Institution: University College London (UCL)

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

Title of case study: Groundwater arsenic pollution: Informing policies and mitigation programmes, leading to improved public health security in Bangladesh

1. Summary of the impact

UCL research findings about the source, transport and fate of arsenic in sediments exploited for water supply in the Bengal Basin have underpinned the development and implementation of policy by the Bangladesh government, international donors and non-governmental organisations (NGOs), and led to improvements in public health security across southern Bangladesh. By demonstrating that arsenic pollution in Bangladesh is not caused by irrigation pumping, the research countered popular demands and government intentions to curb irrigation, thereby supporting the country's continued food-grain self-sufficiency. Subsequent UCL explanations of the geochemical and hydraulic processes controlling groundwater arsenic have underpinned further revision of the government's strategies for monitoring groundwater and mitigating the crisis; the resultant reduction in arsenic exposure among approximately 10 million people has significantly enhanced public health security.

2. Underpinning research

Arsenic exposure – the adverse effects of which include cancers, diseases of the vascular system, and death – presents a serious global threat to public health. Since 1990, extensive arsenic pollution of groundwater has been recognised in Quaternary fluvio-deltaic sediments exploited for water supply. The problem is especially acute across the densely populated floodplains of Southeast Asia, where shallow groundwater constitutes the only bacteriologically safe source of water for more than 100 million inhabitants. In Bangladesh and West Bengal alone – where shallow groundwater contains arsenic at concentrations up to 100 times the World Health Organization (WHO) guideline limit for drinking water – some 70 million people are affected, and sustainable mitigation solutions are far from universally implemented.

Research conducted since 1997 by John McArthur and William Burgess in the Department of Earth Sciences at UCL has addressed the distribution, source, transport and fate of arsenic in the Bengal Basin, taken as a type area for Quaternary fluvio-deltaic aquifers. McArthur and Burgess' first published contribution in 1998 (with graduate student Nickson and collaborators in Bangladesh) set out their deduction, from the geochemical context and analysis of water from 46 wells in Bangadesh, that groundwater arsenic derives from reduction of arsenic-bearing iron oxyhydroxides in the sediments [1]. This finding overturned the previous consensus that arsenic enters groundwater by oxidation of arsenic-bearing pyrite in response to water-table lowering by irrigation pumping. The research demonstrated that arsenic pollution in Bangladesh is a natural phenomenon, rather than being caused by irrigation pumping.

Extensive fieldwork and laboratory analysis of groundwater and sediment cores from West Bengal, conceived by McArthur and executed in conjunction with lead collaborator D. M. Banerjee (University of Delhi) and other collaborators in the UK and India (as indicated by the author lists on references [2-4]), were conducted between 2000 and 2008. This work exposed buried peat as the main cause of the chemical reaction giving rise to severe arsenic pollution in the groundwater [2]. Building on this, the research team developed and used their 'palaeosol' model [3] to demonstrate that the current distribution of arsenic in groundwater reflects the distribution of palaeo-channels and palaeo-interfluves that developed between 125,000 and 18,000 years ago, as sea-level fell and a late-Pleistocene landscape developed across the Bengal Basin. This model applies to delta regions worldwide, and is valuable as a guide both for groundwater monitoring and for siting arsenic-safe tubewells [4].

Also between 2000 and 2008, Burgess worked in an equal collaboration with P. Ravenscroft (consultant in Dhaka) and K. M. Ahmed (Dhaka University) on an interpretation of more than 3,000 groundwater analyses, supplemented by sediment core analysis and permeability measurements. Using data from these studies, they established a hydrogeological synthesis of arsenic occurrence across southern Bangladesh [5]. Burgess, with graduate students at UCL, then developed conceptual and numerical models to show how groundwater flow controls present-day arsenic concentration at shallow pumping wells, and to posit future trends. At basin-scale, Burgess worked

