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Dr. Ari M. Michelsen: Life Dedicated to Advances in Water Resources Development

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This article is dedicated in memory of Dr. Ari M. Michelsen, 2018 Warren A. Hall Medal recipient, in recognizing his scholarly accomplishments in natural resources economics and policy.

Ari Michelsen was born on August 10, 1954 in Oslo, Norway to Frances (Blumve) and Arve Michelsen. The family returned to the U.S. to live in Maryland throughout his school years. He received a B.S. in Conservation and Resource Management from the University of Maryland in 1976, followed by his M.S. (1983) in Economics, and Ph.D. (1988) in Agricultural and Resource Economics from Colorado State University, where he was advised by Dr. Robert Young.

Michelsen was a nationally and internationally renowned scholar in economics and resource policy. He started his professional career as a consultant on energy. After completing his Ph.D. he worked as faculty and Associate Director at University of Wyoming (1989-1994) and as faculty at Washington State University, Vancouver (1994-1999). In 1999 he joined Texas A&M University as Professor of Agricultural Economics and Resident Director of Texas A&M AgriLife Research Center at El Paso. He specialized in integrated water resources management, valuation, conservation, markets and policy analysis. His research focused on the effectiveness of agricultural and residential water conservation programs, water markets and prices, impacts of endangered species water acquisition programs, regulatory impacts and decision support systems for river basin resource management, and water policy analysis in the U.S., China, and Chile. During his career, he authored or co-authored over 140 publications and technical reports. His research projects not only advanced our knowledge of water resources (drought and flood) in the arid region, but also greatly impacted regional water resources planning and management. Two papers were particularly impactful. "Group Decision Making in Water Resources Management Using Multiple Objective Analysis" (*Journal of Water Resources Planning and Management,* 2004) and "Economic Impact of Alternative Policy Responses to Prolonged and Severe Drought in the Rio Grande Basin" (*Water Resources Research,* 2005) became the most cited papers of his published work, advancing methodology in the Decision Support System analysis. His work on economic assessment of flood control infrastructure and salinity control in the Rio Grande Basin could provide economic benefits of millions of dollars to the community. Moreover, his work on best management practices (BMPs) for water conservation has been used to develop management strategies in Texas regional water plans as well as the state water plan. Ari was selected as the Regent Fellow, the highest honor bestowed upon faculty members by the A&M System. His work had positive impact not only at the institution or agency level, but also at community, state, national, and international levels. Michelsen received the Fellow of American Water Resources Association (AWRA) in recognizing his outstanding professional achievement. A passionate scholar, he advised graduate students, postdoctoral associates, and visiting scholars; many of whom continued their career as academics, while others became successful practitioners in the water resources field.

Dr. Michelsen was active in international cooperation. He initiated and led the efforts in U.S.-Mexico Transboundary Aquifer Assessment Program (Public Act Public Law 109-448 enacted in 2006), a joint program of USGS and the Water Resources Research Institutes in Texas, New Mexico and Arizona, to develop scientific knowledge of US-MX bi-national aquifers in those three states. He was frequently invited to participate in international collaborative work. Following are just a few examples of projects in which Ari played a significant role:

- Workshops on the theory and empirical application of economic models and design of multiple objective decision support systems for water resources management for the United Nations Development Program, and lectures and roundtable for the USDA – Foreign Agricultural Service (2000)
- Invited Lecturer by the U.S. State Department China Embassy for the Year on Water Rights, Markets and Prices, eight cities (2002)
- Invited Lecturer on Economics of Water Resources and Integrated Management for the headwaters region of the Yellow and Yangtz Rivers, Qinghai Provence, Xining, Chengdu and Beijing by Chinese Academy of Sciences and Ministry of Water Resources (2004)
- Economic analysis and decision support project development and courses for the United Nations Development Program, Macroeconomic Based Water Resources Management Study for North China, involving numerous Chinese government agencies and organizations, Tsinghua and other Universities in Beijing, Jinan, Ningbo, Shanxi, Tianjin, Shanghai, and Shenyang, China (1991-1994)

It is worth noting that several colleagues with whom he worked these projects were elected as Academicians of Chinese Academies of Sciences and Engineering.

Ari was invited to participate in the Innovation and Natural Disaster Resiliency for the Biobio Region of Chile, IRDC Workshop and lectures (2010) and Integrated Sustainable Economic-Environmental-Social Development Analysis Framework for Patagonia, Pan American Studies Institute NSF Workshop (2008), EULA, University of Concepcion, Chile. He served as the IWRM Session Coordinator of the 5th World Water Forum (2009). and as Thematic Priority Core Group Chair of the 6th World Water Forum (2010-2012). This forum, the world's biggest water-related event and organized by the World Water Council, aimed "to promote awareness, build political commitment and trigger action on critical water issues at all levels, to facilitate the efficient conservation, protection, development, planning, management and use of water in all its dimensions on an environmentally sustainable basis for the benefit of all life."

As the Resident Director of the El Paso Center he was responsible for strategic planning, research programs, outreach, fiscal affairs, personnel management, and facilities. He was a successful leader, empowering faculty to achieve success in their research programs and providing support for the community by meeting their needs in areas such as sustainable development, economic growth, and heathy ecosystems. He also provided great leadership and outstanding service in national and international professional communities. He served twice as the President of UCOWR and on the Board of Directors, and as the President and on the Board of Directors of AWRA. He loved the UCOWR community, so much so that his whole family often participated in UCOWR conferences and activities. He was proud of his two outstanding daughters: Sonja and Anna. Sonja is following her father's footsteps, working in the water resources field. Ari served in various capacities in numerous local, regional, and state organizations and national professional societies, such as USGS National Water Census Advisory Committee; Texas Economists Board of Directors, Western Regional Research Project; Paso del Norte Watershed Council; New Mexico-Texas Water Commission; and Far West Texas Regional Water Planning Group.

In summary, Dr. Ari M. Michelsen was a passionate scholar, dedicated professional leader, and beloved colleague with distinguished achievements in natural resources economics and outstanding contributions to the professional community. His unfinished journey will continue as we advance our knowledge in water resources development and extend our dedicated service to our communities.

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Student Training and Workforce Development at the USGS Water Resources Research Institutes

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Abstract: Measures of student training and workforce development are key academic, social, and economic metrics. A principal component of the United States Geological Survey Water Resources Research Act Program is the training of water scientists and engineers through participation in research and other mentoring. This training occurs through Water Resources Research Institutes known as the National Institutes for Water Resources. Though the institutes have a demonstrated record in student training, there has been limited synthesis of data on students trained at state and national levels to clarify these contributions to workforce development. We investigated student support at the 54 institutes from 2000 through 2015 using archived data, including a survey of institute practices. Institutes play a key role in water resources training within a greater science, technology, engineering, and mathematics (STEM) framework. Institutes pooled supported on average 678 (sd = 83) students per year (range 518 to 788), providing 10,853 student support years during this period. Individual institutes supported on average 201 (sd = 102) students per year (range 76 to 646). While 98% of institutes used data on students supported to fulfill required reporting, fewer used these data for institute promotion (45%), website or social media engagement (41%), and development/donor activities (16%). Consistency in data collection and management among institutes, coupled with refined use of student support data, such as documenting disciplines and dates of degrees earned, post-support job placement, and diversity and equity metrics, would further demonstrate the value of this investment in student training and workforce development.

Keywords: *STEM, United States Geological Survey, workforce development, student training, water resources*

Measures of student training and workforce development are key social, economic, and academic metrics valued by multiple sectors of society including industry, universities and colleges, and state and federal governments, among others. Skilled workers are in demand nationally and internationally (Bauer and Kunze 2004; Abella 2006; Carnevale et al. 2011; Boeri et al. 2012). In the United States of America (U.S.), concern regarding the future U.S. workforce and student training in science and technology has been expressed by the U.S. Congress (National Academy of Sciences 2007, 2010; U.S. Congress Joint Economic Committee 2012) as well as the President's Council of Advisors on Science and Technology (2012). Further, the U.S. science, technology, engineering, and mathematics (STEM) workforce has connectivity worldwide as noted by Carnevale et al. (2011) "…STEM is already one of America's more global workforces and likely to become more so as innovation continues to expand globally."

The status of the STEM workforce, on which much scholarship and management of water resources is arguably based, has proven complex. Heterogeneity in the STEM labor market has been demonstrated by geographic location, U.S. citizenship, and employment sector (Xue and Larson 2014); and student diversion and attrition in the STEM disciplines affect workforce supply and demand (Carnevale et al. 2011; Xue and Larson 2014). While academia may be facing a STEM skill surplus (Carnevale et al. 2011; Anft 2013; Xue and Larson 2014; Ghaffarzadegan et al. 2015), the private sector, and in particular government and government-related sectors, are experiencing skill shortages in some STEM areas (Carnevale et al. 2011; Xue and Larson 2014). For example, some federal agencies in the U.S. that require STEM cognitive competencies (Carnevale et al. 2011), including the United States Geological Survey (USGS), are facing future workforce shortages (USGS 2015). This is illustrated further by the USGS Bureau Workforce Plan: 2015-2020 (2015) which reports that 35% of permanent USGS employees were expected to be eligible for retirement in 2017. Concomitant with a skill shortage at the USGS is increasing pressure on our freshwater resources which is expected to be exacerbated by an increasing global population, climate change, geopolitical instability, and other factors (Eckstein 2010; Petersen-Perlman et al. 2012; Dawadi and Ahmad 2013; Gleick 2014), highlighting the importance of understanding current student training and workforce development in water resources research and management.

Recognizing the role and mandates of the USGS in water resources research, technology transfer, and student training (Water Resources Research Act 1984) we explored workforce development by examining student training through the USGS Water Resources Research Act (WRRA) Program. One of four internal programs addressing the USGS Water Mission Area, the WRRA Program conducts workforce training via the support of undergraduate and graduate level students, post-graduate associates, and interns as authorized by section 104 of the WRRA (1984). The WRRA Program is a Federal-State partnership which: plans, facilitates, and conducts research to aid in the resolution of State and regional water problems; promotes technology transfer and the dissemination and application of research results; provides for competitive grants to be awarded under the WRRA, and; provides for the training of scientists and engineers through their participation in research and outreach (WRRA 1984).

Individual member institutes authorized by the WRRA (1984) are organized as the National Institutes for Water Resources (NIWR). The NIWR cooperates with the USGS WRRA Program to support, coordinate, and facilitate research through Annual Base Grants, National Competitive Grants, Coordination Grants, and in operating the NIWR-USGS Student Internship Program. In supporting students through the above grants and internship, institutes provide for the training of the next generation of scientists and engineers in support of WRRA (1984) mandates. The life and physical sciences and engineering are among STEM occupational areas that are well represented in the WRRA Program-NIWR research portfolio and student training activities. There are 54 university-based Water Resources Research Institutes or centers, one in each of the 50 U.S. states in addition to the District of Columbia, and the U.S. Territories of Puerto Rico, the U.S. Virgin Islands, and Guam.

The institutes chronicle a notable investment in workforce development overall, training more than 25,000 students in their first 50 years at more than 150 universities as well as mentoring USGS Interns (NIWR 2015). However, the synthesis, analysis, and presentation of these data at the state and national level to better understand and document institute contributions to education and workforce development have been modest to date. Further, the extent to which institutes individually collect, utilize, archive, or otherwise maintain data on students supported for use at the national, state, or local level has not been evaluated. Additionally, opportunities exist for exploring the use of data on students supported by institutes; including standardizing, collecting, and managing data to better define and inform the federal investment in these programs. As an example, the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), Educational Partnership Program (EPP) with Minority-Serving Institutions documents degrees earned by EPP graduated students and recruitment of EPP students into the NOAA workforce (Robinson et al. 2007). Here, we investigate student education and training activities of the WRRA Program in the development of water resource professionals within the context of the STEM workforce. Findings will inform understanding of institute student support and the role this support plays in training the next generation of water scientists and managers.

Methods

We investigated WRRA Program student education and training activities for the most recent 16-year period for which federal reporting data were complete at the onset of our study, 2000 through 2015. Among our objectives were the compilation, synthesis, and analysis of archived data on students supported by the WRRA Program at the state and national level; an understanding of the use of these data by member institutes, and; a gap analysis of data opportunities and needs associated with student training. All work presented was conducted in collaboration with the USGS, NIWR, and University of Hawaiʻi Water Resources Research Center (WRRC). Mean values are presented with one standard deviation (*sd*). Linear regression analysis was conducted to evaluate temporal trends with alpha set at 0.05.

Student Support at the Water Resources Research Institutes

We extracted archived data from a national institute reporting database (NIWR.net) on students supported by the 54 institutes as reported to the WRRA Program. We compiled, synthesized, and analyzed data reported by each institute by year, student category, and funding instrument. Student categories included undergraduate students, master-level graduate students, doctoral-level graduate students, and post-doctoral associates. Available data did not specify Master of Arts or Master of Science degrees and master-level students are pooled here. Doctoral students are reported in NIWR.net as seeking Doctor of Philosophy (Ph.D.) degrees.

Funding instrument categories included Annual Base Grants, National Competitive Grant Program funding (NCGP), Coordination Grants, and the NIWR-USGS Internship program. Annual Base Grants require a minimum non-federal institute match of two dollars to every one federal dollar awarded. The NCGP requires a minimum non-federal match of one dollar to every one federal dollar awarded to institutes. Coordination Grants and the NIWR-USGS Internship program do not require non-federal funding match. As non-federal funding match may exceed minimum requirements, the ratio of federal to non-federal dollars could vary by project. Student support reported in NIWR.net and analyzed here represents federal project dollars combined with any associated non-federal match. Available data did not allow discernment of student support by federal support vs. non-federal match.

Institutes reported the number of students they supported each year in NIWR.net. However, although individual students could potentially be supported for more than one year by an institute, identities or other identifiers of individual students supported were not reported. As such, it was not possible to ascertain the total number of individual (unique) students supported across years. Instead, multi-year student support was evaluated by calculating the sum of students supported in the years of interest, referred to here as student support years. To explore this student support from a national perspective, institute data were pooled to provide a comprehensive summary of support by student category and funding instrument each year.

Student Data and use of Student Metrics at the Water Resources Research Institutes

We report on the outcomes of a WRRA Program Initiative to examine, document, and summarize the extent and use of data collected on students supported by individual institutes. The WRRA Program asked institutes to complete a voluntary online survey of institute practices. Survey questions addressed types of data collected, how such data are obtained and managed, and current uses of these data. To explore survey nonresponse bias, a survey response rate was calculated by dividing the total number of completed surveys by the total number of member institutes and multiplied by 100. A survey was archived as complete if a survey participant clicked "done" and submitted the survey online. Item nonresponse rate by survey question was not calculated as the survey structure required participants to answer each question.

Gap Analysis for Data Opportunities and Needs Related to Student Support

Using results from the activities described above, we generated a gap analysis of data opportunities and needs related to student support at the USGS Water Resources Research Institutes.

This qualitative assessment derives from the synthesis of available data presented above and interpretation of these data by the authors. The gap analysis for select student support data elements includes a description of the current circumstances (current state), identifies an associated desired state (the opportunity), ascertains one or more deficiencies in achieving the desired state (the need or gap), and provides recommended actions to address the need identified.

Results

Student Support at the Water Resources Research Institutes

All institutes pooled (N = 54) supported on average 678 (*sd* = 83) students per year (range 518 to 788) providing 10,853 student support years from 2000 through 2015. The number of students supported increased (linear regression analysis, $p = 0.02$) during this 16-year period by approximately 10 students each year (Figure 1A).

Individual institute investment in student support varied as measured by student support years. Total student support years by institute during the 16-year period examined ranged from 76 to 646 (Figure 1B). On average, each institute provided 201 (*sd* = 102) years of student support in total from 2000 through 2015; the median number of student support years by institute over this period was 175.

Student Support by Degree Sought. From 2000 through 2015, the WRRA Program-NIWR provided support for students working toward degrees at the undergraduate, master, Ph.D., and post-doctoral levels. The total 10,853 student support years were allocated as follows: 4,304 at the undergraduate level, 3,781 at the master level, 2,344 at the Ph.D. level, and 424 at the post-doctoral level. There were significant increases in the number of undergraduate and Ph.D. students, and post-doctoral associates supported from 2000 through 2015 (linear regression analysis, $p \leq 0.05$ for all) (Figure 2). Support of undergraduate students increased by five students per year during this period, followed by Ph.D. students with an increase of about four students per year, and post-doctoral associates at just over one student per year. No change in the number of students supported over this period was detected for master-level students.

Student Support by Funding Instrument. Funding instruments through which students were supported included Annual Base Grants, the NCGP, Coordination Grants, and the NIWR-USGS Student Internship Program (Figure 3). Annual Base Grants to member institutes were the primary funding mechanism from 2000 through 2015, accounting for 9,010 or 83% of all student support years. The next most common funding instrument for student support was Coordination Grants (1,640 student support years or 15% of all student support years), followed by the NIWR-USGS Internship Program (202 student support years or 2% of all student support years), and the NCGP (96 student support years or 1% of all student support years).

Student funding via Annual Base Grants increased significantly by approximately 14 students per year from 2000 through 2015 (linear regression equation, $p < 0.005$) with a trend toward increased variability in the number of students supported beginning in approximately 2007. The NIWR-USGS Internship Program decreased funding of students on average by just over one student per year from 2000 to 2015 and this was also significant (linear regression equation, $p < 0.005$). Funding of students via Coordination Grants also decreased on average by two students per year over the period examined, though this trend was not significant. In contrast to Annual Base Grants, there is a trend toward decreasing variability in number of students supported for Coordination Grants beginning in approximately 2007. The number of students supported via the NCGP remained constant at approximately six students per year from 2000 through 2015.

Student Data and use of Student Metrics at the Water Resources Research Institutes

Forty-four of 54 WRRA Program-NIWR institutes participated in the survey on student data collection and use of student metrics for a survey response rate of 81%. Seventy percent of institutes responding to the survey indicated they keep and maintain the data they report to NIWR.net on students or fellows supported. Institutes manage these data in a variety of ways (Figure 4). The most common way institutes manage these data is in the original file reports submitted by institute researchers, other faculty, or the institute itself (70% or 31 institutes). NIWR.net is the second most common tool used by institutes to manage student or fellow data (52% or 23 institutes), followed by software spreadsheets (36% or 16 institutes), fiscal or human resources files (20% or nine institutes), and database systems other than NIWR.net (16% or seven institutes). Four institutes (9%) reported they manage these data in other ways.

Fifty-nine percent of institutes responding to the survey indicated they do not collect and maintain any data on students or fellows supported beyond that which is required for NIWR or USGS reporting

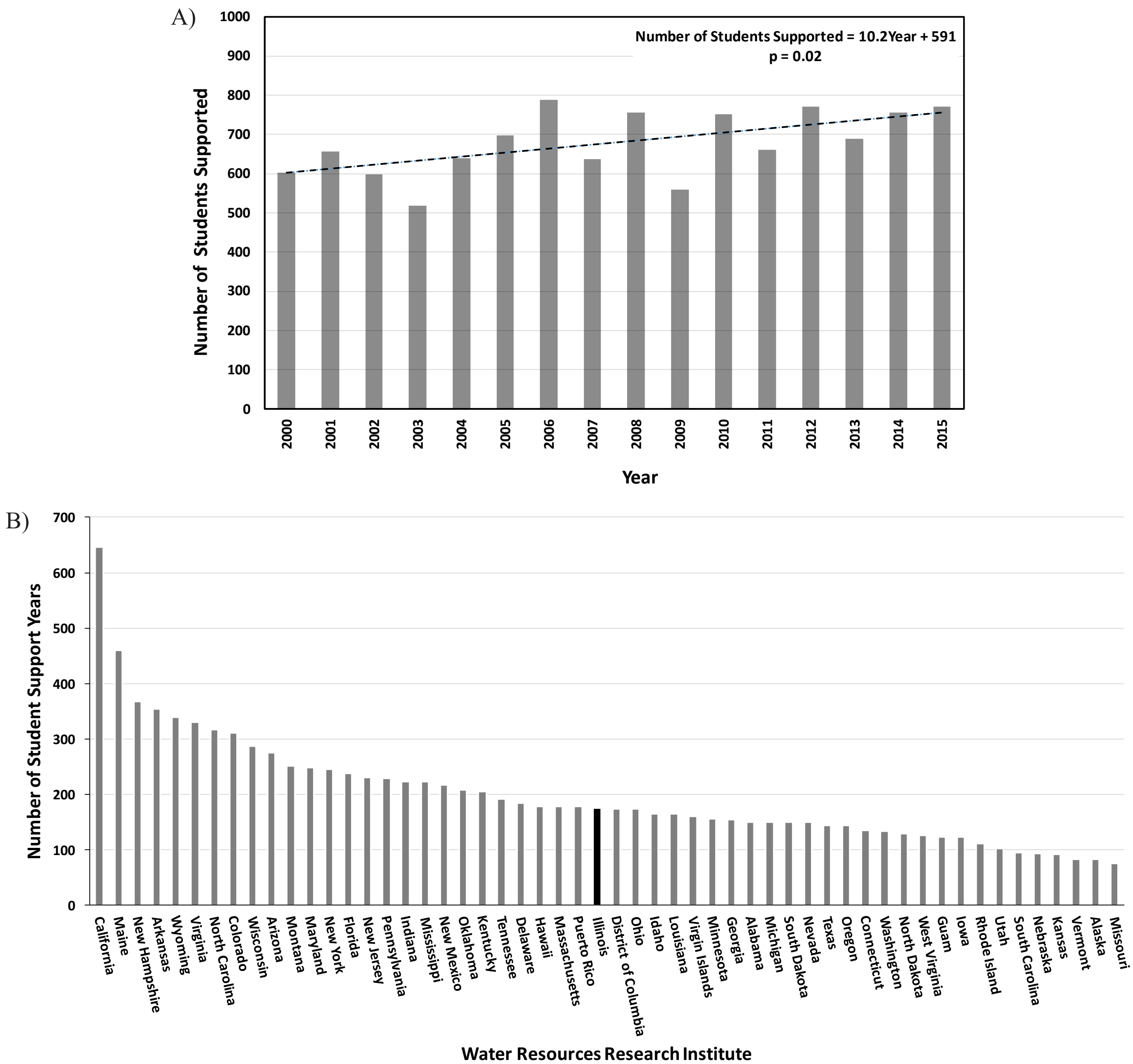

Figure 1. Student support at the United States Geological Survey, Water Resources Research Act Program from 2000 through 2015 by A) number of students supported by year for all water resources research institutes pooled. Linear regression (dashed line) analysis shows a significant increase in students supported during the period examined ($p = 0.02$); and B) number of student support years by water resources research institute for all years pooled. The median number of student support years is indicated by the black bar (Illinois). A student support year is defined as the support of one student for one year.

purposes with the remaining 41% of institutes reporting they do collect and maintain data beyond that required for reporting purposes.

Most institutes report they are collecting data on student or fellow name (80% or 35 institutes) and degree sought (82% or 36 institutes). However, confirming the functional linking of these two data fields and other student training data fields collected was not within the scope of the present work. Other information collected by institutes included date of degree earned and funding instrument/type (41% or 18 institutes for both). About one in four institutes (27% or 12 institutes) collect and maintain student contact information. Nine percent of institutes (four institutes) collect and maintain data on student post-support professional (job) placement.

The current use of student support metrics by institutes is principally for required reporting. Essentially all institutes responding to the survey (98% or 43 institutes) report using these data for required NIWR, USGS, or university reporting purposes. Less than one-half of institutes responding use these data for institute promotion (45% or 20 institutes) or website and social media engagement (41% or 18 institutes) (Figure 5). Seven institutes (16%) use data on students or fellows supported for development/donor activities. Two institutes (5%) use data on students or fellows supported for other purposes.

The importance of student support/training to both the mission of individual institutes as well as nationally is widely acknowledged by institutes with ≥ 80% of all institutes responding student support/training is "very important" to both.

Gap Analysis for Data Opportunities and Needs Related to Student Support

A gap analysis for data opportunities and needs related to student support is provided in

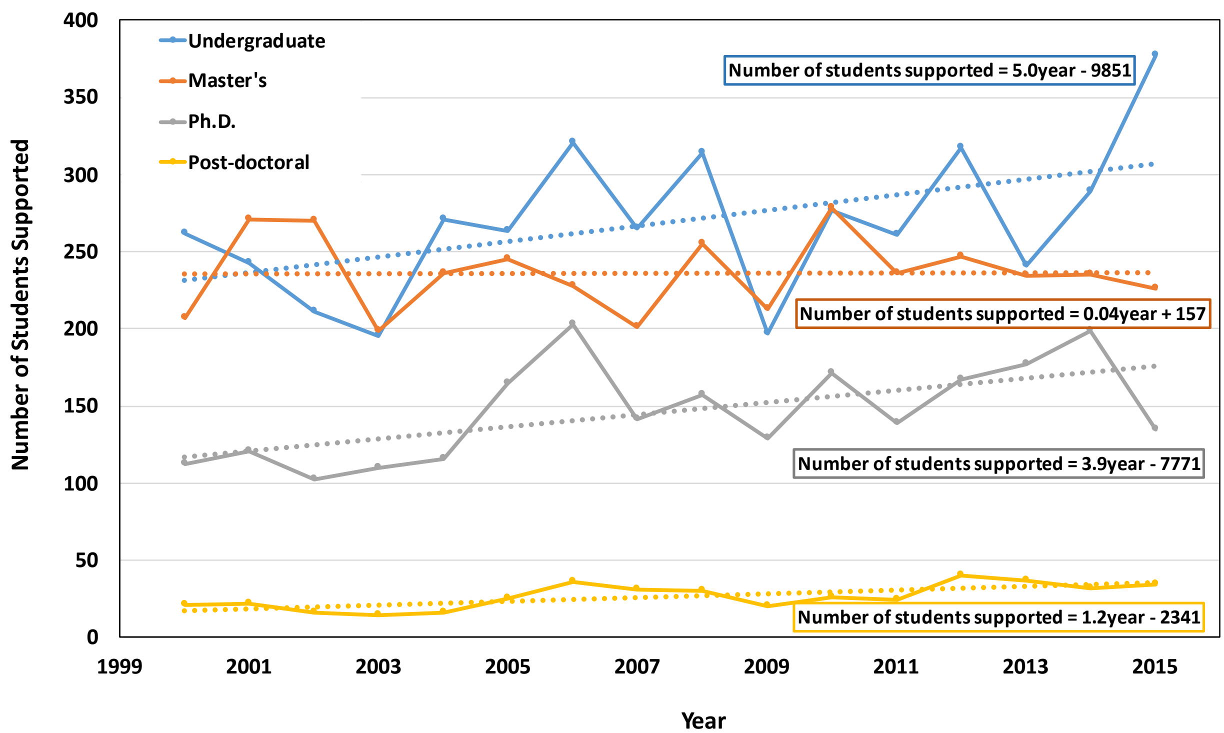

Figure 2. Number of students supported by the United States Geological Survey, Water Resources Research Act from 2000 through 2015 by year and university degree sought for all water resources research institutes pooled. Solid lines connect data points by year. Dotted lines are fitted using linear regression. Number of students supported significantly increased for undergraduate students (blue circles), Ph.D. students (gray circles), and post-doctoral associates (yellow circles) (linear regression analysis, $p \leq 0.05$ for all); no significant change was detected for master students (orange circles).

Table 1. Overall, four areas were identified that provide opportunities to increase the utility and value of student support data and associated metrics. These four areas address: achieving consistent and comparable data collection among institutes; achieving consistent and comparable data management among institutes; utilizing metrics associated with student training broadly and effectively internally and externally, and; enhancing data collected to document student training outcomes and inform strategic investment in student support.

Selected deficiencies (gaps) to capitalizing on the opportunities noted above are also provided in Table 1. While specific gaps are provided for each area, a gap identified for all areas is a user-friendly, enhanced, and interactive online database readily accessible to individual institutes, NIWR, and the WRRA Program. Other gaps identified include: clear national guidelines on collection and reporting of student support data; opportunities for use of student training metrics that are well defined and supported at the state or national level; and data on job recruitment, placement, and retention of supported students. Eight specific actions are also identified in Table 1 to address one or more described gaps.

Discussion

Student Support at the Water Resources Research Institutes

The USGS Water Resources Research Institutes play a key role in providing training in water resources within a greater STEM occupational framework, as evidenced by the support of approximately 700 students each year via federal WRRA Program funding. Though investigation of specific disciplines studied by supported students was beyond the scope of this study, institute research and associated student training is focused heavily on STEM disciplines. The increase in overall student support from 2000 through 2015, by about 10 students each year, is

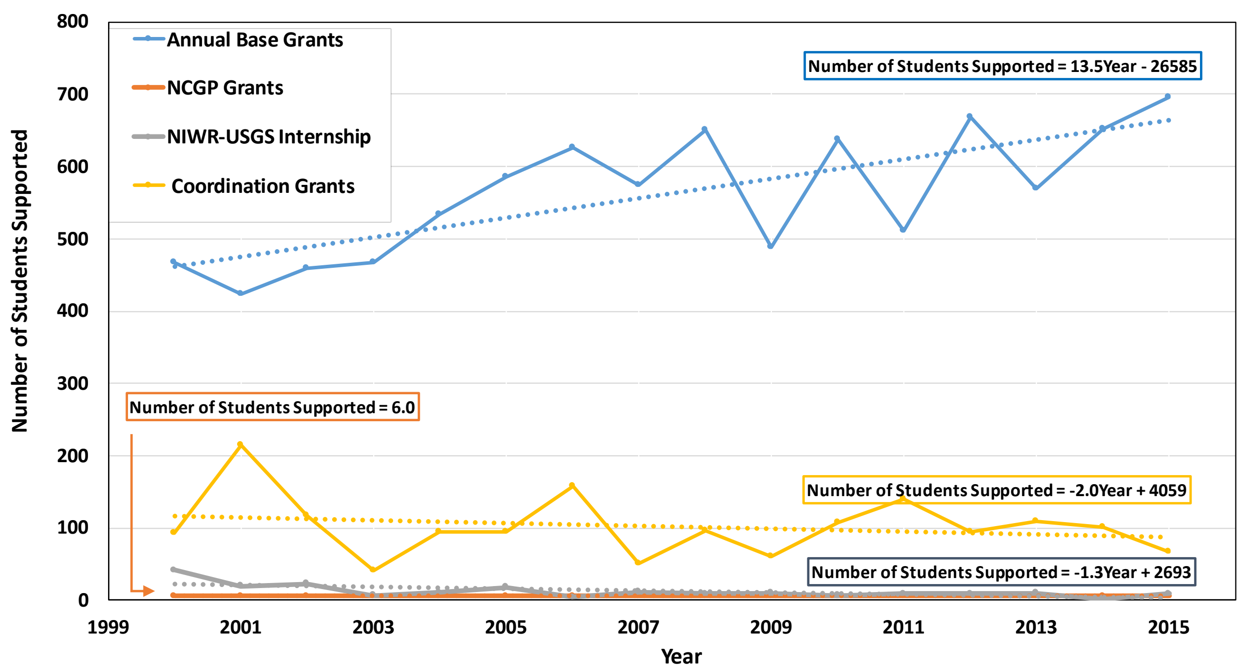

Figure 3. Number of students supported by the United States Geological Survey, Water Resources Research Act Program from 2000 through 2015 by federal funding instrument for all water resources research institutes pooled. Solid lines connect data points by year. Dotted lines are fitted using linear regression. Number of students supported significantly increased for Annual Base Grants (blue circles) and significantly decreased for the NIWR-USGS Student Internship Program (gray circles) (linear regression analysis, $p < 0.005$ for both); no significant change was detected for the National Competitive Grant Program (NCGP; orange circles) or Coordination Grants (yellow circles).

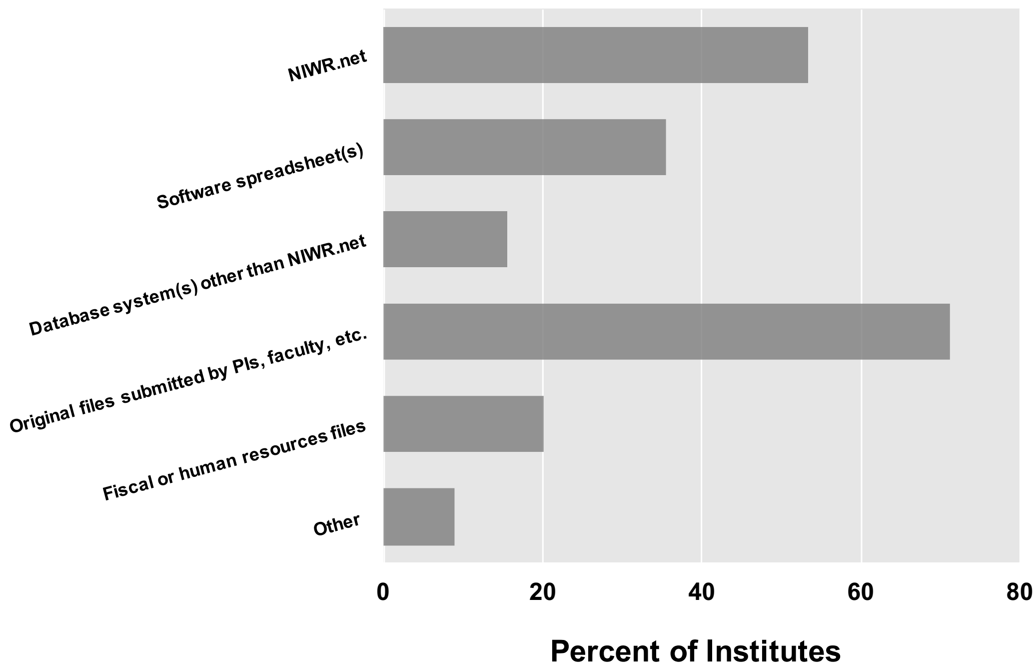

Figure 4. Water Resources Research Institute responses to the survey question, "How does your state water institute manage data on students or fellows supported?" The total number of institutes responding to this question was 44. Individual institutes could choose multiple responses; percentages may not add to 100%. PIs refer to Principal Investigators of funded research. NIWR.net is the federal reporting database to which institutes are required to submit yearly reporting.

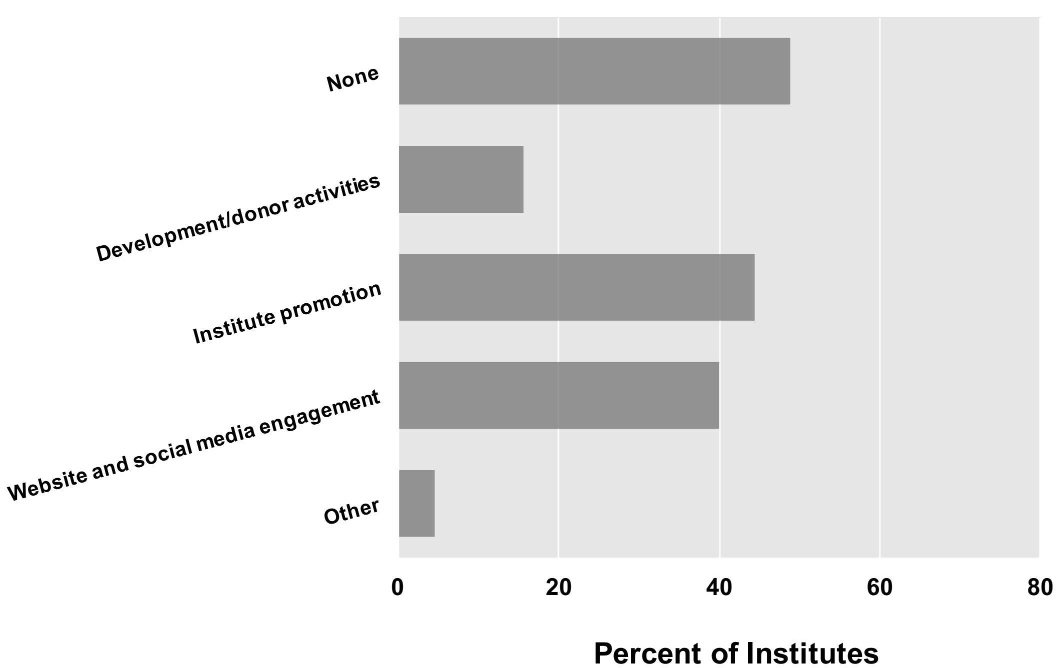

Figure 5. Water Resources Research Institute responses to the survey question, "[Other than required reporting], in what ways does your state water institute currently use data on students or fellows supported?" The total number of institutes responding to this question was 44. Individual institutes could choose multiple responses; percentages may not add to 100%.

Table 1. Gap analysis for data opportunities and needs related to student training at the United States Geological Survey (USGS) Water Resources Research Institutes.

Current State	Desired State (Opportunity)	Deficiency (Gap or Need)	Action
1. Data collection on student training is inconsistent among state water resources research institutes.	Data collection on student training is consistent and comparable among state water resources research institutes.	Clear national guidelines on data collection and reporting of student support and training.	Clarify national guidelines on student data collection and reporting.
			Improve standardization of student data collection.
			Update and enhance information collected on student training.
		User-friendly, enhanced, and interactive online database.	Evaluate, identify, and implement tools to enhance student support tracking and outcomes.
2. Management of data on students supported is inconsistent among state water resources research institutes.	Management of data on students supported is consistent and comparable among state water resources research institutes.	User-friendly, enhanced, and interactive online database.	Evaluate, identify, and implement tools to enhance student support tracking and outcomes.
3. Metrics associated with student training are underutilized.	Metrics associated with student training are broadly utilized.	User-friendly, enhanced, and interactive online database.	Evaluate, identify, and implement tools to enhance student support tracking and outcomes.
		Opportunities for use of student training metrics are well defined and supported at the state and national level.	Develop strategies for use of student support metrics at the state and national level and share with state water resources research institutes.
			Conduct outreach and “inreach” on student support and associated metrics with USGS, state water resources research institutes, stakeholders, constituents, and others.
4. Outcomes of student training are not documented.	Outcomes of student training are documented and investment in student support is strategic.	User-friendly, enhanced, and interactive online database.	Evaluate, identify, and implement tools to enhance student support tracking and outcomes.
		Data on workforce placement of supported students.	Identification and ranking of alumni search strategies for populating student training database(s).
		Data on recruitment, placement, and retention of supported students within the USGS.	Develop and conduct survey to evaluate role of institutes in workforce training and recruitment at the USGS.

a judicious investment in our nation's workforce. The absolute increase in investment in student training is laudable given the static federal funding of the institutes during the time-period examined (WRRA 1964, 1984) and speaks to the recognition of student training and workforce development as a vital service provided by the WRRA Program via institutes.

Students supported by institutes represent individuals who are likely to have contributed to the greater STEM workforce and the level of this training provides some insight on the nature of these contributions. As the largest single category of students trained from 2000 through 2015, undergraduate students are notable insofar as workforce undergraduate-level STEM competencies are increasing in value nationally and internationally (Carnevale et al. 2011). Training of undergraduate students, irrespective of an earned degree, can address workforce trends. In manufacturing, a need for sub-baccalaureate STEM skills was reflected in an estimated 600,000 unfilled technical positions in 2011 in the U.S. alone (Deloitte and The Manufacturing Institute 2011). Over 25% of STEM workers are educated at the post high-school diploma, sub-baccalaureate level and the wages of these workers exceed those of their non-STEM counterparts (Carnevale et al. 2011). The life and physical sciences and engineering, including engineering technicians, are among STEM occupational areas that are well represented in institutes' research portfolios and, by extension, student training (though some portion of WRRA Program supported students may represent non-STEM disciplines). Undergraduate study also results in a subset of supported students subsequently earning baccalaureate or higher degrees, credentials possessed by the majority of those occupying STEM jobs (Carnevale et al. 2011). Further, undergraduate student participation in research is correlated with student engagement (Miller et al. 2011) and success (Fechheimer et al. 2011) and undergraduates who participate in multi-year research experiences report enhanced workforce preparation (Thiry et al. 2011: Thiry et al. 2012). Undergraduate student training is clearly a fundamental aspect of workforce development, and the increase in undergraduate support by institutes from 2000 through 2015 is notable.

In 2015, just 12% of the U.S. population held an advanced degree, those beyond the baccalaureate (Ryan and Bauman 2016), though this level of training is increasingly important in disciplines related to water resources. In 2018, 64% of all STEM occupations are estimated to require a level of education at the bachelor's degree or higher and this is particularly relevant in the life and physical sciences, areas related to water resources, where nearly one-half of these occupations will require advanced degrees (Carnevale et al. 2011). Congruently, 60% of institute student support has been directed toward those pursuing advanced degrees or receiving post-doctoral training. Master-level student training by institutes is second only to that of undergraduate student training and master student support represents the greatest component of graduate student support at institutes. This likely speaks to the roles of master-level training as preparation for direct post-degree employment as well as for doctoral-level study in some disciplines. The available data did not allow for the determination of the terminal degree earned by students supported by institutes, information which would assist in defining the outcomes of student support. It is unclear why, in contrast to all other student categories, there has been no increase in master-level student training by institutes over the 16-year period examined.

Support provided by institutes at Ph.D. and post-doctoral levels represents students seeking the highest levels of educational achievement. Pooled, the increase in student support for doctoral and post-doctoral students accounts for about one-half of the overall increase over the time period examined (with the remainder of the increase supporting additional undergraduate students). Academia has been identified as having a STEM Ph.D. surplus, particularly with regard to disciplines common to water resources (Teitelbaum 2003; Anft 2013) while other sectors, including government, may be facing a shortage (Carnevale et al. 2011; Xue and Larson 2014). Investigation of the degrees held by employees of key U.S. agencies, such as the USGS, would enrich the understanding of the potential value of institute student support to these agencies. One transcendent circumstance of the U.S. workforce at all levels and sectors is the retirement wave of workers born from 1946 to 1964, the "baby boomer" generation. Baby boomer retirements are predicted to have a disproportionately greater affect in STEM (Carnevale et al. 2011), and by extension water resources research and management disciplines, which institute trained students may address.

The variability of student support years among institutes over the time period examined is of interest. Each institute receives an annual core federal award of equal value, the variability in student support among institutes thus reflects other circumstances. For example, the structure and content of competitive research proposals awarded funding through each institute, i.e., researchers' requests for student support within proposals or the success of proposals that include student training, may both vary by institute. The variability observed may also result from WRRA Program researchers directing student training costs to leveraged intra- or extramural funding, even if students are participating on WRRA Program projects, and the inconsistent reporting of these students among institutes. Further, variable garnering of extramural funding by institutes and the application of these funds toward exceeding the minimum required WRRA Program non-federal match results in some institutes having a larger funding base from which to support student training. The variability in the number of students supported by institute may also reflect differences in the cost required to support students at various institute universities as well as variable costs associated with supporting undergraduate vs. graduate students.

The investment in student support by institutes reported here is conservative, documenting only students supported or trained via the WRRA Program and reported via NIWR.net. As previously noted, a mandate of some federal WRRA Program funding requires institutes to match non-federal project funds to federal dollars awarded, with some institutes exceeding the minimum required match. This leveraging amplifies the federal investment and increases the reach of institute student training, though it is not clear that consistent reporting of student training associated with non-federal match funds is occurring. Additionally, many institutes support students on projects not reported to the NIWR.net database, for example, select intra- and extramural funds obtained by institute researchers and directed to student training. Thus, the magnitude, influence, and reach of institute student support is greater than that documented by current reporting protocols. Achieving data collection and reporting on student training that is consistent and comparable among institutes, and appropriately recognizes leveraged support, would ameliorate some of the above uncertainties.

The primary WRRA Program funding mechanism by which students are trained at institutes is via competitive Annual Base Grants awarded to scholars researching issues related to water resources at our nation's universities. Regardless of degree sought by supported students, students are mentored and trained under the supervision of these scholars while participating in funded research, a documented contributor to student success (Fechheimer et al. 2011), persistence in STEM disciplines (Lopatto 2004, 2007) and workforce preparation (Thiry et al. 2011; Thiry et al. 2012).

The decline of students supported in the NIWR-USGS internship program is unfortunate as this program "provides undergraduate and graduate students with career enhancing field, laboratory, and research experience through participation in USGS activities as interns" (USGS 2018). Like undergraduate research, internships have been shown to be a high impact learning experience, result in high student engagement, and are uniquely perceived by students as relevant to long-term career goals (Miller et al. 2011). Thiry et al. (2011) showed that participation in out-of-class experiential activities such as internships and research by STEM undergraduates nurtured professional and personal gains. Mentoring, inclusive of internships and undergraduate research, has also been identified as having the largest perceived impact on academic performance for minority students in STEM disciplines (Kendricks et al. 2013). Concordant with the above, employers increasingly value internships as a pipeline for workforce recruitment (Robinson et al. 2007; Nace 2017). The collaborative NIWR-USGS Internship may be an underutilized asset that has the potential to serve as an enhanced conduit for diverse employee recruitment at the USGS and beyond.

