In this issue, Yan Zheng (School of Environmental Science and Engineering, Southern University of Science and Technology) discusses her seminal work on arsenic in groundwater in Bangladesh entitled “Redox control of arsenic mobilization in Bangladesh groundwater” with commentators Joseph Ayotte (Hydrologist, U.S. Geological Survey, New England Water Science Center, Pembroke, New Hampshire, U.S.) and Jing Sun (Professor, Institute of Geochemistry, Chinese Academy of Sciences; Associated Editor, Frontiers in Water, Solid Earth Sciences; Editorial Board, Bulletin of Geological Science and Technology.)

Q1. This article was published 17 years ago, how did people perceive groundwater arsenic contamination back then? What is the most important scientific contribution of this article? What are the possible reasons you think why this article is highly cited?

Yan: The study investigated arsenic in groundwater of Bangladesh. So if by people you mean the people of Bangladesh, it was the high time that awareness of arsenic is being rapidly raised through the largest well water screening effort ever undertaken by humanities to date. More than 5 million wells have just been screened using field test kits in less than 5 years, painted green if the arsenic concentration is less than 50 microgram per liter, the Bangladesh drinking water standard. There was, of course, frustration among the people. This is also easy to see: for any household with a well that had been painted “red”, meaning that...
the well water contained more than 50 microgram per liter of arsenic (note WHO’s guideline value is substantially lower at 10 microgram per liter), there is an immediate crisis. Where would you obtain your drinking water from? Unfortunately, even today, tens of millions in Bangladesh still live in this crisis.

The most important scientific contribution is the colors in the arsenic map (Fig. 1). They are the best (see later for interesting stories)! Reader’s experience is what makes a paper complete so I can only guess. This paper laid out the Bengal Deltaic aquifer’s geological history succinctly. It sought to explain the major ion compositions of the groundwater before it attempted to explain why arsenic is low and high at various places, and introduced the idea of flushing not only of arsenic but of the redox driver, organic matter. In hindsight, much more efforts should have been devoted to investigating why arsenic in groundwater can be low at places where groundwater arsenic is generally high. Because low arsenic groundwater is a more useful water resource for supply.

Joe: At the time in the United States, there was a lot of discussion around the lowering of the drinking water standard for public water supplies from 50 to 10 micrograms per liter. Although there was a lot known about arsenic in public supplies, there was very little known about arsenic in private well water. This was a major concern because private wells are the main source of water for rural communities or for people outside of public-supply areas. The 2001 lowering of the arsenic standard gave rise to a lot of science but specifically to the need to better characterize and understand the quality of water in private domestic wells.

As was true for many of the studies of arsenic that occurred early on, maps of the arsenic hazard published by Dr. Zheng were very valuable. There is a hidden value in these maps—the visual understanding of what might control high arsenic concentrations in an area. In many cases, including in this article, the two-dimensional maps reveal insights into arsenic mobility, such as redox controls, which is three-dimensional. This led to new research that explored arsenic mobility with a larger understanding of the geologic and hydrologic framework and gave rise to now-common three-dimensional characterization and predictive modeling. Additionally, researchers are still discovering how information about redox controls on the mobilization of arsenic can help explain the sources of arsenic and better define how it gets into drinking water. This fact means that Dr. Zheng’s paper is still very relevant today and may help explain its high citation rate.

Q2. How did the knowledge learned from this article shape your research related to groundwater issues in Bangladesh and elsewhere afterwards and your professional career in general?

Yan: At the time I was a newly minted marine geochemistry PhD so this was a starting point for hydrogeochemistry. I recall reading several hydrogeology books and a few hundred papers in 1999 in order to
make this switch. Honestly, I didn’t think this paper discovered anything that was entirely unknown. In my reading I was so impressed by Garrels, R.M., 1967 (Ref: Genesis of some ground waters from igneous rocks. In: Abelson, P.H. (Ed.), Research in Geochemistry. John Wiley & Sons, New York, pp. 405–421) (Fig. 2). There were many clues about iron-redox driven arsenic mobilization in other earth systems previously, and even in groundwater systems. So this really is me doing the homework. Having to think through where to go to study, how to do field measurements (Fig. 3), and to collect groundwater samples and maintain redox states (there was arsenic speciation data collected by anion exchange columns that took a looooong time each column), taught me a lot. After this, I feel I am qualified to study groundwater chemistry (Fig. 4). So this was a practice to become a hydrogeochemist if you wish.

