Understanding the Wye Catchment

Project Final Report

July 2024

Environment Agency

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Executive summary

The Wye Catchment Partnership (WCP) is preparing a new catchment management plan. The Environment Agency commissioned Mott MacDonald to support the catchment partnership with work that assesses potential opportunities and trade-offs in the development of the plan. Mott MacDonald has supported the partnership with a two-step project known as “Understanding the Wye”. The first step is a Participatory System Mapping (PSM) component that pools the collective insights of catchment stakeholders across the partnership and shows conceptually how the catchment functions as a multi-faceted system. The second step uses an integrated model to show in numerical terms how the catchment functions across water quality and flow metrics.

The system mapping was undertaken by WCP members in November and December 2023 and used to understand interconnected links between catchment interventions and outcomes. The system maps have been used to develop a planning diagram and a long-list of catchment interventions and metrics. These interventions and metrics have been tabled to inform ongoing work on the development of the catchment management plan.

The modelling of the Wye catchment has been undertaken using Imperial College London’s Water System Integrated Water Model (WSIMOD). WSIMOD is a model that takes a broad perspective on the catchment and can show concurrent impacts on water quality and flow, rather than being a model that takes a narrow perspective that gives better precision on a smaller range of variables. Its value comes in scoping out the broader potential of a plan rather than in precise predictions of specific impacts. WSIMOD allows for future scenarios and potential interventions in the catchment to be modelled and their impact on river flows and water quality to be quantified. A future scenario of climate change and population growth was modelled, and this showed that future pressures could decrease the magnitude of low flows during a drought by up to 11%, increase high flows during a 1 in 1 year flood by 8%, increase mean soluble reactive phosphorus (SRP) by 20% and increase mean organic phosphorus by 18%.

We have modelled a range of options across soil health, tree cover, manure and fertiliser application rates and wastewater treatment upgrades setting out the contribution of different interventions in isolation and combination. The headline results from the modelling are that the management of soils, and in particular infiltration rates, across the catchment has the greatest positive impact on flows. We modelled an option of improved soil health in 40% agricultural land England and 20% agricultural land Wales, with an increased percolation of 30% on improved land and found the magnitude of low flows (Q95) increased between 4% and 6% in the Lugg and lower Wye and 3% in the Upper Wye. The Magnitude of high flows (Q0.3) decreased between 0.5% and 1.2%. The management of manures and fertiliser application has the greatest positive impact on water quality. We found a reduction in 25% manure and fertiliser application rates reduced the river’s average dissolved inorganic nitrogen (DIN) by 12% to 28%; the average SRP by 3% to 25% and the average organic phosphorous by 3% to 18% depending on the location in the catchment. We also modelled a “negative option” which relates to a decline in soil health showing that reduced infiltration across the catchment could decrease flows during a drought between 28-40%, increase high flows by up to 6% and increase average SRP by 17% and average organic phosphorus by 20%.

In the case of options to reduce manure and fertiliser we included an ambitious option based on the RePhoKus drawdown scenario which would require a 49% reduction in manure application rates and 75% reduction in fertiliser application rates across the catchment.[1] The most beneficial combination of options for the river included the enhanced reduction in fertiliser and manure as part of a portfolio of additional measures. This portfolio could achieve up to a 15% increase in the magnitude of flows during a drought, and a 2% reduction in high flows during a 1 in 1 year flood and reductions in DIN by 35-72%, SRP reductions between 29-82% and organic phosphorus reduction between 25-57% depending on the location within the catchment. The model remains available for other options to be assessed should the opportunity for other high impact portfolios arise.

We recommend that the high-level system map and planning diagram be maintained as live documents so that they continue to inform and underpin development of the Wye catchment plan. The system maps should be used as the basis of a monitoring, evaluation and learning (MEL) framework for the catchment management plan that sets out how to measure impact, evaluate success and continually improve the plan. The planning diagram may be used as a co-ordination tool to enable overlaps and common metrics to be identified across the various contributing plans relevant to the catchment. As further data is collected, we recommended that the WSIMOD model is updated with improved baselining and enhanced option analysis is undertaken. We also recommended that the analytical modelling undertaken in WSIMOD is used as a platform for more detailed analysis using more focused tools to assess specific metrics, e.g., SAGIS-SIMCAT for water quality source apportionment. Using outputs from more focussed models to inform inputs in WSIMOD, then high-level assumptions around tree coverage and soil types, where the WSIMOD currently lacks precision, may be improved upon. This combined approach, also drawing on ongoing data collection, would be an appropriate strategy as the plan moves into a cycle of implementation, monitoring and improvement.

We believe this method is replicable and would have relevance in other catchments facing interconnected challenges around water quality, high and low flows. Applications may be in support of regional and subregional planning, nutrient neutrality and in drainage and wastewater management planning.

The iconic River Wye faces numerous challenges to restore the natural environment and recreate a thriving landscape with its considerable agricultural, economic, cultural, environmental and social value. The collaborative endeavour in this project and willingness to try innovative methods exhibited in this project provides a platform to address those challenges.

[1] See Withers, Rothwell, Forber et al. (2022) Re-focusing Phosphorus use in the Wye Catchment (zenodo.org)

1 Introduction

The Wye Catchment Partnership (WCP) has reconvened after a period of abeyance during the Covid-19 pandemic and is preparing a new catchment management plan. The Environment Agency has commissioned Mott MacDonald to support the WCP in developing the plan by providing a systems perspective comprising both participatory system mapping (PSM) and integrated water system modelling. With both of these processes, ownership of the catchment management plan remains with the WCP: the facilitation of the system mapping and the modelling are subservient to the development of the catchment management. The WCP has representation from catchment stakeholders in Wales and in England. This project covers the whole catchment on both sides of the border.

A Task and Finish group was set up by the catchment partnership to create the catchment management plan. The establishment of this group occurred after the main work on the PSM and before the modelling. This was a good time for the interaction of this project with the development of the plan because the PSM had created a degree of shared understanding and a spirit of collaboration based on the co-learning function of system mapping. The system maps were used to inform thinking around how change occurs in the catchment (results chains), the challenges and trade-offs in the catchment as a system, and what to measure (the selection of metrics). The system maps were held as live documents and updated to reflect and inform the discussion around the development of the plan. The Task and Finish group were able to engage with the modelling and direct Mott MacDonald on options to be modelled in collaboration with the modelling team.

We refer to the method comprising PSM and integrated modelling in support of the development of a collaborative plan as a Systems approach to Integrated Water Management (SIWM). We use Imperial College London's Water System Integrated Water Model (WSIMOD) for the modelling. In this project the WSIMOD model set up and validation was undertaken by Imperial College London (Annex B).

The Environment Agency's interest in this work is two-fold. Their main aim is to support the development of a plan for a catchment of considerable significance and one that is facing environmental challenges that require an integrated, systemic response. In addition, the Environment Agency have been supporting the development of systems approaches in wider catchment planning. The method used in this project was developed on projects by Defra, the Environment Agency and others, principally including:

- A Systems Analysis for Water Resources. Defra (2020)
- Oxford to Cambridge Arc Integrated Water Management Framework (IWMF) Phase 1. Environment Agency (2022)
- 100108845-5.1-F Sub-regional integrated water management strategy East London Greater London Authority (2023)
- Chalk Stream Systems. Environment Agency (2023)

This report includes a short overview on lessons learnt in order to contribute to the ongoing development of the approach, this is found in Annex E.

2 Approach

This project uses the Systems Integrated Water Management (SIWM) method with the steps shown in Figure 2-1. The SIWM comprises the following steps, undertaken in this case by the associated actors:

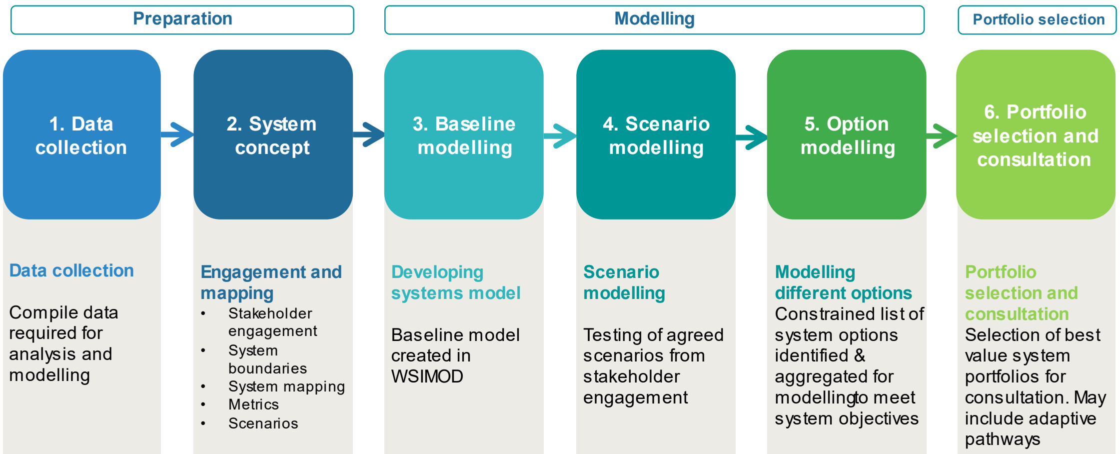
Preparation

1. Data collection
   a. Data collection for the model set-up was undertaken by Imperial College London and is described in Annex B.
   b. Data collection for the preparation of the catchment management plan has been undertaken by the WCP.
   c. Additional data collection for steps 4 and 5 has been undertaken by Mott MacDonald and is described in Annex C.
2. System Concept
   a. The conceptual understanding of the system has been co-created with the WCP through the system mapping and is described in Section 3.

Modelling and Portfolio Selection

3. The baseline modelling is described in Annex B.
4. The scenario model represents a future climate change scenario combined with a projected human population growth scenario for the catchment.
5. Option modelling assesses the impact of different interventions against this future scenario. Two rounds of option modelling were undertaken so that the second round could be informed by the results of the first – thereby the second round produced a more nuanced set of options in combination. Options were informed by the Task and Finish group sub-group.
6. The final portfolio of options to be included in the plan will be created by the Wye catchment partnership. This project has provided guidance for that collaborative planning exercise rather than creating the final portfolio of options on their behalf.

Figure 2-1: Summary of SIWM Method



3 Participatory System Mapping

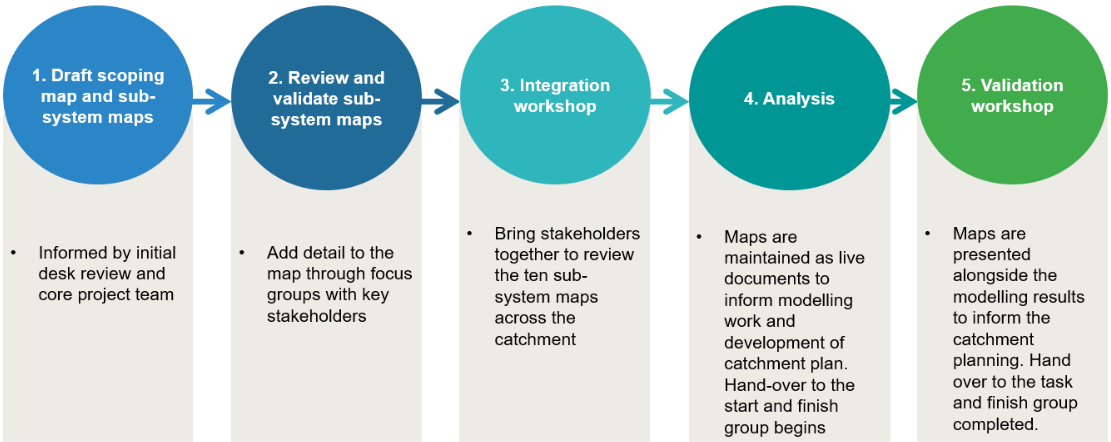
This section outlines our approach to system mapping of the Wye catchment.

3.1 Summary of our Participatory System Mapping method

Participatory System Mapping (PSM) is a collaborative process whereby a system map is co-created through workshops and focus groups with stakeholders and key partners. There is a strong element of co-learning across the participants who engage with the development of the map as they increasingly understand the system from each other's perspectives.

The system map created for the Wye catchment, as part of PSM, provides a baseline understanding of the elements, relationships, and processes within this complex catchment. Our five-step approach is outlined in Figure 3-1.

Figure 3-1: Mott MacDonald's five step approach to participatory system mapping



3.2 High-level Wye catchment map

Figure 3-2 shows the high-level understanding of the Wye catchment mapped as a system.[2] It shows how farming, forestry, tourism, water resources, infrastructure, flooding, and biodiversity all interact with river health. Mott MacDonald held focus groups with members of the catchment partnership working within each area to co-create their detailed sub-system maps (see Section 3.3). We then held an in-person workshop at Llangoed Hall near Brecon on the 7th of December 2023 with 32 attendees (excluding Mott MacDonald). At the workshop, stakeholders were asked to consider what good looks like across the catchment and how change could be implemented through specific interventions and measured through metrics. It generated discussion on how good functioning of the system can achieve the beneficial outcomes that the catchment stakeholders want to achieve. Stakeholders were subsequently asked to review and comment on intervention categories on the system maps and our initial list of metrics.

The high-level system map is available here[3]. Metrics are discussed below and can be shown on this map by using the filter on the top left called "System feature". It is possible to toggle to the planning diagram with the filter on the top left of the screen, next to the word "public". The text panel on the left can be removed by clicking on the diagram and returned by clicking on the

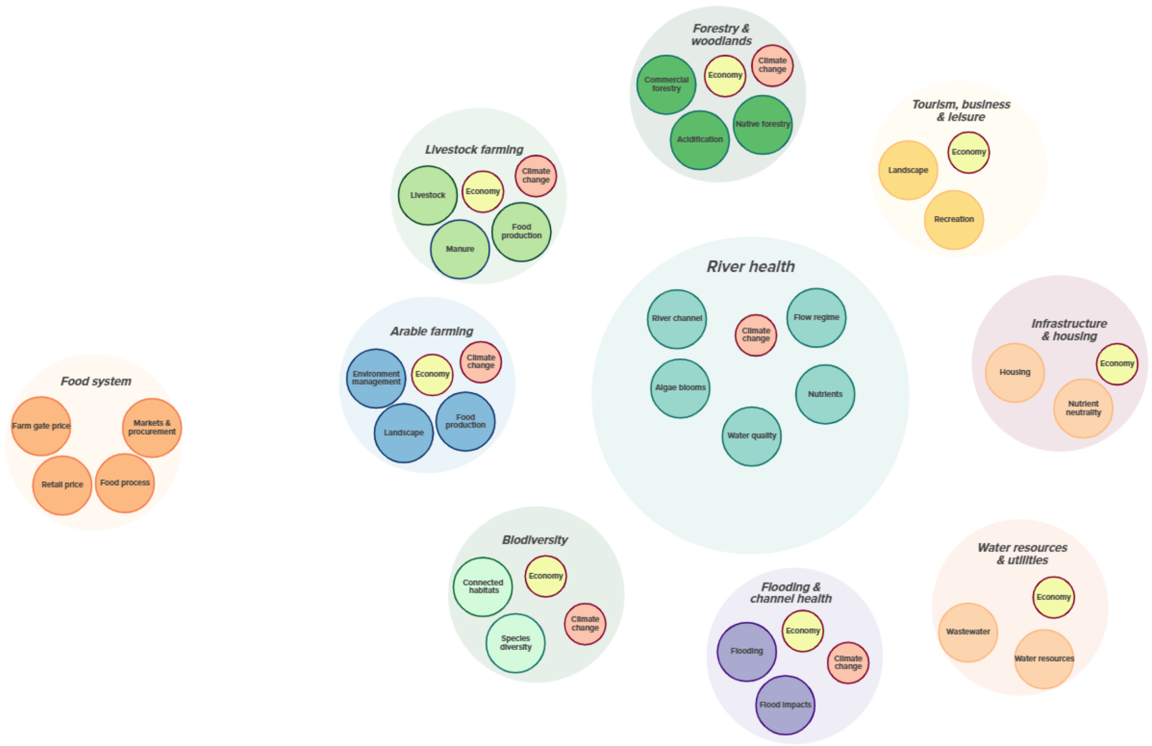
[2] See Figure A. in Annex A for a configuration of the High level system map showing metrics under consideration for the catchment plan.

[3] WPDMMPSMKMV3 • High-level systems map / Untitled view • Kumu

three dots on the left of the screen. The map can be recentred with the button showing two converging arrows on the right of the screen.

Conceptually the map shows a ring of eight subs-systems (Arable farming, Biodiversity etc.) that have interactions with each other many of which are mediated via their interaction with River Health which is the sub-system represented in the middle of the map. The Food sub-system sits on one side because its influence on river health is indirect, mediated via its influence on arable and livestock farming. The focus of the catchment plan is on the subsystems around River Health, but the Food system is included as it is important context that shapes the behaviour of the other systems. Similarly, climate change is another driver of change from beyond the catchment, but in this case it is shown in relation to the sub-systems that it influences.

Figure 3-2: High level Wye catchment system map



Available online here: WPDMMPSMKMV3 • High-level systems map / Untitled view • Kumu

3.3 Detailed system maps

Mott MacDonald held ten focus groups to create sub-system maps for the Wye catchment. The sub-system maps addressed the topics shown at a high level in Figure 3-2. Due to the high level of interest in the development of a plan for the Wye catchment engagement with the mapping was rich creating vibrant discussion about important issues and trade-offs in the catchment.

The detailed system maps show potential interventions and metrics for use in the catchment plan. The lists of interventions and metrics were recorded and have informed the work of the Task and Finish group. The detailed system maps stimulated the creation of those lists, but in light of the high attendance and level of engagement the maps became large (450 nodes) and hard to read. Therefore, the high-level system map, including the planning diagram, are being maintained as live documents and the more detailed map is no longer being maintained and updated. They have served their purpose and the insights are being taken forward with the intervention and metric lists which are live documents. The long list of interventions and metrics derived from the system maps are shown in Annex A both as lists and as annotated versions of the high-level system map and planning diagram.

3.4 Planning diagram

Analysis of the detailed sub-system maps enabled Mott MacDonald to reorganise and summarise the ten sub-system maps into a single planning diagram, as shown in Figure 3-3.[4] This provides a co-ordinating framework for different organisations making plans in the catchment. The primary aim of the high-level plan is for the WCP to identify synergies across different plans being prepared in the Wye.

The high-level map consists of the following categories:

- Intervention categories – the change to the system.
- Intermediate objectives – what the interventions do.
- Outcomes – what the interventions achieve.
- Impact – what the intervention ultimately contributes to that is beyond the original scope of the intervention.

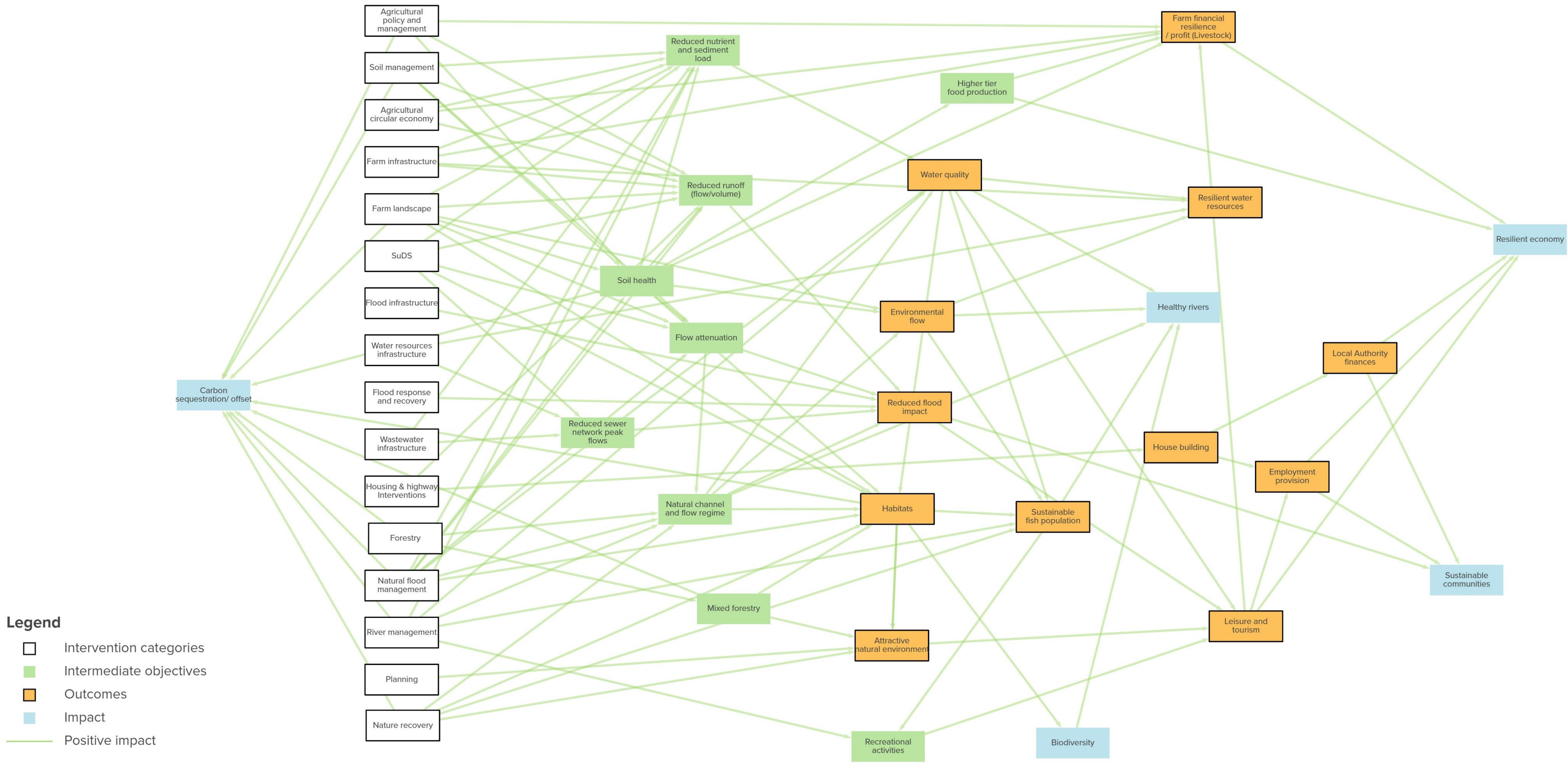
The planning diagram can be filtered to show synergies across agriculture, infrastructure and development, landscape/catchment/river, and social and economic intervention types. It can also be filtered by sub-system, showing which interventions, system objectives or outcomes are relevant for each organisational area operating within the catchment. Metrics can be added to illustrate which part of the planning diagram can be measured through modelling or the WCP plan.

