwcs cyfanswm y ffosfforws (r^2 0.59) ledled yr is-ddalgylchoedd. Mae'r berthynas hon yn awgrymu fod hyd at 5% o'r P amaethyddol oedd dros ben bob blwyddyn yn cael ei golli'n uniongyrchol mewn dŵr ffo stormydd, a bod hyd at 60% o fflwcs y ffosfforws hydawdd adweithiol a chyfanswm y ffosfforws o ffynonellau gwasgaredig yn deillio o gronfeydd P mewn pridd etifeddol, a bod hyn yn dibynnu ar swm y P oedd dros ben. Pe ystyrir fod y swm dros ben ar gyfartaledd yn nalgylch y Cleddau yn 8.5 kg P/ha, roedd y P etifeddol yn cyfrif am 0.4 kg P/ha o'r fflwcs yng nghyfanswm y ffosfforws, sef 0.77 kg P/ha.

Mae amcangyfrifon o ddosraniad ffynhonnell y sector, gan ddefnyddio'r model SEPERATE o fewn prif ardaloedd ACA'r dalgylchoedd hefyd yn nodi cyfraniad amlwg gan amaethyddiaeth, sef 83% yn nalgylch y Cleddau Wen (Gorllewinol) a 91% yn nalgylch y Cleddau Ddu (Dwyreiniol). Mae'r canlyniadau hyn yn tynnu sylw at yr angen i leihau'r P amaethyddol sydd dros ben, yn ogystal â'r rhaglen gyfredol o gael gwared â P yn well yn y Gwaith Trin Dŵr Gwastraff (WwTW).

Bydd y mewnbynnau P dros ben parhaus sy'n deillio o amaethyddiaeth bob blwyddyn, nid yn unig yn arwain at golledion P uniongyrchol a chynyddol yn y dŵr ffo bob blwyddyn, ond hefyd bydd swm y P yn y pridd a dirlawnder y P yn cynyddu, a hefyd bydd P yn dianc yn y dŵr ffo. Mae'n debygol y bydd newid yn yr hinsawdd yn gwaethygu'r colledion hyn ac mae'r ymchwil hwn yn awgrymu bod angen gostyngiadau yn y P amaethyddol sydd dros ben, i alluogi cyrraedd y targedau er mwyn sicrhau cyflwr ffafriol o fewn yr ACA. Amcangyfrifir y bod cael gwared ar y P amaethyddol cyfartalog bob blwyddyn, sef tua 8.5 kg P/ha ar hyn o bryd, wedi arwain at leihau'r fflwcs yn y ffosfforws hydawdd adweithiol a'r fflwcs sydd yng nghyfanswm y P ar gyfran fyddai rhwng 40 a 60% yn afonydd y Cleddau Wen a'r Cleddau Ddu. Roedd y gostyngiadau canrannol hyn yn cyfateb i ostyngiad yng nghrynodiad y ffosfforws hydawdd adweithiol yn swm y ffosfforws amaethyddol dros gyfnod o amser o tua 0.02 mg/L yn nalgylch y Cleddau Wen (Gorllewinol)a gostyngiad o 0.01 mg/L yn nalgylch y Cleddau Ddu (Dwyreiniol).

Argymhellir ymchwil pellach er mwyn gwneud y canlynol:
a. Cynnal Dadansoddiad Llif Sylweddau ar gyfer nitrogen (N) ac ailadrodd pellach o'r P-SFA yn seiliedig ar adborth rhanddeiliaid yn y dalgylch.
b. Gwella rhaglenni monitro maetholion ledled y dalgylch, er mwyn cael gwell cofnodion o'r amrywiad amserol a ffurf yr N a'r P sydd yn yr afonydd.
c. Asesu'r symiau a dosbarthiad y P etifeddol ym mhriddoedd y dalgylch a'u cyfraddau rhyddhau posibl mewn dŵr ffo o'r tir yn ystod stormydd.

Glossary

P – Elemental Phosphorus.

Agricultural soil P efficiency – the ratio of crop P offtake (grass and arable) to crop P inputs (fertilisers, manures and biosolids) expressed as a percentage.

Agricultural P surplus – the difference between what P is added (inorganic fertilisers, manures, slurries and biosolids) to the agricultural soil surface (total area of managed crops and grassland excluding rough grazing land), and what P is removed in harvested crops and grass (kg/ha/yr).

Baseflow Index (BFI) – a measure of the proportion of the annual river flow that derives from groundwater stores and assessed on a scale of 0-1. Low values represent impermeable landscapes and high values represent permeable landscapes.

Catchment P efficiency - the ratio of total catchment P imports to catchment P exports expressed as a percentage.

CQ analysis – a form of analysis which looks at the relationship between measured nutrient concentrations (C) and the rates of river flow (Q) to help describe nutrient behaviour and potential source attributions within a waterbody.

CSOs – Combined Storm Overflows. This term encompasses P discharge from combined sewer overflows (CSOs), pumping stations and storm tanks.

Food system P use efficiency - the ratio between the P in useful products produced (agricultural and food P exports plus local food consumed divided by total catchment P imports) expressed as a percentage.

GES – Good Ecological Status.

NAPI – Net Anthropogenic Phosphorus Inputs – the net P input pressure from farming and the human population exerted on the entire catchment area (kg/ha/yr).

Nutrient Neutrality - the term used to refer to a requirement that additional development (e.g. housebuilding) does not increase the net nutrient loading to water (i.e. has a neutral impact).

River P flux – the amount of P export from the river calculated as the product of the mean annual flow over a given area (usually the catchment outlet), and the annual average flow-weighted P concentration.

SFA – Substance Flow Analysis - modelling approach to map stocks and flows of phosphorus within a defined food system.

Secondary P resources – the term used to describe those P inputs into the food system which are derived from recycled materials rather than from rock phosphate directly.

SRP – Soluble Reactive Phosphorus – the soluble fraction of inorganic P in the water column measured by colorimetry on a 0.45 μm filtered water sample. Assumed here to be synonymous with 'orthophosphate' as routinely measured in water by Natural Resources Wales (NRW), and the form of P used in target setting for 'Good Ecological Status' under the Water Framework Directive (WFD), Sites of Special Scientific Interest (SSSIs) and Special Areas of Conservation (SACs).

TP – Total Phosphorus – all inorganic and organic fractions of P in the water column measured by acid digestion and colorimetry. This is the form of P used in target setting for favourable condition of the Ramsar by Natural England.

WFD – Water Framework Directive.

WwTW – Wastewater Treatment Works (also known as Water Recycling Centres).

1. Introduction

The Western and Eastern Cleddau catchments are important agricultural, fisheries, recreational and conservation areas in south-West Wales with a vibrant rural community and tourist economy. The two main rivers (Eastern Cleddau and Western Cleddau) flow into the ecologically important Daugleddau estuary that enters the large natural harbour and port at Milford Haven. A healthy and clean water environment is critical for the biodiversity of their natural habitats, fishing, tourism, the rural economy and the provision of potable water to the area. Nutrient (phosphorus (P) and nitrogen (N)) pressures in the catchment continue to cause concern for the freshwater and marine Special Areas of Conservation (SAC). Over 70% of assessed waterbodies failed to achieve the P targets required to restore favourable condition to features of the freshwater SAC (Hatton-Ellis and Jones, 2021). The effects of climate change will likely exacerbate nutrient enrichment of these protected areas in the future, and actions are needed to reduce these P and N input pressures to improve the state of the water environment and help restore the status of the SACs and supporting Sites of Special Scientific Interest (SSSIs).

In addition to the River Basin Management Plan (RBMP) required under the Water Framework Directive (WFD), the stakeholders in the catchment recognise the need to address nutrient pollution in the Cleddau waterways and are actively supporting the development of a Nutrient Management Plan (NMP) to lower river P concentrations to target levels (Arcadis, 2025). The plan is designed to identify the sources of excess nutrients, calculate the P load reductions necessary to comply with the SAC targets and outline the opportunities to remove the excess nutrients. This study was commissioned by The Cleddau Project and the Western Wales Nutrient Management Board to better understand the sector P input pressures impacting the Western and Eastern Cleddau freshwaters (i.e. excluding coastal streams draining to the estuary, and their effect on source discharges of P into the rivers. This understanding will better enable the development of coherent management policies and practical mitigation solutions to tackle the causes of water P pollution as part of the NMP.

To better define the contributions of the two main food system sectors (agriculture and human wastewater) responsible for freshwater P pollution in the Western and Eastern Cleddau rivers, the study investigated how the magnitude and distribution of sector P input pressures in the Western and Eastern Cleddau catchments calculated using Substance Flow Analysis (SFA) linked to the river P concentrations and flux and the implications for future management of P in the catchment. More specifically the objectives of the study were to:

(a) analyse the current sector inputs, outputs and internal flows of P associated with the production and consumption of food within the Western Cleddau and Eastern Cleddau catchments.

(b) examine how these current sector P input pressures influence river P concentrations and flux across the catchments.

(c) appraise the implications for future management of P in the catchments and make recommendations to improve the evidence base to justify mitigation options.

1.1 The Cleddau catchment study area

The Western Cleddau (313 km^2) and Eastern Cleddau (230 km^2) catchments in Pembrokeshire, south-West Wales flow into the Daugleddau estuary. The Western Cleddau river has its source at Llangloffan Fen and flows for 30 km to the estuary, whilst the Eastern Cleddau river flows for 26 km from its source in the Preseli Hills. The Eastern Cleddau catchment has a small artificial reservoir (Rosebush), and a large reservoir (Llys-y-Fran) that supplies potable water for west Prembrokeshire and/or for amenity tourism. Parts of the catchment are underlain by a groundwater aquifer and water is abstracted at Canaston Mill (Eastern Cleddau) and Crowhill (Western Cleddau) to provide a source of potable water for south Pembrokeshire and also for industry and agriculture. During low flow periods, water from the Llys-y-Fran reservoir in the Eastern Cleddau catchment supports the annual water abstraction at Canaston (ca. 0.04 m^3/s). Annual rainfall is high ranging from ca. 1700 mm in the Preseli Hills to ca. 1100mm in the lowlands. The Baseflow Index of river flow is 0.55 (Eastern Cleddau) and 0.63 (Western Cleddau), which signifies that ca. 60% of the annual river flow is derived from water infiltrating the landscape to groundwaters rather than in surface runoff (Marsh and Hannaford, 2008).

A total of 8 study sub-catchments were identified based on the location of the three gauging stations (Treffgarne, Prendergast Mill and Canaston Bridge) and an analysis of the catchment river P record, which suggested lower P signals from the Preseli Hills in the north-East and the area around the Lys-y-Fran reservoir in the north West of the Eastern Cleddau catchment (Figure 1). Three sub-catchments in the Western Cleddau included the area above Treffgarne (Treffgarne), the area above Prendergast Mill (Prendergast Mill) and the area of the whole Western Cleddau (Western Cleddau). The four sub-catchments in the Eastern Cleddau catchment included the upstream area above the confluence with the Afon Rhyd-afallen in the north-East (Glancleddau), the area of the Syfynwy tributary above the junction with the Ty-Llosg Brook which includes the Lys-y-Fran reservoir (Lys-y-Fran), the area above Canaston Bridge (Canaston Bridge) and the whole of the Eastern Cleddau catchment (Eastern Cleddau). An additional sub-catchment that represents the area below the Glancleddau and Lys-y-Fran sub-catchments to Canaston Bridge was derived (Lower Canaston). The whole Cleddau catchment was taken as the combined area of the Western Cleddau and Eastern

Cleddau sub-catchments (Whole Cleddau). The Western Cleddau and Eastern Cleddau sub-catchments extend below the tidal limit at Haverfordwest and Canaston, respectively.

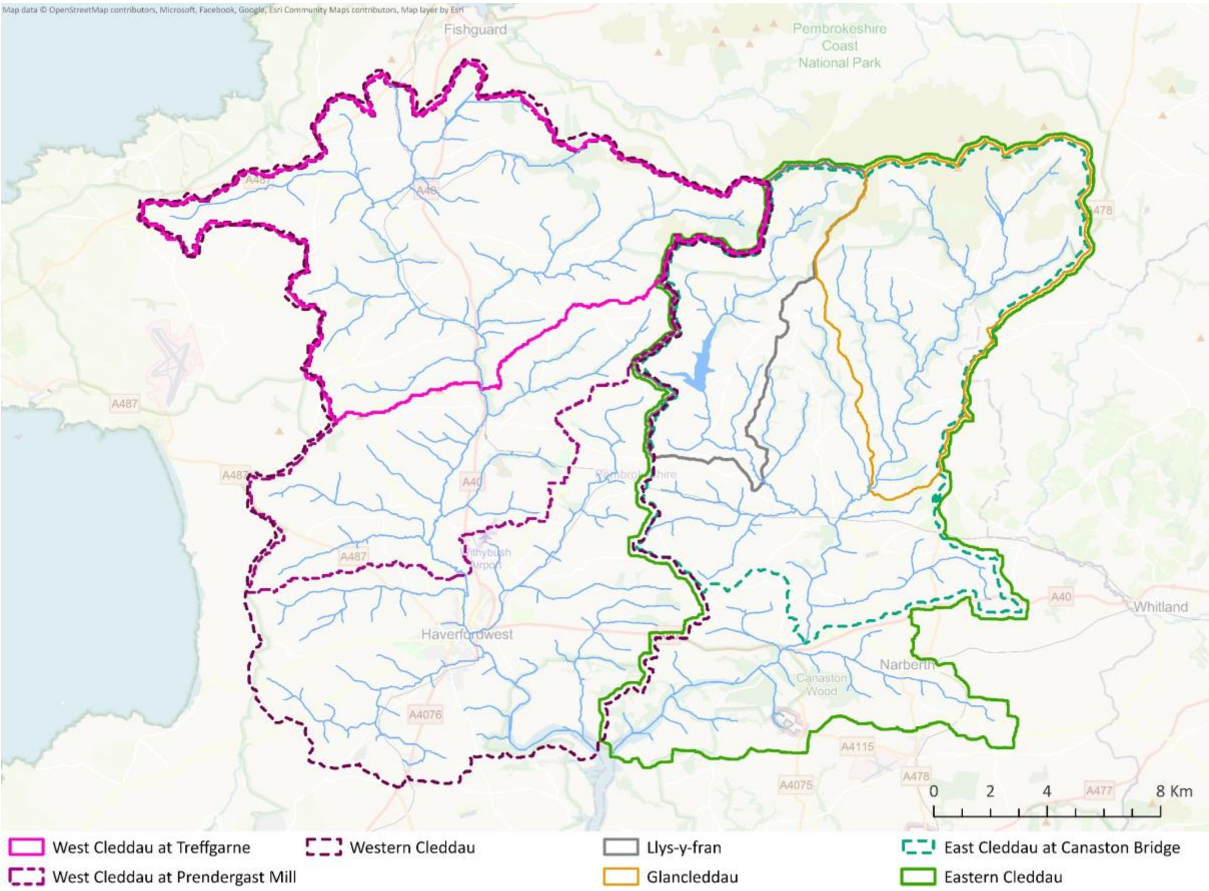

Figure 1. Sub-catchment study areas in the Cleddau catchment. Note: boundaries have been offset for display purposes only. The sub-catchments are not discrete and are nested.

