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Research Article

Development and evaluation of an intensive short course: the Quantitative Microbial Risk Assessment Interdisciplinary Instructional Institute (QMRA III)

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ABSTRACT Quantitative microbial risk assessment (QMRA) is a growing interdisciplinary field addressing exposures to microbial pathogens and infectious disease processes. Risk science is inherently interdisciplinary, but few of the contributing disciplinary programs offer courses and training specifically in QMRA. To develop multidisciplinary training in QMRA, an annual 10-day long intensive workshop was conducted from 2015 to 2019—the Quantitative Microbial Risk Assessment Interdisciplinary Instructional Institute (QMRA III). National leaders in the fields of public health, engineering, microbiology, epidemiology, communications, public policy, and QMRA served as instructors and mentors over the course of the program. To provide cross-training, multidisciplinary teams of 5–6 trainees were created from the approximately 30 trainees each year. A formal assessment of the program was performed based on observations and surveys containing Likert-type scales and open-ended prompts. In addition, a longitudinal alumni survey was also disseminated to facilitate the future redevelopment of QMRA institutes and determine the impact of the program. Across all years, trainees experienced statistically significant increases ($P < 0.05$) in their perceptions of their QMRA abilities (e.g., use of specific computer programs) and knowledge of QMRA constructs (e.g., risk management). In addition, 12 publications, three conference presentations, and two research grants were derived from the QMRA III institute projects or tangential research. The success of QMRA III indicates that a short course format can effectively address many multidisciplinary training needs. Key features of QMRA III, including the inter-disciplinary training approach, hands-on exercises, real-world institute projects, and interaction through a mentoring process, were vital for training multidisciplinary teams housing multiple forms of expertise. Future QMRA institutes are being redeveloped to leverage hybrid learning formats that can further the multidisciplinary training and mentoring objectives.

KEYWORDS risk assessment, environmental microbiology, education, short course, assessment

Quantitative microbial risk assessment (QMRA) is widely accepted for addressing risks of developing infectious diseases using mathematical approaches and integrated data sets (1). The processes and cutting-edge norms of QMRA are documented by the World Health Organization (WHO) (2), U.S. Environmental Protection Agency (EPA) (3), National Research Council (NRC) (4), and recent publications (5–8). Lying at the confluence of mathematics, biology, engineering, and policy, QMRA is a complex but highly useful approach applicable to a wide variety of microbial pathogens and infectious disease processes associated with societal problems (9–11). QMRA has now matured to a research domain addressing exposures to microbial pathogens and infectious disease processes across a number of applications including drinking and

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recreational water quality, biofilms in water distribution systems and biosolids, food safety, bioterrorism, indoor air quality, hospital-acquired infections, surface disinfection, etc. (9, 12–15). In response to the COVID-19 pandemic, QMRA is also used to evaluate the risk for acquiring SARS-CoV-2 infections in varied scenarios, such as for occupational exposures in wastewater treatment plants (16, 17) and fomite transmission from contaminated surfaces (18).

Most training programs for advanced graduates and professionals are focused on disciplinary approaches and traditions (19). However, clinicians, governments, and researchers need interdisciplinary tools and expertise to describe and understand risks related to pathogen infections, so that action can be taken to rapidly and efficiently reduce morbidity and mortality. Training opportunities that provide sufficient statistical and quantitative skills with the necessary integration of those skills are generally insufficient to meet the demand for QMRA (20). While purpose-specific QMRA tools and models exist and are publicly available they are generally not targeted for use by non-quantitative scientists. Similarly, most quantitative scientists do not possess the necessary skills in social sciences to adequately address issues of human behavior that affect risks associated with exposure to pathogenic agents or responses to real or perceived health risks. For instance, risk communication and risk perception are topics traditionally taught under social science domains that are integral components of risk analysis thus important to consider when developing quantitative risk assessments (19, 21) or to evaluate risk management alternatives to prevent or reduce microbial risks (i.e., wearing masks, hand hygiene, etc.). Increasing the capability for multidisciplinary researchers to incorporate microbial risk assessments into their research is urgently needed to facilitate the dissemination of cutting-edge scientific information and tools to meet the challenges of emerging diseases.

Interdisciplinarity allows for co-creation and knowledge generation between collaborators with different areas of expertise (22) and provides opportunities to approach complex problems from different viewpoints using different ways of knowing (23). Interdisciplinary collaboration often occurs naturally in private industry where problems are typically approached as an open-ended question. Scientists and engineers consult a “toolbox” of all of the available methods pertaining to a problem and choose an approach as well as collaborators based on the specifics of a particular case (22). Interdisciplinary education research based upon the trainees from various discipline programs, such as health sciences and social sciences, reported three common and major challenges with such programs (24): (i) engagement by trainees from heterogeneous disciplinary and personal backgrounds can create situations where course trainees and instructors struggle to address in effective communication; (ii) the material coverage may assume that course trainees have the necessary background knowledge to engage with the course material results, while the trainees were in a heavy workload; (iii) without careful course design and engagement between program leads, interdisciplinary courses can become highly incoherent and may suffer from lack of agreement between disciplines and meaningless overlap and repetition of material. For academic institutions that need to facilitate convergent research to solve the world’s most challenging problems, the efforts to foster this kind of interdisciplinarity are often confounded by the highly disciplinary nature of academic organizations (25). Many institutions have recognized this issue and attempted to combat it by introducing future scientists and researchers to interdisciplinarity early in their academic careers. Semester-long courses on interdisciplinary topics or the integration of interdisciplinary problems into undergraduate or graduate degree programs have become common tools, by which collaboration across fields and disciplines is fostered (26, 27). Short, intensive courses, which bring together researchers from multiple disciplines, institutions, and nations have also arisen as a means, by which interdisciplinarity can be fostered outside of formal training programs. This is the case for QMRA, with interdisciplinary short courses funded by EPA, DHS, and NIH becoming a standard for training in this important interdisciplinary approach.

