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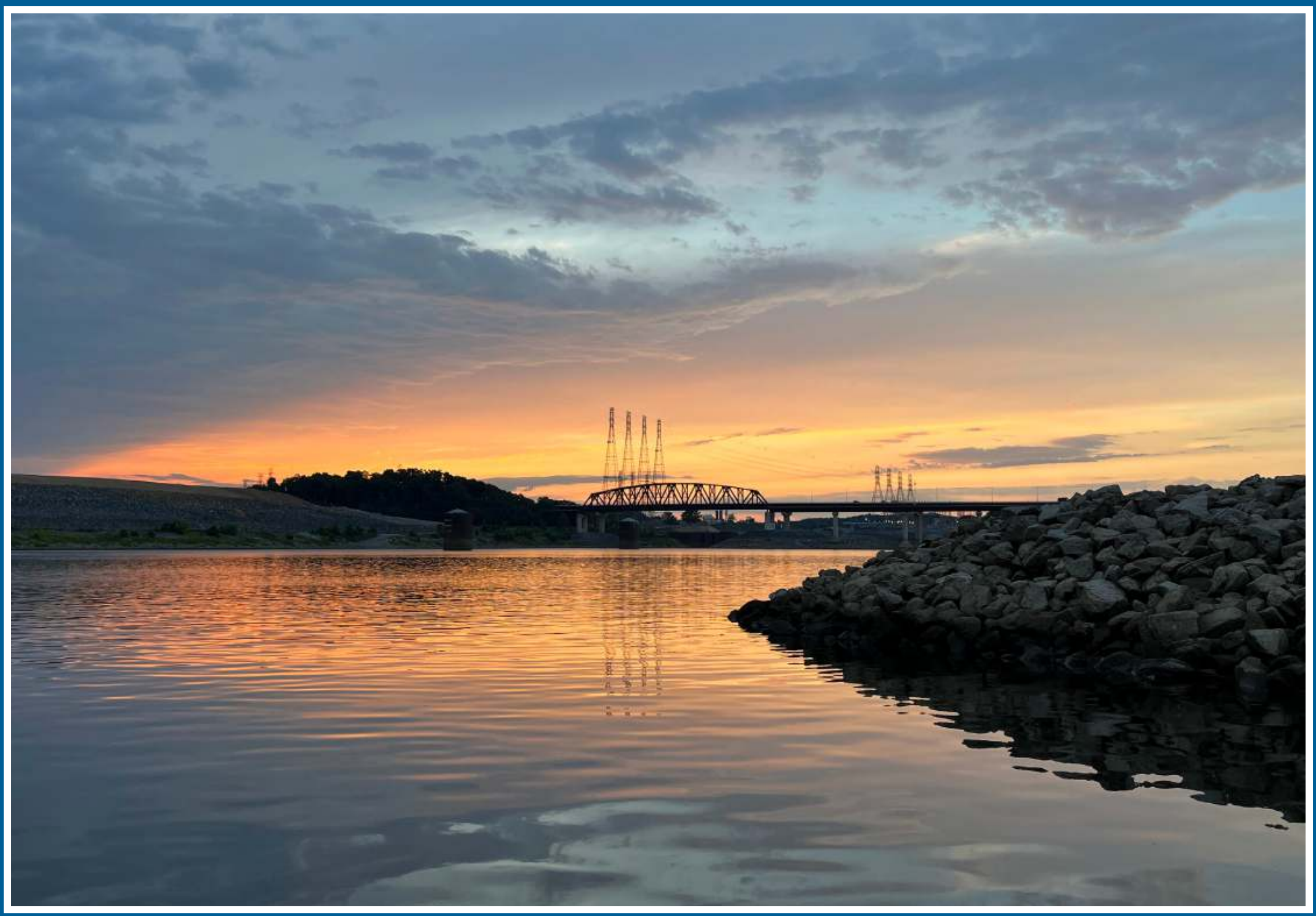

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Reflections on the Adaptation of a Postgraduate Degree in Water Management from In-person to Remote Delivery

