Institution: University of Stirling		
Unit of Assessment: 14. Geography and Environmental Studies		
Title of case study: Transforming inland water quality management through a global satellite observatory		
Period when the underpinning research was undertaken: 2012-2020		
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:**
Andrew Tyler	Professor & Deputy Dean	1994 - Present
Peter Hunter	Senior Lecturer	2007 - Present
Evangelos Spyrakos	Lecturer	2012 - Present
Claire Neil	NERC KE Fellow (now Honorary Lecturer)	2015 - 07/2020
Period when the claimed impact occurred: 2016-2020		
Is this case study continued from a case study submitted in 2014? No		

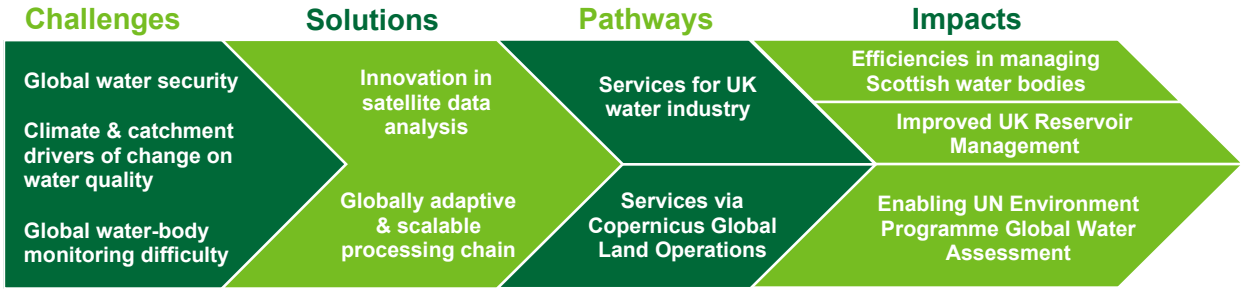
1. Summary of the impact

Accurate and efficient monitoring of inland water quality is essential to ensure global water security. Before the University of Stirling conducted this research, monitoring at the global scale was infeasible. Our research has enabled global satellite monitoring of lakes and reservoirs that is:

Impact 1: transforming how the Scottish Environment Protection Agency manage water bodies, going beyond compliance monitoring for lake and reservoir condition.

Impact 2: optimising UK reservoir management for increased efficiencies, proactive environmental protection and safeguarding water quality for **Anglian Water and Scottish Water**.

Impact 3: giving the United Nations an unrivalled level of global water quality monitoring (>50% of inland water bodies), which underpins a multitude of international and national water security initiatives and strategies under Sustainable Development Goal 6 - Clean Water and Sanitation.



2. Underpinning research

Creating the Step Change in Global-Scale Observation

Challenges: Critical for global water security, lakes and reservoirs represent some of the most vulnerable ecosystems to climate change and anthropogenic disturbance. With an estimated 117 million lakes globally, these systems represent over 85% of the world's surface freshwater. However, significantly fewer than 1% of these (by number) are being monitored regularly for management purposes: this represents a fundamental global ecosystem that we know relatively little about. Earth observation (EO) offers unrivalled opportunity to monitor and assess the changing status of water globally, but the ability to retrieve such information reliably from spaceborne sensors has been hindered by the complexity of water colour variation in inland and coastal environments.

Solutions - Innovation in satellite data analysis: The Stirling-led NERC GloboLakes project (2012-2018) (www.globolakes.ac.uk) [**F1**] pioneered the application of EO for lake condition monitoring including temperature [**R1**] from the local to the global scale. This breakthrough was brought about by a highly novel approach for identifying key differences in the reflectance signatures of inland waters (optical water types; OWTs). Classification of OWTs [**R2**] transformed our ability to select, optimise, and apply OWT-tuned algorithms for the retrieval of information on

water constituents such as chlorophyll-*a* [**R3**]. This step change benefited greatly from the collaboration that we led with over 30 international partners, providing data on more than 1500 lakes that are now openly available via the community-owned LIMNADES database (https://limnades.stir.ac.uk), developed and managed by Stirling.

