Advances in Karst Science

William B. White
Janet S. Herman
Ellen K. Herman
Marian Rutigliano *Editors*

Karst Groundwater Contamination and Public Health

Beyond Case Studies

Springer

Advances in Karst Science

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Editors

Karst Groundwater Contamination and Public Health

Beyond Case Studies

Proceedings of a Conference Held in San Juan, Puerto Rico, January 27 to February 1, 2016

Organized by the Karst Waters Institute

Springer

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Preface

The conference **Karst Groundwater Contamination and Public Health** took place in the Hilton Condado Plaza Hotel in San Juan, Puerto Rico, on January 27–30, 2016. The 76 attendees were 45 professionals, 26 students, and 5 family members. The attendees came from seven countries: Austria, Denmark, France, Italy, Germany, Switzerland, and the United States. There were 30 oral presentations, 20 poster presentations, and 12 short, “snap” talks. The presenters were invited to contribute written versions of their presentations to this volume.

The conference was organized by the Karst Waters Institute, and the program and an initial set of abstracts were published as KWI Special Publication 19, available on-line at the KWI website. Special Publication 19 also contains information on the mid-conference field trip and the guidebook for the two-day field trip that followed the conference.

This volume presents the written contributions. In order to preserve a complete record of the conference, all presentations are included except for some of the snap talks. They are of three varieties:

Full papers: These were reviewed by the editors and, if necessary, by outside reviewers. Authors were asked to revise their papers as needed.

Extended Abstracts: Authors who did not wish to publish their complete work in the Proceedings were invited to prepare a summary as an extended abstract. These extended abstracts, essentially short papers, contain figures and references and should be considered citable sources of information. The extended abstracts were reviewed by the editors and modified as necessary.

Additional Papers: A few authors who did not wish to contribute to the Proceedings are represented by their original program abstracts. These have been combined into a single document that appears in the Summary section of the book.

In addition to the formal papers, the book contains introductory chapters that set forth the expectations of the conference and its interdisciplinary framework. The conference closed with an open discussion of needed research directions and opportunities. A summary of this discussion appears in the final chapter of the book.

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February 2017

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Contents

Part I

Introduction to the Conference

Contaminated Groundwater in Karst: Why Is It an Issue? An Introduction to the KWI San Juan Conference

William B. White, Janet S. Herman, Ellen K. Herman, and Marian Rutigliano

Abstract
The Karst Waters Institute sponsored a conference on karst groundwater contamination and its impacts on public health. The objective was to facilitate communication between hydrogeologists and the biomedical community, especially those dealing with public health issues. This volume contains the papers presented at the conference.

1 The Issue

If one were to compile a list of the necessities for a healthy human population, a source of pure water would be in the top tier of the list along with clean air, nutritious food, adequate shelter, and reliable sanitation. Pure, drinkable water is a priceless resource that is in limited supply on Earth, and it is vulnerable to contamination from the very beings who depend upon it.

Humans produce a wide variety of substances deleterious to health when introduced into water supplies. Surface streams, rivers, and reservoirs are easily contaminated, and as a result, water supplies drawn from surface sources require extensive filtration and treatment before introduction into water distribution systems. Water supplies drawn from wells for individual homes and farms often receive no treatment, and water supplies from municipal wells require much less treatment than water from surface sources. This comfortable assumption of safety without treatment does not apply to karst aquifers where surface water and groundwater are intermixed in a complicated way that is highly specific to individual aquifers. But karst aquifers are not to be ignored. Although hard data are limited, it has been claimed that 40 or more percent of the groundwater drawn for domestic and public water supplies in the USA is drawn from karst aquifers. Consider the number of towns that have grown up around the proverbial “big spring.”

2 Karst Aquifers: What’s Special?

Karst aquifers are those for which the host rock has significant solubility in water. Suitable host rocks for karst development are mostly carbonates and evaporites. Of these, only aquifers in carbonate rocks, limestone and dolomite, are likely to have a sufficiently low concentration of dissolved solids to be useful as water supplies. Dissolution of the host rock by infiltrating meteoric water enlarges pore spaces, widens fractures, and develops integrated systems of conduits that act as drainage networks. The process may have begun as early as the mid-Miocene although the active parts of the systems frequently date only from the late Pliocene or early Pleistocene. The consequence of the dissolutional modification of the aquifer host rock is that the hydraulics of groundwater flow in karst aquifers is often remarkably different from the hydraulics of porous media.

Because of the open pathways along fractures and conduits and the generally high flow velocities, karst aquifers can

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transmit contaminants and sediments that are not even a threat to porous media aquifers. Pathways from contaminant sources to actual or potential water supplies are complex and poorly predictable. There have been a substantial number of studies of the movement of specific contaminants in specific aquifer locations—case studies—but much less consideration of more generalized concepts of contaminant injection, storage, transmission, and release. More importantly, even less attention has been given to the actual impact of contaminated karst aquifers on public health. It can be established that a karst aquifer is contaminated, but what is the threat to the people who are using the water?

3 The Conference

It was to provide a comprehensive overview of groundwater contamination in karst aquifers and its impact on public health that this conference was convened in San Juan, Puerto Rico. The Puerto Rico karst is an especially appropriate setting for this meeting in that it provides drinking water for private residences and municipal water supplies and, at the same time, has been significantly impacted by unlined landfills and industrial outfalls. The conference consisted mainly of invited speakers with a poster session available for contributed papers. Invited speakers were chosen to provide the broadest possible coverage and the widest possible range of points of view. Thus, there are papers on the hydrogeology of karst aquifers, mechanisms of contaminant transport, the epidemiology of contaminated groundwater, and the impact of contaminated groundwater on public health.

The storage and movement of water in aquifers, including karst aquifers, is the province of the geological sciences and the community of hydrogeologists. The investigation of the effects of contaminated water on public health is the realm of the biomedical community who have little occasion to communicate with the earth science community. The conference was designed to encourage cross-disciplinary discussion by the selection of keynote speakers and by such devices as long coffee breaks, a poster session with a bar and snack table, and a mid-session field trip for all participants. The keynote papers are published together in the first section of the book and illustrate the range of topics discussed.

4 How to Address the Issue of Contaminated Karst Groundwater

4.1 Step One: Characterize the Specific Karst Aquifer of Interest

The term "karst aquifer" is not a label for a specific thing. Rather, karst aquifers represent a large and complex family of aquifers ranging from those little different from aquifers in sandstone or river gravel to "aquifers" that are little more than roofed-over surface streams. As might be expected, the devil is in the detail, and the first task of those evaluating contaminated aquifers is to delineate the hydrogeology, the effective boundaries of the aquifer—the groundwater basin—and the characteristics of its internal drainage. To this end, a large number of tools have been developed over the past decades (see, e.g., Goldscheider and Drew (2007) or Kresic (2013)). Some conference papers illustrated contemporary approaches to the hydrogeology of karst aquifers and are collected under the heading "Aquifer Studies."