Student Data and use of Student Metrics at the Water Resources Research Institutes

The local archiving of data on student support by a majority of institutes, albeit by a variety of protocols, presents an opportunity to utilize archived data for documenting post-support outcomes, such as degrees earned (in addition to sought) and workforce placement. Data management protocols most certainly impact the effectiveness and responsiveness with which institutes can access, query, and summarize student support metrics. The use of the NIWR.net database for data management by just over one-half of institutes responding suggests it presently does not exhaustively meet the database needs of institutes or that institutes do not have the access or information technology capacity to optimize use of NIWR.net. The reported use of original file reports or fiscal or human resources files by nearly all institutes (90%), coupled with modest use of other database systems (16% of institutes) and software spreadsheets (36% of institutes), clearly indicates opportunities exist to enhance and facilitate management of student support data at the institute and national WRRA Program levels.

Enhanced data management of student information in consistency and scope would also improve interpretation of these data at all programmatic levels. The ongoing collection of an assortment of student training elements (data types/fields) by a majority of member institutes is a platform for embarking on these efforts. Though 80% of institutes report local collecting of data on student names, the functional linking of unique student identifiers, such as name, with other data fields such as degree(s) sought is unknown and was beyond the scope of this study. While institute investment in student support years was calculated, the lack of accessibility to data on student identifiers prevented the calculation of the absolute number of individual (unique) students supported over multiple years at both institute and national scales. However, the types of data collected presently by some institutes, such as student name and degree sought, indicate the potential for using archived data to generate meaningful student training outcome metrics, such as degrees earned and post-support job placement of supported students.

To our knowledge, no information on the diversity of students supported by institutes or the participation of minority and underserved groups in institute student training is currently known or collected. Presently, workforce diversity remains below targeted levels at the USGS (USGS 2015). A trifecta of mentoring, undergraduate research, and academic support has been shown to increase diversity and retention in undergraduate STEM disciplines (Wilson et al. 2012); all areas in which institutes have a university role. Program's implementing such actions have demonstrated success in preparing minority scientists and engineers for academic achievement (Summers and Hrabowski 2006) including enhancing minority representation in the NOAA workforce (Robinson et al. 2007). Enhanced minority and underserved student engagement at the institutes, and development and implementation of metrics to better define this engagement, are identified as avenues toward achieving race, ethnic, gender, and disability diversity within the greater USGS workforce.

Enhanced collection of student support data and management of these data and derived metrics will benefit from clear and supportive guidelines from WRRA Program leadership in collaboration with individual institutes on the type and scope of data sought. For example, just 41% of institutes participating in the survey report collecting or maintaining data on funding sources of student support at the institute level, though this is a codified element of federal reporting on student training funded by the WRRA Program. Thus, these data, while reported to the WRRA Program via NIWR.net by institutes, may not be readily archived for use at the institute level. Further, the robustness of data on student training could likely be enhanced through ongoing clarification of WRRA Program reporting requirements, particularly with regard to leveraged funding. Additionally, as noted previously, data management protocols (e.g., user-friendly databases) impact the effectiveness with which institutes can access, query, and summarize student support metrics, but also critically affect the capacity of individual institutes to collect these data in a consistent and comparable manner.

With over 80% of institutes reporting that student training is very important both at the institute and national level, the value of student training is broadly recognized. As such, considerable opportunity exists to enhance and expand use of alumni metrics to evaluate effectiveness of WRRA Program student support as well as amplify state, regional, and national support for institutes both within and outside of the USGS.

Gap Analysis for Data Opportunities and Needs Related to Student Support

Our gap analysis of student support data opportunities and needs is a sample framework from which understanding of student training efforts and outcomes might be enhanced with an emphasis on student data collection and management, and use of alumni data. Ultimately, knowledge of student support outcomes, such as post-support degrees earned and workforce placement, can document the value of the federal and state investment in institute supported students as well as direct this investment strategically to meet federal mandates and societal workforce needs.

Across all data opportunities described, a cross-cutting deficiency (gap) identified is the lack of a user-friendly, enhanced, and interactive online database for use by institutes, the WRRA Program, and NIWR. Such a database would facilitate collection, management, and effective use of student support and training data while allowing for the eventual documentation of post-support outcomes. While NIWR.net is a functional database, its utility for routine use by personnel at institutes is not currently realized and extant NIWR.net data fields do not address all identified gaps.

Key outcomes of the gap analyses are proposed actions to prepare for and initiate data collection on job recruitment, placement, and retention of institute supported students, including by the USGS. Additionally, data on degrees earned and workforce placement can assist individual institutes and the WRRA Program in refining student support investment to optimize value to students themselves, i.e., investment might be directed to increase the probability of student professional success in response to workforce needs. Exploration of the diversity, equity, and participation of minority and underserved groups receiving student support could assist in determining to what extent student support is meeting diversity targets at local, state, and national levels.

The 11 specific actions identified in Table 1 to address one or more described gaps support four strategic opportunities available to WRRA Program leadership to engage individual institutes. Individual institute engagement is critical insofar as individual institutes may have developed and implemented *ad hoc* alumni data solutions at the state level that may be scaled nationally. Other solutions that may have significant utility at the national level may require adaptation to be equally useful at the state and university level and vice versa. Additionally, where possible, extant solutions to similar needs should be leveraged. For example, the National Sea Grant College Program (Sea Grant) in the U.S. Department of Commerce's NOAA, has a similar management framework to the WRRA Program; including being comprised of individual member programs at our nation's universities and colleges and parallel legislative mandates. Sea Grant efforts to document student training nationally continue to increase (National Sea Grant College Program 2018) and about one in five NOAA personnel are estimated to have been trained or supported by the National Sea Grant College Program (Authors, unpublished data). More broadly, information about students supported by NOAA programs are compiled with a focus on NOAA mission-related STEM disciplines (NOAA 2018) in part through a Student Tracker Database that identifies students trained with EPP funds (Robinson et al. 2007). Solutions developed and implemented by Sea Grant or other relevant entities that could be applied or adapted by the WRRA Program to address gaps is recommended.

Conclusion

The USGS Water Resources Research Institutes play a significant role in training our nation's water resource research and management professionals and contribute to the development of the STEM workforce. The concentration of institute student support at the undergraduate and master-level of study is appropriate to predicted workforce needs. The participation in research by institute supported students at all levels of study, particularly undergraduates, is likely to increase students' future success. However, the NIWR-USGS Internship program may be an underutilized asset and presents an opportunity to potentially bolster workforce recruitment, particularly at the USGS. Opportunities also exist to augment data collection and data management on institute student training and refine the use of these data, such as documenting disciplines and dates of degrees earned by students, and post-training job placement. Another notable opportunity is initiating collection of information on student diversity and participation of minority and underserved groups in institute student training. Student training is recognized by institutes as an important programmatic element and support to more broadly utilize metrics associated with student training is recommended. Increased use of such information would illustrate the contributions of this training to workforce development at the state and national level. Exploration of institute alumni workforce placement will also illuminate the role student support plays in training the next generation of water scientists and managers in all sectors, and further clarify the value of this investment to society.

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Understanding the Water Resources of a Small Rural Community: Citizen Science in Cascabel, Arizona

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Abstract: Cascabel residents have cooperated in assembling and discussing a dataset addressing community concerns about groundwater quality and sustainability of water supply in their reach of the semi-arid San Pedro Valley. Most of the groundwater is drawn from Holocene sediments underlying the pre-entrenchment floodplain of the San Pedro River and similar sediments in major tributaries. Stable O and H isotopes distinguish two main floodplain aquifers: A, containing groundwater derived from the Valley flanks, and B, containing groundwater labeled by the presence of ancient water from a hot-spring system. In aquifer A, unpalatable groundwater containing dissolved ferrous iron and hydrogen sulfide is associated with clay containing buried wetland sediments that supply nutrients for microbial reduction of iron and sulfate. In aquifer B, groundwater is palatable, and static water levels at three locations have generally declined since the early 1990s, probably as a result of natural drainage in the upgradient part of the aquifer. Most groundwater from both aquifers contains measurable tritium, indicating vulnerability to multi-decadal drought.

Keywords: *stable isotopes, tritium, static water level, water quality, aquifer vulnerability, drought*

Cascabel is a dispersed community of a few hundred people along the San Pedro River, northwest of Benson and east of Tucson, Arizona, United States. At the time of first contact with the Spanish Empire during the 16th century, this part of the San Pedro Valley was occupied by the Sobaipuri people, who practiced irrigated agriculture, and lived in small towns such as Baicatcán, close to the map location of Cascabel (Latitude 32.2910°, Longitude -110.3794°). The Sobaipuri abandoned the Valley under pressure from Apache raids during the 18th century, and sought refuge in the Santa Cruz Valley to the west (Spicer 1962). By the late 19th century, cattle ranchers had become established in the Valley (Tellman and Huckleberry 2009; Cascabel Community Center 2017). Ranching on semi-arid rangeland and irrigated farming on river bottom land continue to the present, but rangeland ranching faces difficulties with persistent drought. Retired ranch land has been subdivided and occupied by retirees, artists, commuters, and weekend visitors from the rapidly expanding city of Tucson.

Residents of Cascabel depend almost entirely on a groundwater supply drawn from numerous private wells. The number of dwellings is increasing as a result of subdivision, but the amount of irrigated land in the community has declined greatly since the middle of the 20th century. Normally, such a situation would favor the long-term availability of groundwater because agriculture in the area has used far more water than all other users combined (Cordova et al. 2015). However, regional drought conditions since the late 1990s, emerging awareness of pre-historic long-term droughts (e.g., Griffin et al. 2013), and observed static water level (SWL) declines locally in Cascabel, have raised community concerns about the future supply of groundwater. Another concern centers on the highly variable quality of groundwater. The community has therefore expressed interest in developing a better understanding of its water resources.

The Nature Conservancy, with the cooperation of private well owners, has sponsored the monitoring of SWLs by Barbara Clark since 1993. Electrical conductivity (EC) and isotope measurements of groundwater samples provided by members of the community since 2007 have been undertaken by Christopher Eastoe, who has also led community workshops on groundwater origin, age, and quality. This report is a summary of the work undertaken by Clark and Eastoe, placed in the context of recently-published regional geophysical and geohydrological studies (Dickinson et al. 2010a, 2010b; Cordova et al. 2015). The aims of this report are to inform the community about its groundwater resource, in particular addressing groundwater sources and residence times, the origins of unpalatable groundwater, and the causes of changing SWLs.

Study Area

Location

This study focuses on a 27 km length of the San Pedro River Valley and the lower reaches of its tributaries, Hot Springs Canyon and Paige Canyon (Figures 1 and 2). The southern limit of the study area is the Benson Narrows, 20 km upstream of the map location of Cascabel (32.2910°, -110.3794°). The altitude of the river channel is 1,010 meters above mean sea level (m amsl) at the Benson Narrows, and 920 m amsl near site 37. The watershed includes surrounding hills at altitudes up to 1,500 m amsl.

Climate

The climate is semi-arid. The average annual rainfall at valley-bottom station 021330 between 1969 and 2013 was 338 mm/year (13.3 inches/year) (Western Regional Climate Center 2017). However, the average annual rainfall may vary greatly, the range being from 209 to 624 mm (8.2 to 24.6 inches) over the same period. Two wet seasons typically occur: a winter-spring season of orographic rain or snow from Pacific fronts (seasonal average 139 mm), and a summer season of convective precipitation from the North American Monsoon, augmented in some years by early autumn tropical depressions (seasonal average 199 mm).

Vegetation

Sonoran Desert vegetation (common genera including *Larrea*, *Acacia*, *Opuntia, Cylindropuntia, Carnegia,* and *Yucca*, along with grasses and annuals) is found on dry slopes away from major watercourses. Bottom land along major watercourses supports mesquite scrub and forest (*Prosopis*) that may extend several hundred meters from the active channels. Riparian cottonwood-willow forest (common genera including *Populus, Salix, Baccharis,* and exotic *Tamarix*) forms a discontinuous band up to a few hundred meters wide beside the active river channel, its development depending on availability of shallow groundwater. Much of the original mesquite scrub and riparian forest was cleared for irrigated agriculture during the 20th century; less than 50% of the cleared area remains under irrigation at present.

Geology and Geomorphology

The geology of the Cascabel area has been described by Drewes (1974), Mark and Goodlin (1985), and Dickinson (1991). Cook et al. (2010) mapped the geomorphology of the San Pedro Valley within 3 km of the river. The present-day regional landscape of hard-rock mountain ranges separated by deep basins filled with unconsolidated to semi-consolidated detritus from the mountains is termed the Basin and Range Province (Fenneman 1931). In southeastern Arizona, the basins and ranges began forming about 15 million years (Ma) ago as a result of tectonic extension of the continental crust (Dickinson 2002). The San Pedro River drains a set of such basins.

Prior to the extension, about 20 Ma ago, sediment eroded from an earlier mountainous terrain was deposited in a series of basins in southern Arizona. In the study area, the sediment consisted of granitic detritus and is termed the San Manuel formation (Dickinson 1991). Between 11 and 5 Ma ago (Miocene and early Pliocene time), an extensional basin that has been named the San Pedro trough (Figure 1) opened within and north of the study area (Dickinson 1991, 2003); the study area corresponds to the narrow southern end of the trough. The southern terminus of the trough was a ridge of Proterozoic granite, still present at the Benson Narrows. Drainage was internal and

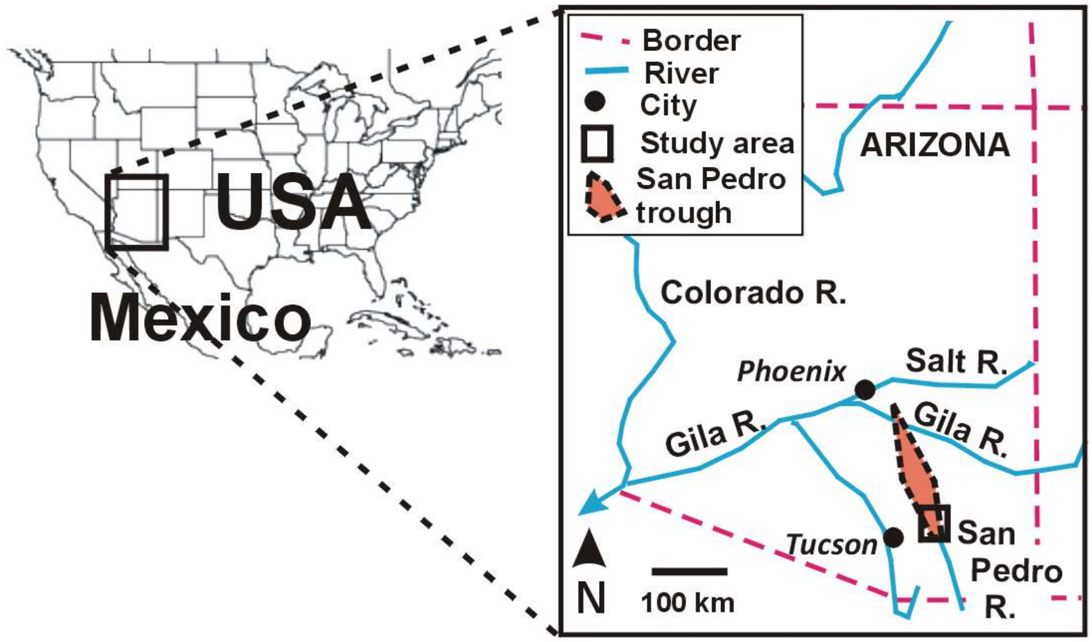

Figure 1. Location map showing the present integrated drainage of the Gila River basin.

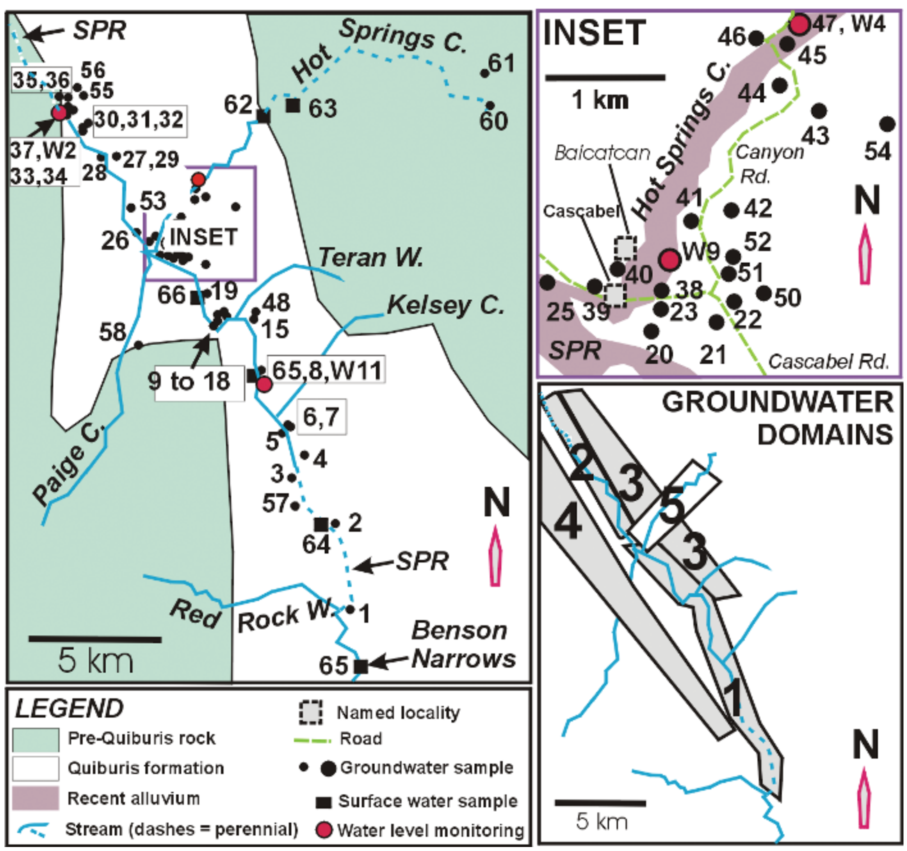

Figure 2. Sample sites and geographic features of the study area. Site numbers: simple numbers are groundwater sample sites as listed in Table 2; W-numbers are water-level measurement sites. Abbreviations: SPR = San Pedro River; C = canyon; W = wash.

directed to the north. Sediments filling the San Pedro trough compose the Quiburis formation. In the Cascabel area, the Quiburis formation consists of fluvial conglomerate and sandstone, in contrast to fine-grained lake sediments in the broader, northern end of the trough (Dickinson 1998).

Thick alluvial fans are exposed in cliffs and badlands of semi-consolidated Quiburis formation along the San Pedro River south of Paige Canyon. Consolidation appears to be due to low-temperature hydrothermal circulation. In that area, Quiburis formation outcrop occurs between altitudes of 960 m amsl (the river bed) and 1,200 m amsl (ridge-tops 2 km to the west of the river). Quiburis formation sediment therefore appears to have filled the center of the river valley to a depth of at least 240 m. In the northwestern part of the study area, Quiburis formation is faulted against a tilt-block of the San Manuel formation. At site 37, where the San Pedro River intersects the fault boundary, the San Manuel formation is clay-rich, impermeable to water, and dips 30° SE.

An integrated external drainage system comprising the Gila River, the San Pedro River, and other tributaries (Figure 1) formed during the Pliocene (Dickinson 1991), leading to erosion of much of the Quiburis formation in the study area. In Cascabel, progressive erosion is recorded as a stepped series of Pleistocene (2 Ma and younger) terraces at the confluence of Hot Springs Canyon and the San Pedro River (Cook et al. 2010).

The present course of the river lies entirely within a band of Holocene (< 12,000 years old) river channel sediments, 250 to 1,500 m wide and partly concealed by late Holocene alluvium (Cook et al. 2010). The top surface of these sediments corresponds with the river floodplain that existed prior to the mid-1800s. The sediments fill a trench that was cut into basin-fill sediments since about 20,000 years ago (Huckleberry et al. 2009). Possibly as early as the 1850s in the Cascabel area (Hereford and Betancourt 2009), the river began excavating an arroyo entrenched up to 6 m into the channel sediments. Late 19th century water-course entrenchment is a regional phenomenon (Bryan 1925), and may have been the result of climate change, removal of beavers, overgrazing, or other human activities (Hereford and Betancourt 2009). Waters and Haynes (2001) documented seven cycles of arroyo formation alternating with refilling of the channel since 8,000 years before the present (BP), including six cycles since 4000 years BP that were synchronous across southeastern Arizona. The banks of the present arroyo in Cascabel expose fluvial sand, coarse gravel, and clay-rich beds that may represent wetland or lake deposits. Charcoal from fluvial sediment near site 57 gave radiocarbon ages of 1090 and 1720 years BP (Table 1).

Several drillers' lithologic well-logs are available for the Holocene river-channel sediments (Arizona Department of Water Resources 2017). Clay, readily identified by drillers, was recorded to depths of 30 m below the surface (Figure 3), mainly upstream of Hot Springs Canyon. Sandy lenses may be present within the clay units. Holocene fluvial sediment may be present below the clay units, but cannot be reliably distinguished from Quiburis formation sediments in drill cuttings. We interpret the distribution of clay within the band of river-channel sediments as indicating the presence of a narrow, filled Holocene river valley at least 30 m deeper than the 1880s floodplain. A narrow body of conductive material, interpreted as clay, was detected in an airborne transient electromagnetic survey beneath the river 3 to 8 km north of the Benson Narrows (Dickinson et al. 2010b).

Hydrology

The San Pedro River in the study area is ephemeral, except for a reach between sites 1 and 2 with very small perennial flow and an intermittent reach beginning at site 37, where the San Manuel formation forms a shallow sill across the aquifer beneath the river (Figure 2). The flowing reaches have tended to decrease in length since 2007 (The Nature Conservancy 2017). Floods lasting days to weeks occur in the river throughout the Cascabel area in summer and autumn as a result of monsoon or cyclonic rain events. Floodwater has passed through the Benson Narrows every summer between 2008 and 2012, but is rare at other times. No base flow has entered the study area at the Narrows in recent years, as shown by data for the Benson Narrows gauge (United States Geological Survey 2017). Low-volume perennial flow is also present in the hard-rock reaches of Hot Springs Canyon (The Nature Conservancy 2017). Hooker Hot Springs and other nearby hot springs in the

Table 1. Radiocarbon dates.

Lab No.	Site	Material	Latitude °	Longitude °	Age (yrs. BP)	$\delta^{13}C$ ‰		
A15773	SPR, Three Links Ranch 7A	Charcoal	32.2009	-110.3149	1090 ± 75	-26.6		
A15774	SPR, Three Links Ranch 7D	Charcoal	32.2009	-110.3149	1720 ± 40	-26.0		
Lab No.	**Site**	**Material**	**Latitude °**	**Longitude °**	**Uncorrected pMC**	**$\delta^{13}C$ ‰**	**Corrected pMC***	**Age**
A14605	Site 11	Groundwater	32.2614	-110.3484	97.8	-11.8	119.5	post-bomb
A14656	Site 19	Groundwater	32.2687	-110.3547	81.3	-9.4	127.8	post-bomb
A7769	Site 60, Hooker Hot Springs	Groundwater	32.3664	32.2382	15.2	-12.7	17.0	14650 yrs BP

*Using $\delta^{13}C$ values as basis of correction (Clark and Fritz 1997, p. 210), and assuming soil gas $\delta^{13}C$ = -19.9‰. Soil carbonate $\delta^{13}C$ = -1 ‰; BP = before the present; pMC = percent modern carbon.

headwaters of Hot Springs Canyon are a source of base flow in that canyon.

Cordova et al. (2015) considered the groundwater hydrology of the area between the Benson Narrows and Redington (19 km downstream from Cascabel). The Cascabel area makes up less than half of the Benson Narrows-Redington area, and is represented by relatively few measurement points. Cordova et al. (2015) presented contour maps of SWLs in 1940 and 2006-2009 (See Figures 14 and 16 in Cordova et al. 2015) and estimates of water use (See Figure 29, in Cordova et al. 2015). Groundwater occurs in a regional aquifer including the Holocene channel-fill sediments and adjacent parts of the Quiburis formation. Groundwater flows towards the river and northwards beneath the river. Between 1970 and 2010, consumption of water for irrigation decreased from about 1400 to 250 m^3/year, while domestic water use increased from about 12 to 20 m^3/year. Modeled estimates of the water budget of their study area for 2001-2009 showed an average annual groundwater inflow and outflow of 1380 and 1500 m^3/year, respectively, i.e., a net decrease in groundwater storage of 1.8 hm^3 per year. Most of the inflow is winter runoff from high mountains to the Valley at Redington; winter inflow is much lower in the Cascabel area. The model estimates include 1.5 hm^3 per year of groundwater inflow into the Cascabel area at the Benson Narrows through a postulated connection between deep basin-fill aquifers in the area. The likely presence of a continuous granite ridge across the Valley at river-level in the Benson Narrows (Drewes 1974) does not support such an interpretation, which will be discussed further below.

In the more intensively studied part of the San Pedro Valley south of the Benson Narrows, both Holocene alluvium and underlying basin fill act as aquifers or a single regional (deeper) aquifer, and a perched, shallow riparian aquifer can be distinguished where the river flows over clay-rich beds (Baillie et al. 2007; Huckleberry et al. 2009; MacNish et al. 2009; Hopkins et al. 2014). At Cascabel, the geometry of the aquifers appears to be comparable, and similar, smaller aquifers are present beneath major tributaries such as Hot Springs and Paige Canyons. However, little water is produced from the regional aquifer more than

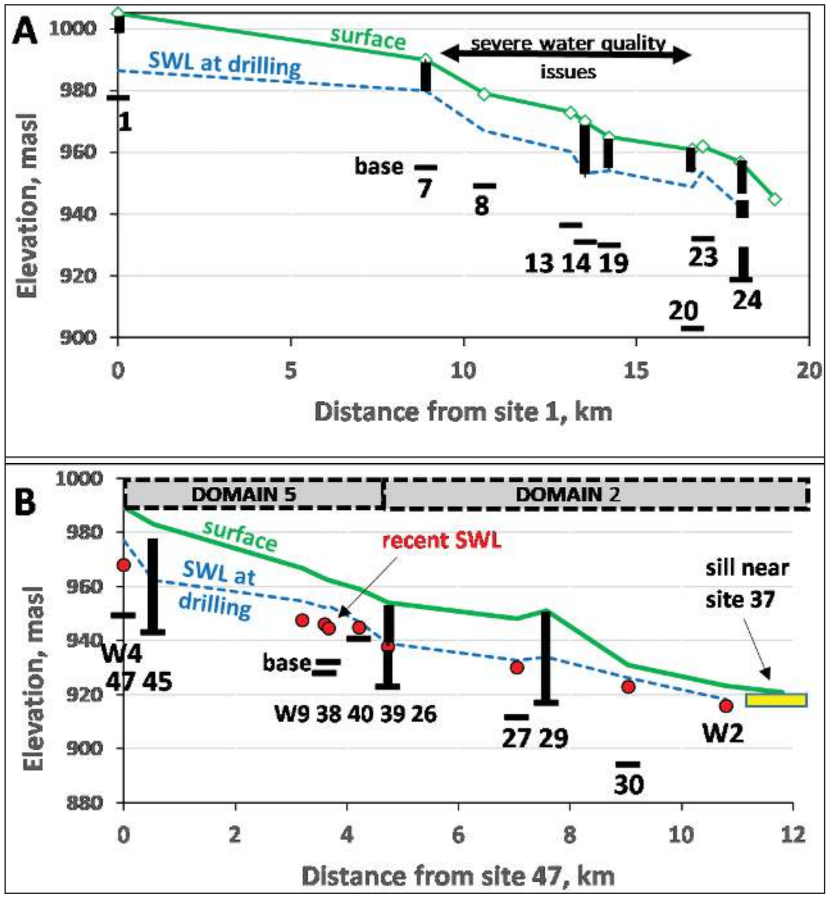

Figure 3. Cross-sections of the topographic profile of stream beds, static water levels, well depths, and clay (black columns) recorded in drillers' logs. Where no clay is recorded, silt, sand, and gravel are present. (A) Along the San Pedro River between sites 1 and 24. (B) From site 45 in Hot Springs Canyon to site W2 on the San Pedro River.

100 m from major floodplains, and almost none from any perched riparian aquifer overlying or within the clay units. The Holocene channel deposits (along with similar deposits in Hot Springs Canyon and Paige Canyon) appear to host most available groundwater in the Cascabel area. Most production wells are situated close to the San Pedro River (Figure 2), either in the Holocene valley fill, or in adjacent Quiburis formation (see Figure 4 for a schematic depiction). Much of the aquifer appears in drillers' logs to be unconfined (Arizona Department of Water Resources 2017). However, for sites 8, 14, 19, 20, 21, and 23, drillers' logs report confined water conditions, most likely reflecting groundwater in sand or gravel below clay beds. A few wells (e.g., sites 48 to 56) apparently produce groundwater from the Quiburis formation far from the river and its main tributaries. Artesian water is known to be present only at site 57.

Methods

Groundwater depths were measured between 1990 and 2016 using a Fisher M Scope WLS water level indicator. Data representing SWLs are presented here; a small number of measurements taken soon after periods of pumping have been excluded. Groundwater samples were obtained from continually active supply wells, springs, or pits dug in the river bed. EC was measured with a Hanna HI9033 meter calibrated with standard 1430 µS/cm KCl solution. Isotope measurements were performed at the Environmental Isotope Laboratory, University of Arizona. Water samples for isotope measurement were collected from surface water, wells that were in continual use, piezometers from which three casing volumes of water were removed prior to sampling, and springs and seeps. Stable O and H isotope ratios were

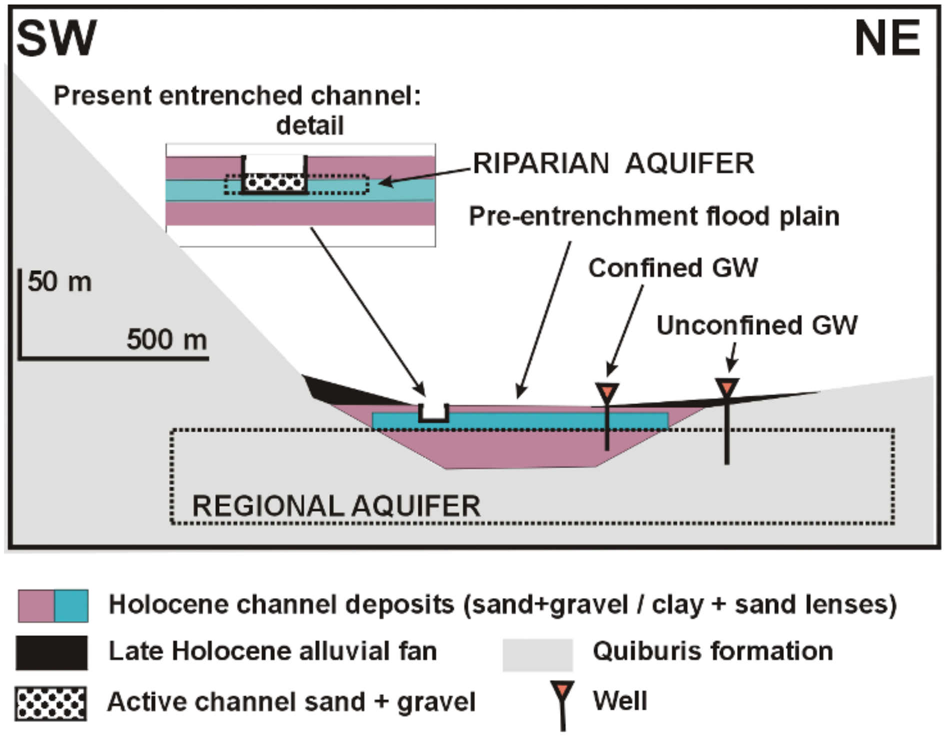

Figure 4. Schematic cross-section of the inner San Pedro Valley near site 19, illustrating groundwater hydrology. The depth of the entrenched river channel is exaggerated. The depth and lateral extent of the saturated zones are not known. The trench occupied by Holocene sediment may include multiple filled arroyos of different ages, as is the case upstream of the study area (Waters and Haynes 2001).

measured on a Finnigan Delta S® dual-inlet mass spectrometer equipped with an automated CO_2 equilibrator (for O) and an automated Cr-reduction furnace (for H). Results are expressed in delta-notation, e.g.,

$$\delta^{18}O \text{ or } \delta D = 1000\{\frac{R(sample)}{R(standard)} - 1\}‰,$$

where R = $^{18}O/^{16}O$ or $^{2}H/^{1}H$.

Analytical precisions (1σ) are 0.08‰ (O) and 0.9‰ (H).

Tritium (^{3}H) and radiocarbon (^{14}C) were measured in a Quantulus 1220 ® Spectrometer by liquid scintillation counting. Tritium was measured on 0.19 L water samples after electrolytic enrichment. Results are expressed in tritium units (TU), where 1 TU corresponds to 1 tritium atom per 10^{18} hydrogen atoms. The detection limit is 0.6 TU. Radiocarbon was measured on CO_2 extracted from 50 L water samples by acid hydrolysis of dissolved inorganic carbon; the carbon was converted to benzene. Results for groundwater are expressed as percent modern carbon (pMC), where 100 pMC corresponds to the composition of the atmosphere in 1950, after correction for industrial effects. The detection limit is 0.2 pMC for undiluted samples. Groundwater ^{14}C results were corrected using stable carbon isotope data (Clark and Fritz 1997, p. 210). Data are listed in Tables 1 and 2.

Results

1. Isotopes

Framework for Presentation. Isotope data for groundwater will be presented with reference to the following domains. Each domain is an area with distinctive geological, isotope, and/or solute content (as will be explained below) within the study area (Figure 2).

Domain 1: the pre-entrenchment floodplain of the San Pedro River, south of the mouth of Hot Springs Canyon, and adjacent land within about 100 m of the floodplain.

Domain 2: the pre-entrenchment floodplain of the San Pedro River, north of the mouth of Hot Springs

Table 2. Sample sites, field data, and isotope measurements.

Site no.	Name	ADWR ID 55-	Lat.⁰ 32.	Long.⁰ -110.	Elev. m amsl	Depth m below surface	SWL m below surface	SWL m amsl	Date	EC	$\delta^{18}O$ ‰	δD ‰	Tritium TU	Quality Problems
GROUNDWATER DOMAIN 1														
1	TNC #12	206443	1510	2950	995	27.3	18.5	977	5/07	667	-8.2	-57		
2	TNC #5	651320	1840	2980	994	60.6	9.1	985	5/07	688	-8.2	-58	0.5	
3	Dewell Ocotillo Rd	608060	1980	3170	994	33.3	10.6	983	5/09	689	-8.7	-61	1.1	
3	Dewell Ocotillo Rd	608060	1980	3170	994	33.3	10.6	983	12/12	718	-8.6	-61		
4	TNC #1	651304	2160	3080	986	15.2	9.1	977	5/07	854	-8.4	-60		
5	HSR cliff pasture	608064	2248	3267	983	30.3	10.6	972	5/09	692	-7.8	-57		
6	HSR dom	608059	2297	3270	984	33.3	12.1	972	5/07	788	-8.1	-58		**H_2S**
7	HSR irr	520298	2310	3228	992	34.8	12.1	980	5/07	906	-8.3	-59	<0.9 (A 0.3)	
8	Mason	573705	2419	3313	979	29.7	12.1	967	5/07	874	-8.2	-59	1.9	
9	USGS Piez. Clayworks	215016	2610	3493	963	9.1	2.7	960	11/08		-8.0	-57		**OM**
10	USGS Piez. Clayworks	215015	2610	3493	964	18.2	3.0	961	11/08		-7.6	-54		**OM**
11	Clark	645667	2614	3484	970	27.3	12.1	958	5/07	812	-7.4	-52		**OM, H_2S, Fe**
11	Clark	645667	2614	3484	970	27.3	12.1	958	3/08	707	-7.4	-52	3.3	**OM, H_2S, Fe**
11	Clark	645667	2614	3484	970	27.3	12.1	958	10/15		-10.2	-74		**OM, H_2S, Fe**
12	Wilson shallow	645666	2626	3548	973	10.3	9.1	964	3/08	1197	-7.9	-55		none
13	Wilson deep	597352	2626	3548	973	36.4	12.7	960	3/08	892	-8.4	-59	3.2	H_2S
13	Wilson deep	597352	2626	3548	973	36.4	12.7	960	3/08	805	-8.4	-59		H_2S
14	La Margarita	525466	2630	3479	970	38.8	16.7	953	3/08	929	-8.2	-60	2.1	**H_2S, Fe**
15	McClure irr	526573	2619	3351	978	35.8	15.8	975	3/08	1566	-8.2	-58		**H_2S**
16	Oasis dom	603369	2636	3449	977	44.8	21.2	956	3/08	900	-8.4	-59		**H_2S**
17	Trumbule	806776	2639	3465	973	27.3	12.1	961	3/08	1054	-8.2	-58		

Table 2 continued.

Site no.	Name	ADWR ID 55-	Lat.° 32.	Long.° -110.	Elev. m amsl	Depth m below surface	SWL m below surface	SWL m amsl	Date	EC	$\delta^{18}O$ ‰	δD ‰	Tritium TU	Quality Problems
GROUNDWATER DOMAIN 1 (cont'd)														
18	Oasis irr	603368	2663	3432	977	30.6	15.2	962	3/08	868	-7.9	-57		
19	Eastoe & Callegary	539606	2687	3547	965	10.7	19.7	954	8/06	966	-8.2	-58	2.5	**Fe, oil film**
20	Thomas dom	515969	2877	3735	961	57.6	12.1	949	5/07	1003	-8.0	-58	3.1	H_2S, Fe
20	Thomas dom	515969	2877	3735	961	57.6	12.1	949	6/14	950	-8.1	-59		
21	Thomas irr	515970	2877	3735	958	37.0	18.2	940	7/09		-8.2	-60	<1.4 (A 0.7)	
22	McLean & Tench dom	521871	2895	3655	967	23.3	16.7	950	5/07	1083	-7.8	-57		**H_2S**
23	Greco	513520	2898	3736	962	29.7	8.5	954	1/09	1069	-8.0	-58		**H_2S, Fe**
24	Whitt	527527	2883	3863	957	37.9	13.6	942	5/09	502	-8.9	-60	3.2	
25	USGS Piez.LCC	215003	2914	3839	950	9.1	4.5	945	11/08		-7.9	-55		
25	USGS Piez. LCC	215004	2914	3839	950	18.2	4.5	945	11/08		-8.1	-59		
GROUNDWATER DOMAIN 2														
26	Community Center	526730	2943	3842	954	31.2	15.2	939	1/09	446	-9.1	-67		H_2S, Fe
27	Cielo Azul	533834	3189	3913	948	36.4	15.2	933	4/11	510	-8.5	-63	5.1	
28	A7 Brown irr	613526	3189	4002	935	37.2	5.2	930						
29	Vogel & Ffoliott	516029	3195	3905	951	37.0	17.0	934	3/12	485	-9.3	-66	<0.9 (A 0.3)	H_2S
30	Corbett irr	607859	3304	4064	931	25.8	4.8	926		738	-8.7	-64		
31	McBride	562275	3312	4062	932	37.9	6.1	926	3/09	561	-8.6	-62		Fe?
32	Elliott	602534	3319	4038	945	51.5	16.7	928	2/09	390	-8.7	-64		
33	Lands	545407	3367	4106	939	30.3	16.7	922	4/09	702	-8.7	-64	1.8	H_2S, Fe
34	Hellriegel	629316	3378	4134	928	15.2	4.8	923	3/14	677	-8.8	-65	1.7	Fe
35	Troutner	650592	3421	4160	937	45.5	34.8	902	12/08	687	-8.6	-64		Fe?
36	Grey	545694	3459	4111	951	70.3	56.1	895	4/09	330	-8.5	-63	<0.5	Fe

Table 2 continued.

Site no.	Name	ADWR ID 55-	Lat.° 32.	Long.° -110.	Elev. m amsl	Depth m below surface	SWL m below surface	SWL m amsl	Date	EC	$\delta^{18}O$ ‰	δD ‰	Tritium TU	Quality Problems
GROUNDWATER DOMAIN 2 (continued)														
37	Seep, E bank of SPR		3382	4181	921				3/14	752	-9.0	-65	2.1	
37	Seep, W bank of SPR		3382	4181	921				3/14		-8.4	-63		
37	Seep, W bank of SPR		3382	4181	921				5/14		-9.0	-63		
37	Seep, W bank of SPR		3382	4181	921				11/14	1335	-10.9	-77		
37	Seep, W bank of SPR		3382	4181	921				11/15	875	-11.3	-80		
GROUNDWATER DOMAIN 3														
48	McClure dom	574422	2628	3283	1025	93.6	55.8	963	3/08	532	-7.8	-57		none
49	Woolard	517873	2876	3678	984	106.1	30.3	954	6/07	376	-8.3	-64		H_2S
50	McLean & Tench remote	909739	2897	3623	991	157.3	34.8	956	12/08	508	-8.3	-61		none
51	Etshokin	542914	2914	3659	982	57.3	40.9	941	5/11	366	-7.7	-59		
52	De Palma	572943	2942	3651	998	90.9	44.8	953	4/11	391	-7.7	-58		
53	Curtis		3020	3861	951				12/08	393	-7.4	-55		
54	Meader	909740	3045	3512	957	110.6	78.8	878	3/12	508	-9.4	-67	<0.6	none
55	Brown & Stanton	572523	3468	4002	999	153.0	84.2	915	12/10	378	-7.9	-59	<0.6	none
56	Brown & Stanton cabin	540613	3520	4051	995	121.2	74.2	921	3/14	360	-7.3	-55	<0.8	none
GROUNDWATER DOMAIN 4														
57	Cienega artesian		1903	3102	987	43.9	0.0	991	12/12	407	-9.4	-68		
58	Paige Canyon well	608070	2702	3804	968	33.5	27	941	3/14	513	-9.7	-68	4.4	
58	Paige Canyon well	608070	2702	3804	968	33.5	27	941	1/15	504	-9.8	-67		
59	Grapevine Spring		2788	4948	1283				2012		-9.5	-68		
GROUNDWATER DOMAIN 5														
38	Otter	807673	2905	3737	963	28.5	10.6	952	5/07	545	-8.8	-65	3.5	none
38	Otter	807673	2905	3737	963	28.5	10.6	952	2015		-8.0	-58		none

Table 2 continued.

Site no.	Name	ADWR ID 55-	Lat.° 32.	Long.° -110.	Elev. m amsl	Depth m below surface	SWL m below surface	SWL m amsl	Date	EC	$\delta^{18}O$ ‰	δD ‰	Tritium TU	Quality Problems
GROUNDWATER DOMAIN 5 (continued)														
39	Newman	631866	2912	3799	959	18.2	12.1	947	2/09	485	-9.0	-66	2.9	
40	Baicatcan	631886	2917	3767	962	30.3	12.1	950	11/16		-8.8	-64		
41	Flood & Loveland	909738	2966	3699	998	83.9	50.0	948	3/12	549	-9.0	-66	6.9	
42	McPherson		3017	3658	1024		73.3	951	5/07	348	-8.8	-64	0.6	none
43	Evans	589398	3049	3575	1055	122.7	84.2	971	3/12	372	-9.3	-67	<1.0	Fe
44	Bribach	549082	3071	3613	1016				3/12	389	-9.2	-67	<0.8	
45	Revere dom	561388	3105	3603	983	45.5	20.6	962	5/07	463	-8.7	-62	3.3	none
46	Henderson	567431	3111	3616	1006	42.4	37.0	969	5/12		-8.9	-65		none
47	HSC. Windmill	553292	3134	3556	989				5/07	475	-9.0	-64		
SHALLOW RIPARIAN GROUNDWATER														
10	SPR river bed		2618	3533	961	*			10/08		-6.9	-49		
10	SPR river bed		2606	3395	965	*			2/09	2510	-5.7	-47		
10	SPR river bed		2618	3533	961	*			11/09	1480	-7.0	-48	6.6	
	SPR river bed					*			11/09		-4.5	-31		
HOOKER HOT SPRINGS														
60	Hooker Hot Springs		3664	2382	1248				1/94		-11.1	-81	<0.8	
61	Hot spring Bass Canyon		3501	2397	1238				1/94		-11.1	-79		
BASE FLOW														
62	HSC at range front		3287	3382	1010				11/13		-9.1	-67		
63	HSC at Narrows		3402	3187	1050				4/08		-9.0	-67		
64	SPR, Three Links		1801	2977	992				3/14		-8.2	-58		
64	SPR, Three Links		1801	2977	992				12/12	624	-8.2	-58		
64	SPR, Three Links		1801	2977	992				6/09	649	-8.2	-58	1.7	
64	SPR, Three Links		1801	2977	992				12/08	655	-8.1	-59		
64	SPR, Three Links		1801	2977	992				6/08	785	-8.2	-59	1.5	

Table 2 continued.

