Institution: University of Manchester		
Unit of Assessment: 7 (Earth Systems and Environmental Sciences)		
Title of case study: Arsenic research identifies avoidable health risks from groundwater arsenic informing increased awareness, policy change and mitigation		
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 submitting HEI:**
Polya DA	Professor	1985 – present
Lloyd JR	Professor	2001 – present
Vaughan DJ	Professor (now Emeritus)	1988 – 2014
van Dongen BE	Reader	2007 – present
Pan J (Mathematics)	Professor	2002 – present
Richards LA	DKO Fellow	2013 – present
Shaw S	Professor	2012 – present
Coker V	Lecturer	2003 – present
Boothman C	Technician/Experimental Officer	2001 – present
Ballentine C	Professor	2001 – 2013
Gault AG	PhD Researcher / PDRA	2002 – 2010
Charnock JM	PDRA	1982 – 2014
Lythgoe PR	Senior Experimental Officer	1982 – 2020
Period when the claimed impact occurred: March 2014 – July 2020		
Is this case study continued from a case study submitted in 2014? N		

1.Summary of the impact

Worldwide over 100,000,000 people are exposed to arsenic through the use of high arsenic groundwaters, resulting in 100,000s of premature deaths annually. Our research has enabled better prediction of groundwater arsenic, has highlighted eating rice as a major arsenic exposure route, and provided quantitative estimates of arsenic-attributable health and economic risks. Our research has informed development of government and non-government policies and actions to reduce the health and economic impacts of exposure to groundwater arsenic. Beneficiaries include:

(i) millions of people globally whose arsenic exposure through eating rice has been reduced;

(ii) [text removed for publication] households in Bihar, India through mitigation of contaminated water supplies; [text removed for publication] and the prevention of [text removed for publication] avoidable premature deaths; and

(iii) populations exposed to chemical environmental agents in England and Wales, where our work has contributed to the development of Environmental Public Health Tracking [text removed for publication].

2. Underpinning research

University of Manchester (UoM) research has developed understanding of: (i) what factors control how arsenic gets into groundwater and hence what factors control its distribution in groundwater in different parts of the world; (ii) what the major routes of exposure to humans of arsenic are; and (iii) what the health and economic costs of these exposures are, both to individuals and to the wider community. All of these advances in understanding have contributed to (and continue to) informing decisions by stakeholders on how best to practically reduce human exposures to toxic arsenic.

Research into the most important global type of groundwater contamination (by population exposed) demonstrated that natural bacteria play a critical role in enabling high concentrations of arsenic to build up in groundwater; a key process is a coupled reduction-oxidation reaction accelerated by these bacteria [1]. This involves the reduction of arsenic-bearing minerals, such as iron oxides/hydroxides coupled with the oxidation of organic matter. The importance of this reaction means the supply of reactive organic matter into a groundwater may serve to accelerate the rate of arsenic release from minerals (where it does not constitute a risk) to the groundwater (where it does constitute a risk through drinking water supply). UoM research (e.g. [1], [2]) has confirmed what others have suggested, namely that massive groundwater-sourced irrigation in some groundwater arsenic impacted countries may lead to reactive organic matter from the surface being drawn into groundwater systems – thereby increasing rates of arsenic release. The UoM research concluded that modified irrigation practices (particularly of rice paddies) is necessary.

UoM researchers were the first to publish on the nature and existence of groundwater arsenic hazard in Cambodia and have since established [3] that a substantial groundwater arsenic hazard also exists in the basins of small rivers – enabling better prediction of groundwater arsenic distribution.

UoM researchers demonstrated that rice is an important exposure route for humans to arsenic particularly for people for whom rice is their main dietary staple [4]. We were the first to directly demonstrate an association between the consumption of arsenic through rice and markers (specifically the frequency of damaged cell nuclei) of cancer-related ill-health outcomes [5]. This work indicated that human exposure to inorganic arsenic through eating rice should be reduced; for example, through a combination of better regulation, better growing practices and/or modified consumer behaviour.

UoM also used environmental analyses and biomarkers to demonstrate human exposure to arsenic from private water supplies in south-west England [6]. In particular, analysis of chemical arsenic species in urine have enabled UoM researchers to distinguish between exposure to generally-thought-to-be non-toxic organic arsenicals from seafood and exposure to highly toxic inorganic arsenic from drinking water. Around 5% of householders with private water supplies in south-west England were found to have such elevated arsenic exposures.

3. References to the research

This research has been funded by UKRI (EPSRC and NERC, totalling GBP2,796,880), EU (approximately GBP3,300,000) and British Council Funding (GBP113,000). Citation counts are from Web of Science (July 2020).