An annual, 10-day long, intensive short course was offered from 2015 to 2019 to train multiple disciplines in QMRA methodology and tools—the Quantitative Microbial Risk Assessment Interdisciplinary Instructional Institute (QMRA III). The target group for QMRA III were those scientists and engineers engaging in risk analysis at any stage of the QMRA process, from hazard identification to risk management and communication, including the disciplines in biological sciences, public health, computer science, biomedical engineering, behavioral sciences, and communications. Taking into account the experience from the Center for Advancing Microbial Risk Assessment (CAMRA) (EPA and DHS: R83236201) (28) with week-long, annual intensive courses, QMRA III was designed to equip the next generation of interdisciplinary QMRA scientists with both the training and tools needed to contribute to or produce highly credible quantitative microbial risk analyses. The program objectives of QMRA III were to (i) cross-train biological, social, and behavioral scientists with quantitative scientists on the fundamentals of QMRA through instruction, demonstration, and practice; (ii) teach trainees how to evaluate risk management strategies, understand risk perception, and communicate risks for disease agents; and (iii) develop case-specific risk analyses in institute projects to address emerging world hazards. This intensive short-course approach was intended to ultimately support increased capacity for science-based public health policies related to emerging and global pathogens and disease prevention.

Fundamental topics for QMRA

As shown in Fig. 1, the risk analysis paradigm consists of risk assessment, risk communication, and risk management. In contrast with chemical and ecological risk frameworks, QMRA creates the space for the overlap between risk assessment, risk management, and risk communication that are equally important for positive health outcomes.

Risk assessment

Among the three areas, the risk assessment (QMRA) consists of four major steps (Fig. 1) in identifying the mathematical approaches for describing the quantitative nature of microbes: hazard identification, dose–response assessment, exposure assessment, and risk characterization (4, 25).

Hazard identification

The initial step in QMRA is to identify the *hazard*, which is defined as a biological agent that has the potential to result in adverse health effects. Hazard identification means to quantify the characteristics of microbial agents and hosts, their interactions, the process of developing the associated disease, and the adverse effects on the host from infection (1).

Dose–response assessment

Dose–response modeling determines the mathematical relationship between adverse health effects, such as infection, illness or mortality, due to a given dose of a pathogen using mechanistic and biologically plausible models (1). Here, *dose* is the number of pathogens that an individual is exposed to per unit time (7). Dose–response models are often developed through fitting data from experimental challenge studies with animals, which requires stochasticity to describe variability and uncertainty.

Exposure assessment

The exposure assessment is the analysis of changes in pathogen concentrations and count arising from different exposure routes in order to generate an estimate of the number of pathogens a person will be exposed to. Exposure assessment considers the detection methods for microorganisms in environments along with integrated biophysical modeling to describe fate and transport of microbial agents in environmental media (e.g., food, water, and air)—their occurrence, persistence, and excretion.

FIG 1 Risk analysis paradigm.

Risk characterization

Risk can be characterized with the estimated exposure dose and a pathogen-specific dose–response model using computational simulation and statistical modeling. When variability and uncertainty of the risk cannot be evaluated probabilistically, risk characterization may also be described by point estimation from exposure dose at various per the dose–response model (6). Uncertainty and variability are usually considered for the risk analysis parameters stochastically (16).

Risk management

Risk management describes the process for identifying appropriate risk mitigation measures—source, engineering, administrative and personal protection equipment (PPE) control strategies, and/or medical countermeasures— and evaluating these strategies for reducing risk using cost-benefit, cost-effectiveness, and other decision analytic methods. Risk management has significant impacts on public health interventions, such as vaccination campaigns and public awareness initiatives. For instance, engineering controls may result in building design changes or ventilation implementations that eliminate the hazards. Regulations and guidelines can provide a framework for managing potential risks. Hospital-cleaning protocols, especially during pandemics, ensure that healthcare environments remain safe and healthy for both patients and healthcare personnel. Ultimately, these risk management measures provide efficient and effective strategies to protect human health.

Risk communication

Risk communication allows for the effective exchange of information about the perception of risks and the risk assessment results with risk managers, risk evaluators, public health scientists, urban planners, and other parties with an interest in risks (19).

As depicted in Fig. 1, risk communication emphasizes the basic principles that ensure the accurate and effective dissemination of risk-related information. Additionally, risk communication draws a distinction between objective risks, which are based on factual data, and subjective risks, which are based on personal perceptions and feelings. Overall, risk communication serves as a bridge between technical risk assessments and the practical steps taken to manage those risks.

METHODS

Instructional team and methods

Fourteen resource faculty served as instructors and mentors over the course of the 5-year QMRA III program and included national leaders in the fields of public health, environmental engineering, microbiology, epidemiology, communications, public policy and QMRA. Instructors were tasked with developing curriculum with each instructor delivering lectures and activities focused on a core topic in QMRA. A steering committee consisting of a subset of resource faculty and representing each of the core disciplines integral to effective QMRA oversees program design and implementation.

The pedagogical design for the QMRA III institute combined passive, active, and experiential learning techniques consisting of lectures (45 min), exercises (45 min), and mentored case study projects (45 min). The detailed 10-day schedule is listed in Table S1. Once the lectures and exercises were completed during the day, trainees worked with mentors and multidisciplinary group members on the case study projects. Although the course was being conducted over a short period of time, the contact hours between instructors/mentors and trainees were equivalent to that of a three-credit college course (~45 h).

Upon completion of the course, the trainees were expected to:

- Understand the QMRA framework, including the problem formulation, hazard(s) identification, dose–response assessment, exposure pathways and assessment, individual, population risk characterization, and risk management evaluation and communication;
- Identify data and data needs, the techniques, the models to use, and the assumptions;
- Develop conclusions on risk assessment and risk analysis;
- Determine the potential management approaches or decision-support systems needed;
- Prepare and present the institute projects in a final QMRA symposium.

In alignment with these objectives, QMRA III provided instruction in the following areas: software instruction (e.g., Excel, R, MatLab @Risk and/or Crystal Ball); statistical techniques (e.g., maximum likelihood estimation, bootstrapping, Bayesian methods); detection and quantitation of microorganisms; detection of infection or disease; sensitivity and specificity of tests; modeling transmission of infection in populations; persistence of microorganisms in the environment; quantifying exposure to microorganisms; risk perception and communication; valuing risk [i.e. value of statistical life (VSL) and disability-adjusted life year (DALY), etc.]; risk management evaluation with cost-benefit analysis and risk communication (Table S1). Assuming some of the trainees had no prior computational experience, tutorials in data analysis and computer modeling applications for risk assessment were also included in the course. Although objectives did not change, modifications to course content were made after the first 2 years based on trainees' feedback, in-course assessment, and external evaluation.

