Institution: University of Reading

Unit of Assessment: 7 Earth Systems & Environmental Sciences

Title of case study: Developing modelling tools to support integrated catchment management

1. Summary of the impact

The intensification of food production, fossil fuel combustion and water consumption has led to substantial increases in the amount of nitrogen and phosphorus flushed from land to water. The accumulation of these nutrients in freshwaters, estuaries and the coastal zone has led to reductions in biodiversity, the loss of ecosystem services, and compromised water security. The UK is a signatory to a raft of international conventions and policies which require reductions in the flux of nutrients from land to the water and restoration of ecosystem health and services. To meet these obligations, policymakers need information on the scale of the problem, the sources of nutrients and the effectiveness of intervention measures.

Research in the Unit has directly addressed this need. It has provided robust scientific evidence of the scale of the problem and the sources of nutrient enrichment, and has provided the capability to test intervention and policy scenarios at field to national scales. It has fed directly into the development of monitoring approaches and mitigation measures now in use by the Environment Agency (EA) and Defra, informed the development of UK Government policy in relation to catchment management, and supported compliance with the EU Water Framework Directive, the renegotiation of the Gothenburg Protocol under the International Convention on Long-Range Transboundary Air Pollution, and reporting on discharges of nutrient pollution to the North East Atlantic under the OSPAR Convention.

2. Underpinning research

The Aquatic Environments Research Centre was created in the Unit in 1995 to undertake research into catchment biogeochemical cycling, with a focus on combining model development with monitoring to directly address the needs of water managers for science evidence and management tools. Since 1995, it has received over £4.8m in funding from NERC (£1.2m), the EU (£1.28m), Government departments and agencies (Defra, £1.57m; EA, £0.48m) as well as the water (£0.16m), and energy industries (£0.2m). The key researchers have been P. Johnes (1993 to date), P. Whitehead (1995-2007) and A. Wade (1998-2002, and 2004 to date), plus research fellows, postdoctoral researchers (including D. Butterfield and M. Futter) and PhD students.

Initial research[1,2,5,6] focused on improving our understanding of the key environmental variables controlling nutrient and sediment fluxes from land to adjacent waters. This involved the development of numerical simulation models to predict nutrient and sediment fluxes, and hence water quality, at field to catchment scales, and showed that the models were most effectively developed and calibrated when confronted with high frequency (daily or sub-daily) observations at multiple field stations. This research demonstrated that nutrient flux behaviours varied from year to year, depending on inter-annual climate variability. The behaviour also varied between catchments of different geological and climatic character, and between sites within catchments depending on the distribution and connectivity of the key source areas in the catchment upstream from each sampling point. Our research also demonstrated the importance of both biotic controls and abiotic controls on the rate and timing of nutrient flux within catchments, the importance of organic and particulate nutrient fractions as components of the total nutrient load transported to inland and coastal waters, and the importance of instream processes in regulating the timing, chemical character and ecosystem impacts of nutrient flux from source to sea.

Several modelling tools were developed by the Unit based on this research. These include the *National Export Coefficient Modelling Framework* and the *Integrated Catchment Model* (INCA). The former[1,2,3,4,8] simulates the total nitrogen (N) and phosphorus (P) load delivered annually to any water body as the sum of the exports from all contributing sources in the catchment. It has been calibrated against observed data in over 75 catchments, and provides a robust and reliable approach both for quantifying the relative contribution of different sources in the catchment, and assessing the likely effects of mitigation measures through scenario testing. The model is highly cited in both academic (>1500 total citations in Web of Science, WoS, searched October 2013) and stakeholder literature (Section 5). In one recent example of application of the model,[8] it was demonstrated that a strategy for reducing the delivery of P from agricultural sources would have only a limited effect on P loadings in reservoirs in southern Portugal, and policy should therefore first focus on reducing the P loading from sewage effluent discharge. In a series of applications at catchment to national scale the model indicated the dominance of animal agriculture in the delivery of both N and P to UK inland and coastal waters in the wetter west of the UK, particularly in rural catchments, the importance of N flux to waters from fertiliser applications to crops and grass in the drier eastern catchments of East Anglia and the Wolds, and the importance of effluent from sewage treatment works in the delivery of P to coastal waters in highly urbanised catchments and downstream from major cities.[3,4] INCA[5,6,7] is a more complex model, providing a daily simulation of the flux of a number of N species and P fractions at catchment scale. It also simulates carbon as well as nitrogen and phosphorus flux, and has recently been adapted to simulate mercury and sediment flux in applications in the UK and more widely in Boreal and upland areas of Europe. It has been calibrated in over 40 UK and European catchments, and is also highly cited in the academic literature (over 800 WoS citations in total).

