The Intersection of Groundwater Contamination and Human Health: Summary of an Interdisciplinary Conference

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Abstract
Some characteristics of karst aquifers make them particularly susceptible to contamination. The reliance on groundwater for drinking supplies in karst regions creates the potential for public health effects. Elucidating potential human exposure and health effects requires an unexploited multidisciplinary approach that was the focus of this conference. Diverse perspectives on the hydrology, geochemistry, and microbiology of karst systems, contaminant transport, exposure concentrations and human health, and regulatory approaches bring us closer to our goal of protecting human health. Summaries of the keynote and research talks are given here. Group discussions are reported as conclusions and recommendations from the conference. New investigative tools, improved quantitative approaches, innovative data analysis, and true multidisciplinary studies are necessary to advance knowledge in this field.

1 Theme of the Conference

Notable public health concerns in the karst regions of Puerto Rico provided initial motivation for this conference convened to explore karst groundwater contamination, consequences for human health, and regulatory issues in karst water resources. This chapter includes summaries of the presentations organized along the same structure as the conference: context for contaminant transport in karst, research advances in tools for investigating hydrological transport, and new findings from studies of exposure concentrations and human health, followed by presentations on regulatory and legal perspectives. Each presentation summary is attributed to the speaker, and their papers or abstracts can be found elsewhere in this volume. The group discussions held after each group of presentations identified emerging themes of needed research directions and management reform. A summary of the group discussions is presented as the conclusion of this chapter without attribution to the individual among the 71 conference participants who articulated the idea.

The question driving this conference was whether and how people's health might be affected by contamination of karst groundwater. The broad scope of topics needing the attention of scientists, health professionals, and policy specialists in order to address that question was established in the welcoming talk by Heather Henry. Recognizing karst aquifers as an important source of drinking water for much of the world, the occurrence of infectious agents and various inorganic and organic contaminant chemicals in karst groundwater requires new multidisciplinary approaches integrating expertise drawn from the domains of human and environmental health, geology and hydrology of karst, and laws and regulations. Henry asserted that a multidisciplinary research approach holds promise as a framework to understand the interactions between contamination in karst aquifers and human exposures as well as developing best practices for engaging communities and stakeholders to protect public health.

Negative public health outcomes in Puerto Rico were elucidated in the conference-opening lecture by José

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Cordero. Cordero described the extent to which preterm birth plagues Puerto Rico. Connections to chemicals in drinking water are suspected, and the Puerto Rico Testsite for Exploring Contamination Threats (PROTECT) team is conducting research funded by the National Institute of Environmental Health Sciences (NIEHS) to test these connections. The geographic association of karst groundwater used for drinking supplies, presence of organic contaminants, and hot spots of preterm births strengthens the likelihood of a causal relationship between the manufacture of birth control pharmaceuticals with its attendant wastewater discharge and the downstream consumption of water leading to deleterious human health outcomes. Additional connections between human health and contaminated water in karst terrains require further elucidation.

1.1 Current State of Knowledge in Karst Contaminant Transport

The stage for groundwater in karst being vulnerable to contamination was set in two initial keynote lectures. William White presented the systematics and mechanisms by which contaminants enter and migrate through karst aquifers. The physical properties of karst systems allow hydraulic behavior that ranges from slow groundwater flow through porous media to swift surface water flow in open channels. As a result of the broad range of aquifer characteristics, contaminants can move into and through the karst subsurface, contaminant transport can occur quickly, and contaminants can sometimes end up in unexpected places. Ingrid Padilla brought the focus of the discussion to the geologically young karst of Puerto Rico. There are 22 Superfund sites in Puerto Rico, and 55% of them are on karst even though only 20% of Puerto Rico is underlain by karst. Padilla pointed out that published maps of contaminant occurrence are artifacts of the way in which groundwater is monitored. Maps neither fully describe contaminant occurrence nor reveal sources of contaminants, because the maps reflect only the available data that come from monitored wells. Overlain on spatially non-uniform monitoring, the monitoring period for some contaminants has been long while only shorter records exist for other contaminants. Data that reflect in time and space what investigators were purposefully looking for resulted in maps of contaminant occurrence that are not true representations of overall groundwater quality. Taken together, the White and Padilla presentations demonstrate the need for improved approaches to investigating contaminants in karst and for making connections to human health.