Applicants and participants

QMRA III was designed for advanced graduate students with a depth of expertise in their disciplinary field, post-doctoral research associates and early career faculty. Applicants were recruited through various avenues such as scientific community listservs, flyers at professional meetings, and academic social media platforms. Between 2015 and 2019, the program attracted a diverse group of applicants globally (Fig. S1), with n = 275 total applicants. Each year, 30%–50% of applicants came from institutions outside the United States. The pool consisted of applicants from multiple levels and career status as well, as shown in Fig. S2, consisting of masters (M.S.) students, doctoral students, postdoctoral fellows, and early career professionals. Applicants self-identified with more than 15 different disciplinary backgrounds which were generally described as department affiliations within their respective institutions. Fig. 2 depicts the disciplinary diversity of applicants in 2015–2019. The departments represented included veterinary medicine, public health, microbiology, food science, applied economics, civil and/or environmental engineering, computer science, and chemistry.

Trainees were selected based on multiple criteria developed by the steering committee. These criteria included domestic students in the U.S. (in line with the institute's funding grant priorities), education backgrounds, research domains, and needs/interests for integrating QMRA into other research projects, etc. To facilitate the project-based learning objectives for the case studies, each cohort was selected to balance participation across multiple disciplinary backgrounds in order to build teams for the case study projects. As shown in Table S2, 23–29 trainees participated each of the 5 years between 2015 and 2019. A total of 132 trainees participated in QMRA III overall.

Mentored case study projects

Modeled after project-based learning (29), trainees worked on active research through case study projects creating new risk assessments for infectious diseases. Project topics were proposed by the institute faculty (Table S3) each year based on current outbreaks, pathogens of concern and emerging microbial hazards in order to develop problems for trainees to address with QMRA from real-world interests. Before the arrival of trainees, institute faculty established guiding research questions and objectives for each topic, identified available sources of data through collaborators and the literature, and drafted an initial problem formulation for trainee teams. A team of six trainees were paired with two experienced mentors. Together, the trainees and mentors worked on their case study throughout the 10-day course. Following the evaluation of the program during the

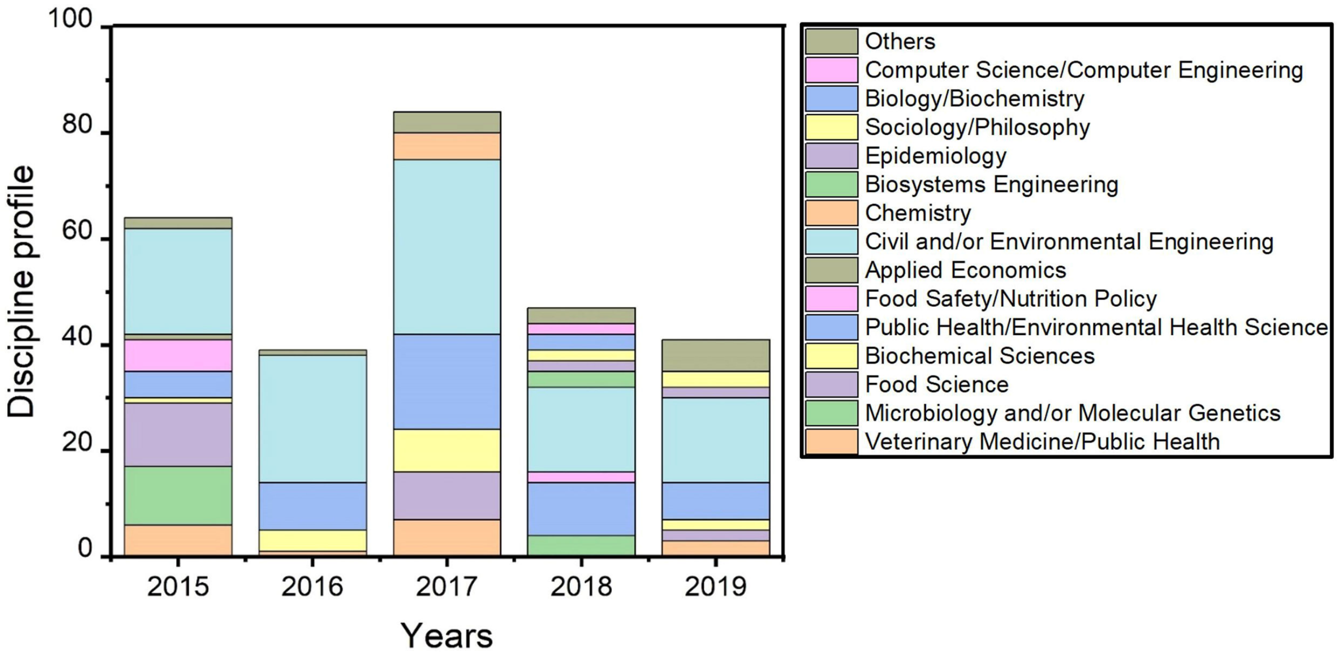

FIG 2 Discipline profile for QMRA III applicants.

first 2 years, additional rotating mentors visited teams throughout the 10-day course to broaden the mentoring perspectives available to trainees. Case study projects involved the integration of data and information as well as assessing, managing, and communicating microbial and infectious disease risks from intentional or accidental contamination within the built and natural environment. Trainees were able to demonstrate the following competencies through their case study work:

- Develop and describe a microbial risk assessment framework [problem, hazard(s), dose–response, exposure pathways, individual and population risk characterization];
- Identify data and data needs to address variability and uncertainty;
- Identify techniques and models;
- Identify assumptions;
- Undertake a QMRA;
- Develop conclusions on risk tolerance for management;
- Identify data gaps;
- Describe potential management approaches or decision-support systems needed;
- Prepare a written report;
- Add QMRA knowledge gained to the QMRAwiki for the broader community;
- Prepare and present the institute projects in a final QMRA symposium;
- Concisely communicate results and recommendations from the risk assessment.

Assessment methods

Institutional review board exemption (IRB No. x15-628e) was obtained from Michigan State University to administer this survey to QMRA III participants. A comprehensive evaluation plan was used to assess the ability of QMRA III to facilitate learning of QMRA information and methods, facilitate diverse research collaborations, conduct and develop risk analyses to address emerging pathogen risks. The institute was evaluated through observation, Likert-type scales, and open-ended prompts. The results from the open-ended prompts were represented in Adhikari *et al.* (20).

Observation

Each QMRA III implementation was observed by an outside evaluator three times, once at the beginning, once in the middle, and once at the end of the institute. Observation focused on interactions between instructors and trainees, including passive engagement through lectures as well as active mentoring.

