Institution: University of Bristol	
Unit of Assessment: 14) Geography and Environmental Studies	
Title of case study: Influencing policy and management to control nutrient enrichment in inland and coastal waters	
Period when the underpinning research was undertaken: 2000 - 2020	
Details of staff conducting the underpinning research from the submitting unit:	

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by HEI:**
Professor Penny Johnes	Professor of Biogeochemistry	01/2014 - present
Professor Jim Freer	Professor of Hydrology	09/2008 - 07/2019
Dr Charlotte Lloyd	Royal Society Research Fellow	01/2012 - present
Dr Gemma Coxon	Lecturer in Hydrology	01/2012 - present

Period when the claimed impact occurred: 2014 - 2020	
Is this case study continued from a case study submitted in 2014? No	

1. Summary of the impact

Working in partnership with stakeholders from international to local (operational) scale, we have produced new methods, models, monitoring techniques and evidence to underpin policy and management of nutrient-enriched waters in the UK and internationally, supporting:

1. **UK policy development and management** to control nutrient pollution in UK waters (Defra, Natural England, Environment Agency);
2. **International policy development** and implementation to address the associated environmental and human health challenges (OECD, UNECE);
3. **Scrutiny of UK government policy and practice** (House of Commons Environmental Audit Committee, and Environment, Food and Rural Affairs Committee); and
4. **Operational planning by the environmental and water sectors** to meet environmental quality requirements under the EU Directives and the AMP (Asset Management Planning) process (Natural England, Wessex Water, Welsh Water, Scottish Water).

2. Underpinning research

Growing global demand for food production and water resources have increased nutrient (nitrogen (N) and phosphorus (P)) inputs to waters. Nutrient-rich fertilisers and manures flushed from farmland to waters, and sewage effluents discharged to waters generate adverse impacts on ecosystem and human health. These include the formation of harmful algal blooms, loss of biodiversity, closure of waters for amenity and recreation use, and the release of greenhouse gases to the atmosphere. These impacts generate significant costs, in real term costs of fertilisers lost from agricultural systems, environmental damage costs to terrestrial, freshwater and marine ecosystems, and external costs for water companies, recreational water users and the public **[a]**. The *European Nitrogen Assessment (2011)* estimated EUR18 billion of fertilisers are lost annually to EU27 air and waters, while the *'Our Nutrient World'* report (2013) estimated USD2 trillion external costs to society worldwide from environmental damage arising from N use alone. The UK Government 2016 Impact Assessment for its 2015 *'Consultation on new basic rules for farmers to tackle diffuse water pollution'* costed their total net value at GBP440 million; and in one of our research catchments Wessex Water have estimated the infrastructure costs of improving P removal from their discharges to one river to be GBP30 million, with GBP2 million annual ongoing operational costs **[j]**.

Nutrient enrichment of waters has been addressed by University of Bristol research under the Defra Demonstration Test Catchments (DTC, 2010-20), NERC DOMAINE Large Grant (2014-19) and Environmental Virtual Observatory (EVOp, 2010-2014) programmes, and in directly commissioned research for stakeholders (2016-2020) **[j]**. This body of work, made possible by the unique combination of facilities, expertise and collaborative opportunities in the University of Bristol's Biogeochemistry Research Centre, High Performance Computing Facility, and Cabot Institute has determined the:

- nature, origins and ecological significance of nutrient flux to waters in catchments of differing environmental character across upland and lowland UK **[1,2,3]**.
- environmental factors controlling the rates and scale of this flux and the pathways by which this pollution is transported from land to water **[1,2]**.
- importance of organic and particulate nutrient fractions as bioavailable and quantitatively significant components of nutrient flux to waters generating ecosystem damage **[2,3]**.
- importance of high-resolution monitoring in capturing episodic, extreme nutrient flux events in catchments of contrasting character, to reduce uncertainties in nutrient flux estimates **[4]**.
- scale of the nutrient challenge in UK waters, delivering the first spatially accurate simulation of nutrient flux from land to all UK waters at $4km^2$ grid scale **[5]**.
- optimal targeting and associated costs of mitigation measures for specific farming and landscape types which would be most likely to generate the greatest reduction in nutrient pollution of waters **[1,6]** and in greenhouse gas emissions to the atmosphere **[6]**.
- potential national patterns of reduction in nutrient emissions to air and water resulting from farmer-uptake of measures developed and/or tested under the DTC programme **[6]**.