4.2 Step Two: How Do the Various Types of Contaminants Move?

The usual suspects that would be a threat to surface waters and to groundwater in non-karstic aquifers comprise the list of contaminants that might impact a karst aquifer. The fundamental differences are the mechanisms by which the contaminants move and are stored in the aquifers, i.e., their fate and transport. There are water-soluble contaminants, of which nitrate is the most widespread, but also agricultural chemicals and leachates from dumps, landfills, and tailings piles. There are non-aqueous phase liquids—gasoline, fuel oil, chlorinated solvents, and many others—that have movement and storage mechanisms that may be quite different from the movement of water in the aquifer. There are microorganisms—bacteria, viruses, and protozoa—that move easily through the karst system. There are particulates, ranging from colloids to cobbles, some benign and some not, that are washed through the system by flood pulses. Cleanup of many of these contaminants ranges from difficult to impossible.

Investigation of contaminant fate and transport is an extremely active area of research. Many of the papers presented at the conference dealt with identification and characterization of contaminated groundwater and with techniques for evaluating the transport of the contaminants by the groundwater. These appear in the section labeled "Karst Groundwater Contaminants and Tools for Their Evaluation."

4.3 Step Three: What Is the Threat to Public Health and What to Do About It?

To return to the initial question: What is the issue? The motivation for this conference was to bring health sciences professionals into a conversation with environmental scientists to focus on karst groundwater, its contamination, and consequent health outcomes. A particular aspect of this intersection of perspectives requires recognition of exposure levels and timescales. Although public health professionals are frequently addressing acute health problems, it is often true that exposure to contaminants of concern in drinking water is a chronic issue. The distinction between exposure to a high concentration of contaminant over a short time and long-term exposures to a ubiquitous background contaminant at low concentrations but over a very long time is crucial to making the connection between contaminated water and human health. Unfortunately, the cumulative effects of long exposures are much more difficult to identify and evaluate. The conference was fortunate to have the participation of the Puerto Rico Testsite for Exploring Contamination Threats (PROTECT), a large and long-term investigation of the effects of low levels of contamination on preterm birth in the north karst belt of Puerto Rico. There were multiple papers from the PROTECT group in the conference. These contributions along with other papers addressing the driving question about health outcomes are found in "Contaminant Exposure and Public Health."

The synthesis of all the scientific contributions to the conference is an attempt to answer the question, "What do we do about it?" Why should groundwater contamination in karst aquifers be treated any differently than contamination of groundwater in any other aquifer, or for that matter, from contamination of surface streams and reservoirs? The contaminants will be from the same sources, have the same properties, and have the same effects on public health regardless of the source from which the contaminated water is drawn. There are three primary reasons why karst aquifers should be treated differently, both from a management and from a regulatory point of view.

(1) The much larger apertures in karst aquifers, ranging from a few millimeters in solutionally widened joints to tens of meters in master conduits, permit the passage of much larger solid contaminants than would be possible in porous media. Bacteria and other microorganisms, for example, can easily pass through a karst aquifer to the point of drinking water extraction, whereas they would have been filtered out during flow through the porous medium of a sand aquifer.

(2) Very short travel times. If a tanker truck full of chlorinated solvents goes off the highway, rolls down an embankment, and breaks open in a river, the authorities know they have an emergency, especially if the accident took place only a few kilometers upstream from the intake to a city water supply. A similar wreck above a non-karst aquifer is a more leisurely affair. The authorities will have to quickly constrain surface runoff, but infiltrating solvent will form a slowly diffusing plume that can be evaluated and treated. However, if a tanker truck spills its load into a sinkhole, the travel to the spring will not take much more time that the flow down the river. Spills in karst regions are as much of an emergency as spills into rivers.

(3) Ready communication between the surface, the localization of all human activities, and the groundwater in a karst aquifer. Wastes from the production of food, mining, energy, and manufacturing, as well as septic, sewage, and urban storm water, are all easily directed to recharging the groundwater via karst features of sinking streams, sinkholes, and thin soils. Taken all together, the inescapable realization is perhaps the most important outcome of the conference: Both the public and the responsible authorities must treat water supplies from karst aquifers with the same level of suspicious evaluation and environmental protection that would be given to a surface water supply. There is a certain nostalgia about "pure mountain spring water," harking to a time when grandmother carried water from the spring in an oaken bucket. Karst springs are usually beautiful, but beautiful does not mean that they should be piped directly into the community's water mains. The most important threat from contaminated karst aquifers may be the lack of understanding on the part of planners and regional authorities and also on the lack of a regulatory framework that takes the peculiarities of karst aquifers into account. This critically important topic is addressed in the collection of papers on "Risk Assessment and Regulatory Issues."

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Public Health and Karst Groundwater Contamination: From Multidisciplinary Research to Exposure Prevention

Heather F. Henry and William A. Suk

Abstract

Karst aquifers account for up to 20% of the world land area and are a source of drinking water for much of the world. Despite the critical value of these aquifers as a drinking water source, there are a growing number of incidences of karst aquifer contamination worldwide, including inadvertent spills, dumping, industrial discharges, or sewage seepage events. Given the porous nature of carbonate rocks, the hydrogeology of karstic aquifers is extremely complex, making it difficult to predict movement of contamination in these aquifers and to identify exposure risks. These contamination events—together with emerging issues such as climate change, exposures to infectious agents, as well as the increase in informal mining practices—indicate the need to explore linkages between karst groundwater, contamination, and health. Accordingly, the issue of karst groundwater contamination presents a unique global public health challenge requiring a multidisciplinary problem-solving approach. The National Institute of Environmental Health Sciences (NIEHS) Superfund Research Program's (SRP) multidisciplinary approach serves as a model for integrating expertise across health, engineering, geological, and community-based approaches to solve problems. Using examples relevant to karst contamination, NIEHS SRP grantees are engaged in research endeavors to address issues of drinking water safety—from remediation to well-testing best practices. It is recommended that continued research addresses karst contamination, with particular attention given to identifying people at risk of exposures and to developing proactive means to prevent further exposures. This is particularly important in the USA, where two-fifths of the population's drinking water comes from karst aquifers. Furthermore, over 40 million US citizens are on private well water for drinking, yet testing for contamination in these wells is often not required. Given the challenges predicting contaminant transport in karst and the lack of uniform private well water testing regulations, there is a need to promote awareness of risks for people living in karst areas among public health, hydrogeology, and government officials, and to use community-based approaches as models for intervention and exposure prevention.

1 Introduction: Karst Contamination—A Global Concern

Public health implications for contamination in karst aquifers are of global concern. It is estimated between 12.5 and 20% of the Earth's land surface that is composed of carbonaceous rocks (Fig. 1) (Williams and Fong 2014; USGS 2016b).

