UPSTREAM THINKING

Evaluating the impact of farm interventions on water quality at the catchment scale

Upstream Thinking
By South West Water

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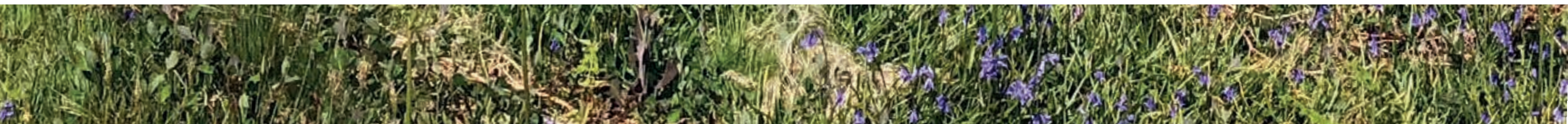
South West
Water



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Upstream Thinking

Evaluating the impact of farm interventions on water quality at the catchment scale

Over the 2015-2020 period, South West Water's Upstream Thinking Programme worked with a wide range of partners to tackle diffuse and point source pollution issues in 11 catchments across Devon and Cornwall. Using natural landscape-scale solutions and on-farm mitigation measures, the project aimed to work with farmers, landowners and project partners to mitigate the impact of farming activities on river ecosystems in the lowlands, and therefore on the production of drinking water. This report showcases the monitoring of water quality on a large scale in a number of test catchments by the University of Exeter to assess the impact of such interventions.

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Foreword by Richard Brazier

The following report represents the culmination of 5 years research to understand the impact of South West Water's ground-breaking Upstream Thinking project 2015-2020. The science and evidence makes an objective assessment of where water quality problems occur and where they might be tackled by using innovative methods of catchment management, to complement more traditional 'end-of-pipe' solutions to treat water and wastewater. A multidisciplinary approach is also taken, drawing on techniques from hydrology, aquatic ecology, water quality science, digital mapping and environmental modelling to provide an evaluation of the combined impact of interventions. Out of the 11 Upstream Thinking catchments, this report showcases results from 6 catchments across the South West, but results can also be used to inform future approaches elsewhere, especially where rainfall event driven pollution of surface waters in intensively farmed landscapes is a problem. The questions answered herein have been co-created by researchers and water industry staff, as well as informed via collaboration with a wide range of stakeholders, including landowners and managers, regulatory bodies such as the Environment Agency, catchment management delivery Partners (Devon and Cornwall Wildlife Trust, Westcountry Rivers Trust, Exmoor National Parks and FWAG-SW). The research portrays a well-rounded understanding of the potential for Upstream Thinking approaches to deliver real change to the way in which we manage our water resources. The approaches, when combined in a strategic and integrated manner, can deliver huge benefits to water quality but also to a wide range of other ecosystem benefits, representing a truly progressive way of working across the South West and indeed any region that seeks to enhance natural capital as well as safeguarding water resources.

Richard Brazier

Professor of Earth Surface Processes and Director of the Centre for Resilience in Environment, Water and Waste, The University of Exeter.

Foreword by David Smith

In 2015, when I was first appointed to the role of Upstream Thinking Programme Manager, one of the first things I did was to look at what had been achieved so far. It was clear that, although there were numerous descriptive case studies of the great work that was going on, along with projected modelled outcomes, there was a gap in the empirical evidence gathering required to make objective long-term observations and investment decisions.

Building on the relationship between South West Water and the University of Exeter, established through the upland peatland monitoring work we had collaborated on since 2011, we established with Dr. Emilie Grand-Clement from Prof. Richard Brazier's team a new programme of evidence gathering on the many Upstream Thinking catchments across the South West, with the aim of understanding the long-term impact of the programme, not just on the rivers but also at SWW's treatment works.

Over the last five years, while the research programme has been running, the Upstream Thinking Partners have engaged with farmers managing over 70,000 hectares, delivered over 850 farm plans and follow-up co-funded grants worth £3.5 million.

This report helps us to begin to understand the value of this investment and the future difference to the quality of water in the rivers that we abstract from, for the benefit of not just our water treatment works but for all river life and users.

David Smith

Upstream Thinking and Biodiversity Team Manager, South West Water Limited.

EXECUTIVE SUMMARY

- Following on from the first phase of the project (2010-2015), Upstream Thinking 2 (2015-2020) aimed to improve water quality through catchment interventions tackling a number of point source and diffuse pollution issues in 11 catchments across Devon and Cornwall. **Page 8.**
- The University of Exeter has been monitoring water quality to assess the impact of catchment interventions using a number of different methods. **Page 14.**
- In rivers, rainfall is a key driver in the mobilisation and movement of pollutants: although there is some inter-annual variability, on an annual scale, there is often a cyclical pattern, with worse water quality in winter and better water quality in summer. Because of their size, water quality issues in reservoirs tend not to be rainfall event driven; seasonal algal blooms are the biggest water quality concern in reservoir sources, primarily occurring in the summer; inter-annual variability in climatic conditions and diffuse pollution is likely to cause variability in the timing and extent of the algal blooms. **Page 20.**
- Across the region, the main interventions used are: establishing new hedges, minimising the volume of dirty water produced (i.e. sent to dirty water store) and fencing off rivers and streams from livestock. **Page 24.**
- Both the SPARROW and Simply-P models used to link interventions to water quality showed marginal improvements across all parameters and catchments: load improvements were estimated to be less than 0.01% for nitrate and Dissolved Organic Carbon, up to 1.8% and 0.5% for suspended sediments and total phosphorus respectively. Reasons for these minimal changes are discussed. **Page 28.**
- Monitoring results in the **Argal** catchment highlight a higher nutrient contribution to the reservoir from the Antron stream compared to the Argal Stream. Efforts should particularly focus on reducing P input, as peaks are concomitant with blue-green algal blooms. Metaldehyde detections were consistently below 100 ng L^{-1} in the catchment and at the Water Treatment Works, and decreased between autumn deployment periods. **Page 36.**
- In **Drift** reservoir, detrending analysis (2012 to 2018) shows that most of the high turbidity peaks were driven by climatic conditions (particularly high rainfall); no statistically significant change in water quality can be observed throughout the duration of the project. Nutrient input of both Total Oxidised Nitrogen and Soluble Reactive Phosphorus into the reservoir during storm events are consistently above targets set by the Environment Agency and SWW. Levels of individual pesticide detections in the reservoir were below 0.1 µg L^{-1} throughout the monitoring periods. **Page 42.**
- In **Upper Tamar Lake** we observed a decrease in turbidity in the feeder stream to the reservoir at high flow between 2016-2017 and 2018-2019; this reduction is not yet detectable in the raw water at the WTW. Two different sources seem to be contributing to Soluble Reactive Phosphorus pollution in the feeder streams during storm events: either a deep zone within the soil, or a more distant, agricultural source further up catchment. Algal blooms are not concomitant with nutrient input to the reservoir, and are therefore likely to be driven, to some extent, by climate combined with existing nutrient loads in reservoir. Three high detections (i.e. > 100 ng L^{-1}) of 2,4D, Fluroxypyr and Trichlopyr were recorded in the catchment and reservoir over the study period. **Page 50.**
- In the **Cober** catchment, the critical threshold of 2 mg L^{-1} of ammonium level was exceeded 0.85% of the time. The reduced frequency of ammonium detections since 2015 is likely to be a result of Upstream Thinking interventions in the catchment. Pesticide monitoring has shown high numbers of detections throughout the monitoring period, with the regulatory limit of 100 ng L^{-1} per compound and per detection exceeded on four occasions in the River Cober. **Page 56.**
- In the River **Fowey**, continuous turbidity measurements in all flow conditions show a slight decrease throughout the 2012-2013 to 2017-2018 hydrological years, and a slight decrease in turbidity and colour at low flow, which may be attributable to Upstream Thinking interventions. Change is however not yet visible at high flows. It is hoped that it will be noticeable after continued engagement and further interventions are implemented in the catchment. Although pesticides are frequently detected in the catchment, the level of concentrations measured in river water are consistently below 100 ng L^{-1}, thereby fulfilling the Upstream Thinking objectives. **Page 60.**
- In the **Exe** catchment, turbidity is driven by rainfall events and increased river flow; high turbidity events occur more frequently in winter, reducing across the study period in line with the overall reductions in flow observed. Although no pesticide detection reached the regulatory limit of 100 ng L^{-1} in treated water, the number of detections in raw water from both SWW drinking water treatment works was high. All compounds of concern for the EA are still detected in the catchment apart from Chlorotoluron, highlighting the need for continued work on the pesticide amnesty. **Page 64.**
- In the sub catchment of the **Headwaters of the Exe (HotE)**, nutrient levels tend to be low. Significantly higher levels in the River Exe compared to the River Barle, potentially indicate more extensive diffuse pollution and a greater need for interventions. Pesticide detections were recorded are more prevalent in the River Barle; the number of pesticide detections in spring makes this the more "at-risk" period. **Page 70.**

CONTENTS

BACKGROUND AND CONTEXT

- Upstream Thinking aims to improve water quality through catchment interventions tackling a number of sources of point source and diffuse pollution issues in 11 catchments across Devon and Cornwall.
- The University of Exeter has been monitoring water quality at catchment scale in a number of test catchments to assess the impact of catchment interventions.
- Water quality problems encountered within catchments include: colour, dissolved organic carbon, turbidity (or sediment pollution), nutrient inputs to reservoirs causing eutrophication, taste and odour compounds, and pesticides.

Understanding and reducing water pollution

The input of contaminants to freshwater resulting from land use, agriculture and wastewater treatment has an impact on the ecology and the health of the waterbody, but also on the production of drinking water, as pollution has to be removed before water is fit for human consumption. This is especially important in South West England, where most drinking water is sourced from surface waters (i.e. rivers and reservoirs). Two different types of pollution are generally considered:

- **Point source pollution:** this type of pollution occurs as contaminants are directly discharged to a body of water in a specific location. These sources of contaminants can include sewage, leaking pipes, farmyard effluents, slurry pits or septic tanks, or accidental spillage of waste into waters; they tend to have the worst impact in summer conditions when the river level is low with less dilution potential.
- **Diffuse pollution:** diffuse pollution happens as a result of the increased overland and subsurface flow occurring from rainfall falling on agricultural land (Figure 1). In its journey to the river system, this flow of water will wash contaminants (e.g. soil, nutrients, herbicides or pesticides) from farmland; this is especially a problem on land that is steep and farmed intensively, right up to stream and riverbanks.

Figure 1 Examples of poor soil management: cattle poaching in Cornwall (top) and dirty water runoff onto the road in the Fowey catchment (bottom); photos by CWT (top) and Giles Rickard, WRT (bottom).

The main pollutants from agriculture are nutrients (phosphate and nitrate in particular), chemicals (e.g. pesticides), faecal bacteria and pathogens from livestock, and soil or sediment from erosion. A number of activities have been identified as causing pollution. For instance, the poor management of slurry and manure can lead to increased leaching of nutrients, whilst the lack of vegetation or barriers in fields can cause sediment loss and water runoff that will enter streams directly.

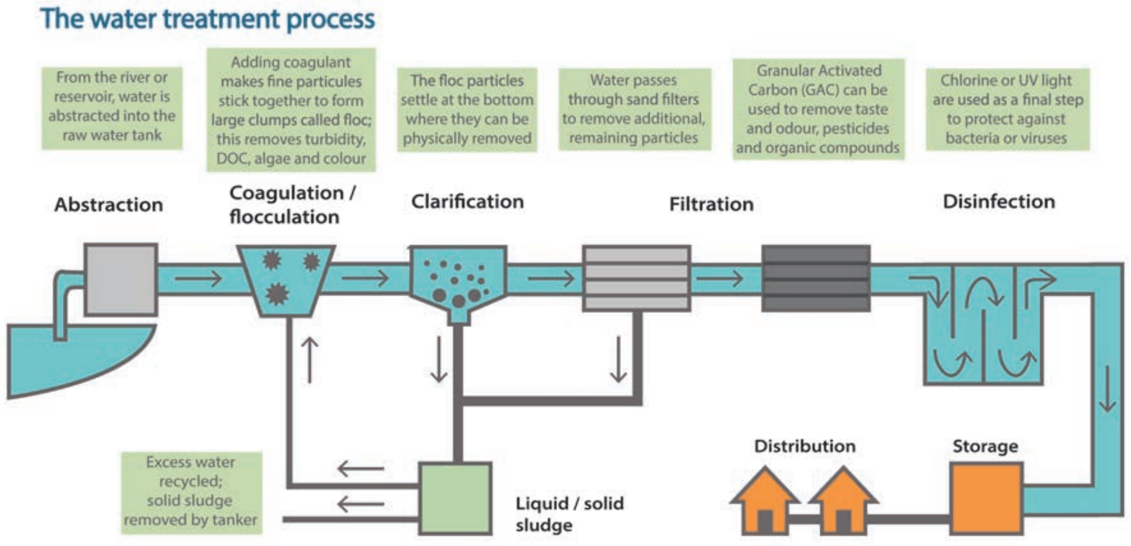
In addition to affecting the ecology and the health of waterbodies, water pollution has a major impact on the production of drinking water. The removal of contamination at water treatment works (WTWs) (Figure 2) is necessary to make water safe for drinking and meet health regulations. The process traditionally involves a number of steps, such as coagulation/flocculation and filtration (Figure 3), which use chemicals and produce waste. The efficiency and cost of production is therefore highly dependent on the quality of the raw water abstracted from rivers. Additionally, high levels of contaminants can lead to a temporary WTW shutdown, when removal is impossible. Such events are expensive and put pressure on the supply network, but can also trigger fines and penalties from either the Drinking Water Inspectorate (DWI) or the regulator OfWat.

Today, throughout the country, **catchment management** has been used as a way to effectively address pollution; a number of practical methods are now widely employed as effective remedies. The overall aim of such an approach is to use sustainable measures by working with farmers and land owners to reduce diffuse and point source pollution to water, improve wildlife and natural habitats, and positively impact on the treatment of water and its cost.

This approach is guided by a number of drivers and regulations, such as the EU Water Framework Directive (WFD) that requires water bodies to meet 'good' ecological status, or the Nitrates Directive to reduce the impact of nitrogen fertilisers on the environment. For the water industry, this has translated into legal requirements set out for South West Water by the Drinking Water Inspectorate and the Environment Agency.

Figure 2 Mayflower WTW in 2019, providing drinking water for the Plymouth area; photo by South West Water.

Figure 3 The different steps of water treatment used to remove contaminants and produce safe drinking water.



Upstream Thinking

Upstream Thinking is an award winning catchment management scheme set up by **South West Water** (SWW). Using natural landscape-scale solutions and on-farm mitigation measures, the project aims to work with farmers, landowners and project partners to mitigate the impact of farming activities on river ecosystems in the lowlands, and therefore on the production of drinking water. In the uplands, the actions are focused on restoring large peatland areas on Exmoor and Dartmoor through the Mires project[1].

Since the second phase of the project starting in 2015, **Cornwall Wildlife Trust** (CWT), **Devon Wildlife Trust** (DWT), **Exmoor National Park** (ENPA), the **Farming and Wildlife Advisory Group** (FWAG) and **Westcountry Rivers Trust** (WRT) have been engaging with land owners in 11 catchments (Figure 4) to identify challenges and opportunities within the farm business. Discussion with farm advisors will generally lead to the recommendation of costed interventions available through a number of funding streams.

Supporting and encouraging farmers to adopt active management practices, as laid out in the farm plans, is a key ambition of Upstream Thinking. Between 2015 and 2020, project partners have collectively established 864 integrated farm management plans and allocated capital grants to a value of £10.5m through SWW funding and £15.4m through match funding, bringing the total investment in catchment management in the south west region to £25.9m.

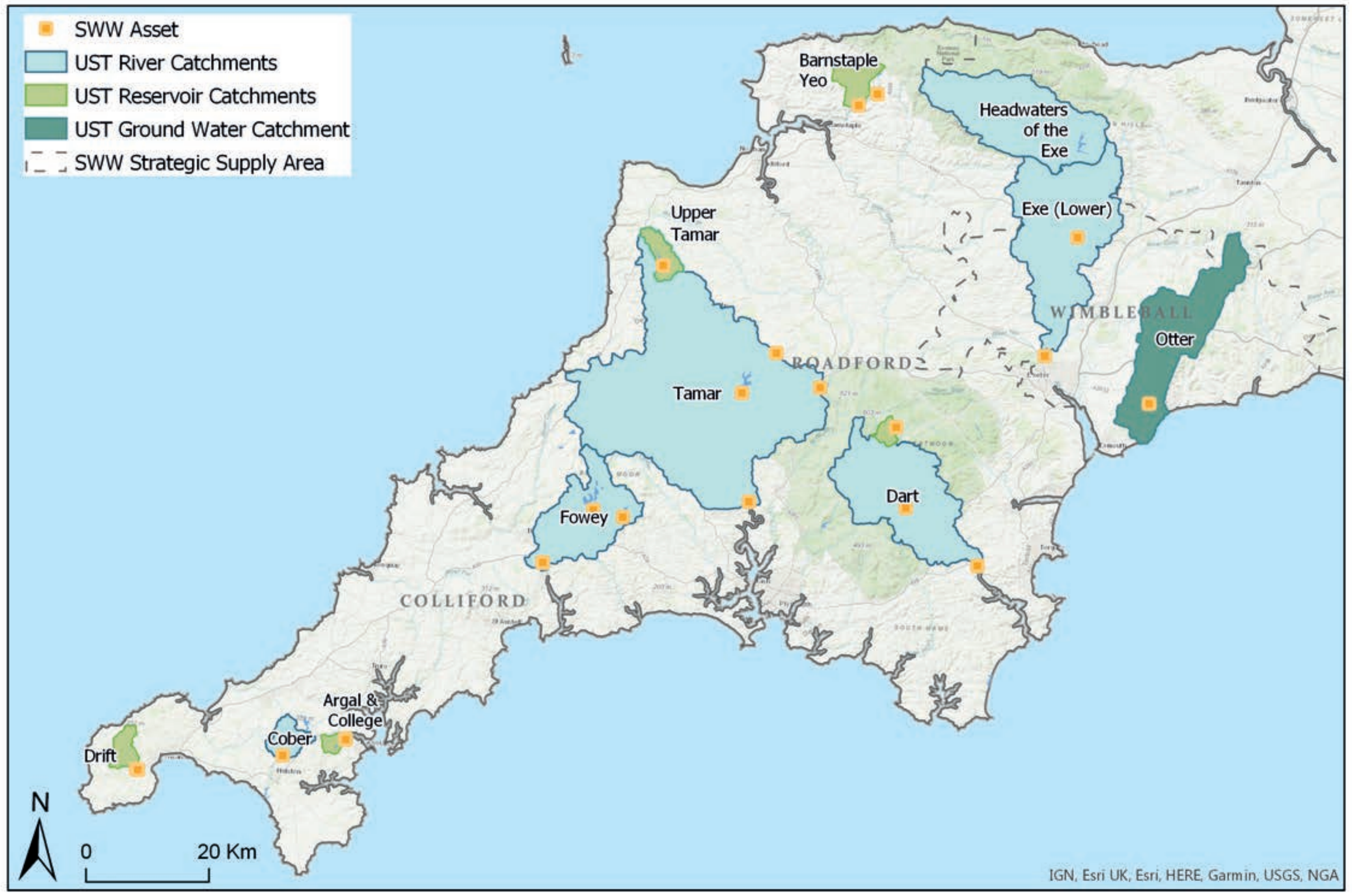


Figure 4 Upstream Thinking catchments and SWW assets (i.e. drinking water treatment works and abstraction points) within the supply areas in the Southwest region; this map also highlights the type of water supply to the water treatment works, i.e. reservoir, river or groundwater.

Understanding change

Overall, Upstream Thinking has delivered demonstrable environmental benefits, such as mire[1,2] or culm grassland[3] habitat restoration or improvement of local biodiversity and water body ecological status. However, whilst the change occurring as a result of the interventions can be identified on a site-by-site basis, the case has yet to be made for significant changes in water quality at large catchment scale where benefits may reduce the costs of water treatment. As a result, a monitoring programme has been set up by the **University of Exeter** (UoE) to address this need and to evaluate the impact of interventions delivered under the second phase of the project (2015-2020) in the target catchments. Additionally, UoE has also been monitoring water quality for the Headwaters of the Exe project (HotE) delivered by ENPA as part of the Upstream Thinking programme.

Within the catchments included in Upstream Thinking (Figure 4), this report focuses on results obtained during the second phase of the project (2015-2020) in a number of test catchments that are representative of the different types of water sources used for drinking water production in the south west region:

- **River catchments:** River Exe (Headwaters of the Exe and Lower Exe), River Fowey and River Cober;
- **Reservoir catchments:** Drift, Argal and Upper Tamar Lake.

The work presented here classifies and maps some of the in-catchment interventions delivered by project partners to reduce water pollution, identifies change (both observed and modelled) for a number of parameters in each catchment, and highlights some of the physical processes that may have occurred.

The mid-Devon hills; photo by DWT.

The main water quality issues affecting catchments in the south west are the following:

Colour in drinking water comes from organic compounds, including dissolved organic carbon, and metal ions (e.g. manganese) leaching from the environment. Colour is therefore largely dependent on agricultural practices and driven by the accelerated drainage of the land. Colour is removed by coagulation and flocculation (Figure 3). Left untreated, excess colour can cause unsightly drinking water and can exceed regulatory standards. The limit for colour in drinking water at the consumer's tap[4] is 20 mg L^{-1}.

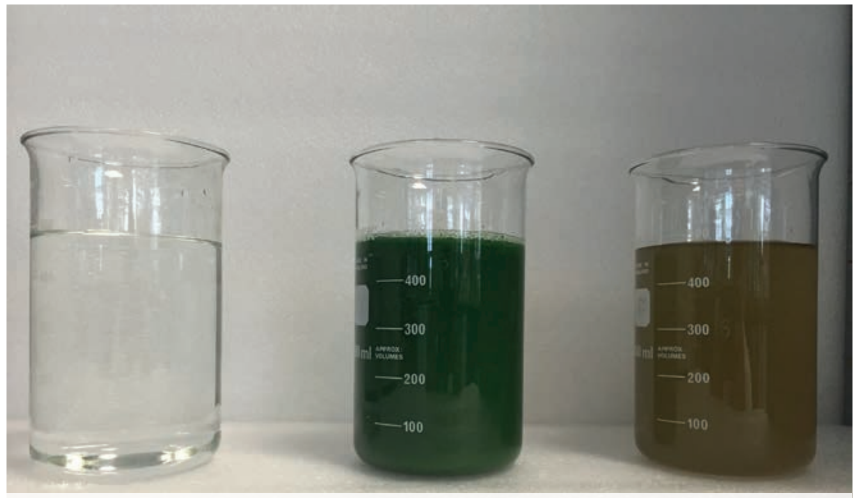
Dissolved organic carbon (DOC) is a term defining a range of compounds causing discolouration of water. It originates from peatlands and other organic-rich soils, or excess application of manures and slurries to the land. DOC has an ability to bind to heavy metals, and gives water a tea colour that has to be removed by coagulation. At the catchment scale, DOC in water is an issue because it represents a loss of carbon from a long-term store, and therefore has a negative impact on global mitigation of climate change. It is a particular problem for the water industry as it is costly to remove and its improper removal can react with chlorine and cause the formation of carcinogenic compounds (e.g. trihalomethanes) in drinking water. There is no regulatory concentration in drinking water specifically for DOC.

Suspended sediment (SS) refers to particles over 2 μm present in water, made out of inorganic (e.g. clay, silt and soil particles) and organic (e.g. algae, bacteria) material. SS is measured by weighing the mass of sediment present in a set volume of water.

Turbidity is closely related to SS. It is defined as a measure of the transparency of the water in the presence of particles in suspension, such as organic waste material, soil, sediment, algae or bacteria. Turbidity mostly originates from erosion of soil and agricultural material, and has detrimental impacts on the ecosystem, including blocking light penetration and clogging the gills of fish. In drinking water, the main issue with turbidity is caused by its aesthetic impact; in the treatment process, it is removed by coagulation and filtration. However, the process is unable to treat raw water with turbidity values above 20 NTU, whilst **legal requirements** limit concentrations at consumer's taps to 4 NTU.

Nutrients (i.e. forms of nitrogen or phosphorus) are essential for plant growth. In surface waters, they originate from fertilisers, runoff from manure or sewage and/or sediment input from point source or diffuse pollution. At high concentrations, they promote algal growth and have toxic effects on aquatic organisms. These excess nutrients, such as **Soluble Reactive Phosphorus** (SRP) and **nitrate** (NO_3), can lead to **eutrophication**, likely to promote algal blooms (see below). Nitrate can be removed from raw water by ion exchange. **Ammonium** (NH_4) concentrations over 2 mg L^{-1} in raw water lead to treatment interruptions.

A feeder stream to the Drift reservoir; photo by Emilie Grand-Clement.



Water quality issues encountered in streams and reservoirs in the South West: high suspended sediment loading from a stream after a rainfall event (right), acute blue-green algal bloom in reservoir (middle) compared with drinking water after the treatment process (left); photo by Paul Henderson.

Blue-green algal (i.e. cyanobacteria) blooms are a recurrent problem in drinking water reservoirs. Blooms form as a result of the rapid and extensive multiplication of cyanobacteria. They are driven by high concentrations of nutrients in the reservoir and by environmental factors (i.e. warm and still conditions). They are problematic for the ecology of the resevoir (e.g. oxygen depletion, prevention of light penetration), cause discolouration of the water, produce harmful cyanotoxins, and release taste and odour compounds as they die-back. Cyanobacteria are removed from raw water through coagulation, flocculation and clarification, followed by various stages of filtration. However, along with other phytoplankton species, the sheer volume to be removed can cause issues during the filtration of water. There is no statutory limit for algae concentrations in drinking water.

Taste and odour compounds, such as geosmin and 2-Methylisoborneol (MIB), originate from algae die-back and from soil bacteria. These compounds give the water a musty taste and smell and are removed through granular activated carbon (Figure 3).

Pesticides originating from both domestic and agricultural usage are a significant issue in most catchments[5]. They present an issue for non-target species (including humans), habitats and ecosystems. The UK drinking water quality regulations specify standards in drinking water of 100 ng L^{-1} (equivalent to 0.1 μg L^{-1}) per compound, or 500 ng L^{-1} (equivalent to 0.5 μg L^{-1}) for total pesticides. Pesticides are removed by activated carbon. **Metaldehyde** is a type of pesticide found in slug pellets and widely used in a number of catchments. It is of particular concern for drinking water production because its degradation in water is particularly slow, making it "semi-permanent" in aquatic ecosystems[6], but also because its removal from water using conventional treatment processes is difficult and therefore costly[7].

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METHODS FOR UNDERSTANDING CHANGES IN WATER QUALITY

Data collection

Evaluating change for a number of pollutants in catchments of different sizes, either due to natural variability or Upstream Thinking interventions, requires a combination of different types of data and information. In turn, teasing out the appropriate information uses a number of different analytical techniques. The data used for this project included:

- Water quality samples collected during rainfall events and baseflow from *in-situ* monitoring locations
- Continuous data and spot samples routinely collected by SWW at each of their assets, i.e. water treatment works (WTWs), reservoirs and drinking water abstraction points
- Passive sampling of acid herbicides and metaldehyde in water, over a continuous 6-week period at multiple locations
- Flow and climatic data collected by the Met Office and the Environment Agency

Sample and data collection by the University of Exeter

In reservoir catchments (i.e. Drift, Argal and Upper Tamar Lake), *in-situ* or semi-permanent monitoring equipment was deployed in feeder streams to characterise water quality entering the reservoir using:

- Automated sensors placed in each feeder stream to collect continuous data on river level, flow, turbidity, conductivity and pH (Figure 1).
- Automated pump samplers collected water samples at defined times during rainfall events (Figure 2); samples were further analysed in the laboratory for Soluble Reactive Phosphorus (SRP), Total Oxidised Nitrogen (TON), ammonium (NH_4), Colour and Dissolved Organic Carbon (DOC).

- The impact of interventions on water quality was monitored using a wide range of datasets: in reservoir catchments, the University of Exeter monitored nutrient inputs in feeder streams during rainfall events; in river catchments, continuous monitoring data from South West Water at water treatment works was used.
- Chemcatchers© were used to detect pesticide levels during critical application times.
- All continuous data was subject to an automated data cleaning process to remove outliers, instrument drift and general noise in the data.
- As diffuse pollution generally occurs during high rainfall events, their automated separation in the continuous flow data allowed an objective comparison between events across very large datasets.
- Additional tools enabled water quality during specific flow conditions over time, and the likely source of pollution, to be understood.

Figure 1 Continuous turbidity sensor (pointed out by the red arrow) and conductivity and pH sensors protected by black tubing (pointed out by the blue arrow) on the River Exe (Pixton gauging station); photo by Paul Henderson.

Figure 2 Pump sampler at the feeder stream to Upper Tamar Lake where water quality is monitored for the Upstream Thinking project; photo by Paul Henderson.

Upon return to the laboratory, samples were filtered. Nutrient concentrations were measured using colorimetric analysis by continuous flow analyser (SEAL, AA3, Figure 3); DOC measurements were made by catalytic oxidisation combustion technique with a total organic carbon instrument (Shimadzu, TOC-L, Figure 3) and colour analysis was measured at 400 nm using a spectrophotometer (BMG Labtech, FLOUstar).

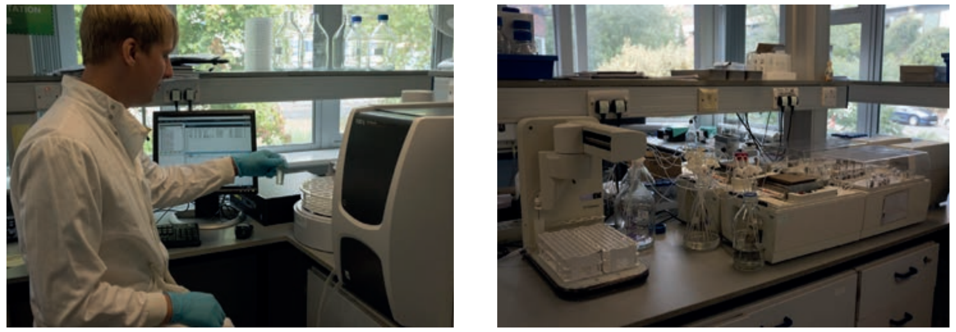


Figure 3 Samples were analysed for Dissolved Organic Carbon on a TOC-L analyser (Shimadzu, Japan) (left) and for nutrients using an AutoAnalyser (AA3, Seal Analytical, Wisconsin, USA) (right); photo by Emilie Grand-Clement.

South West Water data

Figure 4 Chemcatcher deployment for pesticide measurement in Cornwall: disks are placed in a cage (above) that is then left in the river and will accumulate contaminants for that duration, thereby giving a picture of the detections in that time period; photo by Tim Ball (SWW).

In river sites, water quality change at a catchment scale was evaluated at SWW assets (i.e. WTWs), making use of the wealth of data collected on a continuous basis. Water quality sensors measuring parameters like colour, turbidity, conductivity and ammonia (when available) are deployed in raw water from rivers to assess the quality of the water before treatment and make decisions on the treatment process to follow. Further monitoring throughout the treatment process enables operators to check its efficiency.

In addition, spot samples are routinely collected by the water industry to meet regulatory requirements (i.e. reporting to the Drinking Water Inspectorate on drinking water compliance) and were used where appropriate. This data includes: algae content, algae species, nutrient content, and taste and odour compounds, all of which need to be treated out of the water before it is suitable for drinking.

Passive samplers (i.e. Chemcatcher©)[1] were deployed in key locations within each catchment to measure acid herbicides and the pesticide metaldehyde (used in slug pellets) detections during two critical application times when these chemicals are normally applied to agricultural land: 6 weeks in the spring and 6 weeks in the autumn of each monitoring year. The passive samplers' disks are set up in a metal cage placed in the river and will accumulate contaminants over a period of time (Figure 4). They provide a valuable resource to identify the extent of herbicide and pesticide use upstream of SWW assets, as well as identifying change between monitoring years. These chemicals are very harmful to humans if left untreated in the water column. As passive samplers provide a Time Weighted Average (TWA) concentration of each compound during the deployment period, they give an idea of the occurrence of pollution and the average concentration over time, but not the short-term response to individual rainfall events.

Other data (EA, Met Office)

A number of climatic variables were used to separate the influence of rainfall or temperature on water quality from the effects of catchment management. Such data originated from the Met Office (i.e. **temperature**[2] and **rainfall data**[3]) and the **Environment Agency**[4] (i.e. river level and flow at gauging stations).

Methods of analysis

Continuous data

Continuous data collection (e.g. water quality, rainfall or flow in multiple catchments, every 15 minutes) over several years at multiple sites yields very large datasets. Data processing and visualisation showed that drift in the instrument and general noise in the data has to be removed before any detailed analysis can be done. This was done using a number of automated data cleaning filters with additional manual checks (Figure 5 and Figure 6). The methods for quality control and data cleaning were selected based on the characteristics of each data set and the information available about the monitoring. Some data required multiple stages of pre-processing to remove errors and outliers before they could be used for analysis.

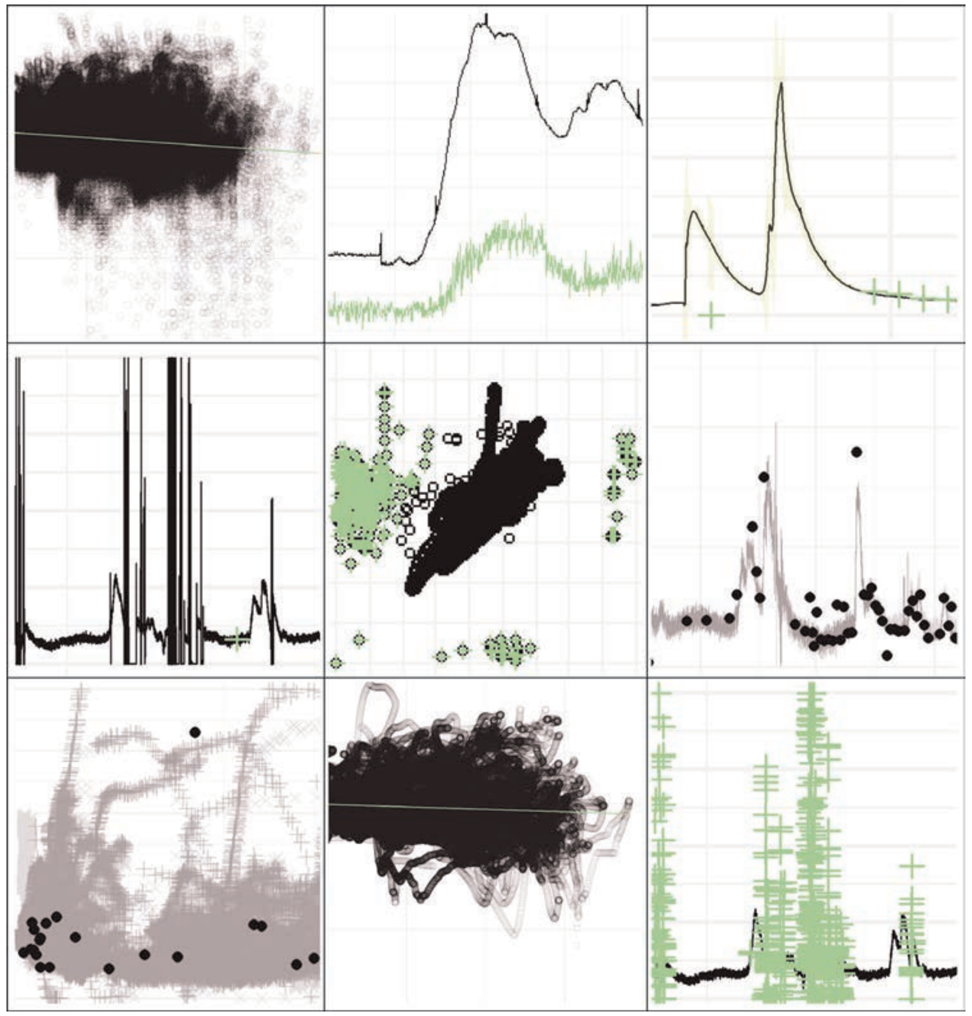


Figure 5 Example plots of data processing and evaluation steps used to remove poor quality data: include flow, water quality signal and spot samples for a range of water quality parameters. The different ways to represent the data (with points plotted against time or compared with each other for each point in time) highlight statistical outliers and poor quality data (in green) that needs removing.