1.1.1 Landscape, soil types, agriculture and population

The catchments of both rivers are largely underlain by Cambrian and Ordovician sandstones, siltstones and shales. Soil types are largely well drained or seasonally waterlogged clay-rich brown earths of fine loamy and fine silty textures and variable depth to rock (Manod, Denbigh and Moorgate Associations). Smaller pockets of more impermeable soils occur locally, peaty soils in the Preseli Hills and heavy alluvial soils bordering the rivers. The landscape is a predominantly low rolling hills except in the headwaters of the Eastern Cleddau where the river is more turbulent as its flows through narrow wooded valleys (National Resources Wales, 2016).

The Eastern Cleddau and Western Cleddau rivers form part of the Cleddau Rivers Special Area of Conservation (SAC), which covers an area of 752 ha ending near the Haverfordwest town weir (Western Cleddau) and Blackpool Bridge (Eastern Cleddau).

Table 1. Agricultural land use, livestock (Welsh Government 2021) and human population (ONS, 2021) in the Cleddau sub-catchments.

Land use in hectares	Western Cleddau	Treffgarne	Prendergast Mill	Eastern Cleddau	Llys-y-fran	Glancleddau	Canaston Bridge
Cereals	2702	1261	1821	930	88	77	414
Other arable (including horticulture and stockfeed)	2015	1207	1635	600	56	34	171
Temporary grass	4208	1536	2908	2630	283	491	1594
Permanent grass	17262	7612	11386	15282	3655	4385	12986
Rough grazing	954	580	731	909	32	766	837
Total sub-catchment area	31260	12636	19783	23057	3978	7045	18187
Livestock numbers							
Total cattle	43792	20779	31829	29392	6204	4195	25422
Total sheep	34297	17620	26172	49516	16121	18899	44142
Total poultry	106000	25000	79000	1086	91	560	1028
Total pigs	317	101	299	54	N/A	N/A	49
Total other animals	706	224	491	692	N/A	N/A	622
Human population	25279[1]	3810	6363	7033	651	1406	4477

[1] The human population in the Western Cleddau includes the large urban conurbation of Haverfordwest, the wastewater effluent of which is treated and discharged at Merlins Bridge into the upper reaches of the tidal Western Cleddau.

At these points the freshwater Cleddau Rivers SAC meets the estuarine portion of the Pembrokeshire Marine SAC, a large marine designation covering 138,069 ha. Whilst the SACs do not overlap they do share some conservation features (river and sea lamphey and otter). In addition to the SAC designations, the foreshore within the SACs is also a Special Site of Scientific Interest (SSSI) and much of the land area surrounding the estuary is within the Pembrokeshire Coast National Park.

Approximately 75% of the land use is permanent and temporary grassland supporting mostly dairy and to a lesser extent sheep farming (Table 1). The agricultural census data indicates that dairy farming accounts for over 40% of the farmed area in both catchments, although the proportion may be as high as 55% including all rented land on dairy farms. Smaller pockets of arable crops (potatoes, maize and cereals) are grown on the more permeable soils largely in the south and Western of the catchments. Agriculture in the Cleddau catchment makes a major contribution to Welsh food production, especially milk (Pembrokeshire produces 25% of all Welsh milk) and potatoes (50% of Welsh potatoes), (National Resources Wales, 2016).

A relatively small rural population is boosted by large numbers of tourists in summer. Visitors to Pembrokeshire have been estimated at 6.3 million (Pembrokeshire County Council, 2025). Haverfordwest in the Western Cleddau catchment is the main urban centre with smaller populations at Narberth, Clynderwen, Letterston, Keeston, and Wolfscastle. There are 7 WwTW in the Eastern Cleddau catchment and 13 in the Western Cleddau catchment, supplemented by numerous permitted wastewater discharges (Figure 2). Apart from Haverfordwest, the majority of the WwTW are small.

1.1.2 SAC compliance and phosphorus targets

The SAC is currently in an unfavourable condition. All monitored areas of the Western Cleddau and two areas of the Eastern Cleddau within the SAC are failing to achieve P targets for compliance (Hatton-Ellis and Jones, 2021; National Resources Wales, 2022). Annual average target orthophosphate-P concentrations for the freshwater SAC range from 0.010-0.015 mg/L in headwaters to 0.040 mg/L downstream. Recent monitoring since 2021 suggest further deterioration with only 28% of assessed waterbodies achieving their P targets (Natural Resources Wales, 2024; Arcadis, 2025). A nutrient neutrality ruling is currently in place to protect the declining SAC condition by prohibiting any development in the catchment area that increases net P loads entering the river network (Natural Resources Wales, 2026a).

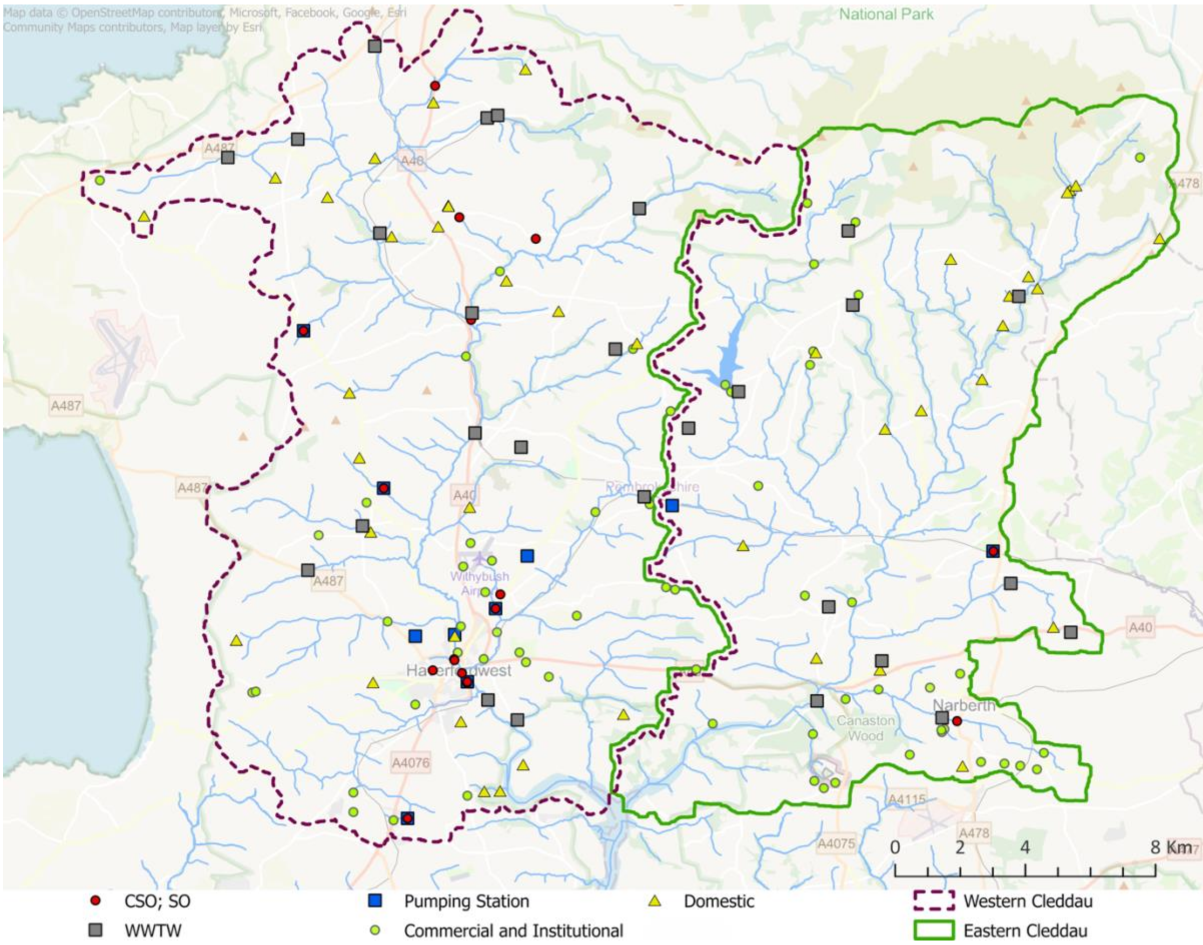

Figure 2. Locations of Wastewater Treatment Works (WwTW), Combined Sewer Overflows (CSO) and Sewage Overflows (SO), Pumping Station, Domestic and other Commercial and Institutional wastewater sources in the Western and Eastern Cleddau catchments (Welsh Water, 2024). Contains Natural Resources Wales information © Natural Resources Wales and database, all rights reserved. Note: catchment boundaries have been offset for display purposes only.

2. Understanding sector P use in the catchments

2.1 Methods

2.1.1 Substance Flow Analysis (SFA)

To provide understanding of how the local food system utilises P, Substance Flow Analysis (SFA) was performed for Western and Eastern Cleddau catchment areas for 2021, which was taken as a baseline year using the latest available census information. The model is produced using STAN software (Cencic and Rechberger., 2008) which applies data reconciliation and error propagation to balance the model according to assigned uncertainty of the data. A conceptual figure illustrating the SFA approach is shown in Figure 3. Uncertainty of data flows was assessed using the systematic approach described by Zoboli et al., (2016). Data for the model included the last detailed Welsh

Government agricultural census data (Welsh Government, 2021) and established crop and livestock coefficients from various sources including national Defra and industry data as detailed in Rothwell et al., (2020, 2022) and local expert knowledge. All flows in the model are presented as tonnes of elemental P per year.

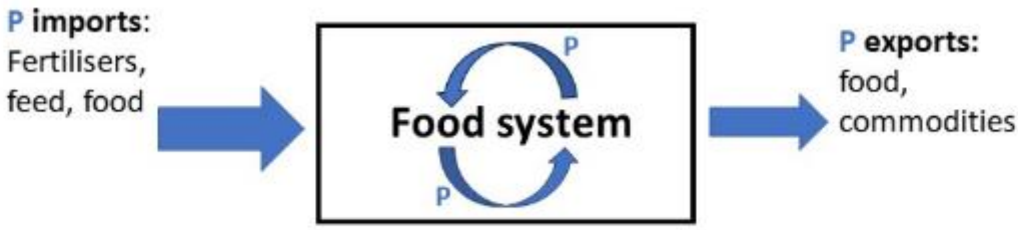

Figure 3. A simple conceptual Substance Flow Analysis (SFA) figure. The SFA assesses the imports, flows, stocks and exports of a particular material (in this case phosphorus (P)) from a defined system using a mass balance approach.

Annual average crop P offtake across the catchments was calculated using crop area census data for ‘cereals’, ‘stockfeed’ (assumed to be predominantly maize) and ‘other arable’ crops (assumed to predominantly potatoes), (Welsh Government, 2021). Locally agreed average cereal crop yield coefficients of 8.5 t/ha for winter wheat, 7 t/ha for winter barley and 5 t/ha for spring barley were used along with established Defra average yields and crop P offtake coefficients (Rothwell et al., 2022). The crop offtake flow includes all crops other than grass that are grown for human or livestock consumption, i.e. it includes all maize, whole crop, and fodder crops grown for livestock, as well as arable and horticultural crops. Seventy percent of cereal grain grown in the catchment was assumed to stay in the catchment as livestock feed based on local intelligence.

Grass P offtake was determined from the census grassland area, yields of temporary and mixed species permanent grass agreed with local consultation, established rough grazing yields (Haygarth et al., 1998) and grass P offtake coefficients (Rothwell et al., 2022). Agreed annual grass DM yields were 8, 6.5 and 5 t DM/ha for temporary and permanent and Less Favoured Area (LFA) grazed grass, respectively for a catchment wide average. Higher average annual yields of 11.5 and 8.5 t DM/ha for temporary and permanent grass, respectively were considered more relevant when calculating P flows for the dairy sector alone. Grass P offtake in all systems assumed 80% utilization established from industry recommendation (Rothwell et al., 2022). Grass production from the census area of rough grazing in each catchment assumed a utilization of 25% (Haygarth et al., 1998).

Livestock product P (meat as animal live weight, exported livestock, milk, and eggs) was estimated using the livestock population census data (Welsh Government, 2021) and meat and egg production coefficients established from Rothwell et al. (2022). Milk yields were agreed locally to represent the range of production methods present in the catchments. Highest average milk yields per cow in the most intensive all year round (AYR) herds were 13250 l/yr, less intensive AYR herds 10500 l/yr and all other non-intensive herds 7500 l/yr.

Livestock manure P excretion was calculated from the census livestock population data and established Defra livestock manure excretion coefficients (Rothwell et al., 2022) apart from dairy cows which were adjusted according to the average milk yield (AFBI, 2024). Livestock P excretion represents manure both deposited directly during grazing and spread from housed animals. Local information identified a net export of manure of around 5% from the catchment areas which is represented in the model.

Livestock feed P inputs and feed P content for the dairy, beef and sheep sectors were established from local consultation. Intensive AYR dairy cows were each assumed to consume 4.25 t/yr DM/cow from imported concentrate (normally purchased) feed, non-intensive dairy cows 2 t/yr DM, all other cattle 0.6 t/yr DM and calves 0.1 t/yr DM. Ewes were each assumed to receive 0.025 t/yr DM and lambs 0.015 t/yr DM. Feed P concentration was taken as 0.47% for dairy cows and 0.45% for all other concentrate feed. Pig and poultry feed was estimated by balance i.e. the P consumed in feed must equal the P excreted in manure and agricultural product (meat and eggs). There is believed to be an import of maize forage into the catchment, and this was estimated to be equivalent to 50% of the maize grown within the catchment areas.

Agricultural P exports from the catchment area are a combination of all livestock products, and all arable and horticultural crops grown for food and feed, assuming 70% of produced grain stays in the catchment for livestock feed and 10% of the food consumed by the human population is assumed to be produced within the catchment area.

Annual average fertiliser P inputs were determined from the census crop areas and average regional (Wales) P fertiliser rates for arable crops and maize from the British Survey of Fertiliser Practice (Defra, 2024). Grass fertiliser P input rates were estimated from local information and set at an overall average application rate of 7 kg/ha P across all temporary and permanent grass.

As the SFA is a nutrient balancing model it does not predict P losses to water directly. The P losses to water must be estimated independently and added to the SFA as an export flow. Diffuse losses of P to water assuming some current mitigation were estimated from the SEPERATE model (Zhang et al., 2014).