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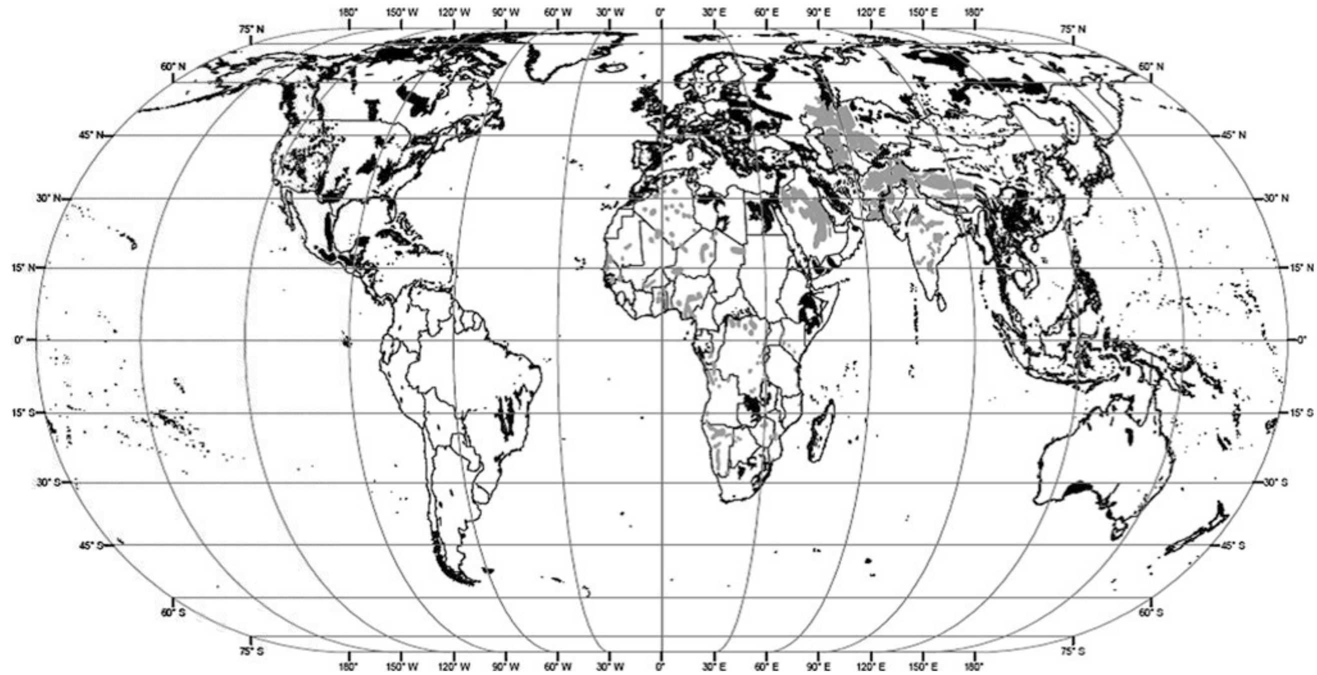

Fig. 1 Karst aquifers worldwide based on Ford and Williams (1989). From Williams and Fong (2014)

These rock formations—limestone and dolomite—form karst, meaning the rock material is slowly dissolved through time leaving behind caves, springs, sinkholes, etc. Unlike non-carbonaceous rock formations, karst hydrogeology is governed by small cracks and fractures as well as larger conduits. These complicated networks of channels create difficulty in predicting transport of water through karst, as well as anything transported along with water, such as contaminants or pathogens (USGS 2016b). Given the porous nature of carbonate rocks, the hydrogeology of karstic aquifers is extremely complex, making it difficult to predict movement of contamination in these aquifers and to identify exposure risks.

Numerous studies report contamination impacts in karst aquifers throughout the world (Du Preez et al. 2016; Xu et al. 2016; Li et al. 2016; Morasch 2013; Krejcova et al. 2013; Huang et al. 2013; Metcalfe et al. 2011). Some studies indicate linkages to increased risk of disease and dysfunction as a result of contamination of aquifers by hazardous substances (Rodriguez et al. 2015; Huang et al. 2013; Long et al. 2012; Hu et al. 2011). There are several emerging global issues that would also overlay with the concerns of contamination in karstic aquifers. Transport of infectious agents through karst aquifers is well documented throughout the world (Somaratne and Hallas 2015; Sinreich et al. 2014; Arcega-Cabrera et al. 2014; Bauer et al. 2013; Wampler and Sisson 2011; Khaldi et al. 2011; Dussart-Baptista et al. 2007). There is growing evidence that co-exposures between contamination and infectious agents confer heightened risk of disease and dysfunction—above what would be expected from exposure to the contaminant alone (Boldenow et al. 2015; Jaligama et al. 2015; Notch et al. 2015). In the way that large above ground metal processing shows impacts to karst aquifers (Du Preez et al. 2016; Deng et al. 2009, 2011), it should be noted that informal mining practices may release mixed contaminants that could impact drinking water resources. Activities on the rise, such as electronic waste (e-waste) mining (Heacock et al. 2016; Grant et al. 2013) as well as informal precious metal mining (Maier et al. 2014), have potential to contaminate water resources, and those in karst aquifers are particularly vulnerable. Lastly, several karst researchers are investigating the impacts of severe weather events related to climate change (Polemio 2016; Thomas et al. 2016; Dura et al. 2010). These surge events impact the movement of contaminants in karst—leading to unanticipated sewage contamination and toxicant transport.

2 Understanding Karst Contamination Issues Requires Multidisciplinary Research Framework

The issue of karst groundwater contamination presents a unique global public health challenge requiring a multidisciplinary problem-solving approach. The National Institute of Environmental Health Sciences (NIEHS) Superfund Research Program's (SRP) multidisciplinary approach serves as a model for integrating expertise across health, engineering, geological, and community-based approaches to solve problems. One such multidisciplinary study is underway in the northwest karstic region of Puerto Rico (PR) where fate and transport modeling and environmental sampling of aquifer contamination are being studied as variables to understand the high incidence of preterm birth in PR (NIEHS 2015; Yu et al. 2015). They are applying state-of-the-art methods to study biological mechanisms involved in preterm birth related to environmental factors (Johns et al. 2015; Watkins et al. 2015; Cantonwine et al. 2014; Ferguson et al. 2014). The epidemiological research is complimented by bidirectional community and stakeholder engagement through providing culturally sensitive risk communication information to pregnant mothers, coordinating with organizations that promote karst conservation, and collaborating with health advocacy groups such as March of Dimes (NIEHS 2016).

The research in the northwestern karst region of Puerto Rico also touches on another issue of high relevance to mainland USA: Contaminant exposure varies widely depending on whether drinking water comes from public versus private sources. Under the Safe Drinking Water Act (SDWA) of 1974, all public drinking water facilities are required to ensure safety of drinking water through setting maximum contaminant levels (MCLs), testing for compliance with the MCLs, and maintaining effective operation of drinking water treatment and delivery systems. Hence, in cities, towns, and municipalities under public drinking water works, contaminant levels are tested for and controlled (assuming compliance with SDWA). However, a major concern stems from the fact that private well users are not protected under the testing and maintenance provisions of the SDWA. These SDWA regulations do not apply to the estimated 40 million US citizens reliant upon private well water for their drinking water (Maupin et al. 2014). For private well water users, rules and regulations for testing are not uniform and vary from state to state. In general, there may be some testing required at the time of well installation; however, these tests rarely account for toxicants that might be associated with discharges from current and/or legacy industry operations (e.g., toxicants such as heavy metals, chlorinated contaminants, or other hazardous substances), nor geogenic hazardous substances (e.g., naturally occurring arsenic). Furthermore, for much of the USA, testing of wells is not required after installation. As a result, the testing of private well water is largely the responsibility of the individual homeowner (EPA 2016a). This places private well water users in a particularly vulnerable position. They may not be aware that well testing is their own responsibility and would not necessarily be aware of contamination sources in their region that may impact their drinking water aquifer.