with UCL research student Hoque and their collaborators in Bangladesh to determine the potential for deep groundwater, which is free of excessive arsenic, to provide a safe alternative water supply. Via their analysis of more than 2,000 borehole records and development of numerical models, Burgess and his collaborators described the major elements of the Bengal Aquifer System to >350m depth, its development over Plio-Quaternary time, and the extent of its vulnerability to contamination by arsenic as a consequence of excessive pumping [6]. This evaluation underpinned recognition of the potential for deep groundwater as a secure mitigation option; Burgess and UCL research fellow M. Shamsudduha presented that option to Bangladesh government authorities at a workshop in Dhaka in January 2013 (see section 4). The analysis of the vulnerability of deep groundwater was an equal collaboration between Burgess, M. Hoque (UCL graduate student), H. Michael (Univ. Delaware, USA), C. Voss and G. Breit (US Geological Survey) and K. M. Ahmed (Dhaka University).

UCL researchers: John M. McArthur (Reader 1997-2000; Professor 2000-present), William G. Burgess (Senior Lecturer in Hydrogeology 1993-present), and Mohammad Shamsudduha (Postgraduate Research Fellow 2012-present).

3. References to the research

[1] Arsenic poisoning of groundwater in Bangladesh, R. Nickson, J. McArthur, W. Burgess, M. Ahmed, P. Ravenscroft and M. Rahman, *Nature*, 395, 338 (1998) doi:10/fvhjxk

[2] Natural organic matter in sedimentary basins and its relation to arsenic in anoxic ground water: the example of West Bengal and its worldwide implications, J. M. McArthur, D. M. Banerjee, K. A. Hudson-Edwards, R. Mishra, R. Purohit, P. Ravenscroft, A. Cronin, R. J. Howarth, A. Chatterjee, T. Talukder, D. Lowry, S. Houghton and D. K. Chadha, *Appl. Geochem.*, 19, 1255-1293 (2004) doi:10/dmzhbv

[3] How paleosols influence groundwater flow and arsenic pollution: A model from the Bengal Basin and its worldwide implication, J. M. McArthur, P. Ravenscroft, D. M. Banerjee, J. Milsom, K. A. Hudson-Edwards, S. Sengupta, C. Bristow, A. Sarkar, S. Tonkin and R. Purohit, *Water Resour. Res.*, 44, W11411 (2008) doi:10/bcjs25

[4] Migration of As, and $^{3}H/^{3}He$ ages, in groundwater from West Bengal: Implications for monitoring, J. M. McArthur, D. M. Banerjee, S. Sengupta, P. Ravenscroft, S. Klump, A. Sarkar, B. Disch and R. Kipfer, *Water Res.*, 44, 4171-4185 (2010) doi:10/bp2dkm

[5] Arsenic in groundwater of the Bengal Basin, Bangladesh: Distribution, field relations, and hydrogeological setting, P. R. Ravenscroft, W. G. Burgess, K. M. Ahmed, M. Burren, J. Perrin *Hydrogeol. J.*, 13(5-6), 727-751 (2005) doi:10/dst9cs

[6] Vulnerability of deep groundwater in the Bengal Aquifer System to contamination by arsenic, W. G. Burgess, M. A. Hoque, H. A. Michael, C. I. Voss, G. N. Breit and K. M. Ahmed, *Nature Geosci.*, 3(2), 83-87 (2010) doi:10/c7zfmc

References [1], [3] and [5] best indicate the quality of the underpinning research.

Grants: The research has been supported by the award of grants to McArthur of more than £750,000 from NERC (2003-2010), with additional funding from the United Nations Children's Fund (UNICEF); and of £58,000 awarded to Burgess from the EPSRC (2012), with additional funding from the UK's Department for International Development and the British Geological Survey.

4. Details of the impact

Between 2008 and 2013, UCL's research into arsenic pollution of groundwater has had significant impacts on policy, practice and public health security in Bangladesh. Specifically, it has guided the development and refinement of policy on groundwater pumping in response to the groundwater arsenic crisis and underpinned practical approaches towards arsenic mitigation and groundwater monitoring; as a result, it has improved public health security across the region. Globally, the research has contributed to the development by UNICEF of policies relating to the investigation and mitigation of arsenic contamination. Key research findings were shared widely with stakeholders beyond academia, partly as a natural outcome of the collaborative nature of the research, to which Bangladesh government departments and NGOs contributed through their provision of access and data. The reach of the impact was further extended by UCL contributions

to national meetings and workshops in Bangladesh, including a workshop titled *Deep groundwater in Bangladesh: UCL research in support of policy development* in January 2013 in Dhaka.