The interactive planning diagram can be accessed on online here[5]. The diagram can be manipulated with the buttons on the screen. Upstream and downstream impacts are foregrounded by selecting a node of interest and pressing the focus button on the right (target sign) and pressing the node impacts or node impacted by button on the lower right. The side panel is removed or returned by pressing the three vertical dots on the left.

[4] See Figure A.2 in Annex A for a configuration of the Planning Diagram showing metrics under consideration for the catchment plan.

[5] WPDMMPSMKMV3 • Planning diagram • Kumu

Figure 3-3: Wye catchment planning diagram



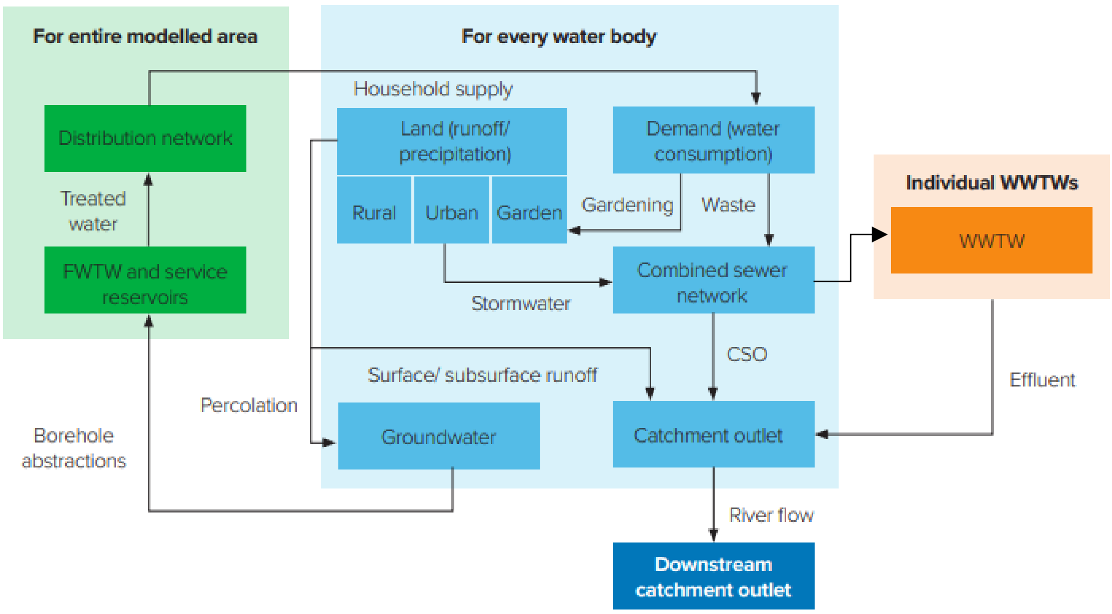
Available online here: [WPDMMPSMKMV3 • Planning diagram • Kumu]

4 Modelling

4.1 WSIMOD Method

The modelling method used is Imperial College London's Water System Integrated Water Model (WSIMOD). WSIMOD is a Python software package which contains modelled representations of many elements of the water cycle. The model framework is shown in Figure 4-1 and is applied as a mass-balance calculation at the spatial resolution of each individual water body catchment. There are 129 water bodies in the Wye catchment. The outputs of the model are timeseries of the river flow and water quality at the outlet of each water body. This modelling was applied across the whole of the Wye catchment. Modelling water quality and water resources together integrates the key variables in water resource, environment, and wastewater planning. The model allows for future scenarios and potential intervention options to be modelled and the likely impact of them on the river flows and water quality to be quantified. This can then be used to inform the catchment management plan.

Figure 4-1: WSIMOD Modelling Framework



4.1.1 Limitations of WSIMOD Method

WSIMOD models a number of different parameters across flow, flow variability and water quality. Other models tend just to model one variable – flow or one aspect of water quality. Models that focus on one variable are more accurate and can be calibrated with greater certainty than models that consider a range of variables concurrently. As such, the role of WSIMOD is to give the high-level view across the way the catchment works as a system – indicating synergies and trade-offs between flood and water quality management for example. But WSIMOD does not provide the accuracy of the more targeted models.

- The model provides a broad picture not detail.
- The spatial and temporal resolution isn't as detailed as some other models. For example, local variability of soil type is not addressed.

- Only certain locations are validated for flows and water quality, rather than whole geographical area.
- The spatial resolution of the model is at waterbody scale and input parameter variations within a single waterbody are not accounted for.

WSIMOD is a useful tool in the early stages of the development of a catchment plan. It shows where to concentrate effort and acts as a range-finding tool for the scale of interventions that could be made. Most importantly it shows the big picture indicating benefits across different catchment outcomes such as flooding, drought, water quality and water resources. Care should be used in interpreting the results – they should not be read as if they were outcomes from a more targeted model with a comprehensive calibration. WSIMOD doesn't consider specific actions, such as buffer strips, but it does show the combined impact of nutrient reductions at the water body level aggregated up across the entire catchment.

It is also important to note that modelling the water system in the catchment should not mean that water is the only medium of contaminant transport that matters. For example, the presence of ammonia gas emissions from agriculture and other sources, and the potential formation and deposition of ammonia particulate matter (e.g., ammonium sulphate or ammonium nitrate) in water, is relevant but is not addressed in this modelling exercise.

4.2 Baseline Model

The baseline catchment model was set up and developed by Imperial College London. The baseline model has catchment specific input information on climate (precipitation, temperature, and evapotranspiration), rural (river network, land cover, crop surfaces, nutrients load) and urban (population, garden area and foul catchments) systems and water resources. The model was validated using publicly available daily flow observations from the National River Flow Archive and monthly water quality data. A copy of the detailed baseline modelling report can be found in Annex B.

4.3 Modelling Metrics

The catchment metrics modelled using WSIMOD are as follows:

- Flow metrics:
  - Q95 – flow rates are greater than this value for over 95% of the time. This is an indicator of low flows and drought conditions.
  - Q5 – flow rates are greater than this value only 5% of the time. This is an indicator of high flows.
  - Q0.3 – flow rate is only higher than this once a year. This is an indicator of flood risk.
- Water quality:
  - The solutes included in the metrics are Soluble Reactive Phosphorus (SRP), organic phosphorus and Dissolved Inorganic Nitrogen (DIN).
  - Each of these solutes were assessed at the 5th percentile (peak concentrations), 95th percentile (background concentrations) and average concentrations (mean).
  - The selection of these solutes for metrics was based upon the fact that they had been validated in the baseline model by Imperial College London and are therefore considered more reliable.

The locations provided for these metrics in the results section are selected because they have the highest degree of validation in the baseline model, see Annex B for more information on model validation.

4.4 Scenario Modelling

A future scenario was developed in collaboration with a working group from the WCP catchment management plan Task and Finish group. It was agreed by the Task and Finish group to develop one future scenario only and run all options against it. The future scenario included climate change using RCP8.5 of the UK Climate Projections, and principal human population growth projections from ONS and StatsWales for England and Wales respectively. For more detailed information on scenario modelling refer to Annex C.3.

4.5 Options Modelling

Options are modelled representations of different interventions within the Wye catchment that could be included in the Wye catchment management plan. Option development was highly influenced by the capabilities of WSIMOD. Options modelled within WSIMOD were developed in collaboration with a sub-group from the catchment management plan Task and Finish group. For more details on the decision-making process refer to the record of meetings in Annex F.

Some options include the different treatment of the river in England and in Wales. The use of national boundaries operates in this case primarily as the distinction between the upland areas and lowland areas for which the national boundary provides a reasonable proxy and is aligned with convenient boundaries in the input data. Adopting this proxy creates a significant efficiency in the modelling meaning more options can be modelled within the project budget and timelines.

Option modelling was undertaken in two rounds so that the results of the first modelling round were known and understood by stakeholders before the magnitude of options in the second round were selected.

The options were developed in five categories:

- Changes to tree cover in the catchment.
- Changes to manure and fertiliser application rates in the catchment.
- Changes to physical soil properties in the catchment.
- Wastewater Treatment Works (WwTW) upgrades.
- Option 4A stands alone in being a decrease in physical soil health properties relating to the development of a low permeability layer in the soil caused by surface compaction.

The options were all modelled against the future scenario.

Round 1 of option modelling completed modelling of the following options:

- Option 1A: Tree coverage increased from 13% to 23%, and all other land use types decreased proportionately.
- Option 2A: Manure and fertiliser application reduced by 49% and 75% respectively uniformly across the catchment as per RePhoKus drawdown scenario recommendations[6].
- Option 4A: Impact of **decreased** physical soil health. Soil percolation coefficient decreased by 50% for all agricultural land across the catchment.
- Option 5A: WwTW upgrades were modelled as per the organic phosphorus removal improvements in datasets provided. 7 out of 16 major WwTWs in the catchment have planned upgrades and the average improvement in phosphorus removal to those works with upgrades was 17%.

[6] Withers, Rothwell, Forber et al. (2022) Re-focusing Phosphorus use in the Wye Catchment (zenodo.org)

Round 2 of option modelling completed modelling of the following options:

- Option 1B: Tree coverage increased from 13% to 30%, and all other land use types decreased proportionately. This increase to 30% was inspired by the global 30by30 target to protect 30% of land for biodiversity conservation by 2030 adopted at the UN Biodiversity Summit COP15 in December 2022[7]. It is recognised that 30% tree cover is an ambitious interpretation of the 30by30 commitment.
- Option 2B: Manure and fertiliser application reduced by 35% and 75% respectively uniformly across the catchment as per RePhoKus balance scenario recommendations[8].
- Option 2C: Manure and fertiliser application reduced by 25% and 25% respectively uniformly across the catchment.
- Option 3: Improved soil health is applied to a proportion of agricultural land. For agricultural land that is considered to have improved soil health the percolation coefficient and field capacity are increased
  - Option 3A: Applied to 40% of agricultural land in England and 20% of agricultural land in Wales. For land that is improved, percolation coefficients were increased by 30% and field capacity increased by 10%.
  - Option 3B: Applied to 65% of agricultural land in England and 40% of agricultural land in Wales. For land that is improved, percolation coefficients were increased by 30% and field capacity increased by 10%.
  - Option 3C: Applied to 40% of agricultural land in England and 20% of agricultural land in Wales. For land that is improved, percolation coefficient was increased by 50% and field capacity increased by 10%.
  - Option 3D: Applied to 65% of agricultural land in England and 40% of agricultural land in Wales. For land that is improved, percolation coefficient was increased by 50% and field capacity increased by 10%.

Combination of options

The modelled options were also run in combination to understand the effects of combining several options at the same time. It was agreed with the sub-group of the Task and Finish group to run a lower and a higher magnitude combination portfolio. For the lower combination portfolio the lower magnitude option from each category was selected and vice versa for the higher combination portfolio. The lower combination was run with two permutations – one to include the RePhoKus balance scenario and one to include the lower reductions of 25% manure and fertilisers. The harmful option of decreased soil permeability is not included in the combination portfolios. The summary of each combination portfolio is given below.

Combination A – lower magnitude with RePhoKus balance:

- Option 1A – Tree cover: absolute 10% increase, from 13% to 23%
- Option 2B – Fertiliser and manure reduction: RePhoKUs balance scenario, fertiliser 75%, manure 35%
- Option 3A – Improved soil health: Percolation coefficient increased by 30%; Field capacity increased by 10%; 40% of agricultural land in England; 20% of agricultural land in Wales.
- Option 5A – WWTW upgrades: 7/16 major WwTW had upgrades, average improvement in phosphorus removal to those works with upgrades was 17%.

[7] Delivering 30by30 on land in England (publishing.service.gov.uk)

[8] Withers, Rothwell, Forber et al. (2022) Re-focusing Phosphorus use in the Wye Catchment (zenodo.org)

Combination B – all higher magnitude options:

- Option 1B – Tree cover: absolute 17% increase, from 13% to 30%
- Option 2A – Fertiliser and manure reduction: RePhoKUs drawdown scenario, fertiliser 75%, manure 49%
- Option 3D – Improved soil health: Percolation coefficient increased by 50%; Field capacity increased by 10%; 65% of agricultural land in England; 40% of agricultural land in Wales.
- Option 5A – WWTW upgrades: 7/16 major WwTW had upgrades, average improvement in phosphorus removal to those works with upgrades was 17%.

Combination C – lower magnitude with 25% manure and fertiliser reductions:

- Option 1A – Tree cover: absolute 10% increase, from 13% to 23%
- Option 2C – Fertiliser and manure reduction: fertiliser 25%, manure 25%
- Option 3A – Improved soil health: Percolation coefficient increased by 30%; Field capacity increased by 10%; 40% of agricultural land in England; 20% of agricultural land in Wales.
- Option 5A – WWTW upgrades: 7/16 major WwTW had upgrades, average improvement in phosphorus removal to those works with upgrades was 17%.

More detailed information on modelling assumptions and methods is available in Annex C.

4.6 Modelling Results

The headline results from the modelling are that the management of soils, and in particular infiltration, across the catchment has the greatest positive impact on flows, and that the management of manures and fertiliser has the greatest positive impact on water quality.

Modelling baseline conditions against climate change and growth scenarios (Figure 4-2) delivers the results we would expect to see i.e. more high flow events in winter (Q0.3 and Q5), more low flow events in summer (Q95), and reduced water quality (resulting from increased phosphorus (SRP) and organic phosphorus levels). The results show this scenario could decrease flows during a drought by up to 11%, increase high flows during a 1 in 1 year flood by 8%, increase mean soluble reactive phosphorus (SRP) by 20% and increase mean organic phosphorus by 18%.

Impacts on flow

Options to improve soil health by increasing infiltration improve the observed flows (Figures 4-3 and 4-4), particularly in the upper catchment. Increasing the area of agricultural land that this option applies to has a much greater impact than increasing percolation/infiltration rates. Reducing infiltration has the opposite effect resulting in a small increase in high flow events but a much more significant increase in low flow events. This suggests that land management measures, in the upper catchment in particular, need to focus on improving soil health by increasing soil infiltration. If infiltration reduces in the future (e.g., through increased soil compaction or reduced organic content) this will have a significant adverse impact on flows in the upper catchment (as shown by the modelled results for option 4A).

The model indicates that tree cover has a very small impact on flows which is not what we would expect to see. This is due to an underestimation of the impact of tree cover on soil health properties (see Appendix C.4.1.2). We would also expect some of the benefits seen in modelling Option 3 (soil health improvements) to apply whereas we would anticipate that this option would include tree planting in the list of measures.

The impact of the various flow option combinations (Figures 4-5 and 4-6) are dominated by the impact of the soil health option included for each. This highlights the importance of good soil health and good infiltration on flow management, in particular for low flow events.

Impacts on water quality

Options to reduce manure and fertiliser application across the catchment results in significant water quality improvements with a significant impact on dissolved inorganic nitrogen (DIN) and soluble reactive phosphate (SRP). There is a relatively small difference in water quality improvements between option 2A (49% manure/75% fertiliser reduction) and 2B (35% manure/75% fertiliser reduction), but a significant difference compared to option 2C (25% manure/25% fertiliser reduction) as shown in Figure 4.7 and Annex D.

Water quality improves in the upper catchment as a result of improved soil health. In the lower catchment and in the Lugg catchment there is an improvement in the concentration of soluble reactive phosphorus and dissolved inorganic nitrogen, but organic-phosphorus declines (Figure 4.7 shows the water quality results for the bottom end of the River Wye). A change in soil percolation rate from 30% to 50% has little impact on water quality but improving soil health across a greater area of land significantly increases the impact. These results support improving soil health at large-scale with a focus on a 30% increase in percolation/infiltration to deliver improved water quality. It should be noted that, due to the nature of the modelling approach with one node per catchment, phosphorus ends being represented in the model as a diffuse source across the catchments, potentially resulting in lower concentrations of ammonia in water at a local level.

Increasing tree cover will improve water quality with increased percentage cover leading to increased water quality improvements (Table 4-1).

The results for upgrading wastewater treatment works are as expected, with phosphorus removal at the works resulting in reduced phosphorus concentrations, particularly in the lower Wye. Decreasing water quality can be seen during periods of low flows and is seen to be more acute during August (the Environment Agency reference summer month) as would be expected.

The modelling indicates that an ambitious combined portfolio of options could achieve up to 15% increase in the magnitude of low flows during a drought, and a 2% reduction in high flows during a 1 in 1 year flood event. A combined portfolio could achieve reductions in dissolved inorganic nitrogen (DIN) by 35-72%, soluble reactive phosphorus (SRP) reductions between 29-82% and organic phosphorus reduction between 25-57% depending on the location within the catchment.

Figure 4-2: Comparison of Baseline model run and Scenario with climate change RCP8.5 and population growth.

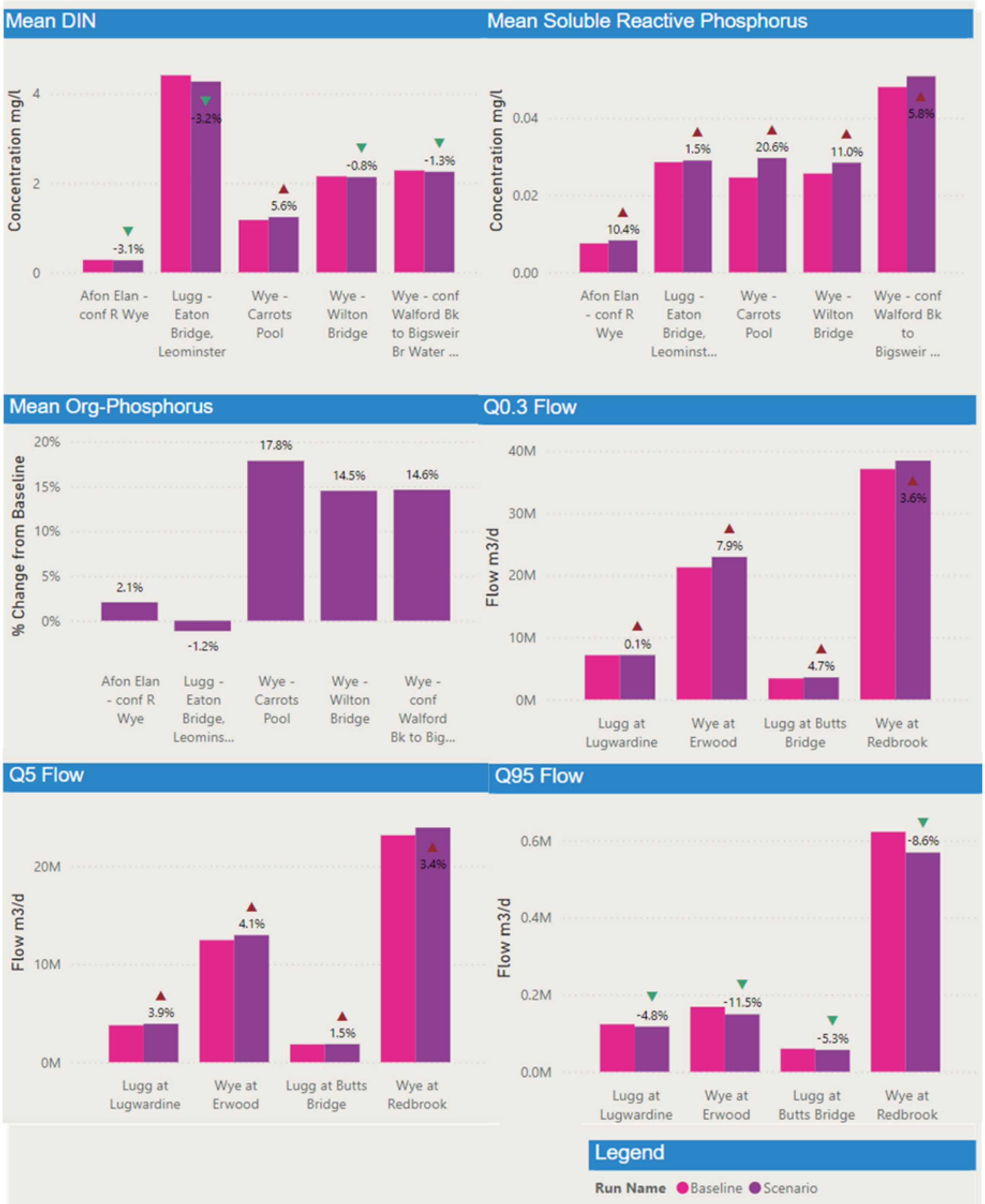


Figure 4-3: Impact of individual options on high flows (Q0.3)

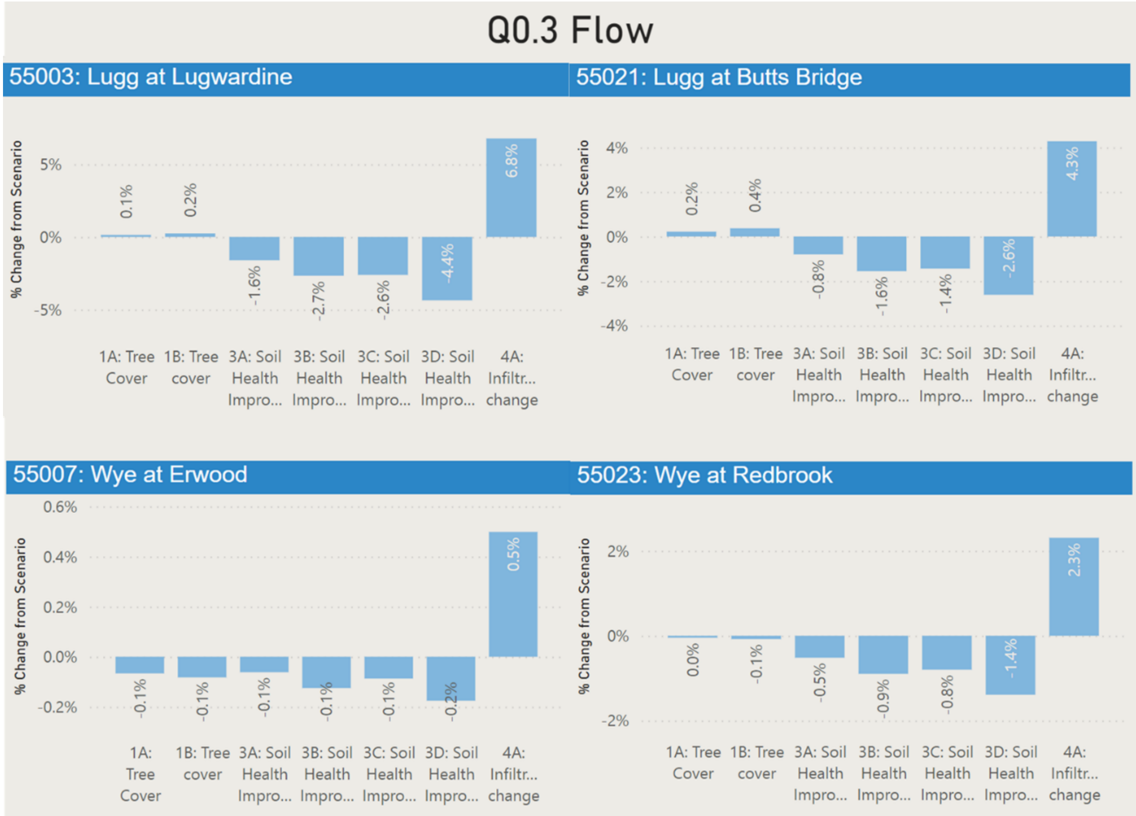


Figure 4-4: Impact of individual options on low flows (Q95)