2 Research Advances

The fundamental question regarding environmental contamination and human health is, first and foremost, “Was anyone exposed?” Establishing exposure is neither straightforward nor part of typical health studies. Knowledge about exposure is built from information on sources of contaminants and their subsequent fate and transport in the environment. Sources, fate, and transport of contaminants are studied by environmental scientists. The hydrogeological, geochemical, and microbiological conditions of a given environment determine the processes controlling contaminant fate and transport. Only after release, biogeochemical alteration, and hydrological migration through the environment can exposure be considered. The medium of exposure is often water, the same medium of transport. Exposure may be by direct consumption through drinking, indirectly through water use in food preparation, or by contact in the environment such as by swimming. Finally, degree of exposure is very difficult to quantify, especially in the analysis of historical data. The goal of elucidating potential human exposure and health effects from the occurrence of contaminants in the environment requires new multidisciplinary studies and research discoveries. Information from studies of the hydrology, geochemistry, and microbiology of karst systems, contaminant transport, exposure concentrations, and regulatory approaches are all needed to bring us closer to our goal. Results of such investigations were presented at this conference.

2.1 Contaminants and Tools for Investigating Contaminant Transport

The Swiss experience with delivering drinking water safe for human consumption is focused in part on microbial contamination. Michael Sinreich described a detailed monitoring study in which bacteria, viruses, and protozoa were all found in higher concentrations in karst waters than in non-karst regions. Although total bacterial cell numbers were stable over the course of storm events, the proportion of *E. coli* was higher directly after storms. Molecular markers revealed a mix of human and ruminant fecal contamination of rural karst springs. A large number of molecularly traced viruses, some of which were pathogens, have been detected, but this study did not include an assessment of outcomes for human health. One conundrum that emerged from this research was the revelation that molecular markers are more persistent in water than are live bacteria, causing new questions about the appropriate connection between concerns for human health and the targets of monitoring by water supply purveyors.

Ashley Bandy studied the transport of bacteria with different tendencies to attach to solids in comparison to the transport of inert particles and of dye. The multiple tracers released into the epikarst overlying a cave system in Kentucky revealed that all particles broke through in advance of the dye, sticky and non-sticky bacterial breakthrough behavior depended on flow conditions, and overall mass recovery of all tracers was extremely low. Although quantification was not possible, clear differences in solute, particle, and bacterial transport were illustrated. The future success of any predictive transport models in capturing the behavior of bacteria in karst systems depends upon a vastly improved understanding of transport mechanisms.

Elucidation of the contamination scenario in each case is key to an effective cleanup response and to improved management of water resources in general. Correct source identification is an invaluable tool to achieve that end. Organic micropollutants indicative of untreated sewage and treated sewage as sources were described in the research presented by Johannes Zirlewagen. By analyzing pharmaceuticals and food additives with inherently different degradation rates and with different histories of usage, Zirlewagen used the presence and ratios of various compounds to indicate the source of contamination. Further, the results were not simply qualitative indication of source but quantitative partitioning of sources into their respective magnitudes of contribution. Ferry Schiperski extended the case for the utility of organic micropollutants detected in karst springs as a powerful tool for revealing hydrological transport processes in karst aquifers. The analysis of both currently used and legacy herbicides proved conclusive in distinguishing a surface water source from an aquifer matrix source of storm flow. Analysis of a food additive provided indication of sewage overflow during some storm events. In contrast to easier-to-measure constituents such as electrical conductivity and turbidity that are routinely monitored, the details of micropollutant concentrations revealed a great deal more about quantitative source contributions than is commonly known for water emerging at karst springs. These investigators are using the insights they have gained to interpret hydrosedimentary evolution of the aquifer as influenced by particle transfer from the land surface, deposition and resuspension within the aquifer, and emergence at the spring. Future research may focus on wider adoption of such analytical methods by other investigators with a view toward informing water management and aquifer protection strategies.

