Institution: University of Glasgow (UofG)		
Unit of Assessment: UoA10 Mathematical Sciences		
Title of case study: Statistical modelling of groundwater pollution enables more effective environmental protection		
Period when the underpinning research was undertaken: 1997−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:**
Professor Adrian Bowman	Professor	1986–2020
Dr Ludger Evers	Lecturer	2008–2020
Dr Marnie Low	Lecturer	2019–present
Period when the claimed impact occurred: 2009 - present		
Is this case study continued from a case study submitted in 2014? Yes		

1. Summary of the impact

Groundwater contamination creates serious environmental and potential health issues. UofG researchers developed statistical modelling and visualisation tools subsequently used by Shell to develop GroundWater Spatiotemporal Data Analysis Tool (GWSDAT), a user-friendly software application to map groundwater pollution. Shell consultants worldwide have used GWSDAT for many years to make well-founded decisions on the management of groundwater, ensuring environmental protection and delivering multi-million dollar cost savings. Since 2014, new tools have been developed and implemented in GWSDAT through a Shell/UofG collaborative project. Many other organisations in the oil and gas, land reclamation and regulatory sectors have now adopted GWSDAT to improve risk assessment, aid decision-making on remediation, and deliver substantial financial savings.

2. Underpinning research

Context

Pollutants which leach into groundwater pose significant environmental threats and potential health concerns. Where there is a risk, boreholes are usually drilled at various spatial locations to allow direct measurement of groundwater pollution. The challenge is to use these measurements at particular times and spatial locations to identify the presence, location, and shape of any pollution plume over the entire spatial region and time period. After a pollution episode, a second challenge is to assess the evidence for the success of any active remediation efforts, or the effects of natural attenuation over time. In addressing both of these challenges, standard historical methods of analysis have generally involved the examination of trends at individual boreholes and spatial patterns at individual time points.

Relevant research at UofG

UofG's Bowman has a long-running research theme on statistical methods that allow the trends and patterns in data to be modelled through flexible regression models. This includes spatiotemporal data [3.2].

Bowman also developed software tools for the creation of interactive visualisations, provided in the 'rpanel' package [3.1] for the widely used R statistical computing environment. Visualisation methods for spatiotemporal data were also included in Bowman's recent article in the *Journal of the Royal Statistical Society* [3.6].

UofG's Evers has extensive experience of both Bayesian and computational methods in statistics which led to new research on models for spatiotemporal data [3.3].

GWSDAT version 1

The employment by Shell of a UofG PhD graduate (Giannitrapani, completed 2005) transferred this methodology to the company, who were at that time seeking practical tools for the interpretation of monitoring data from boreholes at oil and gas installations around the world. The GWSDAT software tool was created in 2009 by Shell staff, using the modelling and visualisation tools described in [3.1] and [3.2]. This was intended for use principally by Shell staff and consultants.

Further UofG research
Shell part-funded a UofG PhD student (Molinari, completed 2014) to strengthen the methodological foundation of GWSDAT. This involved a spatiotemporal p-spline smoothing model, implemented in a fully Bayesian framework. Rapid delivery of results was a key requirement, and this was achieved through innovative application of linear algebra techniques. The model and computational methods are described in [3.3].

GWSDAT version 2
These methods were incorporated into GWSDAT by Shell staff and subsequently released in 2014 as open-source software, for use by any interested parties.
Further UofG research
Shell part-funded a second PhD student (Low, née McLean, completed 2019) who established that a spatiotemporal model can deliver more accurate and informative estimation of a pollution plume than standard spatial or temporal methods alone [3.5]. Design issues were also addressed through optimal sampling strategies (from a spatiotemporal perspective) to maximise the use of resources, the removal of monitoring points when a network of locations is reduced and the addition of new points when a network is expanded. [3.4]. This research is being developed further by another PhD student (Radvanyi, started 2020), fully funded by Shell.

GWSDAT version 3
As the use of GWSDAT grew, a further new version of the tool was created in a joint venture of the UofG and Shell. This was released in 2018 as an on-line tool (gwsdat.net) but is also available in desktop form where remote or secure use is required.

3. References to the research

3.1 Bowman, AW, Crawford, E, Alexander, G & Bowman, RW (2007). rpanel: simple interactive controls for R functions using the tcltk package. *Journal of Statistical Software* 17, issue 9. https://doi.org/10.18637/jss.v017.i09
3.2 Bowman, AW, Giannitrapani, M & Scott, EM (2009). Spatiotemporal smoothing and sulphur dioxide trends over Europe. *Applied Statistic https://www.un-igrac.org/resource/groundwater-monitoring-country-profile-indonesia*, 58, 5, 737−752 https://doi.org/10.1111/j.1467-9876.2009.00671.x
3.3 Evers, L and Molinari, DA and Bowman, AW and Jones, WR and Spence, MJ (2015). Efficient and automatic methods for flexible regression on spatiotemporal data, with applications to groundwater monitoring. *Environmetrics*, 26, 431−441. https://doi.org/10.1002/env.2347
3.4 McLean, MI (2018). Spatio-temporal models for the analysis and optimisation of groundwater quality monitoring networks. PhD thesis, University of Glasgow. http://theses.gla.ac.uk/38975/
3.5 McLean, M, Evers, L, Bowman, AW, Bonte, M and Jones, WR (2019). Statistical modelling of groundwater contamination monitoring data: a comparison of spatial and spatiotemporal methods. *Science of the Total Environment* 652, 1339−1346. https://doi.org/10.1016/j.scitotenv.2018.10.231
3.6 Bowman, AW (2019). Graphics for uncertainty. *Journal of the Royal Statistical Society, Series A,* 182, 403−418. https://doi.org/10.1111/rssa.12379