Joe: In 2004, we were just starting to understand the extent of the arsenic hazard in New England in the
northeast corner of the United States. Data we had compiled showed a pattern to high arsenic concentrations that we identified as geogenic, when previously this was not known. Dr. Zheng’s paper described the redox conditions in Bangladesh that led to the mobilization of arsenic into groundwater, and although we were aware of such conditions, this paper helped solidify our understanding of the impact of reducing conditions on arsenic mobility in our region. Dr. Zheng’s characterization of redox status, using the thermodynamic progression of redox couples of common groundwater constituents, allowed her to understand where arsenic was occurring in the aquifer. Although different in the northeastern United States, the framework still applied and was directly applicable to our own work.

Jing: I actually did not read this article until I entered the Ph.D program in Columbia University in 2010. I joined the Columbia Superfund Research Program and got to know Dr. Yan Zheng then as she was one of the PIs of our project. At that time, it was fascinating for me to know that one of the biggest environmental threats to populations around the world was geogenic. Beside studying groundwater issues in Bangladesh, a major work Dr. Zheng did in our project in fact was to partner with state and local governments to reduce arsenic exposure in communities that rely on arsenic-contaminated household wells in Maine, New Jersey and Minnesota, U.S. Because of the work from Dr. Zheng and her team (Figs. 5 and 6), Maine legislature established the Private Well Safe Drinking Water Fund in 2017, to improve the rate of testing of residential private drinking water wells (see https://www.mainelegislature.org/legis/statutes/22/title22sec2660-W.html). It was nice for me to see that what scientists do can really help people, which to some extent strengthened my belief in becoming such a scientist.

My Ph.D thesis work was about developing improved strategies of remediating arsenic contaminated aquifers. As learnt from Dr. Zheng’s paper, arsenic naturally contained within aquifer sediments is often solubilized under suboxic conditions where the host minerals - iron(III) oxides are unstable. Therefore, during my Ph.D, I spent a lot of time trying to find a mineral that is arsenic-sequestering and stable under typical redox conditions of high arsenic aquifer, and to find ways to form the mineral. The mineral I found is magnetite. How to form magnetite in situ and thereby mitigate the groundwater arsenic problem is still one of the projects I am focusing on.
Q3. This article was in a special issue: Arsenic in Groundwater of Sedimentary Aquifers. What are the upside and the downside of submitting an article to a special issue?

Yan: The upside is that it has higher chances to be read by those who are interested in the topic and who are looking for other people’s papers in the same special issue. A minor benefit is that the guest editors, being well versed in the topic, are likely going to be able to identify more appropriate reviewers for the article. The downside is not very many now that most journals publish the article as soon as they are accepted electronically. In the dark ages of early 2000s when articles are actually printed, you’d have to suffer a very long in press time to wait for the whole special issue to appear, which was the case of this paper.

Joe: Special issues of journals are useful in many ways in that they represent a collection of recent research into a topic. In this case, it was a way to quickly identify an international body of work that might apply to one’s own study of an issue in another part of the globe. One downside is perhaps the possibility of overlooking other work that might also be relevant but is less obvious. That is, it is difficult, because of timing, to get the best mix of papers into a special issue. That said, these issues are minor really, considering the benefits.

Q4. As a prestigious and knowledgeable expert, could you briefly summarize and envision the hot research topics on the groundwater quality and public health in the near future, as well as describe your personal research interests related to it?

Yan: It is an interesting question. Groundwater and public health scientists share one dilemma. If we do a good job, then no one will notice anything amiss. Both disciplines are overlooked until disasters strike, like the current pandemic, or the groundwater arsenic calamity. I would hate to make such a prediction because I would rather envision there will never be any hot research topics because health effects of poor groundwater quality have caused deaths and diseases. Sadly, because humanities have long treated groundwater as a “grave” for all things polluting, the groundwater quality problems are going to get bigger everywhere and will limit our ability to use groundwater to buffer the effects of climate change. We always “discover” new contaminants in groundwater and act very “surprised” each time when it is actually entirely predictable based on the way we have been treating groundwater. I would rather see efforts devoted to serious discussions on governance of groundwater. Simple things such as do not extract more than what the nature is recharging and you can top-off by augmenting recharge. We got to get very serious about managing and monitoring our groundwater use, including groundwater quality. And do so in a meaningful way with proper monitoring network and trained people.