Karst springs in the Alps hundreds of kilometers distant from Vienna supply high-quality water to the capital that has undergone as little treatment as possible. This strategy for minimal treatment is critically dependent upon careful source-water monitoring so that abstraction from any individual spring can be managed to achieve the best water quality. The target for monitoring is any indication of fecal pollution, and Hermann Stadler collected measurements over the course of rainfall events using automatic samplers and satellite communication. Spectral absorption at 254 nm, a function of dissolved organic carbon concentration plus turbidity levels, can be measured remotely with an automatic probe. During rainfall events, absorption increased along with increasing *E. coli* numbers. Because spectral absorption began to increase slightly in advance of *E. coli* appearing at the springs in concerning numbers, it proved a useful early indicator for water management decisions. Andreas Farnleitner advanced fecal hazard assessment for the Austrian alpine springs using molecular source tracking. The great variability in *E. coli* occurrence in springs was shown to be in part due to its growth outside the enteric system, casting suspicion on its usefulness as an indicator of human pathogens. Instead, *Bacteroides* spp. are clear indication of fecal contamination, but quantitative molecular RNA analysis is required to distinguish human from ruminant (cows, mountain goats) sources. Now, the water supply managers are using quantitative microbial risk assessment to plan the level of treatment necessary for protection of human health.

Non-infectious agents such as metals in drinking water present potential risk to human health. The processes controlling metal mobility in karst waters in Florida illuminated the role that flow conditions played in mobilization of metals. In the study system, high dissolved organic carbon concentrations are characteristic of organic-acid-rich surface waters, low dissolved oxygen levels are typical of most of the limestone aquifer with some anoxic groundwater in the deep matrix, and fully oxygenated conditions prevail in cave passages. Amy Brown explained how groundwater–surface water interactions contrasted greatly between intense summer thunderstorms that tended to recharge high-DOC surface water to the subsurface and the steady rain of the winter wet season that tended to displace old anoxic water from the matrix into conduits and cave passages. The contrasting patterns of water influx and efflux within the highly heterogeneous karst system were the ultimate controls on metal mobilization.

Biodegradation of organic contaminants such as fuel hydrocarbons may reduce the concentrations of constituents of concern for human health effects, yet the rapid transport of groundwater in karst aquifers is often assumed to minimize the potential for biodegradation. Thomas Byl showed, however, that plenty of bacteria to affect biodegradation are present. Although attached bacteria may not find sufficient surface area in karst aquifers to maximize biofilm formation, free-floating bacteria use flagella and buoyancy control to move toward biodegradable contaminants. The rate of biodegradation can be enhanced by the addition of electron acceptors, co-metabolizing substrate, and vitamin B that is used by many redox enzymes, and Byl found improved rates of biodegradation when soy infant formula was introduced to the contaminated aquifer.

Ljiljana Rajic took a different approach to experimentally manipulating groundwater redox conditions without the addition of chemicals. With trichloroethylene (TCE) as the target contaminant, solar-powered electrolysis showed promise for reduction to ethane at the cathode. Coupled to TCE reduction, oxidation of ferrous iron at the anode to ferric oxyhydroxide precipitate can act as sorption substrate for other contaminants such as chromium, arsenic, and selenium. In practice, a simpler application of solar-powered electrolysis may be more immediately useful. Using palladium to catalyze the production of hydrogen peroxide in the presence of Fe(II) resulted in the release of hydroxyl radicals to a flow cell emplaced in a well. Pumping contaminated groundwater through the flow cell resulted in lowered contaminant concentrations. The continuous generation of reactive oxygen species for the degradation of organic contaminants may be a useful point-of-use treatment strategy.

