Institution: University of Glasgow (UofG)		
Unit of Assessment: 10 Mathematical Sciences		
Title of case study: Improving national water quality monitoring and network design through new statistical methods		
Period when the underpinning research was undertaken: 2009−present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Claire Miller	Professor	2007–present
Prof. Marian Scott	Professor	1983–present
Period when the claimed impact occurred: December 2013−Present		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Environment agencies invest substantial financial and staff resources in monitoring UK river networks to improve water quality at a time of increased financial pressures. UofG developed innovative statistical modelling tools to interrogate existing Environment Agency data and assess the ability of current and future monitoring network designs to provide evidence on water quality trends. This evidence crucially demonstrated to the European Commission that UK water quality monitoring policies were compliant with European directives and enabled the Environment Agency to design a new spatially representative network improving water quality monitoring within practical and budget constraints.

2. Underpinning research

Context:

The European Union (EU) Water Framework Directive (WFD), 2000/60/EC (European Parliament, 2000), established an integrated framework for the protection of surface waters. Each member state is required to demonstrate compliance with these EU directives through statutory reporting of water quality monitoring. While the position beyond Brexit is unclear, regulation and compliance to maintain/improve water quality will continue through, for example, the UK government 25-year environment plan.

Claire Miller and Marian Scott have been developing innovative spatiotemporal statistical methods to investigate trends in water quality data over the past 15 years. Work from 2009 has focussed on the specific challenges presented by river network data including the river flow and connectedness of the river structure **[3.1, 3.2]**. The statistical methods in **[3.3]** were one of the first illustrations of incorporating correlated error structures into generalised additive models to efficiently estimate temporal trends and seasonal patterns in water quality. In response to **[3.3]** the Risk and Forecasting Manager of the Environment Agency (at that time), Robert Willows, recognised the value of these statistical approaches developed to efficiently investigate complex spatiotemporal trends in river water quality and approached Miller and colleagues regarding a collaborative research project.

Statistical analysis of water quality monitoring:

The resultant research collaboration (jointly funded between EA and UofG) developed statistical models to describe spatial and temporal patterns of nutrients within river networks in England and Wales. The statistical research evaluated the changes in nutrient patterns (based on nitrogen/phosphorus weekly to monthly measurements) in river water over time (over a 20–40 year period up until 2010) and spatially for each of 59 large hydrological areas to identify evidence of past and current trends in the concentration of nutrients in rivers, and how these vary between

catchments **[3.1]**. The research was conducted by Miller & Scott and colleagues and Ana-Maria Magdalina (PDRA, UofG, June 2009–June 2010) in collaboration with Willows and his team between August 2009 and April 2013.

Re-designing monitoring networks:
Following this, UofG developed statistical methods and software **[3.2]** to identify common spatiotemporal patterns within river network nutrient data (October 2011–April 2016, Kelly Gallacher, PhD Glasgow with Miller, Scott & Willows, and Linda Pope and John Douglass (evidence directorate EA) and colleagues at the Scottish Environment Protection Agency (SEPA)).

Three online open access web applications were produced using **[3.2]** to enable the EA to explore and utilise their river water quality data and to investigate the effect of reducing the monitoring network size on water quality monitoring, potentially saving effort and cost (August 2017−January 2018, Craig Wilkie PDRA (UofG) with Miller & Scott & Douglass, with Sian Davies and Hannah Green (EA)). The online apps are based on monthly/seasonal measurements of nitrogen and phosphorus river water quality recorded at individual river monitoring sites over time. Predictions and related uncertainty information are improved by incorporating information on the flow direction of the river and monitoring site connectedness (e.g. where water from site 1 flows to site 2 but site 2 does not flow to site 1). This information indicates that very dense monitoring networks are not required in order to obtain robust information on water quality. Monitoring efforts can be substantially reduced while still retaining high power to detect changes.

Simulation studies **[3.4]** for spatially representative GRTS (Generalised Random Tesselation Stratified) designs provide evidence for the appropriate size and design for new monitoring networks (August−September 2018 with Marnie Mclean PDRA (UofG) with Miller, Scott, Davies, Green).