Having created the first fully-characterised global OWT classification [**R2**], the next step was to retrieve this information reliably from satellites. Critical to the success of the GloboLakes project and subsequent research has been the development and implementation of a robust atmospheric correction model and pairing this with water quality algorithms parameterised for global application [**R4, R5**]. The GloboLakes' solution is globally-adaptive, using a dynamic selection of OWT-algorithms that reliably retrieve water quality information from inland and coastal waters [**R3**].

Following our pioneering globally-adaptive solution, we worked in partnership with the Plymouth Marine Laboratory and Brockmann Consult (Germany) to develop the first open and free operational inland water processing chain: Calimnos. This delivers the capability to monitor some 50% of the world's inland surface waters (for waterbodies >0.1km^2). We have also worked with researchers around the world to support the global assessment of the trophic state of inland waters using satellite data [e.g. **R6**].

Solutions - Building operational processing chains & research infrastructures: New projects stemmed from innovation within GloboLakes [**F1**], including the development of innovative and higher-level products such as phytoplankton size classes, harmful algal bloom indicators and carbon fixation in inland (FP7 INFORM) [**F2**] and coastal waters (H2020 CoastObs) [**F3**]. H2020 EOMORES [**F4**] has developed a framework for operational monitoring services for inland and coastal waters based on the most up-to-date satellite data, innovative *in situ* instruments and ecological models. Services and products are co-developed with 12 end-users (industry, regulators) across Europe, and a Memorandum of Understanding provides a commercial framework for exploitation.

The Calimnos processing chain developed for GloboLakes [**F1**] now supports NEODAAS services (www.neodaas.ac.uk), which uniquely provides processed EO data for a wide range of UK science users. Across Europe it underpins the Copernicus Global Land Operations "Cryosphere and Water" service (https://land.copernicus.eu/global/products/lwq) (CGLOPS-2) [**E4**]. Rigorous validation of satellite data for these optically complex environments is central to future progress and this is being pursued as part of the H2020 MONOCLE [**F7**] and ESA Lakes CCI projects [**F8**]. This also supports the development of the European Strategy Forum on Research Infrastructures (ESFRI) Pan-European Infrastructure on River-Sea Systems (DANUBIUS-RI) where Stirling and the Plymouth Marine Laboratory (PML) co-lead the Observation Node [**F9, F10**].

The latest generation of European Space Agency satellites (Sentinel-3 OLCI and Sentinel-2 MSI constellations) lets us shift the monitoring paradigm from one that has been too infrequent (e.g. bi-monthly), reactive, and spatially limited; to frequent, proactive and highly targeted cost-efficient *in situ* monitoring that promotes catchment and water management by both statutory agencies and industry. Our research is also informing the development of a harmful algae bloom climate monitoring service through collaboration with the UK environmental regulators, health agencies and water industry [**F6**]. Stirling has generated water quality data from the full Sentinel-2 MSI archive for 933 UK lakes (Figure 1) and since late 2020 is providing weekly data in near-real-time through a new web-based service (www.eo4ukwater.stir.ac.uk).

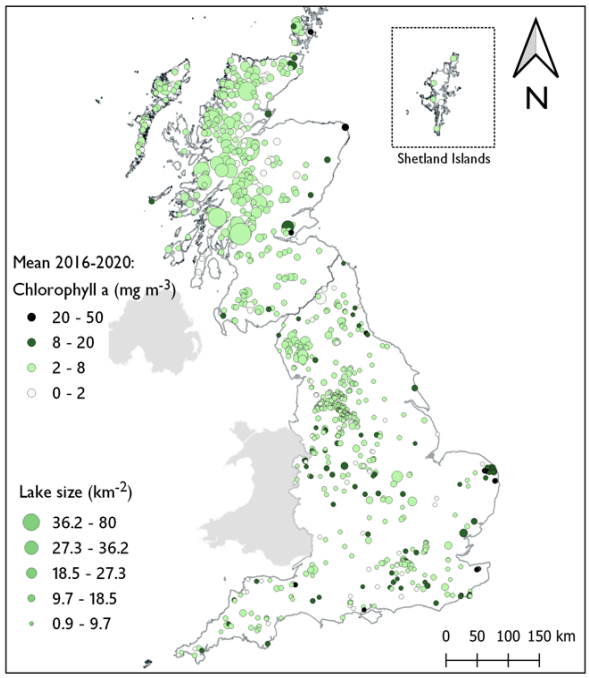


Figure 1. Chlorophyll *a* concentrations and lake area of 933 lakes and reservoirs currently being observed by Stirling's UK Lake Observatory.