Hence, NIEHS SRP-funded research study in northwestern Puerto Rico is investigating linkages between karst aquifer and drinking water quality (whether private or public)—using these data as a model for better understanding fate and transport of contaminants in karst groundwater. Furthermore, the researchers are measuring for contaminant exposure utilizing innovative biomonitoring tools. With this integrated approach, hydrogeological research has advanced the understanding of movement of hazardous substances in the karstic groundwater and provided critical geospatial information useful for the epidemiological studies (Anaya et al. 2014). This multidisciplinary research approach is forging a new model framework to understand the interactions between contamination and human exposures in karst aquifers—and developing best practices for engaging communities and stakeholders to protect public health, to conserve these unique karst ecosystems, as well as protecting these vulnerable karst aquifers.

3 Future Directions: Drinking Water Protections in the USA and Karst Aquifers

Given the uncertainty of risk from contaminant transport through karst aquifers, there is need to develop new policies, integrate data networks, and expand outreach to those potentially vulnerable to exposures. Using the USA as an example, there would be a tremendous benefit to focus policy, research, and outreach to states/communities/regions with a high percentage of private well use (Fig. 2) drawing from karst aquifers (Fig. 3). Overlaying karst aquifer regions with data about private well usage in the USA can be used to identify states and communities that would benefit from targeted communication campaigns to bring awareness about the nature of karst aquifers in terms of contaminant transport.

Bringing together stakeholders from multiple sectors is a first step to identify risk factors for environmental exposures and to develop effective interventions to prevent further exposures. The Karst Waters Institute's "Karst, Groundwater Contamination & Public Health: Moving Beyond Case Studies" 2016 meeting in Puerto Rico brought to light concerns from multiple stakeholders, including community groups, karst conservation groups, health researchers, government regulators (from the USA and worldwide), as well as experts in hydrogeology and engineering (KWI 2016). The need for maintaining this community of practice is evident, as the exchange between and across disciplines is invaluable for practical solutions such as modeling contaminant transport in karst aquifers, developing effective guidance for private well users, as well as engaging communities. Another recent focus group was convened by the North Carolina Environmental Health Collaborative (NC EHC) titled "Safe Water from Every Tap" held in North Carolina in 2015. This summit identified critical barriers to well testing by convening a multistakeholder group of local

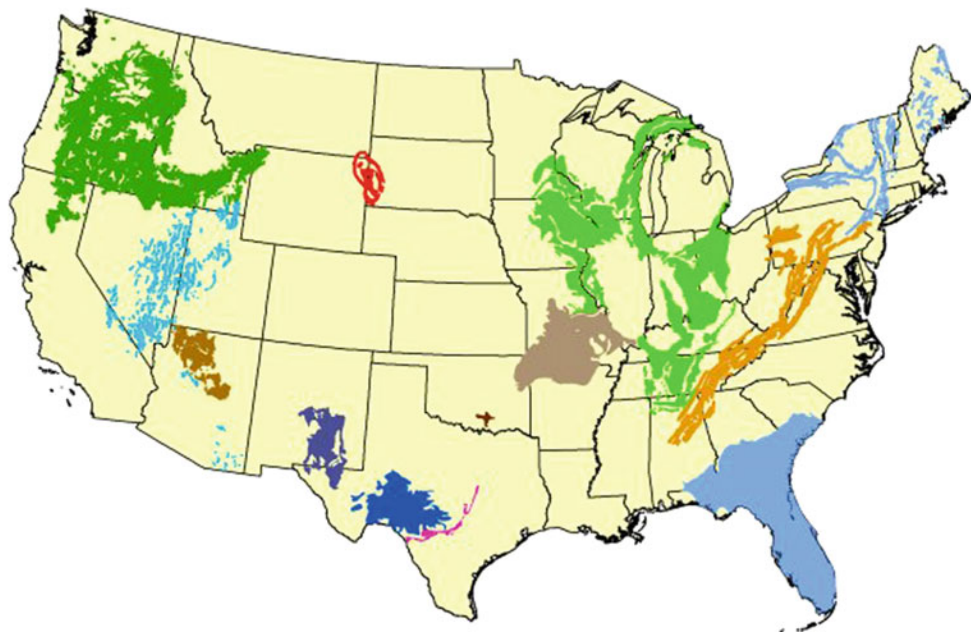

Fig. 2 Principal karst aquifers of the USA (USGS 2016a)

health departments, state and federal agency representatives, water utilities, and industries (RTEHC 2015). In addition to the recommendation to expand efforts to better inform communities about well testing, the summit also identified new well-testing regulations and policies that may be used as models to reduce the gap of regulation for private well users. An example is the Private Well Testing Act (PWTA) of New Jersey (2011), a consumer information law requiring private drinking well testing for real estate transactions (prior to closing) and for rental properties (every five years). The PWTA is a model of new policy relevant to contaminant transport risks—regardless of the aquifer type—because the test includes 32 contaminants of human health concern (metals, hydrocarbons, chlorinated contaminants). Another provision of the PWTA is that data are incorporated into a statewide groundwater quality analysis database maintained by the NJ Department of Environmental Protection (NJDEP) (Atherholt et al. 2009). This additional effort by NJDEP, to maintain and analyze their data, addresses challenges identified in both the Karst Waters Institute and the North Carolina Environmental Health Collaborative conferences. Access to groundwater data is difficult and becomes a limiting factor in reaching out to those who may be at greatest risk.

It follows that well-testing communication efforts might prioritize outreach to families, communities, and counties where drinking water comes from private wells in karstic aquifers. In terms of data integration, there are several tools, such as geographical information systems (GIS), that can be used to overlay multiple data layers—such as hydrogeological layers, contaminant-release information, or locations of Superfund sites (Hollingsworth et al. 2008; NLM TOXMAP 2016). Tools like these are being used to explore the extent of contamination in karst, and in one such study, it is estimated that as many as 23% of Superfund sites are found in karst regions (Cotto-Ramos 2015). Despite the availability of hydrogeological and hazardous substance mapping databases, there remain challenges to identifying those most at risk in terms of an intersection between karst, contamination, and private well users. This is because state and county records of private well locations are not always available in database form; furthermore, these data are not often publicly available. Established collaborations between researchers (i.e., health, geospatial, environmental monitoring) and staff at state departments of health and environment (where records are often located) can be critical to identifying those who may be at greatest risk for environmental exposures. An example of such collaboration is the NIEHS SRP-funded research project mapping high areas of arsenic and locations of private wells in the state of North Carolina, a project made successful by interactions between the researchers and the NC Department of Health (Sanders et al. 2011). The researchers identified areas of high risk of exposure to arsenic from private wells—and they have since followed up with outreach to these vulnerable communities. This reinforces the need for coordination and integration between multiple sectors: government, health, geological, and community outreach expertise.