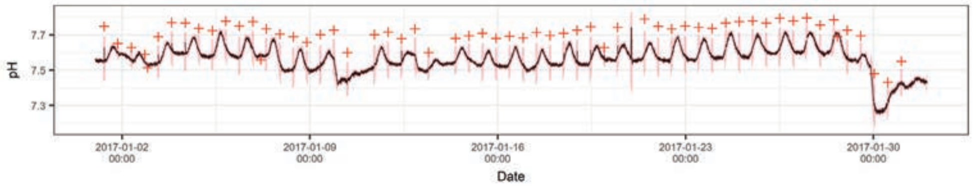


Figure 6 Time series showing the continuous pH dataset (black line) in the River Exe on which a local outlier filter has been applied in order to isolate and remove datapoints (red crosses) that are not part of natural variability of the dataset.

The importance of rainfall events

As diffuse pollution from agricultural activities tends to occur when contaminants are washed down the catchment by overland flow, rainfall events are critical times to quantify the occurrence of pollution in water bodies. Such events can generate a range of responses from water quality parameters, which depend mainly on the type and source of the pollutant (Figure 7). These data provide a precise picture of pollutant variation during a narrow window and enable us to quantify the load of each pollutant during each rainfall event. The rainfall event approach was used both in the *in-situ* sampling strategy carried out by the UoE, and also in the analysis of continuous data collected by SWW.

The analysis of the continuous data required the separation of events based on river flow and rainfall (Figure 8). The automation of this process allowed an objective comparison across the very large datasets[5]. Event metrics were calculated to describe change in each pollutant or flow response. Over the course of a year, in large rivers such as the Fowey or the Exe, on average, 40 events per year were extracted; in smaller, flashier streams, like the feeder streams to reservoirs, the average number of rainfall events extracted per year was 94.

Example of silted pond needing improved water drainage; Photo by Annabel Martin (WRT).

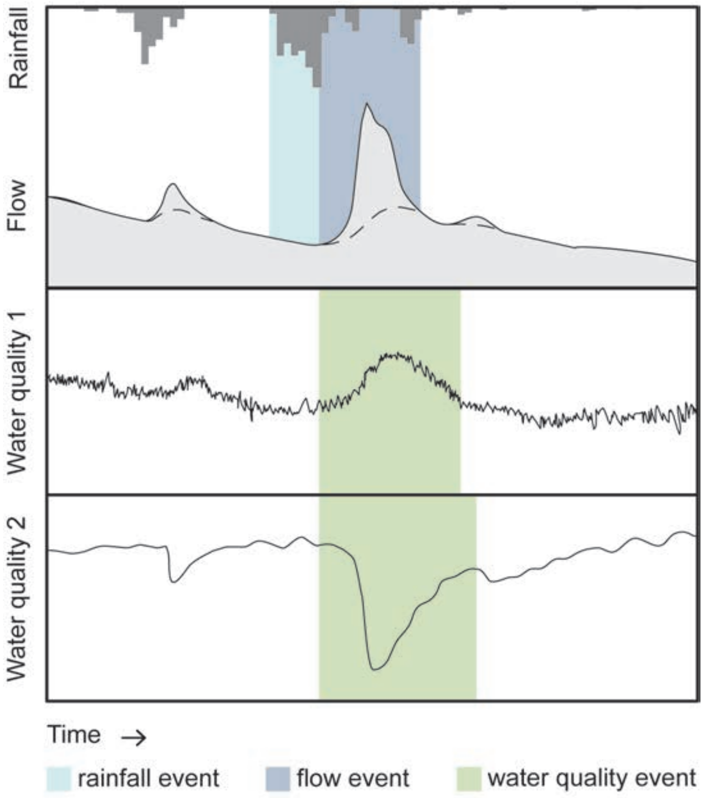


Figure 7 Rainfall in the catchment generating a response in rivers and streams (top), i.e. an increase in flow, and two different associated responses of water quality parameters: an increase (i.e. concentration) (middle) or a decrease (i.e. dilution) (bottom).

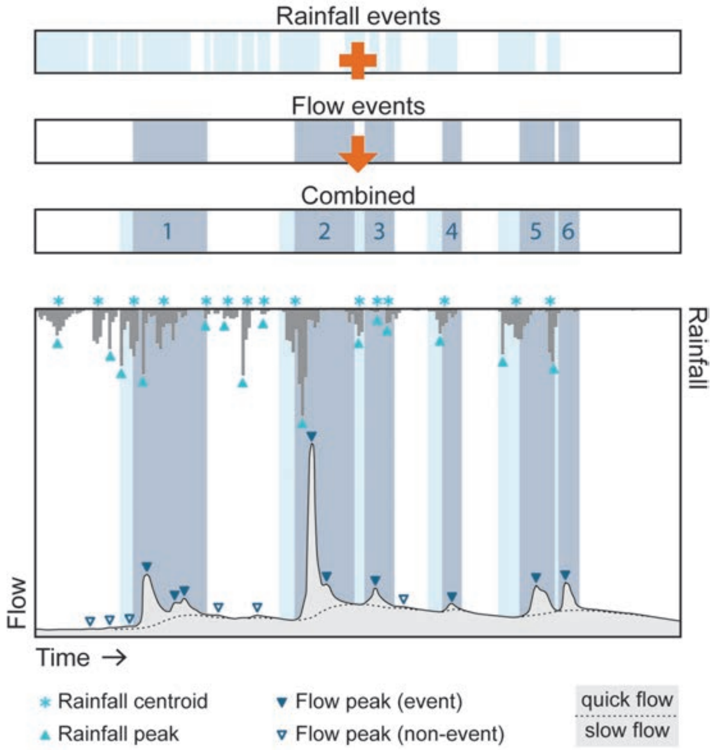


Figure 8 Rainfall and flow events were automatically identified and combined using digitally filtered quick and slow flow estimates and dynamic thresholds (i.e. threshold that changes with the year and season, therefore enabling events to be identified under different conditions).

Flow duration curves

One of the ways to identify different types of flow (i.e. low or high flow) is to use a flow duration curve showing the proportion of time where a specific flow level is reached or exceeded (e.g. Figure 9A, with more information on the calculation method found in the Glossary section). For example, in the feeder stream to Upper Tamar Lake in the period 2017-2019, the flow was at least 0.5 $m^3 s^{-1}$ for 70% of the time (i.e. Q70).

Using the flow duration curve method, the following metrics were calculated:

- Q5 and Q10, i.e. the flow equalled or exceeded for 5% or 10% of the time respectively, were indicative of high flow conditions;
- Q95 and Q70, i.e. the flow reached 95% or 70% of the time respectively, were indicative of low flow conditions).

These metrics were then used to apply limits to the corresponding continuous timeseries of flow (Figure 9B) to identify low or high flow conditions before performing further data analysis on these subsets of data.

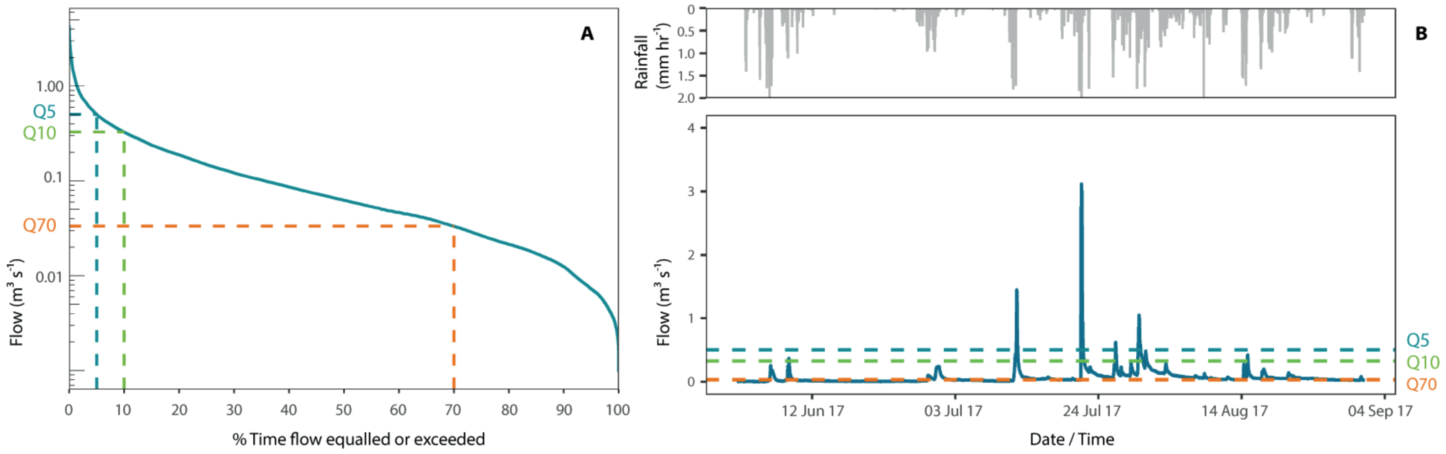


Figure 9 The flow duration curve (A) gives an indication of the flow experienced at 70%, 10% and 5% frequency, as shown by the dashed line linking % time equalled or exceeded (X axis) to the corresponding flow (Y axis); these flow values can then be applied to the flow time series (B) with the same colour dashed lines.

River fencing; photo by Martin Ross, SWW.

Peak counting

Another way to look at change is to count the number of peaks of contaminants and their magnitude between different time periods (Figure 10). For this purpose, a peak is classified as a local maxima of the 12 hour (flow and turbidity) or 24 hour (colour) median which exceeds the 5 day median. Local maxima below the 5 day median are considered to represent 'normal operating conditions' (on a short term). Once identified, they can be counted and compared to the whole record.

Figure 10 For simple peak counting the local maxima (orange triangles) in the short-term average (black line) which exceed the 5-day average (orange dashed line) are counted as peaks.

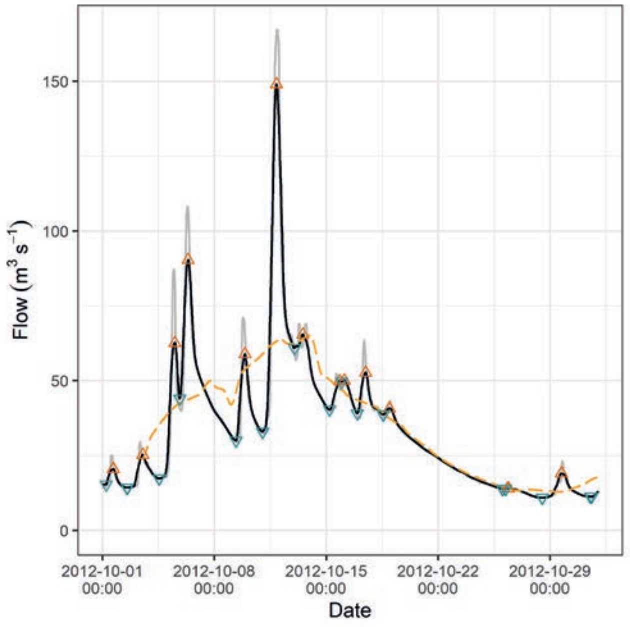
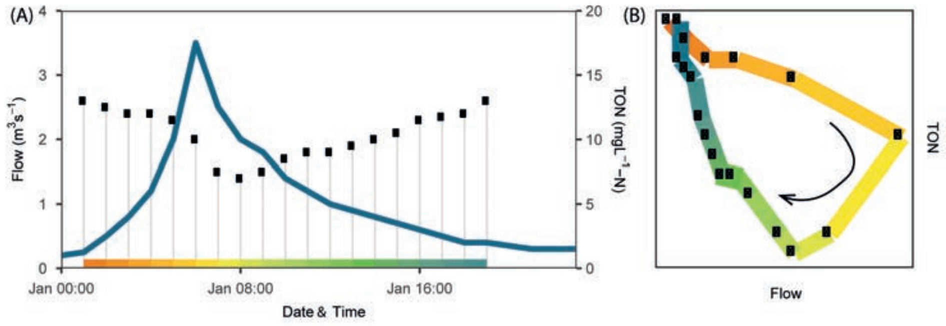


Figure 11 (A) Timeseries showing flow (blue line expressed in $m^3 s^{-1}$) and spot sample results of Total Oxidised Nitrogen ($mg L^{-1}$) during a specific rainfall event; (B) corresponding clockwise hysteresis loop representing flow (X axis) and matching TON concentration (Y axis) over time.



Hysteresis loops

The behaviour of the pollution during a rainfall event, i.e. whether the pollutant concentration increases or decreases with changes in river flow, and whether there is a delayed response in contamination compared to stream flow (or vice versa), can be analysed by looking at the hysteresis patterns, or the 'looping' of the relationships over time[6]. Figure 11 represents the change in levels of a pollutant with flow during an event, both as a time series and as a 'hysteresis loop'. The shape and direction of these hysteresis loops are analysed using a number of different metrics, such as the Hysteresis Index and loop area[7,8]. The comparison of these metrics between sites or contaminants, along with other information (such as conditions before an event), can also be used to gather information on the behaviour and origin of diffuse pollution in the catchment, based on how long it takes to travel through the catchment, and how this changes over the seasons or through time. For example, Figure 11 shows that, as flow increases from the start of the event, TON concentration decreases until flow has passed its maximum; TON concentration starts to increase as flow reduces – also known as clockwise hysteresis. Such a pattern can indicate that the contaminant is being diluted by rain water during storms, and further shows a lack of input of diffuse pollution. Anticlockwise hysteresis, and the timing of the contaminant peaks in relation to flow, can also indicate the distance of pollutant sources. For instance, the longer the lag between contaminant and flow peaks, the further the distance of the contaminant sources. However, such behaviour is also impacted by flashiness and how reactive the catchment is.

A combination of these methods will be used in the following sections to identify water quality change in each catchment.

Example of water samples collected after a rainfall event; photo by Alan Puttock (UoE).

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UNDERSTANDING BACKGROUND CONDITIONS AND PATTERNS OF CHANGE

General variability in rainfall and runoff

Seasonal and inter-annual variability

As the occurrence of pollution events is, to a large extent, dependent on rainfall, climatic variability will naturally lead to different types of responses. Therefore, not considering seasonal and inter-annual climatic variability in water quality analysis can risk mistaking the reasons for water quality change. Similarly, climatic variability might hide smaller water quality changes. In this section, continuous flow data were used to identify significant variations in general flow and climatic conditions between monitoring years in view of contributing to further analysis.

- In rivers, rainfall is a key driver in the mobilisation and movement of pollutants, and water quality tends to worsen during rainfall events.
- Rainfall driven differences between river base flows in the summer and in the winter result in seasonal scale variations in water quality data. Although there is some inter-annual variability, on an annual scale, there is often a cyclical pattern, with worse water quality in winter and better water quality in summer.
- Although rapid, short-term changes in water quality are linked to individual rainfall events and flow responses, the behaviour during these events is still influenced by the seasonal differences.
- Because of their size, water quality issues in reservoirs tend to not be rainfall event driven; seasonal algal blooms are the biggest water quality concern in reservoir sources, primarily occurring in the summer.
- Inter-annual variability in climatic conditions and diffuse pollution is likely to cause variability in the timing and extent of the algal blooms.
- Differences between reservoirs in the South West and understanding the extent of the water quality problems across the region allows Upstream Thinking interventions to be focussed in the most appropriate catchments.

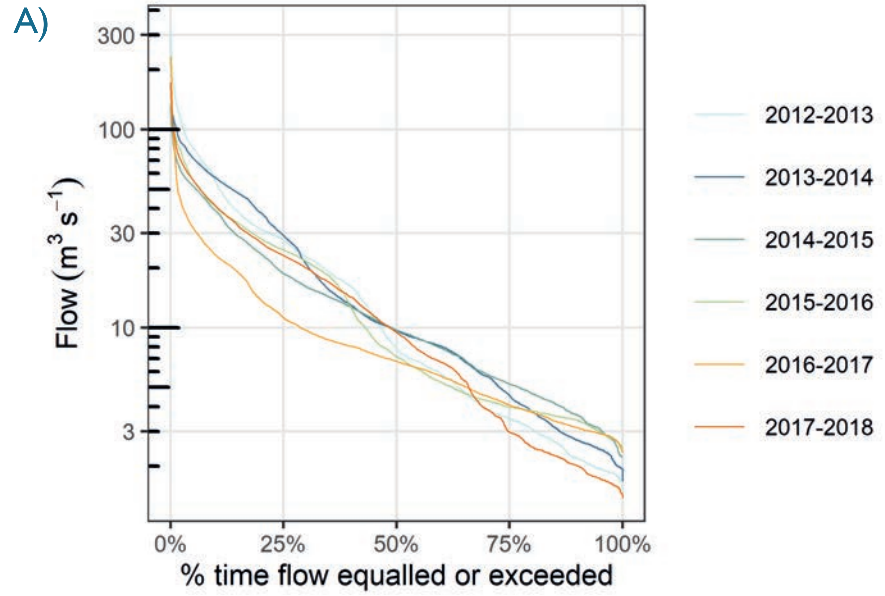
Drift reservoir; photo by Emilie Grand-Clement.

Through the use of flow duration curves (FDC) for each of the monitoring years and per season in the Exe, Figure 1 shows how climatic variability has affected river flows. In particular, this plot highlights a number of abnormal periods:

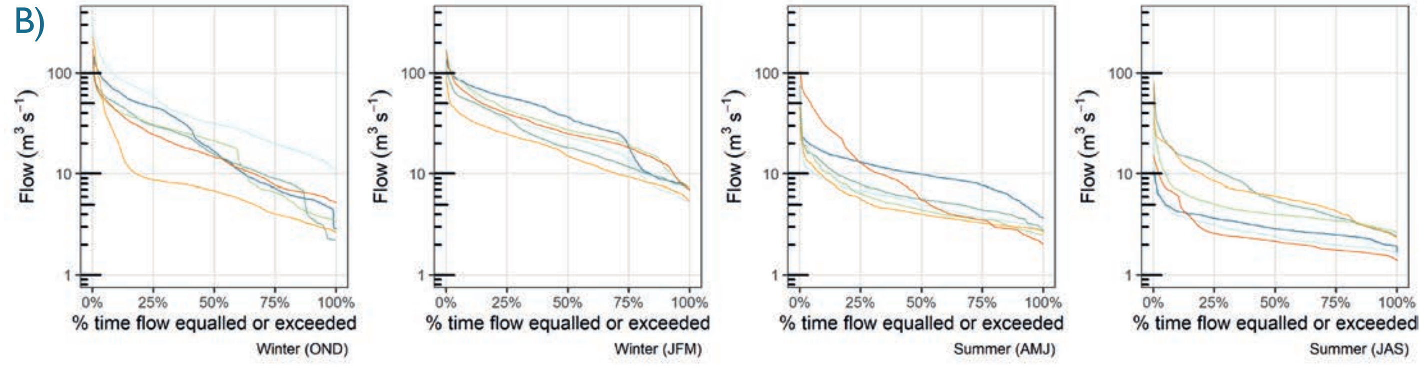
- The year 2013-2014 was identified as the wettest winter on UK record[1];
- The year 2016-2017 was the driest year during the study[2];
- In addition some years show particular change in one season;
- Particularly high flow during winter 2012-2013 (October to March), and significantly higher than the following years, with FDC curve placed higher on the plot;
- A high spring flow (April to June) in 2013-2014;
- A dry period in winter of 2016-2017: from October to December (Figure 1B) flow measured between 5 and 75% of the time is significantly lower than other years, and closer to observed summer flow range;
- During winter 2017-2018 the UK was affected by a prolonged winter cold period with heavy snowfall on a number of days during February and March 2018. This cannot be seen in the seasonal plot but will be seen in event scale responses;
- A period of particularly low flow during summer 2018, as a result of the warmest and driest year on record in the UK, with cumulative summer rainfall across the UK recorded as only 73% of the long term average[3].

These variations are observed across the whole region, and are particularly shown in data from the Exe (Figure 1). For example, in 2016 -2017, a flow of 10 $m^3 s^{-1}$ is exceeded for only 28.8% of the year; in 2013-2014 flows are greater than 10 $m^3 s^{-1}$ for 48.6% of the year. The flow values exceeded for only 5% time, representing the highest flow rates, are 31.9 $m^3 s^{-1}$ and 71.6 $m^3 s^{-1}$ for 2016-2017 and 2013-2014 respectively. This shows that in 2013-2014 the flow is high for a larger proportion of the year, and that the highest flows are also greater. Looking at the seasonal plots (Fig 1B), this can also be seen as the 2013-2014 curves sits towards the top of the plot for the winter months, and the 2016-2017 curve sits well below the others during early winter (October to December), and slightly below between January and July.

A)



B)



Winter (OND)

Winter (JFM)

Summer (AMJ)

Summer (JAS)

Figure 1 The flow duration curves for the River Exe at Northbridge show some of the differences in flows between years and seasons (A) by hydrological year, and (B) displayed for the seasons over the same period; each line represents the flow for a different hydrological year between 2012-2013 and 2017-2018.

River patterns

River and pollution dynamics

The dynamics in river systems are driven by rainfall events, with runoff over and through the land feeding streams, rivers and other water bodies. As well as directly affecting chemical processes, climatic conditions influence the rainfall and runoff patterns: changes in the frequency and intensity of rainfall events will affect the pathways that water takes to reach streams and rivers, the speed it travels, and in turn, the patterns seen in rivers for different pollutants. Understanding how rivers respond to rainfall, the differences between the normally wet hydrological winter and dry hydrological summer (Figure 2A) and the wider climatic influences, helps untangle how these patterns change over timescales (from minutes to months). When it rains and river flows increase, pollutant concentrations either increase (concentration) as they are washed in from different sources, or decrease (dilution) with the addition of 'cleaner' water. Alternatively, levels of pollutants might stay the same (static); in complex or larger catchments, there might be a mix of behaviours in different sub-catchments and at different times. These behaviours can be broadly grouped by the type of pollutant. Across the river sites and feeder streams in this study, ammonia, colour and turbidity typically increase as flows increase following rainfall events. Some nutrients (e.g. Total Oxidised Nitrogen) and other indicators such as dissolved oxygen (DO), pH and conductivity drop as the flow increases. Both dissolved oxygen and pH display strong daily changes (diurnal cycles) (Figure 2C), these are more pronounced over the summer months.

Year on year variability

One of the benefits and challenges of monitoring over multiple years is that it enables the observation of year by year variation due to different climatic and flow conditions. Being able to see this variation helps identify patterns in the behaviour of different contaminants in the rivers and in feeder streams to reservoirs, pointing to both key risks to rivers (e.g. heavy rainfall in the middle of drought conditions) but also provides insight into how a changing climate could affect these in the long term.

For example, over the monitoring period, the first couple of winters (2012-2013 and 2013-2014) were wetter (Figure 1B) with higher base flows in rivers across the South West. Across all the sites, and in the number and magnitude of peaks in colour and turbidity. Conversely, the dry winter of 2016-2017 resulted in much lower base flow levels, with reduced turbidity peaks and overall values. While the dry summer of 2018 reduced the turbidity and the highest colour peaks associated with rainfall events, there were overall increases in colour recorded for this summer.

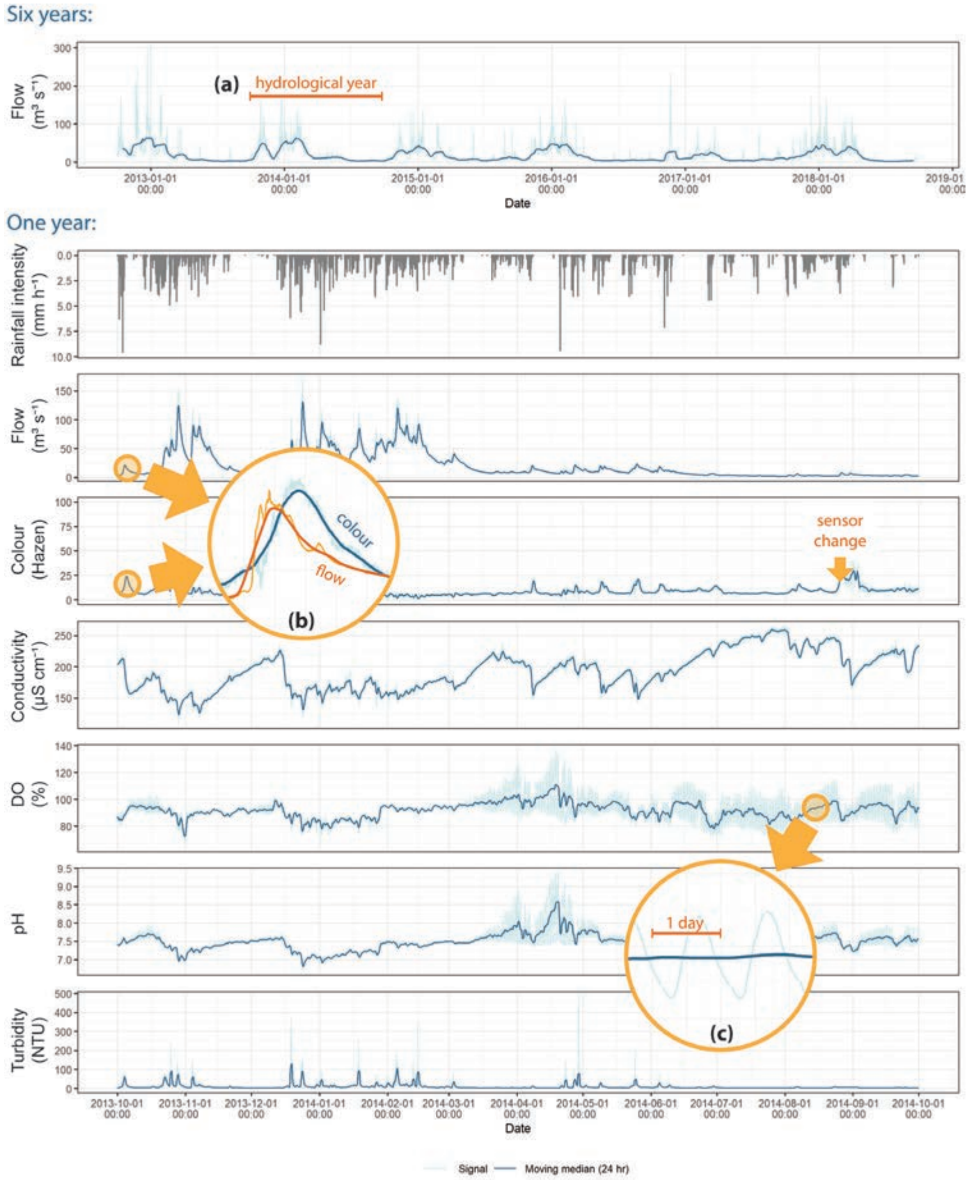


Figure 2 Water quality signal from the river displaying patterns of different scales with (a) inter-annual and seasonal changes across the monitoring period (e.g. increased flow in the hydrological winter); and a breakdown of the year 2013-2014 showing (b) clear rainfall events with either concentration (colour, turbidity) or dilution (conductivity, dissolved oxygen, and pH) effects and (c) diurnal (daily) cycles in the recorded signal.

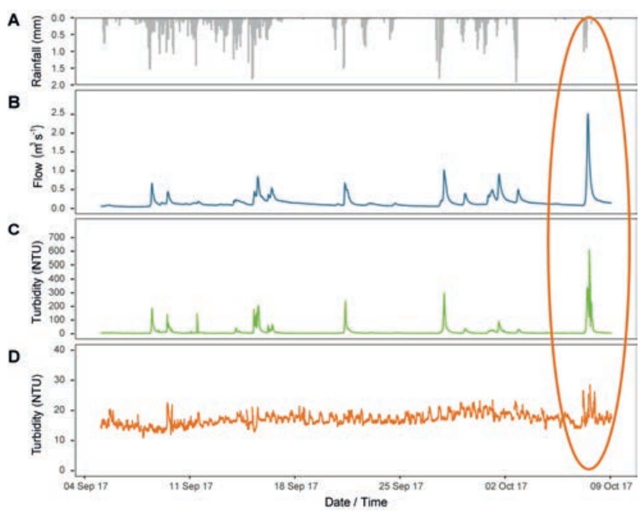


Figure 3 Rainfall (A), flow (B) and turbidity in the feeder stream to Upper Tamar Lake (C), and turbidity in the reservoir (D) between September and October 2017. Note the difference in scales between locations C and D; orange circle highlights a significant rainfall event that has impact on flow, and turbidity both in the feeder stream and in the reservoir.

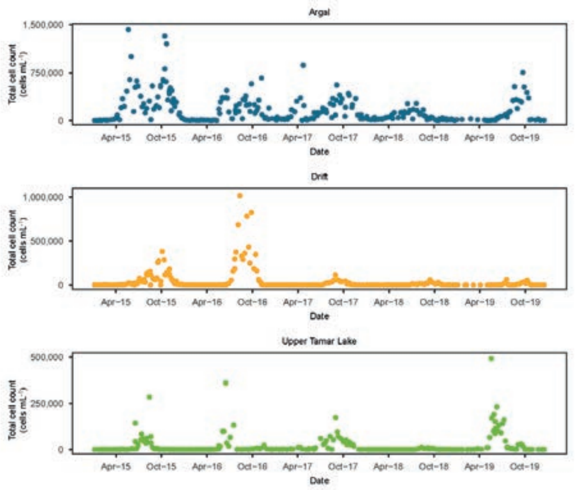


Figure 4 Algal blooms between 2015 and 2015 for Argal Lake (top), Drift reservoir (middle) and Upper Tamar Lake (bottom) measured in total cell count (cells mL^{-1}).

Reservoir sites – what do they have in common?

Reservoir patterns

As explained previously, the majority of pollution delivery in rivers and feeder streams to reservoirs occurs during rainfall events. In continuous datasets, such events have identifiable patterns matching that of flow rise and fall (See p17). For example, Figure 3 B and C shows an example of the turbidity time series (i.e. turbidity data plotted in time order) in the feeder stream to Upper Tamar Lake that clearly increases and decreases following rainfall and flow variations, illustrating the erosion of soil and flow of sediment into the lake. However, reservoirs experience a very different dynamic to that of rivers, which is generally not driven by rainfall events. This is shown by the turbidity signal measured in the reservoir (Figure 3D): on this plot, the turbidity signal does not follow flow variations. Turbidity values in the reservoir also show less change and do not reach such high concentrations as the turbidity in the feeder stream (i.e. remains between ca. 10 and 20 NTU). Instead, the signal experiences smaller variations, some of which may be due to daily variations. However, large rainfall events, such as the one occurring in October 2017, can be noticeable in the turbidity signal.

Seasonality of algal blooms in reservoirs

The occurrence of rainfall events are less of a direct water quality concern for the production of drinking water in reservoir sources than that from river sources. Instead, water quality issues in large bodies of water are affected by reservoir dynamics and tend to occur over longer timescales. In particular, a common water quality issue, especially in the South West region, has been the occurrence of large algal blooms occurring seasonally. Algal blooms are a particular problem for the ecology of the water body as they prevent light penetration into the water. They are also a problem for drinking water production, as they have to be physically removed during the treatment process, and produce harmful toxins.

Although the input of nutrients from diffuse pollution to reservoirs is one of the controls on algal blooms, others factors also include: total nutrient content already present in the reservoir, hydrology (i.e. reservoir level), mixing, general water chemistry (e.g. pH or conductivity), temperature or sunlight.

Figure 4 shows the occurrence of algal blooms in each of the reservoirs within the project. It highlights in particular the occurrence of peaks that tend to occur in the summer to autumn; inter-annual variability in climatic conditions are likely to explain differences in the timing of blooms. For instance, at Argal Lake, 2015 sees a first algal peak in spring, followed by another one in the autumn. Figure 4 also highlights differences between reservoirs: discrepancies in the timing of peaks between reservoirs in the same region is likely to be due to local conditions, and specific in-reservoir dynamics. For example, the double peak of 2015 at Argal Lake is not observed in Drift or Upper Tamar Lake. Finally, the scale of the algal bloom is very different between reservoirs: with a maximum cell count measured between 2015 and 2019 of c.a. 1,500,000 cells mL^{-1}, Argal Lake is the worst affected, compared to Drift (i.e. maximum cell count of c.a. 1,000,000 cells mL^{-1}) and Upper Tamar Lake (maximum cell count of c.a. 500,000 cells mL^{-1}).

Such periodicity highlights the at-risk period for these water sources, but also the need for further understanding of reservoir dynamics that may be able to help to improve water quality in these water sources.

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MAPPING CATCHMENT INTERVENTIONS

- Mapping and quantifying catchment interventions in each catchment is an essential step for assessing their impact on water quality.
- Activities listed by project partners were re-classified into the relevant mitigation methods using the Farmscoper software to (1) homogenise the terminology used across partners and (2) identify the water quality parameters affected by each individual measure.
- Establishing new hedges, minimising the volume of dirty water produced (i.e. sent to dirty water store) and fencing off rivers and streams from livestock were the three main interventions used across the region. However, differences in recording methods, e.g. terminologies used, resulted in a large number of interventions falling into an "unclassified" category.
- This work has highlighted the need to establish a uniform and efficient way to record such information, as it has proven essential for further water quality assessment.

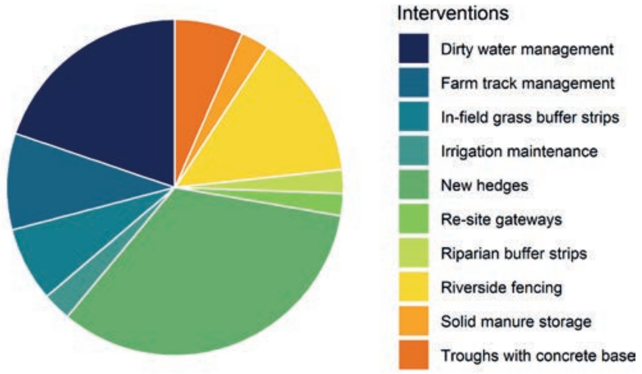

Figure 1 Top 10 interventions (as classified for Farmscoper) used in Upstream Thinking in all catchments ranked by occurrence.

Mapping and quantifying in-catchment interventions

Over the course of the Upstream Thinking programme, project partners have worked in 11 catchments and carried out interventions aimed at reducing water pollution and improving biodiversity in a wide variety of ways. Mapping the extent and the type of such interventions is an important step to visualise and identify the direct impact on water quality, and for further modelling of potential water quality change. However, it is also a challenging exercise because of the diversity of interventions used throughout the region and the difficulty of quantifying direct impacts on water quality parameters.

Farm advisors use their experience and knowledge of catchments to engage with farmers. Through farm visits and discussions they work together to identify opportunities and challenges for the farm business and land management practices. The output of their work is the development of a targeted farm plan (also known as a Water and Environment Plan) which contains advice, recommendations and costed actions, which when implemented can improve land management, soil health and therefore, water quality. For example, reductions in nutrient or sediment losses to watercourses might occur following the identification of opportunities to create in-field buffers or by altering application timings and rates for manures, slurries, pesticides or herbicides.

A number of 'tool kits' are used for offering advice and to part-fund interventions: (1) funding schemes such as Upstream Thinking (through SWW investment), Countryside Stewardship or Catchment Sensitive Farming; and (2) the DEFRA/ADAS Farmscoper Inventory of Mitigation Methods[1], which is a decision support tool used to make an assessment of diffuse agricultural pollution loads on a farm and to quantify the potential impacts of the recommended on-farm mitigation methods (interventions) on those pollutants[2].

The mapping of in-catchment interventions was done by the UoE, based on spatial data of catchment interventions provided by project partners. This allowed spatial analysis of Upstream Thinking activities, including an assessment of catchment coverage and an identification of the most commonly employed intervention activities used to tackle water pollution from agriculture, promote best farming practice and improve biodiversity.

In order to perform modelling of water quality change and to quantify the catchment coverage of specific interventions, the activities listed by partners were (where possible) re-classified into the relevant Farmscoper mitigation methods. This step enabled the understanding of water quality parameters affected by each individual measure, and also ensured that consistent terminology was used across partners and that data were comparable.

The spatial data were collected as points, lines and polygons. However, in order to gain an understanding of the area improved by the Upstream Thinking interventions that were implemented, a field-scale polygon area was applied to all point and linear interventions. These areas (expressed in hectares), combined with existing polygon data, provided a total cumulative area that could be assumed to be 'impacted' by interventions.

What are the main interventions delivered by Upstream Thinking?

Farm engagement by the Devon Wildlife Trust; photo by DWT.