Likert-type surveys

Trainees completed an entrance survey before attending the workshop and an exit survey on completion of the QMRA institute. There were five perception scales in the assessment surveys (Supplement 1): Perceptions of QMRA-Related Ability (11 items), QMRA-Specific Ability (3 items), Knowledge—Hazard Identification (11 items), Knowledge—Dose–Response and Exposure Assessment, (13 items) Knowledge–Risk Management (6 items). In the survey, trainees were asked to evaluate their ability (Supplement 1) as No Ability, Low Ability, Intermediate Ability, or High Ability on QMRA-related Ability and QMRA-Specific Ability. Trainees also rated how well they understood the key components in the risk assessment paradigm (i.e., hazard identification, dose–response and exposure assessment, and risk management) on a Strongly Disagree, Disagree, Agree, or Strongly Agree scale (Supplement 1). For each scale, No Ability/Strongly Disagree were coded ordinally as one and High Ability/Strongly agree coded as 4. An average score across all items related to a specific construct was calculated for the five perceptions scales.

Between 2015 and 2018, 90 pre-workshop and 86 post-workshop surveys were collected (Table 1). Given the small number of responses that could be matched in

2015 and 2016, independent sample tests were run by Mann–Whitney *U* tests on the pre- and post-survey results; based on the paired sample results in 2017 and 2018, Wilcoxon Signed-Ranks test was used to conduct the statistical analysis. In the final year of the program 2019, knowledge data were not collected and instead were replaced with the open-ended questions focused on mentoring, resources, and general suggestions (Supplement 2). In 2019, 22 and 21 surveys for pre- and post- workshop were collected, respectively. The 2019 assessment was used to collect information that would be of use for future QMRA IV workshops (NIH R25GM135058) and is not included here.

Longitudinal alumni survey

Trainees from the 2015–2016 program years completed a longitudinal survey in 2017 to evaluate the effectiveness of QMRA III training program on their education and careers (Supplement 3 and 4). Longitudinal surveys, a common tool used to evaluate the efficacy of training programs and interventions in both industry and the public sphere (30, 31), present one potential avenue, by which these courses may be evaluated. One of the primary benefits of longitudinal surveys of program trainees is that they can be used to collect data across a number of outcome variables (31). For example, a longitudinal survey of students who participate in a professional training program can be used to examine the temporal effect of the program on student knowledge, the impacts of student networking opportunities, and organizational adoption of practices discussed in the program (32). Thus, these surveys may be of particular utility in the evaluation of interdisciplinary training. To identify the long-term impacts of QMRA III on the trainees, questions about: (i) whether the trainees used QMRA tools in their careers; and (ii) if they used QMRA tools, how many times did they use them for grant proposals, conference presentations, course development, publications, and research design. Trainees also rated the lectures based on their usefulness in their academic and research careers in the years following the workshop (Supplement 3). A total of 36 responses were collected from trainees who participated in the 2015 and 2016 QMRA III. In total, 59% of 2015 trainees and 63% of trainees responded to the survey.

RESULTS

Case study project outcomes

The 24 QMRA III case study projects completed from 2015 to 2019 are listed in Table S3. Focusing on a variety of emerging or incompletely understood pathogens, case studies provided trainees with experiences in using QMRA to address complex problems

TABLE 1 Change in scores (Post-Pre) for 2015–2018 scales

Variable	2015 (32 trainees attended)		2016 (27 trainees attended)		2017 (28 trainees attended)		2018 (25 trainees attended)	
Number of surveys								
Pre	24 (75%)		17 (63%)		26 (93%)		23 (92%)	
Post	26 (81%)		14 (52%)		25 (89%)		21 (84%)	
Test	Mann–Whitney *U* test; 11 paired surveys		Mann–Whitney *U* test; 11 paired surveys		Wilcoxon signed-ranks Test; 24 paired surveys		Wilcoxon signed-ranks Test; 21 paired surveys	
	Post-pre score	***P* value**	**Post-pre score**	***P* value**	**Post-pre score**	***P* value**	**Post-pre score**	***P* value**
Perceptions of QMRA-related ability	0.66	<0.001	1.03	<0.001	0.66	<0.0001	0.77	<0.0001
Perceptions of QMRA-specific ability	1.16	<0.001	1.67	<0.001	1.16	<0.0001	1.4	<0.0001
Perceptions of knowledge—hazard identification	0.45	<0.001	0.62	<0.01	0.45	<0.0001	0.53	<0.0001
Perceptions of knowledge—dose–response and exposure assessment	1.17	<0.001	1.2	<0.001	1.1	<0.0001	1.06	<0.0001
Perceptions of knowledge–risk management	0.89	<0.001	1.04	< 0.001	0.89	<0.0001	0.73	<0.0001

within multidisciplinary teams. There were 12 published articles derived from the QMRA III institute projects or tangential research (Table S4). Several more manuscripts are in the pipeline for publications. There were three conference presentations published as proceedings of American Society for Engineering Education (ASEE) Annual Conference & Exposition (19, 20, 33). Additionally, several projects led to funded grant projects (34) and tangential contributions to risk sciences based on data and modeling needs that were identified.

Assessment results

Observation results

Observed by an outside evaluator, the QMRA III workshops were very structured and designed to encourage interaction among the students and instructor—lectures were paired nicely with activities. Students appeared attentive and interested in the topics covered in the workshop, with less potential for distraction given the switch to a new space; this was a much better space for collaboration than used in the previous year. Overall, the interaction between leaders and students seemed adequate and productive for student learning.

Survey results

The changes in average pre- and post-test scores are presented in Table 1 and detailed score distributions are shown in Fig. 3, indicating that trainees perceived positive impacts of QMRA III on their ability and knowledge. Across all years 2015–2018, trainees experienced statistically significant increases ($P < 0.05$) in their perceptions of their QMRA-related abilities (e.g., use of specific computer programs) and knowledge of QMRA constructs (e.g., risk management).

The longitudinal alumni survey results

Survey results are summarized in Table 2. Nearly half of respondents indicated they used the dose–response models and QMRAwiki (https://qmrawiki.org) after the workshop, and 21%–59% of trainees also used the QMRA models and tools for a variety of research and educational activities, for example, grant proposal, conference presentation, course development, and publication. 33% and 26% of respondents indicated that QMRA III increased their collaborations with colleagues in public health and bioscience, respectively. Respondents (52%) also indicated that colleagues (who did not attend QMRA III) had benefited from the respondent's participation in the QMRA III workshop. These results reflected the effectiveness of the workshop in delivering QMRA knowledge and skills. Trainees described learning new techniques and language and applying this learning in their research, including writing proposals, designing research methods, and interpreting research results (Supplement 4).