Lastly, translating research findings to stakeholders—as well as impacted individuals and communities—is important to bring awareness to the connections of karst, contamination, and public health. The US EPA provides Web sites with general guidance for private well owners to help identify symptoms indicative of well water contamination

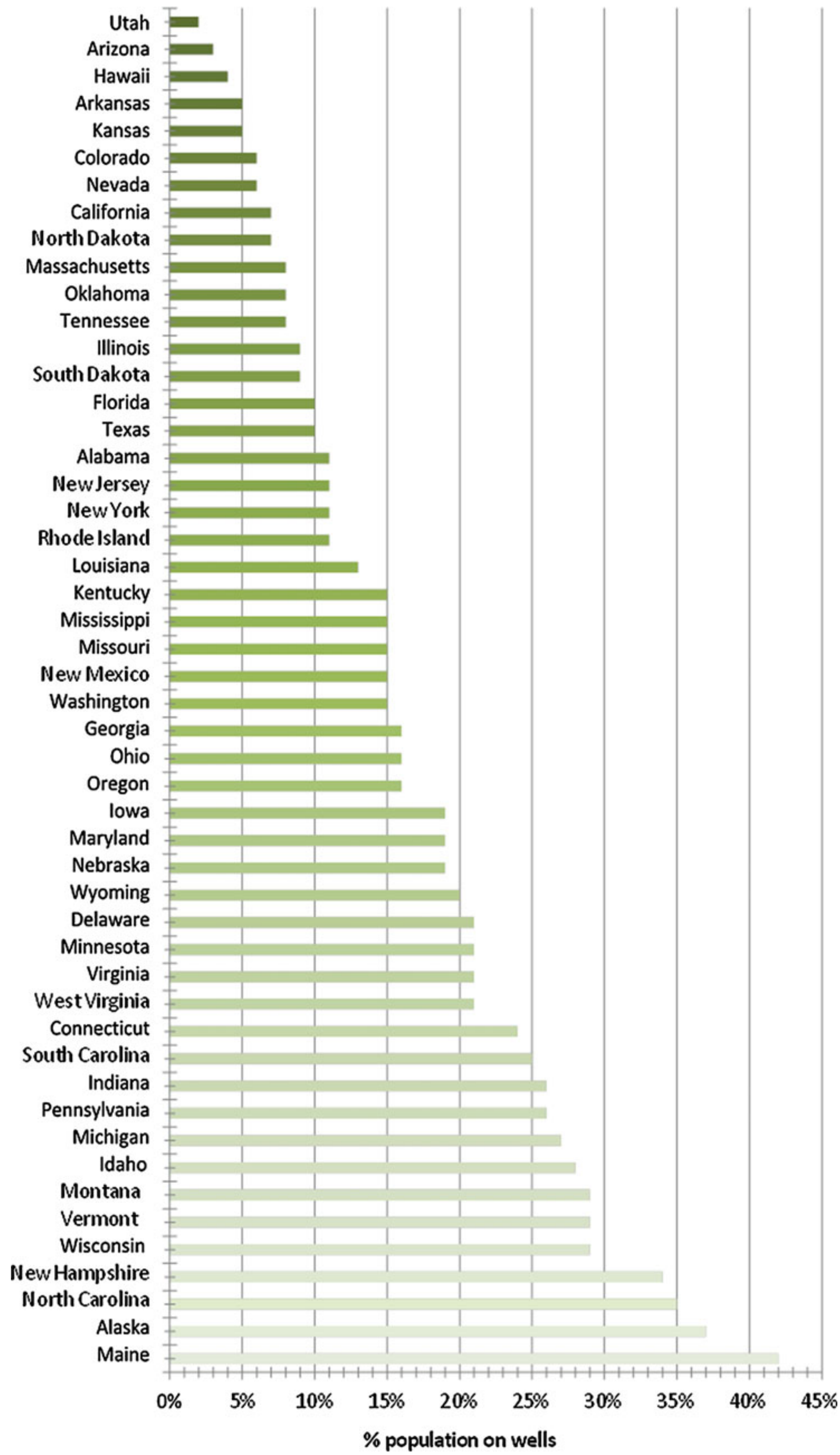

Fig. 3 Percentage of residents on private well drinking water based on data from Maupin et al. (2014) and Research Triangle Environmental Health Collaborative (2015)

(EPA 2016a, b). They have also developed the Drinking Water Mapping Application to Protect Source Waters (DWMAPS) as a resource for communities to answer questions about potential contaminant impacts on their water supply (EPA 2016c). The DWMAPS mapping tool integrates information about pollution sources, which can help a private well user identify potential exposure risks. These are helpful resources for state and county offices to understand whether there is cause for concern for their communities—and for community members who are already aware of potential contamination concerns with their water.

However, as mentioned previously, many of the 40 million private well users may not be aware that well testing is their own responsibility and would not necessarily be aware of contamination sources in their region that may impact their drinking water aquifer. For this reason, a more proactive approach to reaching out to communities at potential risk is ideal. Utilizing a multidisciplinary framework incorporating health, monitoring, and community engagement research studies, several NIEHS-funded Superfund Research Centers are engaging with communities to develop effective communication approaches to help private well owners navigate the process of well testing. Their efforts range from using geospatial databases to identify private well-using communities in areas of elevated groundwater arsenic (Sanders et al. 2011); identifying socioeconomic patterns that reveal barriers to testing (Flanagan et al. 2016a, b, c; Flanagan et al. 2015a, b; Lothrop et al. 2015); developing communication campaigns to appeal to most vulnerable citizens; and providing non-technical information about the advantages and disadvantages of testing and treatment products on the market (Paul et al. 2015). Through their successful efforts, it is clear that working within communities to tailor community-specific outreach campaigns is essential to inspire individuals to be proactive about well testing.

4 Summary and Conclusions

Karst aquifers are an important source of drinking water for much of the world; however, incidences of karst aquifer contamination worldwide impact global public health. These contamination events—inadvertent spills, dumping, industrial discharges, or sewage seepage events—co-occur with growing emerging issues such as the impact of climate change on karst flow, infectious agents, and informal mining. There continues to be a need to explore linkages between karst groundwater, contamination, and health. Using a multidisciplinary approach, NIEHS SRP grantees are engaged in the research endeavors needed to make the connection between karst aquifer contamination and the potential health impacts. In addition, NIEHS SRP researchers design studies to identify communities of potential high risk of exposure leading to a possible negative health outcome—and then translate findings to practitioners (such as state public health staff) and develop prevention opportunities with impacted communities. For example, several NIEHS SRP community engagement leaders have initiated outreach campaigns for well testing among private well users where exposure to naturally occurring arsenic may be possible. This type of outreach is important to promote public health in that private well users are responsible, sometimes unknowingly, for testing and treating their own wells to ensure safe drinking water quality. Of relevance to karst aquifer contamination, there would be a public health benefit to utilize these effective community engagement practices to tailor well-testing communications for private well water users in karst aquifers, where movement of contaminants are difficult to predict.