Numerical models that identify land areas with a particular susceptibility index for potential contamination are used as part of the regulatory strategy to protect drinking water supplies. Whether these models are suitable for application to karst regions has not been determined. A test of a widely used model for a problem of nitrate contamination of groundwater in Florida revealed shortcomings in its application to karst aquifers. Philip van Beynen proposed a new karst aquifer vulnerability index and argued that it was a necessary tool in successful water resources management.

The fundamental dilemma of addressing groundwater contamination in karst is the great uncertainty about where within the karst subsurface the contaminant is located. Malcolm Field presented a scenario for karst aquifers in which dense non-aqueous phase liquids (DNAPL) might have drained into a sinkhole and might be present in spring discharge, but in between the input and output, the investigator knows nothing about where the contaminant is and what is happening to it. From a regulatory perspective, remediation success is evaluated by recovery of the contaminant, but such an assessment may be impossible for karst systems. If karst is then technically impractical to remediate, prevention becomes the only employable strategy. Therein lies a regulatory disconnect: although the national US Environmental Protection Agency (EPA) controls remediation requirements, it is some local entity that establishes land-use policies that would affect prevention. EPA is not an effective agency in prevention strategies, but other national-level agencies may successfully play a role in proactively protecting karst. For instance, the US Fish and Wildlife Service can use the Endangered Species Act to change local land and resource use that effectively prevents contamination of the karst subsurface.

2.2 Exposure Concentrations

The hydrogeological transport presentations touched on numerous contaminants of demonstrated deleterious effects on human health: metals, fuel hydrocarbons, synthetic organic compounds such as pesticides and solvents, inorganic chemicals, bacteria, and viruses. The occurrence and fate of such compounds were the focus of the transport studies. Direct demonstration of consequences for human health was beyond the scope of the fate-and-transport studies. Human health was more explicitly the focus of investigations by the next set of speakers.

In 2015, the World Health Organization published a Global Action Plan on antimicrobial resistance that included recognition of the role for water and the environment in any effective plan for the future protection of human health. Fabienne Petit described research into the occurrence of antibiotic resistance of *E. coli* in karst groundwater in France. Quantification of the distribution of various strains in the overall *E. coli* population was the basis for assessing the prevalence of antibiotic-resistant bacteria. Human and bovine *E. coli* showed more resistance, and their relative prevalence in the overall pool of *E. coli* cells collected in water samples depended upon prevailing hydrological conditions. During rainfall events, there were more antibiotic-resistant strains in water samples. In fact, these *E. coli* tended to associate with non-settleable organic floc. In contrast, under dry conditions, there were more antibiotic-sensitive strains present, and these cells tended to associate with mineral particles. To devise an effective disinfection scheme, detailed monitoring of bacterial strains in environmental waters is appropriate yet rarely employed. All *E. coli* persisted for more than 2 days in the environment, and Petit concluded there was a permanent reservoir of genes in the aquifer such that the potential for gene transfer existed, causing significant concern for future human health.

Teasing apart human from bovine fecal contamination is fundamentally important to assessing the risk to human health. Maureen Muldoon demonstrated extreme fecal contamination of karst groundwater in Wisconsin where confined animal feeding operations generate a liquid waste slurry that is applied to the sometimes snow-covered land surface. Currently, manure application is based on nitrogen needs for corn production and to minimize surface water runoff. Snowmelt or rain-on-snow events result in brown, smelly, high-nitrate groundwater in domestic wells. Federal regulations managing nutrients apply to runoff not infiltration, so regulatory policy is not preventing manure contamination of groundwater. The practical issue for human health outcomes is the question of if and when viruses or bacteria arrive at wells. Anecdotal evidence of gastrointestinal illness abounds, but direct confirmation of enteric organisms in drinking water has proved elusive. Although qPCR analyses of human and bovine viruses and of bovine *Bacteroides* are possible, collecting a large volume of water from a domestic well in a time series that includes samples prior to, during, and after the "brown-water event" has proven difficult.