4. Details of the impact

GWSDAT is used worldwide by major industries and government agencies to (a) protect environmental quality, (b) provide a scientific basis for decision-making, and (c) contribute to substantial cost savings. Users are able to map sites in detail, identify regions of high contamination, pinpoint locations where further monitoring is required, and evaluate changes due to management interventions. The following examples have been chosen to illustrate the nature and size of the benefits. The later material demonstrates the reach of the software.

Shell
In 2013, Shell identified that GWSDAT was used as a primary means of evaluating groundwater status by around 200 consultants in 70 countries, delivering the evidence base for environmental

decisions and producing cost savings amounting to over USD3 million per year. In 2019, Shell confirmed that:

> *"The cost savings, according to one survey of environmental engineers, run into millions of dollars. These come from accelerating the analysis of complex data sets, identifying spills earlier, reducing the reliance on engineering treatment solutions, closing out of longer-term monitoring, and simplifying the preparation of reports. More importantly though, the tool has improved the way we monitor groundwater around our sites and assets."* [5.1b]

Shell's VP for Environment stated in 2020:

"The partnership between Shell Global Solutions and the University of Glasgow on GWSDAT is a fantastic collaboration which has improved Shell's management and interpretation of groundwater data leading to value creation through more effective and sustainable remediation." [5.1a]

Environmental Protection Agency, USA

Edwards Air Force Base is a high-profile aircraft R&D site. In 2017, there was considerable controversy on whether a groundwater contamination plume was stable and whether the decision to shut down hydraulic extraction had been correct. Existing analysis was inconclusive. EPA then used GWSDAT. This convincingly demonstrated the narrowing of the plume while the extraction system was operational and enlargement when it was shut off. This enabled well-directed environmental decisions on a long-term remedy, involving multi-million dollar investment. The EPA hydrogeologist commented:

> *"I now recommend the software for use by project managers and their contractors across all the EPA regions in the USA. Its ability to provide real insight quickly and objectively is a huge asset."* [5.2]

Dept. of Environmental Conservation, New York State

At a Long Island site, historical releases of gasoline related compounds (BTEX) raised concerns about effects on the groundwater which is the sole-source aquifer for nearly 1.3 million residents. In 2018, the Professional Geologist stated:

> *"GWSDAT has been implemented at the subject site to answer important questions about the residual nature and fate of the BTEX plume and ... to direct further investigation activities with precision. As a result, fewer wells have been required to be installed, which resulted in savings of at least $150,000 in drilling costs. Moreover, GWSDAT will be used to support future decision-making that could save millions of dollars' worth of remediation work."*
>
> *"GWSDAT is an invaluable tool for sites that pose a threat to public health."* [5.3]

Remediation of chlorinated solvent sites

RSK Group is a major environmental consultancy with offices across Europe, the Middle East, Africa and Western Asia. Since 2016 *RSK Group* have managed a project involving underground leakage from a storage tank at a metal-working factory site. GWSDAT clearly demonstrated the positive impact of remediation. In another project, GWSDAT demonstrated significant decline in pollution but highlighted one location where contamination remained high. The *RSK Benelux* Technical Director, commented:

> "*GWSDAT is an excellent tool …[which] ... provides a firm scientific basis for good decision-making. It is the only tool I know which can perform analysis across space and time simultaneously. … I continually direct my staff towards it for analysis ...*" [5.4]

Multiple sites in Canada

Stantec Consulting have used GWSDAT extensively in Canada since 2016. At two different petrol station sites, contamination was shown to be under control, leading to shutdown of remediation and annual savings of USD192,000 and USD36,000 respectively. Elsewhere, after a pipeline release in an environmentally sensitive area, GWSDAT provided evidence which allowed the monitoring programme to be amended, providing annual savings of USD155,000. [5.5]

A retail site near Copenhagen

This high-end site suffered an undetected and protracted spill from a fuel line. After a full site investigation (2012−2014), subsequent GWSDAT analysis supported the approval of EUR3 million full scale remediation (2014−2015). Thereafter, GWSDAT clearly established the stability of the situation. In 2018 the site was signed off for no further action, allowing the client to regain its full value. The Remediation Services Team Leader commented:

> *"GWSDAT has proved to be an invaluable tool, not only in the high-profile project described above but in many other projects where a large series of groundwater data is available."* [5.6]

Further details of these selected examples, and others, are available at gwsdat.net/case-studies.