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Part II

Keynote Papers

Team Science Applied to Environmental Health Research: Karst Hydrogeology and Preterm Birth in Puerto Rico

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Abstract

Understanding the interaction of environmental contamination and its impact on human health stretches the disciplinary demands required for effective research. Team science is required to understand the origin of contaminants, their pathways to human, their health effects, and for development of effective mitigation. We describe a team science model applied to the study of preterm birth in a region of karst hydrogeology, the Puerto Rico Testsite for Exploring Contamination Threats (PROTECT). This research program uses an innovative, holistic, source-to-outcome transdisciplinary approach that integrates epidemiological, toxicological, analytical, fate-transport, and remediation studies, along with a unified sampling infrastructure, a centralized, indexed data repository and a data management system. PROTECT is contributing new knowledge about the risk that contaminants may pose in pregnancy resulting in preterm birth, how these contaminants reach karst aquifers, and what are the biological mechanisms by which environmental contaminants may promote preterm birth. PROTECT also is developing novel remediation approaches that will target removal of contaminants linked to preterm births from ground water. These integrated efforts offer unique opportunities to address a serious public health problem and its solution would result in a healthier population and a healthier environment.

1 Introduction

Conducting environmental health research today requires a diverse research team that can address the breadth of disciplines needed to understand the complex dynamics of the environment and its interaction with human populations. Where biology and chemistry might have once sufficed, research teams must now include a broad array of disciplines to (1) identify routes of human exposure to chemicals, (2) understand the health effects resulting from human

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exposure to these chemicals, (3) recognize their impacts on public health, and (4) develop effective interventions to remediate contamination and improve the health of the impacted population. A transdisciplinary approach, implemented in a team science management structure, can provide a platform to understand the interactions between the environment and human populations and translate research findings into strategies to improve human health and the environment. Project PROTECT (Puerto Rico Testsite for Exploring Contamination Threats) is currently ongoing in Puerto Rico.

The study of groundwater contamination is an important component as it is a major threat to water resources and consequently human health. Understanding the fate and transport of contaminants in groundwater, that may lead to human exposure and adverse health outcomes, is needed to understand health impacts and to develop intervention strategies. Aquifers in karst systems are highly heterogeneous, which complicates understanding fate and transport of contaminants (Fig. 1). Karst groundwater systems develop in soluble rocks and are typically characterized by well-developed conduit porosity and high permeability zones. These characteristics make aquifers in karst areas highly productive and an important freshwater resource for human consumption and ecological integrity. Exposure from contaminated karst aquifers is very relevant to the U.S. as about 40% of the groundwater used for drinking comes from karst aquifers (USGS 2013). Worldwide, karst aquifers contribute about 25% of the drinking water; these aquifers are distributed throughout Asia, Europe, other parts of the Caribbean, and Australia (Hartmann et al. 2014). Karst aquifers present highly susceptible pathways for contamination of water supplies due to the presence of fissures, sinkholes and sinking streams that can rapidly inject contaminants at or near the land surface. Once in the aquifer, the contaminants can be readily transported via solutional openings in the subsurface such as conduits and underground streams. Filtration processes that can retard contaminant movement, commonly found in alluvial aquifers, are rarely present in karst aquifers. There is a significant lack of understanding of contaminant transport in karst and a critical need for development of remediation strategies for such complex and potentially deleterious systems. This is particularly relevant where availability of water resources from highly productive aquifers in karst regions spawn industrial and urban development, which promotes economic growth but increases the potential for extensive contamination of the groundwater resources. The dynamics of the solubility, flow, and exposure to contaminants through karstic groundwater is made more complex by the presence of some contaminants as non-aqueous phase liquids (NAPLs) and interactions between different contaminant groups.

In Puerto Rico, risk of exposure to contaminants thorough groundwater is high because many waste sites exist, particularly on the north coast. Eight of the 16 Superfund sites, and many of existing unlined landfills in Puerto Rico, exist over karstic aquifers in the northern part of the island. Such high level of contamination is a public health threat on the island. An overlay of Superfund sites (EPA 2013) on karst regions in the U.S. (Tobin and Weary 2004) shows that 23% of all Superfund sites are located in karst areas. In Puerto

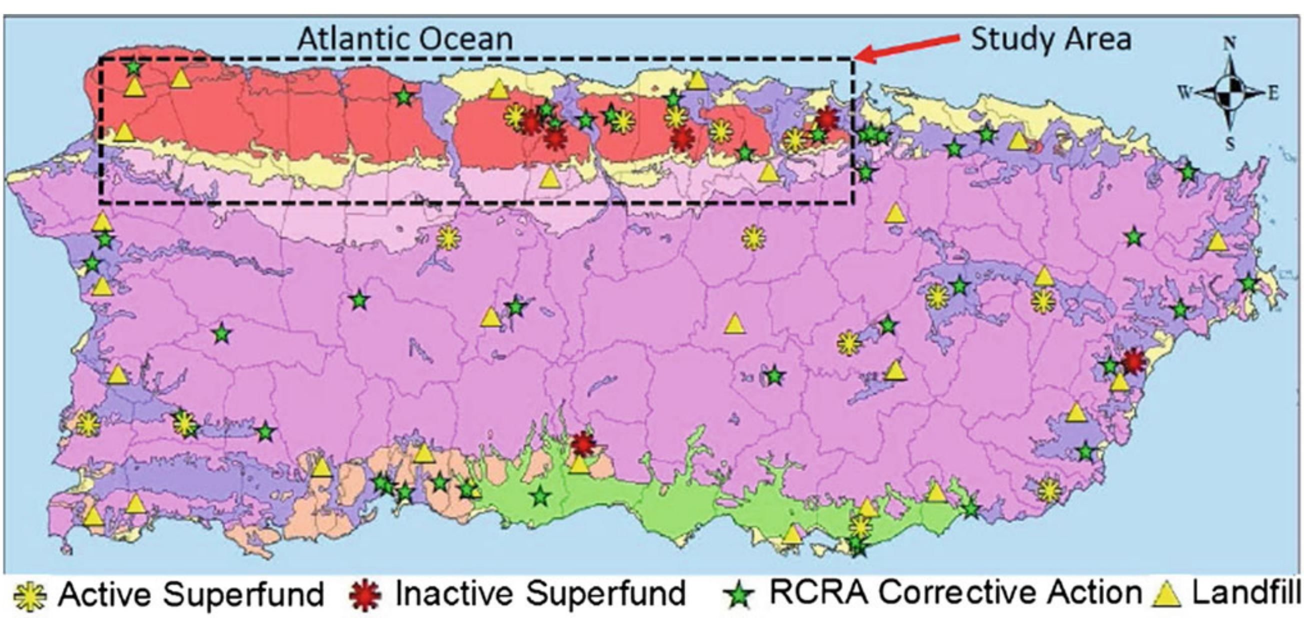


Fig. 1 Hydrogeology and major potential contamination sites in Puerto Rico. North coast limestone aquifer in *orange* and *light pink*

Rico, 45% are within the northern karst region of the island (Fig. 1). This region has been affected by a long history of toxic spills into the subsurface (EPA 2011; Hunter and Arbona 1995; Zack et al. 1987) and is coincidentally among the areas with the highest groundwater extraction in Puerto Rico (Molina-Rivera and Goméz-Goméz 2008). Serious contamination has prompted inclusion of 16 National Priority List (NPL) and 15 corrective action sites within the Resource Conservation and Recovery Act (RCRA) in the north coast region of Puerto Rico between 1983 and 2012. Recent (Padilla et al. 2011) and past (Guzmán-Ríos et al. 1986) studies in this region have consistently reported the presence of organic contaminants in the karst groundwater system. In spite of the known contamination, the connection between exposure to a complex mix of environmental factors, including drinking water contamination in karst regions, and the high rates of adverse health outcomes for children in Puerto Rico has not been comprehensively or integratively investigated.