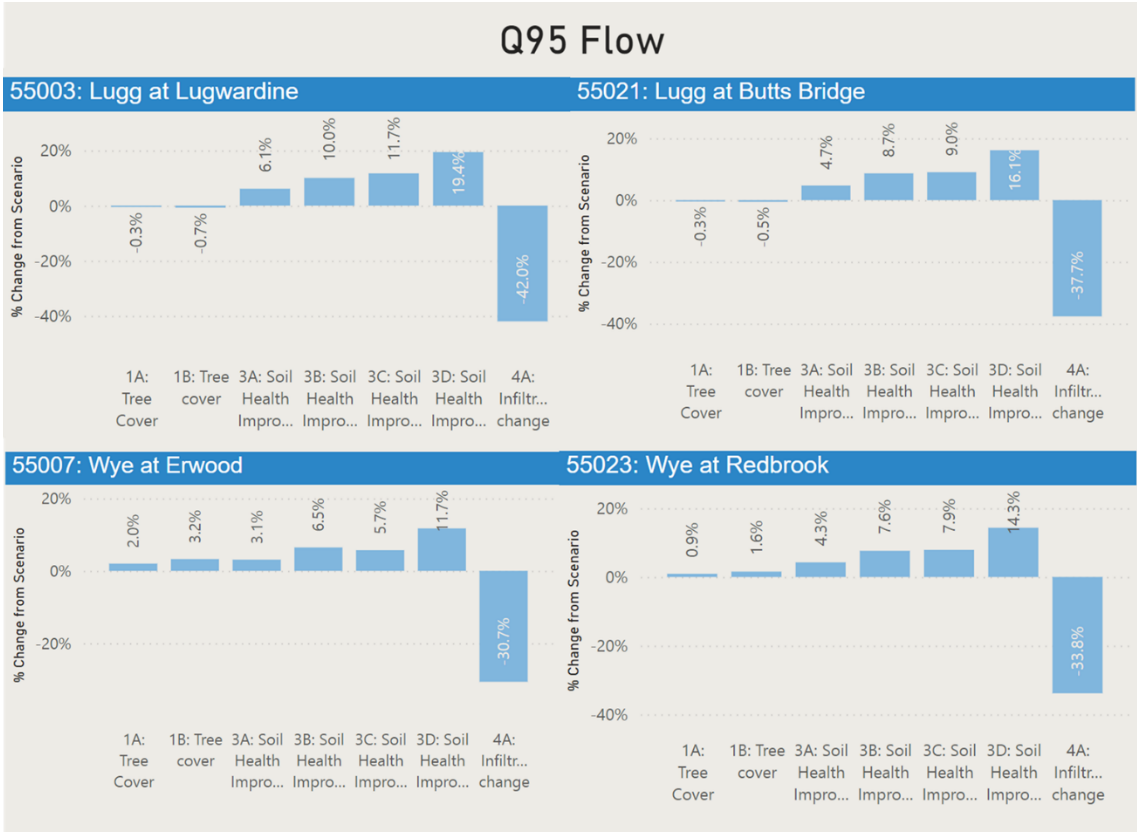


Figure 4-5: Impact of combined options on very high flows (Q0.03)

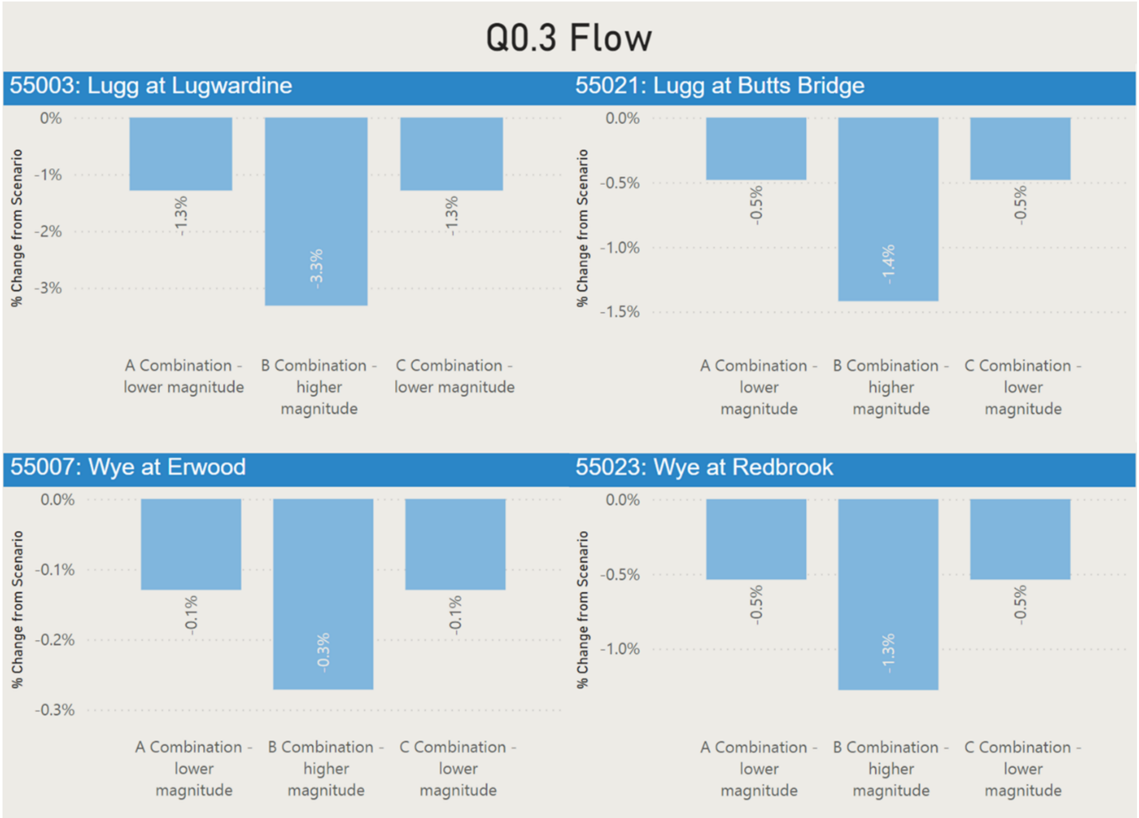


Figure 4-6: Impact of combined options on low flows (Q95)

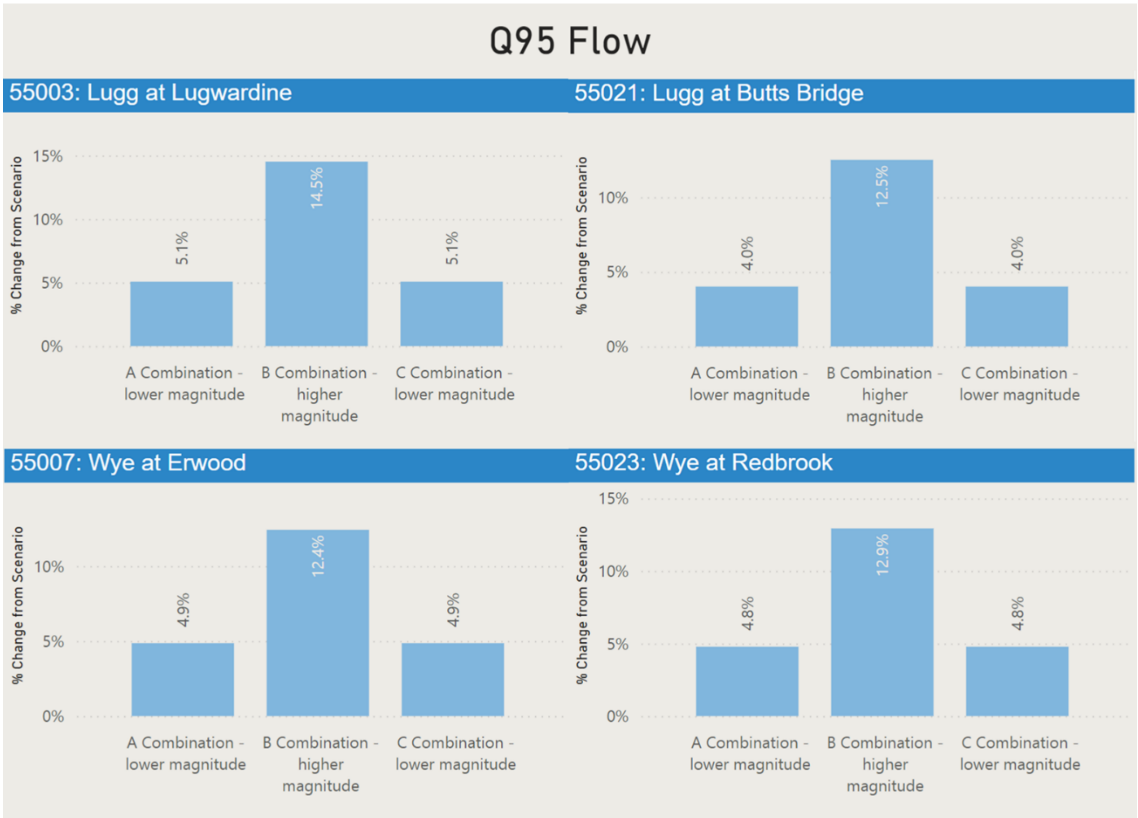
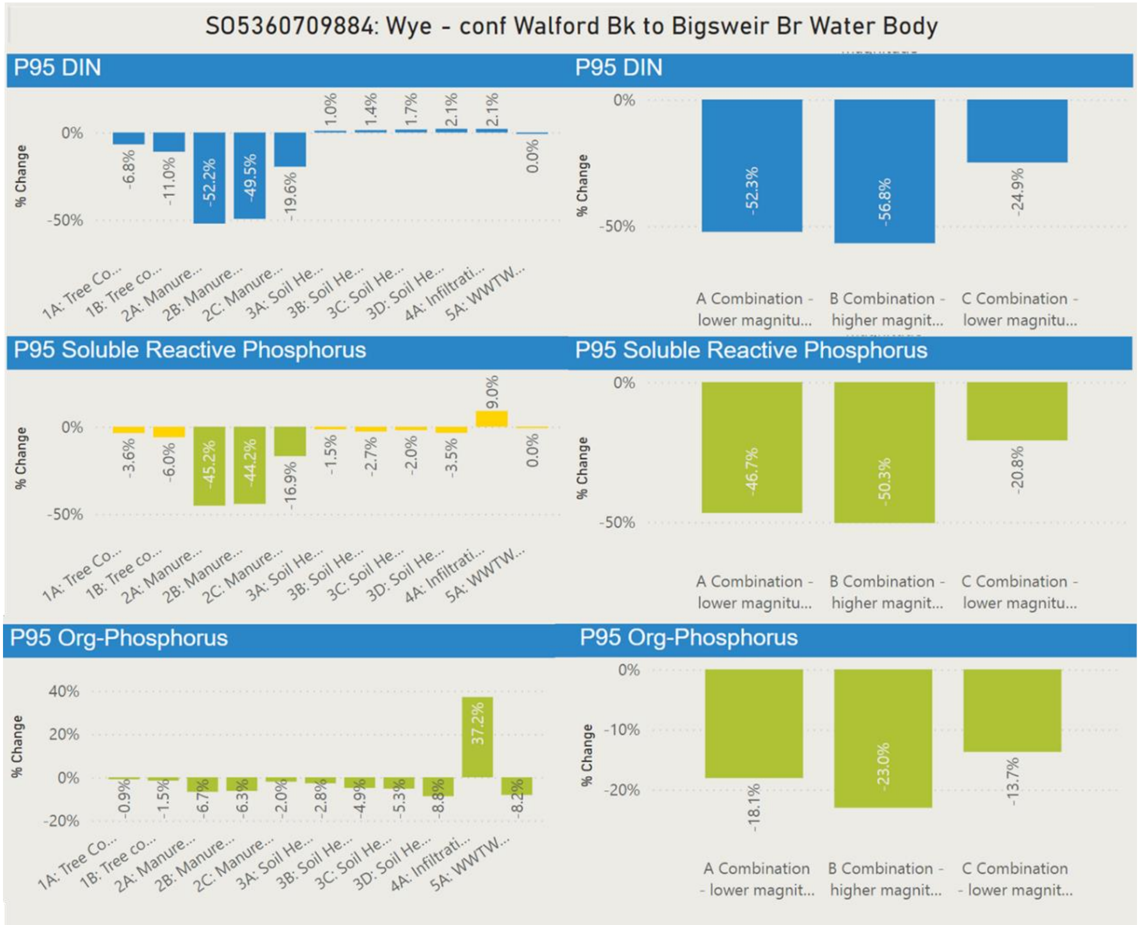


Figure 4-7: Impact of 95th percentile of concentration of DIN, SRP and Org-Phosphorous at downstream monitoring point, Wye – conf Walford Bk to Bigsweir Br Water Body



Note: Water quality graphs for other monitoring locations in the catchment are provided in Annex D.

Table 4-1: Summary of option modelling results – Table 1

Option 1A	Option 1B	Option 2A	Option 2B	Option 2C
Tree cover increased from 13% to 23%	Tree cover increased from 13% to 30%	49% manure and 75% fertiliser reduction	35% manure and 75% fertiliser reduction	25% manure and 25% fertiliser reduction
Flows: • Very small change in flows (<2%) • Change depends on where in the catchment, as tree cover varies across the catchment. **Water quality:** • Improved water quality across the catchment. • Average DIN reduction 5.1% to 7.9% • Average SRP reduction 2.9% to 6.5% • Average organic phosphorous reduction 0.2% to 1.7%	**Flows:** • Very small change in flows (<3%) • Change depends on where in the catchment, as tree cover varies across the catchment. **Water quality:** • Improved water quality across the catchment. • Average DIN reduction 8.5% to 13.2% • Average SRP reduction 4.8% to 10.6% • Average organic phosphorous reduction 0.3% to 2.9%	**Flows:** • No impact **Water quality:** • Significant improvement across the catchment and across pollutants • Average DIN reduction 31.7% to 67.8% • Average SRP reduction 22.9% to 78.8% • Average organic phosphorous reduction 8% to 56% • Note: Reduction values were taken from the RePhoKUs Catchment zero drawdown scenario and therefore significant.	**Flows:** • No impact **Water quality:** • Significant improvement across the catchment and across pollutants • Average DIN reduction 29.4% to 63.4% • Average SRP reduction 22.4% to 77.3% • Average organic phosphorous reduction 7.5% to 52.2% • Note: Reduction values were taken from the RePhoKUs Catchment zero balance scenario and therefore significant.	**Flows:** • No impact **Water quality:** • Significant improvement across the catchment and across pollutants • Average DIN reduction 12.2% to 28% • Average SRP reduction 3.2% to 25.1% • Average organic phosphorous reduction 2.6% to 17.6%

Table 4-2: Summary of option modelling results – Table 2

Option 3A	Option 3B	Option 3C	Option 3D	Option 4A	Option 5A
Improved soil health – 40% agricultural land England, 20% agricultural land Wales. Increased percolation by 30% on improved land.	Improved soil health – 65% agricultural land England, 40% agricultural land Wales. Increased percolation by 30% on improved land.	Improved soil health – 40% agricultural land England, 20% agricultural land Wales. Increased percolation by 50% on improved land.	Improved soil health – 65% agricultural land England, 40% agricultural land Wales. Increased percolation by 50% on improved land.	Impact of Infiltration rates on flooding – Percolation coefficient decreased by 50% for all agricultural land (negative option)	WwTW upgrades
Flows: • Magnitude of low flows (Q95) increased between 4.3% and 5.7% in the Lugg and lower Wye, 2.9% Upper Wye. • Magnitude of high flows (Q0.3) decrease between 0.5% and 1.2% **Water quality:** • Small impact on water quality, varying across the catchment. • Average DIN varies from reduction of 1% to increase of 0.7% • Average SRP reduction 1.7% to 2.5% • Average organic phosphorous reduction 1.3% to increase 3.3%	**Flows:** • Magnitude of low flows (Q95) increased between 7.6% and 9.9% in the Lugg and lower Wye, 5.7% Upper Wye. • Magnitude of high flows (Q0.3) decrease between 0.9% and 2% **Water quality:** • Small impact on water quality, varying across the catchment. • Average DIN varies from reduction of 2.1% to increase of 0.5% • Average SRP reduction 3.2% to 4.3% • Average organic phosphorous reduction 2.4% to increase 5.5%	**Flows:** • Magnitude of low flows (Q95) increased between 7.9% and 11% in the Lugg and lower Wye, 5.3% Upper Wye. • Magnitude of high flows (Q0.3) decrease between 0.6% and 1.9% **Water quality:** • Small impact on water quality, varying across the catchment. • Average DIN reduction 1.1% to increase 1.7% • Average SRP reduction 1.8% to 2.6% • Average organic phosphorous reduction 2.8% to increase 3.4%	**Flows:** • Magnitude of low flows (Q95) increased between 14.2% and 18.6% in the Lugg and lower Wye, 10.5% Upper Wye. • Magnitude of high flows (Q0.3) decrease between 1.1% and 3.3% **Water quality:** • Small impact on water quality, varying across the catchment. • Average DIN reduction 2.3% to increase 2.4% • Average SRP reduction 3.5% to 4.9% • Average organic phosphorous reduction 4.7% to increase 5.8%	**Flows:** • Magnitude of low flows (Q95) decrease between 28.4% and 40.2% • Magnitude of high flows (Q0.3) decrease between 0.1% and 5.6% **Water quality:** • Average DIN reduction 3.2% to increase 8.1% • Average SRP increase from 0% to 16.7% • Average organic phosphorous increase 0% to 20.4%	**Flows:** • No impact **Organic phosphorus:** • Decrease in phosphorus concentration observed in the downstream locations. • Decrease of 8.3% observed at Wye – conf Walford Bk to Bigsweir Br

Table 4-3: Summary of option modelling results – Table 3 (Combined Option Portfolios)

Combination A	Combination B	Combination C
Lower magnitude – RePhoKus Balance Scenario 1A, 2B, 3A, 5A	Higher magnitude – RePhoKus Drawdown Scenario 1B, 2A, 3D, 5A	Lower magnitude – not RePhoKus 1A, 2C, 3A, 5A
Lower magnitude of all options apart from manure which is middle magnitude.	Higher magnitude of all options	Lower magnitude of all options
Flows: • Mostly governed by 3A (Improved soil health) • Impact of 1A (Tree cover) on low flows observed in Upper Wye. • Magnitude of low flows (Q95) increased between 4.3% and 4.9% across catchment. • Magnitude of high flows (Q0.3) decrease between 0.8% and 1.0% **Water quality:** • Impact governed by 2B (fertiliser and manure reduction). • Average DIN reduction 30.2% to 66.2% • Average SRP reduction 25.1% to 79% • Average organic phosphorous reduction 20.5% to 52.9%	**Flows:** • Mostly governed by 3A (Improved soil health) • Impact of 1A (Tree cover) on low flows observed in Upper Wye. • Magnitude of low flows (Q95) increased between 11.5% and 14.4% across catchment. • Magnitude of high flows (Q0.3) decrease between 1.1% and 2.3% **Water quality:** • Impact governed by 2A (fertiliser and manure reduction). • Average DIN reduction 35.5% to 72.2% • Average SRP reduction 28.7% to 81.5% • Average organic phosphorous reduction 24.5% to 57.2%	**Flows:** • As seen in Combination A **Water quality:** • Combined impact of 2C (fertiliser and manure reduction) and 1A (tree cover) • Impact of WWTW upgrades seen in downstream nodes • Average DIN reduction 17% to 33.5% • Average SRP reduction 6.4% to 31.9% • Average organic phosphorous reduction 13.6% to 18.1%

5 Conclusions and Next Steps

5.1 Conclusions

The significance of this project lies in its process as well as the outcomes. The PSM was a process that enabled detailed consideration of complex and, at times, contested topics within the catchment. The process led to the production of a long list of interventions and metrics that are now being taken forward in a collaborative planning exercise in the catchment management plan Task and Finish group. The PSM created progression between wide deliberative engagement and towards the drafting of a manageable plan. As one participant observed “it took the WCP from the storming phase to the norming phase”. The invitation to join the catchment management plan Task and Finish group was open to all attendees of the WCP meetings and a sub-group of this group guided the option modelling again showing the social function of this work in representing an opportunity for substantive collaboration in collective analysis underpinning the emerging catchment plan.

The system mapping and metric selection drew attention to the fact that there are things that can be changed within the catchment, such as improvement of soil health, and there are systemic realities beyond the catchment that influence the catchments, such as the social and economic drivers around costs and revenues in the food system. A recurring theme in discussions around the project was the need to highlight political issues in the wider systemic context to political actors beyond the catchment, but yet to come together to produce a workable plan that addresses issues over which actors in the catchment plan have direct control and influence – which are the focus of the catchment plan.