3. References to the research (Stirling authors in **bold** text)

R1. Maberly SC, […] **Tyler AN** (2020) Global lake thermal regions shift under climate change. *Nature Communications*. 11, 1232. https://doi.org/10.1038/s41467-020-15108-z.

R2. Spyrakos E, […] **Hunter P**, […] **Neil C**, […] **Tyler A** (2018) Optical types of inland and coastal waters. *Limnology and Oceanography.* 63, 846-870. https://doi.org/10.1002/lno.10674.

R3. Neil C, Spyrakos E, Hunter PD, Tyler AN (2019) A global approach for chlorophyll-*a* retrieval across optically complex inland waters based on optical water types. *Remote Sensing of Environment.* 229, 159-178. https://doi.org/10.1016/j.rse.2019.04.027.

R4. Warren MA, […] **Spyrakos E**, et al. (2019) Assessment of atmospheric correction algorithms for the Sentinel-2A MultiSpectral Imager over coastal and inland waters. *Remote Sensing of Environment.* 225, 267-289. https://doi.org/10.1016/j.rse.2019.03.018.

R5. De Keukelaere L, […] **Hunter P, Neil C,** et al. (2018) Atmospheric correction of Landsat-8/OLI and Sentinel-2/MSI data using iCOR algorithm: validation for coastal and inland waters. *European Journal of Remote Sensing.* 51, 525-542. https://doi.org/10.1080/22797254.2018.1457937.

R6. Wang S, Li J, Zhang B, **Spyrakos, E, Tyler A**, et al. (2018) Trophic state assessment of global inland waters using a MODIS-derived Forel-Ule index. *Remote Sensing of Environment.* 217, 444-460. https://doi.org/10.1016/j.rse.2018.08.026.

Funding:

F1. 2012-2018: NERC GloboLakes: Global Observatory of Lake Responses to Environmental Change (NE/J024279/1). Consortium Lead PI on GBP2,900,000. Stirling leads consortium of 5 UK and over 20 international partner organisations.

F2. 2013-2017: EU FP7 INFORM: FP7-SPACE-2013-1(SPA.2013.1.1-07) Improved monitoring and forecasting of ecological status of European INland waters by combining Future earth ObseRvation data and Models. EUR350,000 to Stirling.

F3. 2017-2020: H2020 CoastObs: Commercial service platform for user-relevant coastal water monitoring services based on Earth observation. EUR2,000,000. EUR339,000 to Stirling.

F4. 2017-2020: H2020 EOMORES: Earth Observation-Based Services for Monitoring and Reporting of Ecological Status. UK Lead PI (Stirling and PML). EUR170,000 to Stirling.

F5. 2018-2019, 2019-2022: NERC KE Fellowships. Exploitation of satellite remote sensing for regulatory monitoring of inland and coastal water quality. Total GBP287,000.

F6. 2019-2020: Delivering resilience to climate impacts on UK freshwater quality: towards national-scale cyanobacterial bloom monitoring and forecasting (NE/J024279/1). NERC GBP50,000

F7. 2018-2022: H2020 MONOCLE: Multiscale Observation Networks for Optical monitoring of Coastal waters, Lakes and Estuaries. EUR5,000,000. EUR498,000 to Stirling.

F8. 2018-2021: ESA Climate change initiative (CCI) CLS-SPA-CAL-PR-17-0299: Lakes ECV. GBP107,000.

F9. 2017-2020: H2020 DANUBIUS-PP: Preparatory Phase for the Pan-European Research Infrastructure Danubius-RI 'The international Centre for Advanced Studies on River-Sea Systems'. Lead UK Consortium (Stirling, PML, CEH, Birmingham). EUR4,000,000; 30 European partners. EUR250,000 to Stirling.