Food and detergent P imports were determined from 2021 population census data and various per capita coefficients. Food P import was estimated from a daily human intake of 1.35 g P/day (Forber et al., 2020), with an assumed 10% of food coming from food produced in the catchment area. Per capita coefficients derived from Rothwell et al. (2022) were used to estimate P imported in detergents (some dishwasher tablets still contain P after 'The Detergents (Amendment) Regulations 2016'), and P added to drinking water for plumbosolvency. Food waste P is taken as 17% of purchased food (WRAP, 2020) and is assumed to leave the catchment.

Discharge of P to water courses from WwTW was estimated using three different methods in order to cross reference the estimate used for the SFA (Method 1). Method 1 used the P pressure from the human population (food, detergent and plumbosolvency) connected to WwTWs and their efficiency of P removal. Population estimates were calculated using codepoint (postcode) 2021 Census data (ONS, 2021) in ArcGIS Pro for each of the study sub-catchments. Geolocated data for each WwTW was used to identify which works fell within each sub-catchment in ArcGIS Pro. The proportion of the population connected to WwTWs was estimated by the difference in population and person equivalent (PE) capacity of the works, the remaining population was assumed to be connected to private package treatment works or septic tanks.

Dietary intake of P per person in the UK is 1.35 g P/day (Forber et al., 2020), plus detergent and plumbosolvency (0.263 g/pp/day) and multiplied by the population gives the total P pressure entering the works from the human population (scaled to a year). Each WwTW had a known PE capacity and P removal efficiency which was either: Secondary Biological (SB), Secondary Activated Sludge (SAS), or SB with chemical dosing (CPhos) (Event Duration Monitoring Annual Returns data 2024 (Welsh Water, 2024), and SAC proposed P limits data 2023 (Welsh Water, 2023)) (Table 2). Using data from Naden et al. (2016), SB and SAS technologies were assessed as having an average 58% removal capacity of P, and SB/CPhos works an average of 84% removal capacity of P. Therefore, using geolocated data the total PE and proportion of PE which was served by works with either 58% or 84% removal capacity of P was known in each sub-catchment. This method estimated a total of 6.73 t P/yr was lost from WwTWs across the Western and Eastern Cleddau catchments.

Method 2 estimated loss of P to water from WwTWs by multiplying dietary intake and detergent and plumbosolvency, by the PE, accounting for the proportion of PE which was served by works with either 58% or 84% removal capacity of P in each sub-catchment. This method estimated 8.74 t P/yr was lost from WwTWs, this higher estimate will probably account for industry discharges which could not be quantified by any other means, or additional population pressure from seasonal tourists.

Method 3 estimated total P exiting WwTWs by using measured TP outflow data provided by Natural Resources Wales (NRW) water quality archives (Natural Resources Wales, 2026b). Measured data were available at 14 of the 17 works but the frequency of monitoring was only approximately monthly with variable date ranges. Average outflow TP values were multiplied by Dry Weather Flows (DWF) values (no measured flow data were available) for each works to give an estimate of TP load exiting works. Current permit data were used where measured TP data was not available for specific works. This method estimated 6 t P/yr was lost from WwTWs.

Table 2. Current estimates for the number of Wastewater Treatment Works (WWTW), person equivalent (PE) totals of works, population connected to sewers (%), and phosphorus (P) removal percent of works in each sub-catchment. Secondary works are those works with secondary biological or secondary activated sludge treatments; tertiary works are those with chemical dosing for the removal of P.

Catchment	number of works (WWTW)	total pe	% population connected to sewers	percent of pe with secondary P (58%) removal	percent of pe with tertiary P removal (84%) removal
Llys-y-fran	3	215	33	100	0
Glancleddau	0	0	0	0	0
Canaston Bridge	6	1995	45	19.5	80.5
Eastern Cleddau	7	7499	90	78.6	21.4
Treffgarne	6	2356	62	100	0
Prendergast Mill	11	3617	57	100	0
Western Cleddau	13	21669	86	100	0

Estimated P loss from combined sewer overflows (CSO), storm tank overflows and septic tanks were taken from the SEPERATE model (Zhang et al., 2014). Total losses from the Wastewater process represented in the catchment SFA models are therefore the combined losses from WwTW (Method 1), CSO, storm tanks and septic tanks.

All biosolids from WwTW are removed from the catchment and some are returned as anaerobic digestate and spread on agricultural land. Local biosolid P input to agriculture was estimated from local information on the volume of biosolids returning to the whole catchment (3125 t) and distributed to the Western and Eastern Cleddau catchments proportional to the area of arable and maize in each catchment.

2.1.2 Sub-catchment P surpluses

Agricultural P surpluses were also calculated for each of the study sub-catchments (Figure 1) using the same approach as the SFA employing livestock and crop census data specific to the sub-catchment areas. The same yield coefficients for grass, crops and livestock excretion were used except for the Glancleddau sub-catchment where grass yields in the more upland farming systems were reduced to 6.5 and 5 t/ha/yr DM for temporary and permanent grass, respectively. The agricultural P surplus was calculated as total P input (manure, fertiliser and biosolids) minus the total P offtake (grass and crops), normalised for the productive agricultural area excluding rough grazing. Combining the net human P pressure from wastewater, which in this case is the P discharged to watercourses, with the agricultural P balance gives the total Net Anthropogenic Phosphorus Inputs (NAPI). NAPI there represents the total P input pressure on Cleddau waterbodies and was calculated for each sub-catchment and for the Western and Eastern Cleddau catchments.

2.1.3 System indicators

To allow comparisons of food system P performance between the two catchments, a suite of system indicator metrics for the two main sectors (agriculture and wastewater) that make up the food system were calculated from the SFA output in each catchment. These metrics included assessment of sector P efficiency and sector P input pressure as well as their proportional losses to water. The P input pressure from agriculture was defined as the annual agricultural P surplus and that from wastewater as the P discharged each year directly to water including P discharge from WwTW, septic tanks, CSOs and storm tanks. The combined P input pressure from both agriculture and wastewater was defined at the Net Anthropogenic P Input (NAPI).

2.1.3 Limitations

Calculating SFA flows at the catchment scale can be challenging, particularly when extrapolating data from national or larger scales to the catchment level. Census data can become more unreliable at smaller scales, and for this study, was provided at very coarse resolution, particularly for the cattle population. Consequently, local information was needed to estimate a distribution of the census data into cattle livestock classes present in the catchment. The poor quality of the census data provided by Welsh Government and the need to introduce local extrapolation introduces unavoidable uncertainty. Similarly, estimating annual average grass yields is challenging as these are typically not recorded unlike arable yields. Considerable effort was made with local expert knowledge to accurately represent typical average grass yields in the catchment and ultimately the values used worked in the SFA models following the principle of mass balance. However again, some uncertainty in those values is unavoidable. There are likely to be undocumented movements of materials across catchment boundaries that are not captured in official statistics, though it is assumed that all the major flows related to the food system are captured in these SFAs. These SFAs therefore represent our best current understanding of P flows into, out of, and within the food systems of the Western and Eastern Cleddau catchments. As better input data becomes available further iteration of the SFA outputs will provide more accurate assessment.

2.2 SFA outputs

2.2.1 Baseline SFA results

The SFA baseline model outputs in Figures 4 and 5 shows that the food system of the Western and Eastern Cleddau catchments imported a total of 521 and 314 t P/yr, respectively. The largest import was in livestock feed at 264 and 158 t P/yr, respectively which represents around half of the food system P imports for both catchments (Table 3). Phosphorus in fertiliser was the second largest import at 217 and 144 t P/yr, respectively and represents 42% of total P imports in the Western Cleddau catchment and 46% of imports in the Eastern Cleddau catchment (Table 3). Other P imports include biosolids returning to the catchment for agricultural application (11 and 4 t P/yr, respectively); maize imported for fodder (13 and 5 t P/yr); and P in food and detergents consumed by the local population (15 and 4 t P/yr).

Total catchment P exports, excluding any system P losses to water, were 293 and 152 t P/yr for the Western and Eastern catchments, respectively and dominated by agricultural products as would be expected in a productive agricultural area. The P in these products (milk, meat, eggs, livestock and crop products) totalled 261 and 134 t P/yr, respectively. Smaller P exports include biosolids, manure, and food waste which totalled 33 and 18 t P/yr. The conversion of total P imports into P in consumed food and agricultural products gives overall catchment food system P efficiencies of 50% and 43% for the Western and Eastern catchments, respectively (Table 3). By way of comparison the catchment P efficiencies in similar livestock dominated catchments of the Blackmore Vale (Stour), Wye and the Somerset Levels and Moors rivers were respectively 50%, 66%, and 58%, with the higher values reflecting a higher proportion of arable land.

The largest internal P flow in both catchments was livestock manure at 475 and 326 t P/yr, respectively which combined with the fertiliser and biosolid inputs give total agricultural P inputs of 703 and 473 t P/yr for the Western and Eastern Cleddau catchments. Cut and grazed grass was the largest harvested offtake in both catchments removing 333 and 269 t P/yr, respectively which combined with crop offtakes of 149 and 44 t P/yr gives total agricultural offtakes of 482 and 313 t P/yr. The balance between agricultural P input and P offtake gives annual agricultural P surpluses of 221 and 161 t P/yr for the Western and Eastern catchments respectively, which averages out at 8.4 and 8.3 kg P/ha/yr over the productive arable and grassland area (excluding rough grazing) (Table 3). This is higher than the UK national average of 5.7 kg/ha/yr for 2021 (Defra 2022) and similar to P surplus values of 9.3, 8.3 and 6.5 kg/ha/yr for the Blackmore Vale (Stour), Wye and Somerset Levels and Moors catchments.

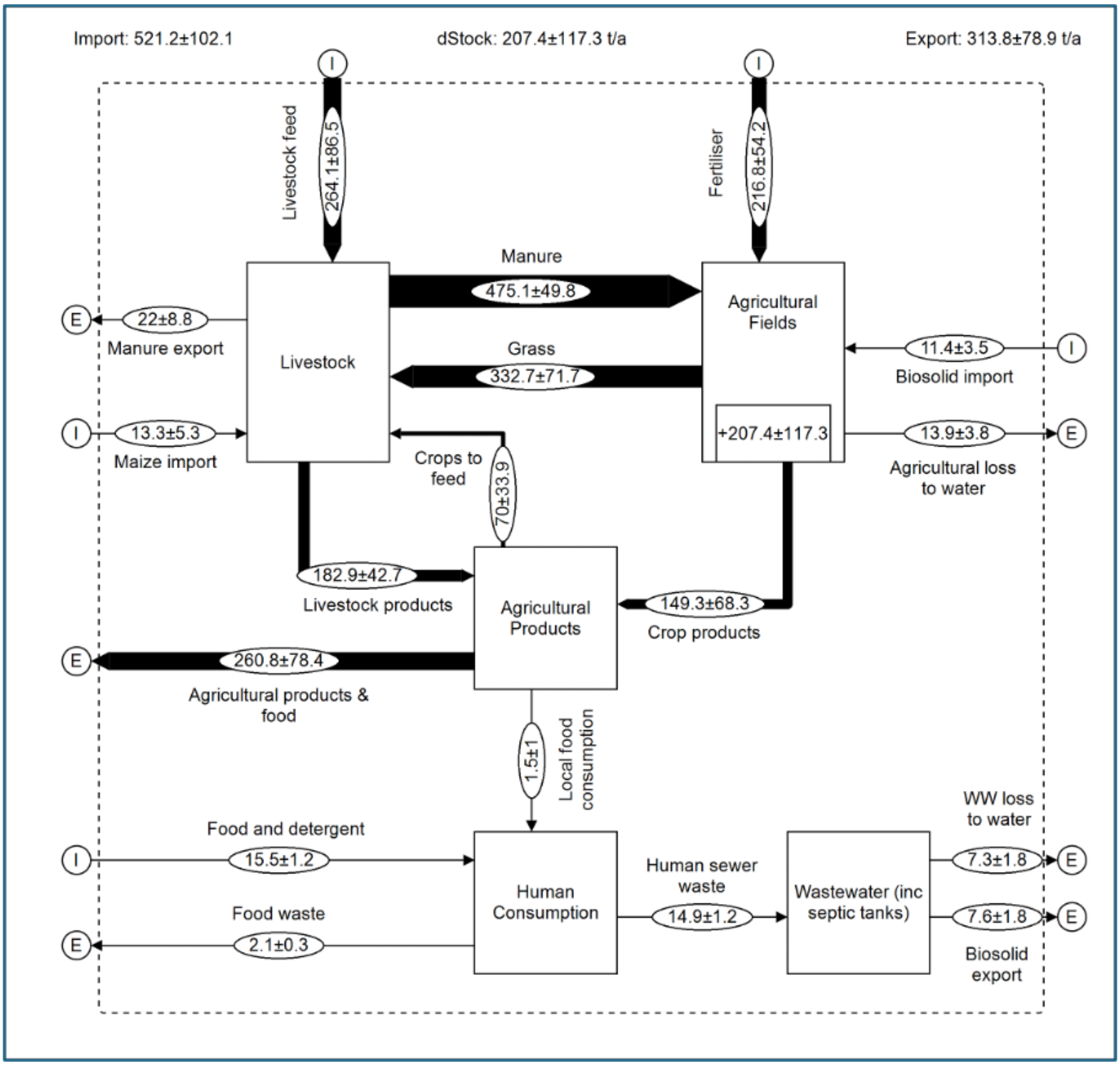

Figure 4. Substance Flow Analysis (SFA) for the Western Cleddau catchment. All flows are t P/yr ± uncertainty for the year 2021. I stands for a P import into the food system, and E stands for a P export from the system. The value within the 'Agricultural Fields' process is the annual soil accumulation of surplus P (t).