The modelling highlighted the following links between catchment function and outcomes:

- Climate change and population growth will apply further pressures to the catchment. Modelling showed that without interventions this scenario could decrease the magnitude of low flows during a drought by up to 11%, increase high flows during a 1 in 1 year flood by 8%, increase mean SRP by 20% and increase mean organic phosphorus by 18%.
- To reduce the magnitude of low flow events, land management measures, in the upper catchment need to focus on improving soil health by increasing soil infiltration over large areas of land. An option of improved soil health in 40% agricultural land England and 20% agricultural land Wales, with an increased percolation of 30% on improved land and found the magnitude of low flows (Q95) increased between 4.3% and 5.7% in the Lugg and lower Wye and 2.9% Upper Wye. In this option the magnitude of high flows (Q0.3) decreases from between 0.5% and 1.2%. These results are enhanced if more soil is improved and if greater increases in infiltration can be achieved. The planning diagram (Figure 3-3) enables us to identify the types of intervention category that could support this e.g., soil management, farm landscape and natural flood management, alongside agricultural policy changes to enable change.
- The results show that if infiltration rates were to reduce in the future (e.g., through increased soil compaction and declining soil health) there will be a significant adverse impact on flows in the upper catchment – worsening drought conditions and increasing the magnitude of high flows. Measures to retain and improve infiltration in the future are therefore critical.
- The management of manures and fertiliser application has the greatest positive impact on water quality. We found a reduction in 25% manure and fertiliser entering the river reduced the average DIN by 12.2% to 28%; the average SRP by 3.2% to 25.1% and the average organic phosphorous by 2.6% to 17.6% depending on the location in the catchment.

- Our results suggest that the RePhoKUs catchment zero balance scenario provides the best option for nutrient reduction across the catchment. This ambitious option would comprise a 49% manure and 75% fertiliser reduction. Although the main focus lies with reducing nutrient inputs from agriculture, the high-level catchment planning diagram also identifies intervention categories for sustainable urban drainage schemes, natural flood management, and river management to support nutrient load reductions.
- The model results show that increasing tree cover will result in water quality improvements, with average DIN reductions of 9-13% and average SRP reductions between 5-11% in the more ambitious tree cover option. Increasing tree cover will also support improving soil health and the flow regulation benefits associated with improved infiltration rates.
- WwTW upgrades will improve water quality, but the required improvements are being driven by regulatory requirements and 'fair share' principles and major improvements should be in place by 2030. This means there is limited opportunity to further improve water quality significantly through this option.

5.2 Next Steps

The metrics and interventions lists created through the PSM have an important democratic legitimacy as a result of the process by which they have been produced. These are informing the development of the catchment plan which is drawing on this work but not beholden to it because the final selection of metrics and interventions needs to be created as a coherent whole on the basis of ongoing engagement and development of the catchment management plan. The use of the high-level system map and planning diagram as a means of articulating and communicating ongoing development of the plan should be considered.

The planning diagram and high-level system maps represent a significant investment across participants of the catchment partnership. These online outputs should be used as live management tools.

The online maps show what the catchment partnership will be measuring and why. The distribution of metrics across the maps shows where the focus of scrutiny is in the plan and by contrast comparative gaps in the monitoring. These maps should form the basis of a monitoring evaluation and learning (MEL) framework for the WCP catchment management plan that sets out how to measure impact, evaluate success and continually improve the plan. Mapping the MEL enhances stakeholder engagement and is therefore enhanced as a tool for mutual accountability across the partnership.

The planning diagram has potential as a coordination tool. There are a number of important plans being made for farming, nutrient management, nature recovery and landscapes that overlap with, and are part of the catchment management plan. The planning diagram could be filtered to show which plans are represented in the overall umbrella plan that the catchment plan represents.[9] The maps could show how different metrics for different plans apply in different locations across the catchment and these could be enhanced by tagging metrics according to type of monitoring or responsibility for monitoring. The system map would represent a single source of truth that would enable coordinated implementation and MEL for the different plans.

The WSIMOD analysis has indicated the big picture in relation to what can be achieved in the catchment and priorities for intervention. This analytical work creates a platform for more detailed analysis with more focussed tools such as SAGIS-SIMCAT. It would be appropriate to follow up with more detailed modelling to address specific issues such as refining the analysis of soil health.

[9] Currently the planning diagram can be filtered with buttons on the top of the map to reflect agriculture, infrastructure & development etc. Similar filters could be applied to identify different plans.

The model set up and creation of the approach represents a significant investment. As further data is collected, the model could be updated with improved baselining and enhanced option analysis as the plan is taken forward and refreshed. This tool has potential for further development with the integration of live data and artificial intelligence (AI) tools as part of a digital monitoring and management platform. As the plan moves into implementation then the management could be further enhanced by linking a correspondence and catchment management function to the digital platform. These digital approaches would be appropriate and cost effective in the development of a plan that had a high level of engagement with landowners, farmers and other landscape stakeholders – as will be required to address the challenges the Wye catchment faces both now and with the future impacts of population growth and climate change.

Application elsewhere

This project has further developed a method implemented to good effect in the Sub-Regional Integrated Water Management Strategy for East London, building the original conceptual work undertaken for the Oxford to Cambridge Integrated Water Management Framework.[10] These origins highlight the applicability of the method to sub-regional planning where an ambition exists to move beyond single planning frameworks to integration across water resources, water quality, flooding and environmental management. This project has gone further by having two rounds of option portfolio development driven by stakeholder choice to inform the catchment plan. The high-level configuration of system maps retains the value of co-creation and communicates collective insights with greater clarity. As such this project represents a maturing innovation that would be relevant in a new round of regional and subregional planning in the water sector. The method has relevance to drainage and wastewater management plans where catchments have complex interconnected challenges across water quality and flooding. It has potential to help water companies create synergies between water resource management plans (WRMP) and drainage and wastewater management plans (DWMP). The method enables investigation of synergies and trade-offs across different interconnected planning domains. The approach is particularly relevant to catchments with nutrient management challenges where there is potential for more joined up methods to create synergies with other catchment objectives such as flooding, water resources and nature recovery.

Final remarks

The iconic River Wye catchment faces numerous challenges to restore the natural environment and recreate the thriving landscape with its considerable agricultural, economic, cultural, environmental and social value. The collaborative endeavour in this project and willingness to try innovative methods exhibited in this project provides a platform to address those challenges.

[10] For a review of lessons learned on previous projects see Annex E. For more on the work in London see Whaley, M.E. et al. (2024) Implementing a systemic approach to water management: piloting a novel multi-level collaborative integrated water management framework in east London | Journal of Water Supply: Research and Technology-Aqua | IWA Publishing (iwaponline.com)

A. Interventions, metrics and annotated system maps

The long list of interventions derived from the detailed system maps are classed as Tier 2 interventions. These interventions were grouped into higher-level Tier 1 intervention categories (see Table A.1-Table A.4).

The long list of metrics derived from the detailed system maps is given in Table A.5.

Table A.1: Tier 1 intervention categories with associated Tier 2 interventions for Agriculture intervention types:

Tier 1 category	Tier 2 intervention
Agricultural circular economy	AD permits allow wider range of waste product inputs
Agricultural circular economy	Livestock manure for export
Agricultural circular economy	Reduce livestock numbers
Agricultural circular economy	Management of manure via AD/incineration
Agricultural circular economy	Recovery of P
Agricultural circular economy	Reduce P in animal feeds
Agricultural policy and management	Appropriate technology uptake
Agricultural policy and management	Regulation, planning & enforcement for agricultural practices
Agricultural policy and management	Advice & guidance for farmers on best practices
Agricultural policy and management	Rural PV
Farm infrastructure	Appropriate land drainage
Farm infrastructure	Farmyard SuDS
Farm infrastructure	Good slurry management & secure storage of organic fertilisers
Farm infrastructure	On farm water storage
Farm infrastructure	Rain water harvesting
Farm infrastructure	Regulation, planning & enforcement for farm infrastructure
Farm landscape	Agro-forestry
Farm landscape	Buffer zones (3D)
Farm landscape	Compensation for repurposing of agricultural land to non-food production
Farm landscape	Land management initiatives
Farm landscape	Landscape Recovery Scheme & other biodiversity grants
Farm landscape	Sustainable irrigation
Farm landscape	Tree planting
Farm landscape	Water companies engage with land users
Soil management	Catchment friendly grazing regimes
Soil management	Sward diversity
Soil management	Appropriate location and timing of crop production
Soil management	Appropriate management of soil type
Soil management	Cover crops
Soil management	Improved soil management/health
Soil management	Management of P, N and C
Soil management	Use less chemical fertiliser

Tier 1 category	Tier 2 intervention
Soil management	Good practice manure spreading

Table A.2: Tier 1 intervention categories with associated Tier 2 interventions for Infrastructure and development intervention types

Tier 1 category	Tier 2 intervention
Flood infrastructure	Flood defences
Flood infrastructure	Flood storage
Flood response & recovery	Flood recovery
Flood response & recovery	Flood response
Flood response & recovery	Property Resilience
Housing & highways	Effective highway drainage systems
Housing & highways	Housing Nutrient Neutrality credit
Housing & highways	Repurpose of agricultural buildings to housing or commercial use
Housing & highways	Trading of Nutrient Neutrality credits
SuDS	Adoption & management of SuDS (Schedule 3)
SuDS	Attenuation SuDS e.g. wet swale, detention basins
SuDS	Infiltration & attenuation SuDS e.g. filter strip, dry swale
SuDS	Infiltration SuDS e.g. urban trees, porous pavements
Wastewater infrastructure	Fixing misconnections
Wastewater infrastructure	Manage chemicals of concern
Wastewater infrastructure	Septic tank refurbishment & replacement
Wastewater infrastructure	Wastewater infrastructure capacity increase
Wastewater infrastructure	Wastewater infrastructure upgrades
Water resources infrastructure	Elan reservoir water releases
Water resources infrastructure	Retrofit existing housing stock for low water use

Table A.3: Tier 1 intervention categories with associated Tier 2 interventions for Landscape/Catchment/River intervention types

Tier 1 category	Tier 2 intervention
Forestry	Establishment of local seed stands
Forestry	Forest redesign
Forestry	Good forestry practice advice
Nature recovery	Buffer zones (3D)
Nature recovery	Habitat creation, management, restoration & enhancement
Nature recovery	Manage for protected areas and species
Natural flood management	Wetland creation
Natural flood management	Buffer zones (3D)
Natural flood management	Headwater flow attenuation in channel eg leaky dams
Natural flood management	Peat restoration
Natural flood management	Restore floodplain function
Natural flood management	Woodland creation
Planning	Diverse landscape
River management	Management of acidified streams
River management	Management of angling

Tier 1 category	Tier 2 intervention
River management	Management of boats & canoes (Concordat)
River management	Management of swimming
River management	Real time water quality data
River management	River restoration
River management	WQ source apportionment to understand impact of mains drainage, septic tanks & PTPs, CSOs etc
River management	Riparian woodland restoration and creation

Table A.4: Tier 1 intervention categories with associated Tier 2 interventions for social and economic intervention types

Tier 1 category	Tier 2 intervention
Behaviour change	Food & farming awareness
Behaviour change	Per capita water consumption reductions
Rural economy	Farm diversification
Rural economy	Managing access & recreation
Rural economy	Sustainable transport services
Rural economy	Social infrastructure (pathways, cycleways, playgrounds).
Rural economy	Carbon credits
Rural economy	Nutrient credits

Table A.5: Metrics identified categorised by metric source, application and related system map

Metric	Source	Horizon	Related sub-system
R-B Index at high flood vulnerability locations	WSIMOD	Option modelling	Flooding and channel health
Q5 at high flood vulnerability locations	WSIMOD	Option modelling	Flooding and channel health
Q95	WSIMOD	Option modelling	Biodiversity
River phosphate concentration (mg/l)	WSIMOD	Option modelling	River health
River nitrate concentrations (mg/l)	WSIMOD	Option modelling	River health
River ammonia concentrations (mg/l)	WSIMOD	Option modelling	River health
Days of water stress / year	WSIMOD	Option modelling	Water resources and utilities
River suspended solids (sediment)	WSIMOD – To be confirmed	To be confirmed	River health
River chemicals of concern – pesticides and PFAS	WSIMOD – To be confirmed	To be confirmed	River health
Duration of spill	WSIMOD – To be confirmed	To be confirmed	Water resources and utilities
Water company customer acceptability	Measured results – To be confirmed	Catchment planning	Water resources and utilities
Water resources net gain (Ml/d)	Measured results – To be confirmed	Catchment planning	Water resources and utilities
Source ratio – environment/effluent flow	Measured results – To be confirmed	Catchment planning	Water resources and utilities

Metric	Source	Horizon	Related sub-system
Nutrient source apportionment	Measured results – To be confirmed	Catchment planning	River health
Number of days salmon migration summer flows (May to Sept) above 1150 Ml/day (Reelbrook gauge)	Measured results – To be confirmed	Implementation	River health
Number of days smolt migration spring flows (April to May) above 960 Ml/day (Boroughwood gauge)	Measured results – To be confirmed	Implementation	River health
Environmental flow indicator (EFI)	Measured results – To be confirmed	Catchment planning	Biodiversity
Dissolved oxygen	WSIMOD – To be confirmed	TBC	Biodiversity
Chemical fertiliser use (kg/ha)	Measured results – To be confirmed	Catchment planning	Arable farming
Manure spread in catchment (tonnes)	Measured results – To be confirmed	Catchment planning	Arable/Livestock farming
River faecal coliform levels	Measured results – To be confirmed	Catchment planning	Tourism, business and leisure
Soil health ©	Planning documents – To be confirmed	Catchment planning	Arable/Livestock farming
Soil health (N)	Planning documents – To be confirmed	Catchment planning	Arable/Livestock farming
Soil health (P)	Planning documents – To be confirmed	Catchment planning	Arable/Livestock farming
Manure exported to AD/energy (tonnes)	Planning documents – To be confirmed	Catchment planning	Arable/Livestock farming
Manure exported out of catchment (tonnes)	Planning documents – To be confirmed	Catchment planning	Livestock farming
Manure produced in catchment (tonnes)	Planning documents – To be confirmed	Catchment planning	Livestock farming
Properties at risk of flooding	Planning documents – To be confirmed	Catchment planning	Flooding
Tonnes carbon equivalent (sequestered)	Planning documents – To be confirmed	Catchment planning	Forestry and woodlands
Number of new houses built	Planning documents – To be confirmed	Catchment planning	Infrastructure and housing
Catchment population	Planning documents – To be confirmed	Catchment planning	Infrastructure and housing
WFD status – morphology	Planning documents – To be confirmed	Catchment planning	Biodiversity
Biodiversity net gain (£ or units)	Planning documents – To be confirmed	Catchment planning	Biodiversity
Visitor numbers	Planning documents – To be confirmed	Catchment planning	Tourism, business and leisure
Peak flow to treatment capacity ratio	Planning documents – To be confirmed	Catchment planning	Water resources and utilities
Biosolids spread to land within catchment (tonnes)	Planning documents – To be confirmed	Catchment planning	Water resources and utilities
Social amenity value (£)	Publicly available data- To be confirmed	Catchment planning	Tourism, business and leisure

Metric	Source	Horizon	Related sub-system
River pH	Publicly available data- To be confirmed	Catchment planning	Forestry and woodlands
BNG units/credits	Publicly available data- To be confirmed	Catchment planning	Infrastructure and housing
Functional connectivity of native woodlands	Publicly available data- To be confirmed	Catchment planning	Forestry and woodlands

These metrics were reviewed, discussed and updated with the CMP Task and Finish Group. The high-level system maps with annotations to show the metrics is shown in Figure A.1. The planning diagram annotated to show metrics is shown in Figure A.2.

The metrics and interventions represent the planning process at the completion of this project in early May 2024. These lists are under consideration by the CMP Task and Finish group to inform the development of the plan. The Task and Finish group will take forward modified lists for the plan as part of their work.

Figure A.1: High level system map with metrics

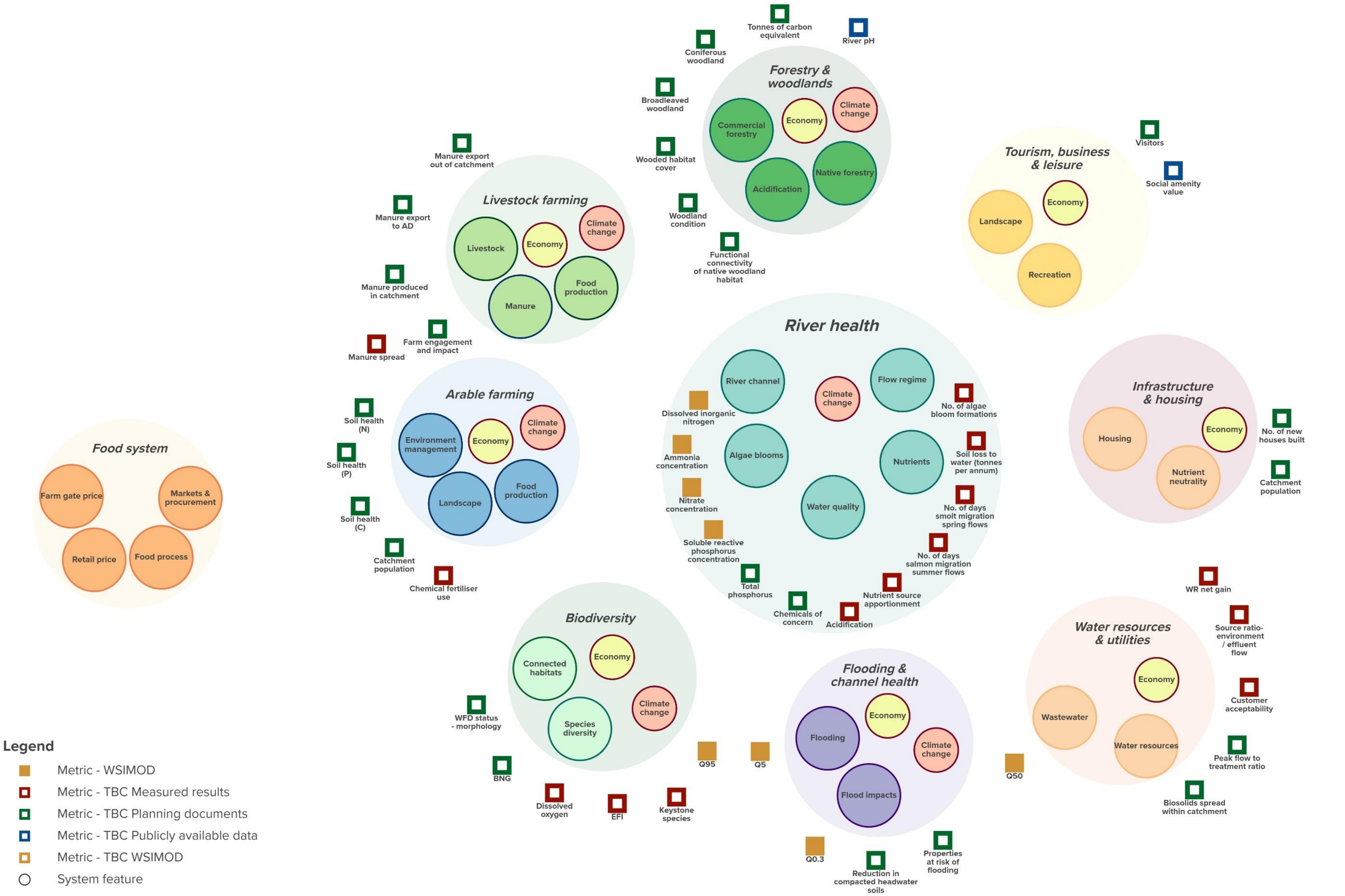
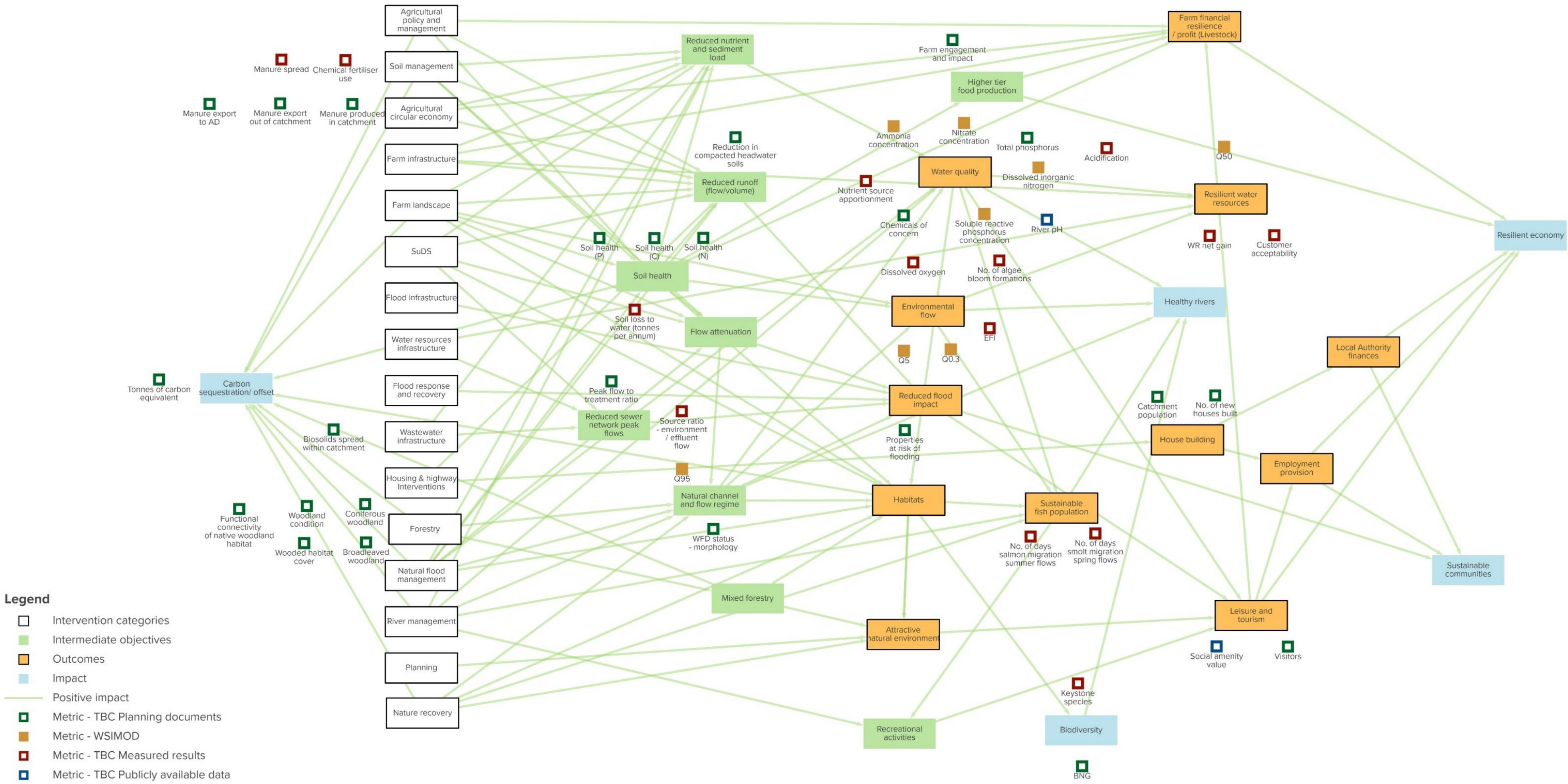


Figure A.2: Planning diagram with metrics



B. Imperial College Baseline Modelling Report

3C project: Baseline evaluation of the Wye catchment for systems water management and coastal protection – final report

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1. Introduction

Integrated water management and catchment planning has been a focus of research for many decades. However, we have only recently started discussing the challenge from a systems perspective in terms of practical application. Indeed integrated management of complex systems is neither feasible, adaptive or preferred and has been shown to be flawed in its both its conceptualisation and practical implementation in the context of real systems. Consequently there is little evidence that integrated water management has ever been fully and successfully implemented. However systems management and process alignment is more likely to be feasible and preferred in the context of complex systems and their dynamics. The need for a systems approach to water and environmental management is defined through understanding the relationships between physical, natural, and socio-economic components of the system, for which the evidence should be provided at adequate spatio-temporal resolutions.