Supporting UNICEF policy and directives: UNICEF has been a leading international provider and facilitator of mitigating actions responding to the arsenic crisis in Southeast Asia. The organisation has adopted UCL's explanation of the underlying processes and causes of groundwater arsenic in the Bengal Basin as the standard paradigm for understanding arsenic pollution in alluvial aquifers worldwide [A]. UCL research provided fundamental support for UNICEF's assessment of global health impacts of groundwater arsenic, which underpinned its development of policies and directives for its country offices, published in 2008 [B]. By demonstrating that the existing state of contamination in Bangladesh was both predictable and manageable, UCL research particularly facilitated UNICEF's proposals for rational and effective responses [A]. Significant projects supported by UNICEF since 2008, and reflecting or responding to those proposals, include the Bangladesh Government's Department of Public Health Engineering (DPHE) 15-year water supply and sanitation 'Sector Development Plan' [C], published in 2011 by the DPHE Policy Support Unit (PSU). The Sector Development Plan describes national strategy for the investment of approximately $20 billion in the water, sanitation and health (WASH) sector. UNICEF Bangladesh's Water and Environmental Sanitation Specialist stated: "Completely outside academic circles, the UCL work, both directly, and indirectly by shaping DPHE reports, quite simply transformed the policy debate in Bangladesh and India, and indeed beyond because it guided my 2007/08 global predictive modelling for UNICEF" [A].

Guiding Bangladesh government policy development: The DPHE Policy Support Unit leads the development of government policy in the water supply and sanitation sector in Bangladesh. The January 2013 Dhaka workshop on *Deep groundwater in Bangladesh*, co-convened by UCL, Dhaka University and the PSU, was attended by representatives of the DPHE, the Bangladesh Water Development Board (BWDB), the Bangladesh Agricultural Development Corporation, the Geological Survey of Bangladesh, the Water Resources Policy Organisation, and the donor (including UNICEF and WaterAid) and NGO communities [D]. It resulted in the submission of an advisory policy statement ('Deep Groundwater in Southern Bangladesh - a vital source of water') [E] to the PSU [D]. This statement promotes deep groundwater as a long-term secure water source to mitigate the effects of arsenic and salinity in southern Bangladesh, and identifies seven points of consensus around which policy should be framed. According to the PSU Director, the UCL research has "made a highly regarded impact in helping the Government of Bangladesh develop its policy towards deep groundwater pumping and water quality protection" [D].

Support for arsenic mitigation programmes: The DPHE is the Bangladesh government authority with principal responsibility for arsenic mitigation through provision of safe water supplies, and BRAC (formerly the Bangladesh Rural Advisory Committee) is the leading NGO in the WASH sector. UCL research has been used by the Arsenic Management Division of the DPHE to develop deep groundwater pumping as a mitigation strategy [F], and informed deep tubewell mitigation provisions developed by BRAC [G]. Decisions on the optimum depth of arsenic mitigation wells in the DPHE 2011 Sector Development Plan [C] and the BRAC 2011 WASH Programme II [H], have been supported by the research on the spatial and depth-distribution of the arsenic source, and the hydraulic structure of the Bengal aquifer system [F, G].

Contributions to public health security: Deep groundwater in Bangladesh is free of excessive arsenic. The implementation of deep groundwater pumping strategies by DPHE and BRAC between 2000 and 2013, to designs informed by UCL research [F, G], is estimated to have reduced arsenic exposure – thereby enhancing health, welfare and quality of life – among a combined total of some 10 million people across southern Bangladesh [F, G]. The BRAC WASH Programme alone involved the drilling of 3,966 deep tubewells between 2006 and 2011, targeting 8.5 million people, mostly living in rural areas [H]. Public health security has also been protected by the UCL research finding that arsenic pollution in Bangladesh is natural, and not caused by pumping for irrigation (reference [1] above). This finding has helped underpin the maintenance of food-grain self sufficiency in the country from 1998 to the present day. In 1998, there were demands both within civil society and at ministerial level for a ban on groundwater irrigation, then thought to be the cause of arsenic pollution. The UCL discovery catalysed and informed public