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Abstract: In early 2020, the COVID-19 pandemic spurred the rapid adaptation of university course delivery to an online format. Though in-person delivery partially resumed in the Fall of 2021, future conditions may favor a return to, or addition of, remote delivery. It is therefore important for instructors, program directors, and institutions to capitalize on this learning opportunity and reflect on adaptation measures' successes (and failures) to inform future online course design. The reworking of McGill University's Master of Science Program in Integrated Water Resources Management (IWRM) provides a case study to evaluate the adaptation of remote teaching of water resource management. Informed by the Community of Inquiry (CoI) framework with a focus on preserving transferable skills, a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was used to evaluate the five core program components. This evaluation framework, which can be applied to most university programs, resulted in several widely relevant insights. For example, remote delivery can create opportunities for greater participation of international students as it eliminates the need for translocation costs. Likewise, a larger variety of guest speakers can participate remotely, giving students greater exposure to different water career paths and research perspectives, ultimately strengthening the program. However, several weaknesses pose threats to online learning. The standard in-person lecture-style format must therefore be amended to maintain engagement and facilitate student-to-student and student-to-instructor learning processes. Course components that can enhance the online experience include breakout rooms, discussion boards, frequent journals/feedback forms, online activities, breaks, virtual office hours, and multi-media presentations.

Keywords: *water management education, IWRM, Community of Inquiry (CoI), SWOT, transferable skills, COVID-19, remote learning*

Since December 2019, the SARS-CoV-2 (COVID-19) virus has expanded across the globe, causing millions of deaths and global socioeconomic disruption (World Health Organization n.d.). As a result, in 2020, the COVID-19 pandemic disrupted university course delivery, with universities worldwide rapidly suspending in-person lecturing and moving courses online to reduce the spread of infectious disease (Sahu 2020).

The shift to emergency remote teaching posed challenges to instructors, students, and their institutions due to differences in engagement, modes of learning, and social interactions. Many instructors were unprepared to use online strategies (Kimmons et al. 2020) and faced challenges related to new technologies, course structure development, materials, evaluations, fostering student engagement, and work-life balance (Pather et al. 2020; Aubry et al. 2021; Watermeyer et al. 2021; Wut and Xu 2021).

Students also faced challenges with the shift to online learning related to software and hardware, internet connection, physical learning environment, and time zones (Aristovnik et al. 2020; Gewin 2020), along with financial stress due to loss of income (Pather et al. 2020; Sundarasen et al. 2020). These challenges disproportionately impacted lower-

Research Implications

- Remote learning is a viable long-term option for teaching water resources management, with benefits for global cohorts and guest speakers.
- Adapting class materials online requires instructors to reevaluate and reimagine course structures to maintain value, learning processes, engagement, and transferable skills development.
- Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, as informed by the Community of Inquiry (CoI) framework, is a useful methodology for evaluating areas of excellence and those needing improvement in materials adapted online.

income students and those with worse Information and Communications Technology (ICT) infrastructure (Aristovnik et al. 2020). Students' social networks, which are important for buffering academic stress, were also impacted by public health measures (e.g., social distancing) (Elmer et al. 2020). Early studies suggest that COVID-19-specific stressors increased the prevalence of anxiety, loneliness, and depressive symptoms among post-secondary students (Elmer et al. 2020; Sundarasen et al. 2020). Institutions also faced major challenges. Research by Watermeyer et al. (2021) suggests that future student recruitment will increasingly be dependent on a university's digital offerings; to maintain admissions, programs must provide equal or greater value to students when programs are offered online (Krishnamurthy 2020).

Given these challenges, it is important for instructors to evaluate the successes and shortcomings of the rapid online adaption of courses and programs to improve future remote course delivery. However, doing so necessitates a theoretical understanding of learning processes and of the differences in modes of learning between remote and in-person instruction. The objective of this paper is therefore to develop a simple but effective framework to aid the evaluation of remote learning adaptation measures. As a result, this paper suggests the use of Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, informed by identified differences and challenges in remote learning and the Community of Inquiry (CoI) framework, as an analysis framework. The developed framework is demonstrated through a case study on the rapid shift of McGill University's Integrated Water Resource Management (IWRM) Master's program from an in-person format to an online format during COVID-19. The paper's authors include the program director (and instructor), an instructor, and two teaching assistants. The framework was applied to the case study using the observations of the authors who were directly involved in and responsible for the rapid adaption of the analyzed courses to a remote format, as well as the creation and delivery of the analyzed courses both before and during the pandemic.