DISCUSSION

Case study impacts

As the institute developed over the years, new collaborations based on the case study groups were also built. For example, the collaboration with Models of Infectious Disease Agent Study (MIDAS) projects was initiated in late 2016 and showed fruit in 2017. The product of a MIDAS project developed a method to choose microbial dose–response models for use in infectious disease transmission systems models (35). QMRA III not only developed impactful institute projects for scholarly articles and presentations but was also timely useful for the rapid development of contemporary public health issues. For example, at the 2018 institute program, one group evaluated the then ongoing hepatitis-A outbreaks related to homeless populations throughout the nation (36). A major knowledge gap, the lack of an appropriate dose–response model for hepatitis-A was identified. This knowledge gap was closed in 2019 along with an innovative method

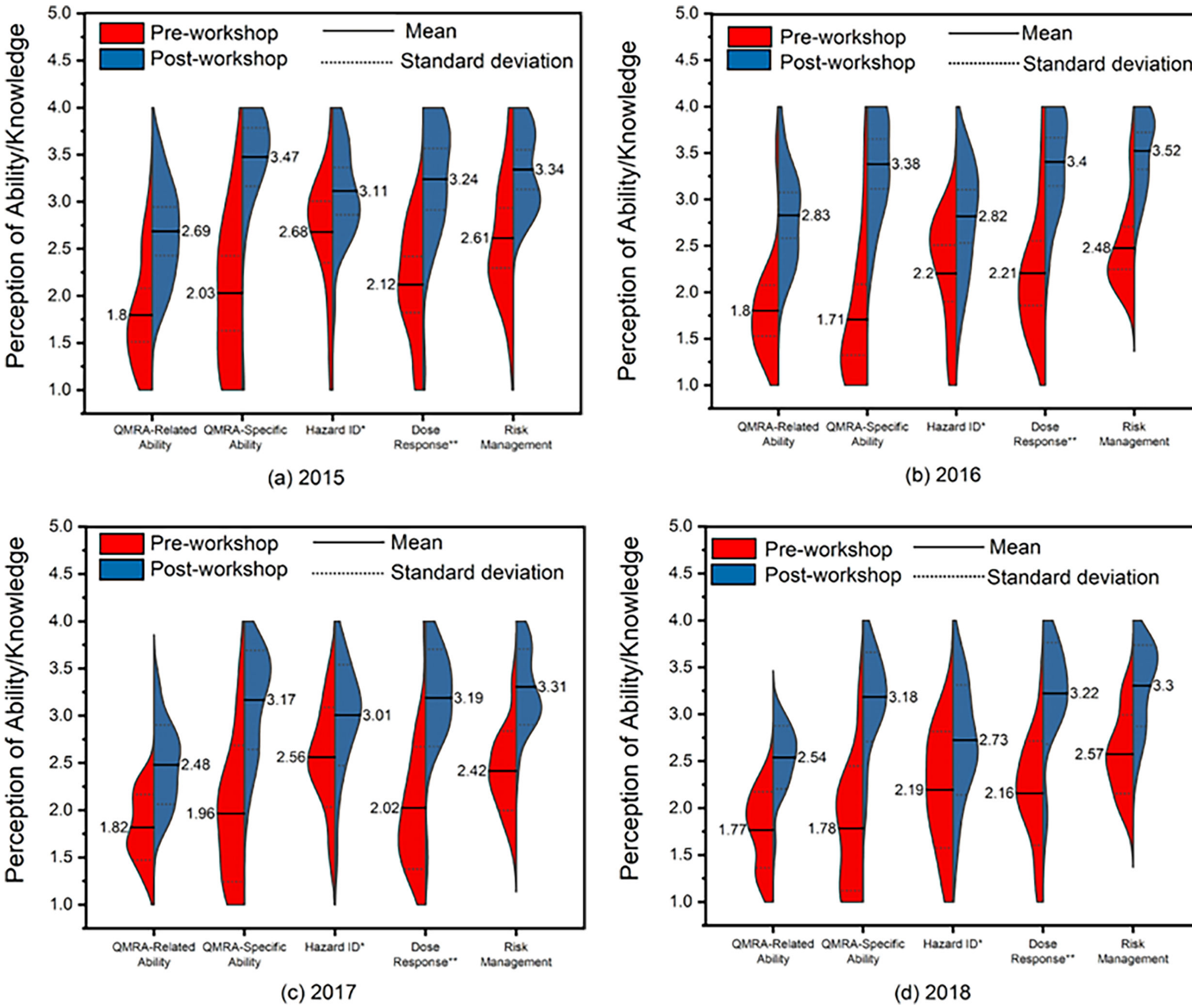

FIG 3 Distribution plots for the perception of ability or knowledge pre- and post-QMRA III workshop. *Hazard Identification; **Dose–Response and Exposure Assessment.

to optimize dose–response models using highly uncertain data (37). Also, the hepatitis-A case study outlined a series of interventions and tested the hypothesis that plastic bag bans are partially related to the outbreaks in CA, USA (38). Another 2018 case study, investigating multiple pathogen contamination from taps, toilets, and showers in a building driving pneumonia risks proved to be impactful as preliminary models identifying simplifying assumptions and key data gaps in two EPA National Priorities Grants under "National Priorities: Impacts of Water Conservation on Water Quality in Premise Plumbing and Water Distribution Systems": (i) R836880 (Faculty: Gurian, Haas, Hamilton; Trainees: Rasheduzzaman and Tolofari); and (ii) R836890 (Faculty: Mitchell and Rose) (33). The framework developed in this model was also used in the COVID-19 pandemic to investigate building reopening risks (39).