3. References to the research

Outputs [include DOIs or ePrints link] (* signals best indicator of quality)

3.1 * Miller, C., Magdalina, A.-M., Willows, R., Bowman, A., Scott, E., Lee, D., Burgess, C., Pope, L., Pannullo, F., and Haggarty, R. (2014) Spatiotemporal statistical modelling of long-term change in river nutrient concentrations in England & Wales. *Science of the Total Environment*, 466-7, pp. 914-923. (doi:10.1016/j.scitotenv.2013.07.113). Partly funded by collaborative project UofG & EA, CI, GBP61,711 funding contribution from EA, 1st Mar 2009–30th Oct 2010, SC080041.

3.2 a. * Gallacher, K., Miller, C., Scott, E.M., Willows, R., Pope, L., Douglass, J (2016). Flow-directed PCA for monitoring networks. *Environmetrics*, 28, 2, (doi: 10.1002/env.2434) Wiley-TIES best paper award 2017. Partly funded by: EPSRC PhD Doctoral Training Grant (K. Gallacher), Oct 2011–Jan 2016.

b. Software development funded by SECURE EPSRC network project, GBP22,277, 1st Nov 2015–30th April 2016 and EPSRC IAA, GBP10,297, 1st Aug 2017–31st Jan 2018. *River network case study to inform strategic monitoring review.* These have resulted in online web applications for EA:

- Exploratory analysis of river network nutrient patterns: app: https://shiny.maths-stats.gla.ac.uk/2259971b/EA_exploratory_analysis_app/
- Identifying clusters of spatiotemporal behaviour: http://shiny.maths-stats.gla.ac.uk/0801723w/EA_clustering_app/
- Evaluating implications of reducing monitoring networks: http://shiny.maths-stats.gla.ac.uk/0801723w/EA_reducing_networks_app/

3.3 * Ferguson, C.A., Carvalho, L., Scott, E.M., Bowman, A.W. and Kirika, A. (2008) Assessing ecological responses to environmental change using statistical models. Journal of Applied Ecology, 45(1), pp. 193–203. (doi:10.1111/j.1365-2664.2007.01428.x)

3.4 McLean, M., Miller, C. and Scott E.M. (2018) technical report. Funded by EA and EPSRC IAA funding, GBP16,000(EA) / GBP2,500 (IAA), 1st Aug 2019–30th Sept 2018. *Investigation of the impact of GRTS river sampling designs.* Project collaborators: Sian Davies, Hannah Green, Mike Dunbar, Stuart Homann (EA). Available on request from host institution.

4. Details of the impact

UofG research has provided the evidence base in support of UK policy regulating environmental water quality, and to inform the design of new monitoring networks: reducing monitoring budgets while improving the spatial representativeness of any network.

Input to policy at a European Union and UK scale. UofG statistical evidence illustrated that monitoring practice by Department for Environment Food and Rural Affairs (DEFRA), as implemented by UK regulatory agencies for monitoring water quality, did not require strengthening from 2014 onwards. Infraction proceedings against the UK by the EU (which would have been '*time consuming, expensive and politically embarrassing'***[5.1]**) were averted by evidencing that current practice within the UK to protect water quality did not require strengthening (at a time when the EU Directorate-General for Environment believed that UK action programmes were too lenient) [5.1].

Details: The results from **[3.1]** were used in statutory reporting by DEFRA to the European Commission **[5.2]**. At the time there was a question over whether the UK policy for monitoring was appropriate. Willows and his colleagues at DEFRA presented the statistical evidence from **[3.1]** to meetings with the European Commission and the Environment Directorate-General for the EU with final reporting in Dec 2013. This enabled DEFRA to understand the extent to which UK policies to reduce nutrient loads from both agricultural and non-agricultural sources were succeeding.

The results from this work evidenced that no changes to the UK's policy were required.

'*We [DEFRA] have directly drawn on the results published by Miller et al (2014) Science of the Total Environment, 466–467, 914–923 in our statutory reporting to the EU Commission'* **[5.2]**

Input to policy at a UK national scale. UofG research informed EA internal planning to shape their strategic monitoring review, from 2016 onwards. Specifically, UofG research informed the design of a smaller spatially representative monitoring network, using GRTS (reducing from 1000's to 100's of monitoring sites) which was approved in February 2020 for implementation from 2021 onwards **[5.3]**.