Through targeted investment by the stakeholders, totalling over £3.6m (and more recently in the NERC Environmental Virtual Observatory and Macronutrient Cycles programmes), we have refined these models to meet a wide variety of stakeholder requirements. We have developed cloud computing-enabled frameworks to allow the models to be up-scaled from the field to the national scale, and from data-rich to data-poor regions, providing a platform for the estimation of nutrient flux to any inland or coastal water body in the UK, from daily to annual time steps, for any year for which input data are available, and tailored to a wide range of scenario testing needs.

3. References to the research

The number of citations each paper are taken from a WoS search (October 2013). Three papers that can be used to evaluate research quality are marked with an asterisk. The research on which most of the impact is based which was undertaken over the interval 1993-2011 and was funded by a series of competitively-won grants from NERC, the EU, Defra and EA, worth £4.8m.

1. *****P.J. Johnes (1996) Evaluation and management of the impact of land use change on the nitrogen and phosphorus delivered to surface waters: the export coefficient modelling approach*.* *Journal of Hydrology,* 183: 323-49. ISSN: 0022-1694 (348 cites)

2. P.J. Johnes and D. Butterfield (2002) Landscape, regional and global estimates of nitrogen flux from land to ocean: errors and uncertainties. *Biogeochemistry* 57/58, 429-476. (25 cites)

3. P.J. Johnes, et al. (2007) Land use scenarios for England and Wales: evaluation of management options to support 'Good Ecological Status' in surface freshwaters. *Soil Use and Management,* 23(S1): 176-196. doi: 10.1111/j.1475-2743.2743.00120.x (28 cites)

4. R. Howarth, et al. (incl. P.J. Johnes) (2012) Nitrogen fluxes from the landscape are controlled by net anthropogenic nitrogen inputs and by climate. *Frontiers in Ecology and the Environment,* 10 (1), 37-43. doi:10.1890/100178 (16 cites)

5. *****P.G. Whitehead, E.J Wilson, D. Butterfield (1998) A semi-distributed Integrated nitrogen model for multiple source assessment in Catchments (INCA): Part 1 – model structure and process equations. *Science of the Total Environment,* 210/211: 547-588. (180 cites)

6. *****R.G. Wilby, P.G. Whitehead, A. J. Wade, D. Butterfield, R. J. Davis, G Watts (2007) Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. Journal of Hydrology 330, 1-2, 204-220. (82 cites)

7. M.N. Futter et al. (incl. A.J. Wade, P.G. Whitehead) (2007) Modeling the mechanisms that control in-stream dissolved organic carbon dynamics in upland and forested catchments, *Water Resources Research,* 43(2), doi:10.1029/2006WR004960 (44 cites)

8. N.G. Matias and P.J. Johnes (2012) Catchment phosphorus losses: an export coefficient modelling approach with scenario analysis for water management, *Water Resources Management*, 26 (5), 1041-1064, doi: 10.1007/s11269-011-9946-3 (2 cites)

4. Details of the impact

Importance, relevance and pathway to impact

Increasing human population densities, intensive agriculture, water consumption, fossil fuel combustion and the generation of waste products from people, farming and industry, have all led to substantial increases in the amount of nutrients (C, N and P) flushed from land to water. In intensively-farmed areas such as the UK, N flux has increased 5-10 fold over the last 80 years. In the USA alone, nutrient enrichment of inland waters is estimated to result in annual economic losses of $2.7 billion, due to deterioration of water quality and reductions in the productivity of both inland and coastal fisheries.[9] The impacts of this enrichment (called eutrophication) are extensive and undesirable, including excessive production of aquatic plant and algal biomass, loss of biodiversity, disruption of food webs, the depletion of oxygen (hypoxia) in the water column with associated fish kills, and the loss of ecosystem services. The UN now rates coastal nutrient pollution as the one of the greatest current threats to the global environment, and the United Nations Environment Programme (UNEP) *Manila Declaration* (January 2012) identified nutrient enrichment of the marine environment as one of the top 3 foci for its *Global Programme of Action for the Protection of the Marine Environment from Land-based Activities*.