QMRA III assessment impacts

The institute content was interdisciplinary, and the education strategy was both broad and comprehensive. Therefore, the success of QMRA III interdisciplinary mentoring and training may be due to the developments in:

TABLE 2 Longitudinal alumni survey[a]

	2015 (*n* = 19, 59%) (%)	2016 (*n* = 17, 63%) (%)	Total (*n* = 36, 61%) (%)
The tools that the trainees used after QMRA III workshop			
Dose–response models	45	31	38
QMRA Wiki	42	47	44
R code provided	11	16	13
Matlab code provided	3	6	4
The number of times that trainees used QMRA tools and models in:			
Grant proposal	37	4	21
Conference presentation	37	15	27
Course development	21	24	22
Publication	42	11	27
Research design	68	48	59
The participation in QMRA III has increased the collaboration across the disciplines of:			
Public health	35	30	33
Social sciences (incl. social/behavioral sciences, risk perception and communication, etc.)	8	6	7
Biological science (incl. microbiology)	30	21	26
Engineering	13	21	17
Statistics (incl. biostatistics)	15	18	17
Other (specify):	0	3	1
The participation in QMRA III benefitted other people by the trainees:			
Students	37	15	26
Advisor	37	41	39
Colleagues	58	44	52
Would the trainees, their colleagues or students be interested in participating in the programs in future:			
An advanced QMRA III workshop	36	42	39
A workshop introducing different tools	29	25	27
Advanced programming in statistical modelling for risk assessment	33	33	33
Not interested	2	0	1
Top five lectures that were most useful for the trainees' academic or research career			
1	QALY/DALY	Introduction to QMRAwiki-Data and Tools	Introduction to QMRAwiki-Data and Tools
2	Introduction to QMRAwiki-Data and Tools	Data Manipulation in Excel	QALY/DALY
3	Microbial Hazard ID and Environmental Exposure	Introduction to R	Data Manipulation in Excel
4	Dose–Response Models	QALY/DALY	Introduction to R
5	Exposure Assessment	Dose–Response Models	Dose–Response Models
Top five tools and techniques that were most useful for the trainees			
1	Introduction to R	Dose–Response Models	Dose–Response Models
2	Risk and Uncertainty in Excel and Crystal Ball	Introduction to QMRAwiki-Data and Tools	Risk and Uncertainty in Excel and Crystal Ball
3	Dose–Response Models	Risk and Uncertainty in Excel and Crystal Ball	Data Manipulation in Excel
4	Data Manipulation in Excel	Microbial Hazard ID and Environmental Exposure	Microbial Hazard ID and Environmental Exposure
5	Use of Epidemiological Data in QMRA	Fate and Transport	Use of Epidemiological Data in QMRA
Top five lectures suggested by the trainees that would be helpful if uploaded as preworkshop materials			
1	Introduction to R	Introduction to R	Introduction to R

(*Continued on next page*)

TABLE 2 Longitudinal alumni survey[a] (*Continued*)

	2015 (n = 19, 59%) (%)	2016 (n = 17, 63%) (%)	Total (n = 36, 61%) (%)
2	Dose–Response Models	Introduction to QMRAwiki-Data and Tools	Dose–Response Models
3	Data Manipulation in Excel	Risk and Uncertainty in Excel and Crystal Ball	Introduction to QMRAwiki-Data and Tools
4	Introduction to QMRAwiki-Data and Tools	Dose –Response Models	Data Manipulation in Excel
5	Exposure Assessment	Bayesian Dose–Response Models	Risk and Uncertainty in Excel and Crystal Ball

[a]ID, identification; QALY, quality-adjusted life year; DALY, disablity-adjusted life year.

- The workshop consisted of the sparse and intermittent use of passive learning, through short lecture periods presented by top scientists in the field of QMRA rather than a single or small group of instructors from different contributory fields;
- Following the lectures, trainees were engaged in active learning through hands-on guided tutorials in the application of each mathematical modeling technique or facilitated discussion on social science topics;
- Research institute projects under the mentorship of program faculty were designed to be reflective exercises and opportunities for trainees to synthesize their knowledge, data, and models to address a new problem. Additionally, the strategic selection of trainees and formation of multidisciplinary teams facilitated both cooperative and collaborative learning.

In other fields, short courses have also been implemented to bring together multidisciplinary groups of graduate students and professionals to tackle problems ranging from noncommunicable disease intervention (35) to the need for resilient coastal infrastructure (29) to the facilitation of interdisciplinarity itself (26). Several themes emerge when comparing the outcomes of these short-course training programs, along with those of workshops and courses aimed primarily at current undergraduate and graduate students which follow similar formats. These features of effective interdisciplinary training agree well with aforementioned QMRA III developments, such as instructors create activities that trainees can actively engage with the material (35–37) and institute projects must be relevant and connected to trainees' work, research, and lived experiences (36–38).

Reflections on the future QMRA institutes

Continuing education workshops and programs that bring together individuals from different career paths are already somewhat common within medicine and the health sciences, where effective patient care depends on interprofessional collaboration (36, 38). The success of a workshop or short course depends on engagement by both trainees and instructors or mentors and a commitment to interdisciplinarity by both groups. For future QMRA institutes, trainees need to engage with instruction, but interdisciplinarity cannot be left up to trainees alone; rather, courses must foster opportunities for collaboration to occur and mentors must help facilitate it (29, 37, 38). In accordance with pre- and post-workshop surveys and the longitudinal survey, there are several iterative changes that could be made to improve the workshop as well as overall workshop perceptions.

Mentoring and workshop resources are two areas that are particularly worth discussing. Trainees consistently expressed that they found mentoring beneficial.

However, the effectiveness of mentoring appeared to be contingent on the amount of time mentors dedicated to their teams. One suggestion was for mentors to allot more time to teams, possibly through a pre-established mentoring meeting schedule. Additionally, the incorporation of a panel or an extension of the time set aside for mentoring and career guidance was recommended. This adjustment would eliminate the necessity for trainees to utilize their day off for career-related discussions. It was also advised to improve the synchronization between progress reports and the different phases of the QMRA model.

Trainees also provided suggestions for workshop resources that would improve their experiences at the workshop. One notable feedback was the desire for more hands-on training as opposed to lectures. Trainees also highlighted the need to place a stronger emphasis on the QMRA flowchart during the lecture sessions. There was a call for the provision of recommended resource texts, especially those related to statistics, well before the workshop commenced. This would enable attendees to be better prepared. Additionally, providing step-by-step examples, such as those involving R-coding, would greatly aid in understanding. Many trainees expressed a preference for dedicating more time during the latter part of the workshop to group projects rather than lectures. Furthermore, the idea of having both pre- and post-workshop courses was brought up as a potential avenue for improving collaborative skills outside the workshop environment. There was an encouragement that institute projects could be devised to tackle real-world challenges, making the workshop more relevant. A mixed response was observed concerning the knowledge of specific topics such as R, statistics, and MatLab. Some found the R lecture non-beneficial, while others expressed a desire for more comprehensive R training. To bridge this gap, a "remedial day" was proposed where attendees could identify their weak spots and seek targeted training. Some even suggested that specific lectures could be set as pre-workshop courses. Moreover, there were suggestions to decrease group sizes. This change would promote a more equitable and inclusive distribution of tasks, particularly the construction of the QMRA model.