From the human population perspective, Puerto Rico has the highest rate of childhood asthma in the U.S., more than twice that of Hispanic children on the mainland (16.5% vs. 7.9%) and its preterm birth rate increased dramatically in 1990s and the first decade of the 21st century. In 2009, Puerto Rico had the highest rate of preterm birth in the US, and the third highest rate in the world in 2012 (Blencowe et al. 2012). Infants born preterm are more likely to die in the first year of life, and those who survive can suffer serious short- and long-term disabilities, including blindness, deafness, cerebral palsy and development disorders. Early studies found that traditional risk factors for preterm births did not explain the high rate observed (Cordero and Mattei 2009) and placed the focus on potential environmental factors. The island has suffered extensive hazardous waste contamination over the years and has the highest density of hazardous waste sites per square mile than any other jurisdiction in the US. Those findings raised questions about the role of environmental contaminants in the high rate of preterm births in Puerto Rico.

PROTECT addresses critical gaps identified in the 2007 Institute of Medicine report on preterm birth (Behrman and Stith Butler 2007). Preterm birth is the second leading cause of death in children under the age of 5 worldwide (Blencowe et al. 2012), and the leading cause of perinatal and infant mortality in the U.S. (Klebanoff and Keim 2011; Callaghan et al. 2006). Reducing preterm birth rates will help save babies, improve their quality of life, and minimize the escalating costs of health care. For the U.S. alone, the most recent estimate is that preterm births cost society over $26 billion annually in 2005 (Behrman and Stith Butler 2007), not including the costs of medical care beyond early childhood or the total cost of special education services and lost productivity (Klebanoff and Keim 2011). The causes of preterm births remain largely unexplained, and interventions geared toward known causes are projected to result in a reduction in preterm births of only 5% by year 2015 (Chang et al. 2013). New approaches are needed to identify modifiable risk factors. Environmental pollutants as potential contributing factors to preterm birth have been greatly understudied (Behrman and Stith Butler 2007). Thus, establishing links between environmental exposures and preterm birth would have major public health significance since many exposures may be modifiable through new policies or interventions at the individual, community, clinical, and state or federal level. Furthermore, by demonstrating that a common toxicological effect—oxidative stress—activates pathways associated with parturition, PROTECT combines new knowledge of biological mechanisms by which environmental contaminants may promote preterm birth. Knowledge of these mechanisms, combined with new information on toxicant-stimulated responses using in vitro model systems, is leading toward to the development of assessment tools for toxicological evaluation of potential chemical risks for preterm birth.

To address these questions, PROTECT, a Superfund Research Program (SRP) Center, was developed and initiated its research program in 2010. PROTECT employs an integrated, transdisciplinary approach and team to study the fate, transport, exposure, health impact and remediation of contaminants, with particular attention to phthalates and chlorinated solvents, both suspect and model agents for the high preterm birth rates in Puerto Rico. To do so, PROTECT uses an innovative, holistic, source-to-outcome structure, integrating epidemiological, toxicological, analytical, fate-transport, and remediation studies, along with a unified sampling infrastructure, a centralized, indexed data repository and a data management system. Administrative, research translation, training and community engagement cores engage and inform stakeholders, provide knowledge-transfer activities to the greater SRP and environmental health community, and provide extensive cross-disciplinary training. In a nutshell, PROTECT is a transdisciplinary model of team science that is responsive to NIEHS, EPA and CDC strategic goals, and addresses priority areas identified by the Institute of Medicine Committee on preterm birth (Behrman and Stith Butler 2007).

2 Approach

PROTECT is a multi-institutional research center with collaborating researchers from Northeastern University; the University of Puerto Rico (Medical Sciences Campus—UPR-MSC, and Mayaguez Campus—UPRM); the University of Michigan; the University of Georgia, West Virginia University, Silent Spring Institute and Earth Soft Inc. The central theme of PROTECT is the study of exposure to Superfund hazardous chemicals and their potential contribution to preterm birth, focusing on Puerto Rico as a testsite with dynamic contamination exposure pathways through aquifers in karst regions.

Effort is centered around the problem-based, solution-oriented theme, to address three goals: (1) define the contribution of environmental chemical exposure to preterm birth, (2) develop new technology for discovery, transport characterization, and green remediation of Superfund hazardous chemicals in aquifers in karst region, and (3) engage stakeholders to support environmental public health practice, innovation and policy; professional development; and awareness around our theme.

The Center is composed of eleven integrated components: five biomedical and environmental research projects, two research support cores and four enrichment cores. PROTECT encompasses five interrelated research projects. **Project 1** is a targeted molecular epidemiology study of phthalate exposure and preterm birth in Puerto Rico. This project is conducting a prospective cohort study to identify novel risk factors for preterm birth, with a focus on exposure to phthalates. It utilizes state-of-the-art methods to estimate phthalate exposure and assess intermediate biomarkers of effect, to provide much needed human data on environmental and other predictors of preterm birth in Puerto Rico, and the biological pathways involved. **Project 2** on mechanistic toxicology explores toxicant activation of pathways of preterm birth in gestational tissues. This project identifies toxicological mechanisms for epidemiologic associations between exposure to select environmental contaminants and adverse birth outcomes through studies of toxicant actions on placental and extraplacental tissues. **Project 3** conducts non-targeted chemical analysis with a focus on discovery of xenobiotics associated with preterm birth. This project seeks to discover xenobiotics that contribute to preterm birth by advancing and applying non-targeted chemical analysis by mass spectrometry to urine from pregnant women in Puerto Rico, placenta (human and animal) and water (tap and groundwater; before and after remediation). **Project 4** focuses on fate and transport and studies dynamic transport and exposure pathways of contaminants in karst groundwater systems in Puerto Rico. This project is characterizing the fate and transport regions and dynamic mechanisms controlling the mobility, persistence, and potential pathways of target contaminants toward exposure and/or remediation zones in karst groundwater in Puerto Rico. **Project 5** focuses on the development of a solar-powered remediation process for contaminated groundwater. The project is developing a novel, environmentally-friendly in situ groundwater remediation technology using solar-powered electrolysis to regulate groundwater redox for transformation of contaminants.

These projects are supported by a human subjects and sampling research support core and by a data management and modeling core which provides effective management of collected data and modeling support. These projects have common requirements of human subject recruitment, collection of human and environmental samples, and management of large volume of data and led to the development of the Research Support Cores. The human subjects and sampling core recruits pregnant women to the cohort, and collects, stores and distributes biological and environmental specimens and data for use by projects. The data management and modeling core provides efficient collection, cleaning, integration and effective management of biomedical and environmental data being collected and analyzed across the PROTECT Center. This core provides support for modeling, GIS, multi-dimensional data mining and visualization, and provide customized user interfaces for efficient and accurate data entry and analysis.