Table 1 provides an overview of the top 10 interventions most often delivered by Upstream Thinking partners between 2015 and 2019, along with their occurrence (Figure 1). This is compiled from the re-classification of interventions into the mitigation measures used by the Farmscoper software. It should be noted however, that there are interventions for which there was either missing data, or there was no equivalent Farmscoper option to re-classify it into and so the list also includes an "Unknown/unclassified" option.

In addition to physical interventions, Upstream Thinking partners also provide advice and recommendations on land management activities and behavioural change to promote best farming practice. This accounts for a further 3,448 ha of activity within the Upstream Thinking catchments. Measures include those aimed at improving water quality and quantity such as access to machinery for soil aeration and also management plans and actions to promote and restore biodiversity and BAP (Biodiversity Action Plan) habitats (i.e. culm grassland restoration).

Intervention	Count	Area (ha)
Establish new hedges	219	7868
Minimise the volume of dirty water produced (sent to dirty water store)	130	5860
Fence off rivers and streams from livestock	92	3097
Farm track management	61	2538
Establish in-field grass buffer strips	47	2347
Construct troughs with concrete base	43	7960
Store solid manure heaps on an impermeable base and collect effluent	18	1067
Irrigation/water supply equipment is maintained and leaks repaired	18	944
Establish riparian buffer strips	15	357
Re-site gateways away from high-risk areas	14	424
Unknown/Unclassified	962	22861
Additional activities		
Revised land management (BAP and non-BAP work)		1788
Soil aeration		1279
Culm restoration		381

Table 1 Top 10 interventions used within the Upstream Thinking project, as defined by Gooday *et al.* (2015). The unknown category includes a wide range of interventions that cannot be classified using the Farmscoper interventions categories as they include broader interventions that do not solely tackle water quality issues (i.e. Biodiversity improvements). Future work will be using a more standardised recording methodology, which will improve the evaluation of catchment management interventions and their impact on WQ and biodiversity.

Figure 2 Planting of new hedges on the edge of a field; photo by DWT.

Figure 3 New water storage installed on a farm on the Dart to store dirty water and reduce the risk of nutrient loss to surface water; photo by DWT.

Figure 4 River fencing; photo by Ben Bennett (WRT).

The top 10 interventions contributing to water quality improvements/reduction in diffuse pollution from agriculture are presented in Table 1 and described below[2]:

1. Establish new hedges

This intervention aims to break-up the hydrological connectivity of the landscape (Figure 2). Hedges can also lower surface run-off volumes and 'trap' soil, thereby reducing sediment and associated nutrient loss. Hedges can also help to protect soils from wind erosion and improve biodiversity.

2. Minimise the volume of dirty water produced (sent to dirty water store)

Reducing the volume of dirty water produced, and therefore stored (Figure 3), means that farms are less likely to run out of storage space and be forced to spread dirty water (or slurry) at times of high risk of runoff, thereby reducing the associated losses of nutrients, Faecal Indicator Organisms (FIOs) and Biochemical Oxygen Demand (BOD) to (surface) water systems.

Figure 5 Cross drain and resurfaced track in the Barnstaple and Yeo catchment.

Figure 6 Buffer strip in the River Otter catchment; Photo by Yog Watkins (WRT).

3. Fence off rivers and streams from livestock

Riverbank trampling by livestock destroys the vegetative cover and can leave soils badly poached, leading to erosion which increases sediment inputs and nutrients to watercourses. Livestock can also add pollutants (nutrients and manure) directly by excreting into the water. Preventing access by fencing streams and rivers eliminates this source of pollution (Figure 4), as well as reducing incidents in livestock of liver fluke and tick-borne diseases, as both parasites dwell in wet areas of fields.

4. Farm track management/track re-surfacing

Farm tracks that are rutted, on sloping land or in poor condition can generate significant volumes of surface runoff in wet conditions, which mobilises sediment and manure-borne pollutants. Track re-surfacing (Figure 5) reduces the pathways of surface water run-off and can reduce the amount of poaching and soil erosion adjacent to the track. Furthermore, improving track drainage and diverting surface runoff to adjacent grass, soakaways or swales can reduce the mobilisation and transport of pollutants.

5. Establish in-field grass buffer strips

In fields where high volumes of surface runoff are generated, a vegetated strip of land (located along the land contour, on upper slopes or in valley bottoms) can reduce and slow down surface runoff (Figure 6), which will reduce sediment and nutrient loss. Buffer strips can also improve biodiversity.

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Figure 7 Livestock trough on hardstanding base; photo by DWT.

Figure 8 Before (left) and after (right) the installation of a new slurry storage with concrete base; photo by FWAG.

Figure 9 Unfenced stream with excessive poaching (left), and fenced stream with riparian buffer strip (right); photo by DWT.

Figure 10 Re-siting of access to field and watercourse fencing installed to prevent livestock access; photo by Devon Wildlife Trust.

6. Construct troughs with concrete base

Animal activity concentrated around drinking troughs leads to poaching and damage to soil, increasing risks of surface runoff and diffuse pollution. Large inputs of excreta in these areas can also be a source of nutrient and fecal matter input losses to nearby watercourses. Constructing water troughs with a firm base (Figure 7) can therefore prevent these types of pollution.

7. Store solid manure heaps on an impermeable base and collect effluent

Storing manure on an impermeable base prevents the seepage and accumulation of nutrients in the soil below the heap, which otherwise may subsequently be lost in surface runoff/drainflow or leaching to ground water (Figure 8). Also, storage on an impermeable surface (e.g. a concrete base) reduces soil compaction caused by farm machinery during the forming and subsequent spreading of field heaps.

8. Irrigation/water supply equipment is maintained and leaks repaired

Losses through leakage can prove costly over time and also cause problems such as soil erosion, poaching, water contamination and increased dirty water disposal costs. These issues are addressed by maintaining irrigation equipment and repairing leaks.

9. Establish riparian buffer strips

A grass or woodland buffer strip can act as a 'natural' buffer distancing agricultural activity from the stream or river and intercepting surface runoff, thereby acting as a sediment trap and filter for nutrients (Figure 9). This reduces direct pollution from fertiliser and organic manure additions, and can also restrict direct livestock access to watercourses. An additional benefit of such features is that they make space for water in times of flood.

10. Re-site gateways away from high-risk areas

Gateways located in high-risk surface runoff areas, such as at the bottom of a slope and near to a watercourse, act as pathways for water runoff. Moving them to lower-risk areas on upper slopes will prevent polluted surface water from leaving fields and help to lessen the risk of surface runoff transporting sediment, associated nutrients and FIOs out of sloping fields and directly into watercourses or onto roads etc (Figure 10).

WATER QUALITY MODELLING

- Linking interventions to water quality is a complicated exercise that was approached using two different models: SPARROW is a statistical model that focuses on estimating annual loads in nitrate and DOC; SimplyP was used to estimate sediment, total phosphorus and soluble reactive phosphorus.
- Overall results from both models estimate very marginal water quality improvements across all parameters and catchments: load improvements were estimated to be less than 0.01% for nitrate and DOC, up to 1.8% and 0.5% for suspended sediments and total phosphorus respectively.
- Both models depend on quantifying interventions using the Farmscoper software, thereby relying on a set terminology and classification; this process is likely to have led to an underestimation of the coverage of interventions, and therefore water quality change. Interventions in the catchments might not have a direct impact on the parameters of interest, explaining in part the small change observed in the results.
- These results make the case for improved recording and mapping of interventions and also highlight the need for extended and sustained in-catchment interventions that would allow greater cumulative benefits. However, even modest reductions in P loading (in the order of Kg) will make a difference on water quality in these catchments.

Method

The objective of modelling water quality was to combine catchment interventions and their location with their known impact on water quality parameters to establish the expected changes in water quality for each catchment. The results can then be used to compare differences between catchment management scenarios of contaminant loadings calculated without and with interventions.

SPARROW

The SPARROW model[1] (Figure 1) is a statistical water quality model used to estimate the annual load of nitrate and Dissolved Organic Carbon (DOC) from point and diffuse catchment sources. Using datasets such as water quality measurements, soil type and rainfall (Table 1), the model is composed of source, transport and degradation factors that are defined using parameters selected based on expert opinion and statistical analysis. For example, the user may determine that manure inputs are important for the nitrate source factor. Not all factors are accounted for, instead the focus is on the most statistically significant variables for each water quality variable.

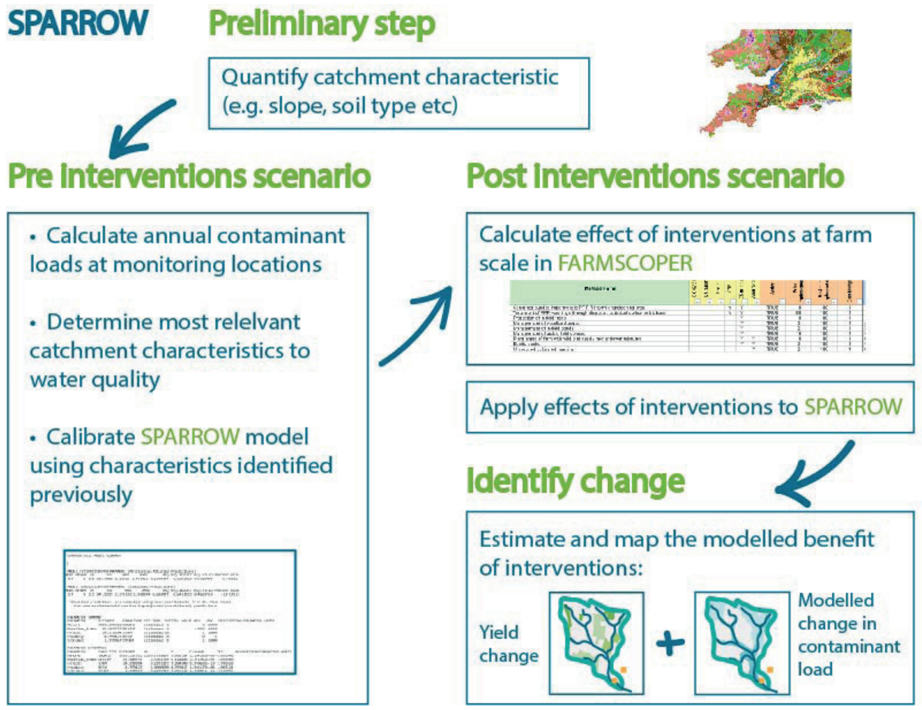

Figure 1 Schematic detailing the workflow used for modelling interventions and the impact on nitrate and Dissolved Organic Carbon (DOC) using the SPARROW model.

Firstly, the change in pollutant yield was mapped (i.e. nitrate or DOC) at the spatial scale reported in Farmscoper (i.e. farm area) (Figure 1). This information was then applied to estimate the expected change after the delivery of the pollutant to the stream, i.e. contaminant load, for the reach in question and displayed through the use of a Geographical Information System (GIS) to map the potential change across catchments (Figure 2).

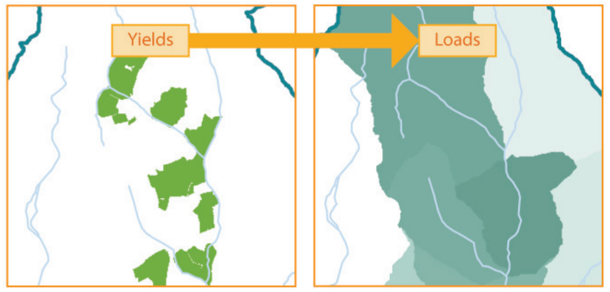

Figure 2 Example of contaminant yields (left) at the farm scale identified by the green areas, leading to calculations of corresponding changes in contaminant loads (right) for the same reach. The darker colours represent greater decrease in loadings.

Data used in the model	Source	Simply-P	Sparrow
Soil type	National Soil Resources Institute, Cranfield	✓	✓
Elevation	Centre for Environmental Data Analysis	✓	✓
Water quality measurements - Suspended sediment - Total phosphorus - Soluble reactive phosphorus - Nitrate - Dissolved organic carbon	SWW, UoE measurements, Environment Agency	✓	✓
Stream flow	National River Flow Archive, Centre for Ecology and Hydrology	✓	
Precipitation	Centre for Environmental Data Analysis	✓	✓
Temperature	Centre for Environmental Data Analysis	✓	
Evapotranspiration	Calculated using meteorological datasets from the UK MetOffice	✓	
Catchment interventions (after reclassification)	UsT Project partners	✓	✓
Land cover	Centre for Ecology and Hydrology	✓	✓
Crop types	Centre for Ecology and Hydrology	✓	
Manure input	Centre for Ecology and Hydrology		✓
Hydrological characteristics (e.g. mean flow, baseflow etc.)	Global Streamflow Characteristics Dataset		✓

Table 1 Types and source of datasets used in the SimplyP and SPARROW models.

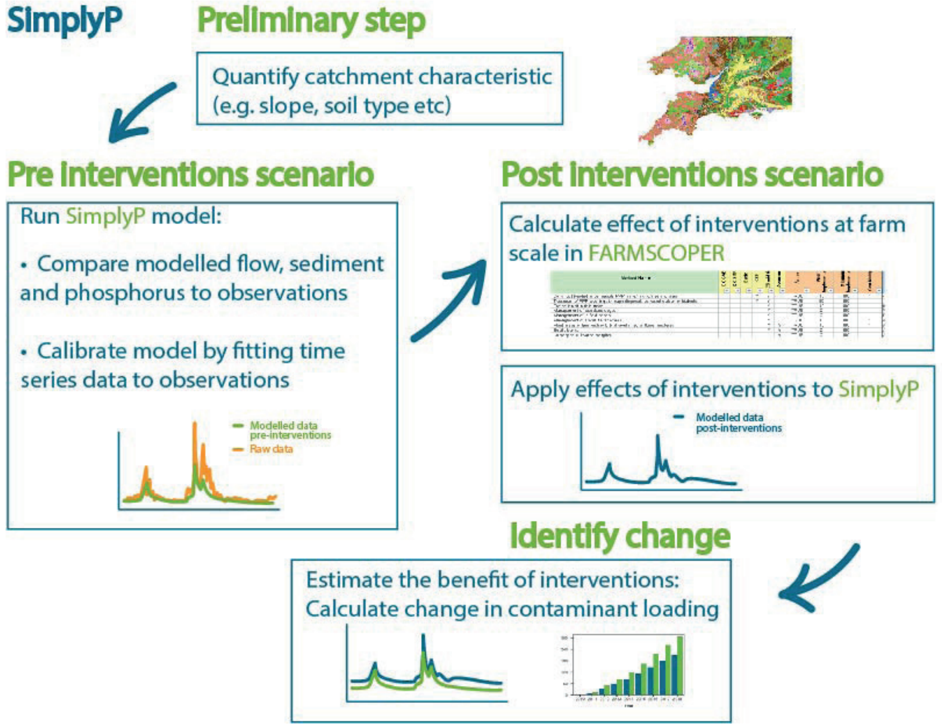

Figure 3 Schematic detailing the workflow used for modelling interventions impact in suspended sediment, total phosphorus and soluble reactive phosphorus using the SimplyP model.

SimplyP

SimplyP[2] is a simple process based water quality model which can be used to estimate the concentration and load of Total Suspended Sediment (TSS), Total Phosphorus (TP) and Soluble Reactive Phosphorus (SRP). The model is separated into three separate components:

- a rainfall-runoff module, used to calculate river flow from rainfall inputs;
- a sediment module, used to relate river flow and land activity to sediment concentrations and loads;
- a Phosphorus (P) module which relates land activity, soil properties, and runoff processes to phosphorus concentrations and loads.

The outputs are a time series for flow, sediment, and P for the period of interest (Figure 3). For this application, interventions were applied together at the start of a 9 year period modelled, based on hydrological and meteorological conditions, between 2010 and 2018. As some impacts are difficult to detect in the immediate years after interventions are put in place, applying the model in this way enables us to determine what sort of effect the interventions from Upstream Thinking would have in the medium term, i.e. 9 years. For example, this enables the consideration of sufficient time to pass for any significant effect to take place with regards to the mass of soil P, which might have reduced if farmers were adding less manure or slurry, but which might take some years for this reduction to manifest.

The results obtained from the modelling work will partly be influenced by the nature and characteristics of the contaminants being modelled. For example, suspended sediments largely originate from erosion during overland flow; for simplicity, the model assumes that temporal variations of suspended sediment will follow that of stream flow to a large extent. TP is a measure of both dissolved and particulate P, the latter originating from sediments and therefore largely relating to stream flow. Finally, SRP is the inorganic fraction of P, originating from the soil. Its presence in water is therefore proportional to the volume of rainfall and dissolved phosphorus in the soil store, which fluctuates over time. Greater rainfall therefore will cause a greater release of SRP from the land, and will accumulate over time. In addition, the use of actual hydrological and meteorological conditions between 2010 and 2018 means that these parameters will, to some extent, influence the variations in water quality. In addition, a detailed description of the technical caveats that may have impacted on the modelling results are presented in Appendix (p78).


A stream in the Cober catchment; photo by Emilie Grand-Clement.

General findings

The changes resulting from Upstream Thinking that each model predicts (Table 2 and Table 3) are modest for all parameters. The maximum modelled loads at catchment scale are estimated to have been less than 0.01% for nitrate and DOC, and up to 1.8% and 0.5% for SS and TP, respectively. Consequently, in some catchments, the actual estimated mass of pollutant removed is negligible compared to other catchments and studies[3]. Sediment mobilised from eroding soil or river banks could reach up to 430,000 kg in the larger Exe catchment over the modelling period, whilst no improvement is recorded in some of the Drift sub catchment. Sediment also shows the greatest change compared to TP and SRP. This is due to the fact that a large part of Phosphorus is bound to soil and sediment particles, and will therefore only be a fraction of TSS. The literature also shows that, although improvements in P loads from agricultural runoff can be observed at farm scale[4], this is rarely observed at catchment or watershed scale[5], due to the accumulation of P in soils and its release during periods of high rainfall, causing potentially long lag times for improvements[6].

Table 2 Maximum estimated change in yield and loads (%) for nitrate and Dissolved Organic Carbon in each Upstream Thinking catchment using the Sparrow model.

	Max yield change (%)		Max load change (%)	
Catchment	DOC	Nitrate	DOC	Nitrate
Argal	NA	0.0069	NA	0.00001
Drift	NA	0.062	NA	0.0001
Upper Tamar Lake	NA	0.59	NA	0.0017
Cober	0.27	0.244	0.0008	0.0005
Fowey	NA	0.22	NA	0.0009
Exe	1	0.81	0.002	0.0031

In the present case, for TP, it means an improvement of less than 1 kg over 9 years in Argal and Upper Tamar Lake, whereas it could be over a tonne in the Lower Exe in the same time frame. This highlights that, although both catchments have about 30% total engagement, this may not directly translate into the establishment of interventions tackling this particular problem. Modelling work on the Axe catchment (outside of UsT intervention area) showed that a reasonable scenario of 25% of intervention uptake in the catchment would only be cost effective if the cumulated P offset was over 200 kg of P. Although this is based on a catchment with different characteristics (e.g. land use, water quality, stream connectivity etc.), it highlights the issue of P improvement that is both costly and uncertain.

			Mean annual improvement (%)			Total load improvement over 9 year		
Catchment	Sub catchment	Catchment area (km2)	Suspended Sediment	Total P	Soluble Reactive P	Suspended Sediment (T)	Total P (kg)	Soluble Reactive P (kg)
Argal	Argal stream	3	0.010	0.006	0.004	0.01	0.1	0.02
Drift	Newlyn River	12	10^{-5}	0.252	0.285	0.0001	38.9	27.0
	Sancreed brook	5	1.752	0.542	0.295	7.4	38.9	12.1
Upper Tamar Lake	NA	8	0.004	0.009	0.013	0.1	1.4	0.7
Cober	NA	26	0.424	0.296	0.140	9.7	23.2	3.3
Fowey	NA	168	0.295	0.207	0.139	29.6	99.8	26.0
Exe	Allers	434	0.299	0.272	0.192	338.2	1236.3	210.6
	Pynes	624	0.252	0.234	0.176	430.0	1631.0	307.8

Table 3 Mean annual improvement (%) over a 9 year period for each catchment for Suspended Sediment, Total Phosphorus and Soluble Reactive Phosphorus, and corresponding load improvement; note that Suspended Sediment is expressed in T and Total P and Soluble Reactive P in kg.

Some of the reasons for these small changes forecasted by the modelling exercise and the differences between catchments are discussed below and illustrated in Figure 4.

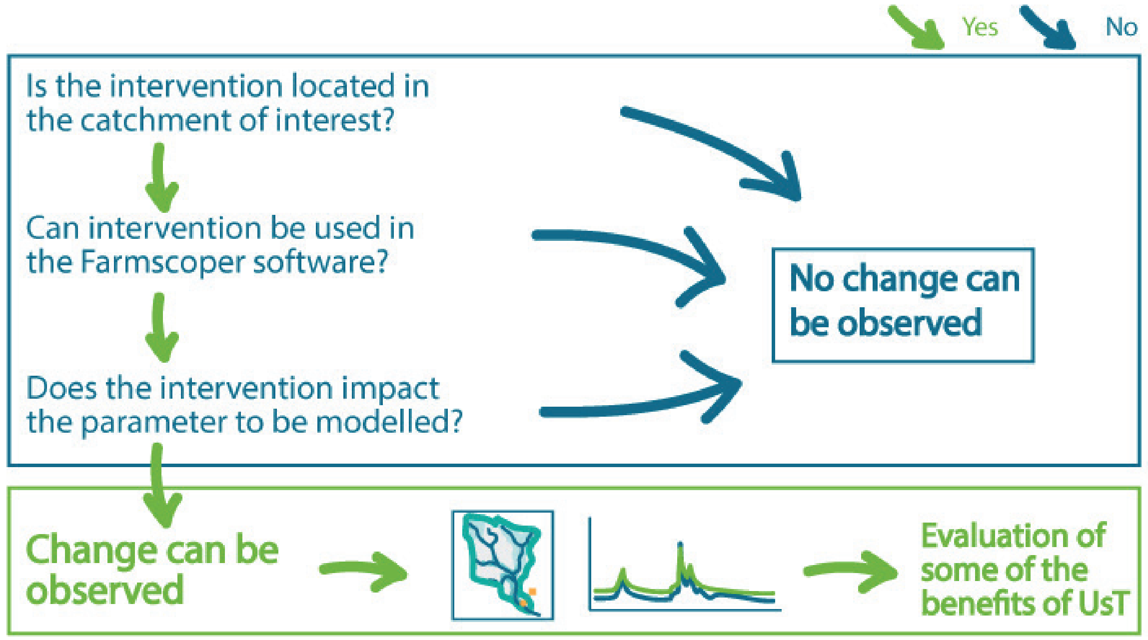

Figure 4 Challenges associated with the modelling exercise and range of factors that may lead to an underestimation of the benefits of in-catchment interventions on water quality from Upstream Thinking interventions.

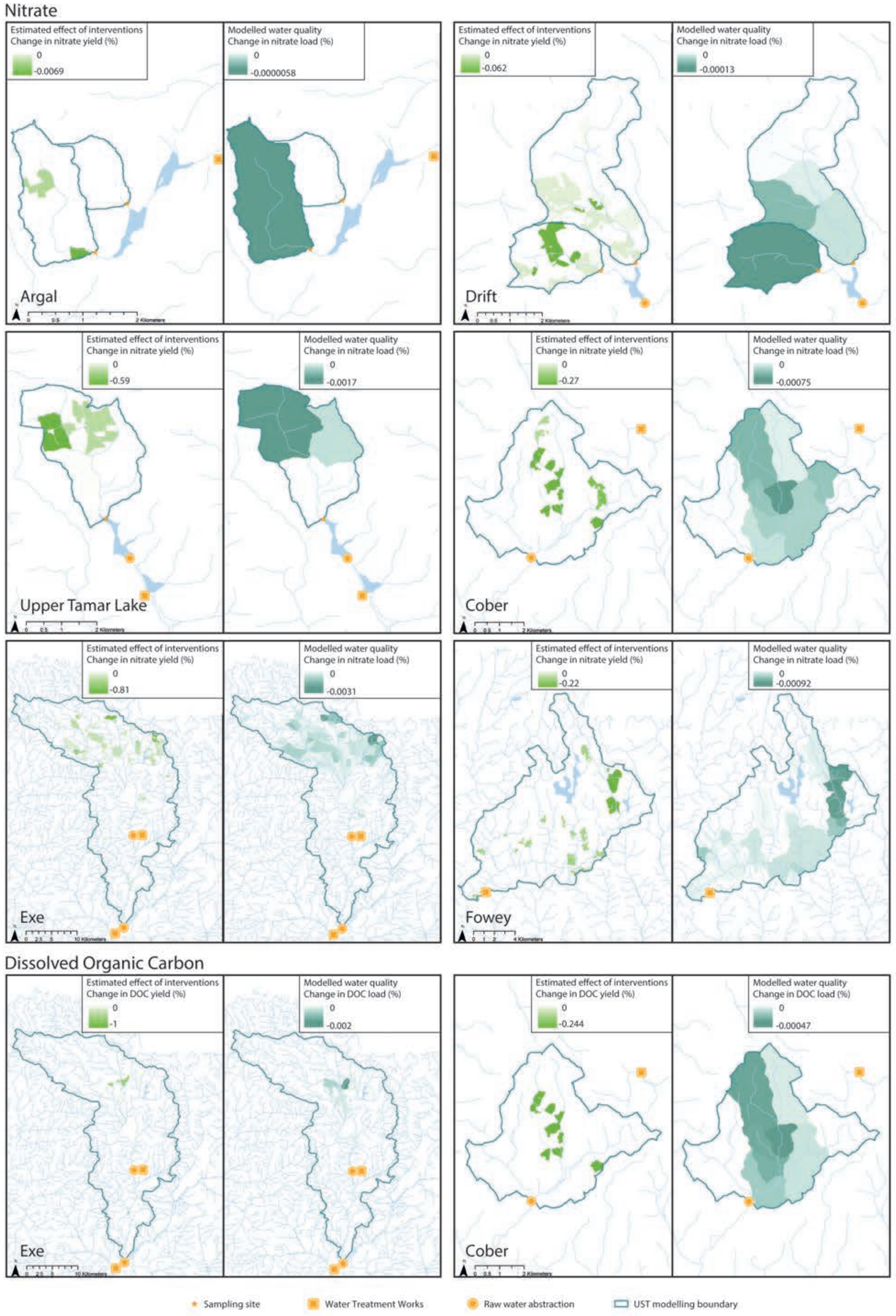

Figure 5 **Estimated impact of mapped interventions on nitrate and DISSOLVED ORGANIC CARBON yields and resulting loads in water courses in the Upstream Thinking catchments using the SimplyP model.**


Maize farming in the Lower Exe; photo by DWT.

Types of interventions and quantification in Farmscoper

This work has focused on estimating the impact of the Upstream Thinking interventions on water quality, rather than that of all catchment management measures. Other interventions carried out via other funding streams, such as the Countryside Stewardship (CS) scheme, were therefore not considered, leading to an underestimation of the activity in the catchment. Additionally, the intervention data went through a reclassification step using the Farmscoper software. This has been a necessary step for the use of both models. However, as Farmscoper relies on a specific nomenclature of interventions, not all activities carried out in the catchment could be categorised and captured by this process. Similarly, some interventions used had biodiversity benefits with a secondary focus on water quality, and were therefore not included in the modelling work.

Overall, these caveats are likely to have led to an underestimation of the extent of catchment management work, translating, in turn, into a likely underestimation of yields and loads modelled.

For example, interventions in the Cober and Argal catchments largely related to habitat improvements. It is difficult to quantify the impact on water quality of interventions which focus on habitat improvement and therefore they do not appear in Farmscoper. As a result benefits of these types of interventions cannot be estimated by this type of modelling. For example, this has resulted in an estimated maximum nitrate load improvement of 0.0005% in the Cober. Similarly, in the Argal catchment, the small number of interventions quantified in farmscoper have led to a modelled 0.01%, 0.006% and 0.004% for TSS, TP and SRP respectively (Table 3).

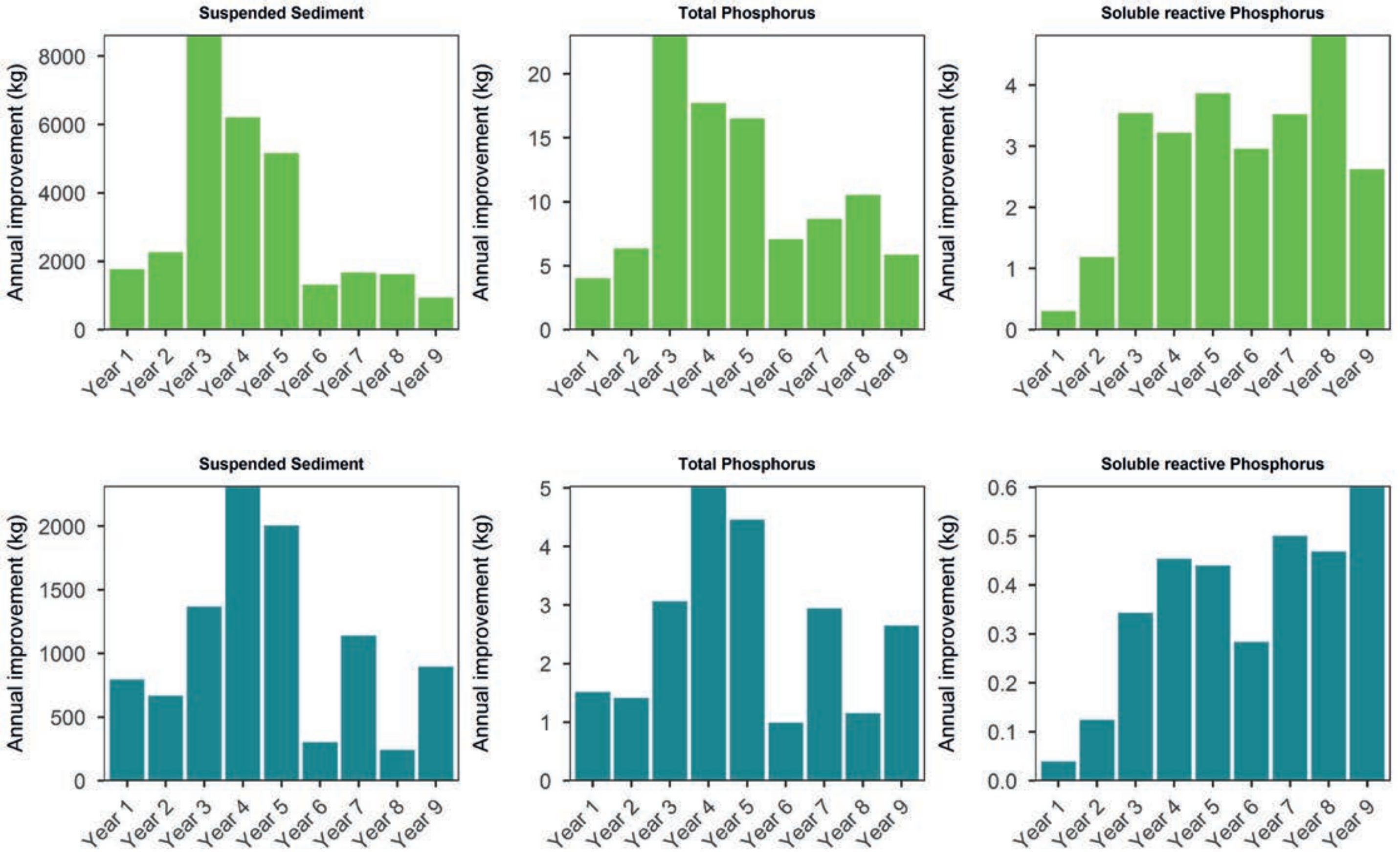

Figure 6 **Annual improvement in contaminant loading per year (kg) for suspended sediment, Total Phosphorus and Soluble Reactive Phosphorus in the River Fowey (top) and the River Cober (bottom).**

Impact of interventions on parameter to be quantified at catchment scale

Our modelling work has particularly focused on parameters found to be generally affected by diffuse pollution from agriculture and that could be modelled, i.e. nitrate, phosphorus, sediment and DOC. On the other hand, the work carried out by project partners in catchments has focused on farm improvements, with the general aim that these interventions will improve water quality and biodiversity. Pesticides were also a focus for project partners, having been identified as problematic by the EA, however they could not be modelled. Whilst there is evidence of the impact of each intervention on a number of water quality parameters, the type of interventions implemented on a farm, to address specific problems, might not address the parameters of interest at catchment scale and/or that were modelled, and therefore resulted in low modelled change.

For example, interventions in the Lower Exe catchments have largely focused on pesticides, with less emphasis on nutrients and sediment yield. In the Argal catchment, the small yield change in nitrate is likely to be the result of two interventions, namely, to re-site gateways away from high risk areas, and to minimise the volume of dirty water, both likely to reduce nitrate (Figure 5).

On the other end of the scale, in the Fowey, most of the interventions occurring in the catchment tend to reduce nutrients[8] (Figure 5). The most significant interventions were to fence off rivers from livestock, which prevents livestock from directly inputting nutrient to the stream via excretion. This led to higher mean loading change of 0.2% for TP and 0.1% for SRP. In Upper Tamar Lake, interventions also had a generally positive impact on nitrate (Figure 5), with interventions that focused on loosening compacted soil, and thus increasing nitrate leaching through the soil, having the greatest effect. However, there were only two relevant interventions for SS and phosphorus in the catchment, namely the loosening of compacted soil, and the improvement of storage of manure and slurry. This has resulted in some of the lowest change observed across the region (Table 3).

Difference between catchments

Using the percentage change to calculate loads (i.e. cumulated mass of contaminant carried out by river flow) showed the same differences between catchments. Unsurprisingly, small catchments (i.e. Argal and Upper Tamar Lake) that have low percentage change were found to show low cumulated improvement (Table 3). Conversely, large catchments show a greater cumulated load, mostly due to the size of the river or stream considered, and flow used in the calculations. This largely explains why the Exe shows a modelled decrease of up to 430 tonnes for TSS, over 1 tonne for TP and 300 kg for SRP. Figure 6 illustrates some of the inter-annual variability in the model output for the River Fowey and the River Cober. As the modelling was based on flow and meteorological conditions between 2010 and 2018, this is reflected in changes in loads per year.

Overall, these results make the case for improved recording and mapping of interventions and also highlight the need for extended and sustained in-catchment interventions that would allow greater cumulative benefits. However, even modest reductions in nutrient loadings will make a difference on water quality in these catchments.


The Argal catchment; photo by Emilie Grand-Clement.

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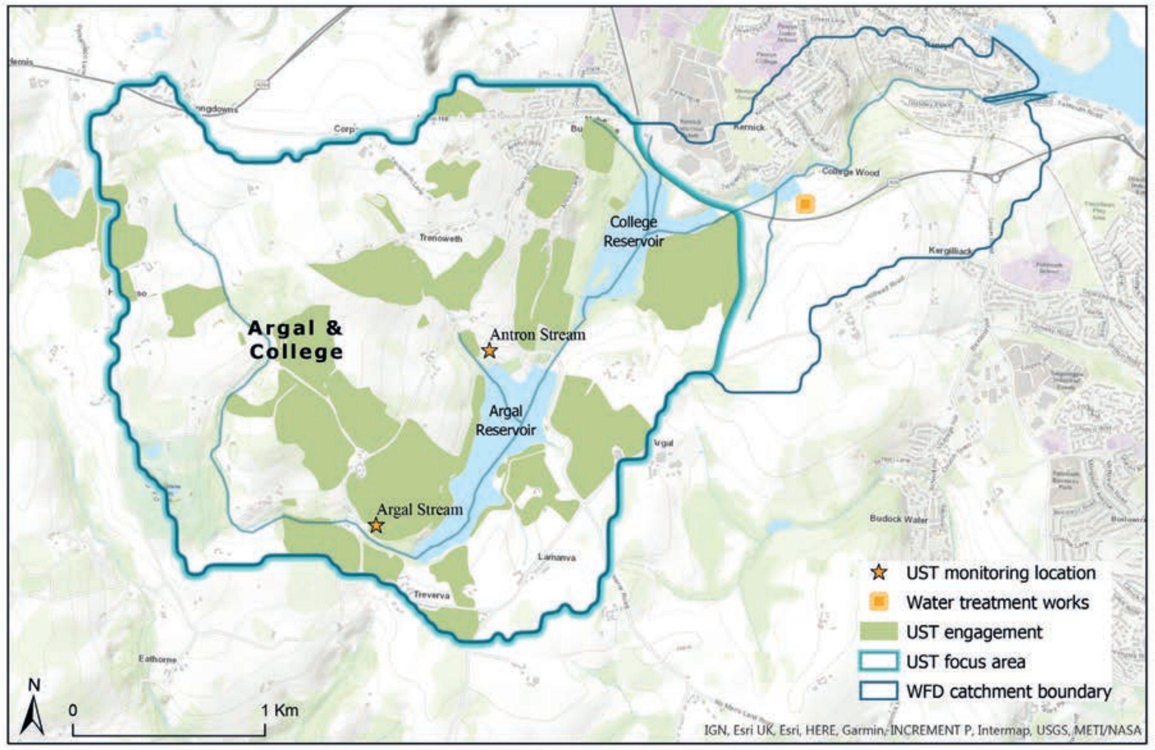
UPSTREAM THINKING IN ACTION: ARGAL AND COLLEGE RESERVOIRS

- Algal blooms and eutrophication related issues are a major problem in the catchment. Monitoring has mostly focused on nutrient inputs (as a driver for eutrophication), algae content and metaldehyde detections.
- The monitoring results at sub-catchment scale highlight the need to focus intervention efforts on the Antron Stream sub-catchment, as it is a higher nutrient contributor to the reservoir than the Argal Stream.
- Efforts should focus on reducing P input, as peaks are concomitant with blue-green algal blooms.
- Passive sampling showed that metaldehyde detections were consistently below 100 ng L^{-1} in the catchment and at the WTW, and decreased between autumn deployment periods.
- Upstream Thinking interventions have the potential to hold the line against environmental degradation.