Joe: As much as we know about the global arsenic hazard, we continue to find high concentrations of arsenic (and increasingly other geogenic contaminants, such as uranium) in groundwater used for drinking water. Many of the high concentrations affect private sources of water supply (private wells). Water from private wells (and features of the wells themselves) remains poorly characterized in many places around the world. This has led to a dichotomy of human exposure to contaminants because water supply from private wells is largely unregulated, whereas public water supply is. Understanding the risk of exposure to arsenic and other geogenic contaminants in drinking water from private water supplies and how it relates to adverse human health outcomes remains a critical need. This need drives much of the work I do at the U.S. Geological Survey, under the Environmental Health Program of the Ecosystems Assessment Mission Area. Our research continues to identify hazards, develop predictive models, and assess potential exposures and adverse health outcomes (Fig. 7). We also develop scientific understanding to
help reduce exposure to these hazards, such as identifying alternative water sources and potential modifications to wells.

**Figure 7.** Probability of groundwater arsenic >10 μg/L in US.

**Q5. In your opinion, what are roles for the decision makers, scholars and ordinary populace to play respectively in reducing arsenic exposure?**

**Yan:** We need a framework for groundwater governance to have these roles sorted. When it comes to private or domestic well water that are relied upon by a very large fraction of rural population in both low- and high-income countries and possibly over one billion people (this number is not known), there is often your water your own problem governance structure which results in the great tragedies we see everywhere. This problem is very prominent in the United States. The United Nations General Assembly voted in 2010 to recognize “the right to safe and clean drinking water as a human right.” But, there are many caveats. The end result is that if you are socio-economically well off, then you have the means to reduce arsenic exposure so this result in an environmental justice problem. This is where government should step in but often it does not. As researchers, we can all spare a little bit of our time to advocate for those who are silently suffering from the exposure to this deadly poison.

**Joe:** From the science end, decision makers and citizens would benefit from requesting research on how to avoid arsenic in drinking water where possible. This means scientific study of well operation, water sources within aquifers, and alternative aquifers, in places where private well use is the main source of water supply. Recent research shows that reduction of exposure through treatment of individual private wells, although technically feasible, may not reduce exposure sufficiently. Decision makers can impart greater equity in safe water by removing the human element (relying on well owner purchase and maintenance of water treatment systems) in favor of water systems that are inherently arsenic free, such as alternative sources of water that do not contain arsenic. In some cases, these may be readily available, such as an alternative aquifer or particular zones in an aquifer, but may require alternative well types or construction. This remains a knowledge gap and there is a dearth of focused scientific investigation aimed at improving well technology.

**Q6. This article involved quite a lot of field work. What is the necessity of field work? What is the challenge?**

**Yan:** Observation is essential to progress in earth science. This is no different for hydrogeochemistry which involves field based observations (Fig. 8). Beyond observations, there are also field experiments which are even more challenging (Fig. 9). The challenges of field work are despite obstacles the scientists are still out there to make credible observations. If one is not driven by getting to the truth, it’s easy to see why frequently the quality of the observation is
poor. So the challenge is to ensure that the field observation and experimental data are valid and can stand the test of time.

Joe: Field work generates observational data. Much of the focus of global arsenic work has migrated toward model development and model-based predictions of arsenic hazard. While the development of models has been of great benefit, their development has only been possible because of the vast amounts of data produced from field work. The challenge is that to improve models and model predictions, it is necessary to also collect new data from the field. It is an iterative process that requires the incorporation of new methods, improved accuracy in measurement, and innovative analysis of those data to inform the next generation of models and modeled predictions. Because it is not feasible to field sample exhaustively at fine scales, careful application of this iterative process will need to continue for a long time.

Jing: The laboratory system often remains simple and unitary, while the natural aquifer is complex and convoluted. Laboratory results, therefore, cannot easily be used to predict the behavior of arsenic in real groundwater systems. This is part of the reason that, despite massive research, how to cost-effectively reduce human exposure to excessive arsenic from drinking and irrigation water in the rural areas still remains a difficult question. This is also the reason that field work is necessary (Fig. 9). Nevertheless, the elements contained in the groundwater are affected by a large number of not only biogeochemical but also physical (hydrogeological) processes. Quantitatively untangling these processes, and deciphering how they interact, in real groundwater systems remains a grand challenge.