To address the need for practical implementation of systems approaches to water management, in 2021 the Imperial College London's (ICL) Centre for Systems Engineering and Innovation (CSEI) have started the collaboration with the Systems Focus team at Mott MacDonald's (MM) Water Consultancy Division, which resulted in developing, together with the Environment Agency, the framework for Systems Approach to Regional Water Planning (SARWP). The framework proposes a 3-step process that combines: (1) participatory approaches to understand and map system structure, catchment challenges and potential solutions with key stakeholders, and align planning assumptions, pioneered by CECAN and others incl. MM; (2) the novel Water Systems Integration Modelling framework (WSIMOD) developed at ICL, which allows for the representation of the water system's demands and impacts of multiple sectors and actors' decisions within a single tool; and (3), an approach to assessment of co-benefits and development of an integrated portfolio of benefits that builds on steps (1) and (2). The approach has been further developed by MM to be used for Systems Approach to Integrated Water Management (SAIWM). Overall, this method creates a shared understanding of system performance resulting in more collaborative and coherent decisions on water resources, water quality and flood management. The approach has been applied to analyses options for integrated water management of the OxCam arc and to support Greater London Authority's (GLA) sub-regional integrated water management project.

This project is covering the initial 3-months (M) phase of testing the application of SARWP approach to coastal catchments through integrated modelling using WSIMOD. We have developed the model for the river Wye catchment and the study focuses on understanding the case study and preliminary analysis. In the future work we hope to link the participatory engagement work undertaken by MM to develop the intervention options portfolio for the Wye catchment to improve catchment water management and protect the coastal system.

2. WSIMOD overview

WSIMOD is a self-contained open-source Python software package which contains modelled representations of many elements of the water cycle which are responsibilities of multiple actors in the water system. Each type of modelled element (e.g., reservoir, hydrological catchment) is generically described as a component. Components are written in such a way that any component can interact with any other component. This enables a flexible representation of the water cycle that is needed to accommodate the wide variety of different built and natural infrastructure configurations. In its default setup, WSIMOD runs on a daily time step. The spatial representation uses the Environment Agency water body catchments as a basic spatial unit. To represent the system, the model needs input information on climate (precipitation, temperature, and evapotranspiration), rural (river network, land cover, crop surfaces, nutrients load) and urban (population, garden area and foul catchments) systems and water resources (urban and irrigation water use). The outputs from the model are the timeseries of the river flow and water quality at the outlet of each water body catchment, which can be further processed into a range of high and low flow and water pollution indicators. To validate model results, we use publicly available daily flow observations form the National River Flow Archive and monthly water quality WIMS data. We use the WSIMOD to assess impact of drivers of change (typically, climate and land use change, but also policy and operational targets) and a range of water management options on the flow and water quality indicators to inform the future planning of water systems. As the model can simulate multiple components of water system, operational and policy constraints and process the results to assess a range of flow and water quality indicators, we see the value of WSIMOD in the context of integrated water planning in the following aspects summarised below.

Evaluation of existing / baseline system performance	A common model that represents a range of subsystems of interest for multiple actors	
	Baseline evaluation using a range of flow and water quality indicators	Critical catchments mapping, pollution attribution, CSO assessment, water systems benchmarking
	Sense checking other physical models	
	Impact of boundary assumptions	
Assessment of impact scenarios and options' effectiveness	Scenario planning (climate change, development, abstraction licenses reform…)	
	Optioneering and optimisation (choice, functional sizing, distribution)	Demand and land management, water infrastructure upgrade, nature based solutions, water neutrality targets development
	Policy reform (abstraction licenses, water quality regulation, …	
	Evaluation of existing plans and development of adaptive planning	

Methods

Sub-catchments

We select the entire Wye catchment as the study region (Figure 1). The river Wye drains a large catchment (4,285km^2) comprising a varied landscape spanning the Welsh and English borders. It rises at Plynlimon

(Wales) and flows towards the southeast through Hereford and Monmouth (England) to discharge into the Severn Estuary at Chepstow (Wales). It has a variety of different land covers throughout including dense urban areas (e.g., Hereford), extensive agriculture (concentrated in the English part) and grassland (widely spreading across both sides), and some highly forested regions in the upland in Wales. It has a mix of distinct hydrogeology with the slightly acid loamy and clayed soil covering the upper Welsh and eastern English sub-catchments and freely draining loamy soil spreading the middle and southern regions. Fertilisers and manure are extensively applied on both arable and grassland, while wastewater treatment plants discharge effluent containing high content of nutrients. The variety and complexity of factors in Wye's urban-rural water cycle make it an ideal modelling case for the highly flexible water system modelling software, WSIMOD. At the water body scale, 51 sub-catchments are in English, while 78 sub-catchments are in Welsh region, resulting in a total number of 129 sub-catchments.

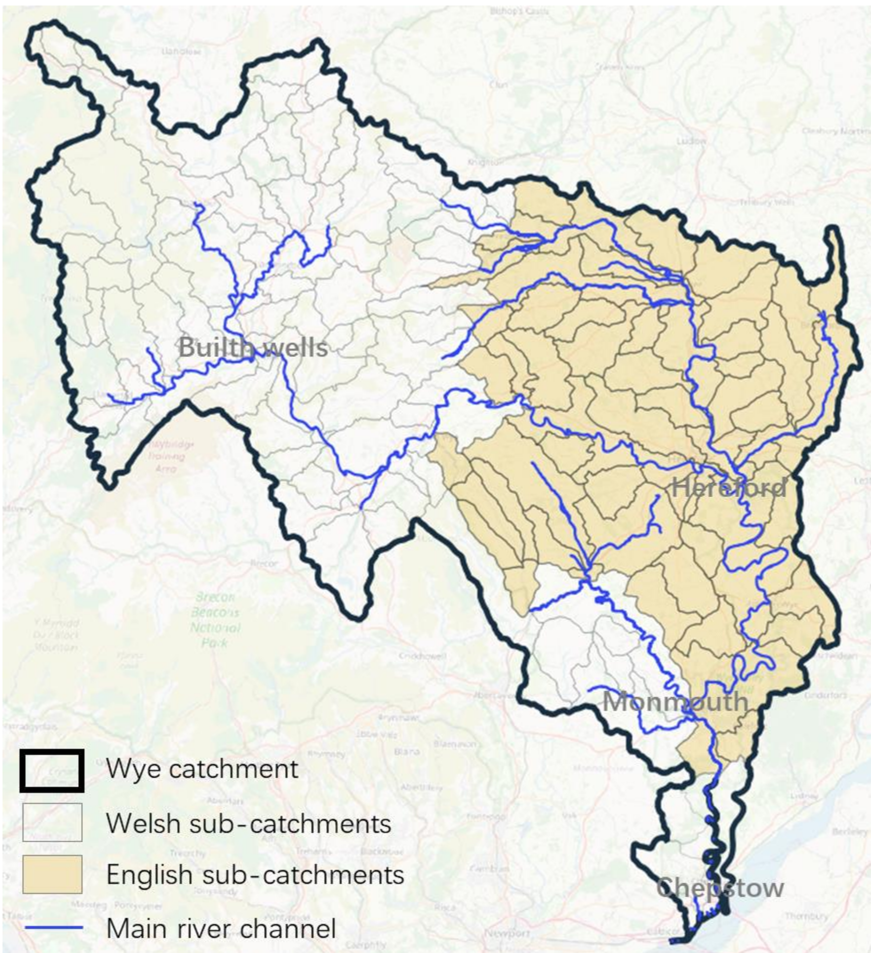

Figure 1: Map of the Wye sub-catchments with river networks

Model structure and assumptions

Below we provide a high-level description of the assumptions used in this application of WSIMOD, with more detailed information on the model and application described in previous publications (1, 2).

WSIMOD provides pre-built conceptualisations of infrastructure and environmental elements of the water cycle (each subsystem is referred to as a component) that can be easily parameterised with publicly available data. The arrangement of these components is selected by a model user. Here we show a generic catchment setup in Figure 2, which has wastewater treatment works (WWTW) with a foul catchment aligned with the hydrological catchment boundaries. All arcs depicted simulate both the flow and water quality between the different components. Surface hydrology processes are implemented using a conceptual rainfall-runoff model (2), agricultural processes and nitrogen/phosphorus cycling are based on HYPE (3), while the groundwater tank aligns with each surface catchment above and follows a residence time formulation as in CatchWat (2). Components for urban water drainage systems, including demand, foul sewer and WWTW are set up wherever a wastewater discharge point is enclosed within the sub-catchment. Urban water supply is conceptualised as a virtual node that can satisfy domestic water demand with unlimited resources, while water for rural irrigation is currently not enabled, both due to insufficient supportive information and data.

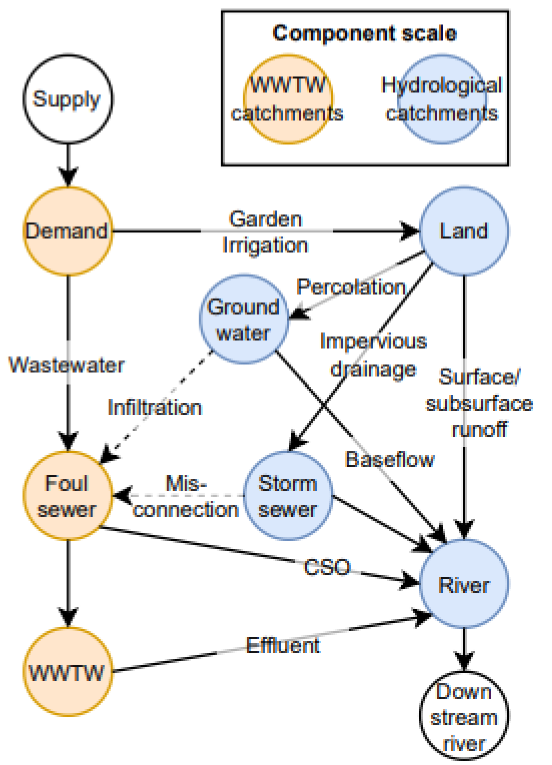

Figure 2: A schematic depicting the flows between different modelled sub-systems within a 'typical' catchment (that contains a WWTW).

Boundary conditions and data

The data for model input and evaluation are summarised in Table 1, with boundary conditions setting in the model explained as follows.

Table 1 Summary of data for modelling input and evaluation

Purpose	Variable	Source	Availability
Input	Catchment boundaries	Catchment data explorer	Full
	Hydroclimatic	HadUK	Full

	Land cover	Crop map	UKCEH	Full
	Non-point source	Fertilisers	UKCEH & BSFP	English sub-catchments only
		Manure		Full
		Deposition	CBED	Full
	Demographic	Population	ONS	Full
	Water drainage	WWTW catchments	UWWTD	Full
		WWTW discharge points		Full
		CSO	EDM	Full
Evaluation	River flow		NRFA	Full
	River water quality		WIMS & NRW	Full

Hydrology – A series of hydroclimatic data is acquired from HadUK at 1 km spatial resolution and aggregated for each sub-catchment, including precipitation, temperature, surface wind speed, vapour pressure, etc. These variables are used to calculate reference evapotranspiration using Penman-Monteith equations as model input.

Land cover and vegetation – The land cover and vegetation information are obtained from UK Centre for Ecology and Hydrology (UKCEH) (Figure 3). According to the land cover statistics in 2019, 40.7% area is permanent grassland, while 37.9% area is arable land, with woodland (15.3%) and built-up area (5.4%) accounting for a minor proportion. The arable area is dominantly concentrated within the English sub-catchments, while grassland and forests are widely spreading in the Welsh sub-catchments. The biggest urban area is Hereford in England. Crop types on the arable land inform the selection of crop parameters in the model, such as crop calendars and crop coefficients for evapotranspiration.

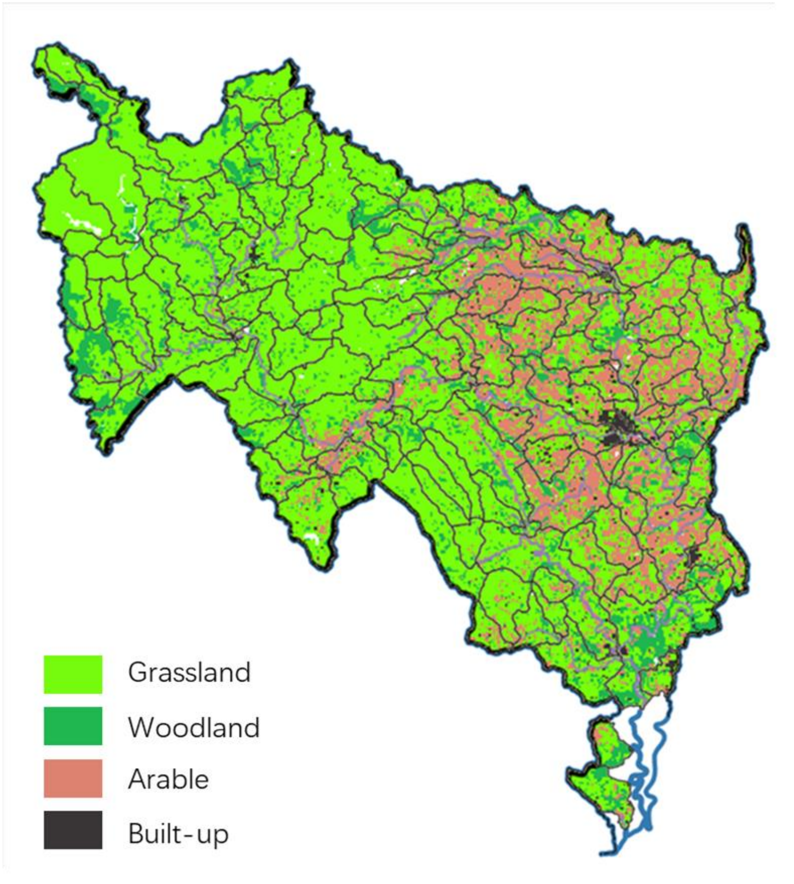

Figure 3 Spatial distribution of land cover based on the UKCEH Land Cover Map (LCM) in 2015

Fertilisers and manure – the spatially-distributed fertiliser data is obtained from UKCEH that is averaged between 2010-2015 for nitrogen and phosphorus, which unfortunately is only available for English sub-catchments. The spatial distribution of manure application for nitrogen and phosphorus is obtained from UKCEH as well, which is available for all sub-catchments. Both data are overlayed with land cover and vegetation as input data for 2010-2015, which are then distributed inter-annually and seasonally based on the British Survey of Fertiliser Practice (BSFP) statistics.

Atmospheric deposition – dry and wet atmospheric depositions for nitrogen are acquired from CBED and aggregated for each sub-catchment, while a uniform phosphorus deposition based on the values reported in the literature (4) is applied across the whole region due to data limitation.

Wastewater – to better conceptualise the urban drainage system, population (from Office of National Statistics (ONS)) and wastewater catchments (from Urban Waste Water Treatment Directive (UWWTD)) are mapped to determine the foul sewer networks collecting sewage, which are then linked to WWTW discharge points. There are 16 wastewater discharge points in total, with the largest wastewater drainage around Hereford (Figure 4). CSO information is incorporated from Event Duration Monitoring (EDM) to set potential direct spills from foul sewers to rivers.

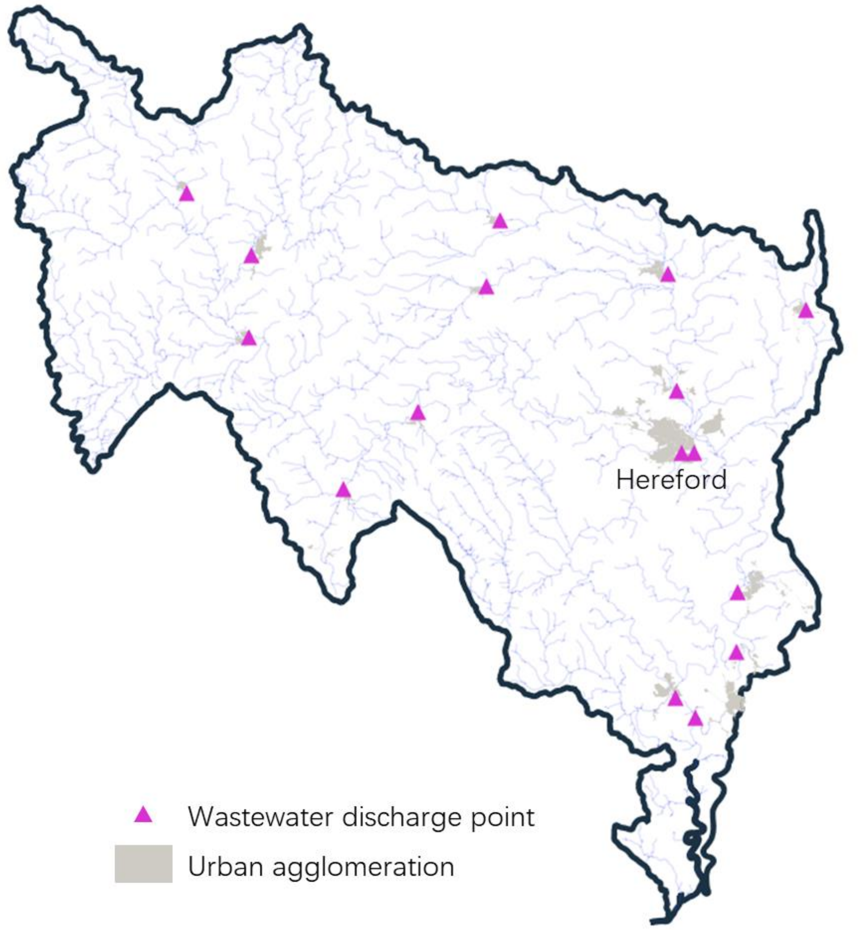

Figure 4 Processed urban agglomeration nodes for domestic water use and the associated wastewater discharge points

Monitoring data – to evaluate the modelling accuracy, both river flow and water quality monitoring data are obtained and processed. The National River Flow Archive (NRFA) stations are spread across both English and Welsh sub-catchments (Figure 5). Water quality monitoring stations come from the water quality sampling dataset from Environment Agency (WIMS) and Natural Resources Wales (NRW), which dominantly concentrate within English sub-catchments with only one station available in the upstream of Wales (Figure 6). It is noted that given the WSIMOD focuses on modelling river water quality at the sub-catchment outlet, we only select stations wherever adjacent, which results in 18 stations for flow and 44 stations for water quality in total.

The model simulates from 1991/01/01 to 2021/12/31 at a daily timestep.

Metric Selected for Baseline Assessment

We select a range of metrics to investigate river flow and water quality status (using nitrate and phosphate as an example) for different purposes. QMED is defined as the median of the annual maxima of the data series, and Q5 is defined as the value which was equalled or exceeded for 5% of the data series. Both evaluate the high values of the simulation results, which indicate flood risks and pollutant concentration peaks. A mean value of the simulated results is evaluated to indicate average river flow and water quality status. Q95 is defined as the value which was equalled or exceeded for 95% of the data series, which evaluates low values indicating drought risks and how good water quality can be during the simulation period.

Table 2 Summary of metrics used for baseline assessment

Metrics	River Flow	Nitrate	Phosphate
QMED Q5	High flows for flood risks indication	Indicate high pollutant concentration during poor water quality periods	
Mean	Indicate average river flow status	Indicate average pollutant concentration	
Q95	Low flows for drought risks indication	Indicate low pollutant concentration during good water quality periods	
Days above an upper threshold	Q5	8 mg/l	0.12 mg/l
Days below a lower threshold	Q95	-	-

We also evaluate the days above and below upper and lower thresholds in a year to reveal yearly variations. The upper and lower threshold for river flow is set as Q5 and Q95, to indicate flood and drought risks in a year, respectively. Only upper thresholds are applied on pollutant concentrations, which are set as 8 mg/l and 0.12 mg/l for nitrate and phosphate, respectively. Both values are regulation standards indicating 'good' water quality status in water bodies adopted in Water Framework Directive (WFD) (5).

Model evaluation

We evaluate the simulated results in comparison with monitoring data at the three stations for flow and water quality, respectively. We show the evaluated performance using Nash-Sucliffe Efficiency (NSE) for flow and percent bias (PB) for water quality, respectively. Considering the number of parameters involved within such a big region, a formal calibration might result in good results for wrong reasons, which does not benefit understanding the system's mechanisms. Instead, we select parameter values based on the best available evidence and expert judgement.

River flow

The results of evaluation metrics show a generally good simulation performance across the whole catchment (Table 3). NSE is larger than 0.7 at 13 out of 18 stations, with mean NSE at 0.61. The temporal pattern of simulated results and observed data also shows a good match, which is illustrated at the three stations from the upstream of Wales (55007) and England (55021) to the downstream outlet of the whole Wye catchment (55023) (Figure 5). An underestimation of peak flows, however, is observed at the stations on the Welsh side (e.g., 55007).