Site no.	Name	ADWR ID 55-	Lat.° 32.	Long.° -110.	Elev. m amsl	Depth m below surface	SWL m below surface	SWL m amsl	Date	EC	δ18O ‰	δD ‰	Tritium TU	Quality Problems
SUMMER FLOODWATER														
64	SPR, Three Links		1801	2977	992				9/6/06	362	-10.1	-68	4.1	
65	SPR, Benson Narrows		1010	1419	2890				9/16/06	344	-7.5	-50	5.0	
19	SPR, site 19		958	2686	3564				9/17/06	456	-7.2	-50	4.1	
6	SPR, site 6		979	2324	3324				6/17/07	1154	-7.4	-55	1.8	
19	SPR, site 19		958	2686	3564				7/30/07		-10.5	-74	5.8	
19	SPR, site 19		958	2686	3564				8/29/07		-7.4	-49		
19	SPR, site 19		958	2686	3564				9/9/07	431	-7.0	-50	3.7	
19	SPR, site 19		958	2686	3564				7/12/08	515	-7.4	-55		
19	SPR, site 19		958	2686	3564				7/13/08	517	-11.6	-82		
19	SPR, site 19		958	2686	3564				7/20/08	754	-10.1	-69		
6	SPR, site 6		979	2324	3324				7/25/08	463	-9.8	-71		
6	SPR, site 6		979	2324	3324				7/29/08	420	-7.0	-49		
6	SPR, site 6		979	2324	3324				8/6/08	398	-6.1	-41		
6	SPR, site 6		979	2324	3324				8/23/08	435	-4.8	-39		
6	SPR, site 6		979	2324	3324				8/27/08	730	-13.3	-97		
19	SPR, site 19		958	2686	3564				8/30/08	449	-11.3	-84		
6	SPR, site 6		979	2324	3324				9/5/08	511	-4.7	-36		
6	SPR, site 6		979	2324	3324				9/11/08	429	-5.8	-40		
6	SPR, site 6		979	2324	3324				9/14/08	500	-7.3	-57	4.4	
6	SPR, site 6		979	2324	3324				9/26/08	292	-10.2	-75		
6	SPR, site 6		979	2324	3324				9/27/08 am	376	-8.4	-64		
19	SPR, site 19		958	2686	3564				9/27/08 pm	489	-7.9	-59	3.9	
19	SPR, site 19		958	2686	3564				9/28/08 am	333	-10.3	-75		
6	SPR, site 6		979	2324	3324				9/29/08	433	-8.2	-63		
6	SPR, site 6		979	2324	3324				7/8/09	495	-5.8	-40		
6	SPR, site 6		979	2324	3324				7/10/09	493	-8.5	-58	4.8	

Table 2 continued.

Site no.	Name	ADWR ID 55-	Lat.° 32.	Long.° -110.	Elev. m amsl	Depth m below surface	SWL m below surface	SWL m amsl	Date	EC	$\delta^{18}O$ ‰	δD ‰	Tritium TU	Quality Problems
FLOODWATER, HURRICANE ODILE			979	2324	3324									
8	SPR, site 8		974	2415	3325				9/19/14		-14.8	-107		
8	SPR, site 8		974	2415	3325				9/20/14		-14.2	-102		
8	SPR, site 8		974	2415	3325				9/29/14		-9.8	-69		
19	SPR, site 19		958	2686	3564				10/4/14		-9.0	-67		

Explanation: SPR = San Pedro River; HSC = Hot Springs Canyon; USGS Piez = Unites States Geological Survey piezometer; LCC = Last Chance Crossing; TNC = The Nature Conservancy; dom = domestic; irr = irrigation; A = apparent tritium.

*Samples taken from excavations made by javelina, < 45 cm deep.

Quality problems: **bold** = severe; H_2S = hydrogen sulfide, rotten egg smell; Fe = dissolved Fe^{2+}; OM = suspended organic matter; "none" indicates an explicit report of no water quality issues; blank cells indicate no information available.

Canyon, and adjacent land within about 100 m of the floodplain.

Domain 3: tributary washes and hill slopes east of the San Pedro floodplain, except for Domain 5.

Domain 4: tributary washes and slopes west of the San Pedro floodplain.

Domain 5: Hot Springs Canyon, including the floodplain within the canyon and adjacent land within 200 m of the floodplain.

Surface Water. Base flow sampled from the San Pedro River at site 64 consistently had ($\delta^{18}O$, δD) near (-8.2, -58‰) between 2008 and 2014 (Table 2). The isotopes do not correspond with those in confined groundwater immediately upstream of the Benson Narrows (Figure 5A). The tritium contents of two base-flow samples were 1.7 and 1.5 TU (Table 2). Surface water from the river during monsoon floods has a very broad range of ($\delta^{18}O$, δD), consistent with data for summer rain in Tucson (See Figure 2 in Eastoe and Dettman 2016). Floodwater following rain from Hurricane Odile in September 2014 extended the range of ($\delta^{18}O$, δD) to even lower values (Figure 5B; Table 2), consistent with the low values of ($\delta^{18}O$, δD) commonly recorded in rainfall associated with tropical cyclonic weather systems in the region (Eastoe et al. 2014). With a single exception (Site 19, Table 2), the tritium content of summer floodwater is 3.9 to 5.8 TU. Base flow from Hot Springs Canyon (Figure 5D) had ($\delta^{18}O$, δD) near (-9.0, -67‰) in 2008 and 2013, and (-8.0, -64‰) in 2017.

Shallow Riparian Groundwater. Shallow riparian groundwater, sampled from pits dug 30-45 cm deep in the river bed by javelina (*Pecari tajacu*), largely has O and H isotopes similar to those of shallow riparian groundwater from the San Pedro River near Benson and St. David, south of the Benson Narrows (Figure 5B). One sample contained 6.6 TU of tritium (Table 2).

Regional Groundwater. In the regional aquifer, each of domains 1, 2, and 4 has a distinctive field of ($\delta^{18}O$, δD) data (Figure 5C; Table 2). The field for domain 3 differs slightly from that of domain 1; domain 3 groundwater plots to the right of domain 1 groundwater, and is therefore slightly more evaporated. Domain 1 groundwater has a similar stable isotope composition to base flow at site 64 (Figure 5A; Table 2). Domain 5 groundwater includes examples similar to Hot Springs Canyon base flow and mixtures of such base flow with water like that in domain 3 (Figure 5C; Table 2). Domain 2 groundwater is similar to domain 5 groundwater (compare Figures 5C and 5D).

Tritium (values listed in Table 2) in domain 1 groundwater and base flow is present at levels less than 2 TU between sites 64 and 8, and 2.1 to 3.3 TU north of site 8, with the exception of site 20. Domain 2 groundwater has tritium contents ranging from below detection to 2.1 TU, with an outlier, 5.1 TU, in confined groundwater below a clay lens at site 27. Three available tritium measurements for domain 3 are all below detection. A single measurement of 4.4 TU was obtained for water in the floodplain of Paige Canyon in domain 4. In domain 5, a distinction exists between groundwater in the floodplain of Hot Springs Canyon (sites 38, 39, and 45; 2.9 to 3.5 TU) and groundwater in the Quiburis formation mesa immediately south of the floodplain (sites 41, 42, 43, and 44; < 1.0 TU with one outlier, 6.9 TU).

Two ^{14}C measurements, 97.8 pMC at site 11 and 81.3 pMC at site 19, were obtained in domain 1 (Table 1). Corrected results for a variety of plausible scenarios (one of which is given in Table 1) indicate post-bomb ages (> 100 pMC) for both.

Relationships with Upstream Groundwater. Base flow and groundwater in domain 1 might originate

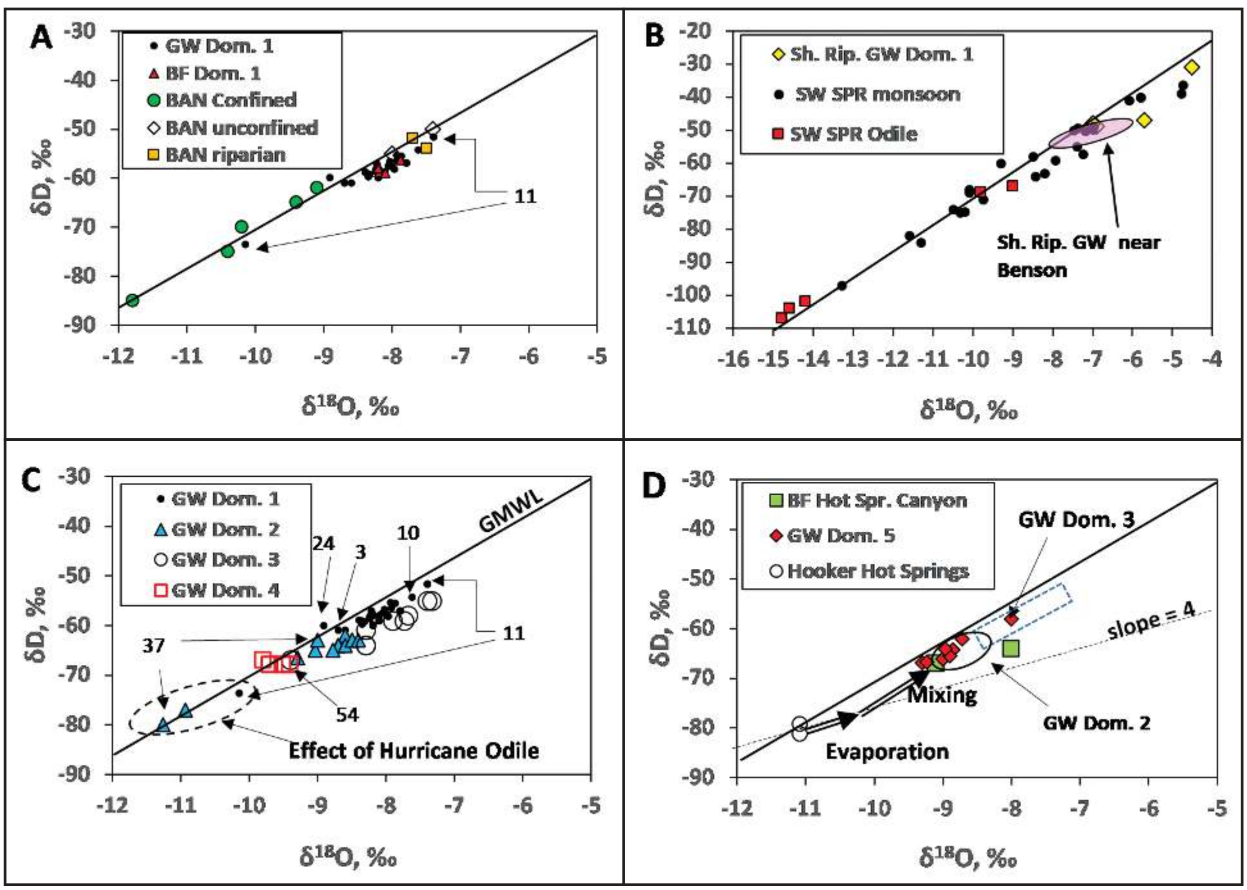

Figure 5. Plots of δD versus $\delta^{18}O$. (A) Comparison of groundwater and base flow in domain 1 with groundwater upstream of Benson Narrows. (B) Comparison of shallow riparian groundwater in domain 1 with San Pedro River surface water. (C) Comparison of groundwater in the regional aquifer in domains 1, 2, 3, and 4. (D) Relationships among groundwater from domains 2, 3, and 5, Hooker Hot Springs, and base flow in Hot Springs Canyon. Abbreviations: BAN = basin above Narrows; BF = base flow; Dom. = domain; GMWL = global meteoric water line of Craig (1961); GW = groundwater; Sh. Rip. = shallow riparian; SPR = San Pedro River; SW = surface water. Numbers are site identifiers, as in Table 2.

upstream of the Benson Narrows (Cordova et al. 2015). Isotope data for deep (confined) groundwater and for shallow riparian groundwater immediately upstream of the Narrows (Hopkins et al. 2014) do not resemble isotope data for domain 1 (Figure 5A), precluding groundwater flow through shallow or deep sediment channels at the Narrows or through deep, concealed channels breaching the granite barrier on either side of the Narrows. Domain 1 groundwater might resemble unconfined groundwater from basin fill above the level of the river bed on the flanks of the Valley, but such water is available both north and south of the Narrows. An exceptional isotope composition in domain 1 occurs at site 11 (Figure 5A), which is 50 m from the entrenched channel of the San Pedro River. In 2007 and 2008, the well yielded groundwater with isotopes like those of shallow riparian groundwater from above the Benson Narrows within domain 1. In 2015, groundwater at site 11 shifted to lower ($\delta^{18}O$, δD) values (Table 2).

Stable Isotope Changes Over Time. The isotopic distinctions between domains 2 and 5 and the other domains, and the clear isotope labeling of Hurricane Odile floodwater can be used to trace changes in the flow paths of groundwater. To date, the following changes have been observed. Site 38 lies within the floodplain of Hot Springs Canyon and is 100 m from site 23 which is part of domain 1. In 2007, stable isotopes indicated domain 5 water at site 38, but by 2015, this had been replaced by domain 1 water. The shift at site 11 in 2015 followed the September 2014 flood caused by inland remnants of Hurricane Odile, when a large volume of low - ($\delta^{18}O$, δD) river water was delivered from upstream of the Benson Narrows (Figure 5B; Table 2). A similar shift was observed in the river-bank spring at site 37 (Figure 5C).

Interpretation of Stable Isotopes. Recharge from the San Pedro River to the small shallow riparian aquifer at Cascabel is dominantly from summer or autumn surface water, because little surface water is available at other times. Notwithstanding the large isotope variability of such water (Figure 5B), the shallow riparian groundwater has isotope compositions restricted to the field observed upstream of the Benson Narrows and in a few samples from Cascabel (Figure 5B). Evolution towards the restricted field was observed in a single flood event on September 26 and 27, 2008 (Table 2). In domain 1, such water appears in the regional aquifer only at site 11, which is strongly influenced by floodwater.

All other groundwater in domain 1, including that discharging to the perennial reach at site 64, arises from a source other than summer and fall surface water. The similarity between groundwater isotopes in domains 1 and 3 is consistent with a source within the broader watershed of the Valley. The isotope pattern of domain 1 can be traced north as far as site 37 (Figure 6), and the area in which it occurs constitutes a distinct part of the regional aquifer, termed the A aquifer for the purposes of discussion below.

Base flow in Hot Springs Canyon has varied over time because of evaporation (Figure 5D). This surface water differs isotopically from water in domains 1 and 3 because of the contribution to base flow of ancient groundwater from hot springs in the headwaters (sites 60 and 61, Figure 2). The hot-spring water evolves by a combination of evaporation and mixing with domain 3 water to yield base flow and domain 5 groundwater of the isotope composition shown in Figure 5D. The slope used for the evaporation trend is 4, as observed elsewhere in the San Pedro Valley (Gungle et al. 2016). Groundwater of domains 2 and 5 is identical in isotopes (except at sites 25 and 37; see Figure 5), indicating that most domain 2 groundwater originates in domain 5. Together, domains 2 and 5 constitute a second distinct part of the regional aquifer, termed the B aquifer (Figure 6).

Domain 4 groundwater has lower ($\delta^{18}O$, δD) than that in domains 1, 2, 3, and 5, consistent with input of runoff from mountains rising to 2500 m amsl west of the Valley. Domain 4 groundwater has not been recognized on the west side of the San Pedro River downstream of the Paige Canyon confluence, but few sample sites are available in that area, and mixing with domain 1 water may occur.

Interpretation of Groundwater Residence Time. The interpretation of tritium in southern Arizona groundwater, summarized as follows, is based on the discussion in Eastoe et al. (2011). The tritium data provide an unequivocal distinction

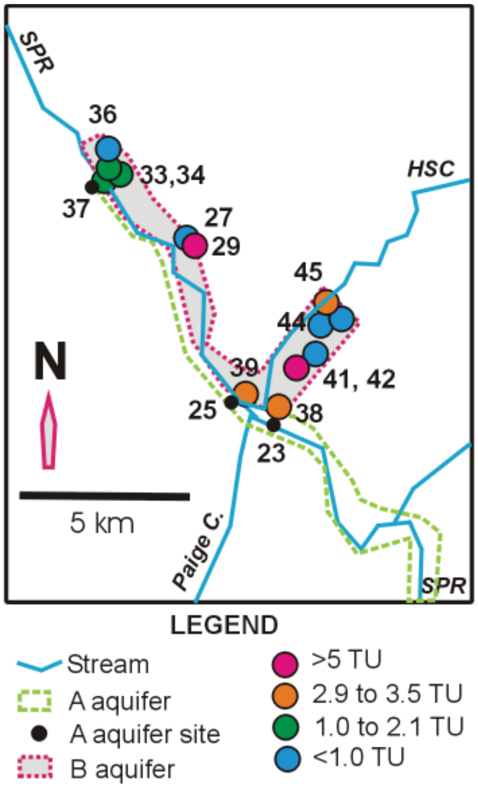

Figure 6. Map of aquifer B, showing tritium measurements, and adjacent parts of aquifer A, showing sites with isotope data like those found in domain 1. Site numbers: simple numbers are groundwater sample sites as listed in Table 2. HSC = Hot Springs Canyon.

in groundwater residence times. Samples with measurable tritium contain some water recharged since the initiation of atmospheric nuclear testing, this affecting tritium in rainwater since about 1953. In the study area, most such samples contain less than 5.2 TU, the annual average tritium content of rainwater in Tucson since 1992. Samples with tritium below the detection level (0.6 TU) indicate groundwater that infiltrated prior to 1953. To this distinction can be added a further interpretation: samples less than 1 TU contain mainly pre-1950s recharge. Tritium present at levels greater than 3 TU is consistent with recharge since 1992, but could also represent mixing of 1960s recharge with water of other ages.

Groundwater with residence times greater than 65 years at the time of publication are found in Quiburis formation sediments of domain 3, and a few examples near the margins of domain 1 (sites 7 and 21), domain 2 (site 36, at the down-gradient limit), and domain 5 (sites 42, 43, and 44, in Quiburis formation sediments). In the other areas that have been sampled, part or all groundwater has been resident for less than 65 years.

In domain 5 groundwater, tritium from recent post-bomb recharge is likely to be diluted by ancient hot-spring water containing no tritium (Table 2). In domains 2 and 5 (the B aquifer), tritium content in groundwater generally decreases downgradient, from Hot Springs Canyon to site 36 (Figure 6; Table 2). Groundwater from site 36 represents pre-1953 recharge, while groundwater immediately upgradient (sites 33, 34, and 37, Table 2) contains some post-1953 recharge. Therefore, groundwater appears to take about 65 years to reach site 36 from Hot Springs Canyon.

A down-gradient transition to higher tritium content from south to north in domain 1 groundwater may represent a larger fraction of post-1953 recharge, probably from Kelsey and Teran Washes, at the northern end of the domain.

2. Water Quality

Data. Measurements of EC are listed in Table 2. Domain 1 groundwater has high EC, 502 – 1566 µS/cm. Domain 2 has low EC east of the river, 330 – 752 µS/cm, but high EC, 1335 µS/cm, west of the river at site 37. Domains 3, 4, and 5 have low-EC groundwater, 348 – 549 µS/cm. In domain 1, high EC corresponds to high hardness. A survey of owners of domestic wells in domains 1, 2, 3, and 5 yielded the information listed under "Quality Problems" in Table 2. In domain 1, between sites 6 and 23 (Figure 2), water is in many cases very hard and unpalatable, owing to the presence of one or more of: hydrogen sulfide (H_2S, rotten-egg smell), dissolved ferrous iron (Fe^{2+}, that becomes suspended orange ferric oxides on exposure to the atmosphere), suspended black organic matter, and oily film with a petrochemical smell. At site 19, water quality is poorest in March and April. In domains 2 and 5, such problems are minor or absent, and water is palatable. Dissolved Fe^{2+} in domain 2 may in some cases originate from corrosion of steel well casings, while transient H_2S appears at site 33 to be associated with a particular tank. In domain 3, water quality problems were reported only from site 49, a well drilled in the floodplain of a wash; other wells drilled deep into Quiburis formation showed no problems.

Interpretation. The presence of H_2S and dissolved Fe^{2+} is due to bacterial processes in aquifers (Bethke et al. 2008). Certain bacteria can reduce dissolved sulfate and ferric iron (Fe^{3+}) present in minerals in aquifers. Required conditions include absence of dissolved oxygen in the groundwater, and availability of organic carbon, commonly acetate produced by fermentation of organic matter. The bacterial processes convert organic carbon to bicarbonate, increasing water hardness. The severest palatability problems occur in association with clay units (Figure 3; Table 2), including wetland deposits in which organic matter is stored. Such deposits are exposed in the river banks between sites 19 and 20. Suspended organic matter has been observed in groundwater at sites 9, 10, and 11, and traces of oily liquid at site 19. Aquifers may be zoned with respect to production of H_2S and dissolved Fe^{2+} at a variety of scales as a result of bacterial competition, nutrient availability, and the insolubility of ferrous sulfide (FeS) (Bethke et al. 2008). Because FeS is insoluble, H_2S and dissolved Fe^{2+} should not coexist in groundwater. The observation of both at sites 11, 14, and 23 suggests that well construction allows rapid mixing of waters from separate permeable beds of different chemistry.

3. Static Water Level

Data. The SWLs shown in Table 2 were recorded at the time of drilling of each well and are probably of variable reliability owing to inconsistent measurement techniques. Reliable SWL measurements have been recorded at sites W2, W4, and W9 since 1993, and at W11 since 2006 (Figure 7). Sites W4 and W9 are in domain 5, site W2 is in domain 2, and W11 is in domain 1. At W4, the upstream site in Hot Springs Canyon, there has been a steady decline of more than 10 m in base water level since 1993. As a result, the well has been intermittently dry since 2010. Transient pulses of SWL increase by as much as 11 m were recorded in 1992, 1996, 1998, 2000, 2007-2008, 2011-2012, and 2016, but have not affected the long-term decline in base water level. At W9, near the confluence of Hot Springs Canyon and the San Pedro River, a similar long-term decline of about 10 m in base water level has been recorded, with transient pulses of higher SWLs in 1992, 1998, 2001, 2007, 2011, and 2016. At W2, the long-term decline in SWLs is 2 to 3 m. Stepwise increases occurred in late 2006 and early 2015. Since 2006, most measurements were made near the winter and summer solstices, and show a seasonal cycle, summer SWLs being lower (in altitude) than winter SWLs. At W11, in domain 1, SWLs fell 3 m between 2006 and 2013, but rose 2 m in 2014 and had not returned to late-2013 levels by late 2016.

Figure 3B shows water level declines in a longitudinal section of the B aquifer. For points other than W2, W4, and W9, the most recent water levels have been measured by community members in 2016. SWLs have declined throughout the B aquifer, except from km 4 to km 7 (Figure 3B) where the northward slope of the water table is least, and where little change has occurred. The largest SWL declines are in domain 5.

Interpretation. At W4 and W9, the evolution of water levels is similar; base SWLs show a steady decline, beginning in the mid-1990s. SWLs above the base level form a small number of transient 1 to 2 year pulses, and reflect periodic enhanced recharge occurring as a result of higher flow in Hot Springs Canyon. The pulses are insufficient to reverse the decline in base SWLs, which is therefore probably a manifestation of climatic drying at decadal or longer time scale. Progressive drying may be occurring at a time scale of centuries, beginning at some time since the end of the 17th century when the Native American settlement at Baicatcán was occupied (Doelle et al. 2012). The settlement would have relied on a perennial surface water supply. Decline in base SWLs since 1993 does not appear related to a particular increase in water withdrawal by pumping. The reason for the size of the most recent pulse recorded at W9 is not known. At W2, the small seasonal cyclicity of SWLs corresponds with irrigation withdrawals for nearby pasture and with transpiration in riparian vegetation, the water demand being highest in the three to four dry months preceding the summer solstice. Field observations indicate that the stepwise increases in SWLs followed protracted flooding in late summer or autumn in 2006 and 2014. The rise in SWL at

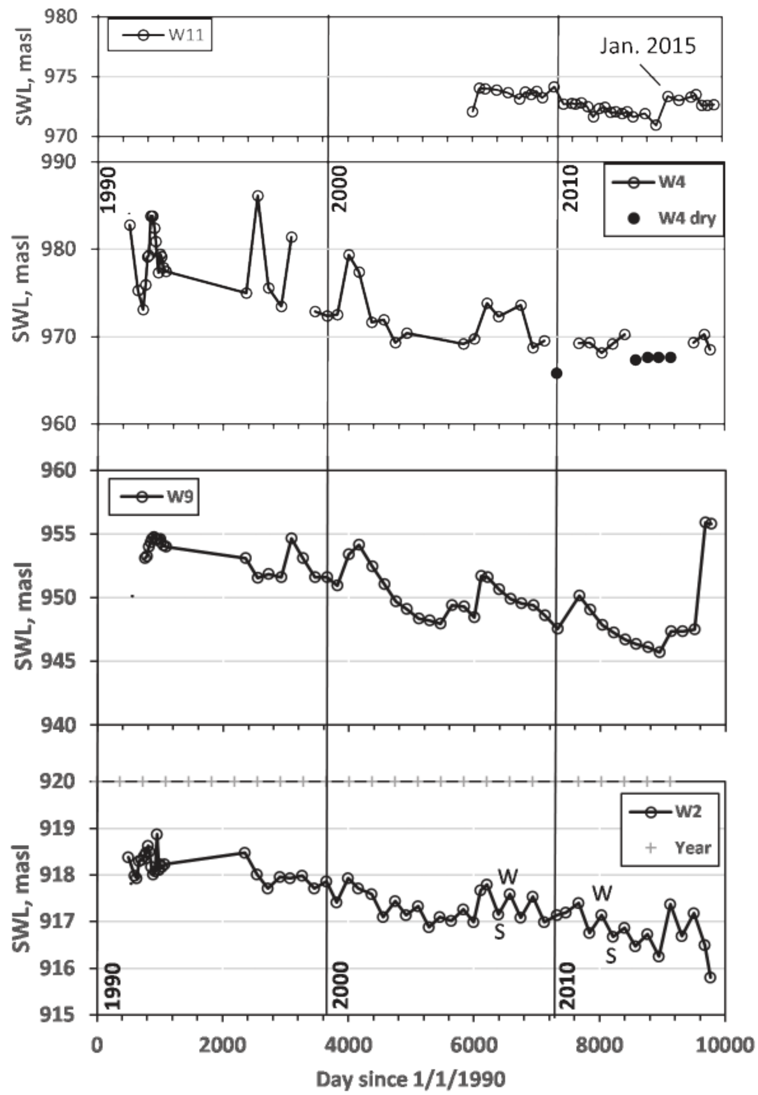

Figure 7. Time-series of static water level at four sites (see Fig. 2 for locations). Depths for the "W4 dry" points indicate the bottom of the well, which has changed owing to sedimentation over time. For site W2, W = winter, and S = summer.

W11 occurred after the late-2014 flood caused by Hurricane Odile, and appears to reflect a multi-year change in conditions.

Discussion - Addressing Community Concerns

Groundwater Origin

Stable O and H isotope data have proved useful to an understanding of water resources in Cascabel. Because of the contribution of ancient hot-spring water to Hot Springs Canyon, it is possible to distinguish aquifers A and B, and to show the importance of Hot Springs Canyon as a source of palatable water supply over the entire extent of aquifer B. Why aquifers A and B persist as separate, adjacent groundwater streams for 7 km downgradient of the mouth of Hot Springs Canyon cannot be demonstrated in the study area. It may be related to the persistence of multiple filled arroyos within the Holocene channel-fill, as has been mapped in the San Pedro Valley 80 km south of Cascabel (Waters and Haynes 2001, Figure 2). For the Cascabel community, the recognition of a separate aquifer B implies that events affecting groundwater in Hot Springs Canyon will eventually affect groundwater throughout aquifer B.

Groundwater Residence Times and Drought Vulnerability

Most groundwater samples in aquifers A and B contain measurable tritium, and therefore include some water recharged since about 1953. It follows that both aquifers are vulnerable to multi-decade droughts such as have occurred in the region in the past millennium and are recorded in tree-rings (Ni et al. 2002; Griffin et al. 2013). The presence of a few samples with no tritium at the margins of the aquifers does not change this interpretation, but indicates that some of the groundwater has been resident since before the 1950s.

The downgradient part of aquifer B (near sites W2, 37) appears less vulnerable than the rest of the aquifer. The decline in SWL has been relatively small (2 to 3 m since 1993, in contrast to about 10 m at W4 and W9), and the aquifer continues to discharge intermittently to surface water in the San Pedro River at site 37. SWLs respond to seasonal demand (e.g., from irrigation or transpiration) and protracted flooding in the river (probably because of mounded bank storage). However, groundwater flow into this area is for the present maintained by drainage of the upgradient part of the aquifer. The sill of San Manuel formation acts as a barrier to subsurface drainage to the north. Prolonged drainage of the upgradient part of aquifer B under continuing conditions of drought and irrigation demand will eventually lead to more rapid decline of SWLs in the downgradient part. SWL decline since 2007 has shortened the wet reach of the riverbed near site 37 (The Nature Conservancy 2017), and what was once perennial discharge has become intermittent.

Pre-bomb recharge is characteristic of domain 3 samples, leading to the interpretation that domain 3 is less vulnerable to drought than aquifers A and B.

Cause of Unpalatable Water

Unpalatable domestic water is reported as a serious and persistent problem in aquifer A from site 6 northward to site 23. Elsewhere, water quality issues are transient, minor, and possibly generated within plumbing or well fixtures. The problem area of aquifer A includes geological features (widespread clay units with local concentrations of organic matter, along with the general availability of oxidized iron and sulfate) sufficient to explain the generation of dissolved Fe^{2+} and H_2S within the aquifer. The causes of unpalatable water are ultimately found in local geology, so that interventions such as the pouring of bleach into wells (which cannot change upgradient geology) are unlikely to bring about permanent improvement in water quality.

Cause of Water Level Declines

SWLs at sites W4 and W9 in Hot Springs Canyon have been in steady decline since the early 1990s. Decline in base levels has been steady at both sites, and not apparently related to the initiation of any particular pumping demand – although the number of wells in the area has increased over the period of observation. Recharge pulses related to increased surface water supply have had only transient effects on SWLs and have not affected the observed long-term decline. The water table of the B aquifer slopes northward (note that site 29 is on land above the floodplain) with no known geological barrier to flow except for the San Manuel formation at sites W2 and 37. Once the recharge flux into Hot Springs Canyon decreases to an amount less than the sum of pumping and natural discharge by subsurface flow, SWLs in the aquifer will decline. This threshold was passed in the mid-1990s, most likely as a result of long-term climate change (reduced rainfall or increased evaporation). Nonetheless, pumping increases discharge, and residents with wells in the B aquifer would be wise to consider what management measures will aid in prolonging their water supply.

The observed isotope shift at site 38 (aquifer B in 2007, changing to aquifer A by 2015) and the lack of a recorded clay aquitard at site 23 (Arizona Department of Water Resources 2017) suggest that decline in the SWLs of the B aquifer may be causing water from the A aquifer to flow into the former B aquifer near site 38. Such flow is consistent with SWLs at sites 23 and 38 (Table 2).

Communicating Groundwater Research to a Rural Community

Progress in this study has been presented to the residents of Cascabel at three well-attended workshops, in 2009, 2015, and 2018. The community has an excellent general level of education. Communication of the information presented in this article has succeeded in varying degrees. The importance of measuring groundwater levels is universally understood by a community so strongly dependent on groundwater; certain community members are involved in systematically observing changes in SWLs. Comprehension of water quality issues is easier for community members with a knowledge of chemistry. The interactions among microbes, geology, and water movement form a moderately complex system that is difficult for many residents to understand. Most residents with physics and chemistry classes in their background would admit to little recent practice in those sciences. Consequently, one form of useful information – the isotope data that allow the mapping of functionally separate aquifers – poses the greatest challenge of all. Even for community members who are comfortable with the concept of isotopes, application of the technique to groundwater studies is new and difficult to absorb during a two-hour workshop. The presenter (CJE) has adopted the approach of asking the audience to accept that different isotope ratios exist and can be distinguished on a plot of δD *versus* $\delta^{18}O$, without needing immediately to understand how the values are calculated.

Future Work

A study in greater detail is possible in the Cascabel area, but was beyond the scope of the present work. Surface water hydrology has not been discussed in detail here, although preliminary data are available (Table 2). To address this problem in the manner suggested by Benettin et al. (2017), a much larger dataset encompassing isotope and geochemical measurements with a time-resolution of days would be required for summer runoff events. The following options are feasible for the community: 1) measurements of volume of base flow, 2) continuation of SWL measurements at established sites, and 3) monitoring of SWLs and EC near site 38, where groundwater flow paths appear to be changing. All would provide useful data for assessing water management options.

Conclusions

Most groundwater in Cascabel is produced from Holocene fluvial sediments near the present channel of the San Pedro River and in Hot Springs Canyon.

Stable isotope data show that two aquifers, distinguished by different water sources, are present in the fluvial sediments. Aquifer A derives water from the river catchment upstream of the mouth of Hot Springs Canyon. Aquifer B derives some isotopically-distinctive water from hot springs in the headwaters of Hot Springs Canyon. Parallel subsurface streams of both water types are identified to a point 7 km downgradient from the mouth of Hot Springs Canyon. At that location, a sill of impermeable rock dams the aquifers, forcing groundwater to discharge to the river bed. A connection between the aquifers may be forming near sites 23 and 38.

Tritium data show that most of the groundwater in aquifers A and B had been resident for less than 60 years at the time of sampling. Both aquifers are susceptible to multi-decade droughts. Groundwater with no detectable tritium (resident for more than 60 years at the time of sampling) is present within the older sediments of the Quiburis formation east of the river.

Severe water quality problems are present in part of aquifer A, in association with abundant wetland sediments locally bearing organic matter. Dissolved Fe^{2+}, H_2S, and elevated hardness are common in that area, and are caused by microbial interactions with local geology.

Static water levels are falling in most of aquifer B, most likely as a result of natural drainage of the aquifer. Drainage appears to be due to climate change (increasing drought prevalence) at decade to century time-scale.

If drought conditions continue, the community will need to consider what management practices might prolong the groundwater supply.

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Barbara Clark has been a potter, a homesteader and a citizen scientist in Cascabel since 1970. She recently retired from The Nature Conservancy.

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Towards Broader Adoption of Educational Innovations in Undergraduate Water Resources Engineering: Views from Academia and Industry

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Abstract: This article investigates the challenges that face the development, community-scale adoption, and long-term sustainability of educational innovations in the field of hydrology and water resources engineering undergraduate education. Adopting a customer-based discovery process, the current study conducted a set of 78 informal interviews with two main groups: faculty members who teach water resources and hydrology courses, and practicing engineers with specialty in the same field. The interviews revealed that the main motivation for faculty to develop or adopt new educational innovations stems from self-efficacy and desire to achieve effective instructional strategies. Other factors, such as institutional requirements and faculty evaluations and incentives, seem to play a modulating role for generating self-created motivation. The results identified time limitations and steep learning-curves as the two adoption hindering factors cited by a majority of the interviewees. Other hindering factors reported were rigidity of resources and lack of assessment data. Industry perspectives on preparedness of recent graduates and relation to current educational practices showed that young engineers may lack critical skills on the proper use and interpretation of data and modeling analyses. The study also discusses potential solutions, such as development of sharing environments to facilitate exchange of data and resources, modular design to support adaptation and compatibility with existing curricula, collaborative efforts to produce shareable evaluation and assessment data, and potential opportunities for collaboration between academia and the professional industry to facilitate development and sustainability of educational innovations.

Keywords: *water resources, education, innovations, adoption, interviews, academia, industry.*

Recent reviews of the literature emphasize the need for formalized approaches to reform hydrology and water resources engineering education (McIntosh and Taylor 2013; Seibert et al. 2013; Ruddell and Wagener 2014). These desired reforms call for tapping into discipline-based advances in data, modeling, and information systems; exposure to modern tools used in engineering practices; adoption of sound educational strategies such as active-learning; and use of real-world case studies to deliver authentic learning experiences. Examples of recent educational developments that strive to introduce pedagogical changes in hydrology and water resources engineering education include development of web-based learning modules (Habib et al. 2012a; Yigzaw et al. 2013; Habib et al. 2018), computer models,and simulation games (Hoekstra 2012; Merwade and Ruddel 2012; Rusca et al. 2012; Seibert and Vis 2012; AghaKouchak et al. 2013; Sanchez et al. 2016), sharing of educational materials via community platforms (Wagener et al. 2012), use of hydrology real-world case studies (Wagener and Zappe 2008), use of geospatial and visualization technologies (Habib et al. 2012b), and the use of real-time environmental monitoring to enhance student engagement (McDonald et al. 2015; Brogan et al. 2016). However, these efforts face challenges in achieving scalability, sustainability, and community-scale adoption (Ruddell and Wagener 2014). This recurring problem has been a major concern for the institutional and financial investments by the STEM education community (McKenna et al. 2011; Singer et al. 2012). Barriers to scalability and adoption have been attributed to various issues such as characteristics of the innovation, faculty perceptions, student resistance, and institutional cultures and resources (Hardgrave et al. 2003; Rogers 2003; Heywood 2006). Rogers's (2003) theory on diffusion of innovation, considered one of the most relevant theoretical perspectives that can guide engineering education innovations (Borrego et al. 2010), identifies five innovation characteristics that influence adoption: relative advantage, compatibility, complexity, trialability, and observability. The ease of implementation and ease of use were also cited by Compeau et al. (2007) and Bourrie et al. (2014) as important factors. A survey of U.S. engineering departments (Borrego et al. 2010) identified several faculty issues that affect adoption of engineering education innovations, including faculty time for preparation and management of labor-intensive innovations, faculty resistance to change, and skepticism regarding evidence of improved student learning. While these factors apply across the general field of engineering education, there is a need to identify discipline-specific factors that may hinder or facilitate adoption of innovations. As suggested by Borrego et al. (2016), the value of a certain innovation varies according to the specific engineering discipline, simply due to the specific technical skills and educational content pertaining to the discipline. This is also supported by earlier studies on behavioral prediction and behavior change (e.g., Theory of Planned Behavior, Ajzen 2018) that link an individual's behavioral intentions and actual behaviors to subjective norms and perceived behavioral control. The likelihood of adoption increases among peers of the same discipline as they share their own developments and communicate experiences in using and deploying the new innovations. Therefore, research on innovation adoption and diffusion has been recommended at the discipline and sub-discipline scales as a strategy for understanding the effectiveness of engineering and science education initiatives and their adoption potential (Henderson et al. 2012; Finelli et al. 2014; Khatri et al. 2016). Examples of pioneering efforts focused on specific engineering disciplines are found in the fields of chemical engineering (e.g., Prince et al. 2013) and electrical and computer engineering (Froyd et al. 2013; Shekhar and Borrego 2016). Other studies offered cross-field comparative assessments (e.g., Cutler et al. 2012). Each engineering discipline has its own social system that controls the culture of adopting new educational innovations (Lattuca and Stark 1995; Wankat et al. 2002), and hydrology and water resources engineering is not an exception in this regard.

The current study reports results collected from a set of 78 informal, open-response qualitative interviews with hydrology and water resources faculty and engineering professionals. The study provides a customer-driven perspective on the propagation, scaling, and adoption of education innovations in the field of hydrology and water resources engineering. The term customer (or user as we refer to it later in the article) refers to the typical user of educational developments (e.g., faculty members teaching hydrology). The results provide insights on the needs, motivations, and hindering factors that affect engineering faculty as developers and potential adopters of educational innovations in this field. Such insights can be used to inform ongoing and future development and management of water resources engineering education innovations and avoid the undesirable paths of lack of adoption and long-term sustainability.

Methodology

Customer-Discovery Approach

The interviews discussed in this study were conducted by the authors as part of their participation in a customer-discovery program known as the Innovation Corps for Learning (I-Corps L) (Chavela Guerra et al. 2014; Smith et al. 2016). The I-Corps L program uses an entrepreneurial approach for business model generation and validation that was proposed earlier in the lean startup movement (e.g., Osterwalder and Pigneur 2010; Blank and Dorf 2012) and social entrepreneurship (e.g., Janus 2018). The main rationale behind this approach is that before expending a significant amount of resources on an innovation, the developer should first confirm that it addresses a specific problem or need of potential customers (or users, in the more general sense). The only way to test the viability of the innovation prior to investing exorbitant amounts of time and money is to get out of the building and talk to potential customers, identify their needs and existing problems, and how they currently manage such problems. Once the needs of users are identified and verified, the next steps in the I-Corps L process (not covered in this paper) focus on formulating a value proposition and looking for a business model on how to further pursue the proposed innovations, including market size and cost and revenue structures.

Adopting this approach, the authors conducted a total of 100 interviews with potential users of educational developments in the area of hydrology and water resources engineering. The study reports on only 78 interviews that were conducted with members from academia and industry. The 22 remaining interviews were deemed uninformative (e.g., interviewees did not teach undergraduate courses, did not teach relevant courses, or did not provide relevant inputs) and as such were excluded from our analysis. The interviews were designed with a customer-centered approach (i.e., focusing on what a user needs from an educational innovation), rather than a developer-centered mindset (i.e., focusing on a specific product or innovation). Using an informal, open-ended interview design (Patton 1990), the interview questions were fairly short and not overly specific, allowing the interviewee to be the center of the conversation. Interviews were conducted either in person, over the phone, or via a teleconferencing venue, and ranged from 30 to 60 minutes. The range of people interviewed in the current study was quite broad in order to capture the hydrology education landscape from as many different points of view as possible. Generally, the interviews were divided into two main categories: academia and industry. The following are brief summaries of each category, including distinction of user segments within each group and what was asked during the interviews.

Interviews with Academia

Academia, in the context of this paper, refers to interviewees associated with post-secondary hydrology and water resources education in civil engineering and geoscience programs. A total of 42 interviews were conducted with instructors from different types of educational institutions including research- and instructional-intensive, and small and large four-year universities. The majority of interviewees were from institutions with medium to intensive research focus, while just eight were from instructional-focused institutions. Three-quarters of the institutions were mid to large-size programs, with the remaining one-quarter considered small in size. These institutions were spread across the United States, covering 22 states, and included faculty with different specializations within the overall domain of water resources and hydrology. The interviewees were about two thirds from civil engineering departments and the rest were from earth sciences. The authors recognize the differences between hydrology as an earth-science, and water resources engineering as an applied field, and the implications of such differences from an educational perspective. However, due to the significant overlap between the two fields and how they are actually taught in both engineering and science departments, a decision was made to not explicitly differentiate between them in designing the interviews and in selecting the potential faculty interviewees.

The main interview questions with academia are summarized as follows:

i. What type of pedagogies are currently being used in the classroom? Is there a need to reform the undergraduate hydrology and water resources curriculum?
ii. Do instructors currently use emerging technologies in the undergraduate classroom? If so, in what way, and if not, why not?
iii. Do instructors look for innovative educational material to use in their classroom? If so, where do they look?
iv. What are the issues with teaching engineering-industry tools and techniques in the classroom? What are the challenges of developing material that encompasses these tools?
v. What is the incentive for instructors to improve their teaching methods using innovative contents and new resources?

Interviews with Industry

Industry needs skilled graduates who are capable of applying hydrologic concepts taught in the classroom to practical real-world engineering problems (DiNatale 2008; Eisel 2008). In today's technology-driven society, and with the recent advancements in data and hydro-informatics, this often requires a deep knowledge of a number of computer applications, data processing tools, and simulation models. Thus, interviewing engineering professionals from industry was important for two main reasons. The first was for an assessment of the preparedness of graduating students to perform on the job, and how this can be traced back to strengths and weaknesses from an undergraduate education perspective. Secondly, it was of interest to discover what type of post-graduation training professionals find necessary, how it is provided, and whether opportunities exist for academia-industry collaborations in addressing undergraduate educational reforms. A total of 36 interviews were conducted with practicing engineers. To capture the full spectrum of industry, both private (consulting firms) and public sectors (state and federal water resources agencies) were considered, along with a good mix in the size (small, medium, and large) of organizations. The breakdown of the interviewees included a mix of junior engineers and senior engineers or managers, with somewhat more from the latter group. The junior engineers were fresh out of school and could provide insight into the transition from an undergraduate setting to the workplace from a first-person point of view. Senior engineers provided a third-person perspective on the transition of recent graduates to the workplace, giving insight on the evolution of the young engineers. The managerial perspective, of course, provides logistical information associated with the training and professional development of engineers.