[1] **Islam FS, Gault AG, Boothman C, Polya DA, Charnock JM**, Chatterjee D. and **Lloyd JR** (2004) Role of Metal Reducing Bacteria in Arsenic Release in Bengal Delta Sediments. *Nature*, **430**, p68-71. DOI: 10.1038/nature02638 (859 citations).

[2] **Rowland HAL, Pederick RL, Polya DA**, Pancost RA, **van Dongen BE, Gault AG**, Bryant C., **Anderson B**, **Charnock JM, Vaughan DJ** and **Lloyd JR** (2007) Control of organic matter type of microbially mediated release of arsenic from contrasting shallow aquifer sediments from Cambodia *Geobiology*, **5**, p281-292. DOI: 10.1111/j.1472-4669.2007.00100.x (138 citations).

[3] **Sovann, C.** and **Polya DA** (2014) Improved groundwater geogenic arsenic hazard map for Cambodia. Arsenic hazard in shallow Cambodian groundwaters, *Environmental Chemistry,* **11**, 595-607. DOI: 10.1071/EN14006 (12 citations).

[4] **Mondal D** and **Polya DA** (2008) Rice is a major exposure route for arsenic in Chakdha Block, West Bengal: a Probabilistic Risk Assessment. *Applied Geochemistry*, **23**, 2986-2997. DOI: 10.1016/j.apgeochem.2008.06.025 (214 citations).

[5] Banerjee M, Banerjee N, Bhattacharjee P, **Mondal D**, **Lythgoe PR**, **Martinez M**, **Pan J**, **Polya DA** and Giri AK. (2013) High arsenic rice is associated with elevated genotoxic

effects in humans. *Scientific Reports*, 3. (Art 2195), DOI:10.1038/srep02195 (95 citations).

[6] **Middleton DRS**, Watts MJ, Hamilton EM, Ander EL, Close RM, Exley KS, Crabbe H, Leonardi GS, Fletcher T, **Polya, DA.** (2016) Urinary arsenic profiles reveal exposures to inorganic arsenic from private drinking water supplies in Cornwall, UK**.** *Scientific Reports***,** 6, Art. No. 25656. DOI: 10.1038/srep25656 (21 citations).

4. Details of the impact

Since 2014, UoM research on arsenic in groundwater has significantly impacted on reducing household exposure to arsenic, policy and practice change around arsenic mitigation, and on water supply management, contributing towards the UN Millennium Development Goal of increasing safe water supply. This impact has directly benefitted at least 100,000 households in Bihar State (India) and shaped Public Health England's (PHE) practices in England. Globally, this research has directly informed the United Nations Children's Fund (UNICEF) updated "Arsenic Primer", where the UoM research findings on the extent, consequences and options for mitigating arsenic contamination are summarised for water sector professionals and agencies responsible for drinking water quality.

The key research findings [1-6] were disseminated to, and discussed with, those directly working on issues of arsenic poisoning. This was undertaken through stakeholder meetings between UoM and partners in India (with local and national Government agencies, appointed as advisors to the Bihar State Pollution Control Board), Myanmar (Ministry of Education) and Cambodia (Ministry of Rural Development, and a National NGO), developing community science projects with schools in India (in Patna, Delhi and Mumbai), as well as presenting the findings of risk assessment work to all the major water supply companies in England and Wales.

Four areas of specific impact have resulted from the underpinning research at the University of Manchester:

i) Informing international best-practice:
The International Water Association (IWA) "Best Practice Guide for the Control of Arsenic in Drinking Water (2017)" relies heavily on the UoM work: 8 out of 24 chapters are co-authored by the Manchester team and the team's work is referenced over 60 times [A]. This best-practice guide has been cited by the World Health Organisation (WHO)/UNICEF in their updated "UNICEF Arsenic Primer" as one of nine publications that are recommended as a general resource on arsenic contamination and mitigation. WHO/UNICEF state that whilst the IWA Best Practice Guide is not always explicitly cited in the Primer, it is regarded as a resource for most of the chapters [B].

ii) Shaping Indian State-level policy:
As a result of their research ([1-5], [B]) in February 2018, Polya and (former Manchester PhD student) Mondal were appointed as Advisors to the Bihar State Pollution Control Board. [Text removed for publication]. Polya and Mondal have presented their work to key stakeholders in Bihar, including UNICEF, the State Minister for the Environment, and the State Health Society, resulting in increased awareness of groundwater arsenic hazard, exposure and health risks [C]. Their input has been specifically noted by the Honourable Deputy Chief Minister for Bihar as inputting to the State's goals to make arsenic free drinking water available to all areas affected by arsenic contamination [C].