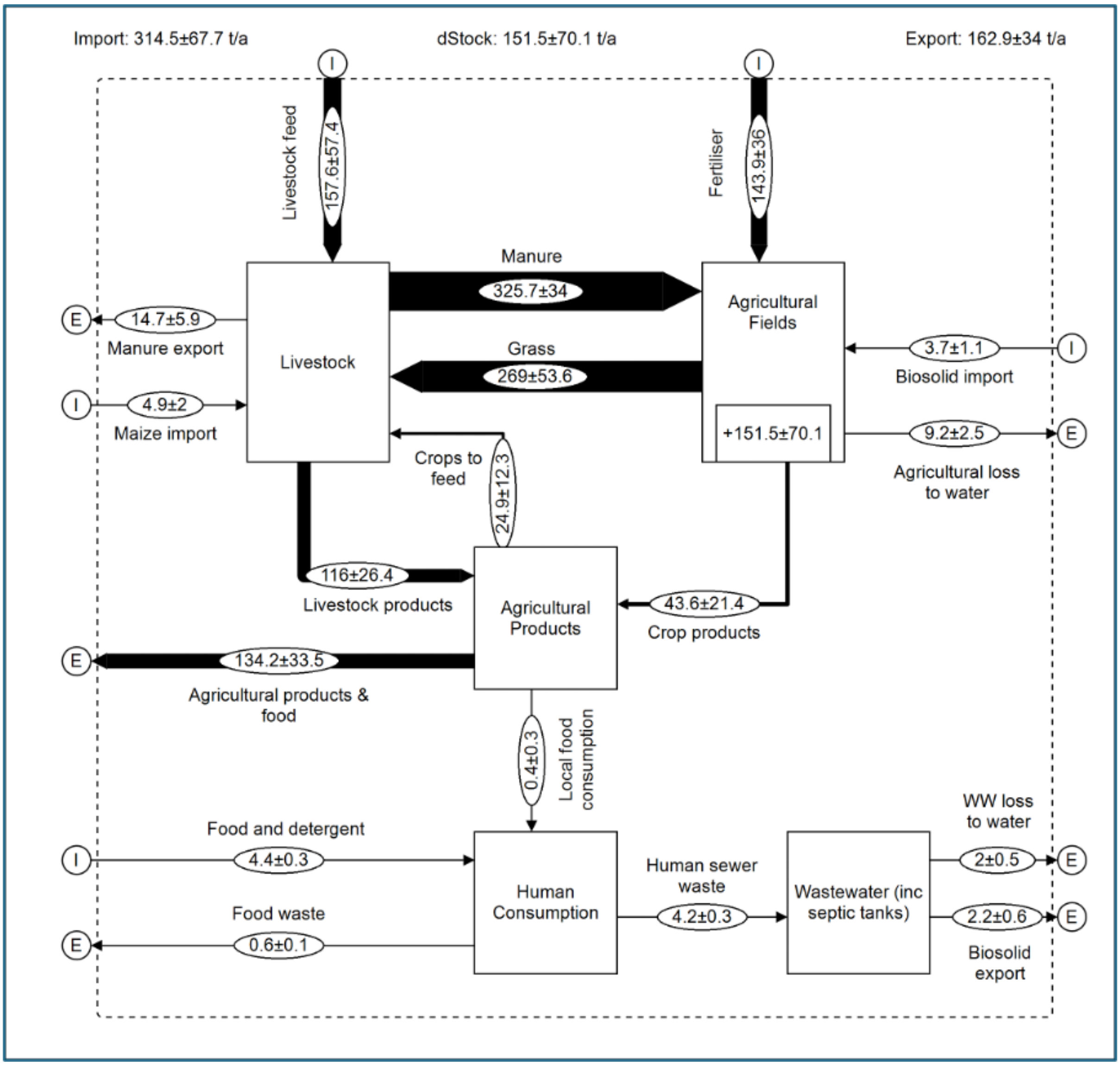

Figure 5. Substance Flow Analysis (SFA) for the Eastern Cleddau catchment. All flows are t P/yr ± uncertainty for the year 2021. I stands for a P import into the food system, and E stands for a P export from the system. The value within the 'Agricultural Fields' process is the annual soil accumulation of surplus P (t).

When considering only the dairy sector soil P balance, P surpluses increase to 15 and 9 kg P/ha/yr (Table 3). The P input from livestock manure (directly deposited and spread from housed livestock) was theoretically enough to meet the P offtake requirements of all crops in both the catchments, with no need for inorganic P fertiliser, meeting 99% of demand in the Western Cleddau and slightly more at 104% in the Eastern Cleddau (Table 3).

Catchment wide agricultural soil P efficiency (crop P offtake/crop P inputs) was 69% and 66% for the Western and Eastern Cleddau catchments (Table 3), which is slightly higher than the previously reported UK national average of 65% (Rothwell et al., 2022). Overall livestock P efficiency (P in livestock products/P intake) was 27% and 25%,respectively although this increases to 34% and 32% in milk production from the dairy herd (Table 3). Phosphorus efficiencies of ca. 30% are typical of high yielding dairy herds (Withers et al., 1999; Oenema and Oenema, 2022).

Table 3. Key indicator metrics for the Western and Eastern Cleddau catchments from the baseline SFA data for 2021.

Sector	Indicator	Western Cleddau	Eastern Cleddau
Catchment Food System	Import total (t P/yr)	521	314
	Import P % as feed	51	50
	Import P % as fert	42	46
	P efficiency %	50	43
	NAPI (kg/ha)	7.2	6.9
Agriculture (whole catchment)	Input (t P/yr)	703	473
	Offtake (t P/yr)	482	313
	Catchment agricultural soil surplus (kg P/ha)	8.4	8.3
	Soil P efficiency (%)	69	66
	Livestock nutrient P efficiency (%)	27	25
	Manure % of crop and grass P offtake (P demand met)	99	104
Dairy sector	Dairy P efficiency (%)	34	32
	Dairy sector surplus (kg P/ha)	15	8.8
Wastewater	P removal efficiency % (overall)	50	41
Food system losses to water	Apportion agriculture (%)	66[1,]	81
	Apportion wastewater (%)	34[2]	19[2]

[1]This apportionment takes account of the large effluent discharge from the Merlins Bridge works serving Haverfordwest. The apportionment for agriculture in the Prendergast Mill catchment which excludes this works increases to 83%. [2]Septic tanks account for 14% and 31% of wastewater P loss to water in the Western and Eastern Cleddau, respectively.

The human population in the catchments consumed 17 and 4.8 t P/yr in food and detergent P, and food waste totalled 2.1 and 0.6 t P/yr, which means 15 and 4.2 t P/yr went to the sewer network and septic tanks in the Western and Eastern catchments. Of this, 7.6 and 2.2 t/P were removed in biosolids at WwTW, leaving 7.3 and 2.0 t P/yr, respectively lost to water from all sources (WwTW, CSO, storm tanks and septic tanks). The proportion of this total derived from CSO, storm tanks and septic tanks was 8, 2 and 14%, respectively in the Western Cleddau and 3, 3 and 31%, respectively in the Eastern Cleddau catchment. When considering all these loss pathways, this represents overall P removal efficiencies of human P of 50% and 41% for the Western and Eastern Cleddau catchments (Table 3).

Diffuse losses to water from agriculture were estimated by the SEPERATE model at 14 and 9 t P/yr for the Western and Eastern catchments, respectively. Losses of P to water in the catchment are therefore apportioned 66% to agriculture and 34% to wastewater in the Western Cleddau and 81% to agriculture and 19% to wastewater in the Eastern Cleddau (Table 3). The much higher proportional contribution of wastewater P losses to water in the Western Cleddau catchment is largely due to the discharges at Haverfordwest in the south of the catchment and are not typical of the majority of the catchment or the area covered by the SAC. Recalculating sector P losses at Prendergast Mill (Western Cledddau) and Canaston Bridge (Eastern Cleddau) provides a better estimate of the sector P input pressures affecting the riverine SAC. At Prendergast Mill, P losses from agriculture and wastewater were 9.34 and 1.96 t P/yr, respectively and at Canaston Bridge were 7.92 and 0.82 t P/yr, respectively. This gives a proportional contribution of 83% and 91% for agriculture in the Prendergast Mill sub-catchment and Canaston Bridge sub-catchment, respectively.

2.2.2 Sub-catchment agricultural P surpluses and NAPI

NAPI values in tonnes were very similar to those of the agricultural P surplus because of the relatively small contribution of the wastewater sector to the total P input pressure. The sub-catchments in the Western Cleddau showed little variation in both agricultural P surpluses and NAPI . In contrast, there was much larger variation in the Eastern Cleddau sub-catchments, with the highest P surplus (16.9 kg/ha) in the Lower Canaston area (a derived value) of the Canaston Bridge sub-catchment and the lowest in the Glancleddau sub-catchment at 5.9 kg P/ha (Table 4). NAPI values ranged from a high of 14.1 kg P/ha in Lower Canaston and a low of 4.3 kg P/ha in Glancleddau. The much larger values in the Lower Canaston area reflect the much larger cattle numbers than in the other sub-catchments in the Eastern Cleddau.

Table 4. Agricultural P surplus and NAPI values for sub-catchments of the Western and Eastern Cleddau. Agricultural surplus is normalised for the productive agricultural land excluding rough grazing and the NAPI is normalised for the whole catchment area.

Sub-catchment	P surplus (tonnes)	P surplus (kg/ha)	NAPI (tonnes)	NAPI (kg/ha)
Treffgarne	108	9.3	111	8.7
Prendergast Mill	180	10.1	181	9.2
Western Cleddau	227	8.5	224	7.2
Glancleddau	29	5.9	30	4.3
Llys-y-Fran	37	9.0	37	9.3
Lower Canaston	100	16.9	99	14.1
Canaston Bridge	166	10.9	166	9.2
Eastern Cleddau	164	8.3	160	6.9

3. Linking sector P use to river P pollution

The P-SFA identified significant annual P input pressures on the waterbodies in the Cleddau sub-catchments due to annual P surpluses generated by the agriculture sector and effluent P discharges from the wastewater sector. This combined sector pressure was defined as the Net Anthropogenic P Input (NAPI). Analysis of the temporal changes in river P concentrations in relation to river flow was undertaken to distinguish which of these two sectors was contributing the majority of the P input pressure at water quality monitoring stations in the Cleddau sub-catchments. The linkages between both the NAPI and the agricultural P surplus and the P flux from land to water were then investigated for each sub-catchment to help identify the impact of a reduction in the catchment P input pressures on river P concentrations and flux.

3.1 Monitoring and analysis details

3.1.1 Analysis of the NRW river P record

The river P concentration record at water quality monitoring stations within each sub-catchment from 2000 onwards were collated from Natural Resources Wales (NRW) water quality archives (NRW, 2026). The river P record provides spot orthophosphate-P (assumed here to be largely synonymous with soluble reactive P (SRP)) concentrations at all monitoring stations and total P (TP) concentrations at a much smaller number of stations. At some stations on the Eastern Cleddau river the time series of SRP data is limited before 2016 by a high detection limit (0.02 mg/L) and blocks of <0.02 values were necessarily deleted from the river record. NRW have advised that anomalously high SRP values were measured at their laboratories between 2014 and 2016 (NRW, 2022), but this was not evident in the river P record within the 2010-2023 monitoring period for the Cleddau rivers.

To overcome uncertainty in the river P record due to the infrequent and inconsistent monitoring (sub-weekly to quarterly over different periods at different monitoring stations), monitoring periods for P flux estimation were based on a stable and consistent chemographic signal over as long a period as possible within the period 2010-2023 when agricultural surpluses and NAPI values were relatively stable. This period spans the 2021 assessment year for quantification of the annual P input pressure in the sub-catchments from the P-SFA and avoids the step change reduction in national P fertiliser use (and agricultural P surplus) that occurred in 2009 which might impact on river P flux (Brownlie et al., 2023; Defra 2022, 2024). A smaller reduction in national P fertiliser use occurred in 2021 but this was assumed not to have any significant impact (Jordan et al., 2024).

Annual river P flux at each monitoring station was computed from average annual flow-weighted SRP (and TP when available) concentrations over the 2010-2023 monitoring period and the long-term mean daily flow as recommended for infrequent sampling (Littlewood 1995; Johnes, 2007). The Cleddau catchment has three river flow gauging stations operating over different periods with data on mean daily flow available from the National River Flow Archive (CEH, 2026) and Hydrometric Register (Marsh and Hanniford, 2008). Treffgarne gauging station has monitored flow in the Western Cleddau river since 2013 and Canaston Bridge has monitored flow in the Eastern Cleddau river since 1960. Prendergast Mill monitored flow on the Western Cleddau from 1965-2004. Strong positive correlations between Canaston Bridge and both Treffgarne (r^2 0.86) and Prendergast Mill (r^2 0.94) allowed estimation of flows for all three stations over the 2010-2023 monitoring period. The long-term daily flow at individual monitoring stations distant from the gauging station were adjusted relative to their respective contributing catchment areas delineated using the Watershed tool and 1m DEM in ArcGIS Pro v3.1. The annual river P flux from the most downstream station on tributaries and in sub-catchments was assumed to capture the combined P losses from both the agriculture and wastewater sectors for that catchment area.

Concentrations of TP were monitored at only a few stations and only for a limited period (2005-2010). Only at Prendergast Mill (Western Cleddau) and Canaston Bridge (Eastern Cleddau) stations on the main river was TP routinely measured over the 2010-2023 monitoring period. Due to this paucity of TP data, river TP flux at diffuse stations could only be calculated from the available data establishing relationships between river SRP and TP concentrations for the different sub-catchments as detailed in Withers et al. (2024). Details of the individual water quality monitoring stations used in each sub-catchment to establish the flow-weighted TP:SRP ratios required to calculate TP flux on tributaries and the sub-catchments are given in Appendix 2.

3.1.2 Citizen science monitoring

Additional data on river flow and SRP concentrations were provided by The Cleddau Catchment Assessment Project (C-CAP) which is a major “citizen science” water testing sub-project throughout the Cleddau catchment in partnership with Western Wales Rivers Trust’s (WWRT) Adopt a Tributary initiative (https://westwalesriverstrust.org/adopt-a-tributary/). The project is designed to compliment and enhance the existing knowledge base, raise awareness amongst the Cleddau stakeholders of water quality issues and the need for better management and has run from April 2024 (https://thecleddauproject.org.uk). There have been 3 phases of monitoring (Phase 1 - April-June 2024; Phase 2 – July 2024 – June 2025 and Phase 3 – August 2025 to present day) across a number of strategic sites across the Western and Eastern Cleddau catchments, some of which are common with the NRW monitoring programme.

The distribution of the sampling sites across the study sub-catchments is shown in Figure 6, with clearly more sites sampled in the Western Cleddau than in the Eastern Cleddau catchment. The location of the C_CAP monitoring sites in relation to permitted wastewater discharges is shown in Appendix 3. Under each phase, citizens have sampled their allotted sites every two weeks at a similar time of day using a standard protocol. River flow (m^3/s) was measured as the product of flow rate and the cross-sectional area of the stream and SRP was measured by the Hanna HI-713 low range photometer. The C-CAP data was used to augment and/or validate area-weighted adjustments to river flow based on catchment area and annual average SRP concentrations measured by NRW. Data are presented here for the sites which are common to both the C-CAP and NRW monitoring programmes.