Measuring actual human exposure to pathogens or contaminants is a special challenge. Instead, public health professionals ordinarily turn to epidemiology, or the study of patterns and occurrences of disease in a population in which co-variants can be well measured. John Meeker explained the complex ways the introduction of a contaminant into the human body can nonetheless lead to many different physiological and biochemical pathways, transformations, and outcomes. In seeking to better understand the connection of exposure to health, biomarkers are emerging as useful tools. Biomarkers can help reveal details of physiological processes acting upon compounds or pathogens without subjecting study participants to direct risk. For the assessment of hypothesized exposure–health connections in a population, the National Health and Nutrition Examination Survey (NHANES) contains useful information on human health; however, making connections to environmental exposures is limited by the privacy restrictions on the health data that remove location information. Giving scientists knowledge of location would allow the identification and assessment of environmental factors associated with human disease outbreaks.

Marian Rutigliano presented a different perspective on making the environment–health connection. Rather than start with human health data and try to assess causative environmental factors, some success has been realized by starting with the environmental occurrence of suspect chemicals and then looking at health data. Some notable traits of karst waters include high lithium concentrations, widespread occurrence of culturable enteric viruses, and elevated *E. coli* associated with high rainfall. Knowing some of these environmental facts about karst, the question then becomes whether there are connections to health outcomes. For high lithium concentrations, public health records show fewer suicides, fewer hospital admissions, and greater incidence of hypothyroidism, all plausible direct health outcomes. The consequence of the presence of viruses and bacteria is more difficult to relate, because unusual numbers of transient illnesses are difficult to detect. Given the role of local hydrological processes in creating exposure events, having spatially distributed human health data would go a long way toward making this type of analysis possible. Recommendations for high-frequency chemical and biological monitoring of karst waters, including preceding and during peak discharge events, arise from the desire to make these connections. Rutigliano also points out that human health is not only influenced by drinking water quality. Vapor exposure to volatile compounds and dermal exposure in recreational waters may also influence human health.

Research into the geographic association of health outcomes and mining activity was presented as an example of the direct connection of environmental contamination to public health. Michael Hendryx used mortality data by county in West Virginia to establish the location of health outcomes, because reports of deaths are easier to obtain than reports of disease occurrence. To test correlations between environmental contamination and public health, geographic information must be included in data about disease occurrence. Hendryx made a strong case for economics being important to building a compelling argument for environmental regulation, because the balance of the cost of restrictions on contaminating industries pales in comparison to the costs associated with diseases and deaths.

A tiered approach to monitoring and regulating water quality was suggested by Samuel Dorevitch. EPA guidance for characterizing and reporting on recreational water quality was presented as a better model for monitoring karst groundwater than the guidance for drinking water in a distribution system. The difference in approaches is that the first results in prioritization of monitoring for more susceptible waters while the second demands uniform monitoring that may not detect rare occurrences of pathogens. Local public health departments have several tools that can be applied to the nexus of human health and water quality. They can (1) order limitations on water usage through advisories, (2) issue permits for on-site septic systems, and (3) collaborate in environmental studies with the disease data that they collect. Dorevitch recommends that environmental scientists interact more with public health officials to gain the type of insights desired by the participants in this conference.

3 Directions in Regulation

Most regulatory policies for protection of drinking water supplies were developed for non-karst regions. Strategies effective for other geological terrains do not work well for karst systems. New approaches to ensuring high-quality drinking water in karst regions are needed.