Professional adoption of GWSDAT

The *Environment Agency* for England issued guidance in 2020 for risk assessment of land contamination with specific direction to GWSDAT as a recommended tool. In the USA, similar endorsement is given by the *Interstate Technology and Regulatory Council*. [5.7] GWSDAT is distributed and promoted by the *American Petroleum Industry* (US) [5.8a] and *CL:AIRE* [5.8b] a UK-based non-profit organisation which promotes the regeneration of contaminated land. *EQuIS,* one of the world's most widely used environmental data management software, provides a facility to export data to GWSDAT, enabling easy interface between the two systems [5.8c]. In addition, presentations on GWSDAT are regularly requested at conference events [5.8d] and GWSDAT expertise appears as an explicit expectation in some job advertisements [5.8e].

GWSDAT continues to inform decision making around Groundwater Management

CPD delivered to hydrogeologists, environmental scientists and other professions is a key impact pathway for the uptake of GWSDAT into industry practice. Dissemination includes both invited presentation to the *Network for Industrially Contaminated Land in Africa* in May 2020 [5.9a] and video training material in the Indonesian language was created by local professionals [5.9b]. GWSDAT has recently been used by projects in Nigeria [5.10a], Egypt [5.10b] and UAE [5.10c] to deliver insight into groundwater conditions in tropical, arid, and semi-arid regions, and to inform management decisions to ensure clean, safe water for all.

5. Sources to corroborate the impact

5.1 a) Corroborating testimonial from VP, Shell Global Solutions. Exemplar quotation to be found at http://gwsdat.net
b) Shell Data Science LinkedIn article. https://www.linkedin.com/pulse/technology-case-transparency-daniel-jeavons/

5.2 US EPA at Edwards Air Force Base. http://gwsdat.net/edwards-air-force-base/

5.3 Dept. of Environmental Conservation, New York State. http://gwsdat.net/new-york-state/

5.4 Remediation of chlorinated solvent sites http://gwsdat.net/case-study-rsk-benelux

5.5 Multiple sites in Canada http://gwsdat.net/case-study-stantec/

5.6 A retail site near Copenhagen http://gwsdat.net/case-study-ejlskov-denmark/

5.7 Recommendation of GWSDAT in regulatory compliance
a) Environment Agency guidance https://www.gov.uk/government/publications/land-contamination-risk-management-lcrm/lcrm-stage-1-risk-assessment.
Reference to GWSDAT at https://www.gov.uk/government/publications/land-contamination-risk-management-lcrm/lcrm-stage-1-risk-assessment#GWSDAT
b) ITRC recommendation https://www.itrcweb.org/gsmc-1/Content/GW%20Stats/Appendix%20D%20Software/D%207%20Groundwater%20Spatio%20Temporal.htm

5.8 Professional adoption of GWSDAT
a) GWSDAT download from American Petroleum industry at https://www.api.org/oil-and-natural-gas/environment/clean-water/ground-water/gwsdat (1000 downloads/annum)
b) GWSDAT download from Cl:AIRE at https://www.claire.co.uk/projects-and-initiatives/gwsdat?showall=1 (200 downloads/annum)
c) EQuIS software integration of GWSDAT

https://6.6.help.earthsoft.com/6.6/enterprise/index.htm?lib_groundwater_spatio-temporal_da.htm

d) Statement from Conference Producer, Environment Analyst http://gwsdat.net/conferences-and-events/
e) Sample job advertisement specifying GWSDAT expertise

5.9 Capacity building with GWSDAT

a) Network for Industrially Contaminated Land in Africa (NiCOLA) presentation, May 2020 (300 views since May 2020) https://www.youtube.com/watch?v=yD1_WP30MNQ. Specific mention of UofG contribution from 12:20.
b) video training material in the Indonesian language was created by local professionals (1000 views since May 2020). http://gwsdat.net/case-study-indonesia/

5.10 GWSDAT use in monitoring groundwater quality and contamination in developing countries:

a) Odoma, A. L., & Ocheri, M. I. (2020). Spatial Variability of Nitrate Levels in Groundwater of Lokoja Town, Kogi State, Nigeria. Current Journal of Applied Science and Technology, 39(8), 7-11. https://doi.org/10.9734/cjast/2020/v39i830586
b) Masoud, A.A., Koike, K. Mashaly, H.A., Gergis, F. (2016) Spatio-temporal trends and change factors of groundwater quality in an arid area with peat rich aquifers: Emergence of water environmental problems in Tanta District, Egypt. Journal of Arid Environments 124, 360-376. https://doi.org/10.1016/j.jaridenv.2015.08.018
c) Yilmaz, Abdullah & Shanableh, Abdallah & Al-Ruzouq, Rami & Kayemah, Naseraldin. (2020). Spatio-Temporal Trend Analysis of Groundwater Levels in Sharjah, UAE. International Journal of Environmental Science and Development. Vol. 11. 9-14. https://doi.org/10.18178/ijesd.2020.11.1.1218.