A series of international agreements require countries to reduce fluxes of nutrients to waters. The *International Convention on Long-Range Transboundary Air Pollution* (CLRTAP) is revising Annex IX of the *Gothenburg Protocol* to further reduce the ammonia emissions from land-based activities; Annex I of the *International Convention for the Protection of the Marine Environment of the North-East Atlantic* (OSPAR) requires the prevention and elimination of coastal water pollution from land-based sources; the *EU Water Framework Directive* (WFD) requires nutrient fluxes to be controlled to support good ecological status in all EU waters, while the *EU Urban Wastewaters Treatment Directive* (UWwTD) requires the removal of P from discharges from major wastewater treatment works across the EU-27. The cost implications of delivering these improvements in water quality are significant. Compliance with UWwTD in the UK alone has been estimated to have cost €350m.[10] The EU WFD is the single biggest piece of environmental legislation to be implemented worldwide: costs will be considerably greater than for compliance with the UWwTD.

To meet these regulatory obligations, government policymakers and water managers need information on the scale of the problem, the sources of nutrients and the likely effectiveness of intervention measures. Routine water quality monitoring provides some information, but not on the total nutrient flux, its sources in complex catchments, the pathways that nutrient fluxes follow from land to water, and how effective different management strategies might be in reducing the rates, timing and impacts of this flux. This knowledge, essential for the development of effective policy and management, can only be provided through the combined use of robust field observations and numerical simulation models, tailored to meet stakeholder needs. Delivery of these tools and advice, underpinned by an holistic understanding of the science, is imperative to ensure that Defra, EA and the other competent authorities in the UK (and comparable authorities internationally) are able to meet their statutory responsibilities in the areas of water, food and energy security, in the wider context of societal needs, government policy and international agreements.

The Unit's contribution and impact

The Unit has directly addressed policymaker and management requirements for robust scientific evidence and management tools. The research has identified key drivers of nutrient fluxes, and helped characterise the magnitude and key sources of these fluxes within complex systems, and clarified both the scale of the management challenge and the sectors which might be most effectively targeted through specific management interventions. Defra, the Environment Agency and the statutory conservation and management agencies have used our research findings to develop and test measures to control nutrient and sediment pollution, support reporting on UK discharges of nutrient pollution to the North Sea (www.ospar.org) and to develop the UK national nitrogen budget submitted to the Task Force for Reactive Nitrogen under the UNECE CLRTAP (www.clrtap.org).

Evidence of impact in the period 2008-2013

In testimonial evidence, Defra[11] state that the Unit's "*modelling effort has provided part of the evidence base that has helped Defra develop and deliver policy on managing water pollution*" and that it "*addresses questions that are of fundamental importance to our prospects of meeting Water Framework Directive targets*". The Environment Agency[12] states that the work in the Unit has delivered "*significant new understanding and evidence*" which has informed its understanding of the dynamics of nitrogen and phosphorus species. Our science research and modelling tools have both been directly used by the EA to support the design and implementation of monitoring and mitigation programmes under the EA- and Defra- funded *Catchment Sensitive Farming and Demonstration Test Catchments* programmes and the development of river basin management plans in Ireland[13]. The modelling tools that we have developed for the end-user community have been based on robust scientific evidence, and tailored to meet specific evidence and policy needs, so their use has been considerable and significant. For example, the export coefficient modelling approach (originally developed by the Unit as a national-scale tool in the 1998 Environment Agency's *Lake Classification and Monitoring* programme) was used by the Environment Agency in the period 2008-2013 to characterise the baseline nutrient status of UK waters, and the extent to which they are at risk of failing to achieve Good Ecological Status under the EU WFD. It was also used to generate the UK N budget submitted to the *Task Force for Reactive Nitrogen, Expert Panel on Nitrogen Budgets* of UNECE (UN Economic Commission for Europe).[14] and inform renegotiation of Annex IX of the Gothenburg Protocol.