The main interview questions for industry professionals are summarized as follows:

i. What is the level of preparedness of graduating water resources engineers as they enter their first job and progress in their career?
ii. Are there any certain gaps in basic knowledge and applied skills that should be addressed at the undergraduate level?
iii. What are the current post-graduation training and professional development strategies?
iv. Are there any opportunities for universities to use advances from the professional field and enhance undergraduate education?

Results: Views from Academia

A total of 42 interviews were conducted with university professors teaching water resources and hydrology related courses. During these interviews, the authors first tried to decipher the motivation underlying the desire to enhance the undergraduate hydrology and water resources engineering education, then discussed challenges associated with developing, discovering, and utilizing innovative resources and materials.

Motivators: What motivates instructors to incorporate innovative teaching materials?

The faculty interviewees expressed a need for improving education in the fields of hydrology and water resources engineering. The majority of the interviews indicated that the main source of motivation to improve course content and teaching strategies is self-created and derives from one's desire to excel at endeavors associated with his or her career. Achievement, self-esteem, and self-efficacy play a large role in this. However, based on interviewees' statements, this source of motivation is modulated and affected by institutional and faculty factors. The interviewees indicated that incentives such as program accreditation, performance reviews, and pressure from superiors (deans/department heads) are not the predominant factors. Instead, factors related to instructor's experience (i.e., junior or experienced) and instructor's priorities (i.e., research or teaching) were highlighted by some of the interviewees to possibly influence the tendency to participate in innovative instructional strategies.

Junior instructors tend to be very ambitious and are likely to strive to bring something new to their classrooms. Additionally, they are more accustomed to quickly adjusting their ways to take advantage of new advancements. Often, they are in the process of developing their courses and want to do so in a way that is most effective and well informed by recent educational research. In contrast, the experienced instructors who have been teaching for many years already have a working curriculum that has been developed, utilized, and proven. This reluctance to change is logical and well-understood, and is often hard to argue with, especially given the lack of tangible incentives. The argument is, however, that the teacher-centered techniques favored by experienced instructors have been proven substantially less efficient in transferring knowledge compared to more contemporary student-centered approaches (e.g., Prince 2004; Cornelius-White 2007; Wright and Weimer 2011).

The variability in priorities amongst universities can also play a major role in course content and methods used in presenting such content. These priorities are often apparent at the level of the individual professor within a university, i.e., emphasis on instruction or research. Professors with high emphasis on teaching tend to adopt new pedagogies and expand the content of their courses more readily than those with more research-focused obligations. From the perspective of the researchers, why invest time and effort into improving a course when the time could better be spent on research, which will have the benefit of improving their professional standing and career advancement. The inverse here, of course, applies to those with high teaching emphasis.

Hindering Factors: What Hinders Developing and Utilizing Innovative Educational Resources?

Interviews with academia members showed that there are many challenges when it comes to sustainable development and utilization of innovative materials. These issues have been summarized into five categories: time limitations, steep learning curves, refurbishing requirements, rigidity of material, and lack of assessment data. Out of these five categories, the first two were cited by nearly all of the interviewees. The importance and relevance of each of these challenges are discussed in the following sections. It should be noted that these challenges are not additive, rather they are highly interactive; i.e., a solution to one may provide a means for overcoming another or, conversely, have an adverse effect on the other.

Time Limitations. Time requirement was by far the most cited hindering factor by nearly all of the interviewees. While instructors see the need for restructuring of the current curriculum, they are either too busy or are not knowledgeable enough to develop new material that addresses emerging resources such as modeling and data analysis techniques. As one of the interviewees stated: "In undergraduate courses, I introduce some modeling software, but only at the level of presentation with no actual use, mainly due to lack of time, but could also be due to lack of material that is ready to use especially in areas out of my immediate specialty." Developing innovative resources is difficult because it requires knowledge in both the subject matter and on educational research. Finding effective pedagogies (e.g., active-learning strategies, problem-based learning) and then structuring material in a way that is presentable to students can be challenging and time-consuming. Most interviewees indicated that they look for peer-developed material. While this solves the pain of developing one's own material, many of the other pains persist and some are magnified. For instance, using peer-developed material that utilizes an unfamiliar software, project, or dataset, may present a learning curve for the professor who is implementing it. Aside from development time, there is also a time requirement for preparation and implementation. One instructor stated that "dynamic lecture material (e.g., case studies with continuously changing datasets) takes too much time and effort to prepare and maintain." It was also the opinion of many interviewees that new, innovative resources should not replace existing material; rather, they should augment it, simply due to the mostly supplementary nature of these new resources. It is easy to see how this translates to more lesson preparation time, strain on class time with an already over-loaded curriculum, more out-of-class time with students (e.g., office hours, email communication), and evaluation and assessment time.

Steep Learning Curves. This was another factor that was cited by a majority of the interviewees who expressed that a large issue for them is the steep learning curve involved when using new, unfamiliar tools and techniques that are part of an innovative resource. For example, one of the interviewees stated that "Pre-customized case studies are useful but professors have to get familiar with these specific cases, which could be a burden to learn and spend time before they assign it to students." Interviewees also indicated that incorporating these advancements in the classroom is problematic for students as well, due to the difficulty in learning to use new tools or software, which might generate student resistance to the new resources. Students must be trained to use a computational model, a GIS tool, or other software before they can apply it in a useful way. This issue was clearly stated by one of the interviewees: "Solution is to build guidance and support mechanisms to students to reduce the learning curve – no matter which different material we choose to use, we need to make sure that we reduce the learning curve for students." The interplay between students' resistance to new materials and faculty's decisions to adopt these materials was also iterated by one of the interviewees: "Adopting digital resources for learning is much needed by the community, but this depends on the level of students and how they are prepared to engage in modelling and data-based analysis; so could be appreciated by the professor, but the challenge is the level of students." Effectively using computational tools and models is not straightforward and is considered an art by the community because of the experience required to use the tool appropriately. Many of these tools are rather crude and are far from intuitive, and even those with friendly graphical user interfaces are still ages behind the easy-to-use mainstream software that students are accustomed to (e.g., online maps, spreadsheet and word processing software). While huge strides have been made in making such tools more user friendly, models need to be properly introduced to students to better understand their applicability and limitations and avoid serious misuse or faulty interpretation of results. The interviews also indicated that the steep learning curves are not only associated with software use, but also with the use of case-studies and real-world projects situated in specific regional basins that may not be familiar to the instructors. One instructor stated that: "I use a textbook that has lots of data applications, but these are mostly based in one state, which could be an obstacle." Despite their educational value, region-specific case studies often require the instructors to learn about the particular basin and the hydrologic problems that pertain to that basin, which might render these peer-authored resources less practical to adopt. This perhaps suggests that effective peer-authored resources should provide adequate context and user-support in order for them to be used effectively and to alleviate the learning curve of interested adopters.

Updating and Refurbishing. Another issue cited by the interviewers deals with the rate at which data and modeling tools become obsolete (e.g., data web links, software versions). Frustration with the high turnover of new materials can be a deterring factor for adoption since "technology glitches can take up class time" as stated by one of the interviewees. Changes to website interfaces and online data portals of major agencies that provide water resources datasets can cause rapid turnover of educational developments. To sustain this pace, data and modeling-based educational resources must be updated frequently in course material, which requires time and effort from the instructors. Compared to textbooks which receive updates (often just moderately modified forms of the previous versions) only every three to five years, materials that are dependent on dynamic resources require continuous adaptation. Additionally, updating of the materials is needed after feedback is received from students or other users. These usually take the form of assessment data on students' experiences with using the materials, impact on students' learning, and expansion or inclusion of supporting resources and improvement to the design of the new resource. Therefore, the ability to easily and quickly update materials is a critical feature that must be available to effectively sustain and scale new educational materials that emphasize the use of technology and research advancements.

Lack of Modularity and Customizability. The interview responses indicated that most instructors, especially those who are senior or those who are not able to commit significant instructional time, have well-developed courses and are simply looking for material that reinforces or supports their current curriculum. For their purpose, the interviewees indicated that resources should be very modular. As one interviewee said, "I need resources that are not 'too rigid', that are 'loose' in format and content; I am looking for 'a la carte' items, and not the 'whole menu'." In contrast, most of the interviewees from the early-career segment expressed an interest in material to build their class around and therefore were looking for larger, more holistic resources that can still be customized to their specific needs (e.g., different datasets or hydrologic basins).

The interviews revealed that material that is not tailored to the specific need of the implementing professor (in content or format) presents additional challenges for development and adoption. For example, will the material be presented during the lecture portion of the class, during laboratory time, as a homework assignment, or as a class project? Each option has its own benefits and challenges; for instance, including new material in the class or in the lab may prove difficult given time constraints and pre-existing course material. However, it may allow the instructor to directly interact with students and to readily provide expert guidance. This, of course, is made more difficult if assigned as an out-of-class assignment. In such cases, it is important for the developer to provide additional user support, specific to the needs of the local students to supplement the absence of the instructor (e.g., detailed instructions, screenshots, videos, templates). Conversely, providing too much support can result in adverse learning effects, where students follow steps blindly and without thinking about what they are trying to accomplish. The ability to modify (add or subtract) material easily is a desirable trait that was expressed by a considerable proportion of the sampled population of interviewees. This can allow instructors to use only a subsection of an existing resource and easily apply it to their needs e.g., changing the region of a case study, removing a section that is outside of the scope of the current class, or adding or removing user support.

Lack of Assessment Data and Tools. The need for both assessment tools (e.g., grading rubrics), as well as evaluation data on the potential value of the new material from a student learning perspective, were cited by some of the interviewees. Instructors often look for evidence (e.g., documented evaluation results on student performance) that the material is effective before implementing it in their class. This becomes a bit of a conundrum especially for pilot efforts which have yet to be tested. Typically, developers attain initial assessment data from their own institution; however, this is usually a rather limited sample size and results of the developer-implementation generally contain some level of bias. Furthermore, the interviewees highlighted another aspect related to the difficulty associated with grading students' work, especially when non-traditional material is being introduced, such as data and modeling techniques. As one of the interviewees stated, "I think the software itself can be useful but as it currently stands, if a student does the exercise, I have no easy way to grade the student."

Results: Views from Industry

A total of 36 practicing engineers were interviewed. Below is a summary of the results of these interviews with recurring topics of discussion on the level of preparedness of recent graduates and how post-graduation training relates to and builds on education at the undergraduate level.

Preparedness of Recent Graduates

Nearly all of the sampled population of senior engineers and managers indicated that young engineers specializing in hydrology and water resources must be able to utilize, understand, and develop models; interpret and analyze results; effectively identify and communicate key findings; and, more importantly, have fundamental knowledge on the theory underlying the model. Understanding when and where assumptions and approximations should be made, and being able to identify sources of uncertainties and articulate limitations of a modeling analysis, are important skills for young engineers, but are not consistently attained by new graduates, as many of the senior interviewees suggested. General knowledge of numerical modeling concepts was cited as a more desirable attribute than detailed training in a specific software. Priority was given to the former due to the large variation of tools and models used among consulting firms. In addition to modeling and data analysis skills, the majority of industry professionals stated that recent graduates typically have underdeveloped engineering soft skills, such as communication, creativity, adaptability, and collaboration. This was also iterated in interviews with engineers from government agencies. While the interviewees acknowledged that such skills are usually hard to teach in traditional classrooms, they expressed that the use of case-based, data and modeling-driven student projects, developed through collaboration with industry, present some unique opportunities to introduce these types of skills into the undergraduate curriculum.

Most of the young engineers who were interviewed were very eager to share their perspectives of undergraduate curriculum. While most of them felt that their undergraduate degree adequately prepared them for their first job, they stated that their knowledge of the use of computer models and related tools was lacking. They were quick to clarify, however, that it was not lack of conceptual or fundamental knowledge, but simply the lack of applicability within real-world hydrologic problems. Building on this, the interviewees complained that textbook problems often focus on using idealized and fairly narrow examples and lack the overall context of how hydrologic analysis can be pursued using data analytics and modeling approaches. This resonates with the comments presented earlier from the senior engineers on the skills needed by young engineers to be able to interpret results in the scope of the project at hand, as opposed to simply performing the analysis.

Post-graduation Training and Professional Development

Developing the skills associated with discipline-specific tools and techniques, engineering soft skills, and the ability to formulate solutions based upon contextual information, is a long-term process that does not end at the undergraduate level, but progresses slowly over several years of post-graduation training. Interviews with industry members were also intended to identify attributes of on-the-job training practices that might be leveraged and built upon in teaching these skills at the undergraduate level. Interviews with senior engineers and training managers indicated that training is obtained in the majority of consulting firms through informal techniques that utilize a mentor/apprentice approach, whereby a junior engineer works closely under a senior engineer until skills have been sufficiently mastered. This 'learn on the job' training with expert guidance is considered by many firms to be the most effective method of training, even compared to more formalized training courses. In addition to being effective for developing a collaborative relationship between the mentor and young engineer, it is also considered efficient from a billable hour stand point; however, the tradeoff here is the extra burden that it puts on the senior engineer.

A second approach that was cited by only a few interviewees involves use of previous projects. If a current project is to an extent similar to a past project, many firms will use this archived project to demonstrate the design process. The junior engineer can then use this past project as a sort of template or guide for designing the current project. Investing time to develop training materials from past projects would reduce the time requirement of senior engineers in the future while still providing junior engineers with expert advice embedded into stand-alone training resources. Interviewees from small firms found this investment infeasible since they do not hire engineers at a rate that would have a timely payoff and the evolution of the tools and techniques of the industry is such that the developed material would be obsolete within a short span of time. This is in many aspects analogous to challenges with developing educational innovations. While this approach does not seem a viable option for small firms, the interviews revealed that there is already evidence of this practice in larger engineering firms. Larger firms apparently have the need (large hiring rate) to justify development of such material and the resources in terms of time and manpower to maintain them. Many firms, however, proceed with caution when this training method is used because past projects often have assumptions or design criteria that may not be always applicable to a future project. Other training opportunities (e.g., online courses, participation in workshops, hiring a consultant to provide in-house training) were mentioned by several of the interviewees, but these were not frequently used due to cost factors.

Summary, Concluding Remarks, and Recommendations

Keeping pace with evidence-based instructional practices has been a challenge confronting STEM education. However, with today's technology-savvy students, and with the recent educational research on effective pedagogies, impactful solutions are beginning to emerge. In many STEM disciplines this is evident with packaging of multimedia content with traditional textbooks, the development of web-based and interactive material by publishing companies, and non-profit educational organizations that provide open-source educational content. In the field of water resources engineering education, recent efforts have focused on aspects such as the use of effective discipline-specific pedagogies (e.g., case-based and active learning approaches), incorporation of research and industry-standard tools and techniques through utilizing data and model-driven experiences, and collaborative efforts to develop a more unified curriculum. While such solutions are promising, resistance to adoption and implementation is still observed, which will eventually undermine the long-term sustainability of proposed educational innovations. To gain further insights into this critical problem, the current study engaged in an interview-based process through talking to potential customer segments (e.g., end-users and decision makers). The focus was on identifying key roadblocks and possible remedies that affect the successful development, adoption, and scaling of emerging innovations, such as faculty motivators and hindering factors, potential partnerships, industry perspectives on preparedness of recent graduates, and potential supporting resources.

The qualitative interviews of this study indicated that there is a lack of tangible motivators in place for faculty to engage in educational innovations. The way in which the universities evaluate professors, with different distributions of focus being allocated to effective instruction versus research productivity (Wagener et al. 2007), seems to play an important role in whether professors are willing to adopt new pedagogies. This suggests that achieving the desirable educational reforms in this field will largely remain in the hands of faculty members who are personally and professionally motivated to pursue such efforts. This was iterated by the interviewees who stated that self-esteem, self-efficacy, and desire for achievements in their careers as educators are the primary motivation for developing or considering the adoption of educational innovations. The results are in line with previous research on how instructors' decisions to engage in effective implementation of research-based instructional practices relies heavily on their instructional and personal preferences (Henderson et al. 2012). These results also highlight the importance of faculty development efforts in promoting sound pedagogical practices and learning theories in order to support effective adoption of innovations, as was recently suggested by Shekhar and Borrego (2016).

Results from interviews with hydrology and water resources engineering faculty members identified key hindering factors for developing and adopting educational innovations in the field (Table 1), including: time limitations, steep learning curves, continuous refurbishment, rigidity of material, locality of case studies to specific hydrologic basins and datasets, and lack of assessment tools and evaluation data. The first two of these factors were cited by a large majority of the interviewees. While the assessment data and tools factor was mentioned by only a few of the interviewees, its importance is evident in the existing literature. Assessment of innovative educational developments is an invaluable aspect of implementation and is critical to the successful scaling and adopting of innovations. These findings point out the importance of crucial, yet often-missing elements of user-support mechanisms to instructors who have the intention to adopt innovations. The expressed need for instructor support, both as built-in features of the innovation (e.g., rubrics, assessment methods) and as post-development support (e.g., follow-up support to resolve problems), agrees with the recently proposed model on design for sustained adoption (Henderson et al. 2015).

Results from interviews with practicing engineers in both private and public sectors revealed some critical information on the need for innovative resources that introduce data and modeling-based skills. Interviews with senior industry members indicated that young engineers have problems formulating solution procedures from context, lack familiarity with real-world hydrologic data, and have deficient knowledge of emerging analytic tools and modeling techniques that are increasingly used by industry to solve

Table 1. Barriers and proposed solutions to increase adoption of educational innovations in hydrology and water resources engineering.

Barriers to Adoption and Scaling	Recommended Solutions and Possible Opportunities
• Steep learning curves for instructors • Time requirements for development and implementation • Specificity of case studies to local basins • Rigidity of material • Lack of assessment data • Lack of assessment tools • Curriculum constraints • Lack of financial resources to sustain development • Refurbishing requirements	• Collaborative development and sharing • Modular design and customizability • Web-based developments to facilitate dissemination and adoption • Iterative and post-development faculty-support mechanisms • Assessment tools provided as part of the developments • Partnerships with water resources engineering industry • Educational initiatives at water resources engineering professional societies • Digital publishing

water resources problems. Young engineers acknowledged deficiencies in the use of computer models and their applicability within real-world hydrologic problems. While the interviewees did not reveal a specific reason for this problem, it is reasonable to attribute it to the lack of context and open-ended problems in traditional textbook problems.

Based on the views and insights gathered during this study, the following strategies for design and dissemination of new water resources engineering educational innovations are recommended (Table 1). To enhance the potential for broader adoption and scaling, educational material should be easily adaptable and flexible in nature, have mild learning curves (for instructors and students), and have a modular design to easily fit into current course curriculum that may already be crowded with existing content. Additionally, material should be consistently maintained and improved to keep up with the upgrading of models, data, and other technologies. Incompatibility of the structure, format, or content of educational innovations with existing work flow of the class requires extensive time and effort to overcome and often results in non-adoption. It is also critical that new material should be accompanied by a rigorous set of assessment resources (e.g., solution keys, rubrics) to encourage and support potential faculty adopters. The development of new educational materials without direct input from potential users often results in incompatibility problems and lack of user-supporting tools. An innovation development approach that is based on continuous and iterative feedback from potential faculty users holds a great potential for successful adoption (Khatri et al. 2016). Similarly, collaborative efforts and sharing of innovations and learning resources among universities can potentially result in the development of assessment data that encourage independent adoption as well as distributing the time and effort of development and upkeep. Furthermore, co-developed material that is well balanced between research specialties of the collaborators may present unprecedented opportunities for student learning. The need for long-term, post-development maintenance and user-support is undoubtedly challenged by lack of continuous streams of financial resources. The typical sources of funding that support educational innovations come from federal and state grants, which are by nature time-limited. This calls on the water resources educational community to look for non-conventional funding mechanisms. Avenues to explore include digital publishing of case-studies and associated datasets and models, possibly as supplements to textbooks or as standalone web resources. These opportunities are increasingly sought by other science and engineering fields and could potentially offer solutions for sustaining and growing the desired resources.

Talking with practicing professionals revealed many untapped resources which may be utilized by water resources engineering faculty through collaborations with industry practitioners. By contributing educationally-rich resources such as case studies, datasets, and existing models, industry can support instructors by easing the time and effort associated with developing educational innovations, and simultaneously contribute to molding the water resources engineering educational curriculum by introducing industry-relevant skills and expectations. Interestingly, there exist many similarities between developing and implementing educational innovations and professional training practices, e.g., refurbishing requirements of formal training resources and educational innovations; criteria for choosing training material and criteria for implementing educational innovations (time and convenience); and the use of web-based training courses and web-based technologies for university educational innovations. Despite constraints that might exist at the industry side (e.g., client confidentiality), studying these similarities can help identify parallel interests and challenges and inform efforts for investing in mutually beneficial academia-industry collaborations. Models of such collaborations exist in capstone classes, internships, and co-ops, and can be extended to other classes where data and modeling resources, for example, may be co-developed and used both by students and by junior engineers for early training purposes.

This research employed a qualitative approach using a sample of open-ended interviews with educators and professionals from different institution types and geographical distributions. The results can be further substantiated by adopting a mixed methods design (Creswell et al. 2003) where both qualitative and quantitative data are collected and analyzed according to the specific archetypes of the interviewees.

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The Impacts of a Civic Engagement Cohort Program for Water Quality Professionals

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Abstract: In this article, researchers report the impact study results of University of Minnesota Extension's civic engagement for water quality cohort program. The cohort curriculum highlights Extension's research-informed, five-stage civic engagement model emphasizing process design and process management. Using a non-random comparison group design, a survey was conducted with participants of three civic engagement cohorts for water quality professionals, as well as a comparison group of water quality professionals not part of a cohort. Survey results were aggregated into the five stages of Extension's civic engagement process: prepare, inquire, analyze, synthesize, and act together. Findings indicated cohort participants experienced significantly better results than members of the comparison group in four of the five stages. A strength of Extension's civic engagement model and curriculum is its emphasis on the collective nature and processual aspects of civic engagement work. Cohort participants received training on civic engagement skills, which are not often emphasized in education for water quality professionals. While both groups reported a high frequency of increased civic engagement skills, cohort participants did not report more frequent collaboration or public engagement behaviors than comparison group members. A challenge for those training water quality professionals is instilling the value of civic engagement skills in addition to the more traditional technical skill sets associated with water quality work. Additionally, ongoing training and organizational support is needed for practitioners to effectively implement new skills and leverage new networks.

Keywords: *Extension, training, professional development, watershed leadership*

With more than 10,000 lakes, Minnesota offers an abundance of water resources that bring opportunities for recreation, agriculture, and tourism. The quality of Minnesota's water, however, is not always good. The list of waterbodies in the state that do not meet Minnesota water quality standards continues to rise as more waters are assessed (Minnesota Pollution Control Agency 2017). Identifying the causes of water pollution is complex, as many sources and issues exist. The topic of water quality and watershed planning can also be considered a "wicked problem" that is "ill-defined" and for which there is no "optimal solution"—only ones that may be "re-solved" over and over again (Rittel and Webber 1973, 155).

Water quality professionals work to address the above issues by considering a range of solutions that include technical, social, and policy approaches. Many water quality professionals come from a technical background, such as engineering, geology, biology, and mathematics. While technical solutions are important, they cannot improve water quality unless implemented. Daniels and Walker (2001) noted the need for public involvement in addition to technical solutions. Water quality professionals can help facilitate public involvement, but to do so they must build their social and leadership skills, as well as their ability to manage complex issues (Snowden and Boone 2007; Morton 2011; Wolfson et al. 2015).

University of Minnesota Extension has worked with residents of Minnesota to address water quality concerns, such as wastewater and stormwater management, agricultural runoff, and aquatic invasive species. This work has primarily focused on technical solutions. In 2012, leadership and civic engagement educators for Extension's Center for Community Vitality collaborated with the Minnesota Pollution Control Agency (MPCA) to help local water quality professionals and volunteers better work with the public on more authentic civic engagement efforts. This effort allowed Extension to test a civic engagement model recently developed by its leadership and civic engagement team (Radke 2013; Radke and Chazdon 2015). Research shows an informed decision is not enough. Addressing these issues requires authentic civic engagement (deliberative dialogue). As a result, water quality civic engagement cohorts formed in several areas of the state.

In this article, researchers report the impact study results of Extension's water quality civic engagement cohort programs. The research team conducted an online survey with the participants of three cohorts, as well as a comparison group of water quality professionals who were not part of a cohort. Researchers studied online survey results to compare civic engagement competencies of cohort participants with the comparison group. Survey results revealed differences in civic engagement behaviors, collaboration opportunities among water quality professionals and the public, the effectiveness of the cohort curriculum, and future training needs. In addition to an online survey, the research team conducted interviews with a small group of program participants using the Success Case Method (Brinkerhoff 2002) to better understand how cohort participation influenced civic engagement activities and networking.

Literature Review

Public Participation in Watershed Management

Public involvement in water quality planning and decision making is desirable since federal, state, and local agencies are often required to invite public participation when addressing nonpoint source water pollution issues. Beyond this requirement, it is important that any water quality solutions are embraced by the stakeholders as those are more likely to be implemented (Prokopy and Floress 2011). The likelihood of robust public participation increases when a diverse group of participants share their experience, knowledge, and ideas (Floress et al. 2009; Selfa and Becerra 2011). Many proponents of public involvement in water quality planning believe it leads to better planning and decision making outcomes because local knowledge is critical to understanding local systems.

Successful watershed partnerships and watershed management are characterized by trust and positive relationships between the parties involved, such as stakeholders and water quality professionals (Foster-Fishman 2001; Leach and Pelkey 2001; Gooch 2004; Leach and Sabatier 2005; Mountjoy et al. 2013). Understanding the concerns of all parties involved is also critical (Downing et al. 2011). The use of participatory approaches and participant led decision making, to the greatest extent possible, have also been found to yield positive results (Smolko et al. 2002; Prokopy and Floress 2011). The International Association of Public Participation (IAP2 2014) Spectrum offers a five-step process for increasing public participation that includes informing, consulting, involving, collaborating, and empowering. While multiple forms of participation may occur simultaneously, the more in-depth approach may not be feasible in situations where actions are legally mandated or time is limited. The goal of any public participation process is to involve others in decision making (also known as co-management or collaboration). This involvement includes equal contribution from both the government and stakeholders (Prokopy and Floress 2011).

Water quality professionals can help facilitate effective public engagement as part of watershed management. According to Brown (2011, 249), water quality professionals may have a range of interest and willingness to involve the public. Some view public engagement as a "time-consuming agency mandate." Others view it as a "moral imperative for public programs and management of public resources in a democratic society." Most people, however, fall somewhere in between (Brown 2011).

Minnesota is currently facing a shift in water quality monitoring, assessment, and management planning. The MPCA is conducting 10-year assessments of major watersheds (Hydrologic Unit Code-8 scale), which involve intensive monitoring of water chemistry and biology at multiple locations in each watershed. Led by the Board of Water and Soil Resources (BWSR), the state is shifting from local water management plans based on county, watershed district, or watershed management organization boundaries, to plans based on major watershed boundaries. Both efforts require that water quality professionals involve the public in a variety of capacities. Expected outcomes include the creation and implementation of watershed plans.

While developing these plans is important, the *process* of establishing them is also critical for implementation to succeed (McCool and Guthrie 2001). For example, several rounds of watershed planning occurred in Pierce County, Washington during the 1990s that used approaches for maximizing participation, learning, and creativity. The process also helped the development of partnerships and resulted in high levels of implementation and process ownership by those involved (Smolko et al. 2002). To achieve this level of public participation related to water quality, government agencies and organizations with convening roles must have staff with the necessary competencies to facilitate this type of participatory process.

The Skill Set of Water Quality Professionals

Watershed work requires successful partnerships with leadership and management (Leach and Pelkey 2001). According to Brown (2011, 250), "Leaders create structured opportunities for talking about water concerns and guide productive discussion among citizens and groups so that areas of agreement and disagreement are transparent but mutually respected."

Watershed leaders and managers engage others through a variety of civic engagement processes to reach desired water quality outcomes. A literature review conducted in 2015 (Illes 2016) was referenced in a subsequent report entitled *Social Indicators for Watershed Leadership* (Bonnell and Baird 2015). This review listed 18 topics (see Appendix) for potential inclusion in watershed leadership and development programming. Bonnell and Baird's (2015) categories and subcategories for watershed leadership, summarized in Table 1, emerged from a qualitative study of successful watershed coordinators in Ohio.

Communication is important when working with stakeholders, elected officials, and partnering organizations. Interpersonal skills are necessary to cultivate professional networks, multidisciplinary teams, and successful partnerships. Brown (2011) and Morton (2011) both note the importance of trust when building relationships to carry out watershed work. Relationships and informal social networks are critical for success (Nelson et al. 2017).

Smolko et al. (2002, 993) commented that: "Participatory methods are seen as "touchy feely," implying that they do nothing more than make the group members feel good about themselves and each other. This is linked to cultural perceptions

Table 1. Framework from the literature review: Attributes of Effective Watershed Leaders, from Bonnell and Baird (2015).

Attributes of Effective Watershed Leaders (categories)	Attributes of Effective Watershed Leaders (subcategories)
Technical	Tools and techniques
	Specialized knowledge base
	Systems thinking/problem-solving/analytical skills
Administrative	Project management
	Grant-writing and management
Social	Communication and education
	Interpersonal and group dynamics
	Community dynamics
	Political dynamics

about leadership. Our culture admires leaders who make decisions quickly and unilaterally which is seemingly at odds with our democratic ideals." In Minnesota, as in most areas, watershed leaders are often skilled in the technical aspects of their work but lack specific training in interpersonal and group communication, team building, and forming partnerships. Bonnell and Baird (2015) suggest more training is needed in these areas. Developing the leadership and civic engagement skills of water quality professionals can happen in a variety of ways, as noted in a summary by Wolfson et al. (2015). This summary provides a comparison of training methodologies and emphasizes the importance of networking, participant interaction (either online or in-person), and the inclusion of local and state-specific perspectives. Wolfson et al. (2015) surveyed study participants who rated organizational and interpersonal skills as critical to their work. The most beneficial competencies included effective communication, organizational and project management skills, facilitative leadership, vision, and collaboration.

Civic Engagement Model and Cohorts

University of Minnesota Extension developed a research-informed model for civic engagement (Radke 2013; Radke and Chazdon 2015). Research shows an informed decision is not enough. Addressing these issues requires authentic civic engagement (deliberative dialogue) to describe an authentic civic engagement process and to create a curriculum for Extension programming. Civic engagement is described as, "Making resourceFULL decisions and taking collective action on public issues through processes of public discussion, reflection, and collaboration" (Radke et al. 2012). The term "resourceFULL" was coined by University of Minnesota Extension to represent decisions that are not lacking in collaboration, trust, and relationships (Radke and Chazdon 2015). The model is framed around five stages: prepare, inquire, analyze, synthesize, and act together (Figure 1).

To strengthen teaching and evaluation, Extension's leadership and civic engagement team, with support from evaluation staff, developed

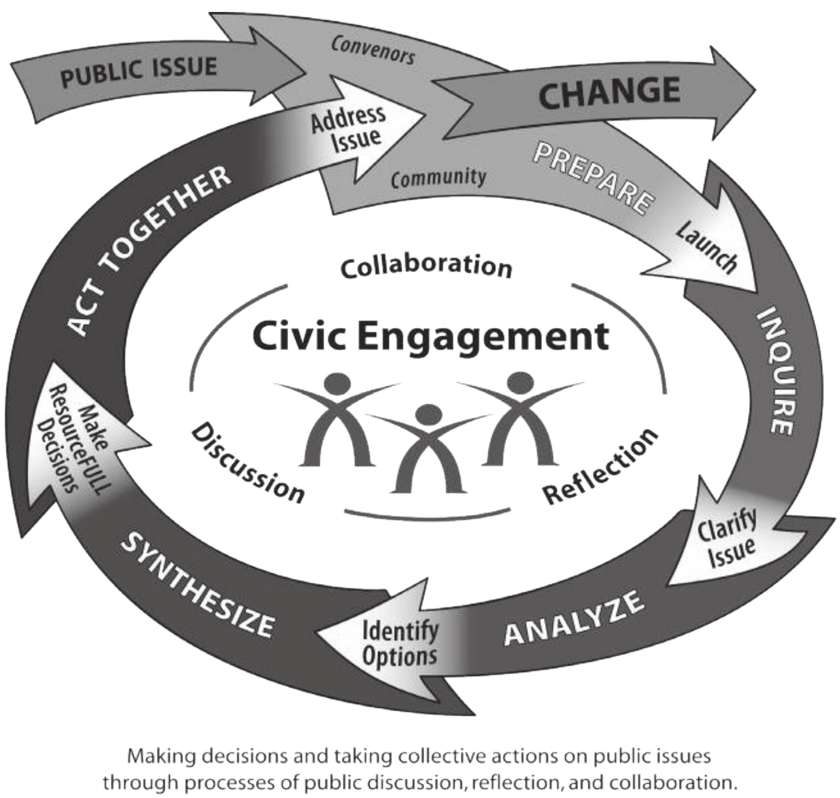

Figure 1. University of Minnesota Extension civic engagement model.

a series of 13 civic engagement competencies associated with the above five stages. These civic engagement competencies were developed based on a literature review of relevant research as well as the practical experiences gained by Extension Educators through teaching and working in communities. Table 2 shows the relationship between the 13 competencies and five stages and provides a general definition of each competency. Competencies needed for the "inquire" and "analyze" stages—framing issues, identifying options, and thinking critically—are the same. Three areas of competency—collaboration, reflection, and discussion—are considered core to all stages of the civic engagement process.

From 2012 to 2017, the MPCA and University of Minnesota Extension worked with local water quality professionals, organizations, and stakeholders who work or volunteer on behalf of water protection and restoration. Through a cohort format, the MPCA and Extension helped these individuals enhance their civic engagement skills. This approach to teaching civic engagement differs from other watershed leadership programs in that civic engagement work is the central focus of the training. The competencies developed for the newly created civic engagement model provided the curriculum basis for the cohorts.

Table 2. Extension's civic engagement model — stages and competencies.

Stage of Civic Engagement	Civic Engagement Competencies
Prepare	• Understanding civic engagement • Assessing community readiness
Inquire and Analyze	• Framing issues • Identifying options • Thinking critically
Synthesize	• Making group decisions • Planning
Act Together	• Communicating • Managing • Evaluating
Core Competencies Needed in All Stages	• Collaborating • Reflecting • Discussing

While not specifically designed as a leadership program, these cohorts covered many of the topics necessary for successful watershed leadership: understanding watershed history, stakeholder analysis, engagement and building trust, decision making, power and interest, balancing technical expertise with local knowledge, facilitating communication and co-learning between these groups, critical thinking, and conflict management skills (Illes 2016). Each cohort aimed to accomplish the following:

1. Build networks for working on water quality within participants' respective region(s),
2. Enhance the capacity of water quality professionals to engage with stakeholders and the public to address water protection and restoration, and
3. Facilitate co-learning among participants on the issue of water quality.

This study focused on three cohorts based on geographical locations: Southeast (SE), Southwest (SW), and Northeast (NE). The cohorts were convened between 2012 to 2014 and were chosen for this study because they occurred a few years ago, giving participants time to apply their skills and knowledge. At the end of each cohort, participants rated the growth of their skills in each of the 13 competency areas, using a retrospective pre-post survey design. They reported strong gains in all competency areas, with the biggest increases related to the "prepare" and "synthesize" stages of the civic engagement process. Figure 2 displays the results from each of the three cohort's retrospective pre- and post- surveys, which were conducted when each cohort ended.

Methods

Researchers employed a mixed-methods strategy to measure the impacts of the water quality civic engagement cohort program. First, a non-random comparison group survey was conducted with participants of three cohorts, as well as a comparison group of water quality professionals not part of a cohort. Second,

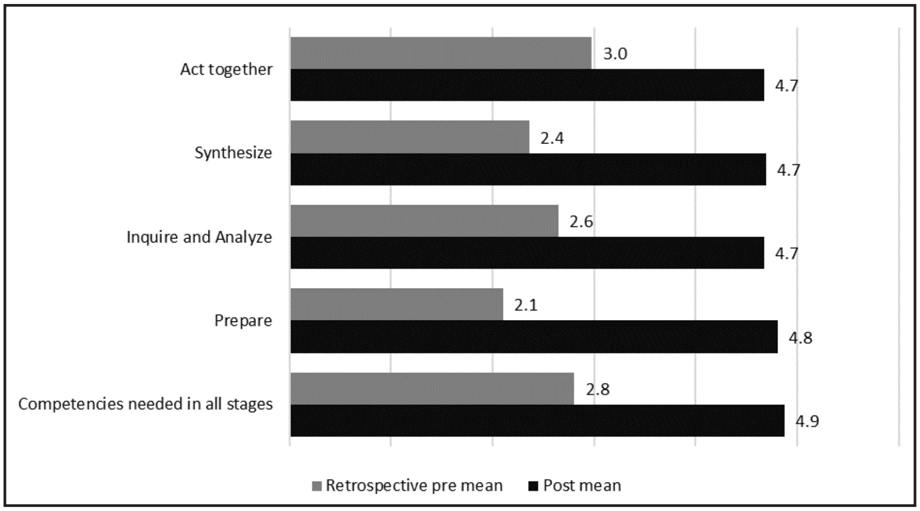

Figure 2. Changes in competencies as measured by end of cohort surveys (n=58). Scale: 1=weak to 6=strong.

following Brinkerhoff's Success Case Method (Brinkerhoff 2002), interviews were conducted with a small group of cohort program participants to better understand how the program influenced their civic engagement practices.

Online Survey

An online survey compared the similarities and differences in civic engagement competencies and behaviors of both program participants and the comparison group. The survey was sent to 63 former cohort program participants, with 39 responding (a 62% response rate). Comparison group members were identified through personal networks of the primary author who is a former water quality professional. After an explanatory email about the study, the survey was sent to 64 comparison group members, with 34 responding (a 53% response rate).

The online survey included three statements designed to measure each of the 13 civic engagement competencies. The survey questions were similar to the competency statements that were developed along with the civic engagement curriculum, and have been used in end of program evaluation surveys. A complete list of these statements is shown in Table 3.

The survey also included a section on civic engagement networking behaviors, specifically, collaboration with other water quality professionals and engagement with members of the public. Participants were asked to think about the past 12 months and indicate the level of frequency they worked or collaborated with others to address soil and water quality in a watershed(s). Table 4 displays the questions asked about each type of networking activity.

Success Case Interviews

Using Brinkerhoff's Success Case Method (Brinkerhoff 2002), a member of the research team conducted interviews with a small group of program participants to better understand how the program influenced their civic engagement practices. The Success Case Method is an evaluation approach that combines survey research with qualitative case study interviews to reveal the results of a program or intervention. The approach begins with a survey that includes questions to identify the strongest examples of success (and sometimes failure). The research team used several open-ended questions from the online survey to identify potential success cases, specifically among the pool of program participants who agreed to be interviewed. Members of the research team also looked for program participants who provided specific examples of how their participation in the program changed their professional practice and helped them successfully collaborate with and engage the public in water quality efforts. Four program participants were interviewed over the phone, and each interview was recorded and transcribed.

Table 3. Survey skills/questions for cohort participants and comparison group.

Skills	Survey Item (response categories: 1 = not at all proficient, 2 = a little proficient, 3 = somewhat proficient, and 4 = highly proficient)
Understanding Civic Engagement	• Explaining the benefits of civic engagement in addressing a public issue. • Articulating an approach for "doing" civic engagement. • Explaining the importance of process design for civic engagement.
Assessing Community Readiness	• Examining a community's level of awareness and concern regarding a public issue. • Conducting stakeholder analysis to identify which interest groups should be included to address a particular public issue. • Determining whether a community is ready to engage in a civic engagement process to address a public issue.
Framing Issues	• Demonstrating questioning techniques that draw out similarities and differences of how participants perceive the issue. • Gathering resources and data to help identify the complexity of the presenting issue. • Framing public issues in ways that include a broad range of stakeholders.
Identifying Options	• Choosing analysis methods that enable groups to generate options to address a public issue. • Applying dialogue and reflection processes to reach a shared understanding of options. • Anticipating stakeholder responses to options.
Critical Thinking	• Identifying the difference between a presenting issue and an underlying issue. • Questioning assumptions when thinking about a public issue. • Examining a public issue from multiple perspectives.
Making Group Decisions	• Choosing group decision making techniques that fit the needs of the situation. • Leading a group to a decision using consensus-building techniques. • Designing processes to move a group from information gathering to decision making.
Planning	• Engaging those directly affected in the planning process. • Identifying the resources needed to successfully implement an action plan. • Choosing strategies to organize and manage the implementation of the action plan.
Communication	• Adapting communication methods to reach participants from diverse perspectives. • Using clear and concise communication skills. • Using active listening skills to promote collective action.
Management	• Facilitating effective working relationships to support collective action. • Modeling effective ways to deal with conflict in a group. • Facilitating processes to effectively manage the action plan.
Evaluation	• Defining measurable benchmarks or indicators to show progress. • Using evaluation activities to determine whether the issue has been addressed or more work is needed. • Using participatory evaluation methods that reinforce civic engagement.
Collaboration	• Designing events that foster collaboration toward solutions on water quality or other public issues. • Seeking inclusivity and diverse perspectives for collective action. • Creating trust and enhancing relationships.
Reflection	• Identifying the times when I need to reflect on a process or problem before acting. • Designing experiences that encourage consideration of diverse points of view with regard to water quality or other public issues. • Communicating the importance of reflection for continuous learning.
Discussion	• Designing events that foster meaningful discussion among diverse interests working on water quality or other public issues. • Using dialogue processes to promote understanding of multiple perspectives. • Facilitating deliberation processes to reach decisions on a public issue.

Table 4. Survey questions regarding networking activities.

Network Behavior Type	Survey Item (response categories: 0 = not at all, 1 = about once/year, 2 = about quarterly, 3 = about monthly, and 4 = weekly or more often)
Collaborating	I worked or collaborated with other agencies or organizations working on soil and water quality in my watershed.
Collaborating	I worked or collaborated with other agencies or organizations in other watersheds.
Collaborating	I actively sought out information beyond those I typically work with on soil and water quality.
Collaborating	I tapped into the skill set of others when I was preparing to engage with the public.
Engaging	I engaged with members of the public to determine the community's readiness to address issues of soil and water quality.
Engaging	I engaged with members of the public to clarify our mutual understanding of soil and water quality issues.
Engaging	I engaged with members of the public to identify options for addressing soil and water quality.
Engaging	I engaged with members of the public for soil and water quality decision making.
Engaging	I engaged with members of the public to implement a soil and water quality plan.

Results

Competency Survey Results

Both survey groups—cohort program participants and comparison group members—were asked a series of questions about their proficiency in 13 competencies: collaboration, reflection, discussion, understanding civic engagement, assessing community readiness, framing issues, identifying options, critical thinking, making group decisions, planning, communication, management, and evaluation. Three survey questions pertained to each competency. Mean scores for each competency were calculated, as well as each stage of the civic engagement process. T-tests were then run to compare differences between the means of both study groups.

When aggregated into the five stages of the civic engagement process, data revealed cohort program participants experienced significantly better results than comparison group members in four of the five stages (with a 95% confidence level or higher). In each of the four areas, program participants reported average scores in the "somewhat proficient" range, while comparison group members tended to score themselves as "a little proficient" or "somewhat proficient." As shown in Figure 3, the largest difference occurred in the "act together" stage. This finding was interesting, given participants reported the weakest improvement in this competency at the end of the cohort programs. Having additional time to practice their new skills may explain the difference in findings. A significant difference did not exist between program participants and the comparison group for the core civic engagement competencies of collaboration, reflection, and discussion.

Statistically significant differences between program participants and the comparison group did occur, however, for 6 of the 13 civic engagement competencies. The competencies with significant differences were managing, evaluating, understanding civic engagement, making group decisions, identifying options, and framing issues. These results are shown in Figure 4.