About the catchment

Background site information

Argal and college reservoirs are within South West Water's Colliford Strategic Supply Area (Figure 1). They are located within the Fal EA Operational catchment, which itself falls within the wider Cornwall West and Fal EA Management Catchment. Abstraction from College No. 4 reservoir stopped in 2007; Argal reservoir is currently the only source used to supply approximately 15,000 homes around Penryn and Falmouth.



IGN, Esri UK, Esri, HERE, Garmin, INCREMENT P, Intermap, USGS, METI/NASA

Figure 1 Map of engagement by the CWT as part of Upstream Thinking in the Argal and College catchment.

Catchment Challenges

Argal and College reservoirs were identified as at risk for: algae (total and blue-green), geosmin, MIB, ammonia and metaldehyde.

Catchment Activities

During Upstream Thinking 2 (2015-2020), **Cornwall Wildlife Trust** (CWT) engaged with farmers in the Argal and College catchment to offer advice and capital grants aimed to improve farming practices and to reduce ammonium and pesticide runoff from farms. They also supported farm businesses into Countryside Stewardship schemes to undertake better management for the reduction of soil and nutrient runoff into the reservoir. Areas of semi-natural habitat were brought into better management for water and wildlife benefits.

Figure 1 illustrates the level of farm engagement in UsT2 within the Argal and College reservoirs catchment. As of May 2019, 33% of the catchment focus area has been engaged in the programme, including such things as farm visits by an advisor, the provision of a farm plan or physical interventions and behaviour changes.

Physical interventions completed via Upstream Thinking, which were quantifiable within the Farmscoper software, amounted to a cumulative total of 22 ha. The interventions most frequently used were re-siting gateways away from high risk areas and minimising the volume of dirty water produced (and sent to dirty water store). It should be noted, however, that numerous additional interventions have occurred that are less easy to quantify or that have happened as a result of the Countryside Stewardship joint working, and are therefore not covered in this assessment.

Water quality in the Argal catchment

Nutrient content in feeder streams

Since 2012, Argal reservoir consistently falls in the "poor" Water Framework Directive (WFD) water quality classification. This is due to Total Phosphorus (TP) and phytoplankton issues that are attributed to agriculture and land management issues. In order to investigate the input to the reservoir, water quality sampling (rainfall events) was conducted in the two feeder streams to Argal reservoir (Figure 2): the Argal Stream and the Antron Stream. Monitoring focused more particularly on nutrient inputs to the reservoir, as these can be a driver for algal blooms. Both sites show concentrations of Soluble Reactive Phosphorous (SRP) and Total Oxidised Nitrogen (TON) frequently above the targets set by the EA and SWW for (TP) and TON, indicating overall high nutrient contribution from the catchments to the reservoir (Figure 3). It is worth noting that our measurements were of inorganic P solely (i.e. SPR) when the regulatory limit is that of TP. As TP also contains organic and inorganic P, the exceedance of this limit by SRP alone confirms the high values that would be even higher if TP had been measured.

Figure 2 Pictures showing the main tributaries to Argal reservoir: Argal stream (left) and Antron stream (right) (photos by Emilie Grand-Clement).

For the events monitored, nutrient concentrations measured in the Antron Stream are consistently higher than that coming from the Argal stream (Figure 3). Despite lower stream flow in the Antron Stream (Figure 3), higher concentrations mean that the total instantaneous load (i.e. mass of nutrients at any one time) input to the reservoir tends to be higher than that from the Argal Stream (Figure 4), making this sub-catchment a higher contributor of diffuse pollution. The lack of significant change between years indicate that no deterioration has occurred during the course of the project which is a positive result. In the wider landscape, it is unfortunately clear that environmental degradation is still worsening. This work demonstrates that more interventions are required to reverse the diffuse pollution problems both in these reservoirs and wider landscape.

Argal reservoir within the catchment (photos by Emilie Grand-Clement).

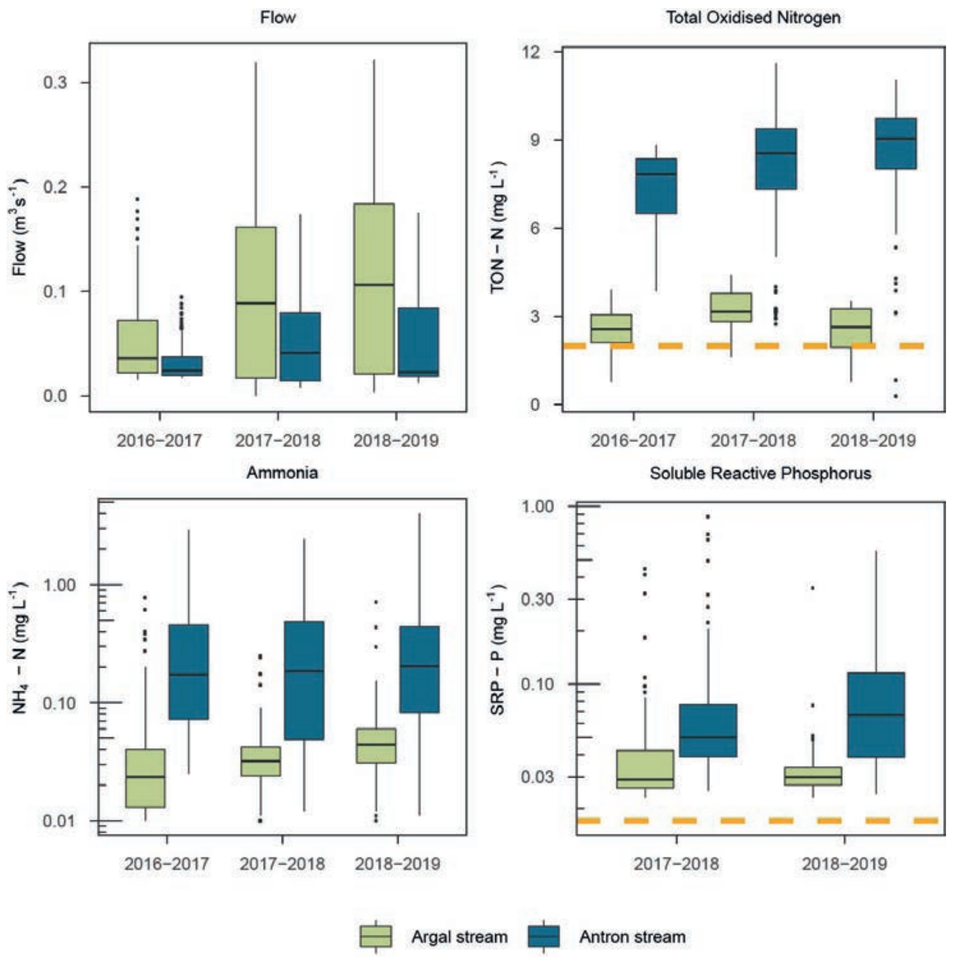


Figure 3 Flow (m^3 s^{-1}), Total Oxidised Nitrogen, ammonium and Soluble Reactive Phosphorus concentrations in feeder streams to Argal lake, with the Antron Stream experiencing worse water quality consistently than the Argal Stream. For both sites, concentrations are consistently above the orange lines representing SWW's limit of 2 mg L^{-1} for Total Oxidised Nitrogen, and the Water Framework Directive good status limit of 0.017 mg L^{-1} for Total Phosphorus in the reservoir, both used as a target for quantifying impacts of the project.

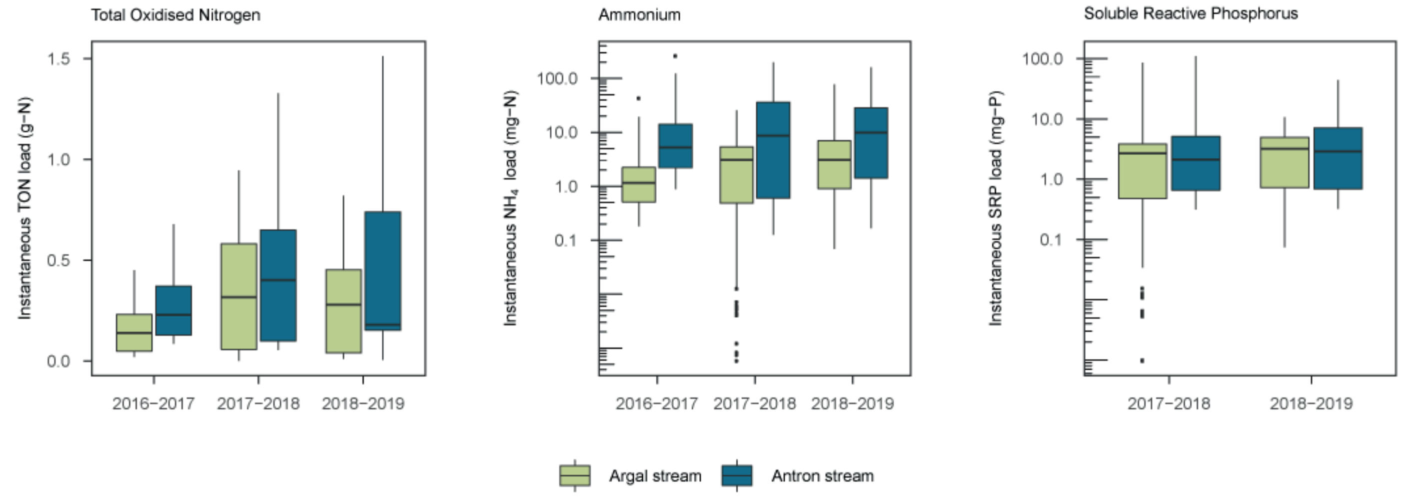
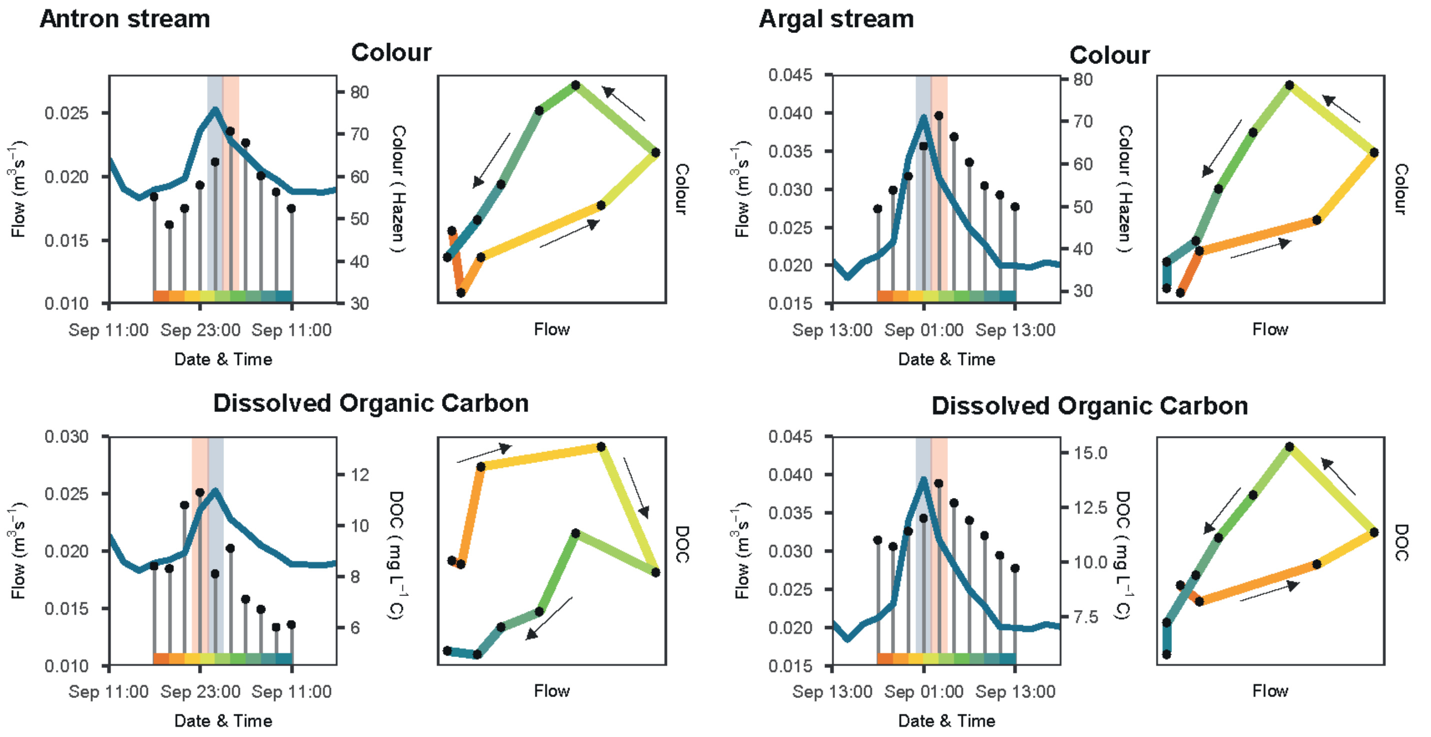


Figure 4 Total Oxidised Nitrogen (mg-N), ammonium (mg-N) and Soluble Reactive Phosphorus (mg-P) loads measured by the project in the two feeder streams to the Argal lake between 2016-2017 and 2018-2019: despite lower streamflow, nutrients loadings at the Antron Stream are significantly higher for all nutrients due to particularly high concentrations.

Water quality and diffuse pollution during rainfall events

In addition, the hysteresis behaviour of DOC and colour between sites during rainfall events gives interesting information on the origin of pollution during storms within the catchment. In the Argal Stream, the maximum concentration (highlighted in red) of both DOC and colour occurs soon after the maximum flow (highlighted in blue) (Figure 5A), which is materialised by two similar anticlockwise hysteresis loops. However, in the Antron Stream, the peak of DOC is desynchronised and occurs earlier than that of colour, as shown by a clockwise loop (Figure 5B). It is likely that DOC peaks earlier because it originates from a different and closer source than colour, for example fields or farmyard hard standings close to the reservoir. However, in the Argal Stream, it is likely that the source of both DOC and colour is the same and further away from the reservoir. This is useful information to investigate pollution sources within catchments, as it allows the project partners to target the most problematic areas.

Figure 5 Relationship between flow (m^3 s^{-1}) and water quality parameters (i.e. Dissolved Organic Carbon (DOC) and colour in mg L^{-1}) for both Argal feeder streams for one storm event, with associated hysteresis loop: the events considered show an anticlockwise loop for colour and a clockwise loop for DOC at the Antron stream, whereas both hysteresis loops are anticlockwise for the Argal stream, highlighting a difference of behaviour for DOC losses between the two streams.



Blue-green algae and nutrient content in the reservoir

Blue-green algal blooms are a major problem for Argal reservoir (Figure 6). The study of algae content is coupled with that of nutrients in the reservoir (Figure 7) as these are a major driver for eutrophication. Overall, data from Argal reservoir shows that this reservoir experiences some of the worst blooms across the region (see Figure 4 p23), with concentrations going up to 1,500,000 cells mL^{-1}. Overall, all parameters show a seasonal pattern, although these do not always coincide with algal blooms. TON concentrations in the reservoir reach their maximum around April and exceed the 2 mg L^{-1} target set by SWW as evidence of successful impact of in-catchment measures for part of the year, making spring the most at-risk period for the treatment of water. Overall, most TP samples collected since 2014 show concentrations higher than the WFD good status targets for total phosphorus. Phosphorus tends to peak in autumn (i.e. October) (Figure 7, middle), although this seasonal trend is less clear. As blue-green algal blooms generally occur in summer/autumn (Figure 7 bottom and Figure 8), blooms are concomitant with P concentrations but not N. In-catchment efforts to limit nutrient input to the reservoir should therefore focus on the reduction of P to reduce blue-green algal blooms, and the significant costs and risks to health that they pose.

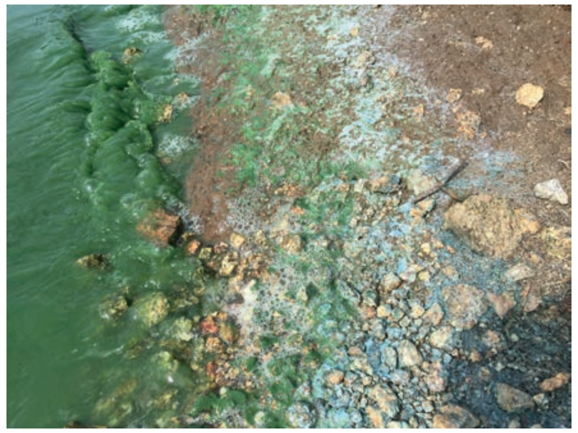


Figure 6 Detail of blue-green algal bloom in Argal reservoir, with marks left on the shore (photo by Emilie Grand-Clement).

Figure 7 Total Oxidised Nitrogen (TON-N, top), Total Phosphorus PO4-P, (middle) and blue-green algae cell count (bottom) between 2014 and 2018 in raw water at Argal WTW; red lines indicate the target limits for each nutrient concentrations in the reservoir.

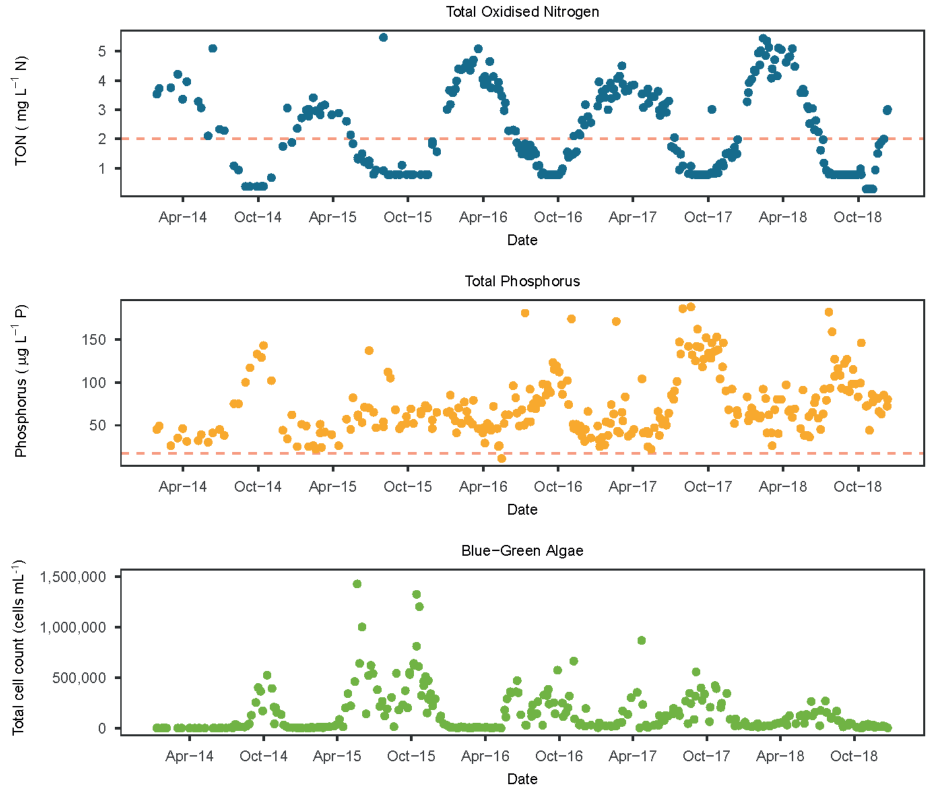


Figure 8 highlights not only the high cell counts of cyanobacteria (i.e. blue-green algae) that can be experienced in Argal Lake during algal blooms (e.g. peaks of monthly mean cell count of ca 800,000 cells mL^{-1} in 2015), but it also shows the overwhelming proportion that blue-green algae make amongst the total algal and diatoms species. This is particularly problematic for the treatment of water, but also for the risk posed by the production of toxins and taste and odour compounds by cyanobacteria. The problems experienced at Argal Lake are particularly challenging and indeed costly for SWW and drinking water production. These results show the need to use catchment management to decrease nutrient input, but also to consider in-reservoir dynamics to understand and predict future blooms, and thus when water is very costly to treat.

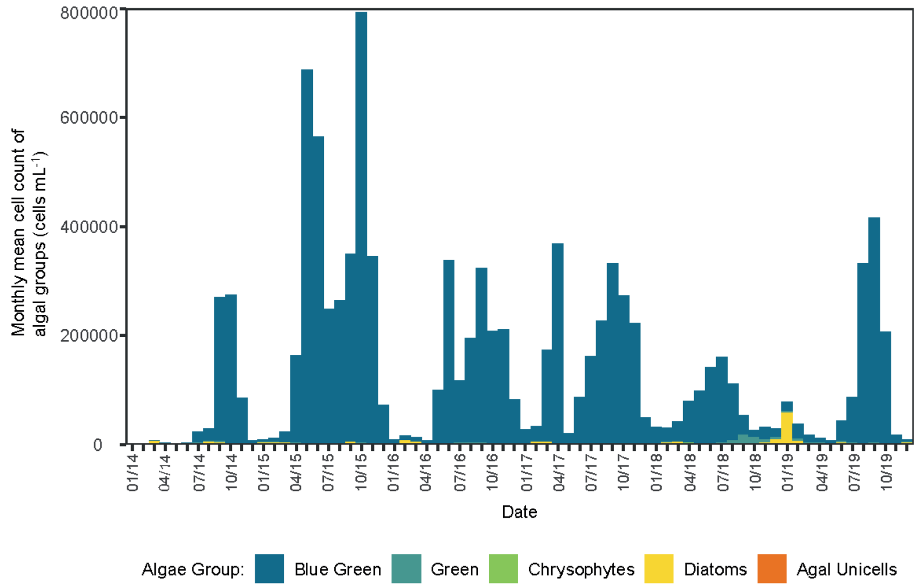


Figure 8 Monthly mean cell count of algae per group species between 2014 and 2018 Argal reservoir.

The Argal stream (photo by Emilie Grand-Clement).

In-situ monitoring equipment by UoE within the Argal catchment (photo by Emilie Grand-Clement).

Pesticides detections within the reservoirs

Another water quality issue in the catchment is pesticides. In particular, metaldehyde was highlighted by the EA as a pesticide of specific concern. This compound is particularly difficult to remove from raw water. These concerns are confirmed by the results from the passive sampling deployment campaigns (Figure 9). Measurements show that metaldehyde was detected in all locations (i.e. both feeder streams and at the WTW) during each spring and autumn deployment periods. More precisely, detections in the streams feeding the reservoirs show an input of metaldehyde at the time of deployment in the catchment whilst measurements at the WTW (i.e. in reservoir water) show the persistence of the compounds in the water body. This explains the higher concentrations being measured at WTW compared to input to the reservoir, which is a serious problem and costly for water treatment.

The maximum concentrations detected in the passive samplers are generally low (i.e. below 35 ng L^{-1}), and well below the regulatory 100 ng L^{-1} limit per compound. However, these are averaged over a period of time, and are therefore likely to hide short-lived spikes that might have occurred during each deployment period, as the pesticides were washed off the farmland that they had been applied to.

Finally, a consistent decrease in concentrations between autumn deployments can be observed across all sites and monitoring years, including at the reservoir. This is a very positive result as it shows the potential for changes in the practical application of pesticides to improve water quality. However, variability in the general period of metaldehyde application (i.e. start and end of usage) and that of monitoring periods might also have prevented the detection of the compound in these locations. More work is clearly needed to reduce the input of pesticides from agriculture in such catchments.

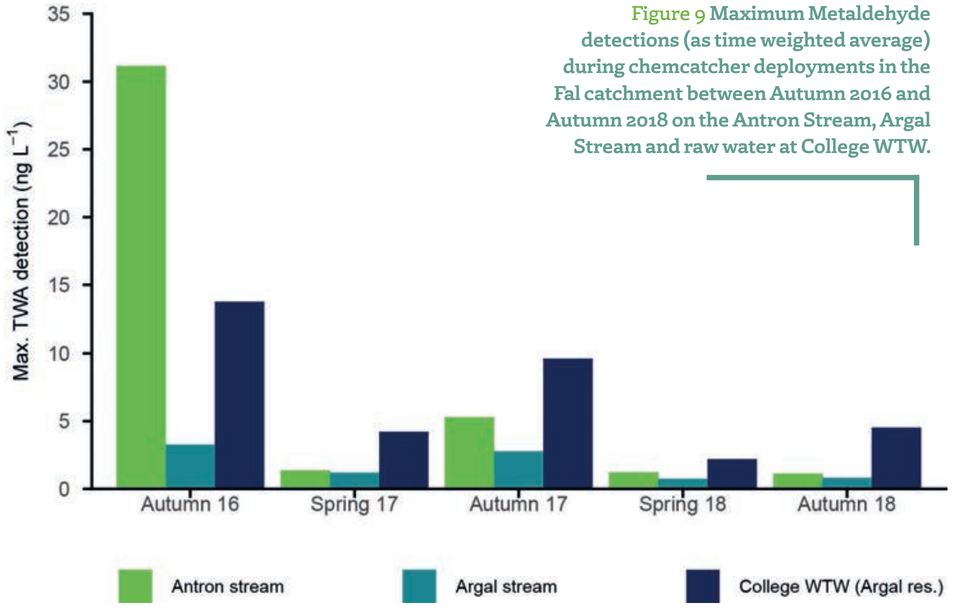


Figure 9 Maximum Metaldehyde detections (as time weighted average) during chemcatcher deployments in the Fal catchment between Autumn 2016 and Autumn 2018 on the Antron Stream, Argal Stream and raw water at College WTW.

Argal reservoir (photos by Emilie Grand-Clement)

Argal reservoir (photos by Emilie Grand-Clement)

UPSTREAM THINKING IN ACTION: DRIFT RESERVOIR

About the catchment

Background site information

Drift Reservoir is located in far west Cornwall, within the Penwith Peninsula (EA) Operational Catchment which falls within the Cornwall West and the Fal (EA) Management Catchment.

Catchment Challenges

Drift Reservoir (Figure 1) is challenged by pesticides (specifically linuron, mecoprop, metaldehyde and pendimethalin) and blue-green algal blooms driven by nutrient enrichment. Interventions in the catchments were led by **Cornwall Wildlife Trust** (CWT).

- Water quality challenges in the reservoir are pesticides and blue-green algal blooms driven by nutrient enrichment;
- Detrending analysis of turbidity data between 2012 and 2018 shows that most of the high peaks were driven by climatic conditions (particularly high rainfall): differences in sediment pollution were due to inter-annual variability rather than catchment management interventions; no statistically significant change in water quality can be observed throughout the duration of the project;
- In feeder streams, all Total Oxidised Nitrogen (TON) concentrations input to the reservoir during rainfall events are higher than the SWW target of 2 mg L^{-1} in the reservoir, highlighting high nutrient input from the catchment;
- Although high TON concentrations were observed during rainfall events in the Sancreed Brook, low river flow in the catchment resulted in lower loads from that site;
- Most Soluble Reactive Phosphorus samples fall within the "moderate" category; nutrient input during rainfall events do not yet meet the criteria set by the EA for reservoir water.
- Levels of individual pesticide detections in the reservoir were below 0.1 μg L^{-1} throughout the monitoring periods.

Figure 1 Drift reservoir (left) within the catchment (right), illustrating the prevalence of intensive arable farming above the reservoir; photos by Emilie Grand-Clement.

Catchment Activities

Catchment activities in the Drift catchment focussed on measures to decrease phosphate inputs and better manage land to improve its ability to intercept nutrients and pesticides. Figure 2 illustrates the level of farm engagement in Upstream Thinking 2 within the Drift reservoir catchment. 73% of the catchment area has been engaged in the programme, including farm visits by an advisor, the provision of a farm plan or physical interventions and behaviour changes.

Physical interventions completed via Upstream Thinking, which were quantifiable within the Farmscoper software, amounted to a cumulative total of 482 ha. The most commonly used interventions are shown in Figure 3. Slurry store improvements and dirty water management all impact on phosphorus losses, whilst establishing new hedges and better farm track management can also provide benefits by reducing sediment losses.

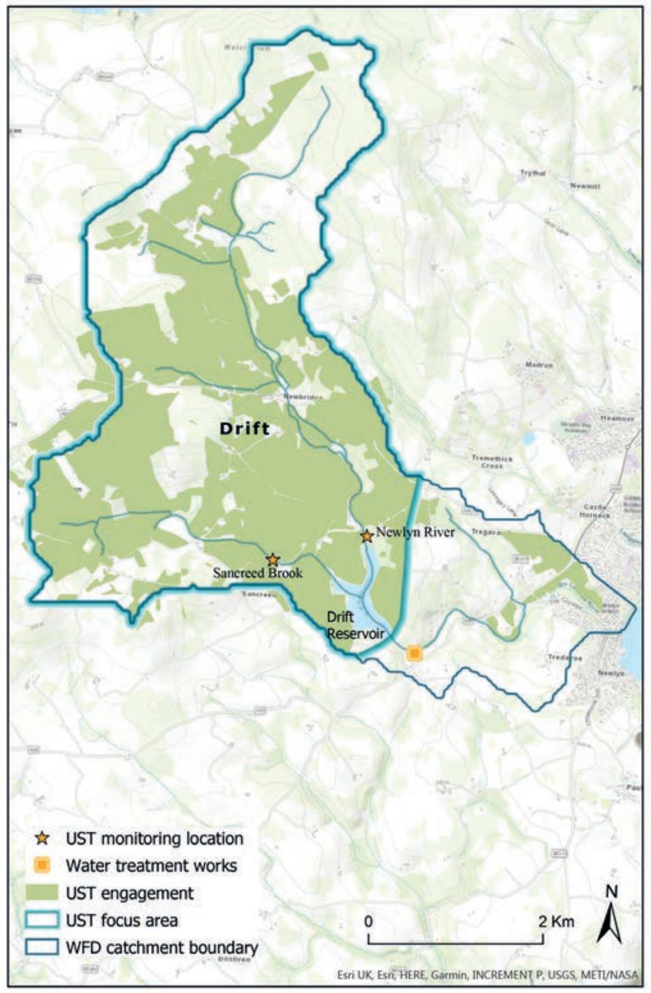


Figure 2 Map of engagement by the CWT as part of UsT in the Drift catchment.

Figure 3 Top 5 interventions (quantified in Farmscoper) used in the Drift catchment.

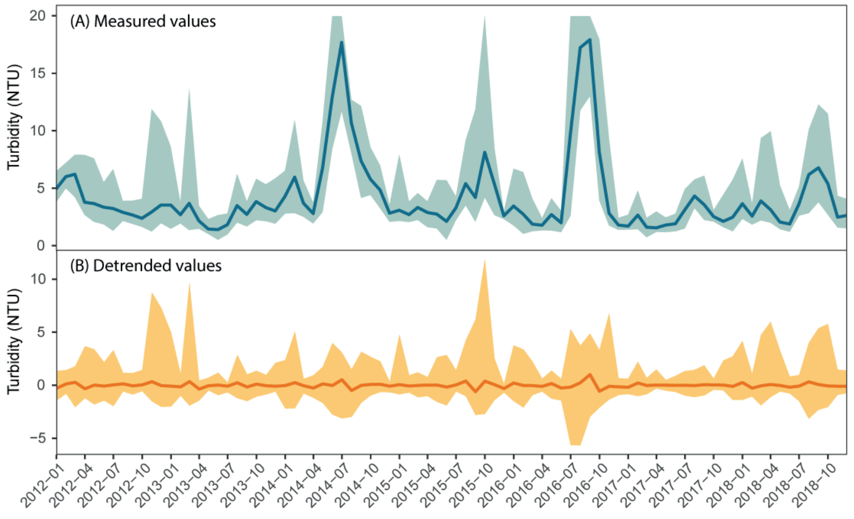


Figure 4 Monthly turbidity variations in Drift reservoir between 2012 and 2018 (A) and detrended monthly averages for the same time period (B), with full line indicating the monthly mean and the ribbon area the associated range of data.

Water quality in the Drift catchment

Turbidity in Drift reservoir

Continuous measurements of turbidity in Drift reservoir enable an understanding of rapid variations in the suspended sediment signal, and is also an invaluable resource to study long-term, seasonal and inter-annual variations of sediment input to the reservoir. Measured turbidity variations at Drift reservoir (Figure 4A) show a cyclic pattern with an annual peak generally occurring in spring to summer, with high turbidity values measured in the summers of 2014 and 2016 (with maximum values reaching ca. 30 NTU). The occurrence of these high peaks is linked to a combination of catchment management, climatic and environmental factors. For instance, low vegetation cover following tillage leaves soils vulnerable to erosion (as well as to losing carbon to the atmosphere); combined with high rainfall and steep slopes, this could have had detrimental impact on water quality in the reservoir.

Figure 4B shows the detrended turbidity signal: in this signal, the influence of climate has been removed from the dataset. This resulting dataset clearly shows the disappearance of the high peaks of summers 2017 and 2016, which can therefore be linked to seasonal conditions, including high energy summer rain storms. Other peaks, however, remain (e.g. January 2013 and October 2015). These events are likely to be driven by environmental conditions in the catchment. While no clear impact of catchment management to improve water quality can be seen since 2015, there is also no deterioration in the water quality over this period. Further interventions would be required to reduce the loss of soil from agricultural fields into the reservoir.

Figure 5 The Sancreed Brook; Photo by Emilie Grand-Clement (UoE).

Nutrient content in feeder streams

Nutrient inputs to the reservoir from the two feeder streams, the Sancreed Brook (Figure 5) and the Newlyn River (Figure 6), were measured during a number of rainfall events. Results (Figure 7) show significantly higher TON concentrations in the Sancreed Brook (e.g. mean concentrations between 3.7 mg L^{-1} and 4.7 mg L^{-1}) than in the Newlyn River (e.g. mean concentrations between 2.5 mg L^{-1} and 3.05 mg L^{-1}) for each hydrological year; for both sites these values are consistently above the target of 2 mg L^{-1} set by SWW in the reservoir as an indicator of improvement.

For phosphate losses during rainfall events, there are little differences between sites. Overall, phosphate values in the catchments place both streams in the “moderate” category, whilst some samples occasionally fall in both “good” and “poor” categories”. Overall, the nutrient input during rainfall events do not yet meet the criteria set by the EA for in reservoir water.

Figure 6 The Newlyn River; Photo by Emilie Grand-Clement (UoE).