Table 3 Summary of model evaluation metrics for river flow and water quality (DIN = dissolved inorganic nitrogen, SRP = soluble reactive phosphorus) using Nash-Sutcliffe efficiency (NSE) and percent bias (PB), respectively (Q25/50/75 = metric quartiles)

Variables	Metrics	No. of stations	Mean	Min	Q25	Q50	Q75	Max

Flow	NSE	18	0.61	-0.96	0.69	0.78	0.83	0.88
DIN	PB	44	-3.84%	-57.70%	-11.42%	-3.47%	4.92%	20.43%
SRP	PB	44	7.21%	-16.25%	-3.63%	5.75%	16.52%	58.55%

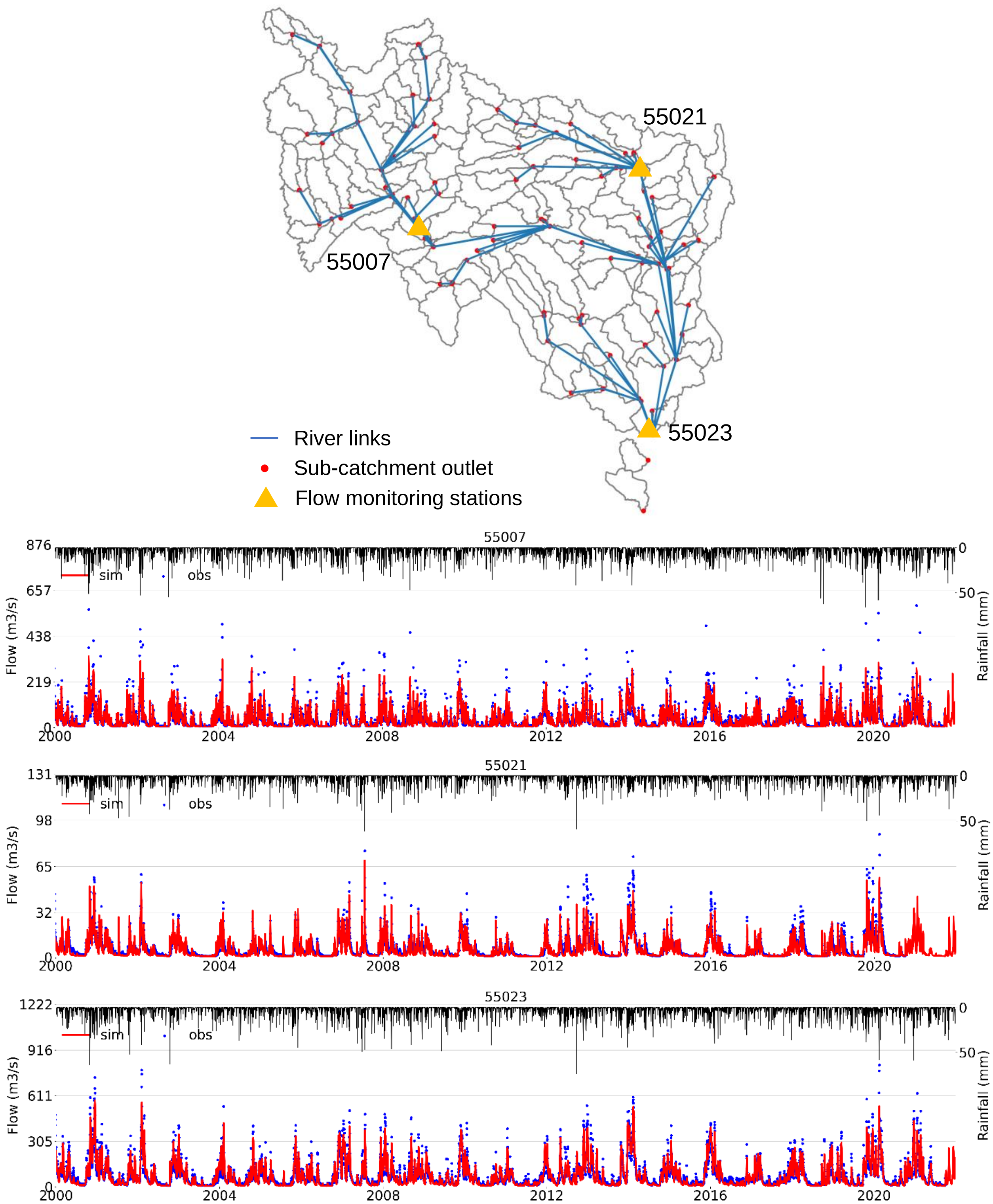

Figure 5: Timeseries simulations and observations of in-river flow at the three NRFA monitoring stations.

Water quality

The simulated dissolved inorganic nitrogen (DIN, as a sum of ammonia, nitrate, and nitrite) and soluble reactive phosphorus (SRP) also show a good prediction against the observed data (Table 3), with the mean PB for DIN and SRP are -3.84% and 7.21%, respectively. PB is within ±20% at 41/44 and 40/44 stations for the respective pollutant, though significant underestimations (-57.70%) of DIN and overestimations (58.55%) of SRP exist at few stations.

The temporal pattern is also well simulated compared with the observed data series, which is illustrated at five stations (Figure 7-8). These five stations monitor water quality at the upstream of Wales (SN965656) and England (MD-50042), welsh rivers flowing through the English region (MD-50024), and downstream of the whole catchment (MD-50027 and SO5360709884), which are chosen to fully reveal the model performance across the region (Figure 6). DIN is generally overestimated from 2000 to 2007 at the upstream of England (MD-50042), which may be inaccurate fertiliser input due to the data availability. SRP is generally overestimated as well at the final outlet (SO5360709884). Given that SRP is well simulated at MD-50027, this overestimation may attribute to the simulated river loads from the Welsh sub-catchments that are adjacent to the outlet. A few outliers in the monitoring data are not captured by the simulation as well, which might be induced by local processes that are not simulated by the model (e.g., rural sewage tanks). Furthermore, we deem the observation series at this station to be of low quality, as many of the SRP samples have a constant value of 0.002 mg/l throughout many years.

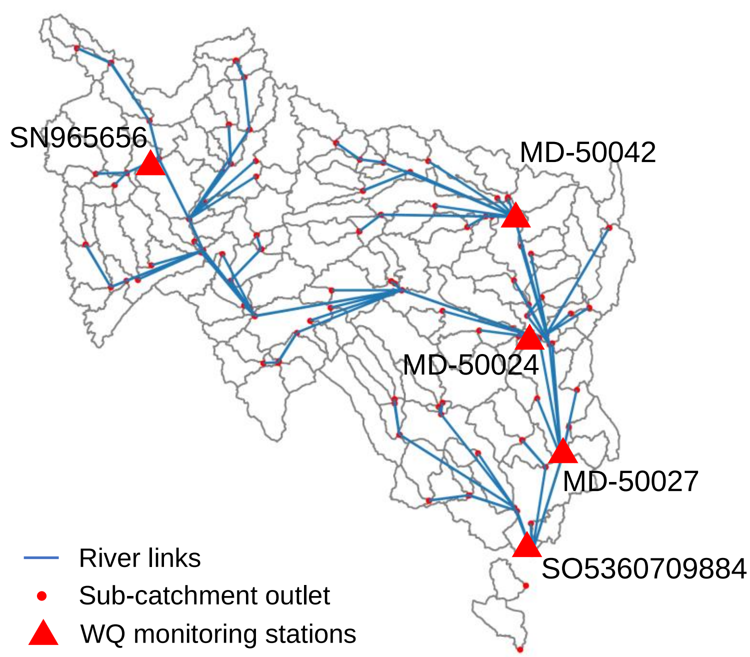

Figure 6: Five EA water quality monitoring stations selected for river water quality model evaluation.

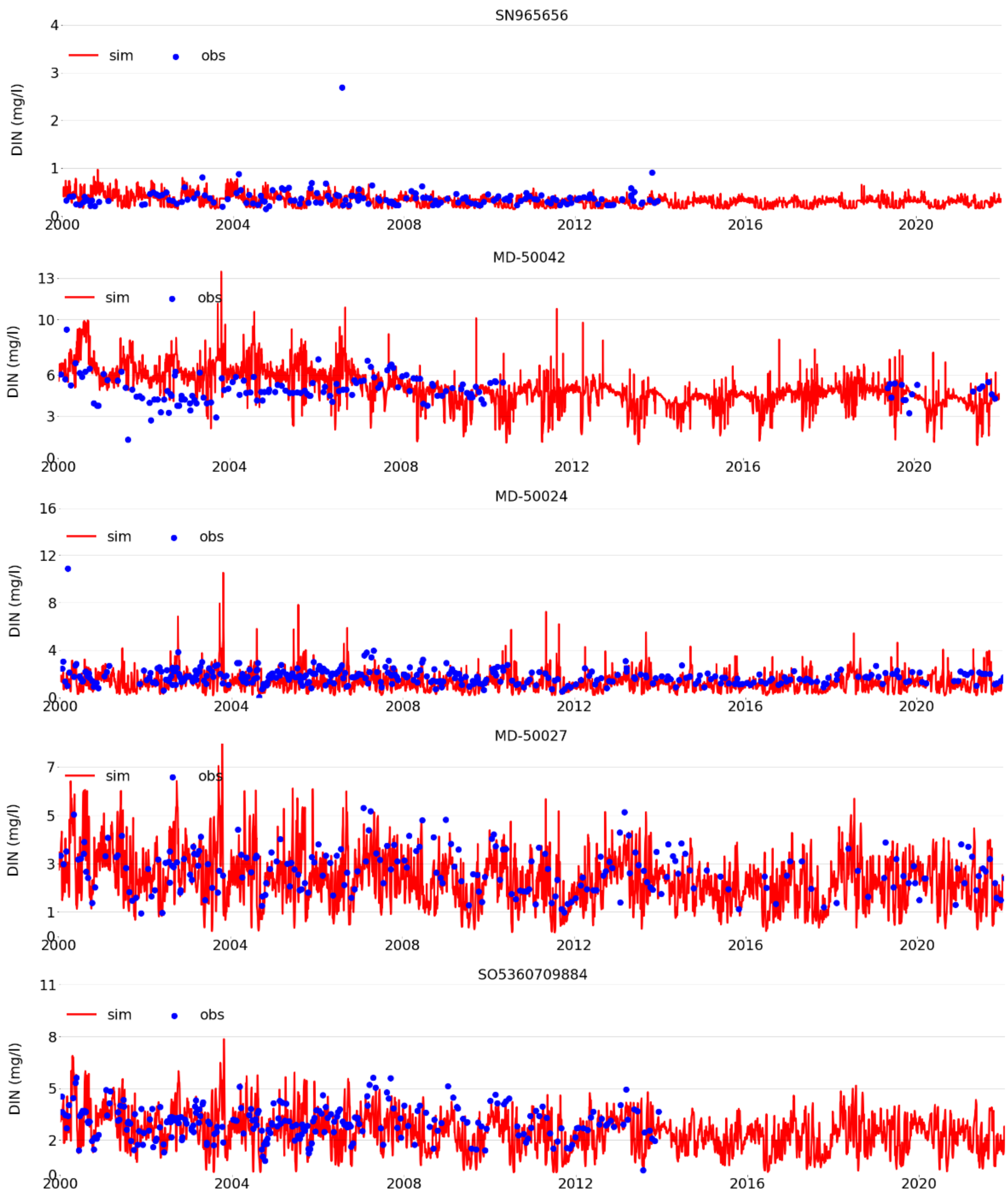

Figure 7: Timeseries simulations and observations of in-river dissolved inorganic nitrogen (DIN) at the five EA monitoring stations.

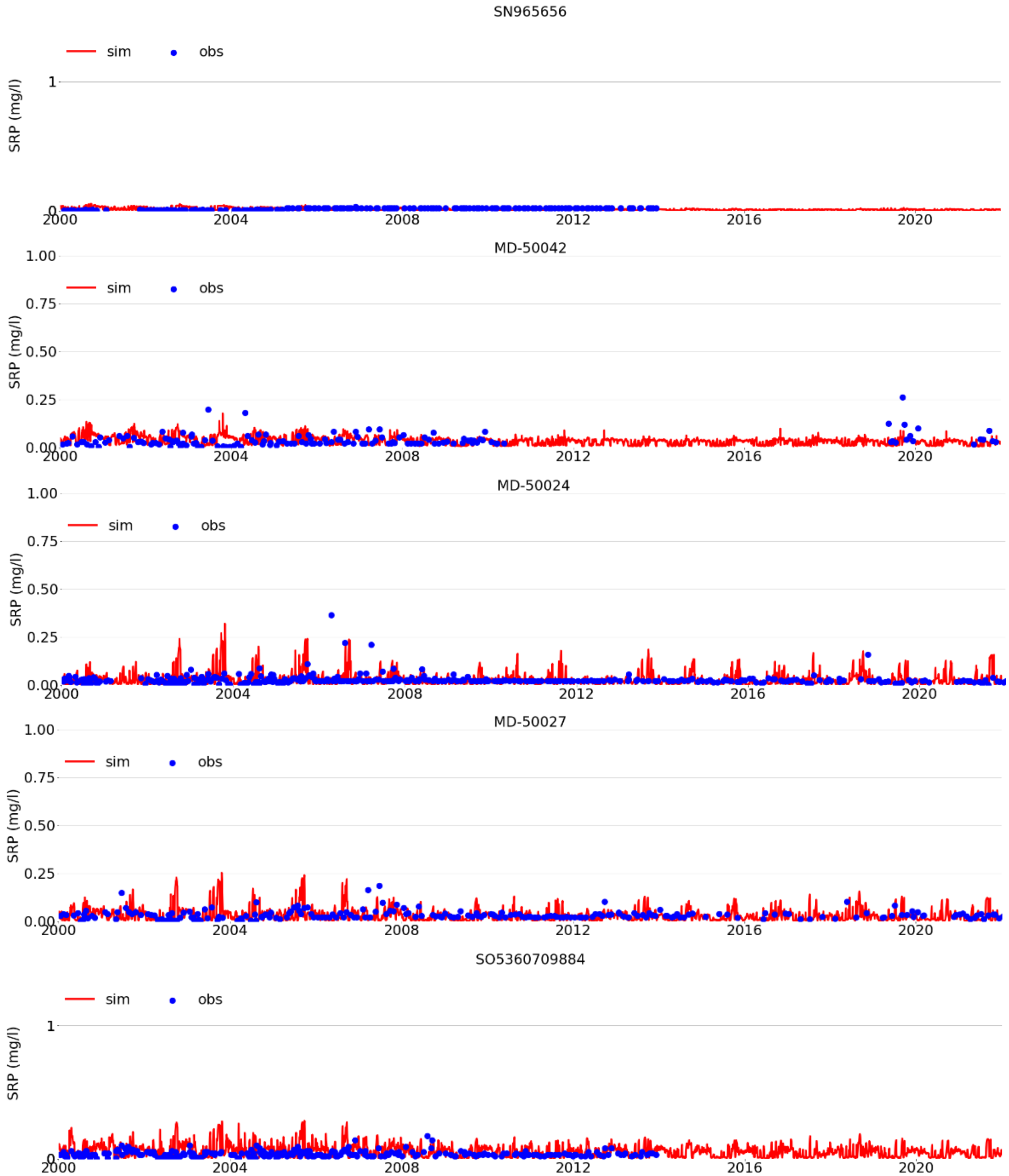

Figure 8: Timeseries simulations and observations of in-river soluble reactive phosphorus (SRP) at the five EA monitoring stations.

From these results, we see quite different spatial distributions at these three locations. DIN at the upstream Welsh sub-catchments was constantly steady with low concentration (< 1 mg/l at SN965656), and significantly increased after the rivers flow through the English sub-catchments, at around 3 mg/l (MD-50024). It is then mixed with river loads from the upstream English sub-catchments (generally < 4 mg/l), resulting in a final concentration generally below 5 mg/l through the outlet. The same pattern can be seen in SRP as well (Figure 8). This spatial distribution indicates the nutrient loads brought by runoffs from rural land and urban effluent in the English sub-catchments are much higher than those in the Welsh sub-catchments, due to more population and intensive land use activities (e.g., fertiliser and manure application practice on larger cropland areas).

Results of metric analysis

The results of metric analysis for river flow and water quality at the catchment outlet of Wye are summarised in Tables 4-5. We choose the catchment outlet as the main analysis point because it aggregates all the human impacts of the whole Wye catchment on the estuary and coasts. For river flow in the whole simulation period, QMED and Q5 are 384.99 m^3/s and 261.94 m^3/s, respectively, while Q95 is 6.50 m^3/s. Few years had more than 30 days when river flows were higher than Q5, including 2002, 2007, 2014, 2019 and 2020, indicating potential risks of flooding. However, drought risks seem to be less severe, with 10 years having less than 10 days when flows were below Q95 since 2003.

Table 4 Summary of metrics for river flow and water quality at the catchment outlet of Wye

Metrics	Flow (m3/s)	Nitrate (mg/l)	Phosphate (mg/l)
Q5	261.94	3.97	0.137
Mean	76.53	2.26	0.055
Q95	6.50	0.58	0.004
QMED	384.99	4.41	0.160

Table 5 Days above and below thresholds for river flow and water quality at the catchment outlet of Wye in each year from 2001 to 2021

Days above/below thresholds		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Flow	Above Q5	2	34	4	17	7	18	32	23	22	0	3	28	19	42	17	21	0	5	32	38	20
	Below Q95	0	28	78	12	57	50	0	0	5	17	51	0	5	0	1	0	19	35	9	0	17
Nitrate	Above 8 mg/l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phosphate	Above 0.12 mg/l	59	60	83	44	63	60	45	12	16	7	16	16	24	8	9	13	16	20	15	13	24

For water quality in the whole simulation period, QMED and Q5 of nitrate are 4.41 and 3.97 mg/l, respectively, demonstrating that even the pollution peaks are highly likely below 8 mg/l and nitrate can thus be classified as 'good' status under WFD. This can also be reflected by the results in Table 5, where no day has simulated nitrate concentration above 8 mg/l during the whole simulation period. For phosphate, the mean concentration over the whole simulation period is 0.055 mg/l, which can be deemed as 'good' status under WFD. However, phosphate concentration can rise up to 0.16 mg/l (as 'moderate' under WFD) in some seasons. The number of days above 0.12 mg/l for phosphate generally decreased since 2006 (60 days). This descending pattern may attribute to the gradual decrease in fertilisers and manure application. However, there are still 10-30 days in a year having phosphate concentration in 'moderate' status, which requires further interventions and management measures in the upstream region.

The baseline results presented have the following implications for understanding the overall hydrological and water quality impacts of the Wye catchment on the estuary and coastal regions:

- **Extreme flow periods** - The number of high-flow days in River Wye was generally been constant over the simulation period, while occasionally low flow conditions can last more than 40 days. These days should be further investigated to understand how extreme river flow conditions can impact the estuary, such as morphology, sea level, river-tidal interactions, and coastal biochemical processes.
- **Nutrients management** - According to the regulation standards from WFD, nitrate discharged from the Wye catchment seems to be a less problematic nutrient for the estuarial nitrogen cycle, potentially due to the reduction of fertiliser and manure applications made throughout the decades, while phosphorus from the river Wye is still a nutrient that may deteriorate the estuarial water quality and ecological status. Interventions on phosphorus should be prioritised for implementation than nitrate.
- **Spatial variability** - The fertilisers and manure application on the English grassland and crop area contribute more to the nutrient load than the Welsh sub-catchments. This highlights the need to further investigate the modelling results in English sub-catchments to identify loads discharge hotspots as prioritised regions for intervention implementations. The dilution effects of Welsh river flows and their interactions with English river flows should be further evaluated as well, to implement interventions more effectively in the English sub-catchments.
- **Urban-rural interactions** - How much impact of phosphorus concentration peaks are induced by urban wastewater discharge is unclear yet, which needs further investigation of the modelling results, especially in the sub-catchments where both urban and rural loads are discharging into rivers. Investigating these urban-rural interactions helps to understand the system's mechanisms and identify opportunities to coordinate urban-rural interventions for higher cost-effectiveness.
- **Model simplification** - Due to the limited water quality effects from Welsh sub-catchments, it might be worth aggregating the sub-catchments as a lumped modelling node to reduce the computational time and complexity of the model.

Recommendations for future work

Enhanced model set-up and evaluation

The current data input is at a minimum requirement for a model set-up and simulations, with many assumptions being made. For example, the fertiliser input across all Welsh catchments is adopted as an aggregated value from the English part of the system due to a lack of data. The performance against observed data is relatively good, which makes the model suitable for evaluating sub-catchment impacts on the river Wye and the subsequent effects on the estuary through the final outlet, in terms of both water quantity and quality. More data and information are needed to expand the ability and accuracy of model simulations, such as abstraction locations and licensing for water resources modelling and spatially distributed fertiliser data for more comprehensive water quality modelling in the Welsh sub-catchments.

Only a part of the model has been evaluated against monitoring stations due to the time limitation. A more thorough model evaluation should be conducted for river flow and water quality in the future. More monitoring data or simulation results from existing models and studies could be collected for validating the simulation of individual processes in this model, such as runoff loads and soil nutrient content.

Scenarios for future simulation

A range of scenarios are listed for simulating impacts from future uncertainties on the system (Table 6), with justifications on whether they are feasible for being simulated by WSIMOD.

Table 6 Summary of scenarios for future simulation and the feasibility of using WSIMOD

Scenarios	**Feasibility**
Urbanisation - city and/or rural	Can be conducted via changing the input of land cover, with more specific information needed (e.g., locations and extents)
Land use change policy (e.g., enforcement changes)	
Adaptation (e.g., the level of land use change for the purpose of SuDS and nature-based solutions, environmental improvements and STW changes in response to the WINEP programme)	Can model some default types of NBS, but need stakeholders' agreement on the type, size and locations
Abstraction regime	Can evaluate the wastewater-related impacts but not supply-related due to the incomplete water resource conceptualisation in the current baseline model
Level of demand for water – dependent on population, per capita consumption, industrial, agricultural, energy demand, etc.	
Economic growth and spending – effects may be captured adequately by other factors	
Climate change – decisions over emissions pathway, climate model, and model outputs, e.g., monthly perturbation factors, or stochastic flow series	Can input hydroclimatic data in various climate change scenarios

For land use scenarios, it is feasible to change the input of land cover and vegetation information. More specific information regarding the location of the change and to what extent the land cover is planned to be changed. Adaptation scenarios such as NBS implementations can be modelled as either changing the parameters of existing nodes or inserting new nodes to represent their unique behaviours. We have successfully implemented several rural and urban NBS at a catchment scale in previous studies (6). However, the types of NBS are very diverse so that stakeholders' agreement is needed to determine which type of NBS is prioritised to be implemented at which locations for scenario formulation. Impacts of future demand or water supply change can only be evaluated on the drainage system, such as increasing wastewater effluent loads. To enable a full evaluation of water resource impacts such as water availability and security, more information is needed for conceptualising water resource systems in the baseline model. Climate change scenarios can be simulated via inputting predictions on future hydroclimatic scenarios.

Based on the results obtained so far, climate scenarios might be valuable to simulate to test how Q5 and Q95 will change at the final outlet as direct effects on the estuary, in both flows and pollutant loads.

Options for future simulation

A range of options are listed for testing their performance on improving the systems conditions (Table 7), with justifications on whether they are feasible for being simulated by WSIMOD.