Differences in means for the remaining seven competencies were not statistically significant, but

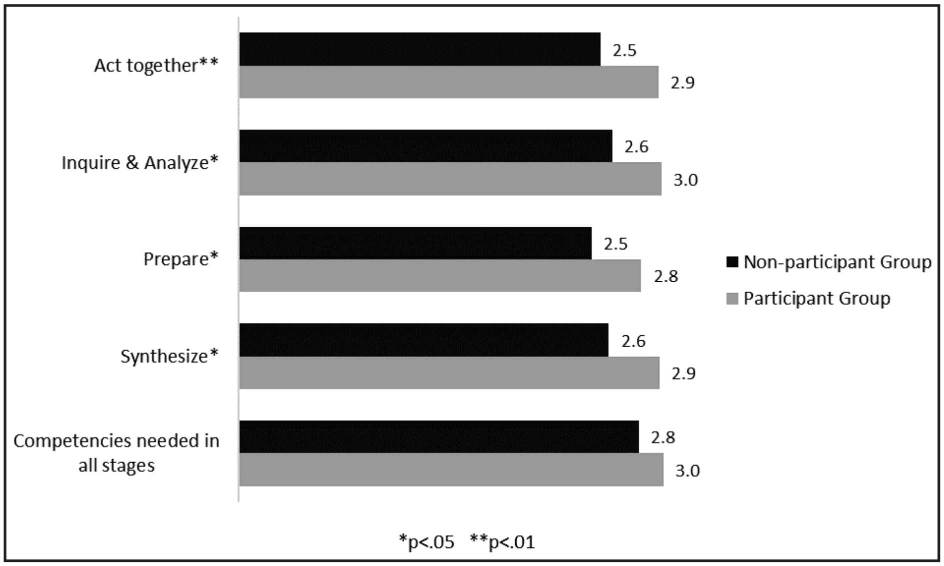

Figure 3. Differences in civic engagement skills, aggregated into stages. Scale: 1=Not proficient, 2=A little proficient, 3=Somewhat proficient, 4=Highly proficient.

all in the right direction (participants had higher means than comparison group members). We speculate that six of these seven competencies—collaborating, planning, communicating, thinking critically, discussing, and reflecting—are general skills many professionals may believe they possess, even without civic engagement training.

Both groups reported relatively weak skills for assessing community readiness, a competency that is specific to the training. Participants may not have recognized the connection between community readiness and stakeholder analysis, which is a better-known aspect of readiness assessment. Still, this may be an area in which training could be strengthened in the future.

The survey also asked participants an open-ended question about challenges or obstacles they faced while engaging stakeholders on water quality or other public issues. Themes that emerged from both groups included lack of time (for staff and public), attendance and participation at engagement offerings (such as community gatherings to talk about water quality concerns), the complexity of water pollution science and solutions, lack of organizational support, and peoples' inability to grasp the shift from their past experiences of "participation" to a more involved approach. While Extension can address some of these topics through its cohort curriculum, others are more appropriately taught by other organizations.

Network Activities

An analysis of networking behaviors, both collaborative connections with peers and engagement connections with the public, showed differences in activity frequency. While we had anticipated the cohort participants would report higher frequencies of networking and engagement, the results did not show this pattern. In fact, the comparison group reported slightly higher levels of networking behavior, but the differences were not statistically significant. These results are shown in Figure 5.

On average, both participants and comparison group members reported a monthly frequency of peer collaboration. They both also reported, on average, a quarterly frequency of public engagement. In response to the open-ended survey questions, both groups shared challenges or obstacles they faced while collaborating with other water quality professionals. This included lack of time, differing priorities among staff and organizations, group dynamics among people within and across organizations, state agencies with different priorities and messages about civic engagement, lack of funding, and the desire to

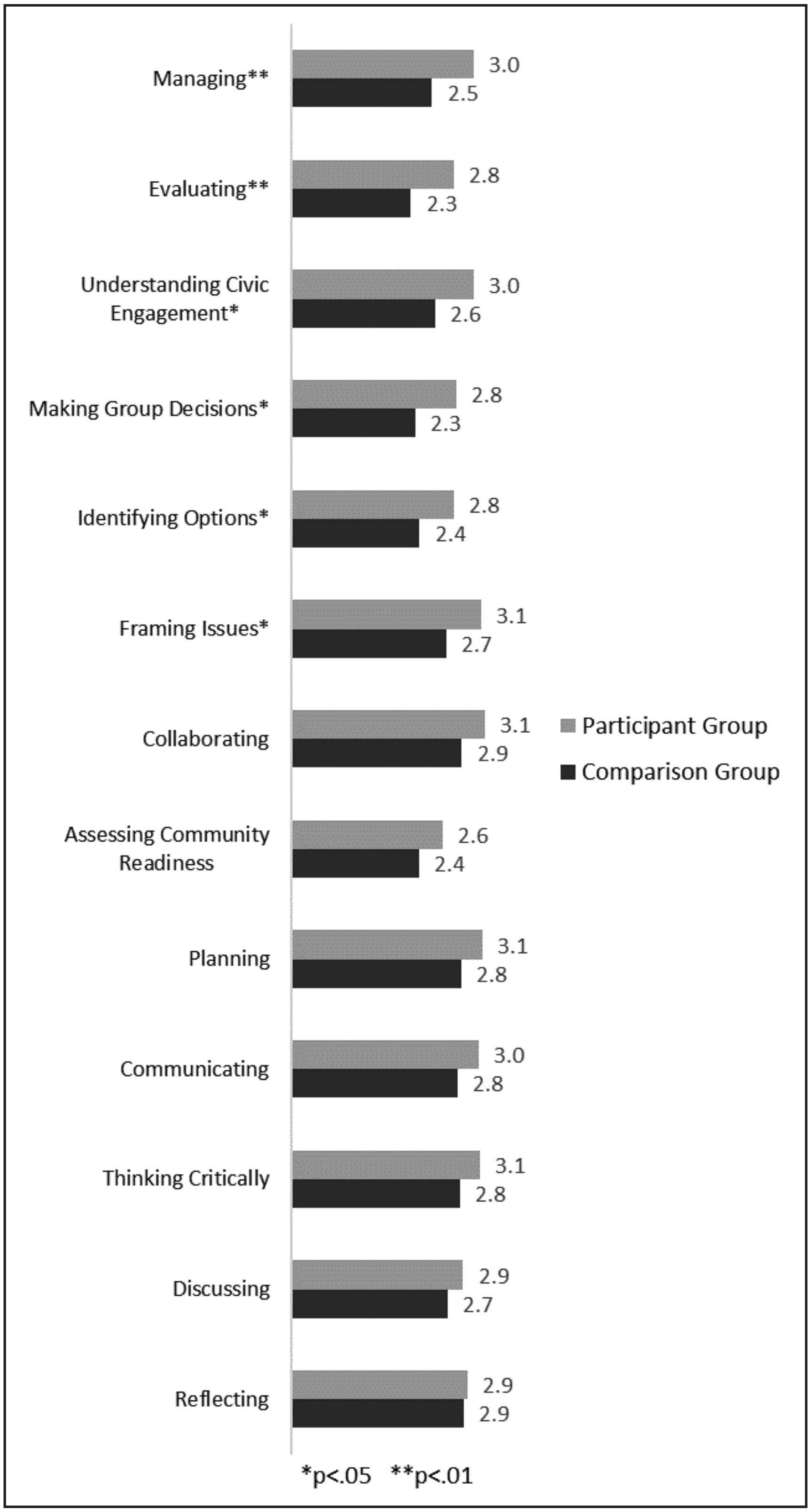

Figure 4. Differences in the 13 civic engagement skill areas. Scale: 1=Not proficient, 2=A little proficient, 3=Somewhat proficient, 4=Highly proficient.

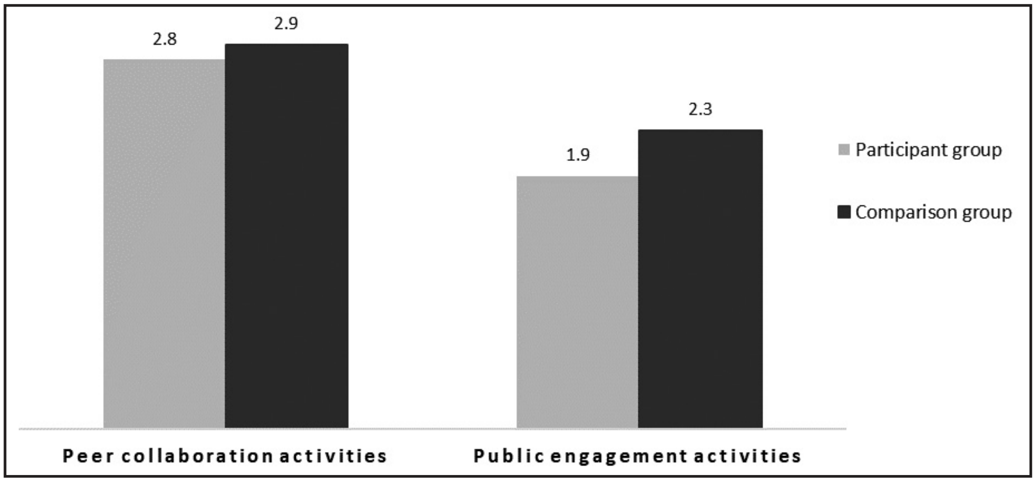

Figure 5. Differences in network activities. Scale: 0=never, 1=about once/year, 2=about quarterly, 3=about monthly, 4=weekly or more often.

accomplish things quickly without taking the time to build trust and relationships. Extension can likely address some of these issues during future cohorts, but others should be attended to outside the cohorts.

While the survey question asked about the frequency of networking behaviors, it did not address the depth or quality of these behaviors. This was a possible weakness in the survey design. In addition, members of the comparison group may have participated in networking opportunities created by cohort members. For example, cohorts in southeast and southwest Minnesota invited outside colleagues to join them for occasional continuing education and networking events. Since watershed planning takes place in various areas across the state, both cohort participants and comparison group members may have collaborated with one another to actively address watershed issues. It is also possible program participants have a better understanding of collaboration and engagement after completing the cohort program, and that additional knowledge was reflected in their survey responses.

Success Case Interview Data and Themes

Four participants from the cohort programs who reported success cases were selected for semi-structured interviews. Brinkerhoff (2002) recommends that a small number of success cases is sufficient to "poignantly illustrate the nature and scope of the success the program is helping to produce" (Brinkerhoff 2002, 16). The interviews were recorded and transcribed, then coded for themes following a grounded theory approach (Glaser and Strauss 1967). They provided deeper insight into specific successes resulting from the cohort program. These successes included effective use of civic engagement strategies, growing citizen leadership, and better peer collaboration and networking. Additionally, participants reported support for, as well as barriers to, carrying out civic engagement efforts.

Using Civic Engagement Strategies Effectively

The interviewees often cited the success of using civic engagement strategies. Participants described effective meetings in which they used specific civic engagement techniques and tools, such as World Cafe (Brown and Isaacs 2005), a gallery walk, group ranking processes, stakeholder analysis, and small group discussions. For one professional, small group discussions were key to successful civic engagement.

"We've tried a lot of variety, but we often will go back to the small group discussion. Our fallback is to try to mix it up in small groups and get those diverse people that may not work together normally, sitting together and talking. I would say that has been one of the key things that we keep using over and over because it really helps."

Intentional meeting design, including the preparation of approaches, timing, and strategies for encouraging participation, was another reported example of effective civic engagement strategies. Process design is a core element of the cohort program. Many participants discussed their success using multiple approaches or combining approaches in meetings. A common theme among all participants was the ability to read a room and determine the efficacy of their strategy. Participants reported experimenting with techniques to discover what worked best for different audiences.

Growing Public Leadership

Another commonly reported success among participants was seeing members of the public taking an active leadership role on local water quality issues. For example, one participant mentioned the success of a cover crop program designed entirely by stakeholders. By engaging diverse stakeholders and inviting them to participate in decision making, a stakeholder-designed, publicly funded five-year program of cover crop research was developed. According to this professional, the cohort program was instrumental in achieving this result.

"I don't think there's any way I would have ever tried it [civic engagement] had I not done the cohort. I think I get stuck in the same old rut of we don't really engage those citizens, we just tell them things. We do the education things, but we don't really bring them in. If I wouldn't have done that, this never would have happened."

Another participant described an effort in which she had applied the skills gained in the civic engagement cohort to train volunteers through a Watershed Restoration and Protection Strategy (WRAPS) grant. These volunteers went on to convene other meetings and ultimately form their own nonprofit.

"The citizens led those meetings. It wasn't agency staff or Extension staff—it was them. Out of that core group of people, [the] Friends of the Root River formed. I'd say half a dozen of those people were part of the civic engagement training."

Collaboration and Networks

The civic engagement cohort program sought to connect professionals and volunteers across agencies by creating a co-learning community. Through the program, participants developed deeper relationships and networks with other regional water quality professionals.

"That was the really nice part of that whole experience—that we got to know [a] cohort of people in a much richer way than just attending meetings and sitting there all night."

Developing these relationships created a network that participants could access for advice or collaboration. This sense of support was often created through shared knowledge and an understanding of civic engagement concepts and techniques. It also resulted in stronger civic engagement planning across agencies.

While the cohort provided a rich opportunity for networking and learning together, participants did face challenges with continued peer collaboration after the program ended. Some cohorts continued to meet semi-regularly, but their meetings soon slowed as other commitments and the time needed to plan the meetings arose. Discontinuing the meetings reduced the strength of the network and bridging opportunities that occurred during the program. Additionally, changing jobs and/or moving from the area where a cohort took place negatively affected networking.

Support for, and Barriers to, Success

Participants identified several critical areas of support, as well as barriers, to their success, which included agency prioritization, organizational support, time, funding, and resources. Prioritizing the need for civic engagement skills when addressing water quality issues has become increasingly important. Participants who reported successes indicated that their agencies valued and desired civic engagement.

Even among the agencies that prioritized civic engagement, however, a lack of staff exposure to civic engagement skills served as a barrier to success. Some professionals observed that many staff members with science backgrounds were both unfamiliar and uncomfortable with civic engagement processes. This resulted in a very limited number of staff trained in, and able to implement, civic engagement practices. As a result, time constraints to focus on civic engagement work and the lack of a strong support system prevented learning. Time was further constrained by the number of duties each professional was responsible for, in addition to developing their civic engagement skills.

Funding also emerged as a way to either support or limit successful civic engagement. While some agencies include civic engagement activities as budget line items, others require professionals to secure external grants. A lack of funding was cited as a critical barrier to success and its absence makes meaningful civic engagement work difficult. This corroborates the findings of Leach and Pelkey (2001) that funding is often cited as a factor in watershed success.

Discussion and Recommendations

A strength of Extension's civic engagement curriculum is its emphasis on the collective nature and processual aspects of civic engagement work. Our comparison group survey found significant differences between cohort program participants and comparison group members in self-reported skills representing four of the five stages of the civic engagement process – prepare, inquire and analyze, synthesize, and act together. These stages of the civic engagement process are not typically emphasized in technical training for water quality professionals. Interestingly, significant differences were not found in the core civic engagement competencies (collaboration, discussion, reflection) needed throughout all stages of the process. We speculate that these competencies are more general, so those who have not received the civic engagement training may feel confident in these skills and may be unaware of the complexity of these skills as discussed in the training.

Success case method findings provided a deeper understanding of how cohort participants used their program experience to succeed in collaboration and public engagement. These stories illustrated ways that participants have used civic engagement strategies effectively, grown public leadership, and collaborated with other water quality professionals. Examples of success included using skills gained in the program to work with farmers to implement a research project and to engage residents who then formed a nonprofit to protect and improve a watershed. These success stories highlight the value of the cohort programs and the difference they made in participants' work. They can also be used as inspiration and examples by Extension and other organizations and agencies working with water quality professionals when planning future civic engagement trainings and cohorts.

Ideas for Program Change

While cohort participants found networking and learning opportunities valuable and intended to continue to meet after their cohorts ended, most formal gatherings happened less than hoped. Time constraints and other job duties influenced the frequency and planning of meetings. To help address the issue, Extension may want to consider offering both formal and informal continuing education, as well as networking opportunities, through alumni events.

Changes to the curriculum and cohort process may also need to be considered. For example, future cohorts might focus more on the concepts and practice of invitation and initial engagement strategies, trust and relationship building, and building and maintaining networks. This change may help participants better manage networks on their own. Also, providing more comprehensive resources on assessing community readiness may be valuable, such as incorporating aspects of the Multilevel Community Capacity Model (Davenport and Seekamp 2013).

Intentional support from participants' employers may also increase the level of civic engagement and network building they can accomplish, as well as avoid burnout of staff (Flora 2004). When staff are tasked with multiple job duties civic engagement activities can become overwhelming and burnout may occur. Additionally, consistent financial support is critical for ongoing civic engagement work. Interviewed participants noted that the amount of funding—or a lack of it—determined how much time and effort they allocated to civic engagement work. Both the MPCA and the BWSR provide support for continuing civic engagement training for water quality professionals. Their assistance is provided through funding and civic engagement training as a part of water quality grants.

Even the most robust civic engagement training and processes may not yield the level of public participation and collaboration desired if the public does not see the need for action. Prokopy et al. (2014, 1179) use the term "catalyst event" to describe an event or series of events that might help to motivate such action and create change. These events could be intentional, such as government actions or funding, or unintentional, such as natural disasters or accidents (Prokopy et al. 2014).

While existing literature on watershed management focuses on a skill set needed for watershed leaders, it does not consider water quality within the broader context of civic engagement. Leadership skills are important to develop, but engaging in robust civic engagement is also a critical part of protecting and improving watersheds. Both public and government agencies often fail to recognize this and make decisions without considering—or implementing—a civic engagement process. There is evidence in the literature that effective civic engagement can lead to more efficient and effective implementation of conservation and protection practices. In addition, it is the right thing to do in a democracy.

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Appendix A

List of 18 topics for potential inclusion in watershed leadership development programming (Illes 2016)

1. Engaging a diversity of stakeholders based on educational level, socio-economic status, and other demographics.
2. Seeking stakeholder diversity in group composition: government/agency, environmental activists, leisure, tourism/economic, industry/farming, cultural, and others.
3. Recognizing and valuing diverse skills sets that participants bring to the group.
4. Ensuring that stakeholders who perceive they are affected are represented in the collaboration; recognizing stakeholders have different motivations for getting involved.
5. Balancing scientific experts' knowledge with normative knowledge of stakeholders in the geographic region.
6. Organizing a democratic process for stakeholder engagement, decision making, and assessing outcomes.
7. Recognizing power dynamics within a collaborative group; allowing all stakeholders a voice and equal consideration in the decision making process; fostering respect for all participants.
8. Facilitating communication between scientists and non-scientist stakeholders to make sure plans are technically sound without over riding normative beliefs and values.

9. Understanding the history of government involvement in addressing watershed issues and potential impacts on future collaborative efforts.
10. Understanding the difference between top-down versus bottom-up decision making and implications for stakeholder buy in.
11. Understanding alternative leadership/decision making structures and processes for collaboration. What structures/processes work best under what circumstances.
12. Building conflict management skills, including facilitating challenging conversations and negotiation.
13. Fostering an environment conducive to critical thinking.
14. Building trust among stakeholders.
15. Facilitating collaborative learning as a process for engaging stakeholders (both expert and lay persons) as co-learners in watershed assessment, planning, and decision making.
16. Engaging stakeholders in all stages of watershed planning, including problem definition, decision making, proposing and evaluating solutions, and adopting a plan.
17. Using information technology to facilitate communication and education (e.g., social media, web-pages, e-newsletters).
18. Educating stakeholders on how to interpret data and utilize scientific studies to inform decision making.

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Using Continuous Response and Self-Report Measures to Understand Spokesperson Evaluation Processes During Water Crises

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Abstract: This study investigated how perceptions of news conference sources varied from measures taken in real-time to those taken retrospectively after exposure to news conference footage. A 4 (source type) X 4 (message replication) mixed design experiment was conducted in which participants viewed four organizational spokespersons responding to water crises involving organizations. Participants evaluated spokespersons using a handheld dial during stimulus exposure, and then, retrospectively, using self-report measures. Evaluation of source trustworthiness tended to increase over time, regardless of the type of source. However, retrospective self-report measures demonstrated that public relations practitioner credibility suffered in comparison to that of other sources. Implications are discussed for public relations practice and future research in source credibility.

Keywords: *source credibility, public relations, engineer, president, dial test, news conference*

Water resource management scholarship has discussed the importance of professional development to effectively address global water issues (McIntosh and Taylor 2013); for example, some have discussed the importance of developing interdisciplinary skill sets such as technical expertise and effective communication skills (Loucks 2008). To this point, communication research has been slow to test and inform effective communication strategies for organizations and professionals who respond to water issues. The important role of (dis)trust in public-water resource management relationships has been noted as it may directly influence management decisions, community engagement, and policy formation (Leahy and Anderson 2008; Smith et al. 2013). However, research to date has not examined how different types of water agency spokespersons may influence individuals' credibility perceptions during water crises.

A crisis may be defined as the manifestation of risk (Heath and Palenchar 2009) or, from an organizational perspective, a significant event with a potentially negative result that may affect an organization or industry and its stakeholders, products or services, or reputation (Fearn-Banks 2007). Public relations practitioners engage in communication efforts on an organization's behalf to avoid conflict, or manage it when it occurs. A primary function of a public relations practitioner or organizational spokesperson during a crisis is to accurately and quickly provide complete information to relevant audiences about the situation (Wilcox and Cameron 2009). A news conference is a common mechanism for relaying such information to news outlets and the public.

Public relations literature indicates that information sources often moderate message effectiveness. While some research suggests cues such as spokesperson gender and ethnicity do not influence perceptions of credibility (Mohammed 2012), other research indicates that in the absence of relevant information (e.g., experience with previous crises), heuristic cues may influence credibility perceptions (Hong and Len-Riós 2015).

Sources affiliated with an organization in crisis tend to be perceived as less credible than sources that are unaffiliated with an organization (Callison and Zillmann 2002; Callison 2004) and sources whose organizational affiliation is unidentified (Callison 2001). Public relations practitioners may not be judged any more negatively than other internal sources affiliated with the same organization (e.g., CEO or engineer) (Callison 2004), but they are perceived as less credible than hired or independent third-party sources (Callison and Zillmann 2002). However, public relations practitioners and the organizations for which they are employed are perceived as less credible than unidentified sources and their affiliate organizations, especially when the spokesperson is conveying company-negative news (Callison 2001).

Initially, early research in the field was conducted to see how a source's credibility influenced communication effectiveness (Hovland and Weiss 1951). These initial study designs involved the explicit manipulation of credibility through attribution of presented information to either a source a priori labeled as "trustworthy" (a respected researcher publishing in a journal, for example) or "untrustworthy" (a well-known gossip columnist publishing in a magazine, for example) source. Subsequently, when participants found certain information more believable, justifiable, or fair, the researchers explained that it was because the trustworthy sources were more credible, although this effect was not stable over time.

Subsequent research in source credibility built upon this foundation, which established that audiences consider source factors when processing and judging the quality of information presented (Hovland et al. 1949; Hovland and Weiss 1951). Further research focused on investigating the construct of credibility itself (McCroskey 1966; Berlo et al. 1969). Berlo and McCroskey both developed credibility scales by rating individual speakers across a variety of items that were ultimately reduced to manageable batteries of items, and as a result, credibility became a common dependent variable in many mass communication studies. Common to this vein of research were pen-and-paper measures requiring research participants to indicate responses on semantic differential scales from among a list of items presented post-message exposure, and this a priori evaluation using itemized scales has dominated the literature. The current study advances this methodology by introducing continuous response during message consumption.

Understanding how individuals evaluate the credibility of spokespersons in water crises could have notable consequences for organizations' crisis management strategies and subsequent reputation and relationship management outcomes. Much research in the source credibility formative theory domain has relied on print stimuli and retrospective self-report measures for assessing evaluations of communicator credibility. Recent research examining credibility perceptions has adopted audiovisual stimuli—primarily examining the influence of audiovisual news content on credibility perceptions (Tewksbury et al. 2011; Nelson and Park 2015). With the availability of audiovisual stimuli and continuous response measurement systems (Biocca et al. 1994), examination of credibility components or other source assessments is possible. Continuous response measurement systems have been used in media research since the 1940s (Millard 1992), but such measurement systems have yet to be widely adopted by source credibility and public relations scholars. Continuous response measurement has been used in the political communication literature. For example, political election research suggests that continuous response measurement is a reliable and valid paradigm for examining immediate positive and negative impressions of televised political candidates to help delineate participants' post-consumption evaluations (Maier et al. 2006).

The current study attempts to make two contributions to research on source credibility. First, the study tests the effects of source identification on perceptions of credibility and trustworthiness in a digital video environment rather than in the more commonly used print format. Second, the current study aims to understand individuals' real-time perceptions of source credibility during exposure to news conference footage, including various spokespersons involved in water crises. Reactions to media content were assessed through dial test measures (i.e., real-time opinions; Biocca et al.

1994) to develop a more nuanced understanding of individuals' perceptions of communicator credibility as the message unfolds in real-time. Given the previous literature, the following hypotheses were posed:

H1: Public relations-labeled sources are viewed as less credible than organizational presidents and engineers when discussing organizational crisis.

H2: Perception formation of source trustworthiness occurs in real-time as identifying factors are revealed such that public relations sources are seen as less trustworthy than other sources when discussing organizational crisis.

Method

Design

The experiment employed a 4 (source type) X 4 (message replication) mixed design. Presentation order served as a between-subjects variable. Source type and message replication served as within-subjects variables. Participants were randomly assigned in groups of no more than six per session to specific conditions. Each participant viewed four messages, each covering a different water crisis (i.e., gas leak in ocean, pipeline rupture in community, wastewater discharge in a river, and water reservoir contamination). Source type and message replication were counterbalanced between groups of participants to mitigate order effects. Each participant saw all four clips in a systematically rotated order, with one of each source type rotated through each different scenario clip.

Participants

Continuous response and questionnaire data were collected from a sample (N = 184) of undergraduate students enrolled in media and communication courses at a large southwestern university. The sample size provided adequate power due to two manipulations being repeated within subject. Nine respondents failed to actively manipulate their assigned continuous response dial (i.e., participants left their dial on a single digit for more than 75% of all stimulus exposure) and were excluded from data analyses. In essence, excluded respondents set down their dials and failed to participate during stimulus exposure.

Stimuli

Experimental stimuli consisted of four excerpts from video press conferences edited to be similar in format and content. Excerpts were taken from real-world press conference footage. To control for the influence of spokesperson characteristics, such as gender and race, on participants' source credibility evaluations, each video clip displayed a Caucasian male spokesperson responding to a crisis event. The stimuli ranged from 43 seconds to 80 seconds (M = 55 seconds). Each clip contained an embedded key superimposed and manipulated by the researchers that identified the source speaking on behalf of the organization. The key appeared in the lower third of the screen on a partially transparent background in accordance with common media practice. Each key contained the same format: Name, Title (e.g., James Phelps, PR Manager for Marion Corporation) with a point size of 24 for the name and a point size of 14 for the source title. Each key appeared 11 seconds into the video and remained on-screen for 8 seconds. Both name and source type were counterbalanced so that each name appeared with each source type across message replications. In the control conditions, only source name was revealed; job title was excluded.

Measurement

Independent Variables. **Source type** was manipulated by varying a source job label as "PR Manager," "President," or "Head Engineer." Also included was a job label control condition where the source was named in the key but not identified as holding a specific job title. All participants viewed each source type so that consumption of the four clips resulted in exposure to one PR source, one CEO-type source, one engineer source (engineer), and one source with no job title. These different sources appeared in one of four news conference scenarios so that no respondent saw the same scenario more than once and so that all source types were seen once by each participant. The design ensured that all source types, scenarios, and orders were counterbalanced.

Message replication was operationalized by the organization affiliated with the video clip, the name of the spokesperson, and the crisis scenario to which spokespersons responded. The organization message replication contained four fictitious organizations considered to be internal source affiliations or four fictitious organizations considered to be external source affiliations. Internal organizations included "Chapman Enterprises," "Montgomery Solutions," "Buchanan Incorporated," and "Marion Corporation." External organizations included "State Commission for Environmental Quality," "County Environmental Restoration Dept.," "Dept. of Regional Environmental Protection," and "Municipal Environmental Board."

Each video clip contained one spokesperson responding on behalf of an organization involved in a water crisis scenario. The name of the spokesperson included four message replications: "Michael Brown," "Robert Davis," "David Johnson," and "James Phelps." The name and organization affiliation of the spokesperson were counterbalanced between video clip scenarios to mitigate interaction effects associated with source name/affiliation and the scenario portrayed in the video clip.

Dependent Variables. Participants' **perception of spokesperson credibility** was assessed via self-report measures by asking respondents to indicate whether each spokesperson they viewed was "dishonest" (reverse coded), "qualified," "intelligent," "sincere," "trustworthy," "knowledgeable," and "credible." Perception of spokesperson credibility was operationalized as participants' score averaged from Likert items ranging from 0 (not at all) to 10 (extremely) per source type.

Participants' **perception of spokesperson trustworthiness** was continuously measured second-by-second for the duration of each video clip. Participants were asked: "Throughout the video, please rate the trustworthiness of the speaker from 0 to 10, where 0 = 'Strongly Distrust' and 10 = 'Strongly Trust.'

Demographics were assessed, including measures of participants' gender, age, and academic major.

Procedure

Participants signed up for a convenient time to participate in a study session by using the college's online recruitment system. Participants arrived at the continuous response theater (i.e., audience testing lab) in the college's research facility in order to participate in a study session. Participants were randomly assigned to an experimental condition, and they participated with a group of no more than six participants.

After participants arrived at the lab, they were given an information sheet and verbal instructions regarding the nature of the study. Participants were randomly assigned a dial with a unique identification number and were asked to indicate their dial's identification number and their session time on their paper-and-pencil questionnaire so that dial data and paper-and-pencil responses could be matched for data analysis procedures. Participants were given instructions regarding the use of handheld dials to evaluate the media content they would view. The handheld dial controllers are coordinated by Perception Analyzer hardware and software. Perception Analyzer handheld wireless units permit respondents to register responses to stimulus material in real-time as it is consumed. The units possess a digital readout that displays the rating the dial is registering with the receiver, which polls all wireless units in operation at one-second intervals.

To practice using the dials, participants answered demographic questions of gender, age, and other demographics. Afterward, participants were instructed to begin with their dials pointed to "5" or neutral. Then participants viewed each of four video clips on a 108-inch projector screen and continuously evaluated the trustworthiness of the speaker on screen. After viewing each of the four video clips, participants completed self-report dependent measures specific to each clip they viewed. Between clips, participants were reminded to begin with their dials pointed to "5" or neutral and to continuously evaluate the trustworthiness of the speaker throughout the duration of the video. Upon completing the final self-report measures, participants were thanked for their time and dismissed.

Results

Post Exposure Data Reduction

Items from the aggregate of participants' self-report measures were subjected to exploratory factor analysis. For the spokesperson credibility scale, one factor emerged with an eigenvalue over 1, accounting for 70.05% of variance. All items (qualified, 0.87; intelligent, 0.89; sincere, 0.80; trustworthy, 0.91; knowledgeable, 0.91; and credible, 0.91) loaded highly on the factor with the exception of dishonest (0.50). Consequently, the dishonest item was removed from the scale and the remaining items were re-analyzed. Again, one factor emerged with an eigenvalue over 1, accounting for 78.30% of variance. All items (qualified, 0.88; intelligent, 0.90; sincere, 0.80; trustworthy, 0.91; knowledgeable, 0.91; and credible, 0.91) loaded highly on the factor. The scale yielded high inter-item consistency ($\propto$ = 0.94); the six items were combined and each participant's mean score was used as their perception of spokesperson credibility in data analysis procedures. Because all items loaded onto a single factor for each scale, promax rotation of the components for each scale was unnecessary.

Analyses

H1 posited that information sources labeled as public relations practitioners would be perceived as less credible than engineers or presidents in times of organizational crisis when gauged after consumption of the messages. Data analysis revealed support for H1. A within-subject design repeated measures ANOVA ($F(3, 516) = 9.12$, $p < 0.05$, $\eta_p^2 = 0.050$) suggested that PR practitioners were labeled less credible ($M = 6.83$, $SD = 2.15$) than were presidents ($M = 7.23$, $SD = 1.87$) and engineers ($M = 7.31$, $SD = 1.84$), who were not significantly different from each other by LSD test. It should be noted that the control information sources, who were identified only by name and not by job title, were significantly less credible ($M = 6.40$, $SD = 1.92$) than any of the three other sources suggesting that no job descriptor is particularly detrimental to perceptions of credibility. A follow-up analysis was conducted to examine participants' perceptions of trustworthiness of each source as a single-item dependent variable (to mirror the single-item continuous response measurement). Analysis revealed a significant effect ($F(3, 519) = 3.18$, $p = 0.02$, $\eta_p^2 = 0.02$) such that engineers ($M = 6.96$, $SD = 2.04$) and presidents ($M = 7.07$, $SD = 2.16$) were perceived as significantly more trustworthy than the control ($M = 6.44$, $SD = 2.26$). However, PR practitioners ($M = 6.71$, $SD = 2.50$) were not perceived as any more or less trustworthy than other source types.

H2 posited that perceptions of sources would vary in real-time as source job descriptions were revealed. As traditional experimental research in source credibility has relied on post-exposure measures that followed consumption of entire stimulus material packages, research has yet to demonstrate the speed at which judgments are made and how those judgments may evolve over the consumption period. H2 was partially supported. Continuous response dial data in the current study suggest that perceptions of source trustworthiness are first made almost instantaneously when source identifiers are revealed to audiences. In fact, when comparing baseline evaluations taken just seconds before sources were identified, to evaluations taken four seconds after source identification occurred, all sources experienced a numerical increase in trustworthiness. A paired samples t-test for each source condition demonstrated that presidents registered the largest bump from baseline ($M_{Pre} = 4.88$; $M_{Post} = 5.08$; $SD_{Pre} = 0.84$; $SD_{Post} = 1.25$) with a raw increase of 0.20 in trustworthiness ($t(172) = 3.53$, $p < 0.001$) while PR practitioners also saw a significant bump of 0.14 ($M_{Pre} = 4.90$; $M_{Post} = 5.04$; $SD_{Pre} = 1.12$; $SD_{Post} = 1.42$) ($t(172) = 2.33$, $p = 0.02$). Engineers saw an increase that approached significance 0.11 ($M_{Pre} = 4.83$; $M_{Post} = 4.94$; $SD_{Pre} = 0.82$; $SD_{Post} = 1.25$) ($t(172) = 1.66$, $p = 0.098$), and the control group, who was identified only by name but without job title, saw the smallest and non-statistically significant increase ($M_{Pre} = 4.89$; $M_{Post} = 4.97$; $SD_{Pre} = 0.89$; $SD_{Post} = 1.35$) ($t(172) = 1.17$, $p = 0.24$).

In an investigation of trustworthiness perceptions for more sustained and prolonged exposure, similar analyses were conducted where pre-exposure baselines were compared to an average of the first one-third of the clip following source identification as well as the second and final third. As can be seen in Table 1, for all source conditions, perceptions of trustworthiness varied consistently and significantly throughout stimulus exposure, with all sources trending in a positive direction throughout the clip. While engineers ($F(3, 516) = 92.24$, $p < 0.001$, $\eta_p^2 = 0.349$), presidents ($F(3, 516) = 94.32$, $p < 0.001$, $\eta_p^2 = 0.354$), and PR practitioners ($F(3, 516) = 72.25$, $p < 0.001$, $\eta_p^2 = 0.296$) saw the largest increases, the control sources all experienced a trustworthiness increase over time ($F(3, 516) = 52.25$, $p < 0.001$, $\eta_p^2 = 0.233$) when comparing these time periods. Figure 1 represents graphically how trustworthiness trended over time within each source category and displays how the control group consistently rated lower than all other sources who were identified by job title.

Table 1. Perception of source trustworthiness over time.

Source	Time of Measurement			
	Pre-Exposure	**First Third***	**Middle Third***	**Final Third***
PR	4.90^{A}	5.73^{B}	6.23^{C}	6.48^{D}
President	4.88^{A}	5.84^{B}	6.37^{C}	6.54^{D}
Engineer	4.83^{A}	5.77^{B}	6.41^{C}	6.58^{D}
Control	4.89^{A}	5.43^{B}	6.00^{C}	6.21^{D}

Note: All means not sharing a superscript are different by LSD post-hoc test horizontally.

*Thirds are averaged dial response in relationship to entirety of stimulus material following exposure to source information revelation per scenario.

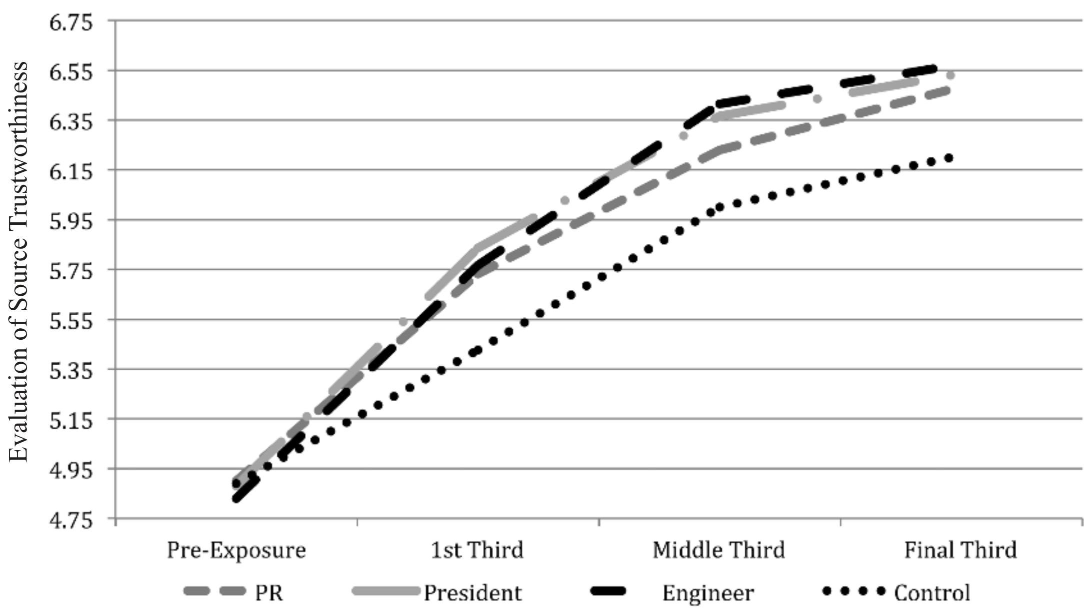

Figure 1. Evaluation of source trustworthiness over duration of clip exposure.
Note: Pre-exposure value was determined by averaging an individual's ratings across the three seconds prior to the source identification key appearing on screen. The thirds ratings were determined by averaging all seconds across the first, second, and final third of all measures taken second-by-second following the timestamp second the key first appeared on screen.

Discussion

Researchers are not new to investigating how the public perceives spokespersons in regard to source credibility effectiveness. However, the extant literature lacks in methodological variety, which could extend the findings into new arenas and broaden the field's ability to generalize across a wider array of contexts. Pencil-and-paper self-report measures that were taken in retrospect following consumption of stimulus material were coupled with continuous response data collected second-by-second while participants watched a news conference unfold. The use of audiovisual content during continuous data collection also provided an opportunity to move source credibility research into the audiovisual context, currently the more typical media consumption environment (Grabe and Bucy 2009).

Sources identified as public relations practitioners were perceived as less credible in retrospective measures, as compared to other identified sources. This finding, as well as past research in the area, suggests that organizations in crisis may want to look elsewhere than the PR department for a spokesperson. However, as shown through these results, the search for a news conference presenter may not require going outside of the company. Specifically, PR sources in this study lagged significantly behind a news conference information source identified as an engineer (engineer in the case of a water crisis) as well as behind a source identified as an agency president, and data revealed the president was evaluated as credible as an engineer during a water crisis.

The fact that the unlabeled control source was the least credible of all those tested lends support to the argument that audiences are looking for source clues to help them evaluate people who provide public information. Without any manifest identifiers for the control source other than his name, it would seem respondents were reluctant to give him any benefit of the doubt and rated him beneath the PR practitioner in terms of credibility. That said, this finding suggests that even a typically poorly perceived identifier is superior to not having one at all.

In terms of the continuous response data, the current study offers a first look at how quickly source revelation may impact opinions in an organizational crisis setting. Within four seconds of a source being labeled, perceptions of that source along the dimension of trustworthiness were impacted. Where in the past, academicians have been limited to the knowledge that source factors influence perceptions at some unknown point after they are revealed, this project sheds light on just how quickly the impact may occur. Additionally, data show perceptions continue to evolve throughout the message consumption time period. Ultimately, one question raised here is what other source factors may be instantly impactful. Similarly, another question specific to effectiveness of public relations practitioners centers on the fact that while trustworthiness of sources improved to similar levels for all job-identified sources, public relations practitioners were evaluated poorly comparatively on the construct of credibility when respondents were asked to consider the news conference in retrospect after it ended. This study offers no explanation of this seeming discrepancy. While data here may imply that there is some disjoint between credibility and trustworthiness, it is also plausible that the cognitive processing required in real-time evaluation differs on some fundamental level from the processing required in a more reflective, post-exposure assessment. Researchers should investigate the nature of these differences. The reported data may suggest that organizational spokespersons should not assume that being perceived as credible equates to being perceived as trustworthy. If so, spokespersons may need to engage in different communication strategies to be perceived as both credible and trustworthy.

Limitations and Recommendations for Future Research

Limitations are inherent in experimental research, and the current study is no exception. One limitation here is the use of trustworthiness as the sole indicator of spokesperson evaluations. While trustworthiness is a well-known dimension underlying the credibility construct (Callison 2001), results from trustworthiness and credibility dependent measures seemed to tell different stories. Although social scientists are trained to utilize a battery of indicators to assess latent constructs (Crano and Brewer 2002), an inherent limitation of the continuous response measurement system used in this study is the fact that participants may only evaluate content by responding to one item and one scaled response. We reported the results of a single-item self-report measure of trustworthiness to compare to the battery of credibility items. Additionally, a follow-up analysis was conducted with the single trustworthiness self-report item, which seemed to trend similarly to the battery of all credibility items. Future research should incorporate multiple sessions and test the array of credibility components using the single-time dial format to more specifically understand how self-report and continuous response evaluations of source credibility unfold over time and in retrospect.

The data seem to suggest that perhaps evaluative processing during and after media consumption influences post-consumption appraisals. That is, perhaps credibility evaluations crystallize over time (as reflected by continuous response measurement), such that when participants are asked to evaluate the credibility of spokespersons after stimulus exposure has ended, rumination about the source's credibility may be reflected in the aggregate post-consumption snapshot provided by self-report measures. Future research should endeavor to better understand how credibility evaluations unfold over time and how to reliably and validly measure and compare continuous and retrospective measures.

The study is limited in its ability to generalize to spokesperson characteristics beyond job title. Future research should examine how additional spokesperson characteristics (e.g., gender, race, etc.) may influence continuous response evaluations of spokesperson credibility. Additionally, public relations practitioners are often employed in roles that bear different titles, such as chief communication officer, public affairs specialist, media relations coordinator, communications manager, and the like. Future research may consider how variations in public relations job titles might influence source credibility evaluations.

Conclusion

The current study offers insight for both academics and industry. Academic researchers investigating source credibility and its impact on perceptions of source effectiveness can glean from this project the idea that factors such as job title not only influence opinions but that these opinions form almost instantly and continue to evolve throughout message consumption. In contrast to past studies that have measured source credibility at a static point in time following all exposure to stimulus material, here data are collected dynamically in real-time as well as in a one-shot post-exposure setting. Comparisons of the two types of data collection suggest that cognitive processing of source factors may vary depending on the task assigned and ability to contemplate a full exposure with speed of response requirements removed. The findings here also suggest more work is needed to effectively relate data gathered through one technique to another.

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Scientist–Nonscientist Teams Explore Methane Sources in Streams Near Oil/Gas Development

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Abstract: New techniques are needed to distinguish between leakage of methane (CH_4) into surface waters from gas wells and natural sources. Here, scientists worked with >50 citizen scientists in a hydrocarbon-rich basin (Pennsylvania, U.S.A.) to measure methane concentrations ([CH_4]) in streams. These measurements were combined with published observations to form a reconnaissance dataset. The dataset was then used to categorize sites as background or as impacted by other sources of gas. For 479 samples at 131 sites, 470 were supersaturated with respect to the atmosphere (≥0.08 µg/L). Sites with the lowest concentrations generally were located in low-productivity, sandstone-underlain upland streams, while other streams contained CH_4 from sources in addition to atmospheric. The median of 63 sites not located near wetland habitats and not affected by known thermogenic influxes yielded an estimate of background [CH_4] in the streams, 0.5 µg/L. The highest individual measurements (~70 µg/L) in the stream dataset were observed in one site near a wetland and one site near a putatively leaking gas well. Inspection of the dataset revealed that values of [CH_4] above a threshold for non-wetland sites, 4 µg/L, signals gas is likely deriving from sources such as leaking gas wells, shallow organic-rich shales, coal, or landfills. Using historical and local volunteer knowledge, we discovered 12 non-wetland sites above the threshold that are potentially contaminated by such sources. Although sources of CH_4 cannot be proven from such surveys of [CH_4], stream sampling with nonscientists nonetheless allows discovery of sites of potential contamination that can be further investigated.