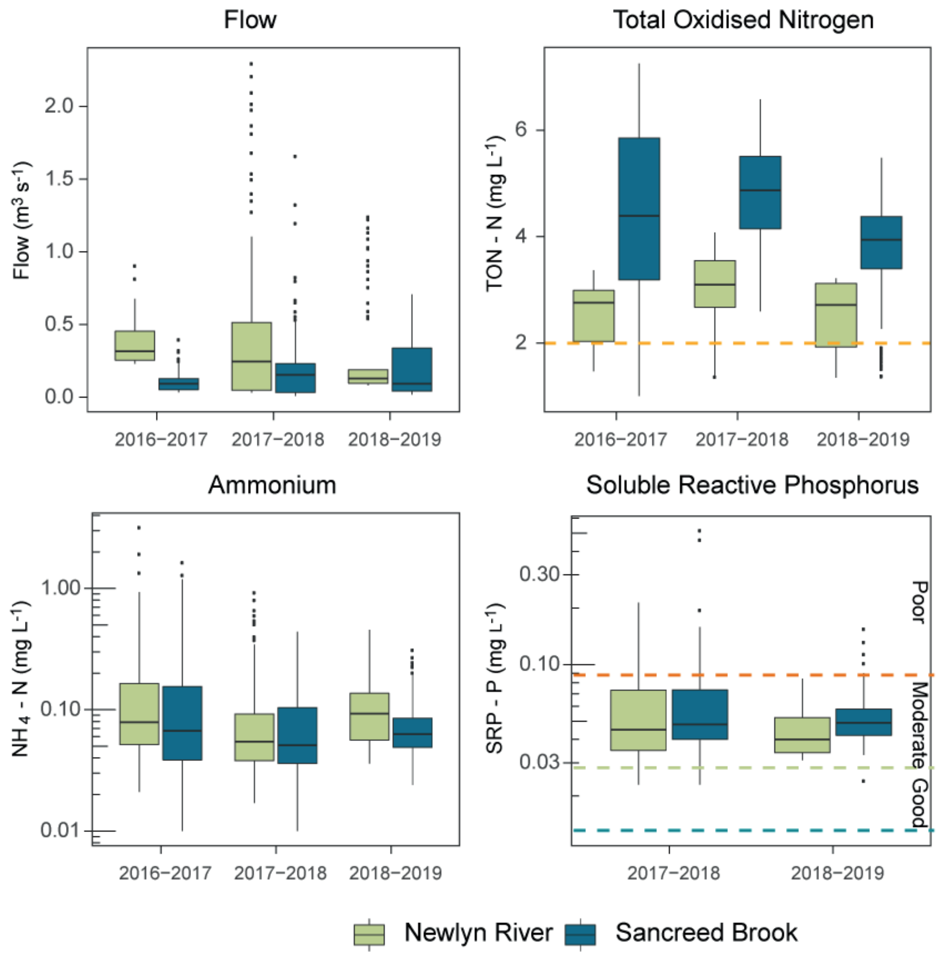


Figure 7 Flow Total Oxidised Nitrogen, ammonium and Soluble Reactive Phosphorus concentrations in the feeder streams to Drift reservoir, with dashed lines representing the regulatory limits for Total Oxidised Nitrogen and total phosphorus respectively.

Figure 7 also shows that the Newlyn River tends to have higher stream flow during monitored events than the Sancreed Brook for 2016-2017 and 2017-2018 monitoring years. This results in slightly higher nutrient loads (i.e. the actual mass of nutrient carried by the stream to the reservoir) compared to Sancreed Brook, despite experiencing lower concentrations (Figure 8). This has implications for catchment management, as interventions in the Newlyn River sub-catchment will have a slightly higher impact on the delivery of nutrients during high flows, thus future catchment interventions could be more valuable in this sub-catchment.

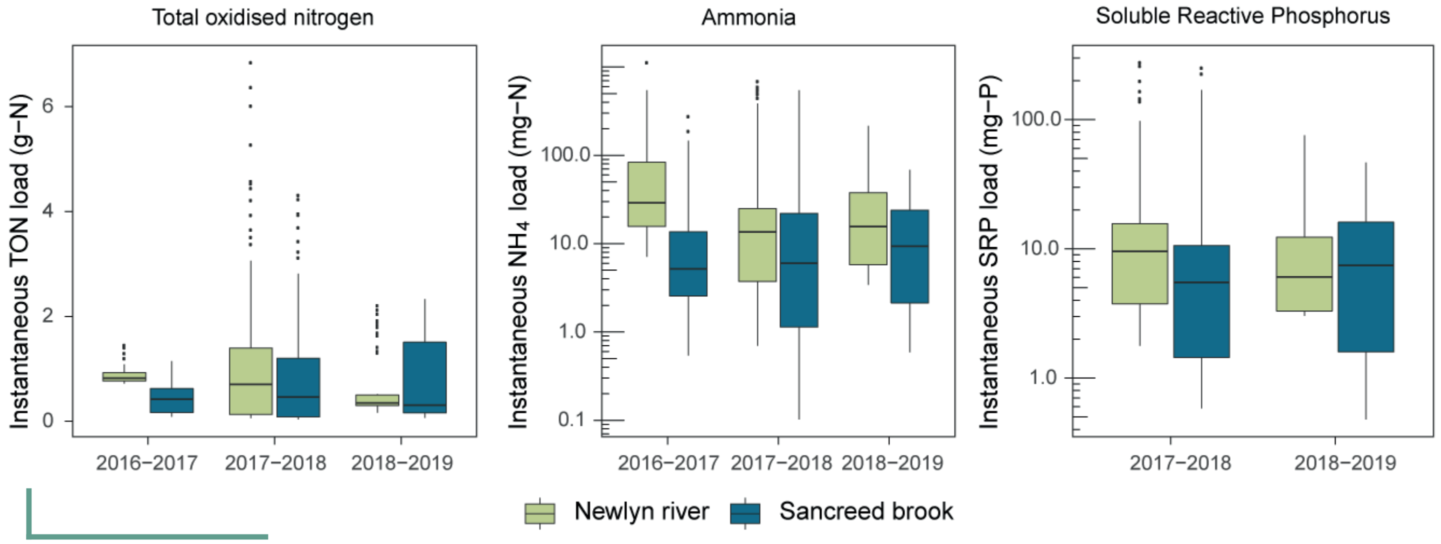


Figure 8 Total Oxidised Nitrogen, ammonia and Soluble Reactive Phosphorus loads (mg) for the rainfall events monitored between 2016-2017 and 2018-2019.

Pump sampler in the Sancreed Brook; Photo by Paul Henderson.

Water quality and diffuse pollution in rainfall events in feeder streams

In addition to nutrient content, the study of pollutant concentrations during specific rainfall events is useful to understand contaminant dynamics. The plots shown in Figure 9 highlight the different type of behaviour generally observed with TON and DOC, resulting in different hysteresis loop patterns in the catchment: TON generally present in the stream is being diluted by rain water during storms (i.e. concentrations decrease as flow increases), indicating that there is no immediate increase in concentration as an input of diffuse pollution; DOC, however is increasing in concentration during the event and peaks simultaneously to the peak in discharge, which indicates that it is flow and rainfall driven, with sources of DOC (such as manures or slurries on fields) being directly connected to the water course during times of high rainfall. These two different types of behaviour are reflected in two different hysteresis loops: clockwise for TON, and anticlockwise for DOC.

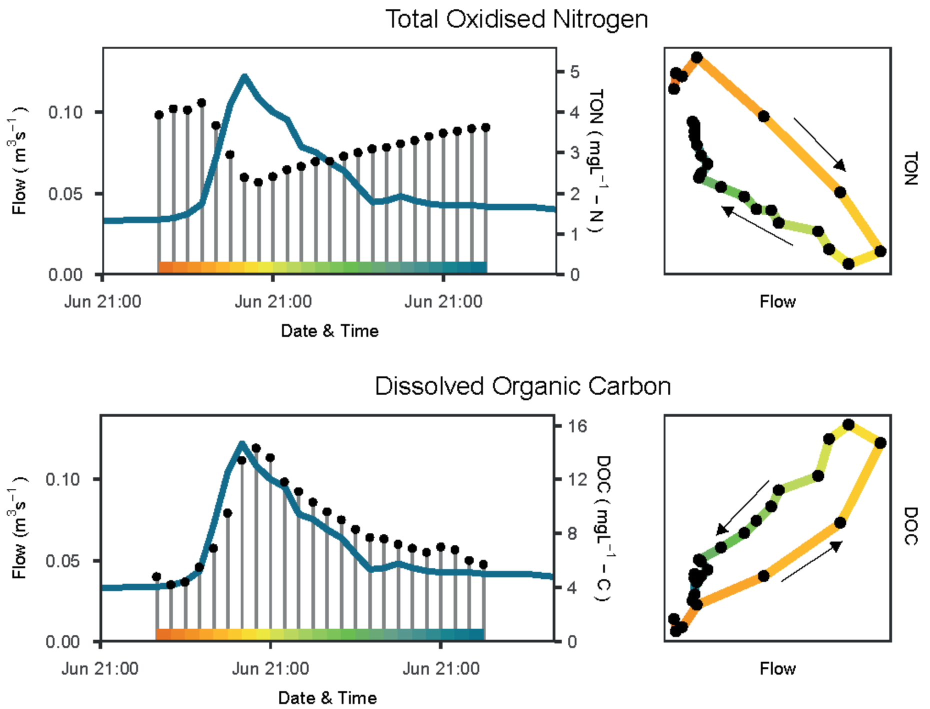


Figure 9 Relationship between flow ($m^3 s^{-1}$) and water quality parameters (i.e. Dissolved Organic Carbon and Total Oxidised Nitrogen) for one rainfall event in the Sancreed Brook sub-catchment, with associated hysteresis loop.

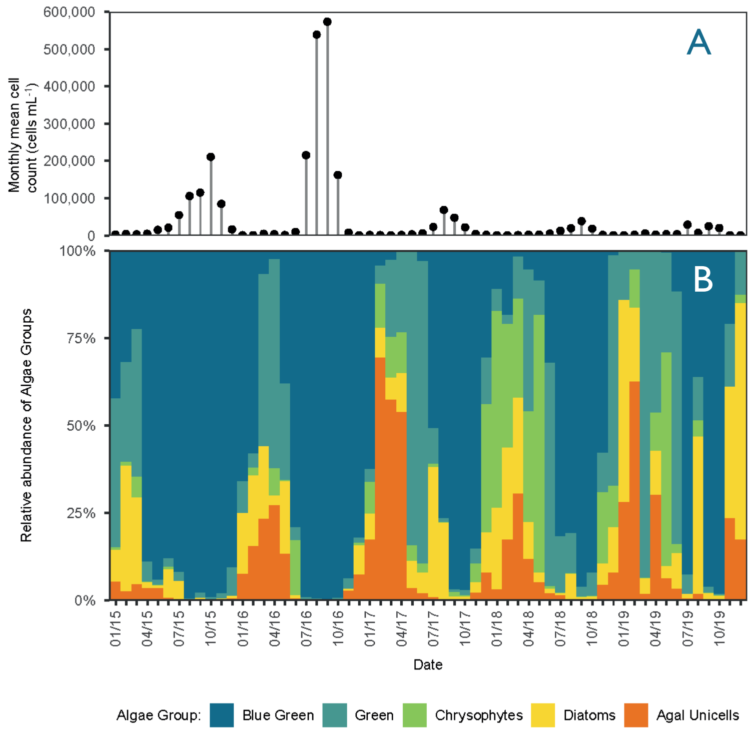


Figure 10 Monthly averages of total algal blooms (A) with corresponding abundance of species (B) between 2014 and 2019 in the raw water at Drift WTW.

Blue-green algae and nutrient content in the reservoir

Algal blooms have been identified as an issue in Drift reservoir. Spot samples collected by SWW at the water treatment works (Figure 10A) show the occurrence of summer algal peaks in Drift reservoir, which was identified as problematic and costly for the water treatment works. Peaks in 2015 and 2016 were particularly prominent, however, their amplitude seems to decrease in the subsequent years. Figure 10B shows the overwhelming presence of cyanobacteria during these peaks whilst other species are only noticeable at other times. Cyanobacteria have been identified as particularly problematic in Drift reservoir due to its significant impact on the treatment process.

In addition, the reduction in nutrient concentrations in the reservoir was an objective of Upstream Thinking. However, the result of the spot samples in raw water at the WTW (Figure 11) shows that nutrient concentrations remained high. For phosphorus, samples consistently fell outside of the WFD target indicting good status (i.e. above 15.76 $\mu g\ L^{-1}$); TON concentrations showed a seasonal pattern, going below the 2 mg-N L^{-1} in the autumn-winter. Neither nutrient shows a clear sign of improvement. This particular result is likely to be linked with the existing nutrient content of the reservoir, which is clearly high, as a legacy of nutrient inputs in previous years. However, in addition, recent levels of input to the reservoir during rainfall events (Figure 11) above these levels are likely to have contributed to the currently high nutrient content of the reservoir.

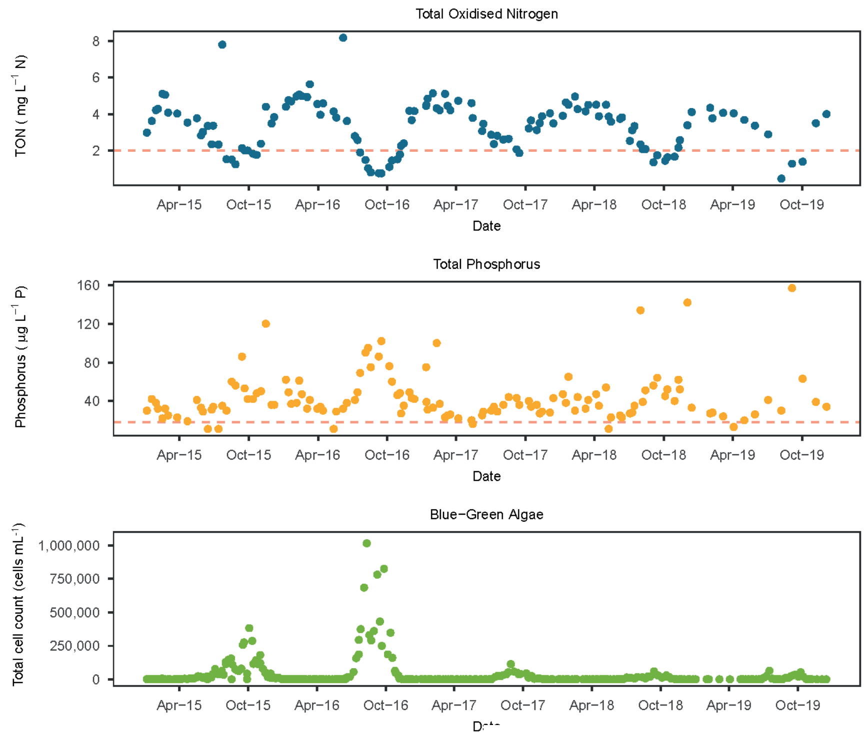


Figure 11 Total Oxidised Nitrogen (top), Phosphorus (middle) and blue-green algae cell count (bottom) between 2014 and 2019 in raw water at Drift WTW; red lines indicate the exceedance limit for each nutrient concentrations in the catchment.

In reservoirs, geosmin which causes taste and odour problems in drinking water, can originate from algae die-back. We would therefore expect increased concentrations of geosmin to occur after algal blooms. Interestingly, geosmin data (Figure 12) shows that this is not necessarily the case. This is, for example, noticeable with peaks in algae occurring in Autumn 2016 that do not result in a significant increase in geosmin; conversely, a number of geosmin peaks seem to occur and be unrelated to algal blooms. This means that geosmin could originate from sources in catchment, i.e. from soil, although a more in depth study would need to be carried out to draw firm conclusions.

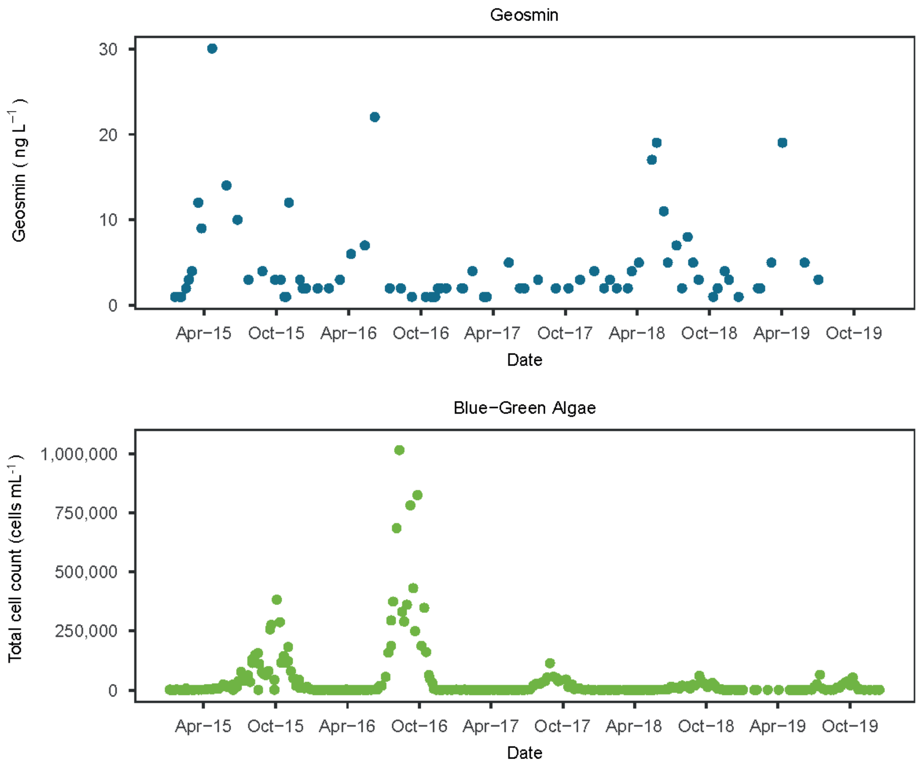


Figure 12 Geosmin (top) and blue-green algae concentrations (bottom) between 2015 and 2019 in raw water at Drift WTW.

Overall, the reduced amplitude of blue-green algal blooms since 2017 is a positive result for the Upstream Thinking objectives. More investigations in the coming years will enable us to identify the importance of climate, within reservoir dynamics and input of nutrients in the catchment in driving algal blooms. This should enable us to better quantify the benefit brought by catchment management to reservoirs and reduce algal blooms and associated water treatment costs.

Pesticide detections within the catchment

Another concern in the catchment has been pesticides getting to the reservoir. Chemcatchers were used to get a better understanding of concentrations at specific times of the year, i.e. 6 weeks in the spring and 6 weeks in the autumn. Chemcatcher deployments in the Drift catchment show a high number of compounds detected (i.e. up to 8 compounds for Drift reservoir, 6 for the Newlyn River, and 7 for the Sancreed Brook). In all locations, 2,4-D, Fluroxypyr and Trychlopyr represents the majority of the compounds detected (Figure 13). These compounds are routinely used as pesticides on farmland.

The total number of detections per site and deployment period ranged between 4 and 15 (Table 1). There is also a slight decrease in the overall number of detections in the Drift reservoir between the first half of the project (Spring 2016 to Spring 2017) and the second half (from Autumn 2017). Although this difference is not statistically significant, it is positive.


High flow in the Newlyn River; Photo by Paul Henderson.

		Spring 16	Autumn 16	Spring 17	Autumn 17	Spring 18	Autumn 18
Total number of detections	Sancreed brook	9	13	4	N/A	N/A	N/A
	Newlyn river	13	9	9	N/A	N/A	N/A
	Drift WTW	15	15	14	7	13	9
Nb single exceedances >100 ng L^{-1}	Sancreed brook	0	0	0	N/A	N/A	N/A
	Newlyn river	0	0	0	N/A	N/A	N/A
	Drift WTW	0	0	0	0	0	0
Exceedance over 500 ng L^{-1}	Sancreed brook	0	0	0	N/A	N/A	N/A
	Newlyn river	0	0	0	N/A	N/A	N/A
	Drift WTW	0	0	0	0	0	0
Max value (ng L^{-1})	Sancreed brook	8	22	1	N/A	N/A	N/A
	Newlyn river	3	4	2	N/A	N/A	N/A
	Drift WTW	3	9	2	5	4	2
Total number of compounds	Sancreed brook	4	6	2	N/A	N/A	N/A
	Total number of compounds	5	3	4	N/A	N/A	N/A
	Drift WTW	5	5	5	3	5	4

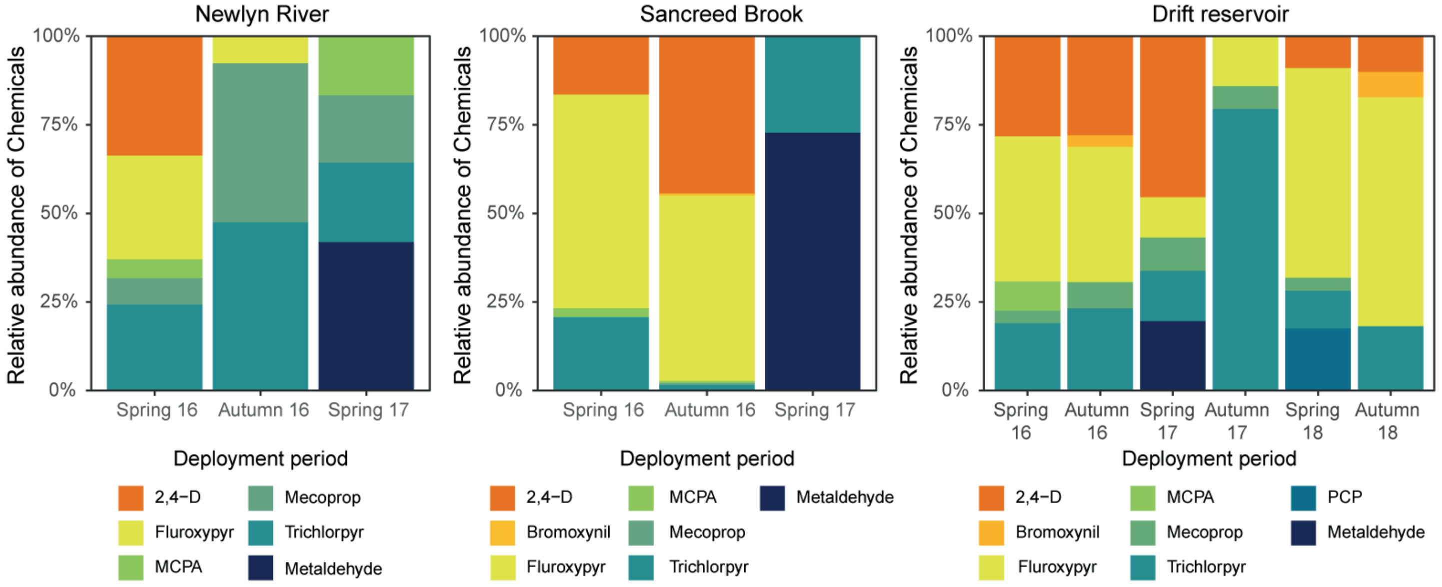
Table 1 Summary of pesticide detections in the Drift catchment between spring 2016 and autumn 2018. The blue shading indicates a severity scale separately applied to each parameter, from light blue (low) to dark blue (high); N/A indicates that no deployments were carried out.


Cattle in the Sancreed Brook; Photo by Paul Henderson.

Certain compounds are also sporadically detected, such as metaldehyde (found in slug pellets) in Spring 2016 in all three locations, and PCP (weed killer) in Spring 2018 only (although the monitoring period of the feeder streams stopped in Autumn 2017).

With an overall maximum concentration of 22 ng L^{-1} in the Sancreed Brook, no site had a single detection above the regulatory limit of 100 ng L^{-1} (in treated water), or a cumulated concentration over 500 ng L^{-1}, which is very positive.

Figure 13 Relative abundance (%) of chemicals detected between Spring 2016 and Autumn 2018 at Drift reservoir, and between Spring 2016 and Spring 2017 for the Newlyn River and the Sancreed Brook.



UPSTREAM THINKING IN ACTION: UPPER TAMAR LAKE

- Upper Tamar Lake has been identified as "at-risk" for pesticides (in particular MPCA, mecoprop and metaldehyde) and blue-green algae caused by excess nutrients;
- Water quality investigations showed a decrease in turbidity in the feeder stream to the reservoir at high flow between 2016-2017 and 2018-2019; however, this reduction is not yet detectable in the overall turbidity of the raw water at the WTW;
- Two different rainfall event dynamics have affected the delivery of Soluble Reactive Phosphorus to the feeder stream, indicating the contribution of either a deep zone within the soil, or from a more distant, agricultural source further up catchment. This information is important to tackle sources of diffuse pollution;
- Algal blooms are not concomitant with nutrient input to the reservoir, and are therefore likely to be driven, to some extent, by climate combined with existing nutrient loads in reservoir;
- A number of high pesticide detections were observed in the catchment and reservoir (e.g. 2,4D, Fluroxypyr and Trichlopyr; the number of detections ranged between 6 and 18 per deployment period).

About the catchment

Background site information

The Tamar catchment is located along the boundary of Devon and Cornwall. The catchment drains an area of about 1,800 km^2. Upper Tamar Lake is a reservoir catchment located the north of the Tamar catchment (Figure 1). The area is predominantly rural. To the south are the Tamar estuary and the city of Plymouth where the majority of the population is based.

Catchment Challenges

Upper Tamar Lake at risk for pesticides (in particular MCPA and mecoprop), metaldehyde and blue-green algal blooms caused by excess nutrients.

Figure 1 Upper Tamar Lake; photo by Emilie Grand-Clement.

Catchment activities

Through Upstream Thinking, project partners have targeted the most polluting areas of the catchments and have focussed around activities such as farm track management, fencing off rivers and establishing buffer strips. As of May 2019, 77% of the Upper Tamar area has been engaged in Upstream Thinking by both **Westcountry Rivers Trust** (WRT) and **Devon Wildlife Trust** (DWT) (Figure 2).

Physical interventions completed via Upstream Thinking, which were quantifiable within the Farmscoper software, amounted to a cumulative area of almost 6,000 ha. The most commonly used interventions are shown in Figure 3. In addition, ca. 4 ha of culm, or species rich grassland, were restored in the catchment by DWT.

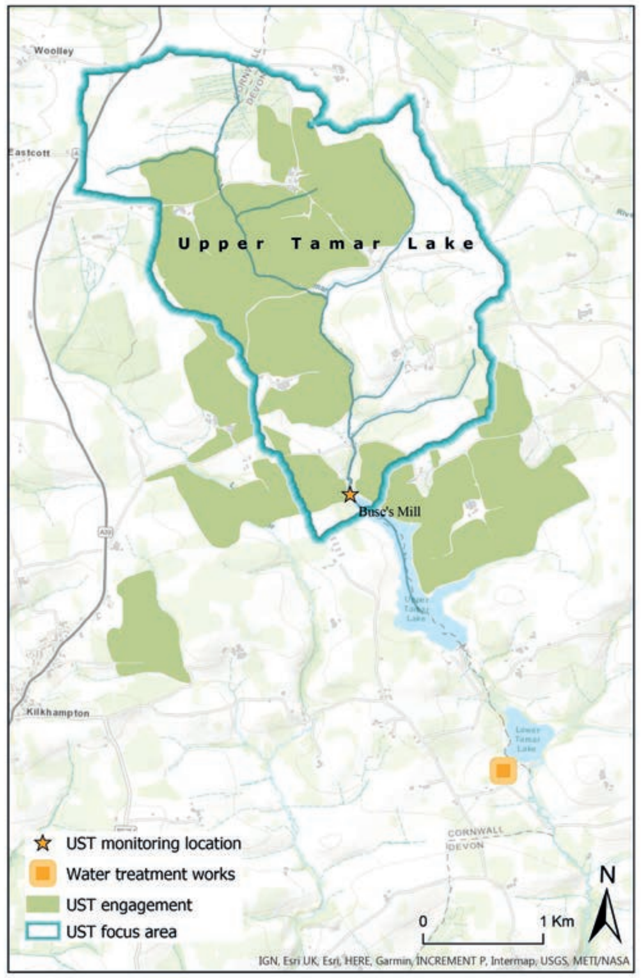


Figure 2 Map of engagement by WRT and DWT as part of UsT in the Upper Tamar Lake catchment.

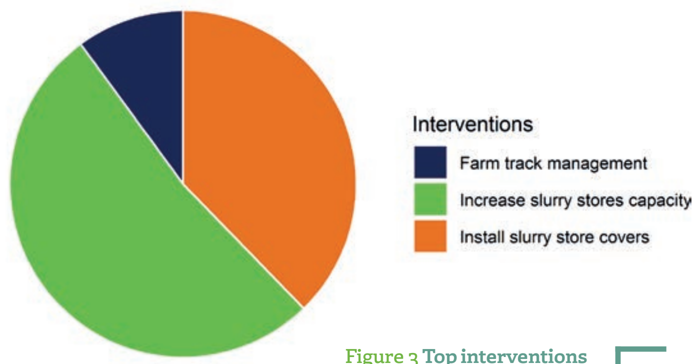


Figure 3 Top interventions (quantified in Farmscoper) used in the Upper Tamar Lake catchment.

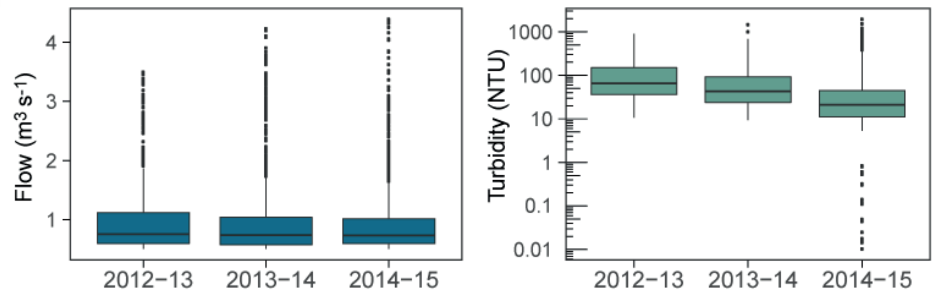


Figure4 High flow (Q5 and above) measured per hydrological year (left) and corresponding turbidity (NTU) measurements in feeder stream to Upper Tamar Lake plotted on a log scale.

Water quality at Upper Tamar Lake

Turbidity in feeder streams

Continuous measurements of turbidity in the feeder stream to Upper Tamar Lake (Figure 4) performed by the University of Exeter indicate a slight decrease in the turbidity or suspended sediment inputs to the lake at high flow (i.e. Q5 flows and above, with stream flow remaining unchanged between hydrological years) between 2016-2017 and 2018-2019. However, this positive, recent change is not yet detectable in the overall turbidity of the raw water at the Water Treatment Works (WTW), with no significant change being observed in concentrations between the hydrological years of 2012-2013 and 2017-2018 (Figure 5).

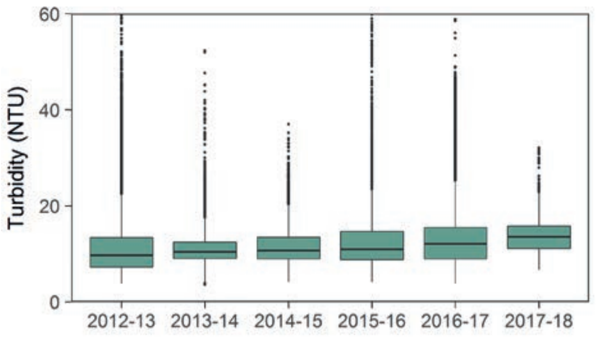


Figure5 Overall changes in turbidity between 2012-2013 and 2017-2018 for all flow records at Tamar Lake WTW.

These results therefore highlight some positive change in turbidity at a small scale that contributes to the lack of deterioration in the reservoir and, over time, will hopefully lead to a reduction in sediment content in the reservoir.

Continuous sensors (left) placed in the feeder stream (right) to Upper Tamar Lake; photo by Paul Henderson.

Water quality and diffuse pollution during rainfall events

Samples were also collected in the feeder stream to the lake (Figure 6) during rainfall events and analysed for nutrient inputs to the reservoir. Soluble Reactive Phosphorus (SRP) measurements during two distinct rainfall events in the feeder stream show the occurrence of two clear patterns at different times. In one case, a peak of SRP occurs just before peak flow (Figure 6, top), which results in a clockwise hysteresis loop. During another event (Figure 6, bottom), the SRP response is delayed and occurs after the peak in stream flow, leading to an anticlockwise hysteresis loop. It has been shown that these differences indicate two different rainfall event dynamics, caused by a difference in the delivery of SRP to the stream. In the case of an anticlockwise loop, the SRP source might originate from another, more distant, source or from the contribution of a deeper zone within the soil compared to the clockwise loop. Such changes in behaviour in nutrient delivery is most likely to be driven by differences in rainfall event characteristics, i.e. rain intensity, duration and antecedent conditions.

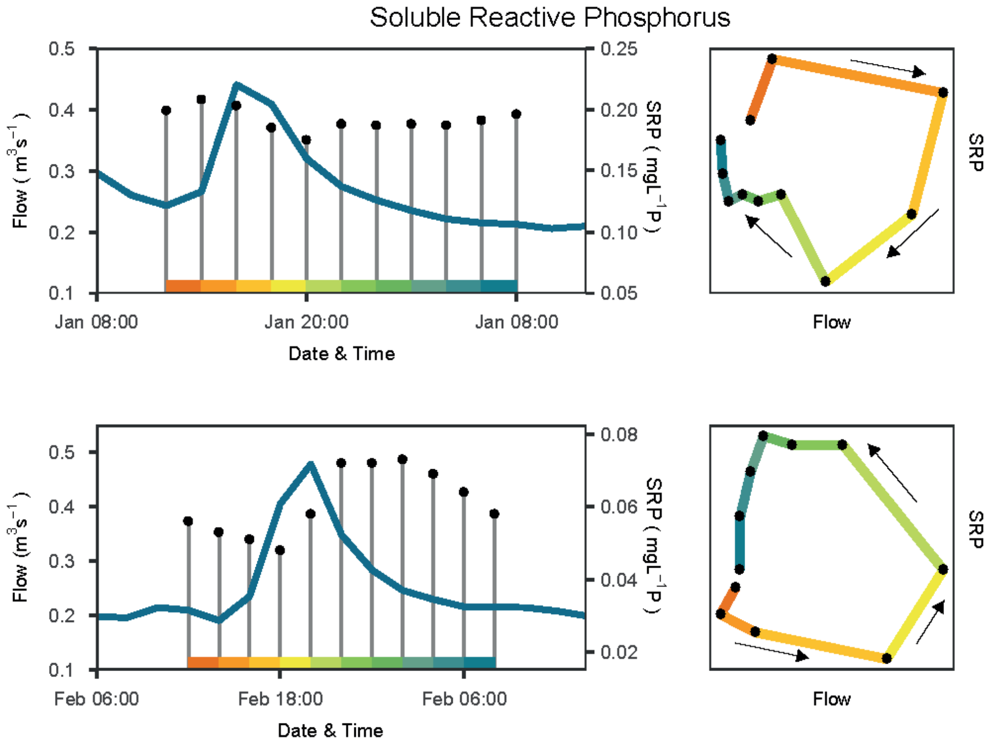


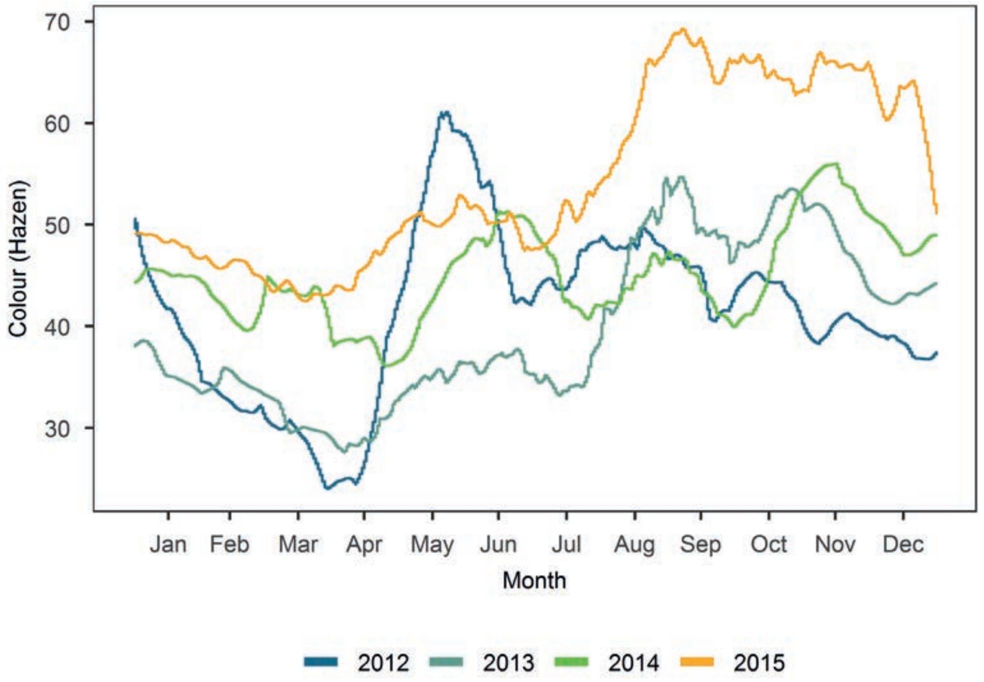
Figure6 Relationship between flow ($m^3 s^{-1}$) and Soluble Reactive Phosphorus ($mg L^{-1}$) during different rainfall events, with associated hysteresis loop.