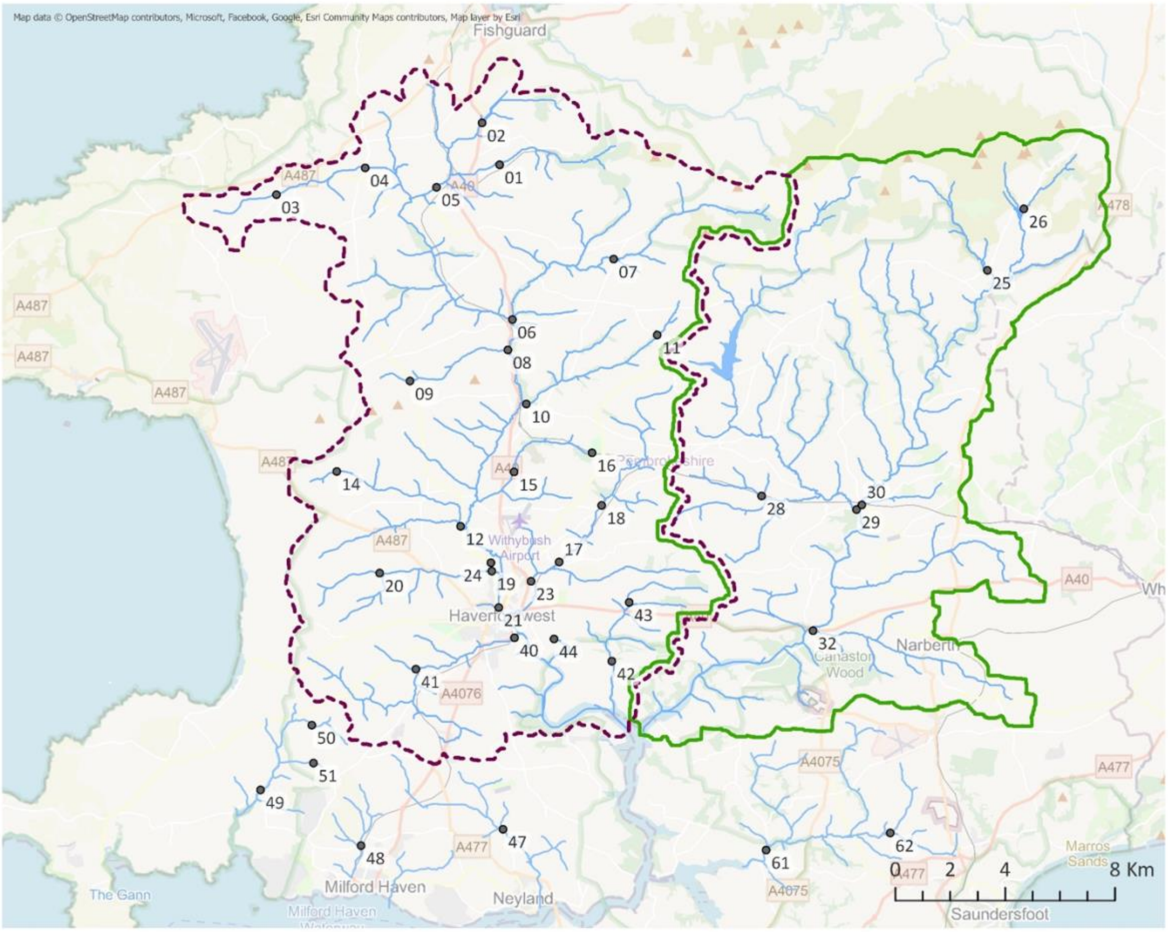

Figure 6. Locations of the Citizen Science monitoring points in the Cleddau catchment as separated by the Eastern and Western boundaries. Note: boundaries have been offset for display purposes only. Data supplied by the C-CAP project (https://thecleddauproject.org.uk).

3.1.3 Sector contributions using CQ analysis

Relationships between concentration (C) and flow (Q) provide information on catchment nutrient sources and their delivery mechanisms. Successive water quality monitoring stations along catchment rivers and tributaries with flow and P concentration (SRP and some TP) data were used to examine CQ relationships and help identify the contributions of the agriculture and wastewater sectors to the river P flux. The CQ relationship is logtransformed, and b is a unitless exponent representing the slope of the relationship (Moatar et al., 2017). The relationship can be analysed across all river flows, or can be split to distinguish different behaviours; nominally this is the median flow to distinguish behaviour at high (b50+) or low (b50-) flows, but can be adjusted to adequately represent the range of CQ responses. Nine types of response are possible (Figure 7).

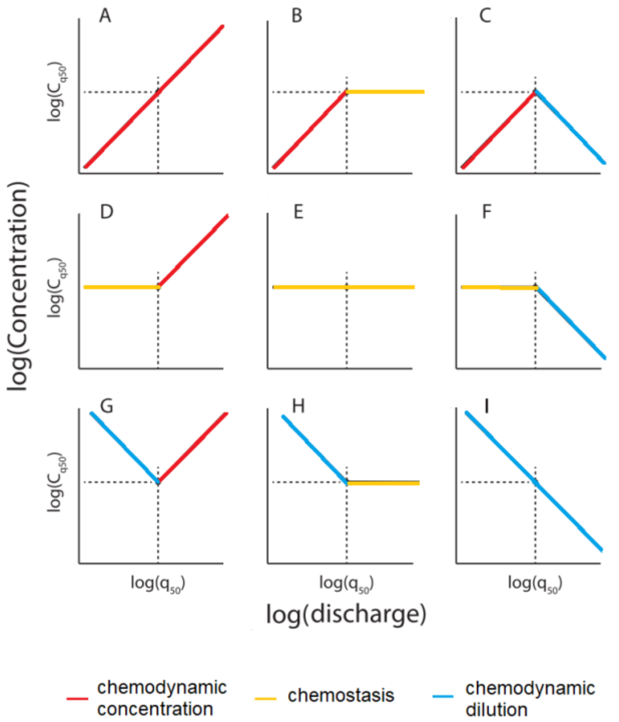

Figure 7. Conceptual schematic of the nine possible concentration (C) flow (Q) relationships when the hydrograph is segmented at the median flow. Chemodynamic concentration (red) patterns are generally associated with diffuse source phosphorus pollution sources. Chemodynamic dilution (blue) patterns are generally associated with point source phosphorus pollution. Edited from Moatar et al. (2017).

Chemodynamic concentration (b>0.1) or "up" patterns (Figure 7, red line) are attributed to enhanced mobilisation of dissolved and particulate P during high flows, due to reconnection of pollution sources via surface or subsurface routes, or mobilisation within the river channel (Moatar et al., 2017). This pattern of P delivery is transport limited, since delivery to the stream is controlled by hydrological connectivity pathways rather than the abundance of a source. Typically, chemodynamic concentration or 'up' patterns of P delivery are associated with *diffuse source P losses* from agriculture during storm events or river bank or bed erosion.

Chemostatic (b>-0.1<0.1) or "flat" behaviour implies a homogenous distribution of a P source (Figure 7, yellow line), which may be small as in upland catchments or large as in intensively farmed catchments. In this type of P behaviour, changes in hydrological connectivity do not affect solute concentrations, or that flow pathways are stable across time.

Chemodynamic dilution (b <0.1) or “down” relationships are attributed to dilution of solutes during high flows (Figure 7, blue line). This pattern of P delivery is source limited, since delivery is determined by P source abundance or rate of release, rather than transport capacity. Chemodynamic dilution or ‘down’ patterns of delivery are associated with more continuously *discharged P losses from point sources* in the catchment, such as wastewater treatment centres, industrial units, septic tanks and farmyards.

To allow comparisons between the catchment P input pressures from the agriculture and wastewater sectors and river P flux across the study sub-catchments, each monitoring station was classified into a wastewater-dominated or diffuse-dominated station based on the CQ b value (Withers et al., 2024).Wastewater-dominated stations were defined as having a b value of <-0.2 and typically showed a strong chemodynamic dilution (down) I type CQ response over the majority of the flow record. Diffuse-dominated stations were defined as those having a b value more positive than -0.2 (Meybeck and Moatar, 2012, Withers et al., 2024) and where any negative b50- slope did not extend well beyond Q50 (i.e. the b50- slope intersected close to the b50+ slope at Q50). These are stations where P flux was largely governed (>80%) by P losses in runoff from agricultural land, since they showed either chemostatic (Type E and H) or P mobilisation behaviour (Types A, D and G) at higher flows (ie > Q50), and also catered for P dilution behaviour (Types G and H) at lower flows (i.e. <Q50) that characterise smaller wastewater source inputs from farmyards (Edwards and Withers, 2008; Harrison et al., 2019). Diffuse stations may also include small contributions of municipal wastewater P inputs at low flow and/or urban runoff from rural areas not captured by WwTW.

The area-weighted average of the annual P flux at individual diffuse stations within a tributary and sub-catchment over the 2010-2023 period was taken as the annual diffuse P flux for that tributary and sub-catchment. Details of the monitoring stations, monitoring periods, CQ response and b values for all diffuse stations identified by CQ analysis are given in Appendix 1.

3.2 Sector P source signals in the river P record

3.2.1 Analysis of NRW monitoring data

Western Cleddau

Annual average and flow-weighted SRP concentrations in the main Western Cledddau river were generally very consistent at ca. 0.04-0.05 mg/L over much of its length, except at its source (Mathry) where SRP concentrations were ca. 0.03 mg/L (Table 5). One station downstream of Prendergast Mill on the main river (Haverfordwest) had much a higher concentration (0.07 mg/L) but the reason is unclear and incompatible with SRP values at a nearby station downstream (New Bridge). Annual average SRP concentrations of ca. 0.04 mg/L were also recorded in the Spittal and Camrose tributaries, but increased up to ca. 0.08 mg/L in the Rudbaxton, Cartlett and Pelcomb tributaries. In the Merlins Brook and Millin Pill tributaries below Haverfordwest, SRP concentrations were ca. 0.05 mg/L and very similar to those in the main river (New Bridge) discharging to the estuary. Concentration spikes of SRP ranged from 0.1-0.4 mg/L at all monitoring stations, occurred sporadically in both summer and winter and generally were higher in tributaries.

Table 5. Average river concentrations and annual flux of soluble reactive P (SRP) and total P (TP) for monitoring stations over the 2010-2023 monitoring period. The river SRP concentration is expressed as an average concentration (AC) and as a flow-weighted concentration (FWC).

Catchment	River/tributary	Monitoring station	SRP (mg/L)			Flux (kg/ha)	
			AC	FWC		SRP	TP
Western Cleddau	***Main river***	US Mathry WwTW	0.026	0.032		0.323	0.518
		Langloffan	0.044	0.033		0.334	0.534
		Wolfscastle	0.046	0.044		0.445	0.712
		Prendergast Mill	0.041	0.046		0.399	0.957
		Haverfordwest	0.072	0.071		0.476	1.14
		New Bridge	0.045	0.050		0.433	1.04
	Tributaries						
	Anghof river	Wolfscastle	0.044	0.042		0.425	0.807
	Spittal Brook	Spittal	0.040	0.045		0.390	0.780
	Rudbaxton	US landfill site	0.080	0.072		0.624	1.248
	Camrose Brook	Cutty Bridge	0.052	0.047		0.407	0.815
	Pelcomb Brook	Crowhill Bridge	0.074	0.064		0.554	1.108
	Cartlett Brook	By-pass Bridge	0.072	0.071		0.615	1.229
	Merlins Brook	Below Kraft Food	0.057	0.052		0.450	0.900
	Millin Pill	Millin Cross	0.051	0.051		0.442	0.883
Eastern Cleddau	***Main river***	Above Glandy	0.004	0.005		0.053	0.118
		Glancleddau	0.013	0.016		0.171	0.376
		Canaston Bridge	0.020	0.024		0.273	1.120
	Tributaries						
	Wern	Llandre	0.004	0.005		0.053	0.118
	Upper Syfynwy	Stepaside Bridge	0.013	0.017		0.236	0.778
	Lower Syfynwy	Gelli	0.023	0.034		0.364	0.855
	Deepford Brook	Pen Dwr	0.043	0.050		0.535	1.257
	Longford Brook	Pont Sian	0.110	0.090		0.963	1.877
	Narberth Brook	Canaston	0.040	0.046		0.492	0.959

[1]US – upstream; WwTW – Wastewater Treatment Works

Concentrations of TP were measured much less frequently and were absent for most of the Western Cleddau tributaries. Some data from 2005-2010 suggested TP concentrations of ca. 0.07mg/L in upstream areas (TP:SRP ratios of 1.6-1.9), whilst a good TP record at Prendergast Mill monitoring station from 2003 showed TP concentrations of 0.09 mg/L (TP:SRP ratio of 2.4).

Where there was a sufficiently long monitoring record, CQ analysis found a dominant wastewater P source signal (Type I) downstream of Mathry WwTW in the headwaters of the Western Cleddau river and a little further downstream at Llangloffan (Figure 8a). Wastewater was also dominant at downstream stations on the Rudbaxton tributary due to effluent discharge from Spittal WwTW and possibly a landfill site. Analysis of effluent discharge from smaller WwTW since 2020 indicated TP concentrations are typically 3 mg/L, but concentrations of less than 1 mg/L were achieved at some works (e.g. Clynderwen, Spittal and Maenclochog). This reflects relatively good performance especially for the smaller treatment works. Effluent discharged from the much larger WwTW at Merlins Bridge for Haverfordwest and Narberth West for Narberth also showed TP concentrations of ca. 3 mg/L.

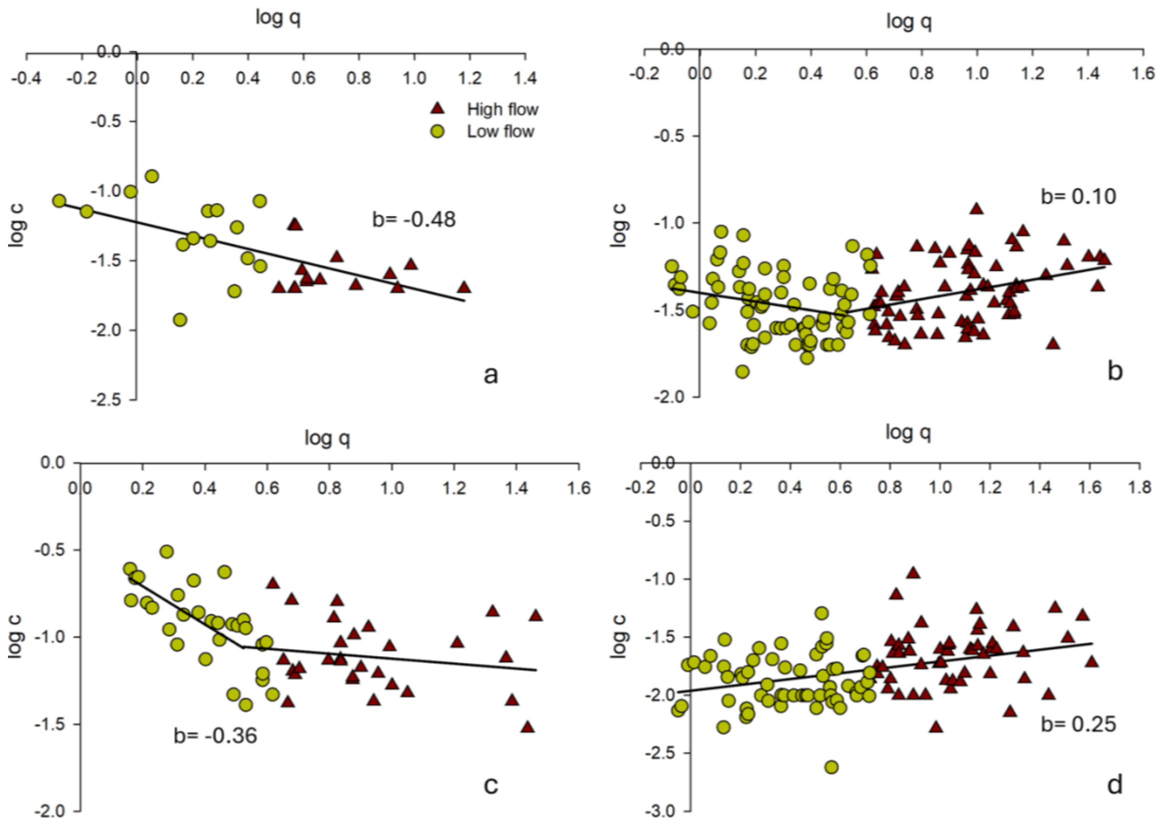

Figure 8. Examples of CQ behaviour at selected water quality monitoring stations in the study catchments: (a) Type I at Llangloffan on the Western Cleddau river; (b) Type G at Prendergast Mill on the Western Cleddau river; (c) Tyle H at Pont Sian on Longford Brook, Eastern Cleddau and (d) Type A at Canaston Bridge on the Eastern Cleddau river.