Table 7 Summary of options for future simulations and the feasibility of using WSIMOD

Options	**Feasibility**
Reduced chicken population (free-range and/or indoors)	Needs to be formulated as changes of fertilisers/manure application rates
Reduced upland sheep stocking density	
Improved nutrient management (e.g., introducing maximum P loading requirement for manure)	Can be conducted via changing manure input
Reforestation	Can be conducted via land cover change
Upland peat restoration	Peat not conceptualised in the baseline model – potentially can be achieved with more extensive information
On-farm measures to improve soil health	Can be reflected by soil nutrient pools but needs more data for validation
WWTW enhancements	Can be conducted via parameters adjustment

It is plausible to test the effects of farm management measures, such as changing chicken and sheep stocks, on soil nutrients and water quality. However, given that there are no farm modules explicitly represented in the model, these measures should be formulated as changes in fertilisers/manure application rates as input into the model. Similarly, limiting the maximum P loading requirement for fertilisers and manure is directly applicable and easily implemented to the baseline model. Reforestation can be simulated as the expansion of forest area and the reduction in other land cover areas, whose locations and degree of implementation should be further specified. For upland restoration, the current baseline model does not have an explicit representation of peat. More information regarding its behaviour should be obtained to enable its simulation. Similarly, the definition of soil health should be further specified. In the model, soil nutrient content could be potentially evaluated if it is treated as the key indicator for soil health, which also needs more sampled data for validating the simulated soil nutrient processes. WWTW enhancements are directly applicable for simulation in the model by adjusting parameters involved in WWTW treatment processes.

Based on the presented results, we find improved nutrient management should be prioritised for phosphorus because the final outlet has more than 10-30 days with ‘moderate’ SRP status. Furthermore, these management measures should be largely implemented in English sub-catchments because the English rivers have generally higher simulated phosphorus concentration than the Welsh rivers and thus contribute more to phosphorus loads through the final outlet into the estuary. WWTW enhancements are still interesting to test as the urban contributions to pollution peaks through wastewater discharge remain unclear at this stage, which needs further analysis of baseline results and option testing. However, upland measures may not be prioritised due to the less contribution of pollution loads from upstream Welsh sub-catchments. Reforestation is expected to reduce nutrient loads from runoffs but also has impacts on reducing groundwater levels via high evapotranspiration and surface runoffs via interception, whose impacts on flow regime should be further investigated.

References

1. B. Dobson, T. Jovanovic, Y. Chen, *et al.*, Integrated modelling to support analysis of COVID-19 impacts on London's water system and in-river water quality. *Front. Water*. **3**, 26 (2021).
2. L. Liu, B. Dobson, A. Mijic, Hierarchical systems integration for coordinated urban- rural water quality management at a catchment scale. *Sci. Total Environ.* **806**, 150642 (2022).
3. G. Lindström, C. Pers, J. Rosberg, *et al.*, Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. *Hydrol. Res.* **41**, 295–319 (2010).
4. Tipping, E., *et al.*, Atmospheric deposition of phosphorus to land and freshwater. *Environmental Science: Processes & Impacts* **16,** 1608-1617 (2014).
5. UKTAG, UK Environmental Standards and Conditions. (2008).
6. L. Liu, B. Dobson, A. Mijic, Optimisation of urban-rural nature-based solutions for integrated catchment water management. *Journal of Environmental Management*, **329**, 117045 (2023).

C. Mott MacDonald Modelling Methodology

C.1 Introduction

C.1.1 Modelling Objectives

The Water Systems Integrated Modelling framework (WSIMOD) tool, developed by ICL, can simulate the integrated catchment system, assess the performance of the system with respect to flow and selected water quality indicators, and analyse the effectiveness of intervention options that are the responsibility of multiple stakeholders, which enables improved quantitative understanding of the catchment. WSIMOD is a compartment-based model that allows the definition of nodes and arcs representing sources, receptors, or processes, which can have an impact on water flows and associated water quality parameters. This includes catchment factors such as population water demand, sewage generation, water treatment plants, etc.

This technical note outlines the methodologies used to apply scenarios and options to the baseline model.

C.2 Modelling limitations

WSIMOD modelling tool is designed to simulate an integrated catchment system to enable users understand the bigger picture. It therefore does not capture fine spatial and temporal details of the catchment or flow and water quality indications. This means that options and scenario must be applied at waterbody scale and cannot consider details such as precisely where buffer strips should be implemented. The baseline model was implemented with a daily timestep meaning variations in metrics lasting only a few hours are not captured by the model. The spatial resolution of the model is at waterbody scale and input parameter variations within a single waterbody are not accounted for. Therefore, the same input parameters have been assumed across the whole of a waterbody, for example each individual waterbody has the same soil infiltration value applied across the whole of it.

C.3 'Future Impacts' Scenario Build

Following stakeholder meetings with relevant parties, a 'future impacts' scenario was agreed considering climate change and population growth to be applied to the WSIMOD model parameters. Changes caused by climate change and population growth are reflected into modifications to the relevant model input parameters, which were rainfall, evapotranspiration, temperature, population numbers. Only the variables setup and calibrated in the current WSIMOD Wye baseline model have been modified.

Based on baseline historical data available (22 years, 1st January 2000 to 31st December 2021) and discussions with the stakeholders, it was agreed to consider climate change and population growth into the near future (1st January 2024 to 31st December 2045) and apply change factors for that window.

C.3.1 Climate Change

Climate change adjustment has been implemented by using multiplication factors for precipitation, temperature, and potential evapotranspiration, using the UK Climate Projections (UKCP18) probabilistic projections[11]. All other model inputs have remained the same. The data was extracted using the Moata UK Climate Data Explorer. The climate change data from

[11] HadUK-Grid gridded and regional average climate observations for the UK, https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb, accessed March 2024

UKCP18 is based on a HadUK baseline 1981-2000, therefore the model input data is first adjusted to account for this timescale difference between the UKCP18 baseline and model baseline.

C.3.1.1 Climate Change Assumptions

The following climate change data from UKCP18 probabilistic projections was used:

- Climate Change Representative Concentration Pathway (RCP): 8.5
- Spatial resolution of climate data: River Basin – Severn
- Temporal resolution of climate data: Monthly
- Statistical value of climate scenario: 50th percentile

C.3.1.2 Methodology

Precipitation and Temperature

The precipitation was scaled using the percentage difference from baseline as given by the UKCP18 probabilistic projection. The temperature was shifted using the temperature difference given by the UKCP18 probabilistic projection.

Evapotranspiration

As predictions for evapotranspiration are not given by the UKCP18 data set a multiplication factor was calculated for this data. The Oudin (2005)[12,13] formula was used to calculate evapotranspiration using the climate adjusted temperature as well as the baseline temperature. The ratio of these two quantities were used to determine a multiplication factor to apply to the baseline evapotranspiration data.

C.3.2 Population Growth

Population growth has been implemented in the model by applying a percentage increase to the population at each demand type node in the model. The percentage increase applied was determined by the local authority of the population site. The population projection data for England was extracted from the ONS website[14] and the principal population projection data for Wales was extracted from StatsWales[15].

C.3.2.1 Modelling Assumptions

Both datasets are 2018-based estimated predicting to 2043, therefore the data is extrapolated linearly to 2045 using the last 5 years of data. The population growth is specified at local authority level, therefore in our modelling population growth is assumed to be constant across a local authority. Some nodes were located between the borders of local authorities, in these cases the population increase was apply for the local authority in which the majority of the node

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[12] Oudin, L., Michel, C., and Anctil, F., 2005a. Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 1-can rainfall-runoff models effectively handle detailed potential evapotranspiration inputs? Journal of Hydrology, 303, 275–289. Doi:10.1016/j.jhydrol.2004.08.02;

[13] Oudin, L., et al., 2005b. Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2-Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling. Journal of Hydrology, 303, 290–306. doi:10.1016/j.jhydrol.2004.08.026

[14] Population projection data for England, https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/datasets/localauthoritiesinenglandz1, accessed March 2024

[15] Principal population projection data for Wales, https://statswales.gov.wales/Catalogue/Population-and-Migration/Population/Projections/Local-Authority/2018-based/populationprojections-by-localauthority-year, accessed March 2024

was located. The population was kept at a constant value throughout the simulation in line with the baseline set up of the model.

C.3.2.2 Methodology

The model has a specified population for each demand node which remains constant throughout the simulation. The percentage increase between the 2021 project population and 2045 projected population was calculated for each local authority and is shown in Table C.6. This percentage increase was then applied to each demand node in the model following the assumptions above.

Table C.6: Percentage population increase for each local authority between 2021-2045.

Local authority	Percentage Increase
Powys	1.3%
Monmouthshire	6.9%
Herefordshire	12.7%
Gloucestershire	14.6%

C.4 Options selection and Implementation

For the option development, stakeholder meetings with the relevant parties were held to determine five options to model. These options were modelled in-combination with the climate change and population growth scenario modelling. Some of the options were implemented at different levels and in-combination to have a greater understanding of the relative impact of those options.

C.4.1 Option 1: Tree cover

A tree cover option was developed to assess the impact of a proportion of the land in the catchment being changed to increase the average tree cover across the catchment.

C.4.1.1 Methodology and assumptions

Each land node in the model has multiple growing surfaces defined within it, these are associated with the different land uses with the waterbody (e.g. trees, grass, maize). A change in tree cover is modelled by adjusting the size of the different growing surfaces to account for the change in land use.

For every waterbody in the catchment, the area modelled with tree cover was increased by a given absolute percentage. The area of other land uses types in the waterbody was then decreased proportionally to ensure the total area of all surfaces was not changed.

C.4.1.2 Limitations

In the baseline model, the values of the following parameters applied to the growing surfaces were specified for a given waterbody and were not altered for different land uses. The parameters were; wilting_point, field_capacity, total_porosity, surface_coefficient, percolation_coefficient, infiltration_capacity. It is expected that the type of land cover would have an impact on these parameters.

Therefore, it is expected that the model underestimates the impact of an increase in tree cover. If further modelling is carried out, it would be recommended that the model is setup and calibrated with these parameters specified for the individual growing surfaces in the model.

C.4.1.3 Modelled options

In the baseline model the tree cover varied across the catchment with an average tree cover of 13%. Two options were agreed upon with stakeholders from the Catchment Partnership, they were:

- Option 1A: absolute 10% increase, from 13% to 23%
- Option 1B: absolute 17% increase, from 13% to 30%

Option 1B was inspired by the global 30by30 target to protect 30% of land for biodiversity conservation by 2030 adopted at the UN Biodiversity Summit COP15 in December 2022[16]. It is recognised that 30% tree cover is an ambitious interpretation of the 30by30 commitment.

C.4.2 Option 2: Manure or fertiliser reductions

C.4.2.1 Methodology and assumptions

The baseline model defined deposition rates of ammonia, nitrates and phosphates from manure and fertilisers application at a waterbody level. To model the reduction in manure and fertiliser application the deposition rates were modified by a specified factor. This factor was defined independently for manure and fertiliser and then applied uniformly across the catchment.

C.4.2.2 Limitations

Reduction in fertiliser and manure application is unlikely to be uniform across the catchment. Future iterations of modelling could consider applying different reduction factors in different regions of the catchment.

C.4.2.3 Modelled options

Three different levels of this options were considered in this study. The first two cases were the two scenarios published in the RePhoKus study[18].

The Phosphorus Substance Flow Analysis (SFA) of the Wye catchment showed the total volume of manure and fertilizer applied to the catchment as.

- Manure = 6110 ± 601 tonnes per year
- Fertilizer = 1143 ± 126 tonnes per year

The Catchment zero P drawdown scenario SFA shows a reduction of manure and fertilizer to a level of:

- Manure = 3143 ± 306 tonnes per year
- Fertilizer = 286 ± 29 tonnes per year

And the Catchment zero P balance scenario SFA shows a reduction of manure and fertilizer to a level of:

- Manure = 3973 ± 381 tonnes per year
- Fertilizer = 286 ± 29 tonnes per year

Therefore, the first two options were modelled as:

- Option 2A: Drawdown scenario, 49% reduction in manure and 75% reduction in fertiliser.

[16] Delivering 30by30 on land in England (publishing.service.gov.uk)

[18] Withers P, Rothwell S, Forber K, Lyon C, 2022, Re-focusing Phosphorous use in the Wye Catchment https://councillors.herefordshire.gov.uk/documents/s50101856/RePhoKUs_Wye_Report_310522.pdf

- Option 2B: Balance scenario, 35% reduction in manure and 75% reduction in fertiliser

The final option was selected to demonstrate a lower impact option:

- Option 2C: Lower magnitude, 25% reduction in manure and 25% reduction in fertiliser

C.4.3 Option 3: Improved soil health

An option demonstrating the impact of improved soil health was developed to assess the impact on the catchment but does not specify the method for improved soil health. This could cover a variety of techniques including regenerative farming methods.

C.4.3.1 Methodology and assumptions

Improved soil health is modelled as an increase in the ability for soil to hold water and increased infiltration rates. It is assumed that the improved soil health has arisen from a variety of farming techniques with an average improvement.

Previous studies suggest that increase in infiltration rates due to regenerative farming techniques can lead vary significantly depending on the techniques and crops being used.[19,20] One study found that the increase infiltration rates due to perennial and no-till were 60% and 6% respectively[21]. Therefore, a range of percolation improvements were considered in this study.

The percolation and field capacity in the baseline model were specified for a given land node (waterbody) and applied to the growing surfaces within that node. Therefore, the percolation coefficient and field capacity in a waterbody were scaled depending on the proportion of land in the waterbody is assumed to have improved soil health. It was assumed that the percentage of land with improved soil health considers agricultural land only and the percentage of land manged varied between England and Wales.

C.4.3.2 Modelled Options

Four options were run to compare both different levels of improvement in percolation co-efficient and different proportions of land managed to improve soil health.

- Option 3A:
  - Percolation coefficient increased by 30%
  - Field capacity increased by 10%
  - 40% of agricultural land in England
  - 20% of agricultural land in Wales
- Option 3B:
  - Percolation coefficient increased by 30%
  - Field capacity increased by 10%
  - 65% of agricultural land in England
  - 40% of agricultural land in Wales
- Option 3C:

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[19] Review of quantification methods for ecosystem services of Ecosystem-based Adaptation measure to drought risks, https://pro-water.eu/sites/default/files/2022-03/D2.2.1_Quantification_methods_for_ES_of_EbA_measures.pdf, Accessed March 2024

[20] Houšková B. Soil Compaction Available Water Content in Soils. EU-China Joint Experts' seminar. Brussels 27.10.2016 2016

[21] Basche. A., DeLonge, M., 2019. Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis, PLOS ONE, doi.org/10.1371/journal.pone.0215702;

- Percolation coefficient increased by 50%
- Field capacity increased by 10%
- 40% of agricultural land in England
- 20% of agricultural land in Wales

- Option 3D:
  - Percolation coefficient increased by 50%
  - Field capacity increased by 10%
  - 65% of agricultural land in England
  - 40% of agricultural land in Wales

C.4.4 Option 4: Impact of infiltration rates on flooding

An extreme option was modelled to assess the impact of reduced infiltration rates within the catchment should soil health decline. A uniform 50% reduction in soil percolation rates was applied to agricultural land across the entire catchment.

C.4.5 Option 5: Wastewater treatment work upgrades

C.4.5.1 Methodology and assumptions

There were 16 major wastewater treatment works (WwTW) included in the baseline model. Improvement to wastewater treatment works can be modelled by increasing the efficient of pollutant removal in the treatment works, this is controlled by the constant in the process parameter for each pollutant.

In this study seven of the 16 WwTW works modelled had upgrades shared with the in the WCP members, recorded as an increase in P-load removal. For those with a non-zero initial P-load removal the efficiency of Phosphorus removal in the WwTW was scaled by the ratio of the initial and final P-load removal in the data shared. For those with zero P-load removal prior to upgrades the average ratio was used.[22]

C.4.5.2 Limitations

The baseline model was set up and calibrated with all WwTW assuming the same treatment efficiency, therefore these improvements were applied to uniform treatment. The efficiency will vary between treatment works and it is recommended that future baseline modelling calibrates with more detailed WwTW data.

C.4.6 Options in combination

Three in-combination runs were modelled.

- **Combination A: Lower magnitude of all options apart from manure which is middle magnitude.**
  - Option 1A: tree cover - absolute 10% increase, from 13% to 23%
  - Option 2B: Balance scenario, 35% reduction in manure and 75% reduction in fertiliser
  - Option 3A: improved soil health
    - Percolation coefficient increased by 30%
    - Field capacity increased by 10%
    - 40% of agricultural land England

[22] Unpublished data supplied by the Wye and Usk Foundation.

    - 20% of agricultural land Wales
  - Option 5A: WWTW upgrades

- **Combination B: Higher magnitude**
  - Option 1B: tree cover - absolute 17% increase, from 13% to 30%
  - Option 2A: Balance scenario, 49% reduction in manure and 75% reduction in fertiliser
  - Option 3D: improved soil health
    - Percolation coefficient increased by 50%
    - Field capacity increased by 10%
    - 65% of agricultural land England
    - 40% of agricultural land Wales
  - Option 5A: WWTW upgrades

- **Combination C: Lower magnitude.**
  - Option 1A: tree cover - absolute 10% increase, from 13% to 23%
  - Option 2C: Balance scenario, 25% reduction in manure and 25% reduction in fertiliser
  - Option 3A: improved soil health
    - Percolation coefficient increased by 30%
    - Field capacity increased by 10%
    - 40% of agricultural land England
    - 20% of agricultural land Wales
  - Option 5A: WWTW upgrades

C.5 Model Outputs

The following model outputs were used to understand the impact the scenario and options had on flow and water quality in the catchment.

- Flow rate.
- Dissolved inorganic Nitrogen.
- Soluble Reactive Phosphorous.
- Organic-phosphorus

The model outputs available were limited to those calibrated in the baseline model report from Imperial College London (see Annex B). The impact on organic- phosphorus had been included additionally in this model because of the pollutants importance when understand WwTW upgrades but is not given in absolute values due to the uncertainty in calibration.

All metrics (Q95, 5th percentile, mean etc.) were calculated over the final 15 years of the model scenario to ensure the data was representative of the average behaviour was not influence by localised events in historical data. The results were given for the locations validated in the baseline report (see Annex B).

D. Additional Modelling Results

The figures in this Annex show the difference in water quality for different options at different locations across the catchment. See Annex B for map of locations. The results are discussed in section 4.6 of the main body of the report.

Figure D.3: Impact of 95th percentile of concentration of DIN, SRP and Org-Phosphorous at the Afon Elan confluence with the River Wye.

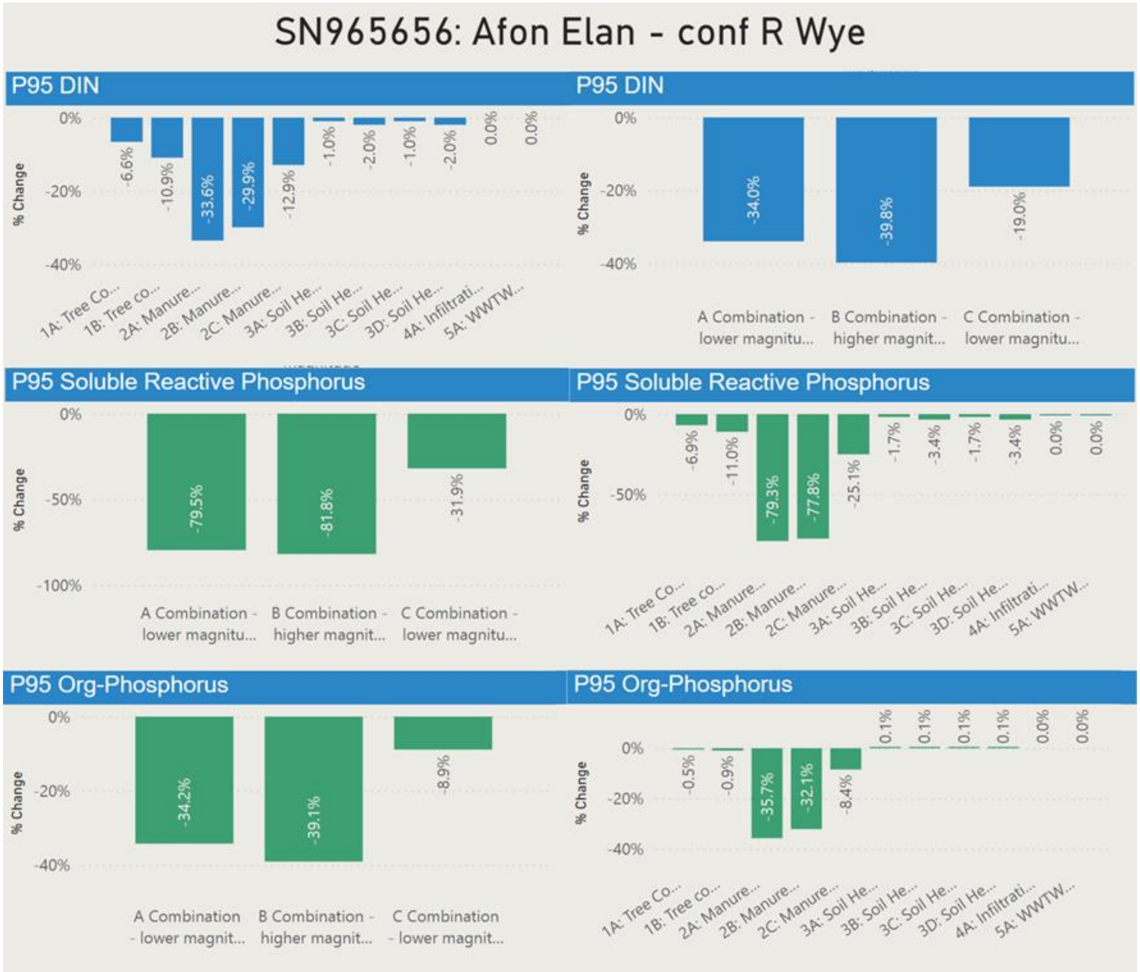


Figure D.4: Impact of 95th percentile of concentration of DIN, SRP and Org-Phosphorous on the River Lugg at Eaton Bridge, Leominster