Seasonality in the reservoir

Using the continuous data collected by SWW at the WTW can give some information on the seasonal variation and inter-annual variability. In particular, daily colour variations plotted throughout the year for 2012 to 2015 (Figure 7) show an interesting pattern: the general occurrence of two peaks of colour a year, the first one in late spring / early summer (e.g. May – June), and the second one, sometimes more sustained, in late summer (i.e. starting in August – September).

There are marked inter-annual differences highlighting the importance of climatic and general environmental factors on water quality, and on colour especially. For instance, 2012 is now considered one of the wettest on record. The impact of such unusual conditions, marked by high rainfall from April to June can be seen by a peak in colour at ca. 60 Hazen. This is due to high rainfall washing contaminants from farmland down the catchment and into the reservoir.

Figure7 Daily colour variations throughout the year between 2012 and 2015 at Upper Tamar Lake raw water.



Upper Tamar Lake; photo by Emilie Grand-Clement.

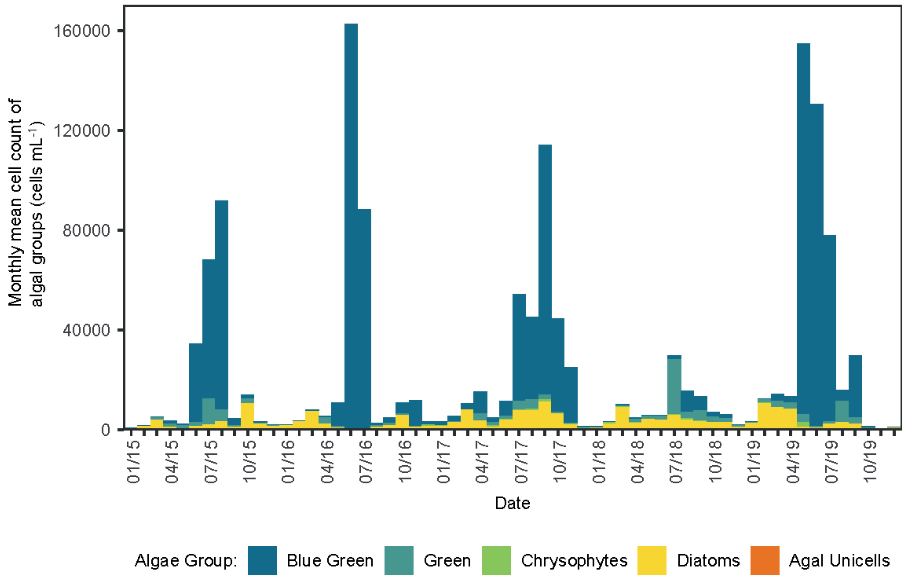


Figure 8 Monthly averages of total algal blooms cell count (cells mL^{-1}) and corresponding abundance of species between 2014 and 2019 at Tamar Lake.

Blue-green algae content in the reservoir

The monthly mean algal counts (Figure 8) as well as measured values across the timeseries (Figure 9) show the occurrence of several algal blooms at Upper Tamar Lake occurring generally in the summer (i.e. June-July). Although a number of outliers were recorded in the dataset (e.g. 300,000 to 500,000 cells mL^{-1}), the peaks in concentrations during blooms tend to be lower, generally reaching up to 200,000 cells mL^{-1}. In later years, algal blooms were also observed to extend into the autumn (i.e. 2017, 2018 and 2019). These blooms are overwhelmingly composed of the toxic blue-green algae species (Figure 9), although diatoms can make a significant part of the total group and are consistently present.

The occurrence of these blooms are often linked to certain environmental characteristics driving algal growth, such as higher temperatures or dry conditions. However, they do not match seasonal peaks in nutrients (Figure 9), as was observed in other locations (see Figure 7 p40): peaks in Total Oxidised Nitrogen (TON) occur in winter, and the seasonal trend in Total Phosphorus (TP) is not clear. It is therefore likely that seasonal variations in algal blooms are largely driven by climate, and the generally high content of nutrient already present in the reservoir. This is a long-term problem that needs to be investigated further by looking at both the nutrient inputs and the overall content already present in the reservoir.

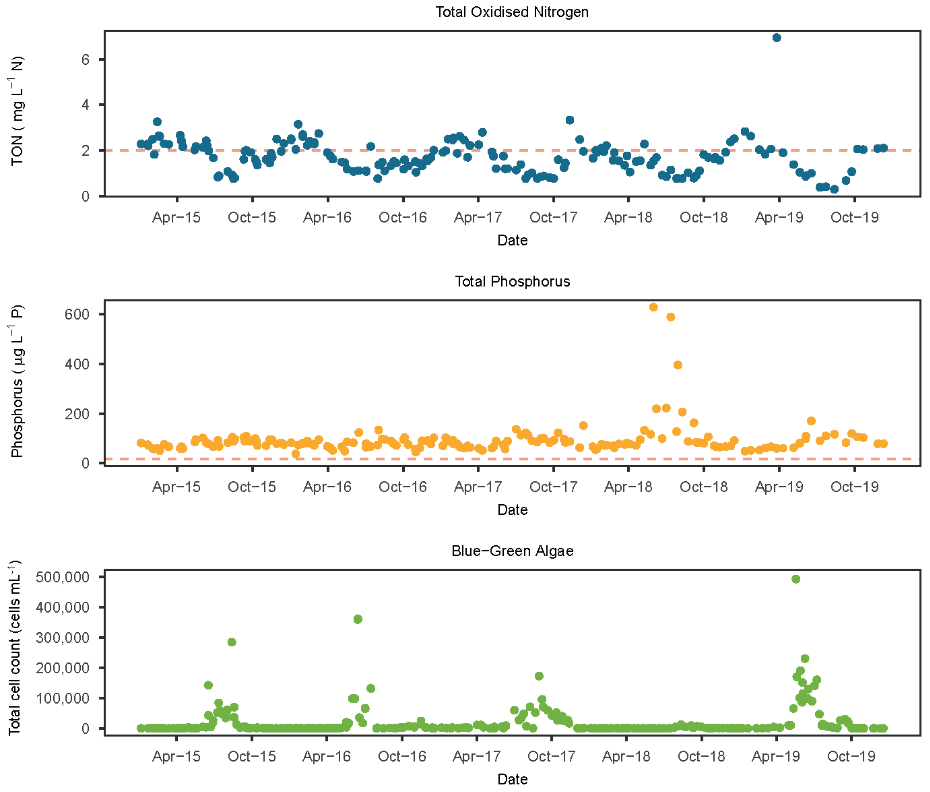
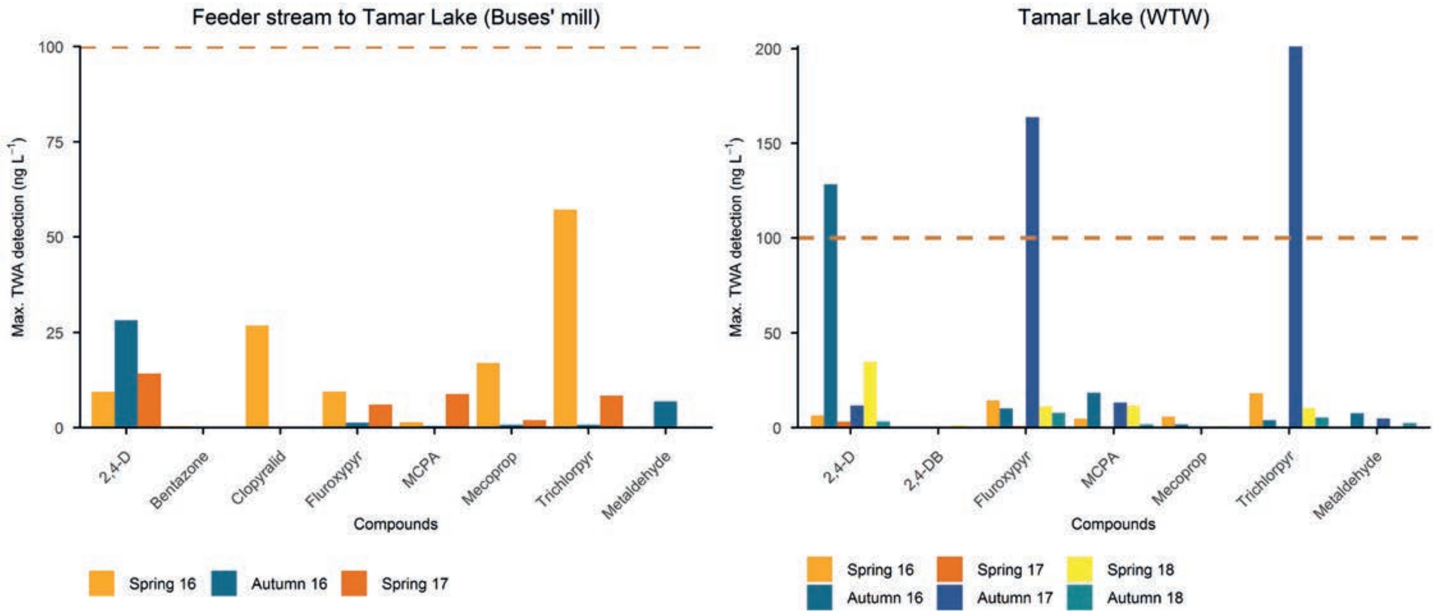


Figure 9 Total Oxidised Nitrogen (top), Total Phosphorus (middle) and blue-green algae cell count (bottom) between 2014 and 2019 in Tamar Lake reservoir; red lines indicate the exceedance limit for each nutrient concentrations.

Pesticide detections within the catchment

Pesticide detections in both feeder stream and reservoir show a high number of compounds being used consistently on intensive farmland in the catchment, with 2,4D, Fluroxypyr and Trichlopyr being detected above the 100 ng L^{-1} in the lake in autumn deployment (Figure 10). MCPA and Mecoprop are also an issue, but to a lesser extent. The autumns of 2016 and 2017 seem to be the most affected times. Overall, the total number of detections (including all chemicals throughout the 6 week period) ranges between 6 and 18 per deployment period. Although there is no obvious decrease during Upstream Thinking, this data helps project partners to understand pesticide sources (i.e. arable farmland), pattern and address its future use in the catchment.

Figure 10 Maximum concentrations (measured as time weighted average) and compounds detected in feeder stream (left) and in Upper Tamar Lake (right) per deployment period, with the red dotted line indicating the 100 ng L^{-1}regulatory limit per pesticide; note the difference in the scales between the plots.



Fencing off ditches at Upper Tamar Lake; photo by Emilie Grand-Clement.

REFERENCES

1. Bieroza, M.Z., and Heathwaite, A.L. (2015). Seasonal variation in phosphorus concentration–discharge hysteresis inferred from high-frequency *in-situ* monitoring. *Journal of Hydrology, 524, 333-347.*

UPSTREAM THINKING IN ACTION: THE RIVER COBER

About the catchment

Background site information

The River Cober catchment (Figure 1 and Figure 2) lies within the Cober and Lizard EA Operational catchment which falls within the wider Cornwall West and Fal EA Management Catchment. It drains a 53.75 km^2 area of West Cornwall. The River Cober (Upper and Lower) itself rises at Nine Maidens Down, winding across Porkellis Moor and passing alongside Helston to reach Cornwall's largest natural lake, the Loe Pool.

Agricultural activity within the catchment is centred around intensive dairy farming, with rough grazing taking place on marginal land. Interventions in the catchments were led by **Cornwall Wildlife Trust** (CWT).

Catchment Challenges

The River Cober was identified as at-risk for pesticides and ammonium. Ammonium has been problematic in the past and can have significant impacts on the water treatment and its cost. The primary source of this pollutant is manure and slurry from agriculture. Concentrations of ammonium can increase rapidly under spate or flood conditions when the sources of ammonium are directly connected to the surface streams and rivers. To deal with this issue, the water treatment works has auto-shutdown facilities in place, which prevent the works from abstracting and treating water when its quality deteriorates beyond certain thresholds. As the security of the water supply is compromised during these periods, it is important that they do not persist for too long.

- The water quality issues in the Cober catchment have been identified as ammonium levels (over 2 mg L^{-1}) and pesticides (MCPA and Mecoprop in particular);
- Ammonium levels were elevated for ca. 1.88% of the time, but the threshold of 2 mg L^{-1} was exceeded in 0.85% of time, adding up to around 74 hours per year (on average across the study period);
- Overall, a positive contribution of Upstream Thinking in the catchment is likely to have reduced the frequency of ammonium detections in the catchment since 2015, as seen in the continuous ammonia signal;
- Use of the Chemcatcher passive sampling devices has shown high numbers of pesticide detections throughout the monitoring period; the regulatory limit of 100 ng L^{-1} per compound and per detection was exceeded on four occasions in the River Cober;
- MCPA and Mecoprop remain present throughout the catchment; metaldehyde has not been detected in the Releath Stream.

Figure1 The River Cober; picture by Emilie Grand-Clement

Catchment Activities

Activities in the Cober catchment started in 2015, i.e. later than some other Upstream Thinking catchments. Ammonium can originate from diffuse and point source pollution and therefore a focus of CWT activity in the Cober catchment was to work with farmers to identify opportunities to improve dirty water management and prevent ammonium runoff. In addition, work was undertaken to improve land management to reduce erosion, buffer run-off and reduce nutrient inputs to the soil and streams.

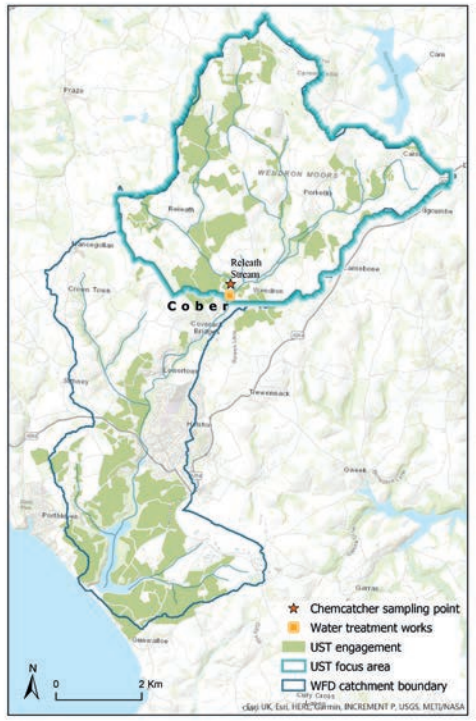


Figure 2 Map of engagement by the CWT as part of UsT in the Cober catchment.

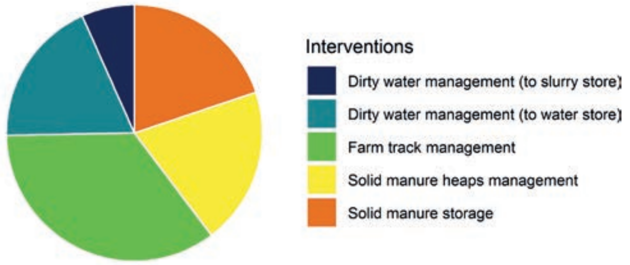


Figure 3 Top 5 interventions (quantified in Farmscoper) used in the Cober catchment.

Figure 2 illustrates the level of farm engagement in UsT2 within the Cober catchment. Whilst the area of catchment engaged appears small (8% of the total UsT focus area), this is mainly because only a small number of farms could be targeted for very specific interventions following identification of key opportunities to reduce ammonium, based on farm type (dairy), proximity to watercourse and land slope.

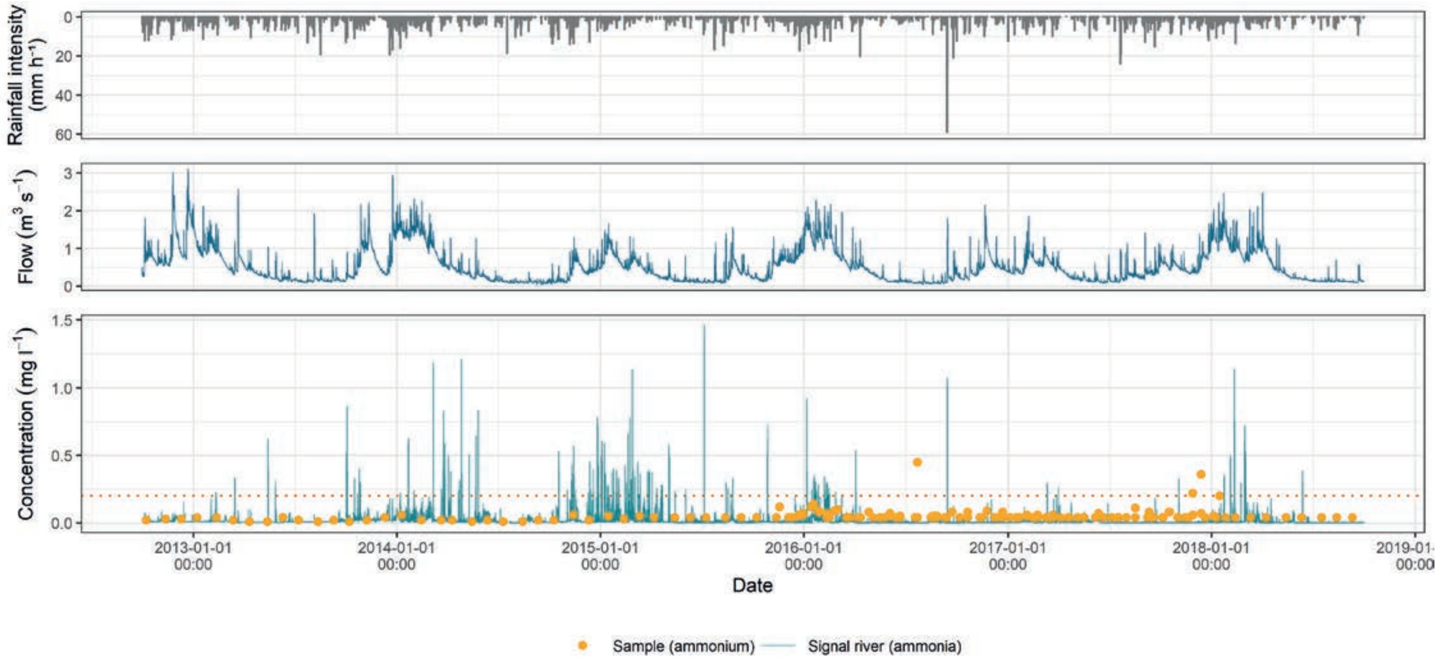
Physical interventions completed via UsT, which were quantifiable within the Farmscoper software, amounted to a cumulative total of 1,026 ha. The most commonly used interventions are shown in Figure 3. They are mostly aimed at targeting nutrients, although farm track management is also thought to have an impact on sediment losses to streams and rivers.

Water quality in the Cober catchment

Ammonium in river water

In the River Cober, the mean concentration of ammonium from samples analysed over the last 15 years is 0.23 mg L^{-1}; in the Releath Stream the mean concentration is 0.094 mg L^{-1}. For the period 2015 to 2018 this drops to 0.044 mg L^{-1} and 0.064 mg L^{-1} for the Cober and the Releath, respectively. Concentrations in the blended raw water at the SWW water treatment works were typically lower, with an average of 0.032 mg L^{-1} over the last 15 years, increasing to 0.047 mg L^{-1} more recently. The median values for sampling points are at or below the limits of detection, showing a positive contribution of Upstream Thinking in the catchment to reducing the frequency of ammonium detections in the catchment.

Figure 4 Timeseries for rainfall, flow and ammonium samples and continuous measurements alongside a threshold (orange dotted line) of 0.2 mg L^{-1}.



High-frequency signals from sensors in the river also play an important role in understanding the behaviour of ammonium. Figure 4 shows the seasonal patterns in flow, ammonium signal, and ammonium samples, with a threshold value of 0.2 mg L^{-1} displayed. Above this level, the works are temporarily shut down to protect the drinking water supply, as such levels are difficult to remove from drinking water.

Values for ammonium are elevated over this threshold for a small proportion of the time (0.85%). Each year these exceedances occur on multiple occasions for short periods of time, adding up to around 74 hours per year (on average across the study period). The signal is elevated for a greater proportion of time (1.88%) over winter in January, February and March (Table 1) and more peaks are seen during these months. Sensor levels for ammonium are, in general, lowest in the summer (July, August and September).

Table 1 Average time per season where the signal exceeds the shutdown threshold of 0.2 mg L^{-1}.

Time Period	Time threshold exceeded	
	Hours	Percentage of time
Winter (OND)	10.6 hr	0.48%
Winter (JFM)	41.3 hr	1.88%
Summer (AMJ)	19.6 hr	0.89%
Summer (JAS)	3.1 hr	0.14%
Hydrological year	74.2 hr	0.85%

Pesticide detection in the Cober catchment

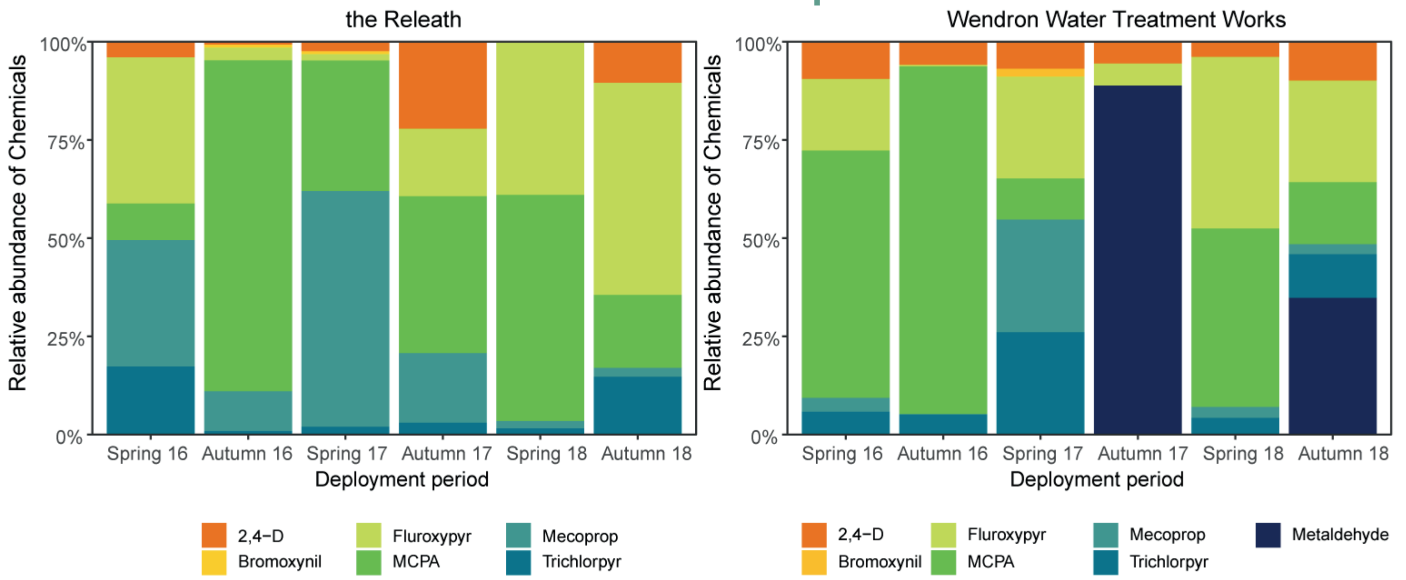
Since 2016, the Cober catchment has experienced a high number of pesticide detections (i.e. between 3 and 16) in all streams monitored (Table 2). This number of detections appears to be slightly lower in the second half of the monitoring period (i.e. between Autumn 2017 and Autumn 2018), with the number of detections in Autumn 2017 being the lowest across all sites.

Table 2 Total number of detections, exceedances above 100 ng L^{-1}, maximum concentrations detected and total number of compounds detected in the river Cober and the Releath stream between spring 2016 and autumn 2018. The blue shading indicates a severity scale separately applied to each parameter, from light blue (low) to dark blue (high).

		Spring 16	Autumn 16	Spring 17	Autumn 17	Spring 18	Autumn 18
Total number of detections	R. Cober (Burras bridge)	N/A	N/A	15	5	8	11
	R. Cober (Porkellis bridge)	15	11	16	3	10	9
	SWW asset - R. Cober	14	12	15	5	12	14
	SWW asset - Releath stream	15	13	14	10	9	8
Exceedances over 100 ng L^{-1}	R. Cober (Burras bridge)	N/A	N/A	1	0	1	0
	R. Cober (Porkellis bridge)	0	1	0	0	0	0
	SWW asset - R. Cober	0	1	0	0	0	0
	SWW asset - Releath stream	0	0	0	0	0	0
Max concentration of individual pesticide (ng L^{-1})	R. Cober (Burras bridge)	N/A	N/A	132	1	197	3
	R. Cober (Porkellis bridge)	92	153	29	1	57	2
	SWW asset - R. Cober	40	110	4	11	9	2
	SWW asset - Releath stream	7	31	27	13	29	3
Total number of compounds	R. Cober (Burras bridge)	N/A	N/A	7	3	4	5
	R. Cober (Porkellis bridge)	5	5	6	2	5	5
	SWW asset - R. Cober	5	5	6	3	5	6
	SWW asset - Releath stream	5	6	6	5	4	5

Similarly, the catchment is experiencing very high single contaminant detections, with values going beyond the regulatory limit of 100 ng L^{-1} on four occasions in the River Cober (e.g. between 110 and 197 ng L^{-1}), one of which was at SWW's water treatment works. Although the Releath Stream has a high number of detections, they never exceed 31 ng L^{-1}.

Figure 5 Relative abundance of compounds detected at SWW water treatment works, with water originating from the Releath Stream (left) and the River Cober (right).



Between two and seven different chemicals were found at each location. Figure 5 shows a comparison between the Releath Stream and the River Cober. The same chemicals are found in both streams, highlighting their usage throughout the catchment. MCPA and Fluroxypyr in particular are found in very high concentrations; the usage of Mecoprop is also consistent across sites and deployment periods but at lower concentrations. All of these compounds can be used in grasslands, which represents one of the main land use types in the catchment. Metaldehyde (the active ingredient found in slug pellets) is the only compound that has been detected in the River Cober (Autumn 2017 and 2018), but never in the Releath. This compound is typically used on edible crops, and may therefore have been used on the 22% of the catchment in arable land. Overall, this data is invaluable information for the Cornwall Wildlife Trust to target pesticide usage in the catchment.


Spring hedge in Cornwall; photo by Sue Hocking (CWT).

UPSTREAM THINKING IN ACTION: THE RIVER FOWEY

About the catchment

Background site information

The Fowey catchment falls within the Colliford Strategic Supply Area, south-west of Bodmin Moor, in Cornwall (Figure 3). SWW abstracts water from the Lower River Fowey for potable supply, with water being fed directly to the water treatment works. Additionally, another abstraction is being used in the catchment (Figure 1). Catchment intervention measures are being delivered by West Country Rivers Trust.

Catchment Challenges

The River Fowey is at risk for pesticides, in particular MCPA and Mecoprop, both used for broadleaf weeds control, and for metaldehyde, a common pesticide against slugs and snails.

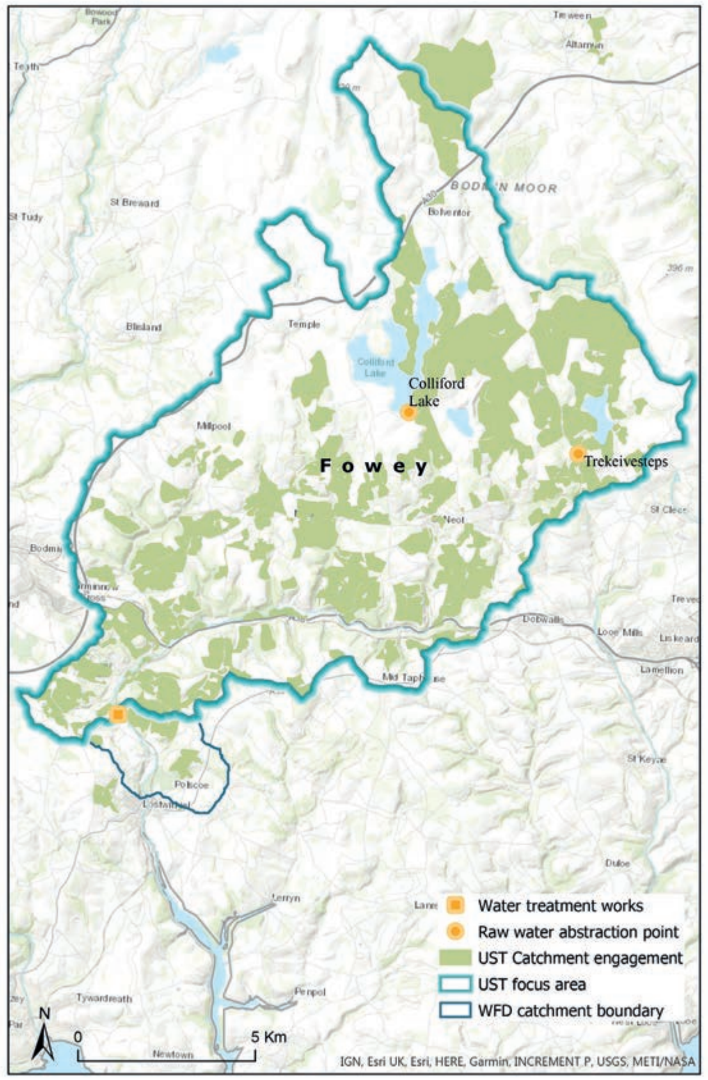
Catchment Activities

Catchment activities delivered through Upstream Thinking 2 have mostly focused on capital grants, such as yard infrastructure to support livestock or dairy enterprises. There have also been pesticide amnesties and support for field trials of alternative methods.

As of May 2019, 33% of the Fowey catchment has been engaged in Upstream Thinking 2 by **Westcountry Rivers Trust** (WRT) (Figure 1), with physical activities focussing on such things as fencing off rivers to prevent livestock access, minimising the volumes of dirty water produced and management of manure. These interventions are known to reduce nitrogen and phosphorus levels in water[1].

- The River Fowey is at risk for pesticides, namely MCPA, mecoprop and metaldehyde.
- Water quality monitoring has also shown a slight decrease in turbidity throughout the 2012-2013 to 2017-2018 period, all flow conditions considered; at low flow the decrease is noticeable for both turbidity and colour, which may be attributable to UsT interventions. As such change is not yet visible at high flows, it is hoped that it will be noticeable after continued engagement and further interventions are implemented in the catchment.
- Although a number of pesticides are detected along the River Fowey and at SWW assets, the he maximum concentration measured in river water (as time weighted average) are consistently below 100 ng L^{-1}, and the total concentration of all pesticides is below 500 ng L^{-1}, thereby fulfilling the Upstream Thinking objectives.
- The frequency of pesticide detections in the raw water in the lower River Fowey has not decreased significantly with time; however, the work carried out has highlighted the most problematic compounds that occur in the river water, enabling project partners to target their actions in the catchment.

Figure 1 Map of engagement by WRT as part of UsT in the Fowey catchment.



The River Fowey at SWW's WTW; photo by Emilie Grand-Clement.

Water quality in the Fowey catchment

Long-term changes in water colour and suspended sediment pollution

When all flow is considered (Figure 2), continuous measurements at the water treatment works in the River Fowey show no significant decrease in colour between hydrological years. However, a slight decrease in turbidity (representing suspended sediment concentrations in water) is observed. More precisely, mean turbidity has been reduced from 7.5 NTU in 2012-2013 to 3.8 NTU in 2017-2018, although maximum values remain the same, with peaks reaching 150 NTU on occasion. Reduction of both colour and turbidity in water is important to reduce primary water treatment costs in drinking water.

When only low flow is considered (Figure 3), both colour and turbidity show a significant decrease between 2012-2013 and 2017-2018: mean colour values change from 15 to 12.9 Hazen, whilst mean turbidity values decrease from 5.4 to 1.4 NTU over the same period. As low flow periods often coincide with high water demand, such results are encouraging, as cleaner water abstracted in the summer months may be less costly to treat. Amongst the interventions used in the catchment, only fencing off watercourses from livestock is likely to have an impact on sediment losses and turbidity, which might explain the small decrease, but also highlights the potential to address these problems more significantly if further measures are adopted across the catchment.

Figure 2 Variations in flow (top), colour (middle) and turbidity (bottom) per hydrological year in the River Fowey between 2012-2013 and 2017-2018, all flow values considered.

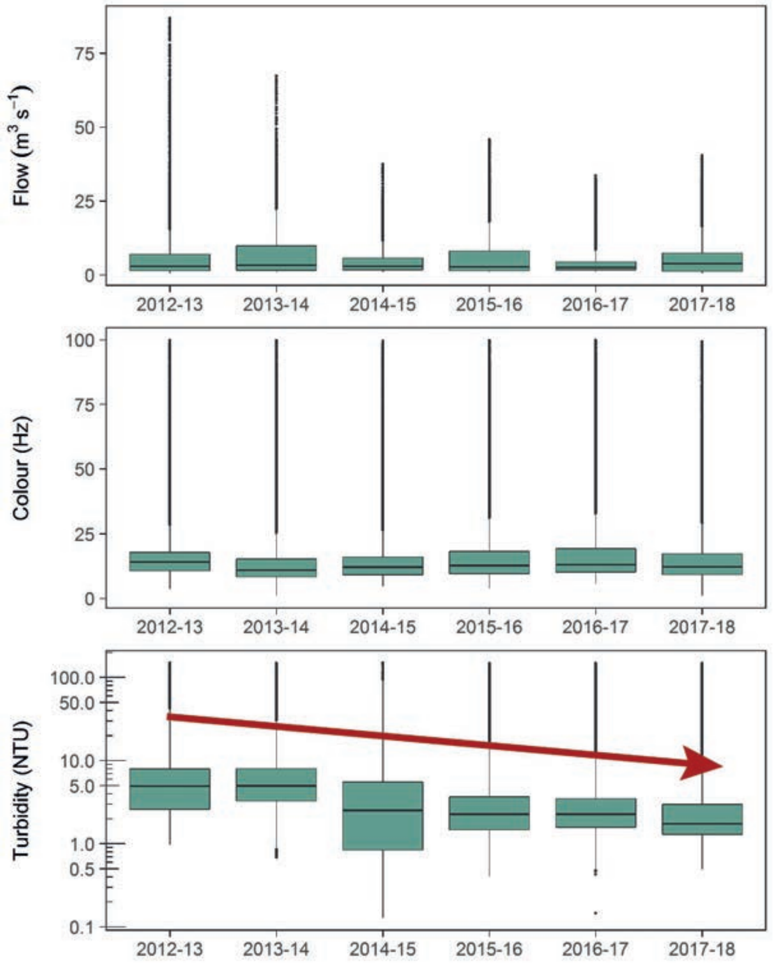
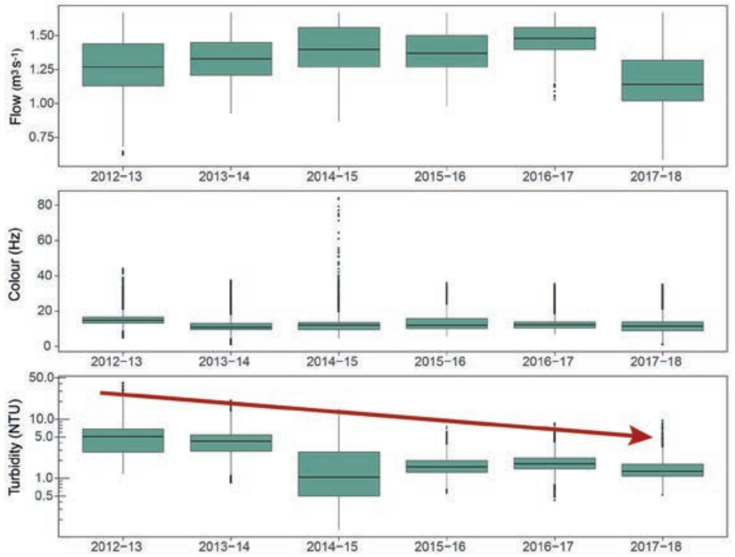


Figure 3 Low flow (≤Q70) variations (top) and corresponding values in colour (middle) and turbidity (bottom) per hydrological year in the river Fowey between 2012-2013 and 2017-2018. The red arrow shows the observed trend between 2012-2013 and 2017-2018.