Monitoring at Clynderwen, Maenclochog, Merlins Bridge and Narberth West WwTW up to 2020 suggest SRP concentrations are ca. 80-85% of TP concentrations in the final effluent. Monitoring upstream and downstream of Mathry WwTW and Keeston WwWW on Knock Brook indicated SRP concentrations increased from 0.026 to 0.058 mg/L and 0.048 to 0.1 mg/L, respectively. Wastewater discharges are therefore likely the main cause of the elevated annual average SRP concentrations measured on the tributaries in the Western Cleddau catchment as compared to the main Western Cleddau river.

However, the majority of monitoring stations on the Western Cleddau river showed a CQ response that was more dominated by diffuse signals (Type E, D, G, H), predominantly from agriculture (Appendix 1). An example of the main type G CQ response is shown in Figure 8b). Type G response clearly still shows some dilution of river P under low flows (Q50-) suggesting some point-source input but this did not account for more than 20% of the total P flux at any of the stations exhibiting G or H type response. The estimated SRP and TP flux at these diffuse stations in the Western Cleddau catchment ranged from 0.3 – 0.6 and 0.5 -1.2 kg/ha, respectively (Table 5). When averaged over the sub-catchments, SRP and TP flux was estimated at 0.43. 0.44 and 0.47 kg/ha and 0.73, 0.80 and 0.90 kg/ha for Treffgarne, Prendergast Mill and Western Cleddau sub-catchments, respectively

The most downstream station on the Western Cleddau river is New Bridge. Although there is no TP record for this station it is just downstream of the Prendergast station which does have a good TP record. Concentrations of Total Nitrogen (TN) at Prendergast Mill are identical to those at River Bridge. This allows an estimate of the potential annual flux of TP and Total Nitrogen (TN) flowing into the estuary from the Western Cleddau river based on the flow-weighted TP:SRP ratios and concentrations of TN at Prendergast Mill. Export of TN and TP at New Bridge flowing into the estuary can therefore be estimated at 38.7 kg/ha and 1.04 kg/ha, respectively and gives a molar N:P ratio of 82. This high ratio suggests the estuary may be more P limited than N limited which is likely to increase phytoplankton abundance and/or cause community regime shifts (Nedwell et al., 2002; Howarth et al., 2011).

Eastern Cleddau

In contrast to the Western Cleddau river, the SRP concentrations monitored on the Eastern Cleddau river were much more variable. In the headwaters of the Preseli hills, the annual average SRP concentrations were only 0.004 mg/L, increasing to ca. 0.013 mg/L at Glancleddau station on the main river (Table 5) . The data record was limited due to the high detection limit (0.02 mg/L) used in water analysis before 2016. The data record in the upstream areas of the Syfynwy tributary was similarly limited and reliable data was only available for the Stepaside station below the Llys-y-Fran reservoir. This station recorded an annual average SRP concentration of 0.013 mg/L during the monitoring period. The Deepford Brook feeding into the Syfynwy tributary recorded SRP concentrations of ca.

0.04-0.05 mg/L as in the Western Cleddau, but this was diluted by the flow from upstream areas and concentrations at both the downstream Gelli station on the Syfynwy and at the Canaston Bridge gauging station on the main river were close to 0.02 mg/L (Table 5). Concentrations of SRP were 0.04 mg/L on the Narberth tributary just above where the Eastern Cleddau joins the estuary.

Contrary to the Western Cleddau catchment, flow-weighted SRP concentrations were always slightly greater than annual average concentrations, and CQ analysis further suggested a strong diffuse-dominated SRP behaviour at the vast majority of monitoring stations with mostly positive b values and type A, G, D and E response patterns (Appendix 1). An example of the typical A type CQ response is shown in Figure 8c. This is to be expected as the population density and therefore numbers of wastewater discharges are much less in the Eastern Cleddau than the Western Cleddau (Table 1 and Figure 2). The monitoring station at Pont Sian on the Longford Brook tributary was the only monitoring station showing a wastewater-dominated SRP signal due to wastewater discharges from Clynderwen and LLanddewi Velfry WwTWs (Figure 8d).

As on the Western Cleddau river network, monitoring of TP concentrations was much less frequent. Data for the 2005-2010 period suggested annual average TP concentrations of 0.04-0.05 mg/L on the main Syfynwy and Narberth tributaries. A good TP record at the Canaston Bridge gauging station from 2003 showed concentrations averaging 0.06 mg/L equivalent to a TP:SRP ratio of 3.1. However, TP concentrations appeared to be increasing over time and values during the 2010-2023 period were up 0.07 mg TP/L (TP:SRP ratio of 3.6). The large non SRP fraction (TP-SRP) at Canaston Bridge suggests more soil erosion occurs in the Eastern Cleddau catchment, although this fraction also includes release of dissolved organic P (DOP) which is likely to be significant in grassland soils under dairy farming (Withers et al., 2026).

In contrast to the Western Cleddau catchment, the estimated SRP and TP flux at diffuse stations in the Eastern Cleddau catchment showed a ten-fold difference between upland and lowland areas ranging from 0.05 – 0.5 and 0.1 - 1.3 kg/ha, respectively (Table 5). When averaged over the sub-catchments, SRP flux was estimated at 0.10, 0.24, 0.39, 0.25 and 0.27 kg/ha for Glancleddau, Llys-y-fran, Lower Canaston, Canaston Bridge and Eastern Cleddau sub-catchments, respectively. Corresponding values for TP flux were 0.23, 0.78, 1.50, 0.75 and 0.77 kg/ha, respectively. The notably higher SRP and TP flux in the Lower Canaston, which was derived as a function of the P fluxes in the other sub-catchments, was due to a doubling of cattle numbers in this part of the catchment compared to the upland areas of the Canaston Mill sub-catchment

The good TP record at Canaston Bridge (the most downstream station on the main river) does allow an estimate of the potential annual flux of TP and Total Nitrogen (TN) flowing into the estuary from the Eastern Cleddau river based on the flow-weighted concentrations of TP and TN. This is estimated at 32.1 kg/ha TN and 1.11 kg/ha TP and gives a wide molar TN:TP ratio of 64. As with the Western Cleddau river, the high N:P ratio is potentially damaging to estuarine biodiversity.

3.2.2 Analysis of citizen science data

River flow

The C-CAP project provided an opportunity to validate the catchment area adjusted estimates of river flow used to calculate river SRP and TP fluxes at monitoring sites and tributaries. A comparison of river flows at sites common to both the NRW and C-CAP monitoring programmes is shown in Table 6. There was generally good agreement between the two flow estimates except for Merlins Brook on the Western Cleddau and the Narberth Brook and Syfynwy river on the Eastern Cleddau. The higher C-CAP flows on the Syfynwy river may well represent additional regulated flows from the Llys-y-fran reservoir to support water abstraction at Canaston bridge, although the latter may also be accounted for in the gauged flow. The reason for the discrepancy at the other two tributaries remains unclear, but overall the use of a catchment-area adjusted gauged flow for P flux estimation at individual stations is supported by these C-CAP data.

Table 6. Comparison of instantaneous river flows for sites measured by the C-CAP project with catchment area-adjusted gauged mean daily flows at monitoring sites common to both C-CAP and NRW monitoring programmes.

C-CAP site	Site name	Area	River flow (m^3/s)		
		km^2	C-CAP	Gauged	Ratio
4	W Cleddau river at Llangloffan	10.3	0.36	0.33	1.09
6	Anghof river	38.9	1.69	1.25	1.35
10	Spittal Brook	17.2	0.46	0.41	1.12
12	Camrose Brook	21.9	0.60	0.60	1.00
15	Rudbaxton Brook	12.7	0.30	0.35	0.86
19	Pelcomb Brook	16.2	0.62	0.45	1.38
23	Cartletts Brook	35.4	0.80	0.97	0.82
28	Deepford Brook	18.4	0.77	0.61	1.26
29	Syfynwy river at Gelli	70.7	3.97	2.33	1.70
30	E Cleddau river at Gelli	87.7	3.30	2.97	1.11
32	Narberth Brook	17.6	1.18	0.58	2.03
40	Merlins Brook	27.8	1.43	0.76	1.88
42	Millin Pill	15.5	0.31	0.43	0.72

Ortho-phosphate-P

A similar comparison between C-CAP data and NRW data for sites common to both monitoring programmes can be made for annual mean orthophosphate-P (SRP) concentrations (Table 7). There is again very good agreement for some sites, but SRP concentrations measured by C-CAP for many of the tributary sites are notably higher than those measured by NRW. At Camrose Brook, Deepford Brook and the Syfynwy river at Gelli the difference is due a greater number and/or magnitude of the concentration spikes in the C-CAP chemical record, while at other sites (Wern Brook, Rudbaxton Brook, Narberth Brook and Millin Pill) the difference is due a consistent discrepancy across the majority of stream flows.

Table 7. Comparison of river orthophosphate-P concentrations monitored by C-CAP with those measured by NRW at monitoring sites common to both programmes.

C-CAP site	Site name	Orthophosphate-P (mg/L)		
		C-CAP	NRW	Ratio
4	W. Cleddau river at Llangloffan	0.045	0.044	1.02
6	Anghof river	0.041	0.046	0.89
10	Spittal Brook	0.040	0.040	1.00
12	Camrose Brook	0.124	0.052	2.38
15	Rudbaxton Brook	0.301	0.080	3.76
19	Pelcomb Brook	0.030	0.074	0.41
21	W. Cleddau river at Haverfordwest	0.027	0.045	0.60
23	Cartletts Brook	0.069	0.072	0.96
24	W. Cleddau river at Crowhill	0.045	0.045	1.00
25	Wern Brook	0.134	0.004	33.50
28	Deepford Brook	0.190	0.043	4.42
29	Syfynwy river at Gelli	0.140	0.023	6.09
32	Narberth Brook	0.165	0.040	4.13
40	Merlins Brook	0.039	0.057	0.68
42	Millin Pill	0.157	0.051	3.08

3.3 Impact of P input pressures on water quality

Both the agricultural P surplus and the NAPI were significantly ($P < 0.05$) positively correlated (r^2 0.7-0.8) with the measured river SRP and TP flux across the sub-catchments in the Eastern Cleddau catchment, although the number of datapoints was limited (Figure 9). In the Western Cleddau catchments, the range in the agricultural P surplus and NAPI was too small to indicate any relationship to river P flux as the datapoints were clustered. However, the river SRP flux in the Western Cleddau sub-catchments were notably greater than those in the Eastern Cleddau catchment at a broadly equivalent P surplus or NAPI value (Figure 9a and c), whilst river TP flux in the Western Cleddau was very similar to that in the Eastern Cleddau at an equivalent P input pressure (Figure 9b and d). These results highlight firstly the greater dilution of the river P signal in the Eastern Cleddau catchment due to the contribution of the cleaner water flowing off the Preseli hills and from the Llys-y-fran reservoir, and secondly the greater contribution of non-SRP P (TP-SRP) in the Eastern Cleddau catchment relative to the Western Cleddau. This is reflected in their greater TP:SRP ratios (Appendix 2) and flow regimes.

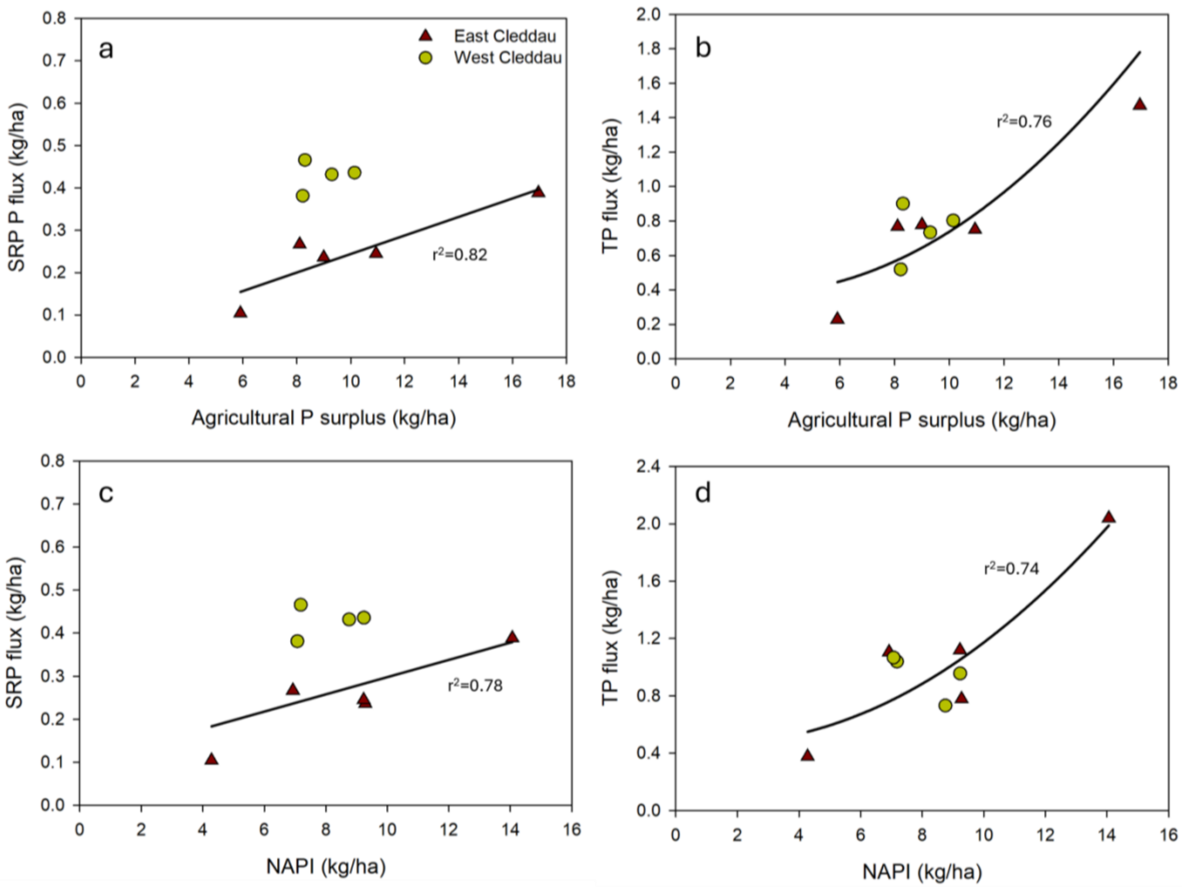

Figure 9. Relationships between the annual agricultural P surplus and (a) river SRP flux and (b) river TP flux and between the Net Anthropogenic P Input (NAPI) and (c) river SRP flux and (d) river TP flux across the study sub-catchments in the Cleddau catchment.