Keywords: *water quality, shale gas, hydraulic fracturing, natural gas, citizen science*

Atmospheric methane (CH_4) concentrations are increasing at unprecedented rates to levels that have not been observed for the past 800,000 years (IPCC 2013). As CH_4 is currently the third most important greenhouse gas in the atmosphere, it is imperative to assess the various sources and sinks to predict future climate consequences. While we have learned a great deal about CH_4 sources over the years (Nisbet et al. 2016), estimating fugitive gas emissions from oil and gas extraction sites and pipelines is challenging. In addition, some leakage from oil and gas wells occurs below-ground where CH_4 can accumulate in aquifers and streams, be degraded by microbiota, or degas into the atmosphere (Vidic et al. 2013; U.S. EPA 2016). Such contamination of water resources by shale gas development – including lateral drilling and high-volume hydraulic fracturing (HVHF) – has spawned considerable public controversy over the last 15 years (Vidic et al. 2013; Brantley et al. 2014; Jackson et al. 2014). This paper explores a new method to survey for subsurface gas leakage.

CH_4 migration and accumulation in surface waters from active or abandoned wells is of concern because it occasionally leads to hazards related to combustion (Harrison 1983; Vidic et al. 2013). In addition, in some basins, CH_4 is the most commonly reported contaminant in water resources related to oil and gas development (Brantley et al. 2014). Monitoring for CH_4 leakage into water is difficult because there are many sources of both biogenic and thermogenic gas (produced and/or consumed at low temperature by bacteria, or at high temperature by thermal degradation of higher chain hydrocarbons in rocks, respectively). Gas from natural sources can mix with leaked fugitive gas (from oil and gas activity), making it difficult to identify leakage (Molofsky et al. 2011; Jackson et al. 2013; Molofsky et al. 2013; Molofsky et al. 2016; Grieve et al. 2018; Wen et al. 2018). One useful technique to distinguish biogenic and thermogenic gas is the measurement of the $^{13}C/^{12}C$ ratio in the CH_4, which is usually reported as $\delta^{13}C_{CH4}$ (Schoell 1980; Whiticar 1999). However, isotopes are generally an ambiguous fingerprint and multiple lines of evidence are always needed to distinguish the source of gas (Baldassare et al. 2014).

Typically, discovering leakage of CH_4 into aquifers relies on the time- and resource-intensive sampling of groundwater in individual water wells (Siegel et al. 2015). Many inadequacies have been noted with respect to such sampling (Jackson and Heagle 2016; Smith et al. 2016). Furthermore, where samples are taken before and after shale-gas development, the locations are generally not revealed because homeowners keep data confidential (Boyer et al. 2012; Brantley et al. 2018). Therefore, although the public needs better estimates of the location and quantity of CH_4 emanating from gas wells into water resources, accurate estimates are notoriously difficult to provide.

Recently, two new approaches were explored for identifying leaking oil and gas wells. The first entails the use of data mining tools to map CH_4 concentrations in groundwater using large datasets to identify concentration anomalies (Li et al. 2016; Li et al. 2017; Zheng et al. 2017a; Zheng et al. 2017b; Wen et al. 2018). The second technique targets publicly accessible streams in watersheds with upwelling groundwater (Heilweil et al. 2015). An added benefit of focusing on streams is that CH_4 emissions from fluvial systems to the atmosphere are globally significant but poorly constrained (estimated between 0.01 and 160 Tg/ CH_4 per year) (Stanley et al. 2016). To explore both approaches and learn more about natural and anthropogenic sources of CH_4, we developed a protocol for sampling, measuring, and categorizing CH_4 concentrations in streams ($[CH_4]$). Using the technique, we then discovered a few sites of potential leakage from oil or gas wells.

Stream sampling has benefits and drawbacks compared to groundwater sampling in households. First, by sampling public streams, no homeowner permissions are needed, and waters can be sampled repeatedly and easily. Second, in upland areas such as those where shale-gas drilling is prevalent in Pennsylvania, streams generally gain discharge from groundwater along their flowpath and therefore can be used to canvas broadly for areas of natural gas leakage (Heilweil et al. 2013; Heilweil et al. 2014; Heilweil et al. 2015). Such gaining streams can collect CH_4 in groundwater from gas-well leakage and from natural upward movement of either biogenic or thermogenic CH_4 (Heilweil et al. 2015).

However, new problems emerge when using streams to survey for gas well leakage: i) resources limit how many of the tens of thousands of kilometers of streams overlying the shale-gas play can be measured; ii) sampling must occur close to the leak before dilution and degassing occurs downstream; iii) leak detection in streams will vary in efficacy depending upon stream discharge level meaning that timing of sampling is important with respect to storms; and iv) influx of contamination can be limited to small stream reaches that are difficult to find without local knowledge of the landscape. To address these problems, we worked with local nonscientists who were taught to take samples and identify sites that might be impacted by leakage.

The intent of this paper is to describe what was learned about $[CH_4]$ in streams from three datasets -- a reconnaissance dataset, a contamination-targeted dataset, and a wetland-lake dataset -- and what we learned about the stream-surveying approach itself. We first describe a reconnaissance dataset of $[CH_4]$ in streams and we separate those data into categories based on the inferred sources of CH_4 (e.g., wetlands, natural thermogenic gas, and fugitive gas from putatively leaking gas wells). From inspection of the reconnaissance dataset, we propose a threshold value for non-wetland streams: when [CH_4] is above the threshold, some additional source of gas is likely to be contaminating the stream, for example, from a leaking well, a coal seam, a shallow shale, or a landfill. The threshold does not prove leakage but rather can be used to focus future research to confirm contamination. Finally, we test the reasonableness of the threshold by comparing it to "contamination-targeted" data near potentially leaking sources in streams. These sites were chosen based on i) data mining techniques developed to identify anomalies and outliers in large datasets of groundwater [CH_4] (Li et al. 2016; Li et al. 2017; Zheng et al. 2017a; Zheng et al. 2017b); ii) historical activity with respect to oil and gas development; and iii) information from nonscientist volunteers.

Methods

Working with Volunteers

Sites sampled for the reconnaissance dataset were chosen from knowledge of shale-gas well locations, accessibility, and the desires of volunteers or watershed group coordinators. Some data were included from volunteer sampling completed in each of two modes: "snapshot" sampling days where volunteers (see acknowledgements) fanned out over a watershed to collect a sampling of water quality on one day, or repetitive sampling of water quality at specific locations by volunteers. For the "snapshot" sampling, we worked with a coldwater fisheries conservation group (Trout Unlimited (TU)) that organized varying numbers of local volunteers (~20 to 30) to sample at 30–50 sites within one watershed during one day. Volunteers collected water samples for CH_4 analyses and measured turbidity using a 120cm Secchi tube, temperature and conductivity using a Lamotte Tracer Pocket Tester, and pH using pH strips at sites chosen by the TU coordinator (data hosted at www.citsci.org). Sites were chosen on the basis of safety, access, locations of current and projected shale gas development, the location of wild and native trout populations, and location within state-owned lands. In the second collaborative mode, Penn State teams worked with groups that were already monitoring a watershed, albeit not for CH_4. For these sites, we trained volunteers to sample water for CH_4 analyses at their own sites, and sites were sampled at multiple times.

Sampling for Reconnaissance Dataset

Two sites near State College, PA (U.S.A.) that are not in the shale-gas play and 129 sites throughout the play were sampled by our team or by watershed volunteers (see acknowledgements). A subset of these data have already been published (Grieve et al. 2018). When possible, samples were collected mid-stream in half liter polycarbonate bottles.

Bottles were transported to the field site filled with 18.2 MΩ·cm purified water to pre-condition the bottle. Initially, the bottle water was discarded downstream of the collection site. The bottles were then submerged with the volunteer and bottle facing upstream, and filled in the middle of the stream when possible. In all cases, bottles were rinsed with stream water three times and then the bottle was filled with stream water and capped with rubber septa underwater without air bubbles. Samples were returned to the laboratory for analysis within five days.

Contamination-Targeted and Wetland-Lake Datasets

For this dataset, stream samples were collected in the same way as described above, but from sites more likely to be contaminated by CH_4 through oil and gas development activity. This "targeted" dataset was sampled in i) the northwestern part of the state where many leaking orphaned and abandoned oil/gas wells have been identified (Kang et al. 2014), ii) New York where natural gas was first used in the U.S. commercially and where gas seepage was reported as early as the 1800s, and iii) sites in Pennsylvania (PA) where geospatial techniques have indicated anomalies in groundwater CH_4 (Li et al. 2016; Li et al. 2017; Zheng et al. 2017a; Zheng et al. 2017b). To identify these latter anomalies, the researchers first attributed much of the variation in CH_4 concentrations in groundwater to natural features such as geological faults or anticlines. The anomalies were then identified as locations away from those geological features where CH_4 was slightly higher in concentration.

Finally, 10 samples also were collected in a wetlands lake at Black Moshannon State Park (Pennsylvania). This site was chosen to determine an estimate of maximum concentrations of biogenic CH_4 in a Pennsylvania wetland. To seek the highest concentrations possible, 10 samples were collected in Black Moshannon Lake at varying locations on July 18, 2015. This date was chosen because this dammed wetland lake flows into Black Moshannon Creek and samples from that creek at the outflux (labelled as BlackMoshannonState - Park Site 1 in the reconnaissance dataset) were observed to have very high [CH_4] in summertime.

Samples taken from the lake were sampled as described for the reconnaissance dataset except using lake water rather than stream water for rinsing. Locations were either on- or off-shore and depths of sampling were about 20 cm.

Laboratory Analysis

Samples were analyzed at the Laboratory for Isotopes and Metals in the Environment, Pennsylvania State University. Helium (~60cc) was introduced into each sample bottle while removing the same volume of water to create a headspace. Bottles were then shaken to equilibrate the dissolved CH_4 into the headspace overnight. Once equilibrated, the headspace CH_4 concentration was measured using standard gas chromatographic (GC) techniques to determine the partial pressure of CH_4 in the headspace (Kampbell and Vandegrift 1998). [CH_4] in the water then was calculated using the Henry's law partition coefficient for the measured CH_4 partial pressure with respect to liquid water.

The technique reproducibly measures [CH_4] in stream waters down to 0.06 µg CH_4/L, lower than most commercial laboratories where detection limits have been reported as 1, 5, or 26 µg CH_4/L (Li et al. 2016). The low detection stems from the vacuum inlet system custom-designed for the GC for samples that have low concentrations and limited volume (Sowers et al. 1997; Sowers and Jubenville 2000). Our detection limit is lower than the equilibrium CH_4 concentration in water (0.08 µg CH_4/L) in contact with present day CH_4 concentrations in air, 1.87 ± 0.01 ppm.

We analyzed storage effects in various bottles (Isotech, VWR, glass), presence or absence of different biocides to inhibit bacterial reactions (Na azide, benzylkonium chloride, potassium hydroxide (KOH)), refrigeration, and the time between sampling and CH_4 analyses. To determine which biocide (if any) was needed in our bottles, we sampled four streams in triplicate and added KOH and benzalkonium chloride to two bottles, keeping the third bottle without preservative. In addition, we added preservative to six blank bottles containing 18.2 MΩ·cm purified water with three additional bottles containing only the purified water. All samples were measured together five days after collection. The mean value for the three process blanks + five identical bottles with either KOH or benzylkonium chloride and distilled water (0.093 ± 0.014 µg CH_4/L) was slightly above the atmosphere-equilibrated value (0.08 µg CH_4/L). Applying a T test to all these data showed that with 95% confidence, data from the "no treatment" samples were indistinguishable from those with biocide additives.

Reproducibility

We estimated overall uncertainty using samples with low CH_4 concentrations collected in triplicate every two to three weeks from two sites (Slab Cabin Run, Spring Creek) near State College, PA (Figure 1, Table S1). We calculated standard deviations around the mean for each of these 63 individual stream sampling events as a measure of the total error associated with the sampling and analyses. This is an overestimate because it incorporates short timescale temporal variability in stream [CH_4] over the period of sampling, typically less than 10 minutes. The average standard deviation for these 64 sample events was 7.5%, and this is considered representative of reproducibility that includes both sampling and analytical uncertainty, as well as in-stream variation for streams with low [CH_4] over short time periods.

To assess such reproducibility for sites with higher [CH_4], we collected consecutive samples within approximately 10 minutes of one another (Table S2) from i) the stream that originates at the wetland lake in Black Moshannon State Park in Centre County, Pennsylvania, thus containing biogenic gas; and ii) a seep close to Sugar Run that is near several putatively leaking shale gas well(s) in Lycoming County, Pennsylvania (Heilweil et al. 2015). For eight consecutive samples from the stream near the wetland ([CH_4] < 10 µg CH_4/L), the relative standard deviation was 11.6%. For seven consecutive samples from the Sugar Run site ([CH_4] ≈ 200 µg CH_4/L), the relative standard deviation equaled 10.8%. These data show that the overall reproducibility of our data, including natural variability over a short time period, sampling, and analysis is about 12%.

Isotopic Measurements

We measured $\delta^{13}C_{CH4}$ on headspace samples from eight sites within the "contamination-targeted" dataset to identify the CH_4 source using a slight modification of a published technique used for samples from ice cores (Sowers et al. 2005). For the modification, we exchanged the stainless steel sample tube from the ice core extraction device with a simple septa allowing injection of headspace gas from our sample bottles directly into the helium carrier stream. We sampled ~5 nmoles of CH_4 from a sample bottle headspace with a gas tight syringe and injected the sample into the helium carrier stream using a pre-concentration device (PreCon) connected to a Thermo Delta V isotope ratio mass spectrometer. The CH_4 was then cryogenically and chromatographically separated from the other headspace constituents before being converted to carbon dioxide for Continuous Flow Isotope Ratio Mass Spectrometry (CF-IRMS). $\delta^{13}C_{CH4}$ results are reported on the VPDB scale. Air standards are run at the start of each day to correct for slight (<0.2‰) day-to-day instrument drift. The measured air standard value is always within 0.2‰ of the assigned value. Analytical uncertainty associated with $\delta^{13}C_{CH4}$ analyses based on replicate analyses of 1% CH_4 in a nitrogen (N_2) flask standard is better than 0.3‰.

Results

Reconnaissance Dataset

Given the difficulties of organizing volunteers and finding safe, public, and accessible sites that also met scientific or watershed group goals, our sampling sites were neither randomly selected nor distributed comprehensively across the Marcellus shale play. Table S1 summarizes all values of [CH_4] for samples collected by the authors and volunteers, as well as from a recent publication (Grieve et al. 2018). These latter values were collected by part of our team in i) two streams (Tunkhannock, Nine Partners) known to receive influxes of thermogenic as well as biogenic CH_4 from natural sources, and ii) two streams (Sugar Run, Meshoppen) that have relatively high [CH_4] and that drain areas with hydraulically fractured shale gas wells that are known to have had leakage problems. Sugar Run is located in Lycoming County near several shale-gas wells cited for leaking CH_4 by the state regulator (Heilweil et al. 2015). The other stream, Meshoppen Creek, is characterized by the presence of both problematic shale-gas wells and wetland habitats (Hammond 2016).

Data from Tunkhannock, Nine Partners, Sugar Run, and Meshoppen are incorporated for comparison in Table S1 because all four may be receiving gas from deep thermogenic sources that flow upward into groundwaters. For example, seep and piezometer waters sampled at Sugar Run revealed 2300 and 4600 µg CH_4/L, respectively (Heilweil et al. 2014) and a seep at Nine Partners Creek revealed 210 µg/L (Grieve et al. 2018). These three samples of upwelling groundwater are plotted on Figure 1 as a comparison with the stream water data. The influx of upwelling CH_4-containing groundwater into streams demonstrates why the stream-based approach may help to find leaking gas wells. Some of the same sites reported by Grieve et al. (2018) were originally sampled and analyzed by Heilweil et al. (2014).

All the data in Table S1 were combined with the streamwater data from Heilweil et al. (2014) for the same sites at Sugar Run to constitute the "reconnaissance dataset". This dataset includes 479 values of [CH_4] measured at 131 sites in Pennsylvania (Figure 1). For each site, individual data were reported along with site-aggregated means (i.e., for time series data). The distribution of values for the 131 site-aggregated means in the reconnaissance dataset is highly skewed (Figure 2); therefore, the best parameter to describe the data is the median, 1 µg/L (Table 1). The concentrations of individual samples range from <0.06 to 68.5 µg/L. In comparison, [CH_4] in some groundwaters in one county of Pennsylvania approach 100,000 µg/L (Li et al. 2016).

Nine sites were undersaturated with respect to the theoretical concentration (0.08 µg/L) in equilibrium with today's atmospheric CH_4: eight samples from Beech Creek watershed and

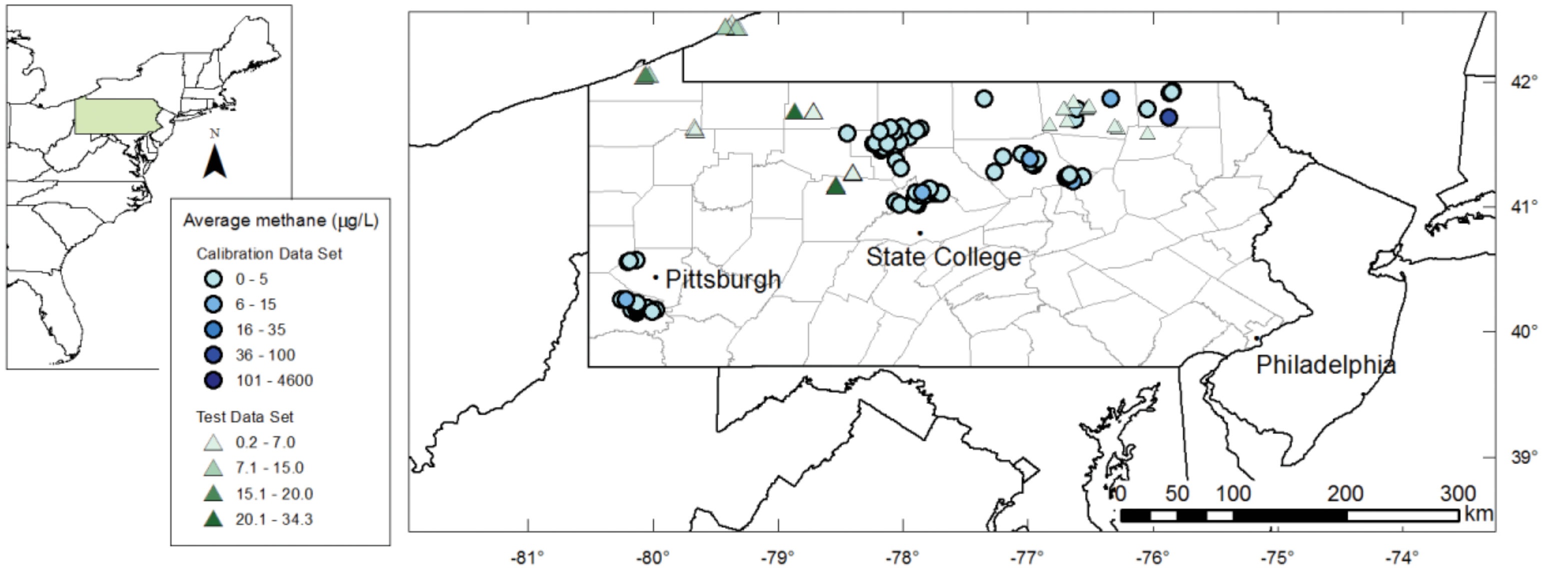

Figure 1. Locations and values of [CH_4] measured at sites in the reconnaissance (circles) and contamination-targetted (triangles) datasets. Blue shading indicates the range of [CH_4] as shown in the legend. Sites were sampled by the authors and watershed groups (Trout Unlimited, Chartiers Creek Watershed Association, Centre County Pennsylvania Senior Environmental Corps, State College Area High School TeenShale Network, and Fern Hollow Nature Center QV Creekers). The reconnaissance dataset also included published stream data at sites in Sugar Run near Hughesville, Meshoppen Creek, Tunkhannock Creek, and Nine Partners Creek (Heilweil et al. 2015; Grieve et al. 2018). For comparison, three groundwater concentrations are also shown from seeps and piezometers near Sugar Run: these are the three highest concentrations and are located near one or more gas wells cited by the state regulator for possible leakage (Heilweil et al. 2015). Samples in the reconnaissance dataset outside the Appalachian Basin at Slab Cabin and Spring Creek near State College, PA are listed in Table S1 but not plotted.

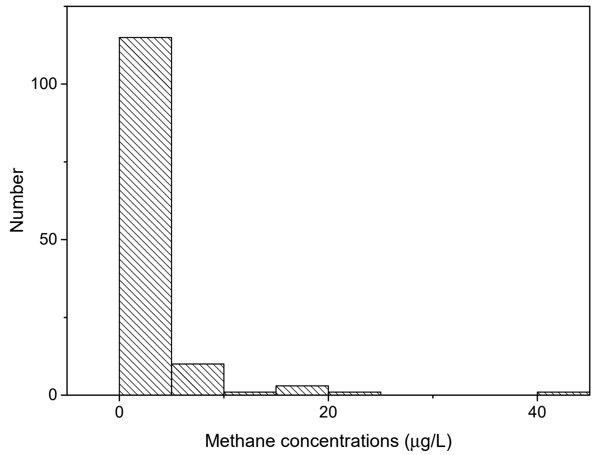

Figure 2. Histogram of the reconnaissance dataset of site-aggregated means for the 131 stream sites (see Figure 1).

one small tributary to Meshoppen Creek. Six of the samples from Beech Creek watershed were below detection (<0.06 µg/L), i.e., sites in or near Council Run, Hayes Run, Sandy Run, and Big Run. These sites as well as the other two below-equilibrium sites in Beech Creek watershed (Beauty Run, North Fork Beech Creek) were sampled by a volunteer group (Pennsylvania Centre County Senior Environmental Corps). All streams with low [CH_4] were underlain largely by sandstone formations; in addition, the Beech Creek streams were identified as relatively low productivity based on measurements of macroinvertebrates (Pennsylvania Centre County Senior Environmental Corps (PA CCSEC) 2017).

Contamination-Targeted and Wetland-Lake Datasets

The contamination-targeted dataset included 42 samples around sites thought to have a high potential for contamination (Figure 1, Table S3). In these sites, [CH_4] varied from 0.2 to 33.7 µg/L (Table S3). One site at Walnut Creek was inadvertently sampled near both an orphaned well and a wetland, but all other sites were far from mapped wetlands. One sample was taken in an area of oil and gas development but also was discovered to be located downstream from an active landfill. Twelve of the targeted non-wetland samples showed [CH_4] > 4 µg/L (Table S3). The eight samples measured for $\delta^{13}C_{CH4}$, also reported in Table S3, all appear to be mixtures of biogenic and thermogenic gas.

The wetland-lake dataset summarizes 10 data values from the lake at Black Moshannon State Park. [CH_4] for the 10 positions around the lake varied from 17.8 to 45.2 µg/L (Table S4).

Discussion

Site Categories

Extended geological and isotopic analysis to determine the source of CH_4 in each stream was beyond project scope. Instead, we explored what could be learned from the reconnaissance dataset using geographic and published information. Specifically, the data were binned into four categories: i) sites with no known or suspected sources of gas other than background; ii) sites with known or suspected inputs of biogenic gas from nearby wetlands; iii) sites with known or suspected inputs from natural sources of thermogenic gas; and iv) sites with inputs of gas hypothesized to derive from a nearby leaking shale-gas well or set of wells.

The four categories are referred to herein as i) other, ii) wetland-biogenic, iii) thermogenic, and iv) putatively anthropogenic. Although such binning of sources is necessarily ambiguous, it leads to some observations explored below. Overall, 63 of 131 sites were categorized as “other”, 37 as “wetland biogenic”, 20 as “thermogenic”, and 11 as “putatively anthropogenic” (Table 1, Figure 3). These short-hand descriptors are not meant to imply that each site derives gas from only a single source. For example, “other” sites likely contain atmospheric gas and biogenic gas from the riparian zone; “wetland-biogenic” sites contain atmospheric CH_4 as well as CH_4 that originates from near-surface methanogen activity within a wetland; “thermogenic” sites contain small amounts of atmospheric and biogenic gas -- but the bulk is thermogenic gas naturally leaking upward from buried shale sources. The “putatively anthropogenic” classification was reserved only for those sites located within 2 km of a set of shale gas wells in the Sugar Run valley where gas well(s) are possibly leaking (Heilweil et al. 2015; Grieve et al. 2018). The point was to determine what can be learned about CH_4 in streams in the Appalachian Basin using such admittedly ambiguous categories. For watershed groups that can afford CH_4 analyses

Table 1. Summary of CH_4 concentrations (µg/L) in the reconnaissance dataset.

		Bin Type			
	All Data	**Other**	**Wetland-Biogenic**	**Thermogenic**	**Putatively Anthropogenic**
			131 Site-Aggregated Means		
Median	1.0	0.5	2.2	1.0	9.8
Minimum	<0.06	<0.06	0.1	0.1	5.0
Maximum	40.1	6.3	40.1	5.3	20.4
N	131	63	37	20	11
			479 Individual Measurements		
Minimum	<0.06	<0.06	0.06	0.1	5.0
Maximum	68.5	6.3	68.5	5.3	67

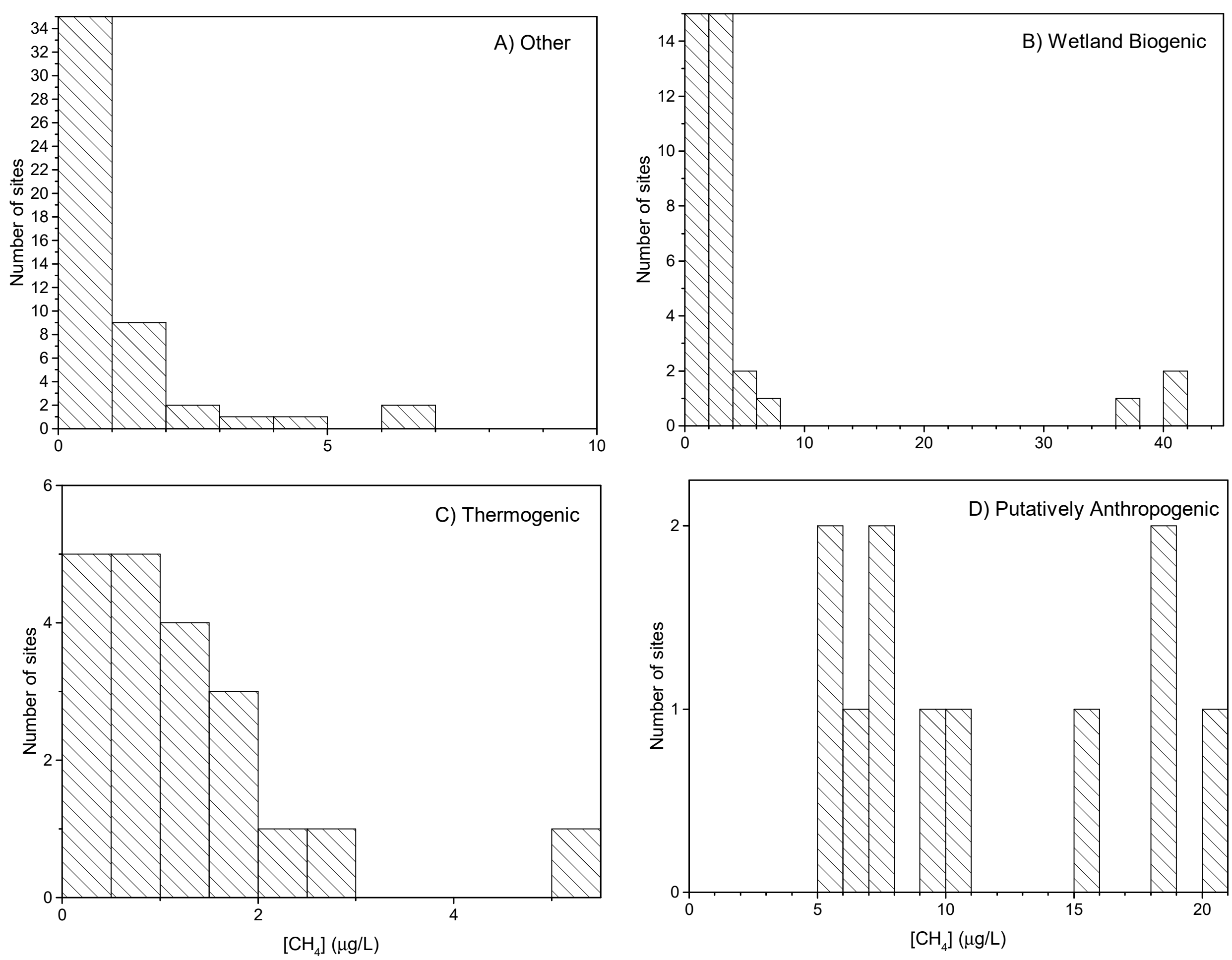

Figure 3. Histogram of site-aggregated average values of $[CH_4]$ for A) "other" sites; B) "wetland-biogenic" sites; C) "thermogenic" sites; and D) "putatively anthropogenic" sites. See text for how sites were categorized and for references. The proposed threshold that warrants more investigation for a non-wetland site is ~4 µg/L.

in streams, for example, could such data from reconnaissance sampling focus future work to highlight leakage from gas wells?

Categorizing Sites

Sites were put in the category "wetland-biogenic" if they were located within the zone of influence of a wetland as defined by the U.S. Fish and Wildlife Service for watershed planners (Castelle et al. 1994). The zone of influence was set equal to 30 meters.

Nine Partners Creek and Tunkhannock Creek in Susquehanna County were the only known sites in the reconnaissance dataset without associated leaking gas wells but with inputs from naturally derived biogenic and thermogenic CH_4. Most of the sites along those two creeks near their confluence were defined as "thermogenic" because i) they were located within 100 meters of natural lineaments (Llewellyn 2014), ii) when measured for isotopes, $\delta^{13}C_{CH4}$ values were heavier than -40 ‰, and iii) they were not located near reportedly leaking gas wells (Grieve et al. 2018) or features such as wetlands, coal seams, or landfills. Lineaments are straight segments of streams or valleys or other features that can be observed on a topographic map and that often represent the surface expressions of faults or joints in Pennsylvania (Llewellyn 2014). Along such faults, CH_4-containing groundwater often travels upward even in the absence of human activities (Llewellyn 2014; Siegel et al. 2015; Li et al. 2016; Wen et al. 2018).

Analyses for Sugar Run waters in Lycoming County from sites within 2 km of Marcellus shale-gas wells that are thought to be leaking into groundwater (Heilweil et al. 2015; Grieve et al. 2018) were all classified as "putatively anthropogenic". The presence of higher order hydrocarbons such as ethane in some of these samples and values of $\delta^{13}C_{CH4}$, $\delta^{13}C_{C2H6}$, and δD_{CH4} are consistent with a thermogenic source for at least some of the gas (Heilweil et al. 2014; Heilweil et al. 2015; Grieve et al. 2018). Sites SR1, SR1.1, SR1.15, SR1.2, SR1.4, SR1.45, SR1.5, SR1.55, SR1.6, SR1.8, and SR2 along Sugar Run were all within 2 km of a nearby gas well that was cited by the Pennsylvania Department of Environmental Protection (PA DEP) for failure to report defective, insufficient, or improperly cemented casing (http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Compliance). These sites were thus binned into the putatively anthropogenic category. Reported values of stream [CH_4] were as high as 67 µg/L in Sugar Run (Heilweil et al. 2014; Heilweil et al. 2015).

After binning analyses into wetland-biogenic, thermogenic, and putatively anthropogenic, the rest of the sites were defined as "other". "Other" sites have no known inputs from wetlands, coal seams, acid mine drainage, landfills, or leaking oil and gas wells, and therefore are defined here as the best estimate of natural background in the north-northwestern half of Pennsylvania. Gas in these streams is thought to derive from the atmosphere and from production in the riparian zone.

Observations about Categories

A priori, we might expect that every category would include sites with low [CH_4] because of dilution effects or degassing. Indeed, the minima for site-aggregated means for the wetland-biogenic and thermogenic sites were the same (0.1 µg/L, Table 1). However, all the samples where [CH_4] values were less than detection fell into the "other" category, lending credence to the binning scheme. Furthermore, the minimum of the site-aggregated means for the putatively anthropogenic category was higher: 5.0 µg/L (Table 1).

The [CH_4] in individual samples categorized as "other" varied from <0.06 to 6.3 µg/L with a median of 0.5 µg/L. Of these site-aggregated means, only one was higher than 5 µg/L. The [CH_4] in individual wetland-biogenic samples varied from 0.06 to 68.5 µg/L with a median of 2.2 µg/L. The highest site-aggregated value (from Meshoppen Creek) was 40.1 µg/L (Heilweil et al. 2014). The [CH_4] in individual thermogenic samples varied from 0.1 to 5.3 µg/L, and the median of the site-aggregated thermogenic values was 1.0 µg/L (Table S1, Table 1). The highest value, 5.3 µg/L, derived from Nine Partners Creek (Grieve et al. 2018). In comparison, the groundwater sampled in groundwater upwelling at the seep near Nine Partners was 40 times higher (220 µg/L) (Grieve et al., 2018). The [CH_4] in individual samples in sites categorized as putatively anthropogenic (Sugar Run) ranged from 5.0 to 67 µg/L with a median value of 9.8 µg/L (the highest value, 67 µg/L, was reported by Heilweil et al. (2014)). Like the comparison of groundwater to stream water for Nine Partners Creek, the groundwater [CH_4] sampled at a piezometer in the bed of Sugar Run was much larger (4600 µg/L) (Heilweil et al. 2014), indicating CH_4-rich groundwater below the stream.

Estimated Background Concentration

Our best estimate of the background [CH_4] in non-wetland streams located in the western and north central parts of Pennsylvania (Figure 1) is the median value, 0.5 µg/L, of the "other" group. None of these samples measured >7 µg/L and all except nine had concentrations equal to or higher than water in equilibrium with today's atmosphere (0.08 µg/L). Many researchers have similarly observed that most stream waters are oversaturated with respect to atmospheric CH_4 concentrations, indicating that streams are a net source of CH_4 to the atmosphere (e.g., De Angelis and Lilley 1987; De Angelis and Scranton 1993; Jones and Mulholland 1998a, 1998b; Bastviken et al. 2011; Stanley et al. 2016). Even the two streams sampled outside the Appalachian Basin (Slab Cabin Run and Spring Creek) showed [CH_4] values above equilibrium (Table S1). Similar observations at other sites have been attributed to CH_4 generation in the riparian zone of streams (Jones and Mulholland 1998a, 1998b).

Comparison to Other Regions

Stanley et al. (2016) recently summarized measurements for stream [CH_4] worldwide. The PA values reported here are much lower than the highest measured values, ~6200 µg/L. Those values were generally found in highly polluted river systems (i.e., Adyar River, India). Stanley et al. (2016) concluded that no relationship was observed in the global dataset with respect to stream size or latitude. However, higher values were often observed in streams that were wetland- or human-impacted (agricultural or urban). In Table 2, the PA values are compared to a few example streams. The PA values are higher than values in Oregon and Tennessee but much lower than reported in Amazon River wetland habitats in Brazil (Bartlett et al. 1990).

Nine of the values reported here were undersaturated with respect to atmospheric CH_4 (<0.08 µg/L). Of these nine sites, it is notable that eight were from first order streams from the same watershed -- Beech Creek. Macroinvertebrate diversity has also been reported in four of these streams (PA CCSEC 2017). These biosurveys document fair (Hayes Run), good to fair (Council Run), and poor to fair (Big Run) macroinvertebrate populations and one site is completely dead (North Fork Beech Creek). The low biodiversity is presumably related to the upland nature of these streams, the low productivity of the sandstone lithologies, and the incidence of acid mine drainage from coal mining in the watershed. Perhaps, the low influx of organic matter and low dissolved organic carbon (DOC) in these upland streams explains both the low macroinvertebrate diversity and the low [CH_4]. Low DOC was observed to correlate with low [CH_4] in the global dataset of Stanley et al. (2016).

Can Stream Surveys Highlight Potential Leakage?

If we could identify a maximum value of [CH_4] in pristine (non-impacted) streams, surveys could be used to identify contamination from leaking wells or other sources directly. However, Heilweil et al. (2014) observed that the maximum [CH_4] within 30 meters of a wetland and within 2 km of a putatively leaking gas well were almost identical: 68.5 µg/L and 67 µg/L, respectively. These sites were included in our reconnaissance dataset and categorized as "wetland-biogenic" (Meshoppen Creek at Parkvale) and "putatively anthropogenic" (Sugar Run), respectively. The maximum [CH_4] therefore cannot easily be used to identify contamination versus wetland inputs.

On the other hand, a threshold value might be useful at least as a signal to highlight the possibility of contamination, even if other lines of evidence would be needed to make the conclusion definitive. For example, inspection of Figure 3A for "other" samples shows no samples above 7 µg/L, suggesting that value could be such a screening threshold.

The maximum value of [CH_4] of the "other" category overlaps with the minimum of the putatively anthropogenic category. We therefore

Table 2. Selected stream and river [CH_4] values.

Location	Range in [CH_4] (µg/L)	Reference
Eastern Tennessee (USA)	0.67 – 1.56	Jones and Mulholland (1998a)
Oregon rivers (USA)	0.08 – 27.8	De Angelis and Lilley (1987)
Peatland stream in United Kingdom	0.8 – 39	Dinsmore et al. (2013), as reviewed by Stanley et al. (2016)
Pennsylvania streams	<0.06 – 68.5	This work (including published data)
Amazon River (Brazil)	1 – 590	Bartlett et al. (1990)
Global compilation	0 – 6190	Stanley et al. (2016)

inspected the highest "other" site for the possibility of contamination. This site, with [CH_4] = 6.3 µg/L, was taken from a tributary to Rose Valley Lake (Lycoming County) on July 29, 2015 near several shale gas wells. Just prior to sampling (on July 16, 2013), the nearest well, API#081-20584 (Lundy North 1HOG well), was cited by the PA DEP for PA DEP 78.86*, "failure to report defective, insufficient, or improperly cemented casing w/in 24 hrs or submit a plan to correct w/in 30 days." The inspector included this comment: "the 13 3/8 in x 9 5/8 in annular space of the 1 H is showing 20 % methane". Based on this inspection, the relatively high [CH_4] value in Rose Lake tributary could represent contamination, and we therefore propose a lower screening threshold, 4 µg/L. Consistent with this threshold, none of the site-aggregated values from the putatively anthropogenic category had [CH_4] < 5 µg/L. In addition, only one sample in the "other" category has a value of [CH_4] at this threshold (Horton Run, 4.2 µg/L). But that site cannot be concluded to be contaminated because it is located 30.87 m from the nearest wetland, i.e., extremely close to our operational definition of a wetland (within 30 m). Therefore, [CH_4] ≈ 4 µg/L is proposed as a good screening threshold for focusing future investigations of sites not located within 30 m of wetland habitat.

Because the threshold value is defined for non-wetland sites, it obviously cannot help identify contamination of wetlands. For example, the highest [CH_4] in a stream, 68.5 µg/L, was measured at Meshoppen Creek sampled at Parkvale, PA in a wetland area, and was thus not considered to be indicative of contamination. However, isotopic data for that site point toward influxes from both biogenic and thermogenic gas (Heilweil et al. 2014; Grieve et al. 2018). Given that Meshoppen is located very close to the township of Dimock -- an area of a relatively large number of reported gas well-related problems that have been investigated by the PA DEP and the U.S. Environmental Protection Agency (U. S. Environmental Protection Agency 2015; Hammond 2016) – the high [CH_4] could also be consistent with an influx from unknown leaking gas well(s). Hammond (2016) concluded that 17 of 18 groundwater wells in the Dimock area, including wells in the Meshoppen Creek valley, were impacted by gas well development.

As a partial test of this ambiguity with respect to Meshoppen, we estimated the maximum [CH_4] values expected for wetlands in Pennsylvania by measuring [CH_4] in 10 locations during the summer in the lake at Black Moshannon State Park, a natural low-flow wetland in an area without shale gas development. Those values (Table S4) never exceeded 45.2 µg/L. These values are similar to measurements in a peatland in the United Kingdom over five years that varied up to 38.4 µg/L ((Dinsmore et al. 2013) as summarized by Stanley et al. (2016)). Such data may indicate that the attribution of dissolved CH_4 in Meshoppen Creek (sampled at Parkvale, PA) strictly to natural wetland influx is worthy of further investigation.

Inferences from the Contamination-Targeted Dataset

To explore if 4 µg/L is an appropriate threshold, we collected a contamination-targeted dataset that we predicted would have a high incidence of above-threshold values. Samples were collected at 42 sites targeted for the possibility of leakage (Figures 1, 4, Table S3). In choosing the sites, wetlands were avoided, although one site near an orphaned well was inadvertently sampled near a wetland (see Table S3). Consistent with our prediction, 13 of 42 targeted samples (12 of 41 non-wetland sites) showed $[CH_4] > 4$ µg/L (Figures 1, 4).

The above-threshold sites include several sites near active, plugged, orphaned, or abandoned oil or gas wells. Some sites were near wells not currently included in the database of orphaned and abandoned wells maintained by the PA DEP, as indicated in Table S3. One site with $[CH_4] = 7.3$ µg/L is located 3 km from three active oil and gas wells -- but is also downstream of a landfill.

Three sites sampled in New York state were above threshold near Fredonia on Lake Erie (Canadaway Creek, Van Buren Point). At Fredonia, gas was used in the early 1800s for the first time globally to power municipal gas lamps. Gas emits naturally into the creek bed and lake from an organic-rich shale located close to the land surface, and has been described for decades in local newspapers.

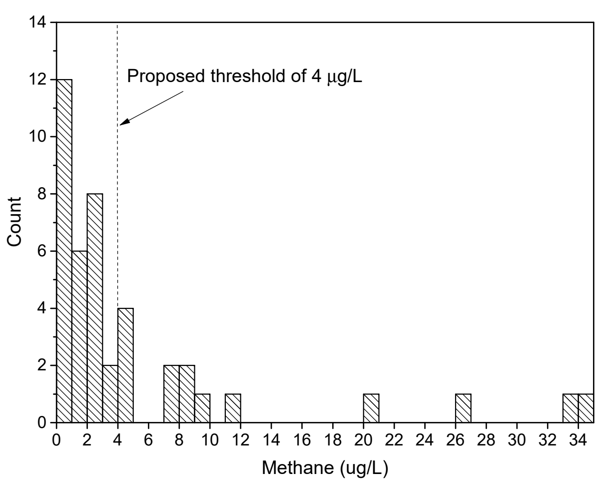

Figure 4. Histogram of the "contamination-targeted" dataset. These values of $[CH_4]$ were measured at sites targeted because of their potential for contamination. The proposed threshold that warrants more investigation for a non-wetland site is ~4 µg/L.

Some above-threshold sites ($[CH_4]$ = 8.5, 9.2, 33.7 µg/L) were located near abandoned oil or gas wells that are listed as some of the highest emitters on a survey of atmospheric emissions from old Pennsylvania oil and gas wells (Kang et al. 2014; Kang et al. 2016). One site near a plugged gas well and near coal mining was particularly high in concentration, $[CH_4] = 34.3$ µg/L; possibly, this site is contaminated by coal CH_4 instead of, or in addition to, CH_4 from the well. One site near an abandoned well near Chappel Fork with $[CH_4] = 26.3$ µg/L was discovered by a volunteer (from a watershed group known as Save our Streams PA) working in collaboration with N. Meghani (marcellusmatters.psu.edu; Penn State) (pers. comm.).