As shown in Table 2, introductions to R and to QMRAwiki-Data and tools were considered highly useful for the trainees in their academic and research career, and these fundamental and introductory lectures were also suggested by the trainees that these topics could be provided as pre-workshop materials. Similar findings were obtained for specific models and tools, such as data manipulation in MS-Excel, dose–response models, and exposure assessment. As the length of workshops need to be correctly aligned with the scope of material to be covered, pre-workshop work can be used to supplement workshops and enhance trainee learning. Specifically, pre-workshop serves as an opportunity for trainees to arrive with a shared knowledge base from multidisciplinary backgrounds (29, 35). The longitudinal survey implies that future QMRA institutes can be implemented with pre-workshop course, which can facilitate the training and mentoring process. Other useful topics such as environmental infectious disease transmission modeling need to be maintained as workshop lectures, because intermediate or high level of interactions may be necessary between mentors and trainees to deliver these knowledge and skills. Findings from the longitudinal survey were deemed important for the improvement of QMRA training and mentoring, as mentors must provide trainees with relevant, ongoing feedback, and courses must include opportunities for trainees to reflect upon materials (37–39).

A future QMRA institute (QMRA IV) has been designed to address the above areas of improvements and prepare and stimulate trainees' ability to engage in team science (NIH 1R25GM135058). QMRA IV emphasizes mentoring in risk science for microbial stressors by creating a community of practice approach online with synchronous meetings online pre- and post-workshop for both individuals and groups. In-person workshops will maximize time needed to support hands-on skills rather than lectures by primarily focusing on experiential learning. Online synchronous meetings and webinars will be followed by in-person experimental experiences.

Conclusion

QMRA has become a widely accepted framework for the study of risk management, providing greater sensitivity in human health risk measurement than conventional approaches in epidemiology. It is promising that a short course format for researchers and practitioners in QMRA-related fields has sufficient efficacy to address the training needs in QMRA. QMRA III incorporated five important features that should be replicated in other interdisciplinary short courses: (i) training across disciplines through targeted development of multidisciplinary teams; (ii) experiential learning facilitated through hands-on computer exercises and mentored case study projects; (iii) access to a variety of data sets from published literature in diverse fields; (iv) use of software for probabilistic assessment; and (v) comprehensive, integrated content including analysis management, policy, and communication.

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ADDITIONAL FILES

The following material is available online.

Supplemental Material

Supplemental material (jmbe00216-23-s0001.docx). Supplemental tables and figures and additional materials.