3.1 Regulatory Issues in Karst Water Resources

Well-head protection is widely used with great success in many regions of the world. In practical terms, this policy limits land use and excludes contaminant release to areas outside a contributing area for a water supply well. James

Berglund explained how practitioners interpret the rule in Minnesota: according to a radial distance equivalent to an anticipated 10-year time-of-travel for water to reach a community well. But, unequivocally, time-of-travel delineation does not work in karst. Yet, state regulations do not allow variance in the application of regulations from site to site, even if the underlying geology is different.

Jesse Richardson emphasized that, legally, legislated regulations must be generally applied, because allowing case-by-case decisions invites arbitrary and capricious enforcement. Further, for laws to be useful, they cannot be vague. Because most regulatory power resides in the states, there are variations in regulations that can be examined for effectiveness. Interestingly, Puerto Rico has the best law for protecting karst water quality, although the Act for Protection and Preservation of the Caves, Sinkholes, and Caverns of Puerto Rico was not devised with that goal in mind. This example points to the role that land use restrictions play in the secondary outcome of water quality. Most zoning of land use is decided at the local level, and local governments are typically underfunded. Establishing a buffer zone around identified karst features is the most common strategy employed, even though the expertise necessary to thoroughly identify such features is often not available. Richardson recommends turning to non-regulatory approaches to restrict land use. Conservation easements and the transfer of development rights may prove to be more successful in preventing the contamination of karst groundwater than existing state regulations meant to protect water resources.

Regulations for emergency response to contaminant spills are usually oriented toward protecting surface waters. Geary Schindel documented hazardous material spills in Texas for which the response is to flush with large volumes of freshwater. In regions underlain by karst, the excessive release of water on the surface can lead to pushing contaminants into the subsurface, thereby entering the drinking water supply. Sewage line breaks with attendant infiltration of wastewater into shallow karst can result in pathogens in groundwater. Ingrid Padilla corroborated the San Antonio experience with sewage leaks by adding observations from Puerto Rico where water distribution lines lose 60% of their supply and the loss rate from sewer lines is even greater. James Berglund had also pointed out concern for water supply contamination in karst arising from abandoned and unsealed wells creating a direct connection to groundwater even if the land surface is adequately protected.

Acts of environmental conservation can be consequential for the protection of human health. Abel Vale related the history of the preservation of natural areas in Puerto Rico as an example of the vital ways in which karst, water, and humans intersect. Laws enacted to protect caves and other karst features as natural resources had cascading positive effects. Initially safeguarding natural areas from urban sprawl and infrastructure development, these laws also brought about the protection of water quality that led to the protection of human health. The non-profit, non-governmental organization Ciudadanos del Karso (Citizens of Karst) in Puerto Rico has actively supported legislation to conserve karst features. Vale presented this strategy as a successful approach to the difficult challenge of protecting water quality and human health.

4 Emerging Themes and Conference Conclusions

Through several days of moderated discussion including all the conference participants, agreement emerged on identification of knowledge gaps, research needs, and future directions.

Karst is particularly prone to contamination. Strong agreement that karst is particularly prone to groundwater contamination is the starting point for summarizing the meeting conclusions. Depending upon the nature of the contaminant, it will behave differently in terms of fate and transport. The amount and timing of contaminant release will determine whether the result is a long-term problem or an immediate emergency. Rapid transport is the key trait of migration in karst, with conduit–matrix interaction critical to determining transport phenomena. Different tracers yield different travel times, a problem that also applies to different contaminants. Rapid transport of constituents with differentially enhanced or retarded breakthrough requires thoughtful and continuously revised decisions about sampling frequency for water quality monitoring. Dealing with highly variable concentrations in monitoring remains an issue in terms of management, because which value should guide the application of regulations is not clear.

Site-specific studies play a crucial role. Karst is such a heterogeneous terrain that it is difficult to generalize its properties for the purposes of developing the best regulations. Explicit consideration of the connection of the land surface to groundwater through epikarst should be part of every hydrological study. Even for all the efforts to move past case studies, site-specific studies are needed for the best regulatory protection or remediation outcome.