This research has generated, for the first time, evidence that existing routine water quality monitoring approaches do not capture the full range of nutrient flux behaviours in catchments **[1, 2]**, the full suite of nutrient fractions currently driving ecosystem damage in freshwater ecosystems **[3]**, and the scale of the uncertainties in nutrient flux estimates arising from current monitoring practice **[4]**. Our novel approaches to modelling and quantifying nutrient fluxes **[5]** build on this evidence, allowing us for the first time to identify the factors controlling fluxes to and impacts in waters as these vary across complex landscapes. This modelling enables data-poor catchments to draw on knowledge and evidence generated from data-rich catchments and, critically, underpins the effective targeting of mitigation efforts and the assessment of pollutant swapping between pollutant forms and environmental sectors **[6]**.

3. References to the research

[1] **Lloyd CEM, Johnes PJ,** Stirling MW, **Carswell A, Freer JE,** Collins JI, Jones JIJ, Hodgkinson RA. (2019) Determining the origins of nutrient flux to waters in catchments: examining the nutrient speciation balance to inform the targeting of mitigation measures. *Sci. Tot. Env.,* 648, 1179-1200. doi:10.1016/j.scitotenv.2018.08.190

[2] **Yates CA, Johnes PJ, Owen AT,** Brailsford FL, Glanville HC, Evans CD, Marshall MR, Jones DL, **Lloyd CEM,** Jickells T, **Evershed RP.** (2019) Variation in dissolved organic matter (DOM) stoichiometry in freshwaters: assessing the influence of land cover and soil C:N ratio on DOM composition. *Limnol. Oceanogr.* doi:10.1002/lno.11186

[3] Mackay EB, Feuchtmayr H, De Ville MM, Thackeray SJ, Callaghan N, Marshall M, Rhodes G, **Yates CA, Johnes PJ,** Maberly SC. (2020) DOM uptake by riverine phytoplankton varies along a gradient of nutrient enrichment. *Sci. Tot. Env.* 722, 137837. doi:10.1016/j.scitotenv.2020

[4] **Lloyd CEM, Freer JE, Johnes PJ, Coxon G.** Collins AL. (2015) Discharge and nutrient uncertainty: implications for nutrient flux estimation in small streams. *Hydrological Processes*, 30, 1, 135-152. doi:10.1002/hyp.10574

[5] Greene S, **Johnes PJ,** Reaney S, Bloomfield JP, **Freer JE,** Macleod CJM. **Odoni N.** (2015) A geospatial framework to support integrated biogeochemical modelling in the UK. *Env. Monitoring and Software* 68, 219-232. doi:10.1016/j.envsoft.2015.02.012

[6] Collins AL, Zhang Y, Winter M, Inman A, Jones JI, **Johnes PJ.** *et al.* (2016) Tackling agricultural diffuse pollution: what might uptake of farmer-preferred measures deliver for emissions to water and air? *Sci. Tot. Env.* 547, 269-81. doi:10.1016/j.scitotenv.2015.12.130

Grant evidence:

- **Johnes, Freer** (joint PIs). Demonstration Test Catchments (DTC) programme. Defra projects WQ0210, WQ0211, WQ0212, 2009-2014; M0304, 2015-2017; LM0304. 2018-2019, GBP9.9 million (GBP4.2 million to Hampshire Avon and Tamar DTCs, GBP1 million to Bristol).
- **Freer, Johnes** (while at University of Reading) (Co-Is). NERC Environmental Virtual Observatory programme. NE/1002200/1, 2010-2014. GBP2 million (GBP270,000 to Bristol).
- **Johnes** (PI) Characterising the Nature, Origins and Ecological Significance of Dissolved Organic Matter in Freshwaters. NERC NE/K010689/1 (Defra, Environment Agency, Natural

England, Natural Resources Wales, Wessex Water, Welsh Water, Scottish Water, The Rivers Trust and Institute for Catalysis, Madrid as project partners), 2014-2019, GBP2.65 million (GBP1.25 million to Bristol).