Details: The statistical tools and evidence in **[3.2]** and **[3.4]** have informed the Environment Agency (EA) about their ability to evaluate pressures on water quality from reduced monitoring networks, as part of a goal to produce a more spatially representative network whilst making cost savings **[5.4]**. Specifically, these tools and evidence have informed EA internal planning to shape their strategic monitoring review and enabled them to quantitatively evaluate the ability of a smaller river water quality monitoring network to provide relevant indicators of water status and change over time. **[3.2, 3.4]** *'gave [the EA] confidence that useful broad scale information could be generated from a smaller network'* and **[3.4]** has *'given [the EA] confidence around the likely network size and helped [the EA] explore indicative costs'* **[5.4]** for a new network, based on applying a spatially representative (GRTS) design tool. Building on the work at UofG, EA has now

proposed a new network design, and is currently testing the proposed new monitoring sites. The work by UofG has *'largely been used to provide judgement on an appropriate network size and [design]'* **[5.4]**, and *'the results directly influenced the final monitoring network design implemented by the EA.'* **[5.3]** UofG provided expert review **[5.3, 5.5]** of the proposed new network and EA staff have been assessing proposed monitoring sites for accessibility throughout 2020. *'The UofG work was critical in providing the necessary evidence and confidence that the new network design was the right one. Monitoring of sites in the new network is expected to start in January 2021.'* **[5.3]**

This was achieved through collaborative work with the EA as follows:
Training and knowledge transfer workshops:

- A workshop was held with 15 EA colleagues in London (2016) to demonstrate the statistical software (and training documentation) in **[3.2]**. Linda Pope from the EA stated, *'We have had very positive feedback on the workshop which has stimulated a lot of thoughts on how we might use these techniques in the future.'* **[5.6]**
- This led to a further focussed UofG-led workshop with 8 EA colleagues in Birmingham (April 2017), organised by Sian Davies (EA – an attendee at the April 2016 workshop), to explore the potential for statistical modelling to inform the EA's review of the size of their water quality monitoring network **[5.3]**. Follow-up resulted in development of online web applications **[3.2]**.

A webinar was held (May 2018) to demonstrate the use of the three online web applications **[3.2]** to disseminate results more widely with the technical team for the strategic water quality monitoring review within the EA. The webinar was very positively received with the visualisation tools assisting participants to understand the web application functionality and underpinning statistical analysis **[5.7]**. This webinar led directly to the commissioning of a follow-up project and report to assess GRTS designs **[3.4]**, and wider interest in the online applications developed from other EA colleagues working in air quality analysis.

Advisory board: Following these three workshops UofG Miller and Scott were asked to participate in EA external strategic advisory board **[5.8]** to discuss implications and next steps in network review and design following **[3.4]**.

Review and critique of new network design: UofG (Miller and Scott) were invited to peer review and critique the EA GRTS designed river monitoring network funded by EA **[5.3,5.5,5.9]**. *'Through 2019, the planning and design of the new monitoring network was carried out by EA supported through consultation with Statistics at UofG.'* with risk assessments for new sites carried out throughout 2020 before planned implementation in 2021 *[5.3]*.

Current and future work: has involved generalisation of the online web applications to enable user practitioners to upload their own data to assess spatiotemporal patterns in quality **[5.4]**, clusters of patterns and relationships and the implications for reducing the size of monitoring networks. These have been developed initially aimed at the EA and are being extended with international collaborators. The online web applications enable informed management decision making without a requirement for statistical expertise to use them.

5. Sources to corroborate the impact [all available in PDF format]

5.1 Emails from Risk and Forecasting manager at the Environment Agency
5.2 Letter from Department for Environment, Food & Rural Affairs (DEFRA) 20th March 2014. Nitrates and pesticides policy team leader for water quality
5.3 Testimonial from Environment Agency – Technical lead, river surveillance network (GRTS)

5.4 Testimonial from Environment Agency – Senior Advisor, Environment & Business Directorate (Water, Land & Biodiversity)
5.5 Peer review and critique of Environment Agency (EA) GRTS designed river monitoring network (April 2020) Contract reference no 308645
5.6 Email feedback from Knowledge Transfer workshop April 2016
5.7 Email feedback from Knowledge Transfer webinar May 2018
5.8 Minutes from Environment Agency Strategic Advisory Group meeting, 3rd Dec 2018
5.9 Tender specification, written by EA, for contract work with UofG