An Environment Agency[15] report outlines the methods and evidence used to identify waters which are, or may become, eutrophic. It uses our research finding[16] that nitrogen is a limiting factor controlling the degree of eutrophication in standing waters that needs to be assessed for all waters, and uses our work to identify appropriate criteria to determine thresholds above which ecologically significant elevated nitrogen loading occurs[17]. This evidence has also been used in the work of the Task Force for Reactive N (further information in http://www.clrtap-tfrn.org/webfm_send/284). A 2012 report by Natural England[18] on Ecosystem Services Indicators recommends that *"subject to the availability of central funds, the contribution of habitat extent to water quality should be established through application of a series of nutrient export coefficients derived from the literature",* citing our most recent publication on this approach.[8] Five reports[13,19,20,21,22] used the findings of a Commissioned Advice Note[3] we prepared for Defra to inform the development of integrated catchment management strategies to reduce nutrient loading on waters in throughout the UK and thereby comply with the EU WFD.

Results from the application of INCA with climate change scenarios, undertaken under a series of EU-funded projects, have fed directly into catchment-scale assessments by our research collaborators in Norway and Finland on behalf of their national environmental management agencies. INCA was also used by the Environment Agency in the development of the *River Basin Management Plan for the Thames River Basin District.*[23] This provided evidence that nutrients released from agriculture or from sewage treatment works in the future could be less diluted, under a changing climate, with the reduced flows and higher concentrations of nutrients promoting algal growth and the dieback of important aquatic plant species; the management plan therefore anticipates a deterioration of water quality in the future.

Background Information

9. Editorial: "A World Awash with Nitrogen", *Science,* 16 Dec. 2011, 334(6062), 1504-1505.
10. EU Commission DG Environment (2010) *Compliance Costs of the Urban Wastewater Treatment Directive* (COWI Document no. 70610-D-DFR, Version 7, issued 25.02.2011)

5. Sources to corroborate the impact:

11. Testimonial letter, Science Programme Manager, Sustainable Land and Soils, Defra. (*)
12. Testimonial letter, Evidence Manager, Risk & Forecasting, Evidence Directorate, EA (*)
13. Teagasc (2009): *Draft WFD River Basin District Management Plans* http://www.teagasc.ie/publications/2010/988/RBDMPs_final.pdf (search for "Johnes")
14. http://www.clrtap-tfrn.org/epnb-3 The link to "UK National N budget" is restricted but details obtainable from Unit or from page 365 of Leip et al. (2011) http://centaur.reading.ac.uk/28386/
15. Environment Agency (2012): *Method Statement for Nitrate Vulnerable Zone review* http://bit.ly/1fd0Vnk (In section 1.3.2 – Category 1-Nutrients & section 2.4, paragraph 1)
16. P. Durand et al. (2011) *Nitrogen processes in aquatic ecosystems.* In: European Nitrogen Assessment, eds M. Sutton et al., Cambridge University Press. pp. 126-146. http://bit.ly/183PysU
17. Grizzetti et al. (2011) Ch. 17 European Nitrogen Assessment:http://centaur.reading.ac.uk/20869/
18. Natural England (2012): *Ecosystem services indicators methodology: Water Quality Theme* http://bit.ly/1dFPdBn (see "Methods for calculating indicator values")
19. *UK National Ecosystem Assessment* (2011) Ch. 20 http://bit.ly/1hFBE7m (search for "Johnes")
20. Natural England (2009): *Environmental Impacts of Land Management*. (In particular, Annex 2, use of cited reference 44). http://publications.naturalengland.org.uk/publication/30026
21. Scottish Government (2009): *Initial evaluation of effectiveness of measures to mitigate diffuse rural pollution.* http://www.scotland.gov.uk/Publications/2009/01/08094303/0*(pages 8,V-24,I-12)*
22. Land Use Policy Group (2008): *A review of environmental benefits supplied by agri-environment schemes.* http://www.snh.gov.uk/docs/A931063.pdf (page 114)
23. Environment Agency (2009): *River Basin Management Plan, Thames River Basin District:* Annex H Adapting to climate change (search for "Whitehead") http://www.environment-agency.gov.uk/research/planning/125035.aspx

(*) Available upon request