This particulate P fraction will include soil particles eroded in land runoff during storm events and dissolved organic P released from the catchment soils. A similar trend of low SRP and high PP fractions in the river was also found in upland areas of the Wye catchment relative to its lowland areas (unpublished data). The data suggest a greater mobilisation of soil and organic particles in the more turbulent flow of upland streams draining more organic and peaty soils. A significant contribution of dissolved organic P in land runoff can also be expected in lowland grassland soils under dairy farming due to their higher organic matter level, as recently demonstrated in the Somerset Levels and Moors catchments (Withers et al., 2026). It should be noted that there is much greater uncertainty in the river TP flux due to the general paucity of TP measurements taken across the catchment tributaries in NRW's routine monitoring programme. The results clearly suggest that a full programme of monitoring that investigates all P fractions in river flow is required to better clarify the sources of the river P signal.

The limited number of sub-catchments in the Cleddau catchments makes it difficult to draw reliable conclusions on the drivers of river P flux across the Cleddau sub-catchments. However the agricultural P surplus and river SRP and TP flux data from the Cleddau sub-catchments were combined with similar data obtained from sub-catchments of the Somerset Levels and Moors (SLM), Stour and Wye rivers with a similar livestock dominated agriculture. The river SRP flux in the Western Cleddau sub-catchments were very similar to those measured in other lowland sub-catchments with more intensive livestock farming and which did not have an upland source to dilute the river P signal (Figure 10a).

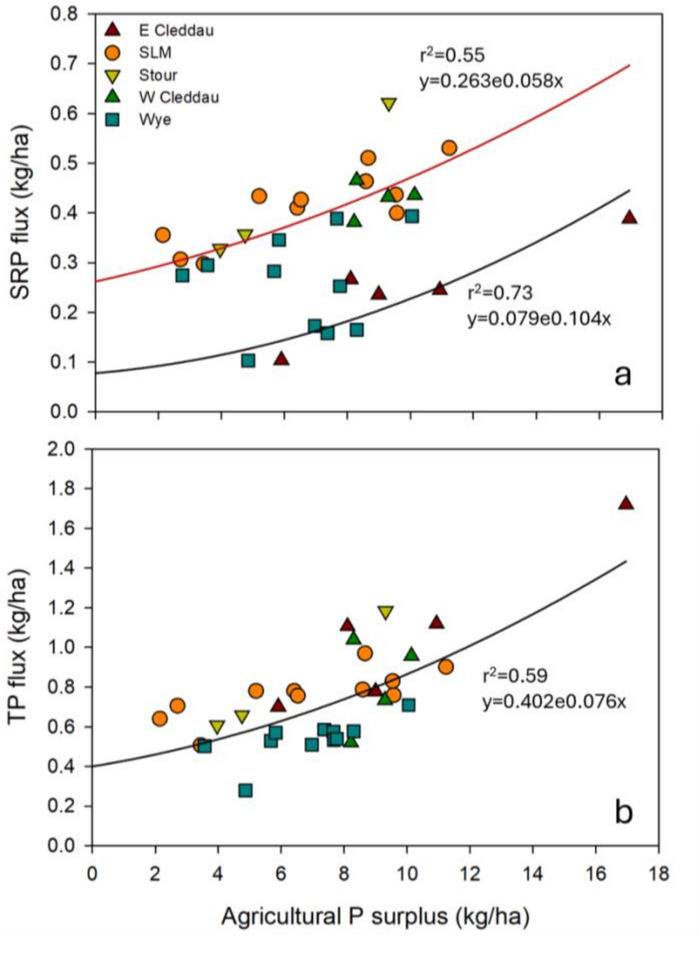

Figure 10. The common relationship between the agricultural P surplus and (a) river SRP flux and (b) river TP flux at diffuse stations across sub-catchments in four river catchments with a livestock dominated agriculture: the Somerset Levels and Moors (SLM), Stour, Wye and Cleddau sub-catchments. The SRP relationship is notably different for sub-catchments with no upland source of river flow (upper regression line) compared to those that do (lower regression line).

Similarly, the river SRP flux in the Eastern Cleddau sub-catchments were very similar to those measured in Wye sub-catchments with a substantial upland contribution to river flow where livestock farming was less intensive and which diluted the downstream P signal (Figure 10a). The relationships were significant at the $P<0.001$ level. The TP flux for all the Cleddau sub-catchments also fitted well with other catchment data (Figure 10b) showing a highly significant ($P <0.001$) increase in the river TP flux as the agricultural surplus is increased.

The combined data was therefore used to estimate the impact of the annual agricultural P surplus on the river P flux in the Cleddau catchments and the potential contribution from the legacy soil P that has accumulated in the past. The relationships indicate that ca. 5% of the annual agricultural P surplus is lost directly in land runoff each year and that this direct annual P loss represents between 10 and 50% of the total TP flux in the river depending on the amount of the surplus up to 10 kg/ha. The intercept of the TP flux relationship (0.4 kg P/ha) represents the loss of P from legacy P in the soils and river sediments and accounts for 50-90% of the total P flux in the river. At the annual agricultural P surplus calculated by the SFA for the Western and Eastern Cleddau catchments (ca. 8.5 kg/ha), the current annual P surplus and legacy P contributed approximately equally (i.e. 50:50) to the river TP flux. These data also suggest that reducing the annual agricultural P surplus to zero would decrease the river TP flux by ca. 50%.

The combined relationships for river SRP flux suggest that at the 8.5 kg/ha agricultural P surplus in the Cleddau catchments, legacy P reserves account for 60% of the total SRP flux to the river in the Western Cleddau and 40% of the SRP flux in the Eastern Cleddau river. The higher contribution of legacy P to river SRP flux in the Western Cleddau compared to the Eastern Cleddau is consistent with a lower proportion of intensively farmed land in the Eastern Cledddau, but may also suggest there is a greater proportion of high P soils in W. Cleddau . However, no soil P data were available for this study.

4. Management options to improve water quality

4.1 Scenario analysis

4.1.1 Scenario methods

The potential impact of a food system and P management change on catchment P flows relative to the baseline SFAs were explored using a scenario SFA model for the Western and Eastern Cleddau catchments. The scenario explored the impacts of reducing unnecessary P inputs and achieving a zero catchment P surplus in the agriculture sector averaged across the whole catchments, i.e. soil P inputs from fertiliser, manure and biosolids match crop and grass offtake to minimise future soil P accumulation and improve food system P efficiency. Under this scenario the legacy soil P reserves do not increase further and there are potential and significant savings in fertiliser P input costs. The scenario provides only one example of possible system change to demonstrate the value of SFA analysis in assessing potential avenues for reducing the P input pressure.

There are many ways to achieve a zero agricultural P surplus, however, in this scenario, P fertiliser import and use across both catchments and in all sectors drops by 50%, biosolid use remains the same as the baseline, and the remaining crop P demand is met by redistribution of manure P within the catchment. Excess manure P above crop demand is then exported outside the catchment area which was assumed to come entirely from the dairy sector as the major livestock type. For the Western Cleddau catchment this represented 27% of dairy sector manure excretion and 28% in the Eastern Cleddau. The scenario is only one example of how system change can impact P flows and system indicator metrics in a catchment and are not presented as recommended actions. Other avenues for reducing the annual agricultural P surplus include reducing the P content of livestock feed, replacing imported protein concentrates with high protein forage crops, more extensive manure processing and export out of the catchment and destocking.

4.1.2 Scenario outputs

The scenario SFA models in Figures 11 and 12 detail the system impact of reducing P fertiliser use by 50% and manure redistribution and export to achieve a zero agricultural P surplus in the Western and Eastern Cleddau catchments. Fertiliser import and use drops to 108 t P/yr and 72 t P/y in the Western and Eastern catchments and the equivalent of 131 t P/yr and 99 t P/yr in livestock manure is exported from the Western and Eastern catchments, meaning total food system imports drop to 413 and 243 t P/yr. Assuming no change in agricultural productivity, as all crop P demand is still met, overall food system P efficiencies increase from 50% to 66% in the Western Cleddau and 43% to 56% in the Eastern Cleddau catchment, respectively (Table 8). Consequently, agricultural soil P efficiency is nearly 100% in both catchments and legacy P reserves are maintained. As the exported manure P has come entirely from the dairy sector the agricultural P balances change to 3 kg P/ha in the Western Cleddau and -1.5 kg P/ha in the Eastern Cleddau. Using the relationship between the P surplus and river TP flux at diffuse stations demonstrated in Figure 10b, the losses to water from agriculture are predicted to drop by 48% to 7.23 t P/yr in the Western Cleddau and by 45% to 5.1 t P/yr in the Eastern Cleddau. As no changes to wastewater management are assumed in this scenario, the source apportionment therefore changes to 51% to agriculture and 49% to wastewater in the Western Cleddau and 70% to agriculture and 30% to wastewater in the Eastern Cleddau (Table 8).

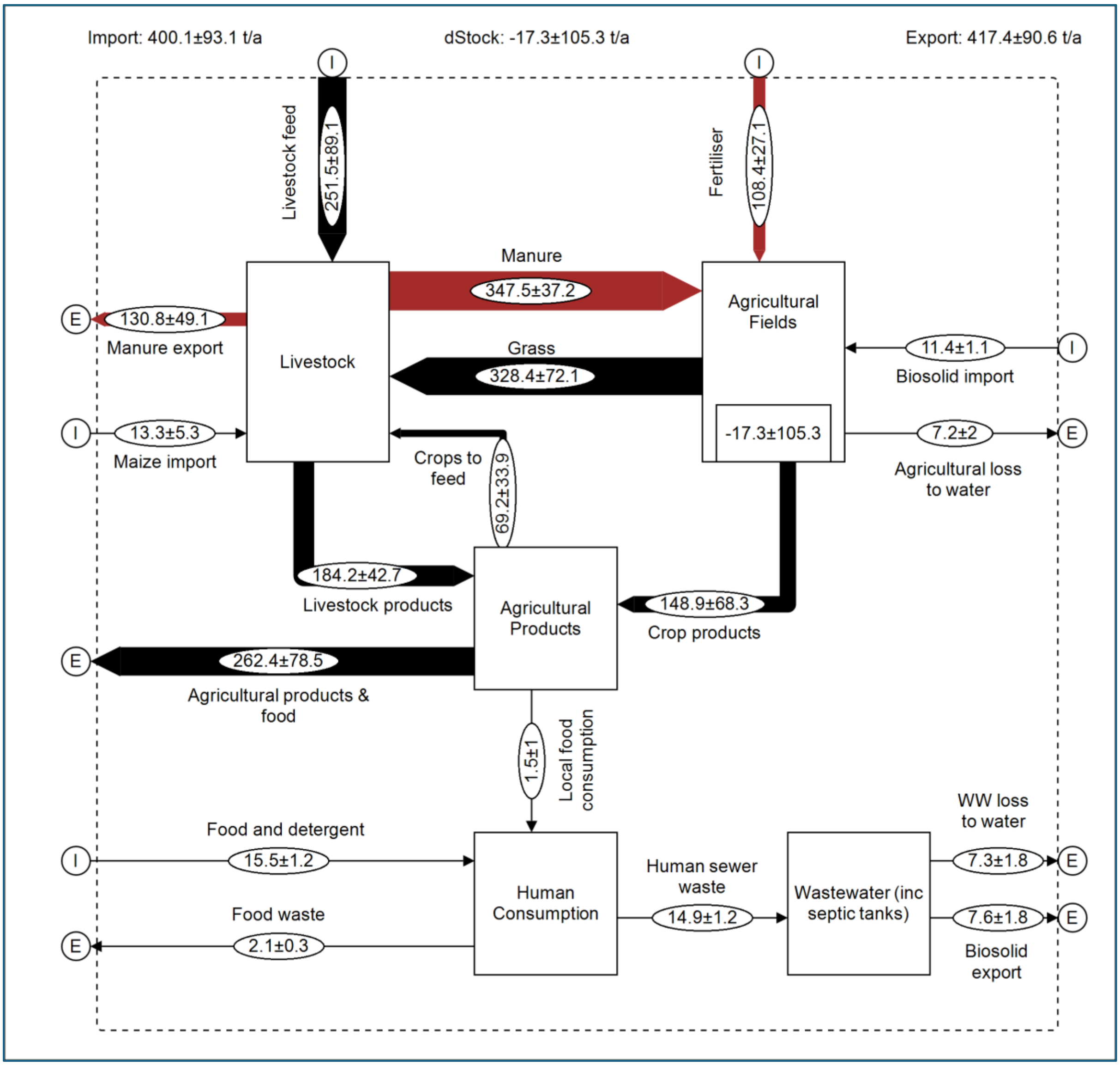

Figure 11. Substance Flow Analysis (SFA) for the Western Cleddau catchment detailing a zero agricultural surplus scenario. Flows in red have changed in the scenario model. All flows are t P/yr ± uncertainty for the year 2021. I stands for a P import into the food system, and E stands for a P export from the system. The value within the 'Agricultural Fields' process is the annual soil accumulation of P (t).