debate about the issue, supporting counter-demands that ensured the continuation of groundwater irrigation. The enduring impact of this reversal is affirmed by UNICEF Bangladesh's Water and Environmental Sanitation Specialist, who notes that "UCL research was central to this process", which has itself been "critical to maintaining food-grain self-sufficiency in Bangladesh and a substantial part of India" [A].

Influence on groundwater monitoring practice: The BWDB is the Bangladesh government authority with responsibility for monitoring the quality and quantity of the groundwater resources nationally. McArthur's research findings on the rate of groundwater flux at the arsenic source regions (reference [4], above), and Burgess's research on the rate of migration of arsenic towards pumping wells (references [5] and [6] above), alerted BWDB [I] and UNICEF [A] to the requirements and timescales for groundwater monitoring. The research findings influenced the BWDB's approach to groundwater monitoring, specifically regarding the security of deep groundwater, and informed their establishment in 2012 of a coastal groundwater network of over 120 monitoring points [I]. BWDB continues to appraise the design of its national deep groundwater monitoring programme in the light of UCL research, most recently through consultation at the January 2013 Dhaka workshop. That workshop, according to the BWDB Deputy Director (Ground Water Hydrology), "gave the opportunity for us to consider the contributions of UCL research and their implications for our approach towards groundwater monitoring. Our joint effort has been guiding BWDB to plan and develop appropriate investigation and monitoring technologies in order to generate good quality hydrogeological data and information for the sustainable use of limited fresh and safe groundwater resource" [I].

5. Sources to corroborate the impact

[A] Correspondence from Water and Environmental Sanitation Specialist, UNICEF Bangladesh – corroborates the impact on UNICEF policy design, the continuing benefits of UCL's role in stopping a ban on groundwater irrigation in Bangladesh, and the influence on groundwater monitoring practice. Available on request.

[B] The Arsenic Primer - Guidance for UNICEF Country Offices on the Investigation and Mitigation of Arsenic Contamination, UNICEF, New York (2008), available online: http://uni.cf/1bB2iKx. (UCL research influenced chapters 1, 2 and 7)

[C] Sector Development Plan, PSU (part of DPHE) (2011), available online: http://bit.ly/18ojqDC – corroborates that the DPHE made decisions on the optimum depth of arsenic mitigation wells (these decisions have been supported by the UCL research), e.g. see pages 33, 34 and 50.

[D] Supporting statement from Project Director (Joint Secretary), PSU – corroborates the contribution of UCL research to Bangladesh government policy development and the details of the 2013 workshop. Available on request.

[E] Appendix H in 'UCL, 2013. The Security of Deep Groundwater in Southeast Bangladesh: Recommendations for Policy to Safeguard against Arsenic and Salinity invasion. Final Report, EPSRC/UCL-BEAMS Knowledge Transfer Project, London.' – corroborates that UCL research informed the development of an advisory policy statement. Available on request.

[F] Supporting statement from Executive Engineer, DPHE – corroborates the influence of UCL research on DPHE deep groundwater pumping mitigation actions, and confirms that approximately 5 million people benefit from these actions. Available on request.

[G] Supporting statement from Senior Director, BRAC – corroborates the influence of UCL research on decisions at BRAC about the depth and locations of deep wells for arsenic mitigation, and confirms that approximately 5 million people benefit from these actions. Available on request.

[H] For corroboration of the details of the WASH Programme see Chapter 1 of Achievements of BRAC Water, Sanitation and Hygiene Programme towards Millennium Development Goals and Beyond, Research Monograph Series No. 60. Research and Evaluation Division, BRAC (May 2013): http://bit.ly/16PXocD.

[I] Supporting statement from Deputy Director (Ground Water Hydrology), BWDB – confirms the contributions of UCL research to BWDB's approach to groundwater monitoring (specifically deep groundwater security). Available on request.