Finally, three sites (Sugar Creek, Towanda, and Tomjack) were discovered using two geospatial techniques relying on data mining of groundwater chemistry (Li et al. 2016; Zheng et al. 2017a; Zheng et al. 2017b; Wen et al. 2018). The first technique (Li et al. 2016) mapped correlations between $[CH_4]$ in groundwater and distance to shale-gas wells for a large dataset of groundwater chemistry. The map showed a spot where CH_4 concentrations in groundwater increased slightly near gas wells near Towanda Creek, and Li et al. (2016) argued this might indicate well leakage. We therefore sampled in Towanda Creek as near that hotspot as possible and discovered one location with $[CH_4] > 4$ µg/L (Table S3).

The second geospatial technique (Zheng et al. 2017a; Zheng et al. 2017b) used the same large dataset of groundwater chemistry and identified sites that appeared to be outliers on the basis of features such as latitude, longitude, distance to conventional gas wells, distance to unconventional gas wells, and distance to faults. Sugar Creek and Tomjack Creek were sampled near the identified outliers on the map and were discovered to have $[CH_4] > 4$ µg/L (Table S3). Above-threshold values of $[CH_4]$ in the streams near the groundwater anomalies are consistent with the possibility of contamination related to gas wells (more investigation is warranted).

Isotopic Measurements in Targeted Dataset

Because some sites in the targeted dataset were discovered with $[CH_4]$ > threshold, a few isotopic measurements were completed to investigate the source of gas. The scope of the project limited the number of isotopic measurements: seven were completed at above-threshold sites and one at a below-threshold site ($[CH_4]$ = 3.7 µg/L).

In PA, thermogenic gas generally has $\delta^{13}CH_4$ > -50 ‰ and biogenic gas < -60 ‰ (Revesz et al. 2010). Eight of the sites in the test dataset were measured for $\delta^{13}CH_4$. For these samples, all showed evidence of thermogenic gas ($\delta^{13}CH_4$ > -50 ‰) – even the below-threshold site. Some were in the range of biogenic + thermogenic (-60 ‰ < $\delta^{13}CH_4$ < -50 ‰), including the sample within 30 m of a wetland and near an active well. That sample had the most negative isotopic signature (-56.9 ‰), indicating a high biogenic contribution. The abandoned well discovered by a volunteer near Chappel Fork had the highest carbon (C) isotopic signature (-26.6 ‰, Table S3), consistent with a very high contribution from thermogenic gas, possibly documenting leakage from the well. Another interpretation is that bacteria-mediated oxidation of the gas has driven the $\delta^{13}CH_4$ to more positive values (Baldassare et al. 2014; Grieve et al. 2018).

One site that was sampled was located near three active oil/gas wells, but also was 400 m downstream of a landfill. At that site, $[CH_4]$ = 7.3 µg/L (Table S3). CH_4 can advect with landfill leachate in groundwater flow (van Breukelen et al. 2003). The measured stream $\delta\ ^{13}C_{CH4}$ values (-43.5 ± 0.2‰, Table S3) at that site were more characteristic of $\delta\ ^{13}C_{CH4}$ values associated with the Marcellus Formation (-43 to -32‰ (Baldassare et al. 2014)) than with landfills (-54 ± 2‰, (Chanton et al. 1999; Bogner and Matthews 2003)). However, oxidation of the gas during transit as leachate could also have shifted the $\delta\ ^{13}C_{CH4}$ to more positive values. In a nearby non-wetland tributary of Walnut Creek located near an orphaned well, the isotopic measurement (Table S3), -34.7 ‰, is consistent with a thermogenic source.

The 28 below-threshold, non-wetland sites included samples from Oil Creek near the location of the world's first commercial oil well (Titusville, PA). This area was heavily drilled in the 1800s before implementation of modern regulations but the Titusville sites all showed $[CH_4]$ below 3 µg/L. This observation could mean that no leakage is occurring or that the discharge in Oil Creek dilutes the CH_4. In fact, one of the samples near Titusville, PA in the test dataset that had $[CH_4]$ values below threshold (2.9 µg/L, Oil Creek) was also measured for C isotopic signature and the value summarized in Table S3 is consistent with thermogenic gas (-49.8 ‰). Thus, the threshold value does not flag all sites above background; hydrologic factors are also important determinants of the stream $[CH_4]$. In contrast to Oil Creek, lower-discharge streams in the Titusville area might show contamination.

Strategies for Finding Leakage

Twelve of 41 non-wetland sites in the targeted dataset were above threshold, consistent with our prediction that many of those targeted sites would be above background. The threshold value can therefore be used in a stream survey to find sites that warrant deeper investigation. However, designing a strategy to survey the tens of thousands of kilometers of streams above the Marcellus shale-gas play in Pennsylvania to find non-wetland streams with $[CH_4]$ > 4 µg/L is daunting. Grieve et al. (2018) argued that to find contamination using a stream survey requires very close spacing of samples because seepage into a stream is commonly restricted to faults or fractures.

By collaborating with citizen scientists, we showed it is possible to increase the sampling density and frequency, while also focusing on areas of interest to the public. The drawbacks of incorporating volunteers into sampling include the requirements for significant organization, safety concerns, general inflexibility in scheduling or choice of location, the lack of volunteers in some locations, and the need for standardized sample handling coordinated with rapid analysis. In addition, sampling to detect CH_4 from leaking gas wells is best completed during dry periods when streams are dominated by baseflow and not diluted, and this can be difficult with volunteers because re-scheduling during storms is difficult.

Despite those problems, our stream survey revealed information about background levels and the overall distribution of $[CH_4]$. Collaboration with volunteers lead to discovery of sites with leaking wells (Table S3). Future surveys with volunteers should grow the dataset to clarify the distribution of $[CH_4]$ in streams by emphasizing smaller streams under baseflow conditions.

Conclusions

This paper summarizes an approach that can incorporate volunteers in stream surveys designed to learn about CH_4 emissions and find leaking gas wells. Citizen scientists lowered the sampling time for the science team, increased spatial sampling density, and discovered leaking wells not reported on the map of the state regulator.

The reconnaissance dataset was tentatively categorized with respect to source using geographic and published information. The best estimate for background [CH_4] in Pennsylvania streams is 0.5 µg/L. Above a screening threshold of ~ 4 µg/L for non-wetland streams, further investigation is warranted to identify additional CH_4 entering from anthropogenic or natural thermogenic sources. Investigations could include frequent measurements of [CH_4], densely spaced stream and groundwater surveys, isotopic measurements, analysis of higher chain hydrocarbons, mapping with respect to gas wells, temporal analysis with respect to oil or gas development, and investigations of nearby gas wells.

Further work is needed to investigate the effects of seasonal variations in stream [CH_4] and the best ways to pick survey sites. One novel approach that showed some success herein is to mine groundwater chemistry data using new algorithms (Li et al. 2016; Li et al. 2017; Zheng et al. 2017a; Zheng et al. 2017b; Wen et al. 2018). Such identifications of anomalies in groundwater maps, when combined with stream chemistry, will elucidate the nature of natural and anthropogenic sources of CH_4 to freshwaters, and, in turn, to the atmosphere.

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Appendix: Summary of Measurements

Table S1. CH_4 concentrations in streams in Pennsylvania.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ μg/L	Mean $[CH_4]$ μg/L	Water Temp °C	pH
9/26/2015	B	Bailey Run (lower)	41.512	-78.046	1.0	1.0		
9/26/2015	O	Bailey Run (upper)	41.524	-78.066	0.5	0.5		
1/14/2016	O	Barberry	40.576	-80.138	0.4	0.4		
1/14/2016		Barberry	40.576	-80.138	0.5			
9/16/2015	O	Beauty Run*	41.078	-77.907	0.5	0.3	12	4.2
3/1/2016		Beauty Run_Kato Rd	41.078	-77.907	0.4		8	4.9
5/5/2016		Beauty Run_Kato Rd	41.078	-77.907	0.06		9	5.7
11/10/2015	O	Beech Creek	41.108	-77.694	0.2	0.2		
8/10/2015	O	BeechCreek_Monument	41.113	-77.705	0.5	0.4	18	4.2
4/11/2016		BeechCreek_Monument	41.113	-77.705	0.2		5	4.1
9/26/2015	O	Berge Run	41.489	-78.052	0.1	0.1		
9/26/2015	O	Big Nelson Run	41.556	-78.034	0.3	0.3		
8/10/2015	O	BigRun	41.111	-77.732	0.5	0.5	16	5.4
9/16/2015		Big Run	41.111	-77.732	1.0		14	4.6
11/9/2015		LHU_Big_Run	41.111	-77.732	0.3		6	4.3
4/11/2016		BigRun	41.111	-77.732	0.1		5	5.2
9/26/2015	O	Billy Buck Run	41.587	-78.442	0.2	0.2		
9/26/2015	O	Birch Run	41.558	-77.951	0.8	0.8		
6/24/2015	O	Black Mo meets Red Mo - Site 3	41.036	-78.060	0.3	0.4	N/A	6.9
6/24/2015		Black Mo meets Red Mo - Site 3	41.036	-78.060	0.2		N/A	N/A
7/8/2015		Black Mo meets Red Mo - Site 3	41.036	-78.060	0.1		N/A	7.1
7/8/2015		Black Mo meets Red Mo - Site 3	41.036	-78.060	0.1		N/A	7.1
7/8/2015		Black Mo meets Red Mo - Site 3	41.036	-78.060	0.1		N/A	7.1
8/19/2015		Black Mo meets Red Mo - Site 3	41.036	-78.060	0.2		N/A	6.4
8/19/2015		Black Mo meets Red Mo - Site 3	41.036	-78.060	0.3		N/A	6.4
8/19/2015		Black Mo meets Red Mo - Site 3	41.036	-78.060	0.2		N/A	6.4
9/16/2015		Black Mo meets Red Mo - Site 3	41.036	-78.060	2.2		N/A	6.8
6/24/2015	O	BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.6	0.6	15.8	7.2
6/24/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.4		15.8	7.2
6/24/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.2		15.8	7.2
7/8/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.5		N/A	7.1
7/8/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.4		N/A	7.1
7/8/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.4		N/A	7.1
8/19/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.7		N/A	7.1
8/19/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.8		N/A	7.1
8/19/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.9		N/A	7.1
9/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.5		N/A	N/A
9/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.2		N/A	N/A
9/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.4		N/A	N/A
10/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.4		N/A	N/A

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ µg/L	Mean $[CH_4]$ µg/L	Water Temp °C	pH
10/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.6		N/A	N/A
10/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.6		N/A	N/A
10/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.4		N/A	N/A
10/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.6		N/A	N/A
10/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.4		N/A	N/A
10/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.8		N/A	N/A
10/16/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	2.1		N/A	N/A
11/10/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.5		N/A	7.0
11/10/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.3		N/A	7.0
11/10/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.5		N/A	7.0
11/10/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.4		N/A	7.0
11/10/2015		BlackMoshannon at Bridge - Site 2	41.016	-78.022	0.3		N/A	7.0
6/24/2015	B	BlackMoshannonState Park- Site 1	40.919	-78.059	0.6	7.8	20.1	6.6
6/24/2015		BlackMoshannonState Park- Site 1	40.919	-78.059	0.2		20.1	6.6
6/24/2015		BlackMoshannonState Park- Site 1	40.919	-78.059	0.5		20.1	6.6
7/8/2015		BlackMoshannonState Park- Site 1	40.919	-78.059	7.9		17.6	6.3
7/8/2015		BlackMoshannonState Park- Site 1	40.919	-78.059	7.6		17.6	6.3
7/8/2015		BlackMoshannonState Park- Site 1	40.919	-78.059	8.8		17.6	6.3
8/19/2015		BlackMoshannonState Park- Site 1	40.919	-78.059	14.7		N/A	6.8
8/19/2015		BlackMoshannonState Park- Site 1	40.919	-78.059	15.2		N/A	6.8
8/19/2015		BlackMoshannonState Park- Site 1	41.016	-78.022	25.6		N/A	6.8
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	6.2		N/A	6.2
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	7.8		N/A	6.2
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	6.7		N/A	6.2
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	6.2		N/A	6.2
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	7.4		N/A	6.2
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	6.0		N/A	6.2
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	7.0		N/A	6.2
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	5.5		N/A	6.2
3/16/2016		BlackMoshannonState Park- Site 1	40.919	-78.059	6.0		N/A	6.2
7/29/2015	O	Caleb Run	41.336	-76.955	0.3	0.3		
6/22/2015	B	Chartiers Creek	40.250	-80.206	3.0	3.0		
6/22/2015	O	Chartiers Run	40.248	-80.212	2.6	2.5		
1/14/2016		Chartiers Run	40.248	-80.212	2.3			
6/22/2015	B	Chartiers Run	40.258	-80.257	2.1	2.1		
10/12/2015	O	Council Run	41.091	-77.819	0.3	0.2	8	7.5
8/10/2015		Council Run	41.091	-77.819	0.2		14	6.8
11/9/2015		Council Run	41.091	-77.819	0.2		6	5.7
5/5/2016		Council Run	41.091	-77.819	<0.06		10	5.4
9/26/2015	O	Driftwood Branch (Emporium)	41.508	-78.236	1.0	1.0		
9/26/2015	O	East Branch of Cowley Run	41.597	-78.183	0.6	0.6		
9/16/2015	B	Eddy Lick Run	41.114	-77.812	0.4	0.4	12	5.8
9/26/2015	O	Elklick Run	41.522	-78.026	1.0	1.0		

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ µg/L	Mean $[CH_4]$ µg/L	Water Temp °C	pH
1/14/2016	B	Fern Hollow	40.573	-80.158	2.3	2.2		
1/14/2016		Fern Hollow	40.573	-80.158	2.2			
9/26/2015	B	First Fork Sinnemahoning Creek (@ SP)	41.451	-78.047	2.8	2.8		
9/26/2015	O	Freeman Run	41.601	-78.064	0.7	0.7		
7/29/2015	O	Hagerman Run	41.422	-77.049	0.1	0.1		
11/9/2015	O	Hayes Run	41.105	-77.759	0.2	0.1	6	5.7
5/5/2016		Hayes Run	41.105	-77.759	<0.06		10	6.2
9/26/2015	O	Horton Run	41.616	-77.875	4.2	4.2		
4/11/2016	O	Jonathan Run	41.020	-77.882	0.4	0.4	8	6.9
9/26/2015	O	Lick Island Run	41.373	-78.053	0.2	0.3		
9/26/2015		Lick Island Run	41.373	-78.053	0.4			
6/22/2015	O	Little Chartiers	40.228	-80.144	2.7	2.4		
8/6/2015		Little Chartiers	40.228	-80.144	2.1			
8/6/2015	B	Little Chartiers	40.157	-80.134	2.9	2.9		
8/6/2015	B	Little Chartiers	40.182	-80.146	2.6	2.6		
10/26/2015	B	Little Chartiers Creek	40.178	-80.136	4.2	4.1		
11/15/2015		Little Chartiers Creek	40.178	-80.136	4.1			
11/15/2015	B	Little Chartiers Creek	40.163	-80.134	2.6	2.6	6.9	5.9
11/15/2015	B	Little Chartiers Creek	40.178	-80.136	2.5	3.3		
11/15/2015		Little Chartiers Creek	40.178	-80.136	4.1			
11/15/2015	B	Little Chartiers Creek	40.195	-80.136	3.2	3.2		
9/26/2015	O	Little Moores Run	41.643	-78.002	0.4	0.4		
9/26/2015	O	Little Portage Creek	41.604	-78.067	0.6	0.6		
9/16/2015	B	Little Sandy Run	41.076	-77.961	1.3	0.8	14	5.4
11/10/2015		Little Sandy Run	41.076	-77.961	0.2		9	6.2
9/26/2015	O	Lower Hunts Run	41.453	-78.174	0.4	0.4		
1/14/2016	O	Marrow	40.558	-80.201	0.4	0.5		
1/14/2016		Marrow	40.558	-80.201	0.5			
9/26/2015	O	McKinnon Branch	41.464	-78.173	0.7	0.7		
11/14/2013	B	Meshoppen Creek (MC1)	41.717	-75.871	11.6	11.6	3	6.6
11/14/2013	B	Trib Meshoppen Creek (MC1 Trib)	41.718	-75.871	0.1	0.07	4	7.8
9/26/2015	O	Middle Hunts Run	41.474	-78.151	0.9	0.9		
7/29/2015	O	Mill Creek West	41.345	-76.972	0.2	0.2		
10/26/2015	O	Mingo Creek	40.195	-80.042	1.0	1.0		
9/26/2015	O	Montour Run	41.307	-78.017	0.2	0.2		
9/26/2015		Montour Run	41.307	-78.017	0.3			
10/12/2015	O	Monument Run	41.113	-77.704	0.3	0.2	9	6.3
4/11/2016		Monument Run	41.113	-77.704	0.1		6	6.3
8/10/2015	B	North Fork Beech Creek	41.05	-77.94	3.0	2.0	14	6.1
11/10/2015		North Fork Beech Creek	41.05	-77.94	3.5		9	5.8
5/5/2016		North Fork Beech Creek	41.05	-77.94	0.06		10	6.3
3/1/2016		North Fork Beech Creek_Clarence Rd	41.05	-77.94	1.2		7	5.8

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	[CH_4] µg/L	Mean [CH_4] µg/L	Water Temp °C	pH
11/10/2015	O	Panther Run	41.112	-77.842	5.7	2.0	9	6.6
8/10/2015		Panther	41.112	-77.842	0.2		13	7.1
4/11/2016		Panther	41.112	-77.842	0.1		7	6.4
1/14/2016	B	Pink House	40.571	-80.159	0.6	0.7		
1/14/2016		Pink House	40.571	-80.159	0.8			
6/22/2015	B	Plum Run	40.258	-80.219	5.3	2.9		
1/14/2016		Plum Run	40.258	-80.219	0.4			
1/14/2016	B	Plum Run (2)	40.255	-80.216	2.6	2.6		
7/31/2013	T	(SAH-13-10) Tunkhannock Creek	41.703	-75.671	1.3	1.3		
7/31/2013		(SAH-13-10) Tunkhannock Creek	41.703	-75.671	1.3			
5/30/2013	T	(SAH-13-9) Tunkhannock Creek	41.707	-75.672	1.6	1.4		
7/31/2013		(SAH-13-11) Tunkhannock Creek	41.707	-75.672	1.0			
7/31/2013		(SAH-13-11) Tunkhannock Creek	41.707	-75.672	1.5			
5/30/2013	T	(SAH-13-8) Tunkhannock Creek	41.710	-75.672	1.9	2.1		
7/31/2013		(SAH-13-12) Tunkhannock Creek	41.710	-75.672	2.2			
7/31/2013		(SAH-13-12) Tunkhannock Creek	41.710	-75.672	2.2			
7/31/2013		(SAH-13-12) Tunkhannock Creek	41.710	-75.672	2.2			
5/30/2013	T	(SAH-13-7) Tunkhannock Creek	41.711	-75.672	2.6	2.6		
5/30/2013	T	(SAH-13-13) 9 Partners Creek	41.712	-75.671	5.3	5.3		
7/31/2013	T	(SAH-13-14) Tunkhannock Creek	41.712	-75.67	0.4	0.3		
11/13/2013		(SAH-13-24) Tunkhannock Creek	41.712	-75.67	0.2			
11/13/2013	T	(SAH-13-25) 9 Partners	41.712	-75.671	1.6	1.6	1.8	6.9
11/13/2013	T	(SAH-13-26) 9 Partners	41.712	-75.671	1.6	1.6	2.1	7.4
11/13/2013	B	(SAH-13-27) 9 Partners	41.713	-75.672	1.3	1.3	2.3	7.3
11/13/2013	B	(SAH-13-28) 9 Partners	41.714	-75.673	1.4	1.4	2.5	7.2
11/13/2013	B	(SAH-13-29) 9 Partners	41.714	-75.674	1.5	1.5	2.6	7.4
11/13/2013	T	(SAH-13-30) 9 Partners	41.715	-75.675	1.5	1.5	2.9	7.5
9/1/2013	B	(SAH-13-19) 9 Partners	41.714	-75.673	2.5	2.5		
8/1/2013	T	(SAH-13-18) Tunkhannock Creek	41.715	-75.668	0.5	0.5		
8/1/2013		(SAH-13-18) Tunkhannock Creek	41.715	-75.668				
7/31/2013	T	(SAH-13-16) Tunkhannock Creek	41.717	-75.698	1.1	1.6		
8/1/2013		(SAH-13-17) Tunkhannock Creek	41.717	-75.664		0.9		
8/1/2013		(SAH-13-17) Tunkhannock Creek	41.717	-75.664				
7/31/2013	T	(SAH-13-15) TribTunkhannock Creek	41.718	-75.66	0.1	0.1		
5/30/2013	B	(SAH-13-6) Tunkhannock Creek	41.719	-75.65	0.7	0.7		
5/30/2013	T	(SAH-13-5) Tunkhannock Creek	41.720	-75.649	0.9	0.9		
5/30/2013	T	(SAH-13-4) Tunkhannock Creek	41.723	-75.646	0.7	0.7		
9/1/2013	T	(SAH-13-20) 9 Partners	41.729	-75.676	0.4	0.4		
9/1/2013	T	(SAH-13-21) 9 Partners	41.729	-75.677	0.4	0.4		
5/30/2013	T	(SAH-13-1) Tunkhannock Creek	41.733	-75.632	0.7	0.7		
5/30/2013	T	(SAH-13-2) Tunkhannock Creek	41.733	-75.630	0.6	0.6		
5/30/2013	T	(SAH-13-3) Tunkhannock Creek	41.733	-75.633	1.0	1.0		

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ µg/L	Mean $[CH_4]$ µg/L	Water Temp °C	pH
9/1/2013	T	(SAH-13-22) 9 Partners	41.763	-75.687	0.2	0.2		
9/1/2013	B	(SAH-13-23) 9 Partners	41.787	-75.687	2.6	2.6		
10/12/2015	O	Salt Lick	41.105	-77.723	0.2	0.2	9.7	6.3
4/11/2016		Salt Lick	41.105	-77.723	0.1		6.9	6.1
9/26/2015	O	Salt Run	41.534	-78.195	0.5	0.5		
11/10/2015	B	Sandy Run*	41.078	-77.908	1.1	1.6	9	5.8
3/1/2016		Sandy Run_Kato Rd	41.078	-77.908	0.4		8	5.4
9/16/2015		SandyRun_Kato	41.078	-77.908	4.6		12	5.4
5/5/2016		SandyRun_Kato	41.078	-77.908	<0.06		9	5.3
9/26/2015	O	Sinnemahoning Portage Creek (Emporium)	41.513	-78.22	0.4	0.4		
6/11/2015	B	Slab Cabin	40.809	-77.826	1.2	0.8	18.3	8.3
6/11/2015		Slab Cabin	40.809	-77.826	1.2		18.3	8.3
6/11/2015		Slab Cabin	40.809	-77.826	1.2		18.3	8.3
6/11/2015		Slab Cabin	40.809	-77.826	1.2		18.3	8.3
6/18/2015		Slab Cabin	40.809	-77.826	0.9		15.3	7.9
6/18/2015		Slab Cabin	40.809	-77.826	0.8		15.3	7.9
6/18/2015		Slab Cabin	40.809	-77.826	1.4		15.3	7.9
6/18/2015		Slab Cabin	40.809	-77.826	1.1		15.3	7.9
6/25/2015		Slab Cabin	40.809	-77.826	0.6		15.3	8.0
6/25/2015		Slab Cabin	40.809	-77.826	0.6		15.3	8.0
6/25/2015		Slab Cabin	40.809	-77.826	0.6		15.3	8.0
6/25/2015		Slab Cabin	40.809	-77.826	0.7		15.3	8.0
6/29/2015		Slab Cabin	40.809	-77.826	1.0		13.5	7.8
6/29/2015		Slab Cabin	40.809	-77.826	0.9		13.5	7.8
6/29/2015		Slab Cabin	40.809	-77.826	0.8		13.5	7.8
6/29/2015		Slab Cabin	40.809	-77.826	0.8		13.5	7.8
7/1/2015		Slab Cabin	40.809	-77.826	0.8		14.0	7.8
7/1/2015		Slab Cabin	40.809	-77.826	1.2		14.0	7.8
7/1/2015		Slab Cabin	40.809	-77.826	1.2		14.0	7.8
7/1/2015		Slab Cabin	40.809	-77.826	1.2		14.0	7.8
7/6/2015		Slab Cabin	40.809	-77.826	1.2		N/A	N/A
7/6/2015		Slab Cabin	40.809	-77.826	1.1		N/A	N/A
7/6/2015		Slab Cabin	40.809	-77.826	0.9		N/A	N/A
7/6/2015		Slab Cabin	40.809	-77.826	1.0		N/A	N/A
7/15/2015		Slab Cabin	40.809	-77.826	0.9		16.3	8.2
7/15/2015		Slab Cabin	40.809	-77.826	1.0		16.3	8.2
7/15/2015		Slab Cabin	40.809	-77.826	1.0		16.3	8.2
7/15/2015		Slab Cabin	40.809	-77.826	1.0		16.3	8.2
7/29/2015		Slab Cabin	40.809	-77.826	0.6		14.3	8.1
7/29/2015		Slab Cabin	40.809	-77.826	0.7		14.3	8.1
7/29/2015		Slab Cabin	40.809	-77.826	0.6		14.3	8.1
7/29/2015		Slab Cabin	40.809	-77.826	0.6		14.3	8.1

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ µg/L	Mean $[CH_4]$ µg/L	Water Temp °C	pH
8/12/2015		Slab Cabin	40.809	-77.826	0.6		14.9	8.2
8/12/2015		Slab Cabin	40.809	-77.826	0.6		14.9	8.2
8/12/2015		Slab Cabin	40.809	-77.826	0.8		14.9	8.2
8/25/2015		Slab Cabin	40.809	-77.826	0.7		17.9	8.4
8/25/2015		Slab Cabin	40.809	-77.826	0.5		17.9	8.4
8/25/2015		Slab Cabin	40.809	-77.826	0.7		17.9	8.4
9/11/2015		Slab Cabin	40.809	-77.826	0.9		18	8.3
9/11/2015		Slab Cabin	40.809	-77.826	0.9		18	8.3
9/11/2015		Slab Cabin	40.809	-77.826	0.5		18	8.3
10/5/2015		Slab Cabin	40.809	-77.826	0.5		N/A	N/A
10/5/2015		Slab Cabin	40.809	-77.826	0.5		N/A	N/A
10/5/2015		Slab Cabin	40.809	-77.826	0.5		N/A	N/A
10/19/2015		Slab Cabin	40.809	-77.826	0.3		8.8	7.9
10/19/2015		Slab Cabin	40.809	-77.826	0.3		8.8	7.9
10/19/2015		Slab Cabin	40.809	-77.826	0.7		8.8	7.9
11/9/2015		Slab Cabin	40.809	-77.826	0.6		8.8	7.9
11/9/2015		Slab Cabin	40.809	-77.826	0.7		8.8	7.9
11/9/2015		Slab Cabin	40.809	-77.826	0.4		8.8	7.9
11/21/2015		Slab Cabin	40.809	-77.826	0.3		8.4	8.3
11/21/2015		Slab Cabin	40.809	-77.826	0.3		8.4	8.3
11/21/2015		Slab Cabin	40.809	-77.826	0.3		8.4	8.3
12/12/2015		Slab Cabin	40.809	-77.826	0.4		10.4	8
12/12/2015		Slab Cabin	40.809	-77.826	0.3		10.4	8
12/12/2015		Slab Cabin	40.809	-77.826	0.3		10.4	8
1/8/2016		Slab Cabin	40.809	-77.826	0.2		4.8	8.0
1/8/2016		Slab Cabin	40.809	-77.826	0.2		4.8	8.0
1/8/2016		Slab Cabin	40.809	-77.826	0.2		4.8	8.0
2/3/2016		Slab Cabin	40.809	-77.826	0.7		4.1	7.5
2/3/2016		Slab Cabin	40.809	-77.826	0.7		4.1	7.5
2/3/2016		Slab Cabin	40.809	-77.826	0.7		4.1	7.5
3/18/2016		Slab Cabin	40.809	-77.826	0.3		9.7	8.0
3/18/2016		Slab Cabin	40.809	-77.826	0.3		9.7	8.0
3/18/2016		Slab Cabin	40.809	-77.826	0.3		9.7	8.0
4/13/2016		Slab Cabin	40.809	-77.826	0.3		14.3	8.4
4/13/2016		Slab Cabin	40.809	-77.826	0.3		14.3	8.4
4/13/2016		Slab Cabin	40.809	-77.826	0.3		14.3	8.4
5/1/2016		Slab Cabin	40.809	-77.826	1.0		11.5	8.0
5/1/2016		Slab Cabin	40.809	-77.826	1.0		11.5	8.0
5/1/2016		Slab Cabin	40.809	-77.826	1.0		11.5	8.0
5/16/2016		Slab Cabin	40.809	-77.826	0.4		16	8.5
5/16/2016		Slab Cabin	40.809	-77.826	0.4		16	8.5
6/8/2016		Slab Cabin	40.809	-77.826	1.0		15.7	8.3
6/8/2016		Slab Cabin	40.809	-77.826	1.0		15.7	8.3

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ µg/L	Mean $[CH_4]$ µg/L	Water Temp ºC	pH
6/8/2016		Slab Cabin	40.809	-77.826	1.0		15.7	8.3
6/23/2016		Slab Cabin	40.809	-77.826	0.9		19	8.2
6/23/2016		Slab Cabin	40.809	-77.826	0.9		19	8.2
6/23/2016		Slab Cabin	40.809	-77.826	0.8		19	8.2
6/30/2016		Slab Cabin	40.809	-77.826	1.1		19.5	8.1
6/30/2016		Slab Cabin	40.809	-77.826	0.7		19.5	8.1
6/30/2016		Slab Cabin	40.809	-77.826	0.8		19.5	8.1
7/13/2016		Slab Cabin	40.809	-77.826	1.1		N/A	N/A
7/13/2016		Slab Cabin	40.809	-77.826	1.0		N/A	N/A
7/13/2016		Slab Cabin	40.809	-77.826	1.0		N/A	N/A
7/27/2016		Slab Cabin	40.809	-77.826	1.2		N/A	N/A
7/27/2016		Slab Cabin	40.809	-77.826	1.2		N/A	N/A
7/27/2016		Slab Cabin	40.809	-77.826	1.3		N/A	N/A
8/15/2016		Slab Cabin	40.809	-77.826	0.8		N/A	N/A
8/15/2016		Slab Cabin	40.809	-77.826	0.8		N/A	N/A
8/15/2016		Slab Cabin	40.809	-77.826	0.8		N/A	N/A
8/28/2016		Slab Cabin	40.809	-77.826	0.7		21.7	8.1
8/28/2016		Slab Cabin	40.809	-77.826	0.9		21.7	8.1
8/28/2016		Slab Cabin	40.809	-77.826	0.8		21.7	8.1
9/21/2016		Slab Cabin	40.809	-77.826	1.0		19.1	8.1
9/21/2016		Slab Cabin	40.809	-77.826	1.0		19.1	8.1
9/21/2016		Slab Cabin	40.809	-77.826	1.0		19.1	8.1
10/9/2016		Slab Cabin	40.809	-77.826	0.7		12.2	7.9
10/9/2016		Slab Cabin	40.809	-77.826	0.7		12.2	7.9
10/9/2016		Slab Cabin	40.809	-77.826	0.7		12.2	7.9
10/23/2016		Slab Cabin	40.809	-77.826	0.7		10.7	7.4
10/23/2016		Slab Cabin	40.809	-77.826	0.6		10.7	7.4
9/16/2015	O	South Fork Beech Creek	41.024	-77.904	0.4	0.4	12	6.2
5/5/2016		South Fork Beech Creek	41.024	-77.904	0.3		10	6.5
9/16/2015	O	Spring above W. Branch of Big Run	41.146	-77.791	0.3	0.2	11	5.3
3/1/2016		Spring above West Branch-Big Run	41.146	-77.791	0.3		9	6.9
5/5/2016		Spring above West Branch-Big Run	41.146	-77.791	<0.06		9	6.0
6/11/2015	B	Spring Creek	40.82	-77.83	1.7	1.2	15.5	8.3
6/11/2015		Spring Creek	40.82	-77.83	1.6		15.5	8.3
6/11/2015		Spring Creek	40.82	-77.83	1.2		15.5	8.3
6/11/2015		Spring Creek	40.82	-77.83	1.6		15.5	8.3
6/11/2015		Spring Creek	40.82	-77.83	1.7		15.5	8.3
6/25/2015		Spring Creek	40.82	-77.83	1.1		13.8	8.0
6/25/2015		Spring Creek	40.82	-77.83	1.1		13.8	8.0
6/25/2015		Spring Creek	40.82	-77.83	1.0		13.8	8.0
6/25/2015		Spring Creek	40.82	-77.83	1.1		13.8	8.0
6/29/2015		Spring Creek	40.82	-77.83	1.3		13.1	7.8
6/29/2015		Spring Creek	40.82	-77.83	1.1		13.1	7.8

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	[CH_4] µg/L	Mean [CH_4] µg/L	Water Temp °C	pH
6/29/2015		Spring Creek	40.82	-77.83	1.3		13.1	7.8
6/29/2015		Spring Creek	40.82	-77.83	1.6		13.1	7.8
7/1/2015		Spring Creek	40.82	-77.83	1.4		13.6	7.8
7/1/2015		Spring Creek	40.82	-77.83	1.4		13.6	7.8
7/1/2015		Spring Creek	40.82	-77.83	1.3		13.6	7.8
7/6/2015		Spring Creek	40.82	-77.83	1.2		N/A	N/A
7/6/2015		Spring Creek	40.82	-77.83	1.7		N/A	N/A
7/6/2015		Spring Creek	40.82	-77.83	1.5		N/A	N/A
7/6/2015		Spring Creek	40.82	-77.83	1.5		N/A	N/A
7/15/2015		Spring Creek	40.82	-77.83	1.2		15.9	8.3
7/15/2015		Spring Creek	40.82	-77.83	1.2		15.9	8.3
7/15/2015		Spring Creek	40.82	-77.83	1.2		15.9	8.3
7/15/2015		Spring Creek	40.82	-77.83	1.1		15.9	8.3
7/29/2015		Spring Creek	40.82	-77.83	1.3		14	8.1
7/29/2015		Spring Creek	40.82	-77.83	1.2		14	8.1
7/29/2015		Spring Creek	40.82	-77.83	1.1		14	8.1
7/29/2015		Spring Creek	40.82	-77.83	1.3		14	8.1
8/12/2015		Spring Creek	40.82	-77.83	1.5		13.7	8.1
8/12/2015		Spring Creek	40.82	-77.83	1.5		13.7	8.1
8/12/2015		Spring Creek	40.82	-77.83	1.7		13.7	8.1
8/25/2015		Spring Creek	40.82	-77.83	1.8		15.8	8.3
8/25/2015		Spring Creek	40.82	-77.83	1.7		15.8	8.3
8/25/2015		Spring Creek	40.82	-77.83	1.8		15.8	8.3
9/11/2015		Spring Creek	40.82	-77.83	1.4		15.9	8.2
9/11/2015		Spring Creek	40.82	-77.83	1.0		15.9	8.2
9/11/2015		Spring Creek	40.82	-77.83	1.6		15.9	8.2
10/5/2015		Spring Creek	40.82	-77.83	1.1		N/A	N/A
10/5/2015		Spring Creek	40.82	-77.83	1.0		N/A	N/A
10/5/2015		Spring Creek	40.82	-77.83	1.0		N/A	N/A
10/19/2015		Spring Creek	40.82	-77.83	0.3		N/A	N/A
10/19/2015		Spring Creek	40.82	-77.83	0.7		N/A	N/A
10/19/2015		Spring Creek	40.82	-77.83	0.7		N/A	N/A
11/9/2015		Spring Creek	40.82	-77.83	0.4		8.4	8.2
11/9/2015		Spring Creek	40.82	-77.83	0.4		8.4	8.2
11/9/2015		Spring Creek	40.82	-77.83	0.3		8.4	8.2
11/21/2015		Spring Creek	40.82	-77.83	1.0		7.7	8.2
11/21/2015		Spring Creek	40.82	-77.83	0.9		7.7	8.2
11/21/2015		Spring Creek	40.82	-77.83	1.1		7.7	8.2
12/12/2015		Spring Creek	40.82	-77.83	0.7		10.1	8.1
12/12/2015		Spring Creek	40.82	-77.83	0.5		10.1	8.1
12/12/2015		Spring Creek	40.82	-77.83	0.6		10.1	8.1
1/8/2016		Spring Creek	40.82	-77.83	0.5		5.6	7.9
1/8/2016		Spring Creek	40.82	-77.83	0.5		5.6	7.9

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ µg/L	Mean $[CH_4]$ µg/L	Water Temp °C	pH
1/8/2016		Spring Creek	40.82	-77.83	0.5		5.6	7.9
2/3/2016		Spring Creek	40.82	-77.83	1.0		5.2	7.5
2/3/2016		Spring Creek	40.82	-77.83	1.1		5.2	7.5
2/3/2016		Spring Creek	40.82	-77.83	0.9		5.2	7.5
3/18/2016		Spring Creek	40.82	-77.83	0.5		9.7	8.2
3/18/2016		Spring Creek	40.82	-77.83	0.5		9.7	8.2
3/18/2016		Spring Creek	40.82	-77.83	0.5		9.7	8.2
4/13/2016		Spring Creek	40.82	-77.83	0.6		12.5	8.5
4/13/2016		Spring Creek	40.82	-77.83	0.7		12.5	8.5
4/13/2016		Spring Creek	40.82	-77.83	0.6		12.5	8.5
5/1/2016		Spring Creek	40.82	-77.83	1.2		10.6	8.1
5/1/2016		Spring Creek	40.82	-77.83	1.2		10.6	8.1
5/1/2016		Spring Creek	40.82	-77.83	1.3		10.6	8.1
5/16/2016		Spring Creek	40.82	-77.83	0.9		13.5	8.4
5/16/2016		Spring Creek	40.82	-77.83	0.7		13.5	8.4
6/8/2016		Spring Creek	40.82	-77.83	1.4		13.8	8.2
6/8/2016		Spring Creek	40.82	-77.83	1.4		13.8	8.2
6/8/2016		Spring Creek	40.82	-77.83	1.4		13.8	8.2
6/23/2016		Spring Creek	40.82	-77.83	1.4		16.4	8.1
6/23/2016		Spring Creek	40.82	-77.83	1.4		16.4	8.1
6/23/2016		Spring Creek	40.82	-77.83	1.3		16.4	8.1
6/30/2016		Spring Creek	40.82	-77.83	1.2		17.1	7.9
6/30/2016		Spring Creek	40.82	-77.83	1.2		17.1	7.9
6/30/2016		Spring Creek	40.82	-77.83	1.1		17.1	7.9
7/13/2016		Spring Creek	40.82	-77.83	1.2		N/A	N/A
7/13/2016		Spring Creek	40.82	-77.83	1.3		N/A	N/A
7/13/2016		Spring Creek	40.82	-77.83	1.2		N/A	N/A
7/27/2016		Spring Creek	40.82	-77.83	1.3		N/A	N/A
7/27/2016		Spring Creek	40.82	-77.83	1.5		N/A	N/A
7/27/2016		Spring Creek	40.82	-77.83	1.4		N/A	N/A
8/15/2016		Spring Creek	40.82	-77.83	2.4		N/A	N/A
8/15/2016		Spring Creek	40.82	-77.83	2.4		N/A	N/A
8/15/2016		Spring Creek	40.82	-77.83	2.4		N/A	N/A
8/28/2016		Spring Creek	40.82	-77.83	2.3		19.4	7.97
8/28/2016		Spring Creek	40.82	-77.83	2.4		19.4	7.97
8/28/2016		Spring Creek	40.82	-77.83	2.6		19.4	7.97
9/21/2016		Spring Creek	40.82	-77.83	1.6		18.2	8.2
9/21/2016		Spring Creek	40.82	-77.83	1.6		18.2	8.2
9/21/2016		Spring Creek	40.82	-77.83	1.5		18.2	8.2
10/9/2016		Spring Creek	40.82	-77.83	1.3		11.1	8.0
10/9/2016		Spring Creek	40.82	-77.83	1.5		11.1	8.0
10/9/2016		Spring Creek	40.82	-77.83	1.4		11.1	8.0
10/23/2016		Spring Creek	40.82	-77.83	2.0		10	7.8

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ μg/L	Mean $[CH_4]$ μg/L	Water Temp °C	pH
10/23/2016		Spring Creek	40.82	-77.83	1.8		10	7.8
10/23/2016		Spring Creek	40.82	-77.83	1.8		10	7.8
7/9/2015	A	SR 1 (Sugar Run)	41.236	-76.696	5.0	5.0	17.07	7.42
7/9/2015		SR 1 (Sugar Run)	41.236	-76.696	5.0			
6/13/2016	A	SR 1.1 (Sugar Run)			20.4	20.4		
7/9/2015	A	SR 1.15 (Sugar Run)	41.236	-76.694	5.4	5.4	16.99	7.25
7/9/2015		SR 1.15 (Sugar Run)	41.236	-76.694	5.4			
7/9/2015	A	SR 1.2 (Sugar Run)	41.237	-76.694	10.0	10.3	17.37	6.83
7/9/2015		SR 1.2 (Sugar Run)	41.237	-76.694	10.0			
6/13/2016		SR 1.2 (Sugar Run)			10.9			
7/9/2015	A	SR 1.4 (Sugar Run)	41.238	-76.693	13.3	15.1	16.42	7.27
7/9/2015		SR 1.4 (Sugar Run)	41.238	-76.693	13.3			
6/13/2016		SR 1.4 (Sugar Run)			18.6			
12/9/2014	A	SR 1.45 (Sugar Run)	41.239	-76.692	9.7	18.0		
7/9/2015		SR 1.45 (Sugar Run)	41.239	-76.692	17.5		16.47	7.08
7/9/2015		SR 1.45 (Sugar Run)	41.239	-76.692	17.5			
6/13/2016		SR 1.45 (Sugar Run)			27.4			
12/9/2014	A	SR 1.5 (Sugar Run)	41.239	-76.692	6.7	11.0		
12/9/2014		SR 1.5 (Sugar Run)	41.239	-76.692	10.1			
12/9/2014		SR 1.5 (Sugar Run)	41.239	-76.692	7.6			
12/9/2014		SR 1.5 (Sugar Run)	41.239	-76.692	9.0			
7/9/2015		SR 1.5 (Sugar Run)	41.239	-76.692	10.6		16.31	7.43
7/9/2015		SR 1.5 (Sugar Run)	41.239	-76.692	10.7			
7/9/2015		SR 1.5 (Sugar Run)	41.239	-76.692	10.4			
6/13/2016		SR 1.5 (Sugar Run)			22.9			
12/9/2014	A	SR 1.55 (Sugar Run)	41.24	-76.692	6.2	7.1		
7/9/2015		SR 1.55 (Sugar Run)	41.24	-76.692	7.5		15.57	7.43
7/9/2015		SR 1.55 (Sugar Run)	41.24	-76.692	7.5			
12/9/2014	A	SR 1.6 (Sugar Run)	41.24	-76.691	6.6	6.5		
12/9/2014		SR 1.6 (Sugar Run)	41.24	-76.691	6.5			
12/9/2014		SR 1.6 (Sugar Run)	41.24	-76.691	5.5			
12/9/2014		SR 1.6 (Sugar Run)	41.24	-76.691	6.2			
7/9/2015		SR 1.6 (Sugar Run)	41.24	-76.691	7.1		16.69	7.34
7/9/2015		SR 1.6 (Sugar Run)	41.24	-76.691	6.5			
7/9/2015		SR 1.6 (Sugar Run)	41.24	-76.691	7.8			
6/13/2016		SR 1.6 (Sugar Run)			5.8			
7/9/2015	A	SR 1.8 (Sugar Run)	41.241	-76.691	9.1	8.5	17.66	7.05
7/9/2015		SR 1.8 (Sugar Run)	41.241	-76.691	9.1			
6/13/2016		SR 1.8 (Sugar Run)			7.4			
7/9/2015	A	SR 2 (Sugar Run)	41.241	-76.69	9.3	8.6	19.1	6.08
7/9/2015		SR 2 (Sugar Run)	41.241	-76.69	9.3			
6/13/2016		SR 2 (Sugar Run)			7.1			
10/26/2015	B	Trib 36989 to Little Chartiers Creek	40.178	-80.166	2.2	2.2		
10/26/2015	O	Trib 39657 to Pigeon Creek	40.178	-79.979	3.1	3.1		

Table S1 Continued.