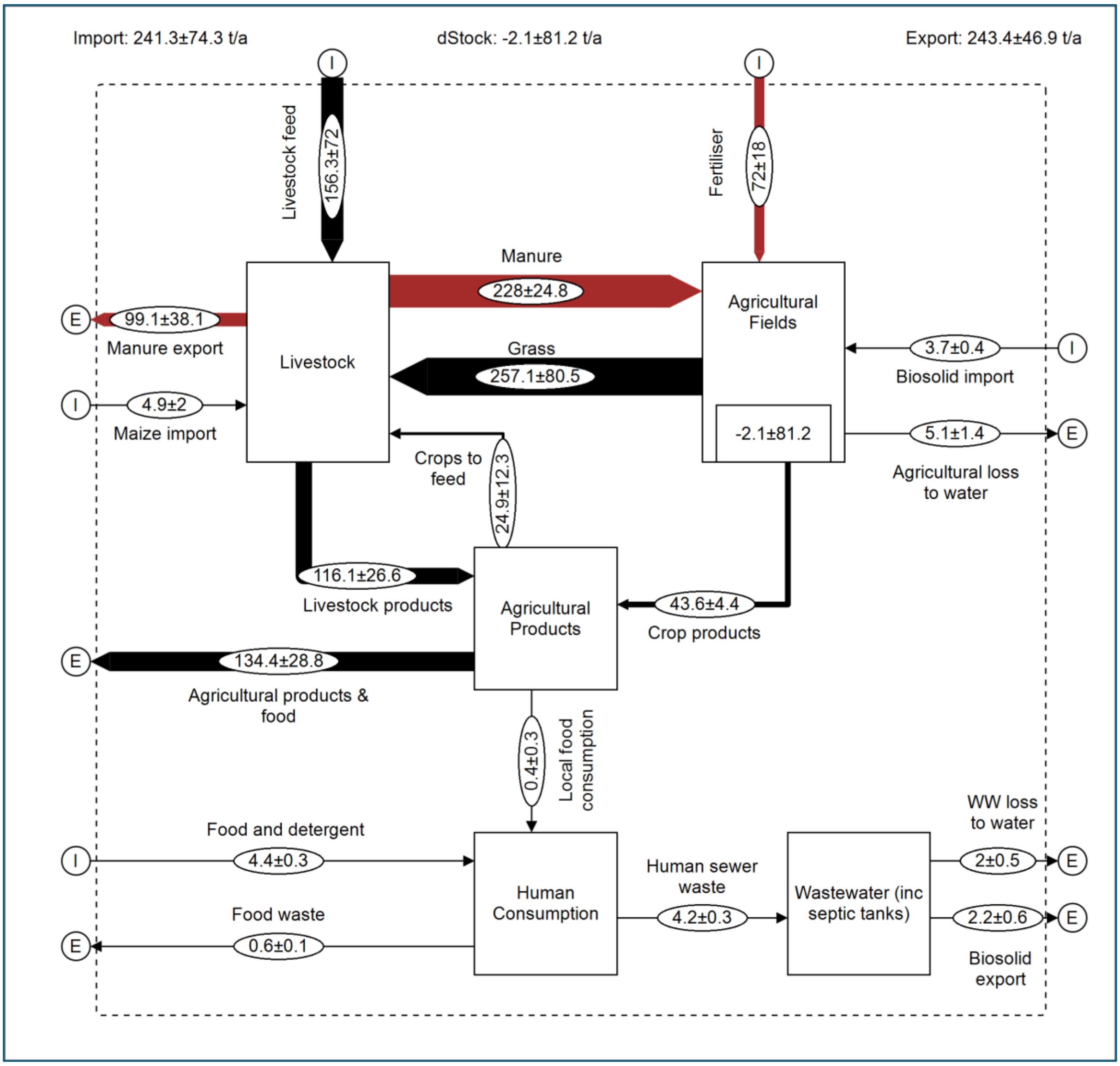

Figure 12. Substance Flow Analysis (SFA) for the Eastern Cleddau catchment detailing a zero agricultural surplus scenario. Flows in red have changed in the scenario model. All flows are t P/yr ± uncertainty for the year 2021. I stands for a P import into the food system, and E stands for a P export from the system. The value within the 'Agricultural Fields' process is the annual soil accumulation of P (t).

Table 8. Key indicator metrics for the Western and Eastern Cleddau catchments under the zero agricultural P surplus scenarios

Sector	Indicator	Western Cleddau Zero Surplus	Eastern Cleddau Zero Surplus
Catchment Food System	Import total (t P/yr)	400	241
	Import P % as feed	63	65
	Import P % as fert	27	30
	P efficiency %	66	56
	NAPI (kg/ha)	-0.1	0.13
Agriculture (whole catchment)	Input (t P/yr)	467	304
	Offtake (t P/yr)	477	301
	Catchment agricultural soil surplus (kg P/ha)	-0.4	0.2
	Soil P efficiency (%)	102	99
	Livestock nutrient P efficiency (%)	28	26
	Manure % of crop and grass P offtake (P demand met)	73	76
Dairy sector	Dairy P efficiency (%)	34	32
	Dairy sector surplus (kg P/ha)	3	-2
Wastewater	P removal efficiency % (overall)	50	41
Losses to water	Apportion agriculture (%)	51	70
	Apportion wastewater (%)	49	30

5. Overall Conclusions and Recommendations

5.1 Conclusions

The SFA found that both the agriculture sector and the wastewater sector used P inefficiently (≤50%) in the catchment food systems leading to annual agricultural P surpluses and wastewater discharges that together form the total P input pressure (NAPI) on the catchment waterbodies amounting to ca. 7 kg/ha/yr averaged over the whole Western Cleddau and Eastern Cleddau catchment areas. Agriculture constituted the majority (>95%) of the NAPI pressure, but unlike direct wastewater discharges, its impact on waterbodies is buffered by the catchment soils.

The largest P import into both catchments in 2021 was in livestock feed (7-10 kg P/ha/yr) and livestock manures were therefore the major P input to the catchments' farmed soils. Fertiliser inputs were also significant (7-8 kg/ha/yr) and the annual agricultural P surplus ranged from 6-11 kg/ha/yr averaged over the productive arable and grassland area of the study sub-catchments. The overall annual agricultural P surplus in both Western and Eastern Cleddau catchments was ca. 8.5 kg/ha in 2021, which is higher than both the UK and England soil P surplus for that year (5.7 and 3.2 kg P/ha/yr). This annual P surplus is very similar to that found in other livestock dominated catchments and nutrient footprinting on farms is required to determine the more detailed spatial distribution of the P surplus across the catchment.

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The SFA estimated there are sufficient quantities of manure P (17-18 kg P/ha/yr) produced each year to meet annual crop and grass P demand (16-18 kg P/ha/yr) based on crops and grass P offtake and suggests that fertiliser P inputs account for the majority of unused surplus P in the catchment food system and should be reduced.

Analysis of river orthophosphate-P (assumed here as synonymous with soluble reactive P (SRP)) concentrations showed consistently higher P pollution in the Western Cleddau catchment (ca. 0.04 mg/L) compared to the Eastern Cleddau catchment (0.02 mg/L). The lower SRP concentrations in the Eastern Cleddau catchment reflect the dilution afforded by the less intensive agriculture and cleaner river flows originating in the Preseli hills and from the Llys-y-Fran reservoir. Tributaries in both catchments tended to have higher SRP concentrations than the main river. River SRP flux ranged from 0.32-0.62 kg/ha across the Western Cleddau tributaries and main river and from 0.05-0.54 kg/ha across the Eastern Cleddau catchment.

Concentrations of TP were generally not routinely monitored except at the two gauging stations at Prendergast Mill and Canaston Bridge. Combining data for these two stations with older data (2005-2010) suggested significant contributions of particulate and dissolved organic P in both catchments (TP:SRP ratios of 1.6-4.1), and especially in the

Eastern Cleddau river. River TP flux ranged from 0.52-1.25 across the Western Cleddau tributaries and main river and from 0.12-1.26 across the Eastern Cleddau river network.

Source apportionment modelling (SEPERATE) estimated losses of TP of 0.44 and 0.23 kg/ha from the agriculture and wastewater sectors, respectively in the Western Cleddau catchment and 0.40 and 0.09 kg/ha, respectively in the Eastern Cleddau catchment. Together these TP losses are significantly less than the downstream TP flux measured in both rivers (ca. 1 kg P/ha). Since modelled P losses from WwTW are very similar to those measured in WwTW effluent discharge, this suggests the contribution from agriculture is underestimated by the model. This is also suggested by the high proportion of water quality monitoring stations with a dominant diffuse pattern of CQ behaviour. Source apportionment based on measured P loads at Prendergast Mill and Canaston Mill suggests over 80% of the river TP flux originates from agriculture in the SAC.

A significant positive relationship (r^2 ca. 0.8) was observed between agricultural P surpluses across the Eastern Cleddau sub-catchments and the SRP and TP flux measured in the river at monitoring stations dominated by diffuse (agricultural) sources as defined by CQ analysis. However the range in the P surplus was too small in the Western Cleddau sub-catchments to independently establish any relationships to river P flux. Data in the Cleddau sub-catchments were similar to data for livestock dominated sub-catchments in other river systems (Somerset Levels and Moors (SLM) Stour and Wye). The combined relationships suggested that legacy soil P contributed ca 60% and 40% of the annual SRP flux in the Western Cleddau and Eastern Cleddau rivers, respectively, and ca. 50% of the total TP flux in both rivers.

The study shows that the high agricultural P surplus and resulting P input pressure (NAPI) is contributing to river P pollution and that management strategies to lower the P surplus will help to reduce riverine P loads and concentrations. According to the combined P surplus-river P flux relationships, reducing the average annual agricultural P surplus to zero was predicted to reduce river TP flux by nearly 50% and reduce SRP concentrations by 0.02 mg/L in the Western Cleddau river and 0.01 mg/L in the Eastern Cleddau river. SFA analysis indicated that a reduction in P fertiliser use and exporting more manure out of the catchment would also improve catchment P use efficiency by 14%. The significant contribution from legacy P reserves shows that further reductions in P inputs to drawdown soil P levels in the catchment would have a beneficial effect but this will require more substantial system change.

The total flux of TN and TP flowing from the Cleddau catchment into the Daugleddau estuary was approximately calculated at 2000 and 60 t/annum, respectively with high molar N:P ratios of 75. Nutrient enrichment of the estuary remains a concern.

5.2 Recommendations

The SFA used best available data for the catchments taking account of local knowledge but makes a number of assumptions, especially with regard to transfers of P into and out of the catchments, which brings some uncertainty. Identifying sector P use at this scale is an iterative process and it is recommended that wider stakeholder feedback on the assumptions presented here are collected to refine the material P flows in a further iteration which could include the latest regional agricultural census data. Stakeholder feedback will also be important to understand the concerns and barriers to uptake of potential management options to reduce the P input pressure on the river network. Nutrient footprinting on farms is recommended to identify these management options.

Given the important role that nitrogen (N) plays in aquatic eutrophication, the designation of the Daugleddau estuary as an SAC and the current concerns over N loads to the estuary, it is recommended to produce an SFA for total N and establish potential links to river N loadings in the catchments.

The study has highlighted the inadequacy of the current routine monitoring programme to capture the full extent of the P loading from the catchment land use, especially the particulate and dissolved organic forms of P which can contribute to downstream eutrophication, including the estuary. It is recommended to expand the monitoring programme at selected sites to include total dissolved P and total P in addition to the current focus on orthophosphate-P.

The C-CAP project provided useful data to help validate estimates of both river flow and variation in orthophosphate-P concentrations. It is recommended to continue and improve accuracy of this programme, and its complimentary monitoring of biological markers of river water quality, to compliment the NRW routine monitoring programme to monitor compliance.

Understanding the linkages between catchment P input pressures, the accumulation, distribution and release rates of soil P and river P export and concentrations is critical for the development of coherent and effective policies and practical actions to reduce landscape-driven river P export. No soil P data were made available for this study and further research is recommended to better understand the current distribution of soil available P (Olsen-P) concentrations across the catchment areas and quantify the historic accumulation of legacy soil P present in Cleddau catchment soils and its release to land runoff.

6. Acknowledgements

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Appendix 1. Details of the diffuse monitoring stations identified by CQ analysis in each sub-catchment, the periods of monitoring, numbers of datapoints, b gradient values and type of CQ behaviour signified by letter from Figure 7.

Catchment	Tributary	Station[1]	Data record	n	b	Type
Western Cleddau	Main river	US Mathry WwTW	2010-2023	74	0.181	G
		Wolfscastle	2010-2023	100	-0.166	G
	Anghof	Wolfscastle	2010-2023	97	-0.130	G
	Spittal Brook	Spittal	2010-2023	111	0.037	G
	Rudbaxton	US landfill site	2010-2022	55	0.352	G
	Camrose Brook	Cutty Bridge	2010-2023	76	-0.175	H
	Main river	Prendergast Mill	2010-2023	138	0.101	G
	Pelcomb Brook	Crowhill Bridge	2010-2023	96	-0.168	H
	Cartlett Brook	By-pass Bridge	2010-2023	93	-0.095	G
	Main river	Haverfordwest	2010-2014	58	0.150	D
		New Bridge	2010-2023	110	0.075	G
	Merlins Brook	Below Kraft Food	2010-2020	46	-0.079	E
	Millin Pill	Millin Cross	2013-2023	58	-0.037	E
Eastern Cleddau	Wern	Llandre	2016-2023	66	0.179	D
	Main river	Above Glandy	2018-2023	28	-0.032	E
		Glancleddau	2016-2023	57	0.208	G
	Syfynwy	Stepaside Bridge	2013-2020	57	0.598	A
		Gelli	2010-2023	48	0.467	A
	Deepford Brook	Pen Dwr	2010-2023	120	0.120	G
	Main river	Canaston Bridge	2010-2023	111	0.293	A
	Narberth Brook	Canaston	2010-2023	77	0.088	G

[1]US – upstream; WwTW – Wastewater Treatment Works.

Appendix 2. Datasets used to examine the relationship between river soluble reactive P (SRP) and total P (TP) concentrations in each sub-catchment of the Eastern and Western Cleddau for predicting TP flux. TP:SRP ratios are given for both mean and flow-weighted (FW) mean concentrations over n samples in the monitoring period.

Catchment	Monitoring Station	Monitoring Period	n	SRP:TP ratio	
				Mean	FW Mean
Western Cleddau	Anghoff at Wolfscastle	2005-2010	46	1.62	1.87
	Wolfscastle	2005-2010	59	1.53	1.57
	Prendergast Mill	2010-2023	136	2.20	2.43
Eastern Cleddau	Llywndwr Bridge	2004-2010	72	2.13	2.17
	Llys-y-fran	2013-2019	35	4.44	3.31
	Syfynwy at Gelli	2005-2010	61	2.26	2.35
	Narberth at Canaston	2004-2010	68	1.68	1.95
	Source	2005-2010	54	2.05	2.21
	Canaston Bridge	2010-2023	106	3.60	4.10

Appendix 3. Locations of Wastewater Treatment Works (WwTW), Combined Sewer Overflows (CSO) and Sewage Overflows (SO), Pumping Station, Domestic and other Commercial and Institutional wastewater sources in relation to the C_CAP monitoring sites on the Western and Eastern Cleddau catchments (Welsh Water, 2024). Contains Natural Resources Wales information © Natural Resources Wales and database, all rights reserved. Note: catchment boundaries have been offset for display purposes only.