Through stakeholder presentations at the Bihar State Pollution Control Board in February 2018, the group's research [4] and [B] has contributed to improved awareness and understanding of environmental arsenic's contribution to the prevalence of cancer within the State [E]. [Text removed for publication]. A student science project with 6 schools/colleges in Bihar, which involved the collection of water samples for analysis in the Manchester

Analytical Geochemistry Unit at UoM also served to raise community awareness of geogenic groundwater contaminants.

iii) Informing EU policy:

UoM research on the association of biomarkers of ill-health with consumption of high inorganic arsenic [5] is cited by the European Food Safety Authority's (EFSA) 2014 report on "Dietary Exposure to inorganic arsenic in the European Population", which recommends that dietary exposure to inorganic arsenic can be reduced through appropriate cultivation strategies [F]. Through highlighting the level of arsenic exposures that result in adverse human health effects and the typical range of dietary arsenic exposure in Europe (provided *via* [5]), this EFSA report underpins the revised European Regulation on Arsenic in Rice (EU Direction 2015/1006 Amending Annex to Regulation (EC) No 1881/2006). This regulates the arsenic content of rice supplied to EU consumers to 200 µg/kg for adults and to 100 µg/kg for children [G]. It is estimated that globally over 50,000 premature deaths annually are attributable to dietary arsenic [G].

iv) Shaping UK and International Public Health Strategy:

The group's research into private drinking water supplies in the UK [6], conducted with the British Geological Survey (BGS), has [text removed for publication]. Environmental Public Health Tracking (EPHT) aims to develop comprehensive public health surveillance and environmental health tracking systems for toxic hazards and health effects to provide the essential context for risk assessment. The UK Government invests GBP340,000 per annum into EPHT through the Department of Health. [Text removed for publication].

In England and Wales, the EPHT programme is a key function to support the forthcoming PHE Environmental Public Health Strategy. Projects in the EPHT programme, including [6] are crucial to enable PHE to develop comprehensive environmental tracking systems for toxic hazards [K]. The UoM research, including [6], is specifically referenced in the EPHT, where the research is acknowledged to have "*confirmed human exposure to arsenic from the use of private water supplies"* [K]. [Text removed for publication].

PHE have confirmed that as a result of the evidence and information they gained through the collaborative research project with UoM-BGS, they now advise other national public health agencies, most recently in the Republic of Georgia and in Ghana, to support the prevention of exposure to hazardous chemicals in drinking water [I].

5. Sources to corroborate the impact

[A] Citations in Best Practice Guide for the Control of Arsenic in Drinking Water DOI: https://doi.org/10.2166/9781780404929

[B] WHO/UNICEF (2018) *Arsenic Primer. Guidance on the Investigation & Mitigation of Arsenic Contamination*, UNICEF, New York,

[C] Letter from the Chairman of the Bihar State Pollution Control Board, India, January 2020

[D] Value of a statistical life (VSL) in India: GBP/INR conversion of 0.010 used. From: Majumber, A. and Madheswaren, S (2018) *Value of statistical life in India: a hedonic wage approach*, The Institute for Social and Economic Change, Bangalore, ISBN 978-81-7791-263-0

[E] Letter from the Director of the Mahavir Cancer Hospital and Research Centre, Bihar, India, January 2020

[F] Citation in European Food Standards Authority (EFSA) Scientific Report (2014) Dietary Exposure to inorganic arsenic in the European Population, *EFSA Journal*, **12** (3): 3597, DOI: 10.2903/j.efsa.2014.3597

[G] Revised European Regulation on Arsenic in Rice - EU Directive 2015/1006 AMENDING ANNEX TO REGULATION (EC) NO 1881/2006

[H] Evidence of annual estimated number of deaths attributed to dietary arsenic - Gibb et al (2015) Estimates of the 2015 global and regional disease burden from four foodborne metals – arsenic, cadmium, lead and methylmercury, *Environmental Research*, **174**, p188-194, DOI: 10.1016/j.envres.2018.12.062
[I] Letter of Support from Head of Environmental Epidemiology, Public Health England**,** January 2020
[J] Colson et al (2015), Structured Expert Judgment for Informing the Return on Investment in Surveillance: The Case of Environmental Public Health Tracking. Vanderbilt Owen Graduate School of Management Research Paper No. 2704189, DOI:10.2139/ssrn.2704189
[K] Public Health England (2018) *Environmental Public Health Tracking in England: Report on recent activities,* Public Health England, London