Date	Type	Site Name	Latitude	Longitude	$[CH_4]$ µg/L	Mean $[CH_4]$ µg/L	Water Temp °C	pH
10/26/2015	O	Trib 39670 to Pigeon Creek	40.163	-80.009	0.4	0.4		
5/21/2013	O	Trib 5.5	41.248	-76.668	0.2	0.2		
7/18/2015	B	Trib Black Moshannon Lake	40.891	-78.042	1.4	1.4		
7/18/2015	B	Trib Black Moshannon Lake	40.894	-78.043	4.3	4.3		
1/14/2016	B	Trib to Plum Run	40.258	-80.218	2.1	2.1		
8/10/2015	O	Trib_to_CouncilRun	41.091	-77.819	0.2	0.2	15	6.6
5/5/2016		Trib_to_CouncilRun	41.091	-77.819	<0.06		10	5.9
10/12/2015		Tributary to Council Run	41.091	-77.819	0.3		8	6.4
11/9/2015		LHU_Trib_to_CouncilRun	41.091	-77.819	0.2		7	5.8
10/12/2015	O	Twin Run	41.108	-77.694	0.3	0.2	9	6.1
4/11/2016		Twin Run	41.108	-77.694	0.1		5	6.4
8/10/2015		Twin Run	41.108	-77.694	0.3		13	5.7
3/1/2016	O	Two Rock Run	41.131	-77.804	0.4	0.4	7	6.9
9/16/2015	O	Two Rock Run	41.108	-77.694	0.8	0.8	13	5.8
8/6/2015	O	Unnamed Tributary (Chartiers)	40.178	-80.175	1.0	1.0		
8/6/2015	O	Unnamed Tributary (Chartiers)	40.183	-80.133	1.3	1.3		
8/6/2015	B	Unnamed Tributary (Chartiers)	40.200	-80.131	3.4	3.4		
8/6/2015	B	Unnamed Tributary (Chartiers)	40.217	-80.153	3.4	3.4		
8/6/2015	B	Unnamed Tributary Chartiers)	40.217	-80.141	1.4	1.4		
6/22/2015	B	Unnamed Tributary 1 (Chartiers)	40.223	-80.135	1.6	2.7		
8/6/2015		Unnamed Tributary 1 (Chartiers)	40.223	-80.135	3.7			
8/6/2015	O	Unnamed Tributary 2 (Chartiers)	40.229	-80.126	2.6	1.8		
6/22/2015		Unnamed Tributary 2 (Chartiers)	40.229	-80.126	1.0			
7/29/2015	O	UNT to Rose Valley Lake	41.384	-76.979	6.3	6.3		
9/26/2015	O	Upper East Fork Sinnemahoning	41.628	-77.86	0.7	0.7		
9/26/2015	O	Upper Hunts Run	41.503	-78.125	0.9	0.9		
1/14/2016	O	Walker	40.570	-80.190	0.5	0.5		
1/14/2016		Walker	40.570	-80.190	0.4			
7/29/2015	O	Wallis Run	41.379	-76.923	0.7	0.7		
9/26/2015	O	West Branch Freeman Run	41.634	-78.103	0.5	0.5		
9/16/2015	O	West Branch of Big Run	41.148	-77.781	0.3	0.2	12	6.5
3/1/2016		West Branch-Big Run	41.148	-77.781	0.3		7	7
5/5/2016		West Branch-Big Run	41.148	-77.781	<0.6		10	6.2
9/26/2015	O	Wildboy Run	41.61	-77.891	1.0	1.0		
9/26/2015	O	West Branch of Cowley Run	41.599	-78.186	0.5	0.5		
10/12/2015	O	Wolf Run	41.111	-77.897	0.4	0.3	11	6.4
4/11/2016		Wolf Run	41.111	-77.897	0.1		7	6.55
8/10/2015	O	LHU_WolfRun_Panther	41.090	-77.868	0.2	0.2	18	5.5
10/12/2015		Wolf Run – Panther Rd.	41.090	-77.868	0.2		12	6.7
4/11/2016		Wolf Run – Panther Rd.	41.090	-77.868	0.1		7	6.2
8/10/2015	O	Wolf Run - State Line	41.111	-77.897	1.2	1.2	15	6

*Type: O = other, B = biogenic, T = thermogenic, A = anthropogenic, N/A indicates data not available due to instrument unavailability.

Table S2. High CH_4 concentrations for samples collected on one day.

Date	Time	Stream ID	Latitude	Longitude	Total CH_4 (μg/L)	Average CH_4 (μg/L)
3/16/16	9:46 AM	Black Moshannon State Park (Site 1)	40.919	-78.059	6.95	6.6 ± 0.8
	9:48 AM				6.19	
	9:49 AM				7.39	
	9:51 AM				7.78	
	9:52 AM				6.66	
	9:53 AM				6.23	
	9:54 AM				6.03	
	9:55 AM				5.45	
6/13/16	12:05 PM	Sugar Run (SR 1.5 SEEP)	41.240	-76.692	231.4	216 ± 23
	12:07 PM				245.5	
	12:08 PM				230.6	
	12:09 PM				203.0	
	12:10 PM				218.9	
	12:11 PM				211.0	
	12:13 PM				173.7	

Table S3. Field data, concentrations, and isotopic data in the contamination-targeted dataset.

Sample Date	Stream ID	Lat	Long	$[CH_4]$ μg/L	T °C	pH	Sp. Cond. μS/cm	DO mg/L	Lat	Long	Comments	$\delta^{13}C_{CH4}$
3/9/16	Laurel Run	41.167	-78.539	0.4					41.167	-78.539	Plugged gas well in Moshannon Forest. SPUD Date: 4/17/1958 Date Plugged: 8/5/1998 Site is located in an area of historic coal mining. Sample sites are approximately 40 meters down gradient of well.	--
	Laurel Run	41.167	-78.539	0.4								
	Laurel Run	41.167	-78.539	0.3								
	Laurel Run	41.167	-78.539	0.4								
	Laurel Run	41.167	-78.539	8.1								
	Laurel Run	41.167	-78.539	34.3							This sample was collected near an outflow pipe. Rocks and sediment were coated with orange colored (Fe) precipitate.	
3/9/16	Elk Bar Run	41.766	-78.719	0.2					41.767	-78.718	Abandoned well in Allegheny State Forest, not part of the PADEP database. Location information obtained from S. Pelepko (PADEP). Gas had been observed bubbling in a wet area near the creek. It was thought there was communication between an abandoned well and a new shale gas well.	--
	Elk Bar Run	41.767	-78.718	2.1								
	Elk Bar Run	41.767	-78.718	2.0								
	Elk Bar Run	41.767	-78.718	2.1								
	Elk Bar Run	41.767	-78.719	2.5								

Table S3 Continued.

Sample Date	Stream ID	Lat	Long	$[CH_4]$ µg/L	T °C	pH	Sp. Cond. µS/cm	DO mg/L	Lat	Long	Comments	$\delta^{13}C_{CH4}$
3/9/16	Bennett Br.	41.276	-78.401	0.4					41.277	-78.401	Abandoned well not part of the PADEP database. Location information obtained from S. Pelepko (PADEP). Well discovered because a nearby camp, located within a cluster of old wells, observed ground catch on fire due to fireworks.	--
	Bennett Br.	41.276	-78.401	0.5								
	Bennett Br.	41.277	-78.401	0.3								
	Bennett Br.	41.277	-78.401	0.4								
5/30/16	Walnut Creek	42.062	-80.027	7.3					42.064	-80.018	Site located approximately 400 m down gradient of Waste Management - Erie, PA Landfill, but near three active oil and gas wells.	-43.6
5/30/16	Trib.1 Walnut Creek	42.061	-80.057	20.0					42.064	-80.053	Located downstream of an active well (dry hole) spudded in 1956, and two culverts. Located within 30 m of a wetland.	-56.9
5/30/16	Trib. 2 Walnut Creek	42.046	-80.071	3.7					42.042	-80.070	Site located downgradient of a PA DEP orphaned well, in an area of many active conventional wells.	-34.7
5/30/16	Oil Creek	41.639	-79.671	2.9					41.639	-79.671	Site located 0.10 mile downstream from active gas well, spud date 5/17/2005. Located upstream from two abandoned wells.	-49.8
7/3/16	Canadaway Creek	42.442	-79.392	1.5	22	8.3	910	6.93			Sampled middle of stream, just above waterfall at bridge (Rigley St.), upstream of bridge, and waterfall. On sandy shale, very flat lying planes of cleaved rock.	--
7/3/16	Canadaway Creek	42.438	-79.333	8.0	22	8.3	831	11.93			Sampled mid channel above Main St. Bridge behind fire station. Cobbly bottom.	
7/3/16	Canadaway Creek	42.476	-79.365	4.3							Sampled along bank near Tenmile Rd. at intersection with highway 5.	
7/3/16	Canadaway Creek	42.433	-79.314	0.8	21	8.3	853	13.25			Sampled along edge. Followed Liberty St. to Porta: dead end street off Porta with stream access.	
7/3/16	Canadaway Creek	42.438	-79.337	2.8							Just downstream of Forest Place. Shaley bed. Parts of creek cutting through thinly bedded black shale.	
7/3/16	East Van Buren point	42.446	-79.420	11.6	21	7.9	1010	11			Stream depth 30 cm, sampled above bridge along road. Steam doesn't reach to the beach/Lake Erie, may be flowing backwards or at a stand still.	
7/3/16	West Van Buren point	42.446	-79.420	1.3	19	7.9	1381	9.31			Sampled along very small stream draining into Lake Erie at edge. Location at end of Lakeshore Boulevard extension. Very shallow.	

Table S3 Continued.

Sample Date	Stream ID	Lat	Long	$[CH_4]$ µg/L	T °C	pH	Sp. Cond. µS/cm	DO mg/L	Lat	Long	Comments	$\delta^{13}C_{CH4}$
7/3/16	Oil Creek	41.615	-79.658	3.6							Sampled at Drake Well Road (Museum Rd) where it crosses Oil Creek. Sampled under bridge near parking lot near edge.	
7/18/16	West Branch Tomjac Creek	41.807	-76.632	4.52							Close to an outlier based on data mining of groundwater (Zheng et al. 2017) in Bradford County.	
7/18/16	Sugar Creek	41.763	-76.688	4.93							Kms downstream of an outlier based on data mining of groundwater (Zheng et al. 2017) in Bradford County.	
7/18/16	Sugar Creek	41.762	-76.699	1.78							Kms downstream of an outlier based on data mining of groundwater (Zheng et al. 2017) in Bradford County.	
7/18/16	Bailey Run	41.781	-76.534	2.70							Downstream of inferred groundwater hotspot (Li et al. 2016) and near an outlier based on data mining of groundwater (Zheng et al. 2017).	
7/19/16	Bailey Run	41.762	-76.550	0.27							Upstream of inferred groundwater hotspot (Li et al. 2016) and near an outlier based on data mining of groundwater (Zheng et al. 2017).	
7/19/16	Bailey Run	41.770	-76.544	2.47							Close upstream of inferred groundwater hotspot (Le et al. 2016) and near an outlier based on data mining of groundwater (Zheng et al. 2017).	
7/19/16	Towanda Creek	41.680	-76.677	4.87							Near inferred groundwater hotspot identified by Li et al. (2016).	
7/19/16	Towanda Creek	41.657	-76.790	2.99							Near inferred groundwater hotspot identified by Li et al. (2016).	
7/19/16	Sugar Run (Bradford Co.)	41.626	-76.274	1.17							Close to outliers based on data mining of groundwater (Zheng et al. 2017) and sites described by Llewellyn et al. (2015).	
7/19/16	Meshoppen Creek	41.614	-76.048	0.69							Near Dimock, PA	
7/19/16	North Branch of Sugar Run	41.640	-76.295	1.04							Close to an outlier based on data mining of groundwater (Zheng et al. 2017) and sites described by Llewellyn et al. (2015).	
7/13/16	Kinzua Creek	41.8	-78.7	33.7					41.770	-78.862	A top emitter, as described by M. Kang (pers. comm.) Well Status: DEP abandoned list (Combined oil and gas): SPUD Date: 1/1/1800. Sample located 0.07 mile down gradient of well. Allegheny State Forest.	-32.4‰

Table S3 Continued.

Sample Date	Stream ID	Lat	Long	[CH_4] µg/L	T °C	pH	Sp. Cond. µS/cm	DO mg/L	Lat	Long	Comments	$\delta^{13}C_{CH4}$
7/13/16	Mud Run	41.8	-78.7	9.2 8.5					41.179	-78.529	A top emitter, as described by M. Kang (pers. comm.) Plugged gas well. SPUD Date: 3/3/1958 Date Plugged: 10/8/1991 Sampling site located 0.39 mile down gradient from well. Allegheny State Forest.	-34.8‰ -44.8‰
7/13/16	Chappel Fork	41.8	-78.7	26.3					41.809	-79.898	Well discovered by L. Barr of Save our Streams PA. Well not on the PADEP orphaned/abandoned well list. Allegheny State Forest.	-26.6‰

Table S4. Wetland-lake dataset (Black Moshannon Lake).

Date Sampled	Sample ID	Latitude	Longitude	[CH_4] (µg/L)
7/18/2015	Black Moshannon Lake-1	40.9071	-78.0559	17.8
7/18/2015	Black Moshannon Lake-2	40.9059	-78.0549	22.7
7/18/2015	Black Moshannon Lake-3	40.9055	-78.0538	19.0
7/18/2015	Black Moshannon Lake-4	40.9017	-78.0568	45.2
7/18/2015	Black Moshannon Lake-5	40.8994	-78.0596	33.7
7/18/2015	Black Moshannon Lake-6	40.8953	-78.0619	26.6
7/18/2015	Black Moshannon Lake-7	40.8999	-78.0541	24.3
7/18/2015	Black Moshannon Lake-8	40.9010	-78.0555	11.1
7/18/2015	Black Moshannon Lake-9	40.9044	-78.0552	23.8
7/18/2015	Black Moshannon Lake-10	40.8943	-78.0434	20.9

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Engaging Stakeholders in Planning for Sea Level Rise and Resilience

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Abstract: This case study describes a region-wide, multi-sectoral, and whole-of-community stakeholder engagement approach for addressing sea level rise (SLR) and flooding. This approach was implemented through a university-led community engagement event, the Hampton Roads Resilient Region Reality Check (H4RC), which allowed an examination of its effectiveness as a mechanism for capturing community-wide perceptions regarding SLR, flooding, and associated risks; engaging stakeholders in discussion within and across different groups; and assessing community willingness to address flooding and SLR. The results show that the event helped participants broaden their perspectives and understanding of flooding and SLR. In an approach that called for participants to engage in social learning across social networks, the event had some effect on individual efficacy. However, there was little impact on participants' already-established perception that the region does not possess significant willingness to take action.

Keywords: *resilience, sea level rise, flooding, stakeholder engagement, social learning, social capital*

This study describes a stakeholder engagement approach built on three key themes: a *region-wide*, multi-sectoral, and *whole-of-community* approach oriented toward *actions* to address sea level rise (SLR) and flooding. We implemented this approach through a community engagement event – the Hampton Roads Resilient Region Reality Check (H4RC). Stakeholders from government, non-profit, business, and civic organizations from across the Hampton Roads region participated in the event. We assess the effectiveness of the approach for capturing community-wide perceptions regarding SLR, flooding, and associated risks; engaging stakeholders in discussion within and across different groups; and assessing community willingness to address flooding and SLR. More importantly, this article discusses the impact of the H4RC as an engagement approach designed with numerous stakeholders in mind.

The Hampton Roads region comprises 17 localities in southeastern Virginia (USA), including the following core cities: Chesapeake, Hampton, Newport News, Norfolk, Portsmouth, Suffolk, and Virginia Beach. Over the last decade, more than 20 studies have analyzed the substantial risk to the region from SLR and associated flooding as well as explored potential solutions (see for example Kleinosky et al. 2007; Hampton Roads Planning District Commission 2012; Li et al. 2012; Hampton Roads Transportation Planning Organization 2013; Virginia Institute of Marine Science 2013; Stiles et al. 2014). The region ranks 10th in the world in the value of assets exposed to increased flooding from storm surges and tidal flooding (Hallegatte et al. 2013). Nuisance flooding happens about nine times annually in the Hampton Roads area and is expected to increase to 182 events per year by 2045 (Spanger-Siegfried et al. 2014). By 2100, SLR could result in direct economic costs estimated between $12 and $87 billion, with up to 877 miles of roads permanently or regularly flooded (Hampton Roads Planning District Commission 2012). In spite of these factors, the region has struggled to plan, act, and cooperate in a regional fashion (Yusuf and St. John III 2017; Yusuf et al. 2018).

With SLR posing such extensive risks to this region, the H4RC pursued engagement of multiple stakeholders in Hampton Roads as part of efforts to build regional resilience by addressing SLR and flooding. Building on Arnstein's ladder of participation (1969), the International Association for Public Participation (IAP2 2007) categorizes public participation on a spectrum from Inform→ Consult→Involve→Collaborate→Empower. The immediate objectives of the H4RC event fit the first two levels along the IAP2 spectrum – inform and consult – while building a foundation for involvement and collaboration.

Sea Level Rise and Focus on Resilience

Resilience is concerned with how a system, community, or individual deals with disturbance and surprise (Intergovernmental Panel on Climate Change 2012). It reflects the capability to withstand crises or disruptions by anticipating risk, limiting the impacts, and rapidly recovering in the face of changes such as those associated with SLR (Bahadur et al. 2013; White et al. 2015). Becoming resilient encompasses a wide variety of strategies that respond to vulnerabilities or adapt to recent or anticipated risks.

Resilience to SLR relies on a socio-ecological system framework, involving more than the ability to recover and reorganize following a disruption; to include the pursuit of integrated, innovative responses and new trajectories through social learning and adaptation (Adger et al. 2005; Folke 2006; Lloyd et al. 2013). Resilience, therefore, is a dynamic process linked to human actors and human agency. It is reflected in the ability to respond to disturbance; engage with uncertainty and potential change; adapt, cope, learn, and innovate; and develop leadership and capacity (Obrist et al. 2010; Bristow and Healy 2014). This ability to take learning and turn it into adaptive actions is enhanced by *social capital*, or the network of "reciprocal social relations" (Putnam 2000, p. 19) that an actor can turn to as a source for cooperation, mutual support, and effectiveness. Scholars have pointed to social capital as a vital component for developing resilient communities (Woolcock 2001; Putnam et al. 2004; Halpern 2005).

Resilient communities are more likely to persist in the face of acute disruptions and chronic stresses. They assess risks, mitigate impacts, and plan for longevity by adapting, evolving, and making informed short-term and long-term investments. To build resilience, residents, businesses, organizations, and governments must work together to create the capacity to respond and even transform themselves.

A community-wide approach is needed because water and flooding cross jurisdictional boundaries (U.S. Geological Survey 1990; Collier 2008) and affect different types of communities. Governments, businesses, and citizens alone cannot solve the problem but need to work together to build resilience. Building resilience requires a collaborative regional approach involving multiple sectors and spanning municipal boundaries (Adger et al. 2005). A whole-of-community approach respects the value and importance of strengthening existing relationships and communication channels between all community stakeholders (Federal Emergency Management Agency (FEMA) 2011). Addressing SLR and flooding through building community resilience requires significant resources and substantial changes. How public participation is managed, who is included, and how it is conducted, is likely to have significant impacts on success as measured by participants and community leaders (Stern and Dietz 2008). How public participation is thought of, valued, conceived, and incorporated into the decision making process also matters. Engaging with key stakeholders helps ensure that solutions reflect underlying stakeholder preferences (to the extent possible), ensure legitimacy of efforts to address SLR, and gain acceptance and support for solutions (Arvai 2003; Renn and Schweizer 2009; Moser and Ekstrom 2011).

Establishing resilience, therefore, requires multiple sectors across the community be engaged in the process of building capacity in a whole-of-community approach that includes representatives from all levels of government, academia, non-governmental organizations, the private sector, and citizens. This approach allows better understanding and bridging the different needs and priorities of various stakeholders, and determining how different stakeholders can contribute to improving regional resilience. Creating an authentic, action-oriented dialogue within the community can empower behavior that strengthens cohesion and resilience from the individual and neighborhood level all the way up to the regional level.

Citizen engagement initiatives in New Hampshire and New York illustrate public participation efforts that resulted in solutions satisfactory to participants, while benefitting social, civic, educational, and business communities. Facilitators from New Hampshire Listens brought together community members to elicit solutions focused on the Great Bay National Estuary Research Reserve. Community conversations, experiential activities, workshops, and other activities during a multi-month phased project enabled community members to work with scientists directly to identify community values and "perceived vulnerabilities associated with climate change" (Aytur et al. 2015, p. 87).

In New York City, community engagement efforts conducted as part of the city's Special Initiative for Rebuilding and Resiliency (SIRR) led to specific priorities for areas effected by Hurricane Sandy (The City of New York 2013). SIRR staff consulted officials in more than 80 elected offices and community boards; more than 300 business, civic, community-based, environmental, faith-based, and labor organizations were involved in the planning process. SIRR staff also conducted 11 public workshops and briefed more than 1,000 residents.

Conceptual Approach and Stakeholder Engagement Event

In civic engagement initiatives where one sector (e.g., regional task force or government entity) partners with another sector (e.g., the public), a challenge is to garner attention and foster interest and commitment among all partners. In an era of growing awareness and concern about SLR, involving community stakeholders in setting priorities for resilience action requires outreach, using a combination of traditional methods (e.g., newspapers, newsletters, flyers, radio, television, direct mail, knocking on doors) and social media. Other key concerns to consider in planning a successful engagement event include the physical location of the event, accessibility and proximity to transportation routes, timing of the event, and the use of a fair and respectful process (Tuxill et al. 2009; McCown et al. 2011).

Informed by the literature on stakeholder engagement, the H4RC engagement process was designed to allow for both in-depth conversation among stakeholders with similar backgrounds, and the wider sharing of ideas across the broad spectrum of stakeholder groups. Three key themes underpinned this engagement approach. First, it adopted a multi-sectoral, whole-of-community framework to ensure inclusivity and diversity of stakeholders. This approach *respects the value and importance of strengthening existing relationships and channels of communication* among the full array of community stakeholders (FEMA 2011; Centers for Disease Control and Prevention 2013). Second, the focus was on *prioritizing actions to address SLR and flooding,* including identifying solutions that are considered feasible by local stakeholders and residents and assessing the community's willingness to act. Third, the emphasis was on *engagement on a regional basis*, rather than on a city by city basis.

Public participation processes can change the way people understand and approach resilience issues, especially if the processes facilitate social learning. Social learning, where a group collaborates in a shared experience, has increasingly become a goal of the resource management process (Reed et al. 2010). *Social learning* permits a convergence of goals among participants who may have different interests and promotes the co-creation of knowledge that can build relationships and mutual understanding (Blackmore 2007). A participation process that integrates social learning has the potential to generate new knowledge and increase the technical and social skills of participants, as well as build relationships and trust (Muro and Jeffrey 2008).

The H4RC came about as the result of both push and pull forces. First, there were several area organizations that were interested in engaging stakeholders on the issue of SLR and flooding resilience. These organizations were willing to combine their resources and expertise to host a region-wide, multi-sectoral public participation event. Second, on the pull side, members of the Hampton Roads community were asking for venues and opportunities to participate in regional efforts to address resilience. The resulting H4RC event was held in March 2015 as a collaboration among multiple organizations: Old Dominion University (ODU), the Urban Land Institute (ULI) Hampton Roads, the Community Engagement Working Group (CEWG) of the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project, and Virginia Sea Grant. The Hampton Roads ULI, through its Urban Resiliency Program, brought to the event practice-based expertise related to resilience. ODU provided academic support for the H4RC, bringing expertise that focused on practice-relevant and applied research. It also provided staff to support the event as facilitators and note takers. The CEWG connected the H4RC to an extensive network of civic, nonprofit, and grassroots organizations. The event was held at ODU in an easily accessible and politically-neutral location in a central city in the region, with ample parking and convenient bus stops.

Methodology

H4RC participants were recruited from a broad spectrum of stakeholder groups spanning sectors most influential to resilience response and action. Invitees included leaders of neighborhood and civic league organizations, staff from federal, state, and local governments, non-governmental (NGOs) or faith-based organizations, regional planning organizations, and businesses such as those in the real estate, construction, tourism, utilities, and transportation industries. An initial list of invitees was developed by the organizing committee. As gaps in the invitation list were identified, additional invitees were added primarily through a snowball method. The selection of participants was purposeful, designed not to be representative, but to bring together diverse stakeholders across multiple sectors.

One-hundred and thirty stakeholders participated in the day-long event. Participants were assigned to discussion tables organized by similar sector and interests. The table groupings were: government planners, government emergency managers, infrastructure managers, real estate businesses, tourism and waterfront businesses, neighborhood representatives, environmental nonprofits, and civic engagement nonprofits. Due to logistical constraints, several mixed tables were also formed.

The event was structured around facilitated discussion of three key questions about the risks of flooding, and identification of each participant's top two priorities from this discussion. Participants were given three questions to discuss: 1) How does flooding affect you?, 2) What should we do about flooding?, and 3) What resources are needed to address flooding?

Participants were given 30 minutes to discuss each question at their respective tables. Scribes from each table entered discussion results into an online document (via Google Docs). Results were made available to all attendees by projecting the document onto a large screen. Correspondingly, after the table discussion a facilitator from each group briefly reported out to all participants the key points from the table discussion. The event moderator and facilitator, who was an ODU community engagement liaison and local public radio host, oversaw this process, taking the summary reports from each table and sharing major themes with all attendees. Calling on each of the table facilitators, she further distilled and clarified their two-minute reports by asking the facilitator to expand on or explain the table's reported concerns and solutions. The overall approach allowed for leveraging sector-specific knowledge while ensuring sharing of ideas across multiple sectors.

After the discussions and report outs, participants were given the opportunity to provide direct input, via a multi-voting prioritization activity, on their individual priorities for taking action to address SLR and flooding. Participants were provided a list of the action items resulting from the second discussion question that asked "What should we do about flooding?" Each participant was given five sticker dots to use to vote for the actions he/she would most want to see supported or resourced.

Article authors collected data as members of the planning team for the engagement event, and as facilitators during the H4RC, had access to notes taken by scribes and other facilitators. Event notes were compiled and archived electronically in real time, and were later analyzed to identify consistent themes. Data were also collected through pre- and post-event web surveys of participants; survey results were analyzed to determine pre-event participant perceptions, changes in perceptions, and perceived outcomes of the event.

Results

Pre-Event Survey Responses

Event participants registered in advance and completed a short survey. Survey results point to several key issues regarding SLR and flooding. First, there were high levels of agreement that the impacts will be felt personally and regionally. As shown in Figure 1, 90% of participants agreed that the region will be severely impacted by flooding, and 90% agreed they will be personally impacted. Second, most stakeholders felt knowledgeable about flooding risks and impacts. When asked about their knowledge of the risks and impacts of flooding, 32% of participants strongly agreed and 48% agreed as shown in Figure 2.

At the same time, there was ambivalence about community and individual willingness to take actions necessary to address flooding and becoming more resilient. Participants were asked to indicate their level of agreement with two statements: 1) My community will take the action necessary to deal with flooding in the next 50 years, and 2) I am willing to pay more taxes or fees to make my community more resilient to flooding. In terms of community willingness, of the 161 participants that responded, 63% either agreed (46%) or strongly agreed (17%) that their community will take necessary actions. However, 32% had no opinions about community willingness and another 5% either disagreed (2%) or strongly disagreed (3%). Similarly, when asked about individual willingness, 47% of participants were willing to pay more in taxes or fees to make their community more resilient (46% agreed and 12% strongly agreed), but 21% either disagreed (17%) or strongly disagreed (4%) and 31% had no opinion.

Facilitated Discussions: Perceptions Regarding SLR Impacts, Possible Solutions and Resource Needs

During the H4RC, the first discussion question asked participants to think about how flooding affected them. Economic-related impacts were most commonly identified by participants, including concerns such as property loss and loss of home property value. Transportation was also recognized, as many participants had personal experiences with road flooding causing disruption to their lives or periods of isolation. For example, one table discussion emphasized that flooding can block roads and damage automobiles, making it difficult to get to and from work thus affecting mobility and connectivity. Another table connected the transportation challenge to concerns about the flow of people in and out of the region before and after a storm and for emergency services. Also highlighted was the interconnectedness of social, economic, and ecological impacts. For example, issues related to social equity and quality of life were raised, including concerns about disparate vulnerabilities to and impacts of flooding across the region, and the effect on community cohesion.

The second discussion revolved around what communities should do about flooding and which actions would be the most effective. Consistent across the proposed actions was the idea that regionally-coordinated revision of zoning and land use is the most effective way to build resilience. Specific tools of land use planning raised ranged from changes to zoning policies and creating regional building standards to strategic, managed retreat from areas that experience flooding. Participants also discussed how public education and outreach was crucial, including creating more citizen emergency response teams, increasing the number of flooding signs, and improving homeowner education.

The third discussion focused on resource needs. Participants agreed that financial resources were important, and that regional collaboration to attract funding for investments in mitigation and adaptation was needed. Additionally, a wide range of non-financial resources were identified, including information sharing networks, a cross-regional communications task force, political will, and education about climate change issues.

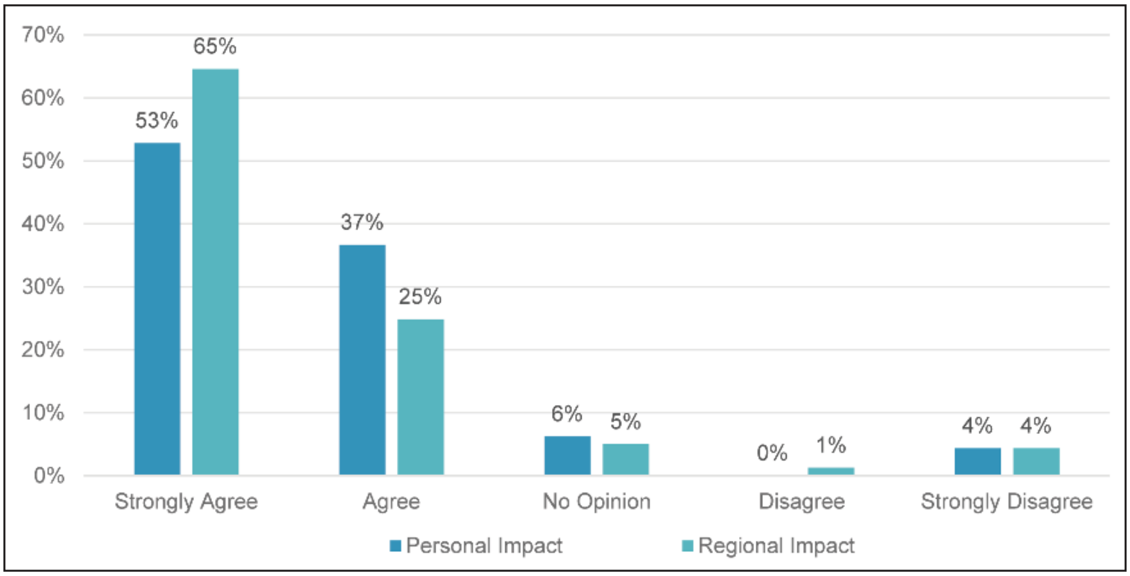

Figure 1. Perceived impacts of flooding (pre-event responses, n=161). Survey questions: 1) Personal Impact: I am likely to be impacted by flooding within the next 50 years. 2) Regional Impact: Hampton Roads will be severely impacted by flooding within the next 50 years unless action is taken.

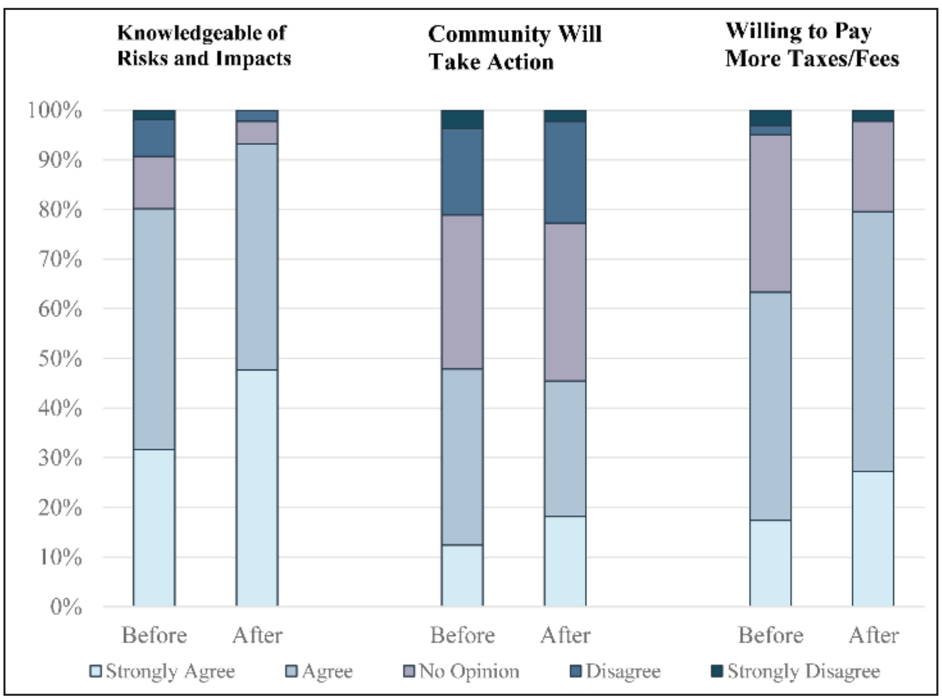

Figure 2. Knowledge of risks and comparison of perceptions before (n=161) and after (n=44) the engagement event.

Multi-voting: Priorities for Action

Table discussions were followed by a multi-voting prioritization exercise. Each participant was given five votes to prioritize the actions he/she identified as most effective for addressing flooding and SLR. The action areas that participants were asked to prioritize were identified during the table discussions. Of the 383 votes that were cast 15% of the votes prioritized regional collaboration to attract funding, 13% public education and outreach, 13% revise zoning and land use, 11% natural solutions, 11% reduce carbon emissions, and 10% living with water designs.

Post-Event Survey Responses: Social Learning and Social Capital

Following the event, participants completed a post-event survey. Responses showed that the H4RC has, to some extent, increased participants' level of knowledge regarding the risks and impacts of flooding. Comparisons of pre- and post-event perceptions are presented in Figure 2. While there was minimal change in participants' perceptions that the community will take the actions necessary to address flooding, there was greater willingness, post-event, among participants to pay more in taxes or fees to make the community more resilient to flooding.

Results suggest that the engagement event affected individual awareness of SLR impact and the need for government response; participants reported higher levels of knowledge about SLR risks and impacts coupled with a greater willingness to pay taxes and fees to build resilience. However, at an aggregate, community-wide level, there was little impact on participants' perception of the community's willingness to act. This result highlights the importance of both social learning and building social capital.

Moreover, participant responses to the post-event survey provided support for the occurrence of *social learning*. In the context of social learning, improved understanding emerges through collaborative processes that enable creation of a shared sense of meaning through interaction with individuals with different perspectives (Weick et al. 2005; Ensor and Harvey 2015). In this sense, the H4RC event can be seen as a process-oriented stakeholder network that offers "an interactive field of discourse occupied by those who share messy (complex, interdependent, emergent) problems and who want/need to talk about them" (Calton and Payne 2003, p. 8). The H4RC offered a collaborative learning environment and facilitated dialogue that prompted distinct concerns of different stakeholder groups, and supported collective sense making by linking and bridging unique perspectives into broader communal meaning. Furthermore, it allowed a wide range of stakeholders to come to some degree of consensus about willingness to take personal action to build resilience. While participants indicated a marked degree of concern regarding whether the region is inclined to take such action, these same participants' willingness to pursue individual measures may portend improvements in collective action as further engagement opportunities develop around the issue of SLR.

Finally, as regards to social learning, our results show that participants were positive about the learning value of the engagement event. For example, over 97% of participants indicated that the engagement event helped them understand perspectives of different stakeholders from different sectors and more than 90% of participants at least agreed that it helped them appreciate the perspectives of different stakeholders (See Table 1).

In addition to social learning, experts have recognized that socio-ecological resilience to environmental shocks and stresses greatly hinges upon the adaptive capacity of their social and ecological systems (Adger et al. 2005). Adaptive capacity of a group or community is intimately tied to their *social capital* – the ability to turn to networks full of "reciprocal social relations" (Putnam 2000, p. 19) – so as to tap the expertise or experience of community members and maximize the usefulness of their social learning (Henly-Shepard et al. 2015). Social capital theories that examine such inclusivity point to the development of *bridging* social capital (or inclusive of many actors) and *linking* social capital (which normally involves ties with centers of power and/or resources) that can promote a healthy, resilient community (Woolcock 2001; Putnam et al. 2004; Halpern 2005). From the perspective of bridging social capital, the physical setup of grouping participants by organizational perspective was a logical approach – allowing

Table 1. Perceptions regarding learning outcomes (n=44).

Helped me…	Strongly Agree	Agree	Neither Agree Nor Disagree	Disagree	Strongly Disagree
Understand the perspectives of different stakeholders from government, business, non-profits, and the community	50.0%	47.7%	2.3%	0.0%	0.0%
Appreciate the perspectives of different stakeholders from government, business, non-profits, and the community	43.2%	47.7%	9.1%	0.0%	0.0%
Understand shared concerns about flooding and SLR	43.2%	45.5%	11.4%	0.0%	0.0%
Understand the challenges the region faces in becoming resilient to flooding and SLR	43.2%	45.5%	11.4%	0.0%	0.0%

participants to meet, face-to-face, with individuals who shared expertise and knowledge that resonated with their backgrounds, therefore affording participants the opportunities to participate in the collaborative social learning process and to extend their networks. Furthermore, the broader report-outs that spanned all stakeholder groups also offered further opportunities for social learning and, therefore, opportunities to improve capacity within their social networks.

As the post-event survey data show, most participants left this event with increased understanding of the challenges of managing SLR and greater inclination to build resilience by a marked willingness to pay more taxes. This suggests that the process used in the H4RC demonstrates the benefits of providing participants opportunities to engage in social learning through an exchange of information and perspectives across a bridging social network, an approach that has built resilience in some post-disaster communities (Storr et al. 2016).

Conclusions and Implications

The premise of our study was that building resilience requires all stakeholder groups be engaged through a whole-of-community approach. Such an approach promotes social learning, allows the different perspectives and knowledge held by various stakeholders to intersect, and therefore results in greater learning and understanding that bridges differences so that stakeholders can contribute to improving regional resilience. Our research found that the H4RC whole-of-community, action-oriented engagement effort at the regional level encouraged such social learning and concurrent social capital that can lead to subsequent efforts to strengthen resilience.

Bringing diverse members of the community together to think about, talk about, and respond to key questions about flooding impacts, possible responses, and resource needs, was an important step in crossing multi-sectoral boundaries to enable knowledge sharing. Indeed, the H4RC demonstrated how multiple stakeholders engage in dialogue about SLR, and begin the process of solidifying, at least to themselves, effective actions to build resilience. Social learning theory maintains that this kind of knowledge acquisition prompts learning and change beyond the individual to the community level, and enables "new shared ways of knowing to emerge that lead to changes in practice" (Ensor and Harvey 2015, p. 510).

Literature on the strength of social capital within communities suggests that bringing together people who are members of differing groups, but who have similar long-term ends, leads to greater impact than relying on individuals who are linked solely by bonding (or close circle) social networks (Agnitsch et al. 2006; Norris et al. 2008; Smith et al. 2012). Therefore, the cohesion and trust developed in social networks are key to developing resilience in the face of potential threats and crisis (Storr et al. 2016). This broader collective approach builds the capacity to engage with uncertainty and potential change, and to adapt, cope, and innovate, as such communal regard "invites transformation, calling us not only to new facts and theories and values but also to new ways of living our lives" (Palmer 1998, p. 38).

Using a participatory community engagement process of resilience building can result in long-term benefits (National Research Council 2008). There are two crucial aspects of this meso-level and macro-level engagement. First, effective engagement is critical for ensuring that resilience-related solutions reflect the underlying multiple stakeholder preferences, ensuring that resilience efforts are considered legitimate by those across the entire community, allowing for widespread acceptance and support for solutions (Arvai 2003; Renn and Schweizer 2009; Moser and Ekstrom 2011). Second, with a whole-of-community sensibility, outcomes related to learning, improved understanding, and greater cohesiveness not only increase the community's ability to respond to disruptions and stress, but also allow it to transform and innovate.

The H4RC event placed a wide variety of community actors in a situation where they could engage with each other within a scenario that was conducive for social learning. Post-event responses indicate that these participants, by and large, realized the social learning value proposition of the engagement event. Participants manifested learning outcomes consistent with Ensor and Harvey's definition of social learning as the product of "knowledge sharing, joint learning, and co-creation of experiences between stakeholders around a shared purpose" (2015, p. 510).

There were, however, some limitations. While some participants noted that they appreciated being able to hear the perspectives of other stakeholder groups, they commented that time constraints limited the opportunities for in-depth information sharing. In addition, while invitations to participate in the H4RC were sent to a wide range of stakeholder groups, some groups (such as residents, neighborhood organizations, and the construction industry) remained under-represented. Organizers of future stakeholder events will need to recognize and make every effort to identify and "bring to the table" community representatives who were underrepresented on this occasion. Deliberate and concerted outreach to community associations, civic leagues, faith communities, and youth organizations is crucial.

As one event in what was envisioned as a series of engagement sessions with stakeholders, this experience created the groundwork necessary for entering into a long process of building alliances, bridging affinity boundaries, and developing long term, meaningful support and commitment (Picketts et al. 2012; Petzold and Ratter 2015; Sarzynski 2015). The H4RC was the beginning of the multi-event, multi-year participatory process that was incorporated into the Hampton Roads Intergovernmental Sea Level Rise Preparedness and Resilience Pilot Planning Project (the Pilot Project). The mission of the two-year Pilot Project was to develop a regional 'whole of government' and 'whole of community' approach to SLR preparedness and resilience that would span jurisdictional and sectorial boundaries. The Pilot Project was challenged by a lack of clarity of purpose and consensus on objectives and ultimately outcomes (Yusuf et al. 2018), but had success in respect to the development of case studies which revealed the interdependencies of critical infrastructure and the important role of public participation and whole-of-community engagement (Considine et al. 2017). What began as cross-sector engagement among key stakeholders in the H4RC ultimately supported the formation of resilience networks within the region and encouraged localities to engage the community at the broader neighborhood level.

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UCOWR
UNIVERSITIES COUNCIL ON WATER RESOURCES

NIWR
The National Institutes for Water Resources

2019 UCOWR/NIWR Annual Water Resources Conference
June 11-13, 2019
Snowbird, UT

Scale new heights as we come both west and up in the spectacular Wasatch Mountains in Snowbird, UT for the 2019 UCOWR/NIWR Annual Conference.

Important Dates
Proposal for special sessions due: 9/21/18
Notification of special session acceptance: 10/5/18
Call for abstracts issued: October 2018
Abstracts due: 1/25/19
Notification of abstract acceptance: February 2019

Have an idea for a special session?

The Conference Planning Committee invites you to propose a special session for the conference. A special session organizers' role is to propose a relevant and timely topic, recruit speakers to submit abstracts to the session, and moderate the session during the June 2018 Conference. Special sessions can be in the form of 5 full length talks, a panel discussion (a group of 4 or more speakers on a specific topic with a moderated discussion), a group of lightning (5 minute) talks followed by group discussion, or a participatory session (interactive session that may feature instruction, skill training, demonstration, or other facilitated activity). Multiple session track proposals are welcome. Those interested in organizing and hosting a special session should provide the following information:

- Title of proposed special session
- A brief description (less than 350 words) stating the importance of the topic and the rationale for the proposed session
- Organizer(s), including contact information
- Type of proposed session(s): full length talks (15 min), panel discussion, lightning talks (5 min) followed by discussion, or participatory session
- A draft list of presenters (to submit abstracts via the general call for abstracts) and their tentative titles.

Submit the above information to Conference Chair, David Stevens (david.stevens@usu.edu), and Technical Program Chair, Kevin Wagner (kevin.wagner@okstate.edu), no later than September 21, 2018.

Proposals for special sessions will be evaluated by the Conference Planning Committee based on the timeliness and relevance of the topic, and the degree to which the topic will bring together key researchers, educators, and practitioners to disseminate recent advances to the water resources community.

Abstracts submitted for an accepted special session will be subject to the same submittal and review process as all other abstracts. Proposed special sessions with less than 5 presenters may be filled with talks from the general call for abstracts. However, we encourage special session organizers to propose complete sessions, divisible by units of 5.

For more info, visit www.ucowr.org. General questions about the conference can be directed to Karl Williard (williard@siu.edu), Executive Director of UCOWR, or Staci Eakins (ucowr@siu.edu), Administrative Assistant.

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