The four enrichment cores include Administration that provides integration, coordination, and operational support, Training, a major component that ensures the development of the next generation of researchers, Research Translation that facilitates the application of research findings into practice, and the Community Engagement Core that ensures a direct connection to the communities of the Northern karst region and the participants in the study with a model report-back system. Figure 2 describes the interaction and integration of the projects and cores into the overall PROTECT model.

3 Integration of Disciplines

PROTECT's strong integration of biomedical (epidemiology, toxicology) and environmental (analytical chemistry, engineering, hydrogeology) disciplines is evident in its goals, each of which requires a highly collaborative approach with significant interaction and sharing of samples, testing and results (Fig. 3). The Research Support Cores are a critical part of the interdisciplinary approach and of the integration of the research activities across disciplines and projects. The Data Management and Modeling Core, through which the projects share and mine results, allows us to test new hypotheses that are based on integration of the multidisciplinary data from multiple projects. This core provides a unified system for data entry, and supplies complex multidisciplinary datasets in a readily usable format, as well as technical assistance with multi-layered data management inquiries, and a centralized repository for all data collected and analyzed (Fig. 4). Importantly, this core is enabling us to cross-index these datasets, carry out database queries and perform data mining, analysis and multilayered mapping and modeling. The Human Subjects and Sampling

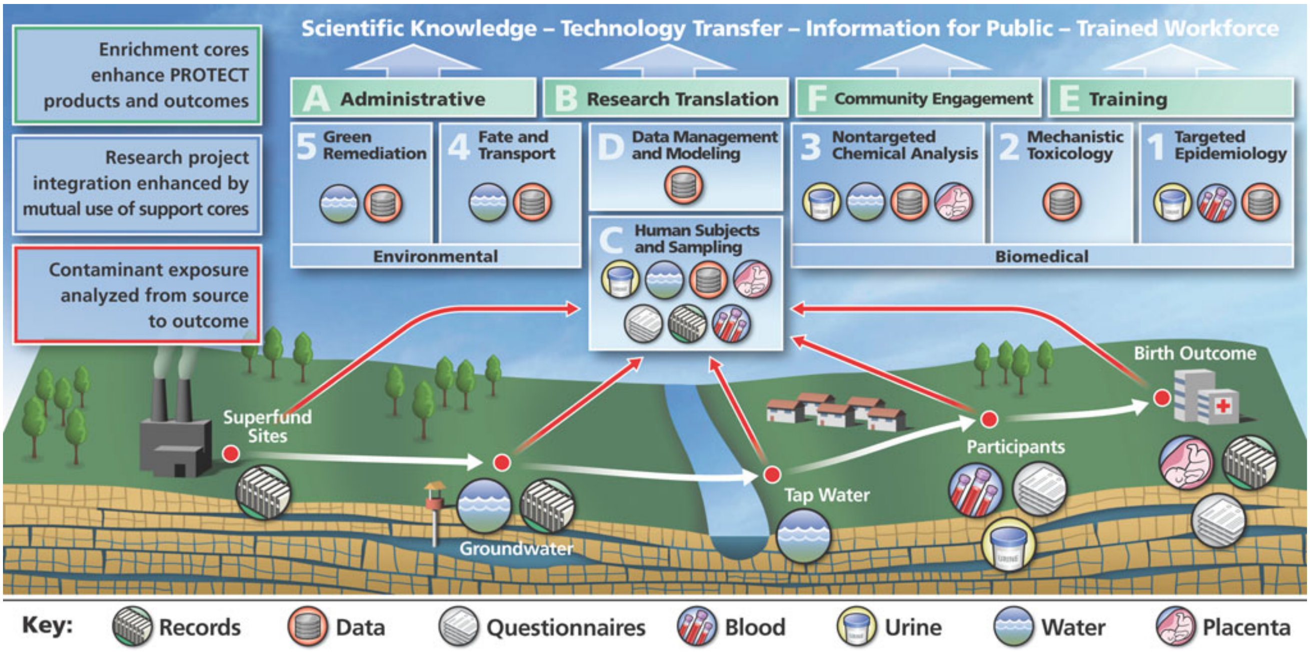
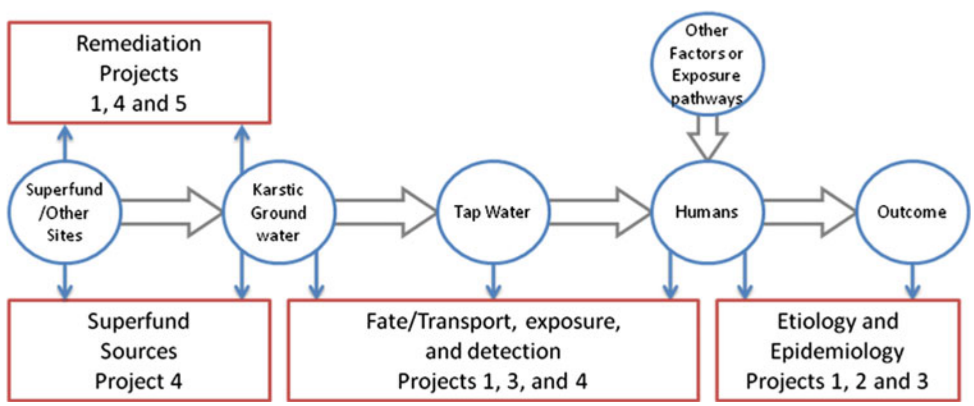


Fig. 2 PROTECT uses a holistic system of research, training, and stakeholder engagement to study contaminant exposure and its potential contribution to preterm birth in Puerto Rico

Fig. 3 Flow chart highlighting relevance of the project to the program



Core systematically unifies the sampling process for all projects. These samples, comprising tap water, groundwater, urine, blood, hair, and placenta, although diverse and for different projects, are consistently and uniquely indexed so that data retrieval and mining is multidisciplinary and consistent for all projects. Many of PROTECT's key outcomes rely on the ability to access both biomedical data and environmental data in a unified, coherent data management and assessment framework (Fig. 4). A critical advantage of using a centralized data repository is the ability to evaluate the relation between multiple causes. PROTECT has the ability to assess cumulative and synergistic risk factors.

In addition to the significant role that the research support cores play in integration of the projects, there are significant bidirectional collaborations and integration directly among the projects. Sharing of samples, data, and results is integral to the projects. For example, the project on mechanistic toxicology provides bidirectional collaboration with epidemiologic investigations and provides mechanistic links for epidemiologic associations observed in the targeted epidemiologic project. Toxicology studies conducted in collaboration with the non-targeted analysis project identified oxidative stress as a response produced by a phthalate metabolite in human placental cells (Tetz et al. 2013a). Stimulated by those findings, the targeted epidemiologic studies found associations between urinary phthalate metabolite concentrations and biomarkers of oxidative stress (Ferguson et al. 2011, 2012). The mechanistic toxicology project collaborates with non-targeted chemical analysis project to provide further insight into toxicological