REFERENCES

1. Haas CN, Rose JB, Gerba CP. 2014. Quantitative microbial risk assessment: Second edition. Wiley-Blackwell. Available from: https://arizona.pure. elsevier. com/ en/ publications/ quantitative - microbial- risk-assessment-second-edition. Retrieved 19 Aug 2021.
2. WHO. 2020. Multisectoral approach to the prevention and control of vector-borne diseases: A conceptual framework. World Health Organization, Geneva. Available from: https://apps.who.int/iris/handle/10665/331861. Retrieved 23 Aug 2021.
3. US EPA. 2010. Quantitative microbial risk assessment to estimate illness in freshwater impacted by 456
4. NRC. 2009. Science and decisions: Advancing risk assessment. The National Academies Press, Washington, DC. Available from: https://www.nap.edu/catalog/12209/science-and-decisions-advancing-risk-assessment. Retrieved 23 Aug 2021.
5. Adhikari U, Chabrelie A, Weir M, Boehnke K, McKenzie E, Ikner L, Wang M, Wang Q, Young K, Haas CN, Rose J, Mitchell J. 2019. A case study evaluating the risk of infection from middle eastern respiratory syndrome coronavirus (MERS-CoV) in a hospital setting through bioaerosols. Risk Anal 39:2608–2624. https://doi.org/10.1111/risa.13389
6. Dean K, Wissler A, Hernandez-Suarez JS, Nejadhashemi AP, Mitchell J. 2020. Modeling the persistence of viruses in untreated groundwater. Sci Total Environ 717:134599. https://doi.org/10.1016/j.scitotenv.2019.134599
7. Dean K, Weir MH, Mitchell J. 2019. Development of a dose–response model for naegleria fowleri. 1. J Water Health 17:63–71. https://doi.org/10.2166/wh.2018.181
8. Weir MH, Mraz AL, Mitchell J. 2019. An advanced risk modeling method to estimate legionellosis risks within a diverse population. Water 12:43. https://doi.org/10.3390/w12010043
9. Ashbolt NJ, Schoen ME, Soller JA, Roser DJ. 2010. Predicting pathogen risks to aid beach management: the real value of quantitative microbial risk assessment (QMRA). Water Res 44:4692–4703. https://doi.org/10.1016/j.watres.2010.06.048
10. Bichai F, Smeets P. 2013. Using QMRA-based regulation as a water quality management tool in the water security challenge: experience from the Netherlands and Australia. Water Res 47:7315–7326. https://doi.org/10.1016/j.watres.2013.09.062
11. Romero-Barrios P, Hempen M, Messens W, Stella P, Hugas M. 2013. Quantitative microbiological risk assessment (QMRA) of food-borne zoonoses at the European level. Food Control 29:343–349. https://doi.org/10.1016/j.foodcont.2012.05.043
12. Bibby K, Casson L, Haas CN, Rycroft T. 2016. Risks from Ebola discharge from hospitals to sewer workers. Water Intelligence Online 15:9781780408316–9781780408316. https://doi.org/10.2166/9781780408316
13. Bivins AW, Sumner T, Kumpel E, Howard G, Cumming O, Ross I, Nelson K, Brown J. 2017. Estimating infection risks and the global burden of diarrheal disease attributable to intermittent water supply using QMRA. Environ Sci Technol 51:7542–7551. https://doi.org/10.1021/acs.est.7b01014
14. Dean K, Mitchell J. 2020. Reverse QMRA for *Pseudomonas aeruginosa* in premise plumbing to inform risk management. J Environ Eng 146:04019120. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001641
15. McBride GB, Stott R, Miller W, Bambic D, Wuertz S. 2013. Discharge-based QMRA for estimation of public health risks from exposure to stormwater-borne pathogens in recreational waters in the United States. Water Res 47:5282–5297. https://doi.org/10.1016/j.watres.2013.06.001
16. Dada AC, Gyawali P. 2021. Quantitative microbial risk assessment (QMRA) of occupational exposure to SARS-CoV-2 in wastewater treatment plants. Sci Total Environ 763:142989. https://doi.org/10.1016/j.scitotenv.2020.142989
17. Zaneti RN, Girardi V, Spilki FR, Mena K, Westphalen APC, da Costa Colares ER, Pozzebon AG, Etchepare RG. 2021. Quantitative microbial risk assessment of SARS-CoV-2 for workers in wastewater treatment plants. Sci Total Environ 754:142163. https://doi.org/10.1016/j.scitotenv.2020.142163
18. Wilson AM, Weir MH, Bloomfield SF, Scott EA, Reynolds KA. 2021. Modeling COVID-19 infection risks for a single hand-to-fomite scenario and potential risk reductions offered by surface disinfection. Am J Infect Control 49:846–848. https://doi.org/10.1016/j.ajic.2020.11.013
19. Mitchell J, Weir M, Libarkin J, Rose J. 2017. The quantitative microbial risk assessment Interdisciplinary instructional Institute (QMRAIII) – A platform for cross disciplinary training of engineers with social and biological scientists to address public health issues In 2017 ASEE Annual Conference & Exposition Proceedings, p 28995, ASEE Conferences, Columbus, Ohio
20. Adhikari U, Mitchell J, Libarkin J, Weir M. 2017. Measuring the success of an educational program through box-and-arrow diagram: A case study of the quantitative microbial risk assessment Interdisciplinary instructional Institute In 2017 ASEE Annual Conference & Exposition Proceedings, p 28659,ASEE Conferences, Columbus, Ohio
21. Owens CEL, Angles ML, Cox PT, Byleveld PM, Osborne NJ, Rahman MB. 2020. Implementation of quantitative microbial risk assessment (QMRA) for public drinking water supplies: systematic review. Water Res 174:115614. https://doi.org/10.1016/j.watres.2020.115614
22. Klaassen RG. 2018. Interdisciplinary education: a case study. Eur J Eng Educ 43:842–859. https://doi.org/10.1080/03043797.2018.1442417
23. Davies M, Devlin M. 2010. Chapter 1 interdisciplinary higher education, p 3–28. In Davies M, Devlin M, Tight M (ed), Interdisciplinary higher education: perspectives and practicalities. Emerald Group Publishing Limited.
24. Gantogtokh O, Quinlan KM. 2017. Challenges of designing Interdisciplinary postgraduate curricula: case studies of interdisciplinary master's programmes at a research-intensive UK University. Teach Educ 22:569–586. https://doi.org/10.1080/13562517.2016.1273211
25. NRC. 2014. Convergence: facilitating transdisciplinary integration of life sciences, physical sciences, engineering, and beyond. National Academies Press, Washington, D.C. Available from: http://www.nap.edu/catalog/18722. Retrieved 1 Dec 2021.
26. Lyall C, Meagher LR. 2012. A masterclass in interdisciplinarity: research into practice in training the next generation of interdisciplinary researchers. Futures 44:608–617. https://doi.org/10.1016/j.futures.2012.03.011
27. Newing H. 2010. Interdisciplinary training in environmental conservation: definitions, progress and future directions. Envir Conserv 37:410–418. https://doi.org/10.1017/S0376892910000743
28. US EPA. 2011. Center for advancing microbial risk assessment: research centers; research project database; Grantee research project. Available from: https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/outlinks.centers/center/158. Retrieved 15 Nov 2022.
29. Judge PK, Buxton JA, Sheahan TC, Phetteplace ER, Kriebel DL, Hamin Infield EM. 2020. Teaching across disciplines: a case study of a project-based short course to teach holistic coastal adaptation design. J Environ Stud Sci 10:341–351. https://doi.org/10.1007/s13412-020-00610-z
30. Ashenfelter O, Card D. 1985. Using the longitudinal structure of earnings to estimate the effect of training programs

31. Piesse A, Judkins D, Kalton G. 2009. Using longitudinal surveys to evaluate interventions, p 303–316. In Methodology of longitudinal surveys
32. Moore JE, Rashid S, Park JS, Khan S, Straus SE. 2018. Longitudinal evaluation of a course to build core competencies in implementation practice. Implement Sci 13:106. https://doi.org/10.1186/s13012-018-0800-3
33. Weir MH, Mitchell J, Libarkin J, Mraz AL. 2017. QMRA Wiki: an educational tool for interdisciplinary teaching of risk modeling in engineering curricula 2017 ASEE Annual Conference & Exposition; Columbus, Ohio. https://doi.org/10.18260/1-2--27787
34. US EPA. 2022. National Priorities: Impacts of Water Conservation on Water Quality in Premise Plumbing and Water Distribution Systems (2016) | Research Project Database | Grantee Research Project | ORD | US EPA. Available from: https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/recipients.display/rfa_id/613/records_per_page/ALL. Retrieved 15 Nov 2022.
35. Galaviz KI, Narayan KMV, Manders O, McFarland DA, Goenka S, Torres-Mejía G, Srinath Reddy K, Rafael Lozano P, Magaña-Valladares L, Prabhakaran D, Ali MK. 2016. The public health leadership and implementation academy (PH-LEADER) for non-communicable diseases. Health Syst Reform 2:222–228. https://doi.org/10.1080/23288604.2016.1224452
36. Clay MC, Lilley SH, Borre K, Harris JR. 1999. Applying adult education principles to the design of a preceptor development program. JIC 13:405–415. https://doi.org/10.3109/13561829909010385
37. Saunders TE, He CY, Koehl P, Ong LLS, So PTC. 2018. Eleven quick tips for running an Interdisciplinary short course for new graduate students. PLoS Comput Biol 14:e1006039. https://doi.org/10.1371/journal.pcbi.1006039
38. Gilkey MB, Earp JAL. 2006. Effective interdisciplinary training: lessons from the university of North Carolina's student health action coalition. Acad Med 81:749–758. https://doi.org/10.1097/00001888-200608000-00014
39. Bonarini A, Romero M. 2013. Robotics and design: an interdisciplinary crash course. IEEE Trans Educ 56:110–115. https://doi.org/10.1109/TE.2012.2222409