- **Johnes** (PI). Determination of the Nature and Origins of Riverine Phosphorus in Catchments Underlain by Upper Greensand. Wessex Water/Natural England, 2016-2019, GBP200,000

4. Details of the impact

The University of Bristol's research has significantly improved understanding of nutrient pollution in water - its scale, sources, impacts and solutions for mitigation in the environmental management and policy-making communities. This has directly influenced water quality policy and practice at all scales of decision-making and management – from the international bodies who help shape and set environmental standards for their member states (the UN, OECD and EU), through to those who implement these policies at the national and local level. In the UK, these include Defra, Environment Agency, Natural England, Natural Resources Wales, and the water companies. Our research has led to better, more cost-effective water quality policy and management in practice, and has informed the scrutiny of these policies and practices by Government and Inter-governmental organisations.

1. UK policy development and management

We were founding members of the consortium funded to establish and run the Demonstration Test Catchments (DTC) programme. Johnes and Freer were Joint Leads with three others on two of the four Catchments (Hampshire Avon, Tamar), while Johnes was National Hydrochemistry Lead and Freer was National Modelling Lead. DTC was funded by Defra (2010-2020) and co-funded by the Environment Agency and Welsh Assembly Government to generate robust science evidence on the effectiveness of on-farm mitigation measures to control nutrient flux to waters, and their impact on freshwater ecosystems. It had over 40 stakeholders (water companies, conservation charities, government departments/ agencies, farmers, and landowners), and a cross-disciplinary community of researchers. Our DTC evidence **[**e.g. **1,4,6]** has led to new policies and management strategies for nutrient enriched waters in the UK **[a]**. Defra state that *"Research from the School of Geographical Sciences has contributed to our understanding of diffuse pollution from agriculture, particularly in relation to nutrient fluxes to watercourses. The research ... has highlighted the benefits of continuous monitoring strategies to capture episodic events in nutrient fluxes and the potential national patterns of reduction in nutrient emissions that might result from farmer-uptake of measures. …This research has informed the development of policy to cost-effectively mitigate diffuse pollution from agriculture."* They also confirm that the research *"has helped improve our understanding of the scale of the current problem of nutrient pollution and possible land management interventions ... to meet the Water Framework Directive objectives"* **[a].**

Outcomes from this research have been used to support policy development, including in the design of agri-environment monitoring and evaluation programmes, and the *New Farming Rules for Water*, for example, in providing hydrochemical evidence of pollutant responses to mitigation efforts, and modelling to identify optimal measures and trade-offs between environmental sectors **[6; a,b]**. Our DTC evidence is widely used by UK Government, with examples including in reporting to the European Environment Agency on UK Bathing Water Quality in 2017 **[b]**; in the Working with Natural Processes - Evidence Directory (2017) produced by a range of Government departments and agencies and charities **[c]**; in the Houses of Parliament POSTNOTE 478 producing advice for MPs on Diffuse Pollution of Water by Agriculture **[d]**; and in the Environment Agency's Technical Report on Phosphorus in the Hampshire Avon Special Area of Conservation (SAC), and its Fine Sediment Pressure Narrative **[e]**.

2. International policy development

The University of Bristol's research has made key contributions to international policy for nutrient enriched waters. Johnes was invited to contribute to OECD and UNECE Task Force for Reactive Nitrogen briefings on N flux in catchments (May 2016). The Task Force provides scientific information which has been used to develop strategies to control air pollution, specifically N, across the 56 member states of the UNECE (United Nations Economic Commission for Europe).