Pollution prevention is essential. Pollution prevention strategies are particularly needed in karst. The community of scientists should determine the best tools for assessing susceptibility of karst to contamination, thereby maximizing prevention. More attention is required in developing remediation strategies for the unavoidable or legacy contamination issues. New modeling tools may prove useful in generalizing the phenomena observed in karst aquifers. In addition, some looming issues have not yet been researched, such as the potential for climate change to alter the microbiology in karst. Bacteria that cause gastrointestinal disease or that cause oxidative stress (a contributing factor in preterm birth) may be more widespread in the warming climate of the future.

Documentation of human health effects requires additional data and a new approach to data analysis. A knowledge gap hinders identification of the environmental cause that directly results in human health effects. The lack of compelling connections stems from several factors. There is a time lag between exposure to a contaminant and the expression of disease. There are both acute and chronic health effects that present at different times. The dilemma was characterized as a time series analysis problem, one that might benefit from creative analysis of big datasets. We need to collect disparate information into an integrated database that includes public health statistics. In epidemiological and multivariate analyses that endeavor to use lots of data, a big problem is finding studies that were conducted and reported in comparable ways. Sharing data is important to make studies intercomparable. In human health studies, there is more uncertainty in any individual variable of study than in nearly any other science. Significant work is required on how to best account for uncertainties.

Collaboration between health and environmental scientists is necessary. Feedback is needed from health scientists to contaminant hydrogeologists and karst scientists about what environmental variables are most useful in predicting or protecting public health. Medical specialists might provide information to field and laboratory scientists on what subtle water quality or microbial changes might have the largest consequences for human health. That is, what environmental knowledge is most useful to human or environmental health studies? In general, scientists need to work with local health departments. Public health departments are the basis for discerning health effects and yet are underfunded. To make progress on the relationship of environmental contaminants and health outcomes, increased workforce—both in terms of expertise and in numbers—is needed.

Revised regulatory approaches are required for karst systems. Appropriate protection of karst groundwater is a highly valued goal. Standard regulations do not sensibly apply to karst, and unique regulations appropriate to the protection of karst are needed. The legal requirement that state regulations be uniformly applied is indefensible given existing scientific knowledge. Scientists might collaborate with lawyers to bring lawsuits challenging current laws. It is possible to make laws to avoid certain activities in karst; some states forbid the construction of landfills on carbonate bedrock and allow no room for negotiation. The fact that some states have more protective regulations than other states argues for national standards. Perhaps a national standard for well construction in karst is appropriate. Failing the establishment of a legal standard, even a national guidance document would be useful in overcoming local variations in regulations. There may be no foolproof strategies for the environmental protection of karst, but we have far more scientific knowledge about the contaminant hydrogeology of karst aquifers than is reflected in the laws and regulations that currently prevail. Meeting participants expressed concern that environmental agencies are underfunded.

Human health is critically dependent upon environmental health. The consensus of the inextricable connection between environmental health and human health should be adopted by all investigators so that all future work is conducted from the point of view that if environmental health is degraded, human health is degraded. Working from this premise offers the best hope for protection of human health. It is public policy, usually motivated by health issues, that drives research in karst.

Cross training in multiple disciplines and effective communication are keys to the future. Broad recommendations emerged from discussions about how to generate new ideas and approaches. Increasing diversity and inclusion in the population of scientists and in the communications at meetings was thought to be a promising approach. Cross training young scientists in all the collaborating disciplines represented at this conference was recommended as appropriate preparation for future professionals. Scientists need to communicate well with the lay public and with politicians. Successful communication to the public requires the delivery of science content to people so they can know how to act, whether in personal or commercial realms. Successful communication of scientific findings in understandable terms will help achieve the desired outcome of engaging stakeholders to protect public health by protecting karst waters.