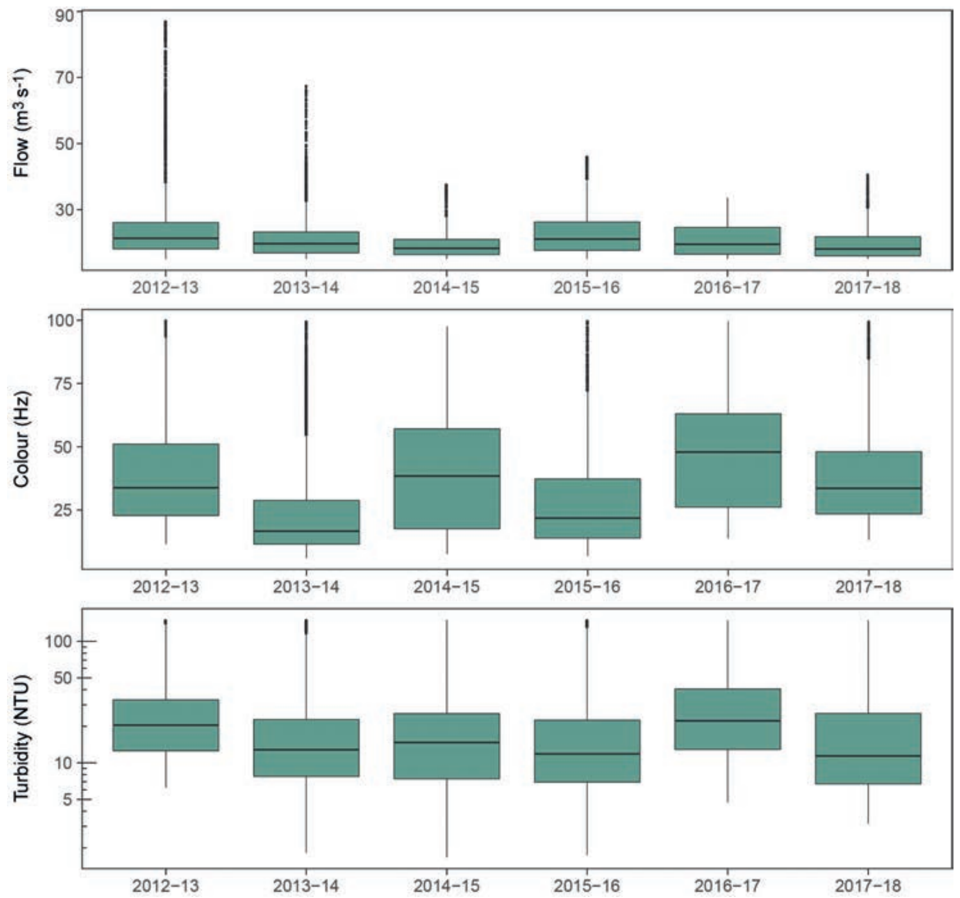


Figure 4 High flow (≥Q5) variations (top) and corresponding values in colour (middle) and turbidity (bottom) per hydrological year in the River Fowey between 2012-2013 and 2017-2018.

However, such change is not observed at high flow (Figure 4), with the difference between years likely due to inter-annual variability. Moreover, high flow conditions are likely to be the most problematic periods for WTWs due to higher diffuse pollution and contaminant concentrations delivered by rainfall events. This lack of change at high flow might indicate that a more extensive range of measures is needed to affect the catchment at large scale.

Pesticide detections within the Fowey catchment

Detections in the Fowey catchment were generally low (Figure 5), with a maximum detection of 35 ng L^{-1} for 2,4-D at the Trekeive steps abstraction point (autumn 2018), and never reached either the 100 ng L^{-1} per compound or the cumulated concentration of 500 ng L^{-1} regulatory limits. Higher concentrations experienced upstream indicate a source of certain compounds higher in the catchment, and a dilution downstream closer to the WTW.

There is, however, no significant change between seasons throughout the project. In fact, the highest detections occurred in autumn 2018, highlighting the need for continued catchment interventions and pesticide amnesties in the Fowey catchment.

In the Fowey catchment; photo by Hazel Kendall (WRT).

Stone bridge on the River Fowey; photo by Hazel Kendall (WRT).

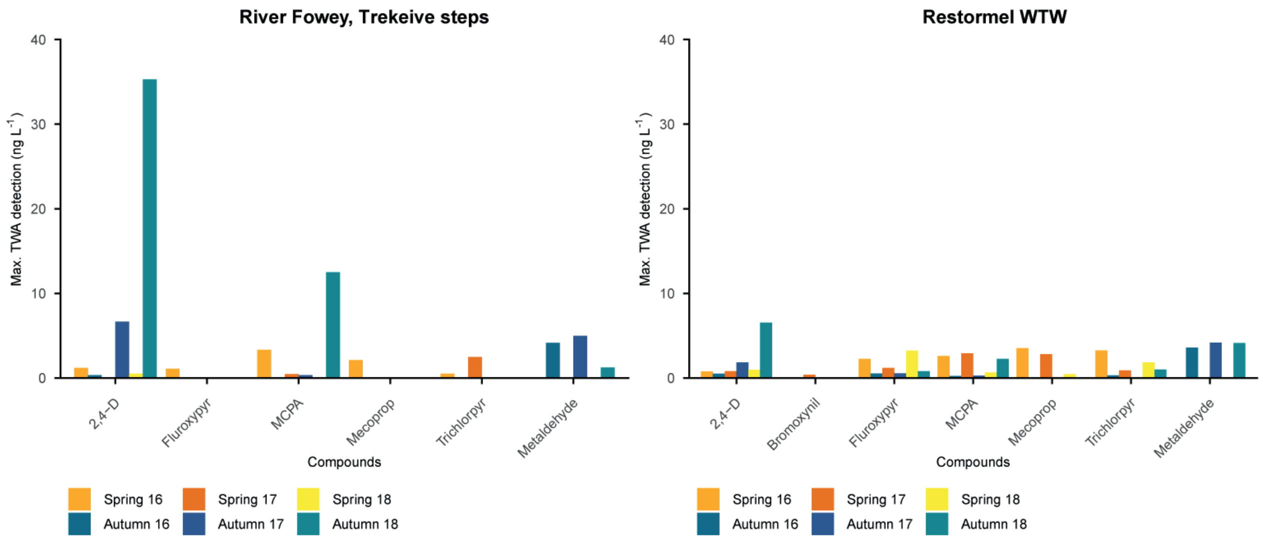


Figure 5 Maximum detections per pesticides as time weighted average between Spring 16 and Autumn 18 in the river Fowey at Trekeive steps (left) and at Restormel WTW (right) during chemcatcher deployment campaigns.

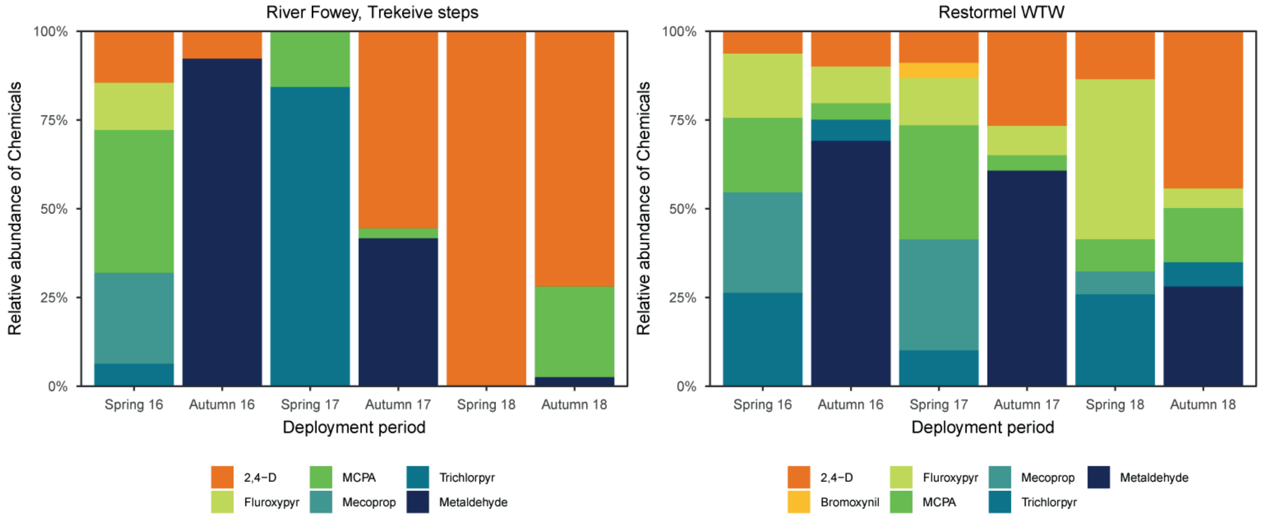


Figure 6 Relative abundance of pesticides found in the River Fowey at Trekeive steps (left) and at Restormel WTW (right) during Chemcatcher deployment campaigns.

Most pesticides in the Fowey catchment are present consistently across most deployment periods and on both locations, such as for example 2,4-D or metaldehyde (in autumn deployments only) as shown on Figure 6. This is a useful assessment of the range of compounds to target in the catchment. For example, MCPA, which had been identified as a particularly problematic compound by the EA between 2009 and 2013, is still detected regularly at the water treatment works, but at low concentrations, whilst Mecoprop (identified as another problematic compound) is being detected during all spring deployments.

The Fowey catchment: a patchwork of woodland, intensive grassland and arable land use; photo by Emilie Grand-Clement.

Most of the pesticides detected at Restormel WTW are also found upstream at Trekeive steps, however their respective proportions vary between deployment periods. Only Bromoxynil is solely found at the WTW, albeit in low concentrations, indicating an intermediate source between Trekeive steps and Restormel WTW.

REFERENCES

1. Cuttle, S.P., *et al.* (2016). A method-centric 'User Manual' for the mitigation of diffuse water pollution from agriculture. *Soil Use and Management*, 32, 162-171.

UPSTREAM THINKING IN ACTION: THE RIVER EXE

- The whole of the Exe catchment is at risk for pesticides (i.e. MCPA, Mecoprop, Chlorotoluron, Triclopyr)
- Turbidity in the River Exe is driven by rainfall events and increased river flow; high turbidity events occur more frequently in winter, reducing across the study period in line with the overall reductions in flow observed.
- Although no pesticide detection reached the regulatory limit of 100 ng L^{-1} in treated water, the number of detections at both SWW drinking water treatment works was high; consistently high and numerous detections in the River Batherm, the River Burn and the River Lowman make them hotspots for pesticides.
- All compounds of concern for the EA are still detected in the catchment apart from Chlorotoluron, highlighting the need for continued work on the pesticide amnesty.

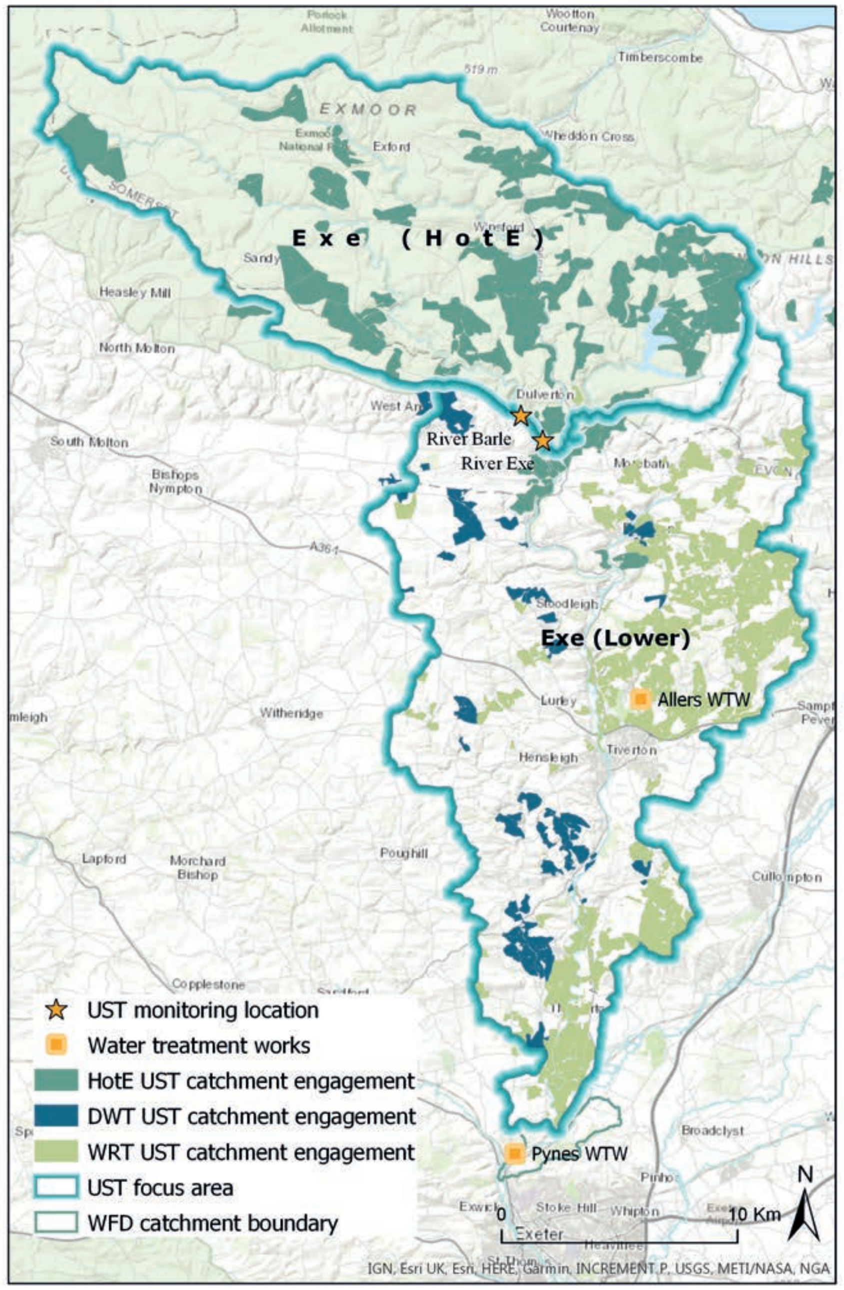


Figure 1 Map of engagement in the Exe by ENPA (through the HotE project), DWT and WRT as part of Upstream Thinking, also showing UoE monitoring locations and water treatment works.

About the catchment

Background site information

The Exe catchment (Figure 1) is within the Wimbleball Strategic Supply Area. The Upper part of the catchment, from the source of the river in the north to Brushford, lies within Exmoor National Park and falls within the **Headwaters of the Exe** (HotE) catchment programme. The catchment covers an area of 27,559 hectares and includes the Rivers Barle, Quarme, Pulham and Haddeo, as well as other smaller tributaries. The area is included in the Devon East Management Catchment and the Exe Main Operational Catchment. The HotE catchment area includes farmland, moorland and some forestry plantations and other woodlands areas. The main land uses in the catchment are upland farming, forestry and game shoots. Recreation and access are also very important in this catchment. Catchment management work for the HotE project was led by Exmoor National Park, with the interventions delivered by **FWAG-SW**.

Further south, Allers and Pynes abstractions and water treatment works provide drinking water for mid-Devon and Exeter, supplying a population of large towns, including Tiverton and Exeter. In both 2015 and 2019, most water bodies in the catchment fell in the Moderate and Good classes of the WFD for their ecological status. For the chemical status, however, there has been a dramatic degradation in the time frame: all water bodies had the "good" chemical status in 2015 but all failed in 2019. The EA states that agriculture and land management is the main reason for this deterioration. Catchment management in the lower part of the Exe was delivered by **Devon Wildlife Trust** (DWT) and **Westcountry Rivers Trust** (WRT)

Catchment Challenges

For the period 2015-2020, the whole of the catchment is at risk for pesticides – particularly MCPA, Mecoprop, Chlorotoluron, Triclopyr, used as a broadleaf weed killer, and metaldehyde (used in slug pellets).

Catchment Activities

Interventions in the HotE project have focused on mitigating sediment loss and reducing pesticides. As of May 2019, almost 30% of the HotE catchment had been engaged in UsT2 with physical activities including establishment of new hedges, farm track management and other works to provide alternative livestock drinking and protect watercourses. Physical interventions completed via UsT, which were quantifiable within the Farmscoper software, amounted to a cumulative total of over 3,500 ha. The most commonly used interventions are shown in Figure 2.

In the lower part of the catchment, activities during UsT2 have focussed on providing advice and guidance to farmers to improve management for pesticides, water quality and water resource issues, and biodiversity. As of May 2019, almost 30% of the Lower Exe had been engaged in UsT2 with physical activities including fencing off rivers from livestock, establishing buffer strips, management of dirty water, farm track management and constructing troughs with concrete bases. Physical interventions completed via UsT, which were quantifiable within the Farmscoper software, amounted to a cumulative area of over 700 ha. The majority of interventions included the building of troughs with a concrete base, which is likely to help reduce sediment loading of waters as well as nutrient loadings. Other commonly used interventions included dirty water and farm track management, in-field grass buffer strips and riverside fencing.

The predicted impact of interventions in the overall Exe catchment on DOC and nitrate is presented (Figure 5 p32).

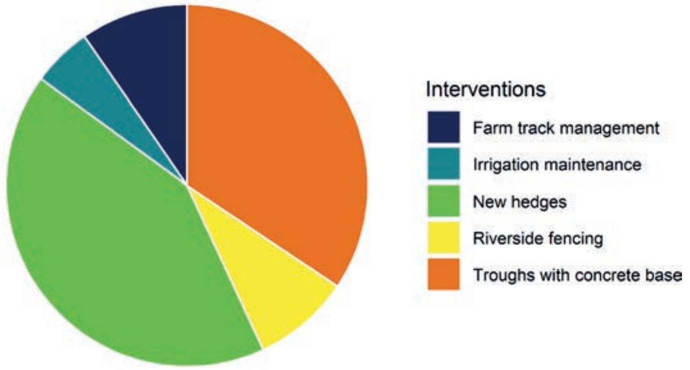


Figure 2 Top 5 interventions (quantified in Farmscoper) used in the Headwaters of the Exe catchment.

The two main rivers in the Exe catchment: The River Barle at Dulverton (top) and the River Exe at Brushford (bottom).

Water quality in the Lower Exe catchment

An understanding of the levels and behaviour of key contaminants in the lower River Exe was built up from spot samples and high-frequency signals at the SWW water treatment works. A summary of the high frequency data for the river water is shown in Table 1. Across all the data collected for this site, the values for the highest colour peaks (occurring alongside peaks in rainfall events) are unavailable, either due to the timings of manual samples or due to the sensor limits for the high frequency data.

Across the study period, the values for the different contaminants generally follow the behaviour seen across the river sites (for more information about these overall patterns see Figure 2 p22.

Parameter	Data completeness*	Min	Max	Mean	Median
Colour (Hazen)	82.5%	0	99.96	10.47	9.19
Conductivity (µS cm^{-1})	91.9%	56.6	366.1	173.12	168.8
Dissolved Oxygen (%)	91.6%	53.08	143.84	94.92	94.92
pH	92.3%	6.002	9.37	7.56	7.52
Turbidity (NTU)	91.5%	0	492.65	9.12	4.45
* Percentage of record with data (after quality control)					

Table 1 River water (Northbridge intake) summary statistics for water quality signals covering the period October 2012 to October 2018.

Seasonal change in water quality

Figure 3 shows the seasonal variation in the signal recorded in the river. Colour values were typically at their lowest in the late winter and spring and highest in late summer. Turbidity values were highest during the wetter hydrological winter, with the exception of the dry winter of 2016 to 2017.

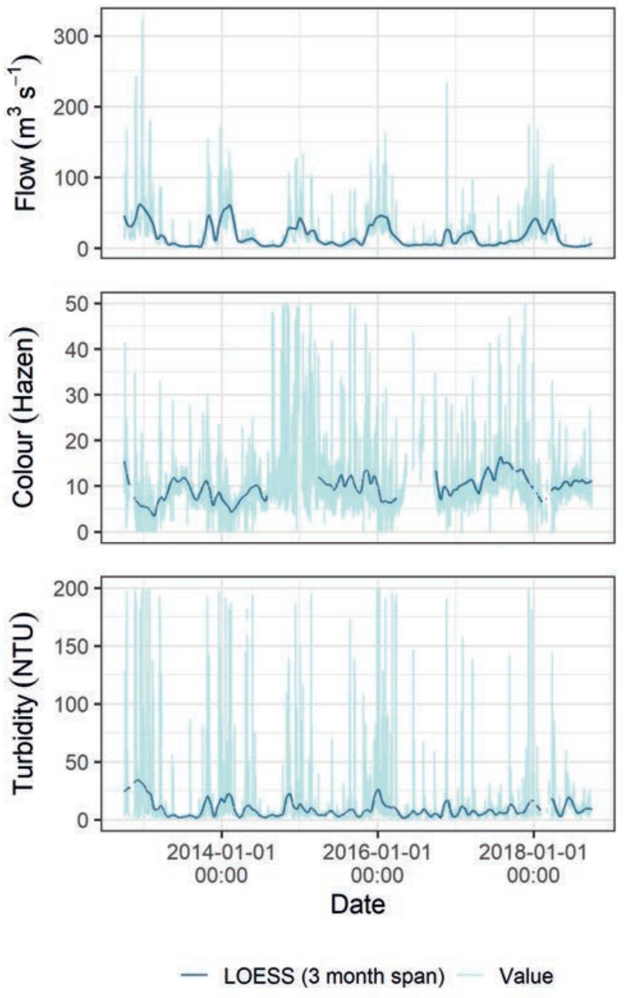


Figure 3 Smoothed and recorded values show annual variation and seasonal cycles for flow, colour and turbidity across the study period. Some of the underlying high-frequency recorded values of colour and turbidity are limited for display purposes.

Field runoff on the road in the Lower Exe (photo by DWT).

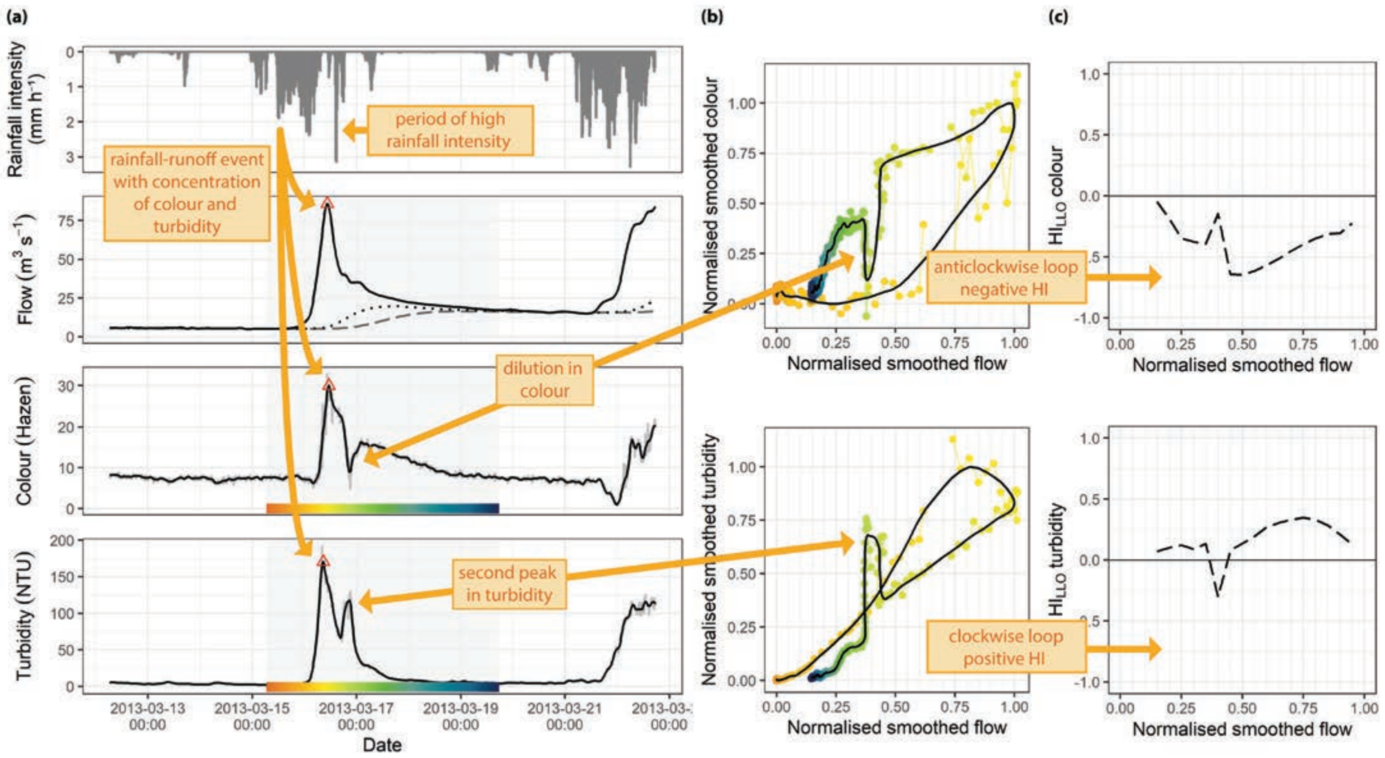


Figure 4 Example of a rainfall event in late winter for the Lower Exe showing (a) time series, (b) hysteresis loops, and (c) the Hysteresis Index calculated across the range of flow conditions for the event.

Water quality during rainfall events

The seasonal patterns for colour and turbidity are influenced by the concentration and dilution effects of the rainfall in the catchment, and the flow conditions in the river. These event scale patterns are related to both contaminant sources and to how they are transported within the catchment.

On the shorter event time scale, the Lower Exe colour displays complex behaviour. Rainfall events are associated with both dilution and concentration, and either behaviour, or both, may be seen during a single flow event. This variability reflects the size of the catchment and the changing dominance of processes affecting overall concentrations in the river. However, even where there are initial dilution effects, generally the highest values for colour still occur after the flow peaks with hysteresis loops formed in an anticlockwise direction. This suggests more distant sources for colour, perhaps from degraded peat in the moorland headwaters of the catchment, or slower pathways for colour enriched waters. Where events show continued concentration effects at the end of the quick flow recession and into the base flow recession, this can also indicate the difference in the transport for colour (throughflow and base flow).

The behaviour of turbidity is more consistent, with all rainfall events analysed showing a concentration effect. For the majority of events analysed the peaks in turbidity occur while the flow in the river is still rising. This 'first-flush' effect is typical for turbidity, and can indicate rapid mobilisation (erosion and transport of sediment) at the start of a rainfall event. The occurrence of the turbidity peak before the flow peak also indicates close proximity to the source (relative to catchment size). However, as there are no notable dilution effects on the falling limb of the events and events often display anticlockwise hysteresis loops, the catchment is not considered to display 'sediment exhaustion'. The continued higher level of turbidity throughout the event, gradually reducing with reduced flows, may represent the transport of sediment from more distant sources^2.

An example of these different behaviours is shown in Figure 5. During this rainfall event there is an initial concentration of colour peaking 45 minutes after the peak in flow. This is then followed by dilution during a period with increased rainfall intensity, but only a small change in flow. There is then a return to higher colour values, gradually decreasing during the remainder of the flow recession. Turbidity also shows elevated concentrations during the rainfall event. However, in contrast, it peaks over an hour before the flow peak, and the increased period of rainfall intensity triggers a sudden increase in turbidity and a second sharp peak. This second peak indicates the occurrence of rapid erosion (such as a bank collapse) or increased transport from nearby sources due to a sudden increase of surface-runoff in a saturated catchment. The behaviour described can also be clearly seen in the hysteresis loops for the event (Figure 4b), and in the Hysteresis Index (HI) values calculated for the event (Figure 4c) with colour response lagging being flow (anticlockwise loop and negative HI), and the turbidity increase occurring more rapidly, but more in-sync with the changes in flow (clockwise loop and overall positive but low HI).

Peaks in turbidity in the River Exe

The annual pattern in the number of turbidity peaks reflects the annual change in peaks of flow. Generally summer peaks in turbidity have a lower magnitude than winter peaks (Figure 5). The overall number of turbidity peaks with a magnitude over the long-term median rose between 2012 and 2018, however there was a fall in the number of peaks in the highest magnitude category (peaks in the top 5% of all turbidity records). Generally, the number of peaks in winter fell, and the reduction in the number of very high magnitude turbidity peaks is pronounced in the early winter months. The number of peaks over the long-term median in summer increased, yet there was no notable increase in very high turbidity peaks during this period.

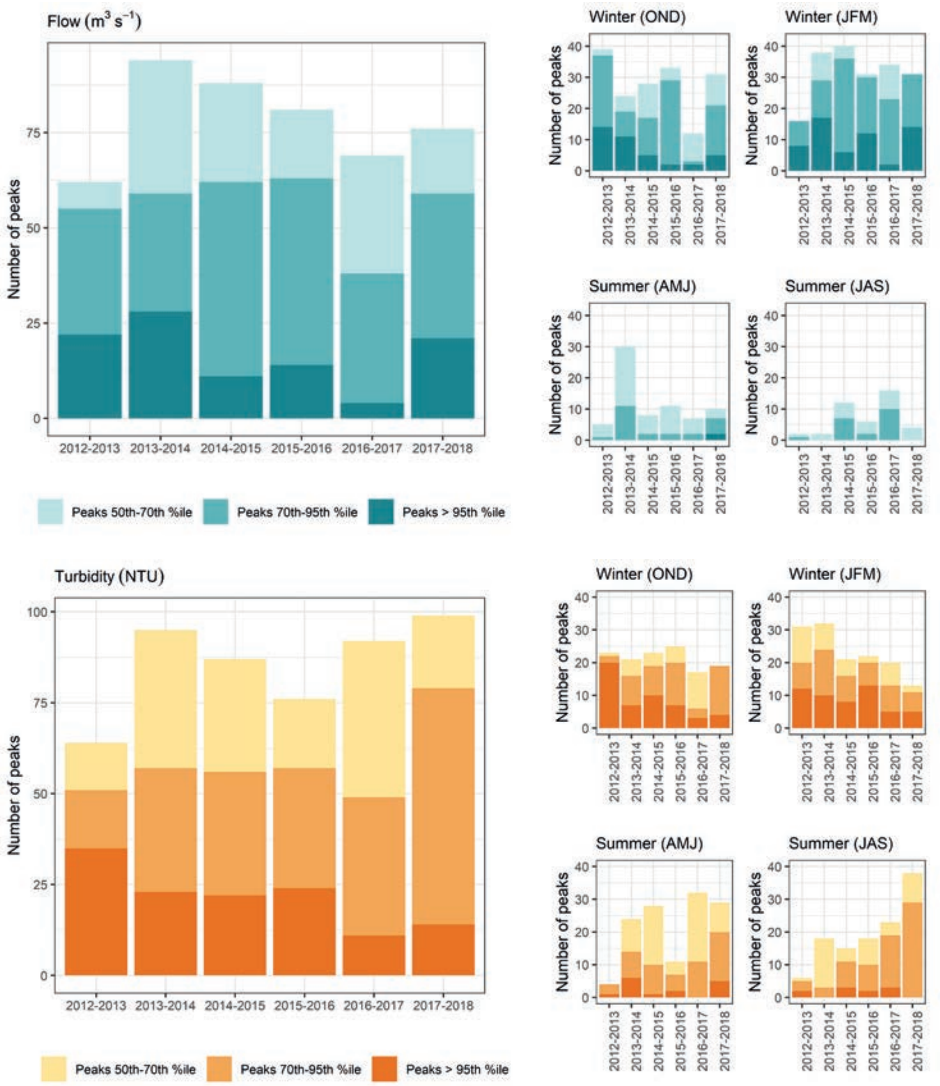


Figure 5 Number of peaks (local maxima) for flow and turbidity exceeding the overall median value; data are presented across the hydrological year (left), and in each of the seasons separately (right).

Grazing in the Exe catchment; photo by Ross Cherrington (WRT).

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		Spring 16	Autumn 16	Spring 17	Autumn 17	Spring 18	Autumn 18
Total number of detections	Allers WTW	10	11	16	8	16	14
	Pynes WTW	19	20	21	14	19	19
Nb single exceedances >100 ng L^{-1}	Allers WTW	0	0	0	0	0	0
	Pynes WTW	0	0	0	0	0	0
Max value (ng L^{-1})	Allers WTW	15	5	9	6	23	3
	Pynes WTW	25	13	15	6	12	6
Total number of compounds	Allers WTW	5	6	6	4	6	6
	Pynes WTW	7	8	9	6	7	7

Table 2 Total number of detections, exceedances above 100 ng L^{-1}, maximum concentrations detected and total number of compounds detected in the River Exe at SWW assets between spring 2016 and autumn 18. The blue shading indicates a severity scale separately applied to each parameter, from light blue (low) to dark blue (high).

Pesticide detections in the Lower Exe catchment

The results of passive sampling monitoring in the Lower Exe are presented in Table 2. Overall the total number of detections on either sites were consistently high throughout the monitoring period (i.e. varying between 8 and 21), with higher values measured further down the catchment, highlighting the contribution of streams located between monitoring locations. Similarly, a number of tributaries within the catchment are hotspots: the River Batherm, the River Burn and the River Lowman have experienced high number of detections (i.e. consistently between 16 and 21 per deployment) but also high detections that frequently go above the 100 ng L^{-1} mark (e.g. 309 ng L^{-1} for the River Batherm in Spring 2018). These high detections are not picked up further down the catchment, where the maximum concentrations (as a time weighted average) recorded reached 25 ng L^{-1} at Pynes WTW, and 23 ng L^{-1} at Allers.

The total number chemicals detected at Pynes WTW is significantly larger than that detected at Allers, with values of 12 and 8 respectively (Table 2). This reflects the nature of the catchment, and the importance of agriculture in the lower part of the catchment, whereas the upper part (i.e. above Allers WTW) is more pastoral. Amongst the compound of concern, only Chlorotoluron was not detected in the catchment; other compounds (i.e. MCPA, Mecoprop, Triclopyr) were present at each monitoring period. Metaldehyde was detected during autumn deployment, which coincides with its prime application period.

Overall, both maximum concentrations measured as time weighted average, and the number of compounds detected in each location indicates that pesticides remains a significant problem in the catchment. Such information is invaluable to justify continued efforts of pesticides amnesty in the catchment.

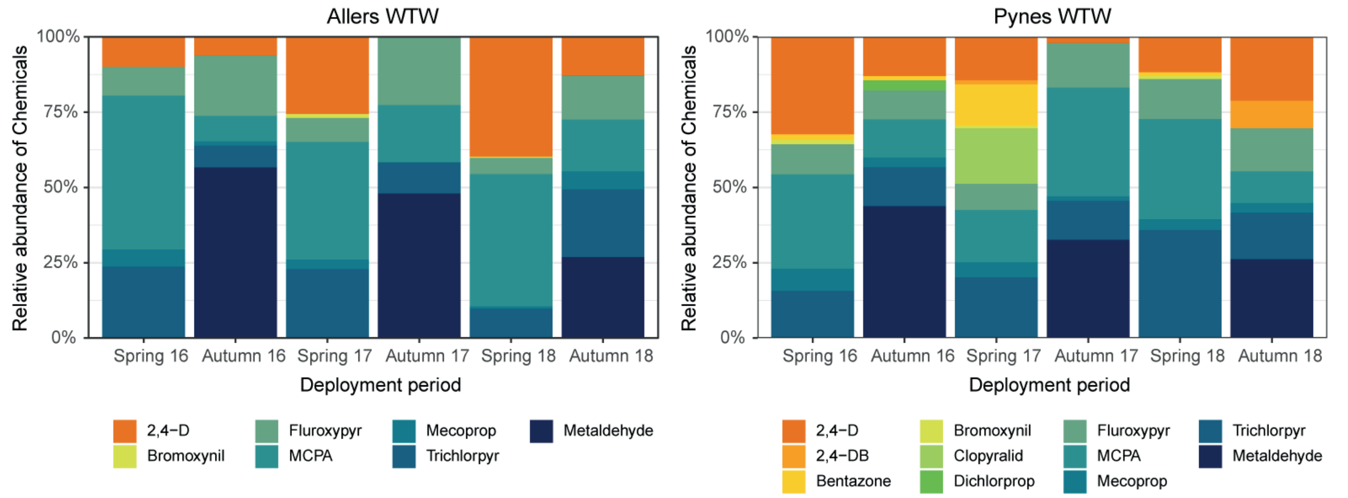


Figure 7 Relative abundance of compounds detected at Allers WTW (left) and Pynes WTW (right).