She presented evidence from our national-scale modelling of water, N and P fluxes to UK waters at $4km^2$ grid scale **[5],** and from our work **[1]** on the range of nutrient species and fractions accessible to the biota and generating adverse ecosystem impacts **[2,3]**. As a result, she was invited to brief OECD Environment Ministers on Nitrogen as sole expert at their *ENV2016 Meeting of the Environmental Policy Committee (EPOC),* 28-29 September 2016, Paris, presenting the University of Bristol's research on the nature **[1,2]** and scale **[5]** of the N challenge, and strategies for targeting mitigation measures **[1,6] [f].** This led to EPOC calling on OECD to *"(i) provide a forum for sharing experiences with addressing nitrogen pollution.…and assessing the consequences of inaction for global value chains; (ii) undertake case studies demonstrating how countries have successfully introduced measures and tools to address nitrogen pollution; (iii) analyse the potential pollution swapping effects…of nitrogen management policies"* **[f].** The resulting OECD 2018 report on *Human Acceleration of the Nitrogen Cycle* calls for international action to control N pollution, using our evidence as presented at the UNECE and ENV2016 meetings **[f**, Acknowledgements, Chapter 1, and Figure 1.4 in particular**].**

Further afield, our DTC research on the need for holistic and high frequency monitoring for policy and management **[1,4],** informed advice from the *US Department of the Interior* and *US Geological Survey* on the need to adopt a new high frequency monitoring approach in order to *"track changes to the ecosystem associated with drought compared to high-rainfall conditions"* and *"advance the development, implementation and evaluation of water management strategies and policies"* in their report on the Sacramento-San Joaquin Delta, North California **[g].** This has led to the USGS adopting new fixed station, sensor and boat based high resolution monitoring in 2019-20 across the San Francisco Bay area for a range of pollution problems, including the generation of cyanobacterial toxins in its waters, and on mercury and methylmercury contamination **[g].**

3. Scrutiny of UK government policy and practice

We presented our DTC, EVOp and DOMAINE evidence to the *House of Commons Environment Audit Committee's (EAC) Nitrates Inquiry* **[h]**, drawing on our research on the scale of the challenge **[5],** differences in the nature and rates of N flux to waters from livestock versus arable farmland, and the importance of sampling at high frequency for all N fractions to develop a holistic assessment of N stressors driving aquatic ecosystem damage **[1,2,3].** This assessment ran contrary to evidence submitted by other organisations from the farming industry **[h].**

The House of Commons EAC report on *UK Progress on Reducing Nitrate Pollution* (2018) cites this evidence extensively to challenge the status quo, relying on our evidence on the multiple nutrient stressors driving ecosystem decline **[1,3]** specifically in their recommendation that *"To make progress on improving the ecological status of water, the Government will have to use higher standards than those used for drinking water. This should include setting stricter standards for nitrates in freshwaters, as is the case in other EU Member States. It will also need to take a holistic approach to different pollutants, their collective impact and their sources"* and that "*The Government should seek to ensure that various EU Directives and regulations are aligned and do not result in a siloed approach to individual pollutants but address them in their totality"* **[h**; ***Recommendations 10 and 11***, paras 59 and 60, and our evidence in footnotes 142, 143**].** They also relied on our evidence on the importance of high frequency monitoring to determine the full range of nutrient stressors impacting on freshwater biota **[1,3,4]** in their recommendation that *"The Environment Agency should … provide evidence that its monitoring is comprehensive in terms of: the range and number of sites; the frequency of testing;…the full range of pollutants and their combined impact upon water quality; the impact of farming practices and pollution mitigation strategies;… as it provides the evidence base for policies and future investment decisions and ensures that Government policies can be scrutinised and progress can be monitored"* **[h; *Recommendation 20***, referencing paras 103, 106, and our evidence in footnotes 277, 278**].** This stimulated a range of media interest, including in *Farmers Guardian*, and *Chief-Exec.com: Essential News for Business Leaders* which directly quote this evidence **[h]**. Elsewhere, the British Ecological Society relied on our DTC work on farmer-uptake of mitigation measures **[6]** in their evidence submitted to the *House of Commons EFRA Select Committee Inquiry into the Rural Payments Agency*, advocating using our approach "*to establish the most effective management options whilst not compromising land profitability*" **[i]**.