F10. 2020-2022: H2020 CERTO: Copernicus Evolution: Research for harmonised Transitional water Observation EUR3,000,000. PI: EUR325,000 to Stirling.

4. Details of the impact

Pathways: From the outset the GloboLakes project appointed an advisory board with key representation from the UK statutory and regulatory agencies, European SMEs, the Group on Earth Observation (GEO) and the Joint Research Centre (JRC; EU Science Hub). This greatly enhanced our ability to deliver and maximise impact from GloboLakes and H2020 research outputs. Stirling contributed to the development of the *state of the art* of International Ocean Colour Coordinating Group (IOCCG) Water Quality Report (Andrew Tyler was an invited member of the IOCCG Committee, 2014-2017), written specifically to highlight the potential of EO for end-users (http://ioccg.org/group/water-quality/). The NERC Knowledge Exchange Fellow Claire Neil's [**F5**] close interaction with the Scottish Environment Protection Agency and water utilities has been critical in translating the EO opportunity into impact. The engagement of UN GEMS/Water by

Andrew Tyler with GloboLakes [**F1**], European projects [**F7,9**], co-organised workshops with the India UK Water Centre (IUKWC) in Stirling and Kerala (2017), and the GEO AquaWatch initiative in Stirling (2018, http://stir.ac.uk/4mu) with UNEP GEMS/Water, highlighted EO capability for water quality monitoring in data-poor regions of the world.

Impact 1 - Regulatory monitoring of Scottish water bodies: The Scottish Environment Protection Agency's (SEPA) strategy recognises that new approaches are required to enable communities and businesses to thrive within the resources of our planet by regulating on a sector-by-sector basis. To deliver this, SEPA is embracing a digital future to facilitate community engagement, collaborations, and knowledge exchange across sectors to tackle the complex multidimensional challenges of climate change, and deliver sustainable economic growth. Since the start of NERC GloboLakes in 2012, SEPA has been working with the EO team at Stirling in realising the potential of EO capability for water quality monitoring. The H2020 EOMORES project and NERC Knowledge Exchange Fellowship (Claire Neil) delivered a step change in the collaboration, adopting the ESA Sentinel 2 platforms to monitor a greater number of inland water bodies. Reflecting the success of this new model of working, enabled by the collaboration with Stirling, SEPA invested in EO capability by appointing Claire Neil to their Team. SEPA's Ecology Unit Manager, Willie Duncan, states:

> *'This provided a clear demonstration of how EO can deliver previously unobtainable levels of targeted and efficient water quality monitoring beyond the requirements of the Water Framework Directive. In 2018 Claire Neil was invited to join SEPA's Remote Sensing Coordination Group. More recently, SEPA created a full-time post to support the development of its remote sensing capabilities and Dr Claire Neil was appointed to this important role.'* [**E1**]

The Covid-19 pandemic then escalated the need to access EO to support SEPA's activities:

> *'The Covid 19 pandemic resulted in the cessation of SEPA's routine water quality sampling programme, and this led to an acceleration in the development work that will see satellite derived water quality data being used for environmental assessment purposes and the subsequent sustainable management of natural resources.'* [**E1**]

SEPA are now working to embed Stirling's EO outputs within their day-to-day operations:

> *'Currently specific applications and internal tools are being developed using outputs generated from University of Stirling projects to assess the impact of nutrient enrichment in lake and coastal ecosystems.'* [**E1**]

Impact 2 - UK water industry: Water colour is impacted by changes from in-water constituents derived from detrital material received from the catchment, or growth of algae in the water body, including potentially harmful cyanobacteria blooms. Our work with Anglian Water, who serve 4,300,000 customers across an area representing 20% of England and Wales, has impacted their Water Resources Management Plan and improved management of their reservoirs. Stuart Knott (Innovation Discovery Project Manager) testifies [**E2**]: '*Claire's fellowship demonstrated for the first time the very real opportunity for Anglian Water to exploit the latest digital technology from satellite-based EO within the concept of a digital grid to monitor and manage our surface waters'.* Anglian Water have deployed Stirling-derived EO to fulfil strategic objectives relating to environmental protection: '*Our partnership has allowed Anglian Water to exploit ESA's Sentinel-2 images of chlorophyll a concentration to identify spatial regions at risk of water quality degradation.'* In relation to reservoir management, Stirling's data:

> '*facilitate the targeted and cost-effective treatment of algae in our reservoirs. […] The benefits of these data include a better understanding of blooms over a long period, medium and short time frame. A better understanding of how Anglian's in-reservoir mixers can impact blooms. Importantly, this data has enabled us to ask more questions and guide research into reservoir management.'* [**E2**]

Covering one third of the UK's land area, including almost 800 islands and responsible for 8.2% of the UK's population, Scottish Water acknowledge the challenges and opportunities in monitoring and managing of water and sanitation in their 2020 Strategic Plan. The strategic plan sets out the response to climate change mitigation and inclusive growth opportunities in Scotland. To deliver on this plan Scottish Water is pioneering its research and innovation in partnership with the University of Stirling. In relation to reservoir management, George Ponton (Head of Research and Innovation) states:

'…*as a result of the NERC GloboLakes project and the NERC Knowledge exchange fellow, we have demonstrated that EO can be used to monitor and manage reservoirs to pre-empt the impact of changing water colour from brownification or algal bloom development. Already we have used this approach to confirm the presence of algae in a drinking water supply reservoir and used the information to inform the operational response to minimise the impacts to our customers.'* [**E3**]

Stirling's EO capability is central to the GBP22,000,000 investment in Scotland's International Environment Centre from the Scottish and UK Government 'City and Region Deal', which is developing a digital twin of the Firth of Forth catchment to drive Scotland's Green Recovery. Ponton concludes:

'*To build on this, Scottish Water and the Scottish Funding Council have now invested GBP3,500,000 in the University of Stirling to work closely with Scottish Water and to bring the Scotland's water sector together and deliver on Scottish Water's Strategic Plan.*' [**E3**]

Going forward, both Anglian Water and Scottish Water highlight the strategic need and benefit of embedding Stirling's EO service within their operational monitoring.

Impact 3 - Global Inland Water Monitoring: filling the gaps where there was no previous monitoring: The United Nations Environment Programme Global Environment Monitoring System for freshwater (GEMS/Water) is mandated to provide the world community with sound quality-assured data to support water management. The mandate was expanded in UNEA-3 (UN Environment Assembly) through resolution 3/27 in December 2017, acknowledging the growing need for water quality monitoring and capacity building activities. The failure of countries to report their ambient water quality status (SDG indicator 6.3.2) affects UNEP's ability to improve the provision of clean, safe, sustainable water and sanitation (SDG 6) strategies, which is fundamental to Agenda 2030, to reduce poverty and end hunger (SDG1&2) and to sustain economic development (SDG 8,9,11&12) and health and wellbeing (SDG3). The need to deliver on these ambitious monitoring goals persuaded UN Environment to exploit the Copernicus Global Land Operations. This impact uses the Calimnos processing chain to deliver water quality products (e.g. measures of chlorophyll, suspended sediment, turbidity) for over 4000 lakes globally [**E4**]. This is contributing to the GEMS/Water goals and bringing SDG6 (Water quality & wastewater monitoring) back on track. This new satellite capability:

[Text redacted from publication at request of stakeholder] [**E5**]

Showing that UNEP thinking has undergone a radical shift toward the use of EO:

[Text redacted from publication at request of stakeholder] [**E5**]

5. Sources to corroborate the impact

E1. Testimonial from Scottish Environment Protection Agency: Ecology Unit Manager.

E2. Testimonial from Anglian Water: Innovation Discovery Project Manager.

E3. Testimonial from Scottish Water: Head of Research and Innovation.

E4. Documentation showing the link between GloboLakes and Copernicus Global Land Operations "Cryosphere and Water" service and confirms GloboLakes provided key science behind the Calimnos Processing, extensively citing GloboLakes, [**R2**] and [**R3**], (http://stir.ac.uk/5kf).

E5. Testimonial. [Text redacted from publication at request of stakeholder].