Q7. Are there hidden interesting stories behind this article? Were there struggling issues or troubles encountered when you wrote it?

Yan: I would like to express my gratitude towards the late Professor Dipankar Chakraborti of the School of Environmental Studies, Jadavpur University, India (Fig. 10). Professor Chakraborti is legendary in his
relentless advocacy for the plight of arsenic affected. I could not have made this map without the >6000 well water As data collected by the bicycle team consisted of his students. One of the students, Ratan Dhar, a Bangladeshi, became my first PhD student, and Professor Chakraborti gave permission to Ratan to share this dataset with me so I can think about it like a geologist. What a generous man. I met Dipankar and Ratan in Feb 2000 in an intimate arsenic conference hosted by Wagner College located on Staten Island, NYC. Ratan had just won a green card lottery so he immigrated to the US. At the conference banquet, Dipankar introduced Ratan and asked him to sing a Bengali song that was one of Tagore’s poems and said that Ratan is most interested in becoming a PhD student. Because it was in Bengali, I didn’t even know what poem it was. But Tagore was and is my favorite poet. And Ratan sang very well! So I immediately went to talk to them and offered Ratan a studentship on the spot. I still could not believe how lucky I was. As they say, the rest is history.

I struggled a lot with the colors in the arsenic map, Fig. 1 of AG 2004 paper. I spent about a week in Adobe Illustrator picking out the perfect color and tested on my Introduction to Geology students.

Figure 11. Yan Zheng with Hun-Bok Jung and Abjihit Murkejee, Beth Weiman, Palash and the local drillers. This was 2007 in Bangladesh.

Q8. Do you have any advice for the next generation of scientists who would like to pursue groundwater-focused M.S., Ph.D and postdoc?

Yan: My advice is that if you like being ignored and left alone, then groundwater is a wonderful topic to get into. It is still full of mystery waiting to be discovered, but only if you are patient. And you are good at plumbing. The world needs more well trained hydrogeologists and hydrogeochemists. I was not trained in this field, but it welcomed me into it (Fig. 11), because there were needs and not enough people were trained to study it. I believe the needs are still there today.

Joe: The importance of the groundwater resource cannot be overstated. There are so many science questions that need investigation and many more that are developing, which means that the field of groundwater science is full of opportunity. I believe that there is opportunity for skilled investigators who are generalists in classic hydrology. This means a strong foundation in math and physics, and hydrology and
geology. Also, being open to interdisciplinary science is valuable — groundwater science informing public health is critically important and is increasingly being sought.

Q9. Women are still underrepresented in the world of scientific research. What do you think needs to be done to tackle this?

Yan: I suppose the correct answer is that we need to do more research to determine the cause of underrepresentation and then solve the problem? Implicit bias is well and alive. Opportunities are clearly not equal. As an individual woman scientist, you can’t count on the world to change so best to adapt and to acknowledge that women scientists need to be more accomplished than male scientists to receive similar recognition. I just focus on what I love to do the most and ignore what others think of me. Institutions and societies are slowly but surely evolving to be more gender conscious if not entirely gender equal so seize on every small little opportunity to make it a better working environment for our daughters and granddaughters. By this I mean both men and women need to work towards gender equality (Fig. 12).

Joe: Although the U.S. Geological Survey, as one example, has come a long way on the topic of equality of women in science (Fig. 13), we still face challenges. Efforts to promote females in STEM at all levels and equality in general have brought us closer to where we should be. Still, we all need to look for ways to affect positive change, and in my experience, the change toward gender equality is improving the workplace for all. More than ever, leaders in our agency, and future leaders, are women. I believe that this is happening because of leadership shown by many of the men and women at the highest levels of our agency. Leadership happens at all levels, but leadership from the top can ultimately transform the workplace.

Jing: It is good to see that now the Chinese society is consciously promoting the career development of female scientists and engineers. Still, I believe that we need to build and improve the platform for the female scientists and engineers, to exchange ideas, to collaborate, to learn from or act as role models, and to jointly promote women’s equal rights and interests.