4. Operational planning by the environmental and water sector

We work closely with the environmental and water sectors, advising Defra via its *Biodiversity Targets Action Group*, its *Water Expert Advisory Group* (chaired by Johnes) and *Nutrient Management Expert Group*, as well as Natural England's *Science Advisory Committee* and Wessex Water's *Catchment Panel*. A recent example of our wide range of research with these stakeholders is a programme we led, working with the British Geological Survey, and funded by Wessex Water and Natural England, to *Determine the origins of phosphorus in the Upper Greensand aquifer*, which contributes phosphorus to the Hampshire Avon SAC. The findings fed directly into a Wessex Water Asset Management Plan (AMP6, 2020-2025) environmental investigation, a key regulatory output **[j]** and the review of standards and thresholds for rivers draining from the Upper Greensand to the Hampshire Avon under the EU Habitats Directive (91/676/eec). Wessex Water confirm that this research *"has been essential in furthering our understanding of anthropogenic sources and transport mechanisms of phosphorus within the Upper Greensand geology…*[which] *will directly inform revisions to the Nutrient Management Plan for the Hampshire Avon, a statutory guidance document identifying measures required by all sectors to achieve the Conservation Targets, under the EU Habitats Directive, within this Special Area of Conservation"* **[j]**.

Wessex Water have also used our DTC evidence **[1,4,6]** to deliver the legally required reduction in the P load that they release to rivers in the form or treated effluent, and offsetting these fluxes against mitigation measures that farmers are paid to implement in the landscape. They state that *"Catchment management offers a viable offsetting option… rather than installing significantly more costly and unsustainable capital infrastructure… We have advocated a Catchment Nutrient Balancing approach within the Tone/Parrett and Dorset Stour catchments to deliver the required load of phosphorus reduction... This approach directly uses data and evidence from the DTC and is £50m less expensive than an asset-only approach.*" **[j]**.

5. Sources to corroborate the impact

[a] **i)** Defra (2016) Demonstration Test Catchments Open Data, **ii)** Defra (2019) Testimonial Letter - Flood and Water Leads, **iii)** Defra (2016) Impact Assessment: Water Quality and Agriculture

[b] European Environment Agency (2018) Country report: UK Bathing Water Quality in 2017

[c] Defra, Welsh Government, Natural Resources Wales, Environment Agency, SEPA, The Woodland Trust (2017) Working with Natural Processes – Evidence Directory

[d] Houses of Parliament Parliamentary Office of Science and Technology (2014) POST Note 478: Diffuse Pollution of Water by Agriculture

[e] **i)** Environment Agency (2015) Annex 4: Phosphorus in the Hampshire Avon SAC Technical Report Final; **ii)** Environment Agency (2019) Fine Sediment Pressure Narrative

[f] **i)** OECD (2016) ENV2016: Meeting of the Environmental Policy Committee (EPOC) at Ministerial level *(N breakout session, pp.17-19)*; **ii)** OECD (2016) ENV2016 Chair's Summary; **iii)** OECD (2018) Human Acceleration of the N Cycle: Managing Risks and Uncertainty

[g] **i)** USGS (2017) An Introduction to High-Frequency Nutrient and Biogeochemical Monitoring for the Sacramento-San Joaquin Delta, Northern California, **ii)** USGS (2020) Monitoring Cyanotoxins in California's Sacramento-San Joaquin Delta: Fixed Stations and High-Resolution Mapping Surveys, **iii)** USGS (2020) High Resolution Temporal and Spatial Mapping of Mercury and Methylmercury in Surface Waters of the Sacramento – San Joaquin Delta

[h] House of Commons EAC (2018) Inquiry into UK Progress on Reducing Nitrate Pollution **i)** Written evidence (NO30026); **ii)** Oral Evidence: Nitrate (HC656); **iii)** UK Progress on Reducing Nitrate Pollution - Eleventh Report of Session 2017-19; **iv)** Farmers Guardian (2018) Make the whole of the UK an NVZ; **v)** Chief-Exec.com (2018) Nitrate: there's something in the water

[i] British Ecological Society (2018) Rural Payments Agency Inquiry: A response to the House of Commons Environment, Food and Rural Affairs Committee

[j] Wessex Water (2019) Testimonial Letter - Director of Environmental Strategy