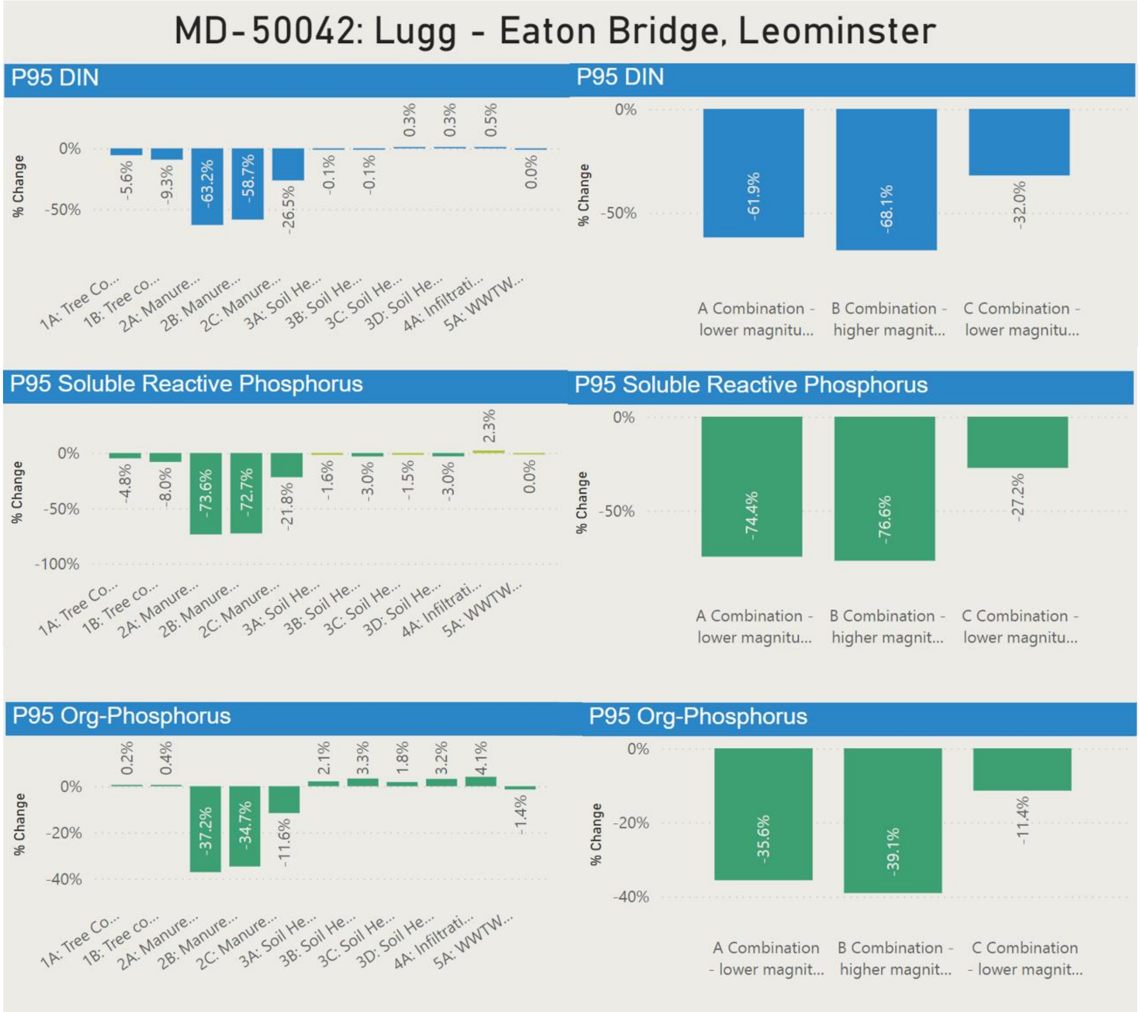


Figure D.5: Impact of 95th percentile of concentration of DIN, SRP and Org-Phosphorous on the River Wye at Carrots Pool.

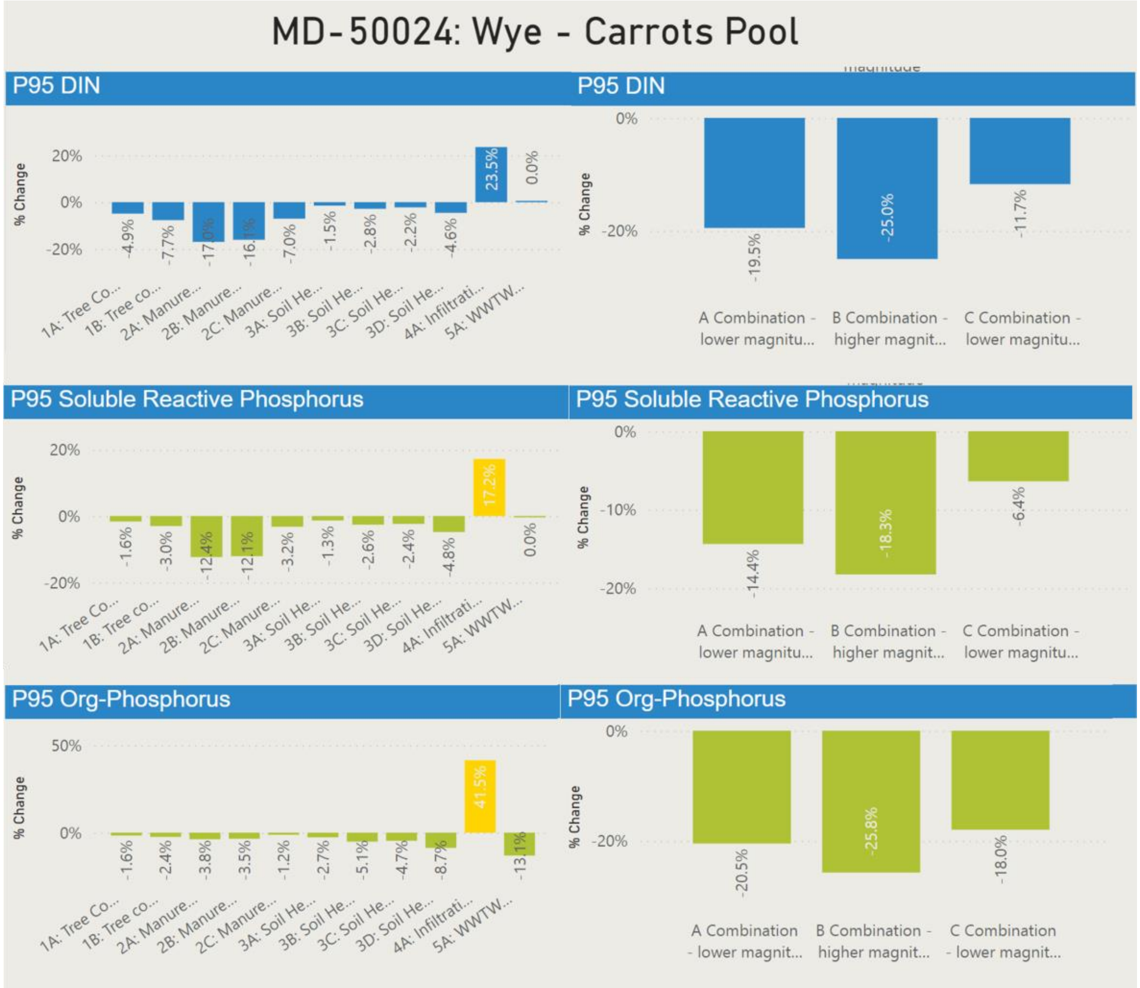
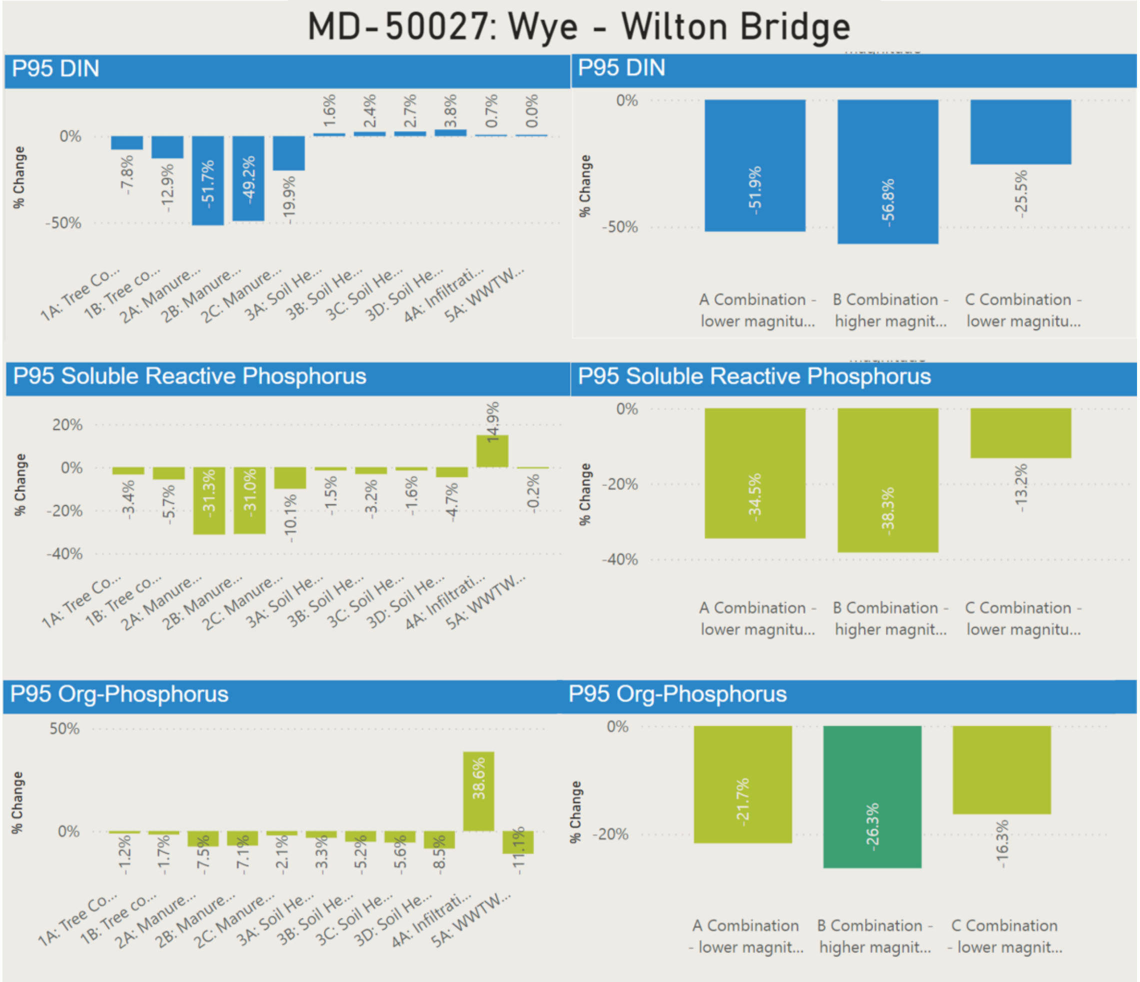


Figure D.6: Impact of 95th percentile of concentration of DIN, SRP and Org-Phosphorous on the River Wye at Wilton Bridge.



E. Lessons Learnt

This is the fifth application of the SIWM method by Mott MacDonald. The lessons learnt in this project are shown below in Table E.7 the context of lessons learnt in the other projects to indicate the journey being undertaken in the application of this method.

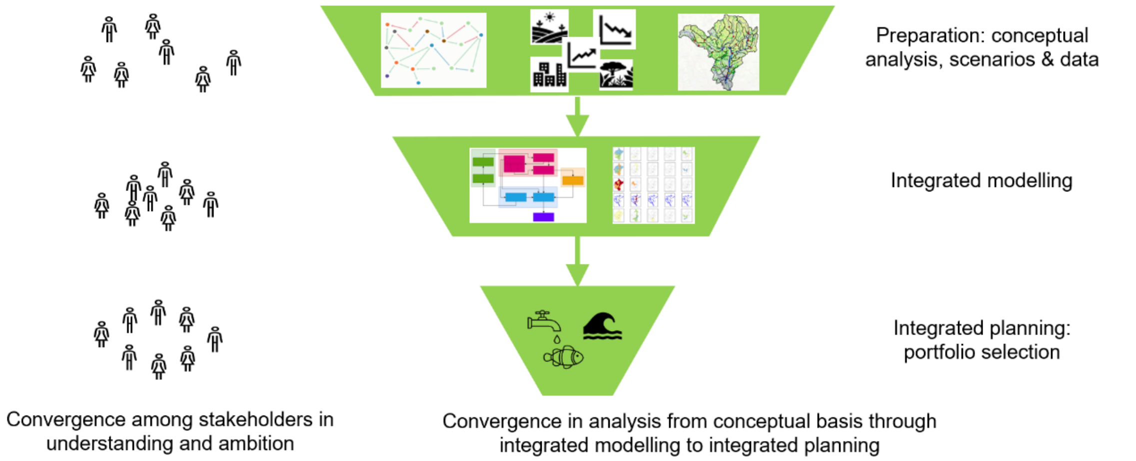
Table E.7: Lessons learnt in applications of SIWM method by Mott MacDonald

Project	New achievements	Elements to reconsider
OxCam Arc IWMF Phase 1 **Environment Agency 2021-2022** This project established the method linking system mapping as the basis of the selection of metrics for an appraisal of interventions in a catchment followed by use of WSIMOD to give a high-level assessment of different portfolios. A case study using the Cam, Rhee and Granta was used.	The conceptual basis of the method was established. The overall concept was well received. The "summation of benefits" approach set out a concept by which different planning processes (WRMP, RBMP etc) could be integrated.	The system mapping was somewhat over-ambitious in scope and at times hard for participants to follow. The mapping included the long-list of intervention categories which meant the maps were large and complex.
Subregional Integrated Water Management Strategy – East London Greater London Authority This project was a live test case for the implementation of the SIWM and was well received by the client and project stakeholders. It took the River Lea catchment as the project boundary and demonstrated benefits of taking an integrated approach across water quality, water resource and flood management.	The stakeholder engagement comprised the project steering group made up of representatives of the participating London Boroughs, the EA and water companies. The group was well planned and chaired and led to an important co-learning process that created a cultural shift towards collaborative working. This human dimension to the project was an important enabler for the implementation of the recommendations including a 90-day action plan.	

The interim report of the London Climate Review described it as "a leading example of IWM."	See Figure E.7 for a conceptual representation of this analytical method.	
Chalk Stream Systems – Environment Agency This case study revisited the River Lea and integrated the Hertfordshire Groundwater Model into the analysis. The system mapping was undertaken by a small group of technical experts in relevant organisations such as the water companies and environmental NGOs. The purpose of the work was to explore second order impacts of chalk stream strategies with the aim of informing and nuancing debate about the management of chalk stream ecosystems.	EA feedback on this study drew attention to the way that the system mapping synthesised expert opinion and provided a useful wide-angle lens on the problem. This scoping exercise was validated by the numerical modelling which quantified the insights identified in the system mapping. This process, in turn, "clarified the exam question" for any subsequent analytical work that could be done. See Figure E.8 for a conceptual representation of this analytical method.	
Rethinking Water Planning (Oxford to Cambridge IWMF Phase 2) This project adopted the SIWM process in modified form in two case studies and used an alternative method relying on expert judgement without modelling as a comparison. In one case study, the River Lea was revisited with a revised version of WSIMOD with an enhanced groundwater model.	The enhanced WSIMOD is an improvement in its capability with respect to groundwater. The project developed a conceptual alternative that enhances expert judgement, but the overall assessment demonstrated the benefit of modelling.	The application was a comparison of methods rather than a live planning case and therefore had limited engagement by catchment stakeholders. As such the project focussed on an analytical contrast between integrated planning and business as usual, but was impeded by shortages of data that could have been addressed in a live context.

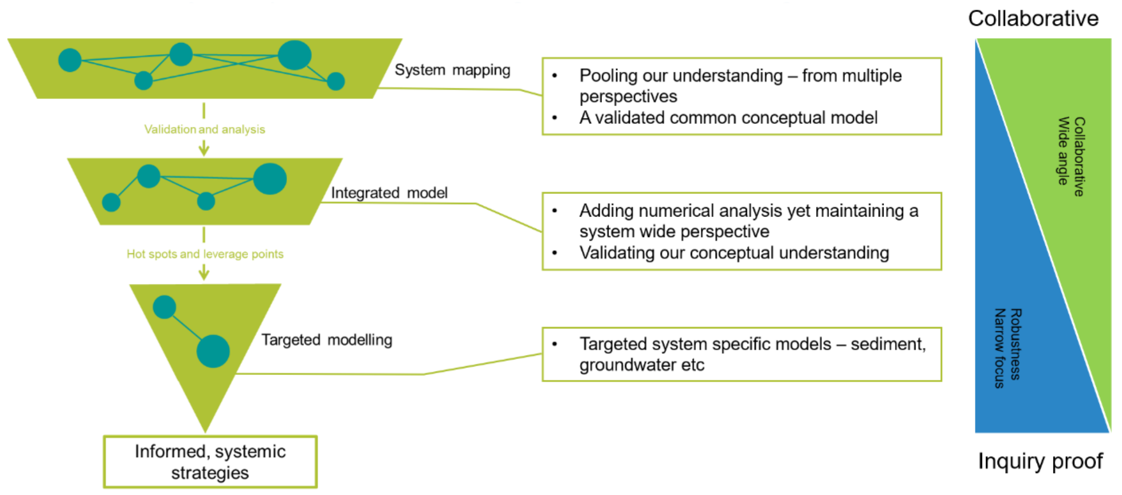
		The learning relates to the importance of co-creation with catchment stakeholders.
Understanding the Wye This project supports (but is distinct from) the creation of a catchment management plan. The project is undertaken in a context with significant political interest over catchment outcomes.	The system mapping was beneficial in its human function of providing a means to record the voice of a wide range of actors. Feedback has been positive about the system mapping enabling collaborative planning. The metrics are shown on a theory of change diagram (planning diagram) as well as on a high-level summary system maps. The modelling has shown the high-level priorities for the catchment providing guidance for the development of the plan. The system mapping and modelling provides tangible steppingstones between the stakeholder engagement and the creation of the plan.	The detailed system map is large, reflecting the fact the way that the emphasis on stakeholder engagement in its use. This large-scale engagement needs appropriate planning and resourcing from the outset. The model set up and baselining was not done in collaboration with the catchment partnership. The link was made at a later stage. Earlier engagement would have been beneficial. Sensitisation and discussion of the role of WSIMOD as a high-level integrated model rather than a detailed deterministic model needs to occur early.

Figure E.7: SIWM method applied in a project with detailed modelling (e.g. London SIWM)



Source: Whaley, M. E., Benton, L., Bromwich, B., Mijic, A., Rousseau, E., Whaley, M. P., & Dobson, B. (2024). Implementing a systemic approach to water management: piloting a novel multi-level collaborative integrated water management framework in east London. *AQUA—Water Infrastructure, Ecosystems and Society.*

Figure E.8: SIWM method applied in a project with detailed modelling (e.g. Chalk Stream Systems)



F. Record of Meetings

F.1 Record of attendees at participatory system mapping focus groups

Ten online focus groups were held with local experts working within each sub-system area to develop the detailed sub-system maps throughout November and December 2023. The organisations that attended these focus groups are given in Table F.8.

Table F.8: Record of attendees at focus groups

Focus group	No. of attendees (excluding Mott MacDonald)	Organisations that had a Representative Attend the Focus Group
River health	5	Herefordshire Wildlife Trust, Herefordshire Council, Environment Agency Friends of the Upper Wye, Lancaster University
Flooding and channel health	6	National Farmers Union, Environment Agency, Natural England Citizen Science, Herefordshire Council, Friends of the Lower Wye
Tourism, business and leisure	4	Wye Valley AONB, Environment Agency, Natural England Wye Salmon Association
Water resources and utilities	5	Environment Agency, National Farmers Union, Dŵr Cymru Welsh Water, Academic - Retired
Livestock farming	12	National Farmers Union, Environment Agency, Wye and Usk Foundation, Hereford Meadows, Lancaster University, Friends of the Upper Wye, Herefordshire Council, Natural England, Farmer, Dŵr Cymru Welsh Water, Natural England
Biodiversity	6	National Farmers Union, Environment Agency, Natural England, Save the Wye, Glasbury - Hay River Wye Alliance
Arable farming	5	Environment Agency, Citizen Science, National Farmers Union, Farm Herefordshire, Natural England
Forestry and woodlands	4	Wye and Usk Foundation, Woodland Trust, Friends of the Upper Wye
Housing and infrastructure	4	Herefordshire Council, CPRE - infrastructure and housing National Farmers Union, Herefordshire Housing Group, Wye Valley AONB
Food system	6	Environment Agency, Wye and Usk Foundation, Avara Foods, National Farmers Union, Friends of the Upper Wye, Natural England

F.2 Record of meetings informing WSIMOD Modelling Decisions

Twelve meetings were held with WCP stakeholders between the 6th February 2024 and 9th April 2024 to inform the WSIMOD modelling assumptions and scenario and options decisions. These meetings were with the catchment management plan Task and Finish group and modelling sub-group. A list of organisations that attended each meeting are given in Table F.9.

Table F.9: Record of meeting attendees for WSMIOD modelling discussions and decisions.

Meeting Reference	Date	Meeting Name	Mott MacDonald	Mott MacDonald	Mott MacDonald	Mott MacDonald	Mott MacDonald	Environment Agency	Environment Agency	Citizen Science	Wye and Usk Foundation	Wye and Usk Foundation	Wye Catchment Partnership	North Star Transition	Herefordshire Council	Farming Connect	Herefordshire Construction Industry Lobby Group	Woodland Trust	Save the Wye Coalition	Individual Attendee	Hay River Wye Alliance	Friends of the River Wye	Individual Attendee	Mott MacDonald
MTG-001	2/6/2024	Wye Catchment Systems Approaches - Phase 2 Modelling		x	x				x	x	x		x											
MTG-002	2/13/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x	x	x	x			x	x	x													
MTG-003	2/16/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x	x	x				x	x			x											
MTG-004	2/19/2024	WCP - Catchment Management Plan Task and Finish Group	x						x	x	x	x		x	x	x	x	x	x	x	x	x	x	
MTG-005	2/20/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x		x	x		x		x														
MTG-006	2/27/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x	x	x	x		x	x	x	x													
MTG-007	3/5/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x	x	x	x			x	x	x							x			x			
MTG-008	3/12/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x		x	x	x		x						x			x				x		x
MTG-009	3/19/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x	x	x	x	x		x		x											x		
MTG-010	3/26/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x		x	x	x		x		x		x											x
MTG-011	4/2/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x	x		x							x		x							x		
MTG-012	4/9/2024	Wye Catchment Systems Approaches - Phase 2 Modelling	x		x	x			x	x	x		x									x		x

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