UPSTREAM THINKING IN ACTION:

THE HEADWATERS OF THE EXE PROJECT - A CASE STUDY

- The sub-catchment of the Headwaters of the Exe (HotE) was used as a case study; monitoring has focused on the outlet of the catchments on the River Barle and the River Exe; results focus on nutrient losses during rainfall events, continuous turbidity and pesticide detections.
- Nutrient levels in the sub catchment tend to be low, although they were significantly higher in the River Exe compared to the River Barle, potentially indicating more extensive diffuse pollution and a greater need for interventions.
- Nutrient losses tend to occur in high flow conditions, i.e. either rainfall events or wetter seasons (for example in the winter)
- Pesticide detections recorded are more prevalent in the River Barle; the number of pesticide detections in spring makes this the more "at-risk" period.
- These results highlight the continued need to implement interventions that can mitigate pesticides loss from land to water.

Context

The Headwaters of the Exe project (HotE) was led by **Exmoor National Park Authority** (ENPA). FWAG-SW was tasked with the delivery of in-catchment interventions, and UoE with the monitoring of water quality. Whilst interventions were examined and modelled at the whole catchment scale (see water modelling section p28), this section details some of the water quality changes that were observed in the sub-catchment over the course of the project, largely focusing on the River Exe (at Pixton gauging station, Figure 1) and the River Barle (at Dulverton; Figure 2).

Figure 1 The River Exe at Pixton gauging station (Brushford); photo by Emilie Grand-Clement.

Figure 2 Continuous sensors on the River Barle at low flow (left) and high flow (right), highlighting different sampling conditions; photos by Paul Henderson.

Water quality change during rainfall events in the River Exe and the River Barle

Contaminant concentrations during rainfall events

In-situ water quality sampling in the River Exe and the River Barle show similar concentrations in DOC and ammonium (NH_4) during rainfall events; however, Total Oxidised Nitrogen (TON) and Soluble Reactive Phosphorus (SRP) were significantly higher in the Exe (Figure 3), potentially indicating more extensive diffuse pollution from agriculture in this sub-catchment. This is, however, concomitant with overall lower flows measured in this river, which tends to coincide with higher TON concentrations.

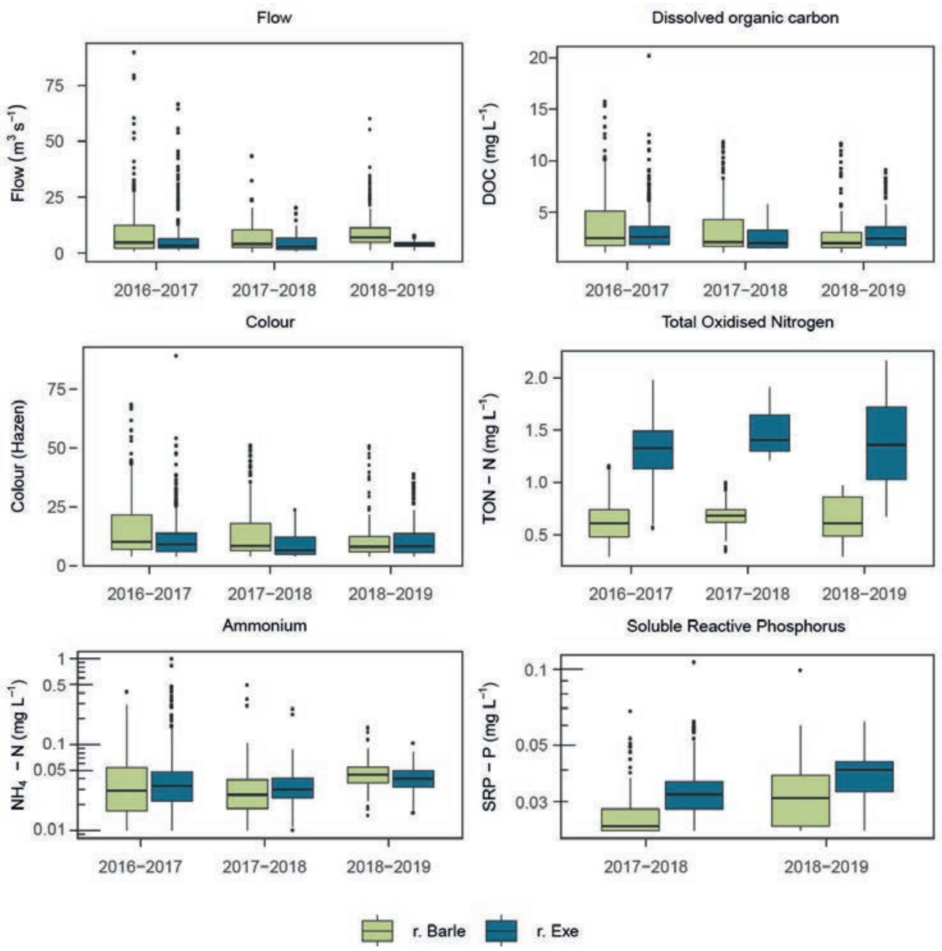
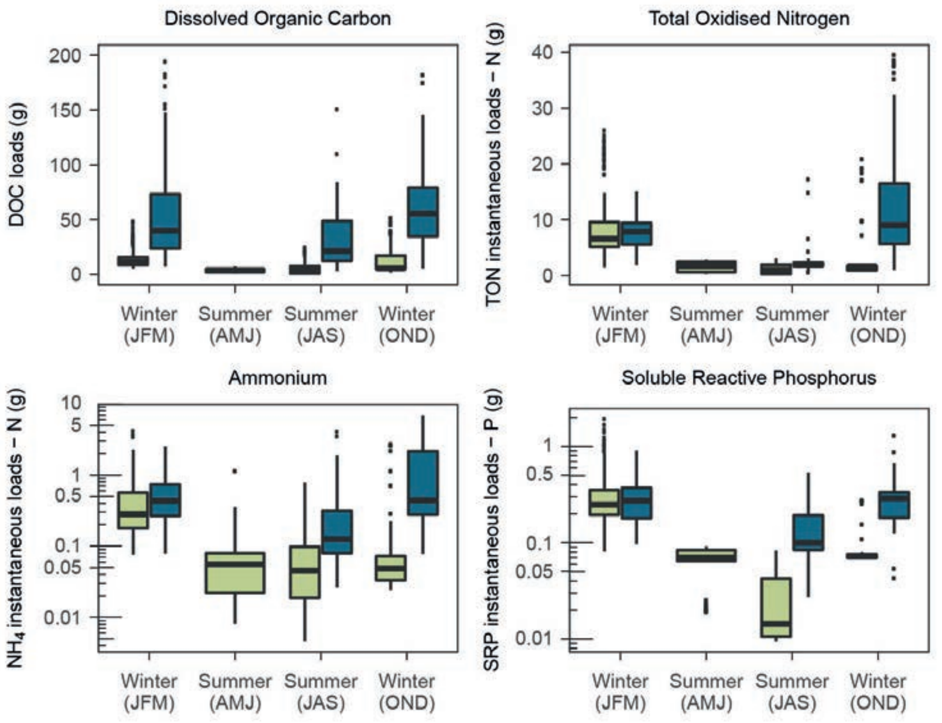


Figure 3 River flow, Dissolved Organic Carbon, Total Oxidised Nitrogen, colour, ammonium and Soluble Reactive Phosphorus concentrations measured at Dulverton and Pixton sites; the top box represents the third quartile and the bottom of the box represents the first quartile, separated by the median.

	Poor		Moderate		Good	
	R. Barle	R. Exe	R. Barle	R. Exe	R. Barle	R. Exe
2017-2018	0.0	0.6	8.4	75.4	91.6	24.0
2018-2019	0.7	0.0	36.6	88.9	62.7	11.1

Table 1 Proportion of the number of samples (%) collected falling within each regulatory limits of phosphate concentrations for poor, moderate and good ecological status for each hydrological year monitored on the River Barle (at Dulverton) and the River Exe (at Pixton).

There is a slight increase in SRP between 2017-2018 and 2018-2019, for both sites. Additionally, results show that a higher proportion of water quality samples fall in the 'moderate status' category in the Exe, compared to the Barle where they are mostly within the 'good ecological status' category, as defined for the Water Framework Directive (Table 1). In addition, the proportion of samples falling into the 'good status' category from the 'moderate status' category between 2017-2018 and 2018-2019 has increased, illustrating that there is a slight degradation in both rivers, for the events sampled.



Seasonal change in different pollutant loads

Instantaneous loads at both sites (Figure 4) show that most nutrient losses occur during wetter, winter months, but also at high flow conditions during other times of the year. This highlights that winter, and wetter conditions, are more "at-risk" periods, and should be considered to tackle water quality improvements.

Figure 4 Instantaneous loads for Dissolved Organic Carbon, Total Oxidised Nitrogen, ammonium and Soluble Reactive Phosphorus per season at Dulverton for the events sampled, with green indicating low flow conditions and blue indicating high flow conditions.

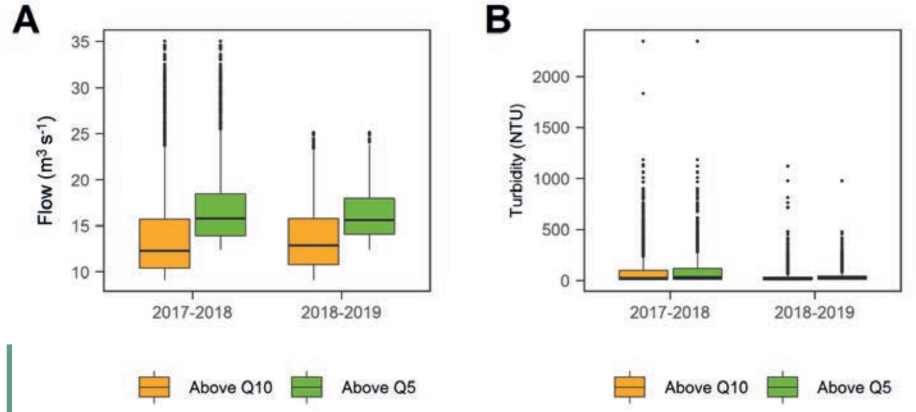


Figure 5 Boxplots representing the variation of flow above Q5 and Q10 (A), and the associated variations in turbidity (B) per Hydrological year in the River Exe.

Turbidity change at high flow

Contamination of freshwaters by sediment, as shown with turbidity data, occurs during high flows. Comparison between the hydrological years measured show no statistically significant change in the flow at both Q5 and Q10 levels (Figure 5). In similar hydrological conditions during subsequent years, there is no statistically significant change in turbidity at high flow, indicating that water quality has not degraded.

Exmoor Ponies at Landacre; photo by Nigel Stone (ENPA).

Pesticide detection in the Headwaters of the Exe sub-catchment

Neither the total number of detections nor the maximum concentrations measured show a clear change between monitoring years at Pixton or Dulverton. Over the six monitoring seasons, the total number of detections per season ranges between 6 and 15 (Table 2). The River Barle tends to experience both higher numbers of detections and higher maximum concentrations per pesticide than the River Exe.

Table 2 Total number of detections, exceedances above 100 ng L^{-1}, maximum concentrations detected and total number of compounds detected in the River Exe (at Pixton Gauging station) and River Barle (at Dulverton) between spring 2016 and autumn 2018. The blue shading indicates a severity scale separately applied to each parameter, from light blue (low) to dark blue (high).

		Spring 16	Autumn 16	Spring 17	Autumn 17	Spring 18	Autumn 18
Total number of detections	R. Barle	15	7	13	6	12	9
	R. Exe	14	9	8	9	13	9
Nb single exceedances >100 ng L^{-1}	R. Barle	0	0	0	0	0	0
	R. Exe	0	0	0	0	0	0
Max value (ng L^{-1})	R. Barle	47	6.9	1.9	31.4	11	6.7
	R. Exe	27.3	3.8	2.2	5	2.3	1.9
Total number of compounds	R. Barle	5	4	5	3	5	5
	R. Exe	6	4	4	4	5	4

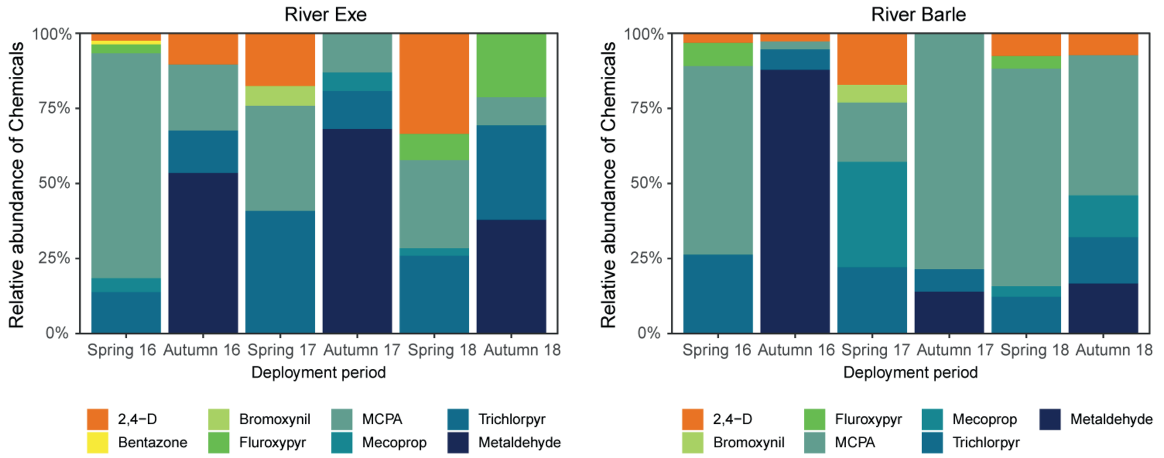


Figure 6 Relative abundance of chemicals found during each deployment period in the River Exe at Pixton gauging station (left) and the River Barle at Dulverton (right).

Spring periods appear to be more "at-risk" than autumn for the number of detections, suggesting that pesticides are more likely to leave the agricultural land and enter the water at this time of year.

All compounds found in both catchments are widely used as broadleaf weed pesticides. MCPA and Trichlopyr are consistently present (Table 2 and Figure 4) during all monitoring periods; 2,4-D and Mecoprop, are also regularly found, but to a lesser extent. Finally, metaldehyde, commonly used in slug pellets, is found during each autumn, corresponding with the prime application time of the chemical on re-seeding grassland.

Sampling on the River Quarme; photo Paul Henderson.

CONCLUDING REMARKS AND FUTURE RESEARCH

Over the past 5 years, scientists at the University of Exeter have monitored the impact of Upstream Thinking, SWW's award winning catchment management project, on water quality. Investigating the impact of 30 different types of interventions on eight water quality parameters in 11 catchments over five years was by no means an easy task. Throughout the project, a wealth of different types of data and information have been gathered, requiring a number of analytical approaches, and giving us some of the answers to the questions initially posed. Of course, the research has also raised new questions, as well as challenged some of the general assumptions about catchment management that prevail, ensuring that continued work in the Upstream Thinking catchments is required to study long-term impacts of the interventions that are now in place.

Changes in water quality in feeder streams to reservoirs: the importance of high flow conditions

Using an analytical approach that considers pollutant inputs during either rainfall events or high flow conditions, we were able to identify some change due to Upstream Thinking interventions. For instance, turbidity (which illustrates the sediment in water) input to Upper Tamar Lake has been significantly reduced during high flow (i.e. flow reached or exceeded 5% of the time, Q5). Such a change is yet to be detected in the reservoir, but potentially shows the positive impact of Upstream Thinking in the tributary which supplies this important drinking water reservoir.

The approach used has also highlighted differences between sub-catchments and confirmed high contributions of diffuse pollution from agriculture from specific locations. Such work is invaluable to justify the need for increased interventions, which target specific agricultural problems in the catchment. This was, for example, the case for the Antron Stream in the Argal catchment that, despite lower stream flow, demonstrated higher contributions of nutrient loadings to the water body, and thus is an area that should be prioritised for future Upstream Thinking interventions.

Data show that algal blooms are the main water quality issue in drinking water reservoirs in the south west of England. We observed discrepancies in the timing and extent of blooms between reservoirs, highlighting the importance of local environmental and meteorological conditions in driving the growth of blooms. Nutrient concentrations during rainfall events (i.e. the main contaminant contribution) were also generally found to be above desired thresholds during a large proportion of the time, thereby contributing to the existing nutrient loading problem already present in the reservoir. Overall, these results highlight the complexity of algal bloom dynamics, especially the need to reduce both the loss of diffuse nutrients from farmland as well as the recycling of nutrients in reservoirs.

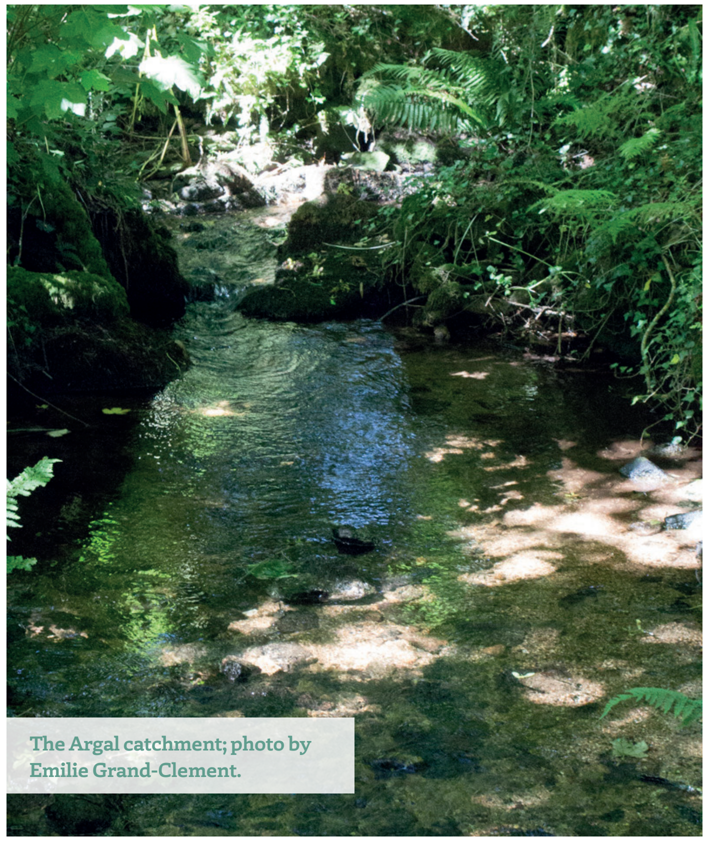
River sites and continuous data: the use of rainfall events to understand change

Investigation of water quality changes at river sites was mostly based on continuous data routinely collected by SWW as a regulatory requirement for their water treatment operation. Across all sites, results highlighted the need for an essential step of critical examination of the quality of the data prior to any analysis. A number of automated and manual data cleaning stages enabled us to identify and effectively remove sensor drift, erroneous data and other sensor issues that may have otherwise biased the conclusions that could be drawn. The quality control approach that we have developed can now be applied to other water quality data collected and across new catchments.

Differences between types of flow in rivers highlighted water quality changes at low flow in certain conditions. For instance, in the River Fowey, turbidity (indicative of suspended sediment levels) at low flow decreased significantly from an annual mean of 5.2 NTU in 2012-2013 to 3.9 NTU in 2017-2018. Although low flow conditions are usually not the main contributor to contaminants in rivers, such change is encouraging for catchment management initiatives, as it shows that interventions can deliver good water quality, wherein sediment pollution is not an issue.

The use of hysteresis loops to study the behaviour of pollutant concentrations in relation to flow during rainfall events has also proven to be an invaluable tool to gain some understanding of the potential origin of pollution at different times. For example, the difference in the direction of hysteresis loops of Soluble Reactive Phosphorus during two distinct rainfall events at Upper Tamar Lake suggest the contribution of two different sources of pollutants.

Finally, seasonal variation has been observed in a number of parameters across multiple catchments, such as the Lower Exe or the Cober. This stresses the importance of considering natural variability in data analysis. Without doing so, the impact of Upstream Thinking approaches might either not be quantified, or might be overstated.



The Argal catchment; photo by Emilie Grand-Clement.

Contamination of water with pesticides and herbicides

The use of passive sampling to monitor acid herbicides and pesticides, such as metaldehyde or mecoprop, has given a good understanding of the extent of pesticide issues in each catchment. Because of the nature of the sampling (i.e. passive samplers deployed over a 6 week period in the spring and 6 week period in the autumn) and the variability in the timing of pesticide usage between years (dependent on weather conditions and crop growth), it is difficult to identify clear change precisely over the course of the Upstream Thinking programme. It was reassuring to observe that, during the monitoring period, the majority of the catchments experienced low concentrations, which are below the target threshold; high concentrations (> 100 ng L^{-1} per compound) were, however, detected in the Cober, Exe and the Tamar catchments. In addition, the use of 'Time Weighted averages' to measure concentrations might also hide the occurrence of short-lived peaks. Therefore, the overall benefit of this work has been in the identification of the compounds detected. Differences between locations within each catchment might also help pinpoint specific issues and help partners address herbicide and pesticide issues, leading to optimal interventions in the next phase of the project.

Predicting change in water quality

Overall, both the SimplyP and SPARROW models have estimated marginal water quality improvement as a result of in-catchment interventions. These results are, to some extent, in agreement with the water quality monitoring conclusions that we drew. There are, however, a number of caveats associated with this modelling work that may have contributed to these low values. First, the difficulty in identifying and classifying interventions in a fixed structure and terminology using the Farmscoper software means that not all interventions could be used in the modelling, thereby leading to a likely underestimation of the coverage, and, in turn, on the modelled water quality changes that might be delivered. A number of interventions also focused on biodiversity improvements, with limited quantifiable impact on water quality, even if this might have occurred. This might have affected certain catchments more than others. In addition, the interventions used to tackle specific on-farm issues might not address parameters included in the modelling.

Extent of the impact of catchment management on water quality

The change in water quality presented in this report is modest. This could be partly due to a number of factors that need highlighting. The duration of the monitoring on the ground by the University of Exeter covered approximately 3.5 years, which is a relatively short amount of time. Additionally, the interventions were not implemented at the same time in all catchments. For instance, they started in 2010 in Upper Tamar, but only in 2016 in the Argal catchment. For these latter catchments, the measured water quality might therefore be more a snapshot of the current situation rather than the result of recent land management change. Upstream Thinking is also only one of the funding streams available for catchment management, which means that the overall extent of the work in each catchment might be larger than what has been quantified in this study and vary between locations. However, this could not be captured within the scope of this study. Finally, no control catchment could be used, as there are no similar catchments (i.e. land use and climate) where no interventions were taking place through any other funding streams that water quality could be compared to.

As improvement in water quality due to Upstream Thinking is generally slow to be noticed, the small changes monitored and predicted across the region highlight the need for cumulative interventions and high coverage within each catchment, and make the case for sustained efforts and continued funding for this work.

Future work: 2020-2025 and beyond

The success of Upstream Thinking in working with project partners to invest in improving water quality and environmental conditions has led to the continuation of the project, now into its third phase. The ambitious new phase over the 2020-2025 period aims to deliver 50,000 ha of interventions in a total of 15 catchments. In addition to improving raw water quality, the project also focuses on promoting landscape restoration and ensuring the long-term resilience of water supply under changing climates. Looking forward, this new phase will be matched by a new monitoring programme that will continue to investigate the impact of in-catchment interventions on water quality and improve the current way of working. Additionally, the results presented here have led to the identification of other avenues to explore, as explained below.

Improved recording of intervention mapping

As presented in the work here, quantification of interventions required their re-classification into the specific Farmscoper software mitigation measures. Due to the wide range of options available and the different definitions used by project partners this proved challenging. To address this and to develop a more unified method moving forward, a change in practice has been developed across the project for the next phase of Upstream Thinking (2020-2025). Through the NERC-funded SWEEP programme, the **Whole Catchment Water Management project** is working with SWW and the UsT Delivery Partners to develop a new on-line spatial recording tool and associated methodology for recording and reporting the location and extent of interventions within catchments. The tool will provide a unique and unified method for all partners to record their activities and provide integrated, spatially explicit data on interventions that will facilitate efficient analysis of their impact on water quality and quantity throughout the next phase of Upstream Thinking, as well as the planning and modelling of the next business plan activities and outcomes (PR24).

Dynamics of reservoir water quality

The bulk of the monitoring work and sample collection in Upstream Thinking 2 has focused on the nutrient inputs to reservoir sites for a number of sites affected by eutrophication and algal blooms. Whilst this approach enabled us to identify changes in the inputs to the reservoir as a result of catchment management, reservoir dynamics ultimately impact on water quality in the water body, and therefore on treatment. In light of the work presented here, increased research on within reservoir dynamics in Southwest England where algal blooms and taste and odour compounds are recurrent issues, is essential to ensure the resilience of the water supply in the region, and will be an important focus of the work carried out in the next phase of Upstream Thinking. This work will also benefit from the addition of a number of catchments in the project.

Emerging contaminants

One of the issues of concern highlighted by the Upstream Thinking programme was herbicide and pesticide detections and usage in catchments. Our work highlights the need for further monitoring of these chemicals and development of this field of research to expand our understanding of a wider breadth of compounds, such as the use of new, emerging contaminants. These compounds are chemicals that have been detected in water bodies, that may cause ecological or human health impact, but that are not yet regulated for and, therefore, do not yet need to be treated out of drinking water. However, as awareness is raised and detection methods improve, it is likely that such compounds will need to be removed during treatment in the future. An understanding of the extent of the problem in the South West would facilitate that step.

Understanding the water treatment process including cost:benefit analyses

One of the concepts behind Upstream Thinking is the idea that investing in catchment management upstream can deliver a number of environmental benefits and improve water quality downstream. Such improvements have the potential to lead to a cost saving for the water industry, as less treatment, energy and chemicals are required to produce drinking water. The few attempts at such estimation[1,2] have highlighted the complexity of such evaluation. This is partly due to the number and variety of parameters to consider (e.g. specific operational factors, uncertainty in quantifying water quality change, regulatory context). We therefore aim to use and build upon our existing knowledge to gain a better understanding of such change in support of cost:benefit analyses of the future Upstream Thinking programmes.

Long-term changes in water quality

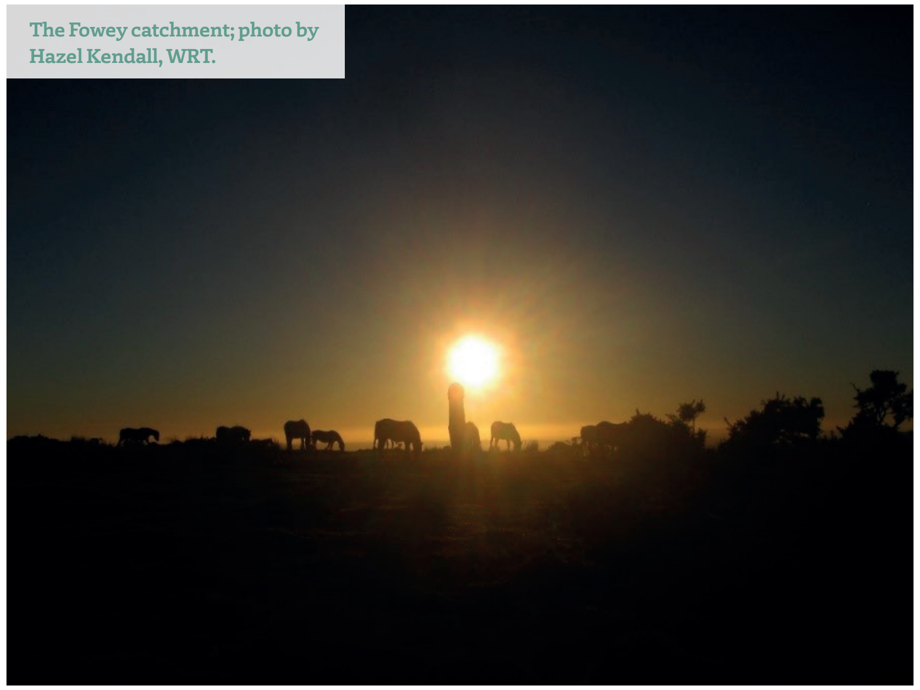
The focus of the project has been to investigate the impact of interventions occurring over a relatively short timescale, i.e. the past 5 years. However, previous research has shown that water quality change may occur at a scale occurring well beyond the scope of the project. For instance, most parameters show a delayed response in their recovery: certain parameters may take decades[3,4], whilst some may get worse initially before getting better[5,6]. Inter-annual variability might also blur the picture, i.e. what is perceived as change might actually reflect the impact of a dry year or of climate change.

The work presented here makes a very strong case for both continuation of interventions to ensure best-practice in the catchment and cumulative benefits, but also for long-term monitoring to identify change at the appropriate timescale. This work will take place in the next phase of the project that will see continued efforts in the current catchments with an additional 5 catchments, and an investigation of the change of a wider number of contaminants delivered through a planned £14.5m of interventions.


Devon sunset; photo by DWT.


A stream in the Argal catchment; photo by Emilie Grand-Clement.


The lower Exe; photo by DWT.


The Fowey catchment; photo by Hazel Kendall, WRT.

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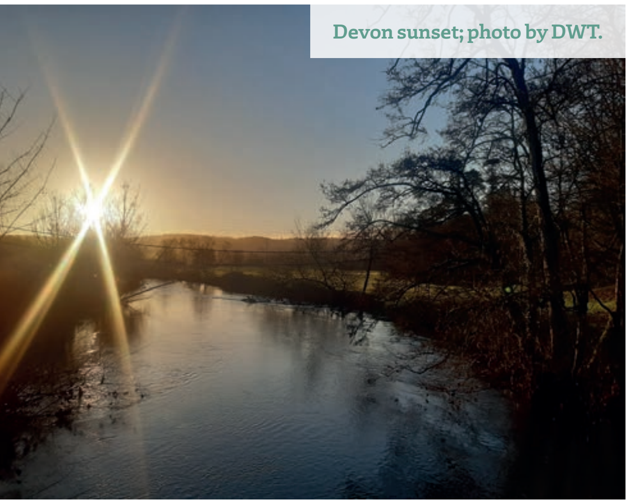
APPENDICES


Devon sunset; photo by DWT.


Maize compaction; photo by DWT.


Sheep farming in Devon; photo by DWT.

Caveats to modelling work

The results from the modelling work reflect an estimated change in the load on a number of parameters using interventions that could be quantified in the Farmscoper software. The following specific caveats apply which may have led to an underestimation of water quality change:

- Some interventions could not be classified for use in Farmscoper as the descriptions were too vague, or if the interventions were for ecological applications rather than water quality
- SimplyP calculates the change in dissolved soil phosphorus (P) based on the ratio of the natural soil P and the agricultural soil P, however sometimes the agricultural soil P is lower than natural soil P which causes the model to fail. As a result, soil P for agricultural and natural land was assumed to be equal to the mean agricultural and natural soil P for all UST catchments
- Applying the effect of interventions for P to SimplyP was complicated in that the actual mechanism wasn't always accounted for in SimplyP (e.g. incidental losses). The effect of interventions had to be applied to the sediment loss factor for interventions that affected erosion processes and applied to the agricultural inputs of P factor for all other interventions.
- For SPARROW, annual loads were calculated by interpolating concentrations between sampling events using river flow as a proxy. However, flow gauges were not always in the same location as the water quality gauge, in fact sometimes the distance between these two types of gauges was quite large. This has implications as to the accuracy of the annual load estimates. However, given that the temporal resolution is daily, it is likely that the actual shape of the flow hydrograph at the water quality gauge would be similar to that of the estimated flow.
- Precipitation for SimplyP was obtained from rainfall radar data, which has been shown to differ from observations, particularly in small catchments. However, this data is the best available.
- For DOC, it wasn't possible to converge on a parameter for degradation with reservoirs, this is likely because there wasn't sufficient water quality data for DOC. As a result the effect of reservoirs wasn't accounted for within the DOC model.
- The effect of reservoirs is also not accounted for in the SimplyP model; however this was determined to be insignificant during tests within the model. This is likely to be because of the relatively small area impounded by the reservoirs in UST catchments.
- For SimplyP, river slope was required, which was calculated from elevation data. However, the elevation data is rounded to the nearest metre, which has implications for the calculation of slope on relatively short stretches of river and/or flat areas.

Abbreviations

AMP6	Asset Management Planning, phase 6 (i.e. 2015-2020)
CWT	Cornwall Wildlife Trust
DOC	Dissolved Organic Carbon
DWT	Devon Wildlife Trust
EA	Environment Agency
ENPA	Exmoor National Park Authority
FWAG	Farming and Wildlife Advisory Group
HotE	Headwaters of the Exe project
MIB	2-Methylisoborneol
NH_4	Ammonium
NTU	Nephelometric Turbidity Unit
SRP	Soluble Reactive Phosphorus
SWW	South West Water
TN	Total Nitrogen
TON	Total Oxidised Nitrogen
TP	Total Phosphorus
UoE	The University of Exeter
UsT	Upstream Thinking
WFD	Water Framework Directive
WRT	Westcountry Rivers Trust
WTW	Water Treatment Works

Sheep farming in the South West; photo by DWT.

River fencing; photo by Martin Ross, SWW.

Definitions and concepts

Catchment

Area defined as receiving rainfall flowing into a specific water body. In the context of Upstream Thinking, catchment boundaries also define the area of intervention by project partners around a water body (river or reservoir) of interest.

Contaminant loading

Loads are the physical mass of contaminant carried by a water body at any given time. They are calculated by multiplying concentration (usually expressed in mg L^{-1}) by the volume of water.

Eutrophication

This process occurs when a water body is overly enriched in nutrients (i.e. forms of nitrogen and phosphorus) generally originating from overland runoff. Excess nutrients leads to an overgrowth of phytoplankton (e.g. algae and diatoms), and depletion of oxygen in the water. This process changes the dynamic of the reservoir and has harmful consequences on aquatic life and the production of drinking water.

Farm plan

Document established by a farm advisor that contains recommendations and costed actions which, if implemented, could improve land management, soil heath and therefore, water quality.

Farmscoper

Decision support tool that can be used to assess diffuse agricultural pollutant loads on a farm and quantify the impacts of farm mitigation methods on these pollutants.

Feeder stream

Stream or tributary providing an inflow of water to a reservoir or a water body.

Flow duration curve

Flow duration curves are used in hydrology to understand the occurrence of various types of flow over a given timescale. They are built by ordering recorded flow values by order of magnitude and subdividing them according to the percentages of time during which specific flows are equalled or exceeded in a given period. Examples of a flow duration curve can be found on Figure 9 p18.

High flow

Period of elevated flow in water body in response to rainfall.

Hydrological year

A hydrological definition of a period of 12 months starting on the 1st October and ending on the 30th September that coincides with the natural progression of hydrologic seasons: in the UK, the hydrological years starts with the early winter rain and increasing river flows, then covers any snow and snowmelt. Rain and river flows typically decrease moving into the spring and summer months. The year ends with the period covering the lowest river flows, but some intense storms, in summer (July, August and September).

Low flow

Flow of water corresponding to dry period or droughts.

Rainfall event

Contained period of continuous rainfall causing overland flow in the catchment, and resulting in a rise and decrease of level in the receiving water body. Rainfall events are critical times for water quality, as overland flow will wash contaminants down from the catchment, leading to increased diffuse pollution.

River flow

Discharge of water in a stream or river expressed in cubic meter per second.

SPARROW

Statistical water quality model used to estimate the annual load of any contaminant from point and diffuse catchment sources; in the present work, it was applied to model and map DOC and nitrate loadings in UsT catchments.

SimplyP

Process based water quality model used in UsT to estimate the concentration and load of suspended sediment, total phosphorus and soluble reactive phosphorus.

Soluble Reactive Phosphorus (SRP)

Phosphorus can exist in many forms; SRP is a measure of orthophosphate, which corresponds to the inorganic soluble P fraction that can be used by plants.

Time series

Dataset comprising a series of data points (i.e. measurements) indexed or plotted in time order, usually taken at equal time interval.

Time weighted average (TWA)

Concentration of compound define as an average over a period of time. Such calculation is particularly used in passive sampling for pesticides where the absorbance of the compounds to the receiving disk changes with time. TWA typically provide a good view of the typical concentrations but hides potential troughs or spikes in contaminants concentrations.

Total Phosphorus (TP)

Measure of all forms of phosphorus that can be present in water, i.e. dissolved and particulate.

Upstream Thinking

Evaluating the impact of farm interventions on
water quality at the catchment scale

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Landscape of the Fowey catchment;
photo by Emilie Grand-Clement.