Theoretical Framework

Evaluating remote learning adaptation measures requires a simple and effective evaluation framework informed by theoretical background about learning processes and skills development in the classroom, and how these are impacted by remote formats. SWOT analysis is a method of assessing and optimizing the effectiveness of an organization. This approach involves the identification of strengths, weaknesses, opportunities, and threats of internal and external environments to propose new strategies. The ideas behind SWOT were introduced in 1908 (Lorhke et al. 2021), gaining broader recognition in the 1980s by Stevenson (1976), Bower (1982), and Weihrich (1982). This framework has since been widely applied in the literature (Ghazinoory et al. 2011; Namugenyi et al. 2019). The simplicity and logical approach of SWOT allows for its application in a wide range of contexts, including learning and educational contexts (Chermack and Kasshanna 2007; Thomas et al. 2014) and digital environments (Ghazinoory et al. 2011). However, critics of SWOT analysis maintain that it is overly simplistic (Helms and Nixon 2010) and that it is used to justify a course of action that has already been taken (Chermack and Kasshanna 2007). Accordingly, SWOT is often applied with other methods to adapt it to a specific context (Ghazinoory et al. 2011; Thomas et al. 2014). This study uses the CoI framework to inform a SWOT analysis and tailor it to the context of emergency adaptation to remote teaching.

Developed by Garrison et al. (2000), the CoI framework presents a model for assessing online learning effectiveness (Garrison and Arbaugh 2007; Garrison et al. 2010). The increasing popularity of this model is attributed to its comprehensive approach and emphasis on the connection between learning and community. To assess online learning effectiveness, the CoI framework defines three elements – social presence, cognitive presence, and teaching presence – each of which is further defined by categories and indicators (Garrison et al. 2000). Social presence, which refers to emotional connection, emphasizes the importance of maintaining a social and emotional connection even through online interactions. Cognitive presence considers the ability of learners to think critically and derive meaning from what they are taught. Finally, teaching presence refers to the role of instructors in guiding learners' interactions to improve learning outcomes (Garrison and Arbaugh 2007). The CoI framework has been extensively applied since its inception and has been validated by scholars such as Arbaugh and Hwang (2006). The applications and findings of this framework are of growing importance due to the recent increase of online learning.

Both the SWOT analysis and the CoI framework have been used to independently assess a transition to remote teaching due to COVID-19 across disciplines and levels of education (O'Brien et al. 2020; Chiroma et al. 2021; Consorti et al. 2021; Oyarzun et al. 2021; Pham et al. 2021; Akbulut et al. 2022), though they have never been combined. Therefore, SWOT analysis informed by the CoI framework provides a novel approach to assess emergency adaptation to online learning. The application of the CoI framework to remote learning informs the SWOT analysis of the selected case study. This preliminary research can be divided by the three elements of the CoI framework.

Maintaining Adequate Social Presence

To maintain value, university courses and programs must foster effective online learning environments. The shift to digital course delivery can impact student-to-student and student-to-instructor interactions, which are important learning processes (Bernard et al. 2009). Information sharing is enhanced through effective social presence, referring to the student's level of emotional connection (Shen et al. 2009). Face-to-face interactions are usually more effective at fostering social presence, leading to better information exchange (Kuong 2014). The digital environment may change the way students and instructors interact, altering or reducing participation, which may be exacerbated by the challenges mentioned above.

Student-to-student interactions face challenges related to teamwork, social presence, and learning from peers (Popvich and Neel 2005; Wut and Xu 2021). Such interactions can be enhanced by encouraging students to meet outside of class (e.g., with Zoom, WhatsApp), using breakout rooms in class, peer evaluations, group work, and incentives (Wut and Xu 2021). Small group interactions allow students to connect and develop social networks (Bryson and Andres 2020).

Student-to-instructor interactions and teaching presence face challenges related to feedback and clarification processes, and fair assessment of participation (Popvich and Neel 2005; Wut and Xu 2021). These interactions can be enhanced through active encouragement of participation through questions (Desai et al. 2009; Gewin 2020; Pather et al. 2020), including the use of polls, active chat monitoring, moderation of breakout rooms, and individual/group consultation sessions. Individual consultations are especially important for students who are struggling with online learning. Instructors can proactively identify potential issues by asking students about their learning environment (e.g., adequate wi-fi signal, quiet work environment) and continuously identify struggling students through frequent check-ins (Hart et al. 2018; Gewin 2020). In response to the identification of problems related to remote learning, instructors should maintain flexibility and compromise while ensuring they communicate and clarify expectations (Moorhouse 2020; Pather et al. 2020). Tracking student participation is also important, as remote learning may reduce student accountability and open opportunities for cheating (Lancaster and Cotarlan 2021).

Maintaining Adequate Cognitive and Teaching Presence

As outlined above, the CoI framework posits that beyond social presence, cognitive presence (students' ability to understand and construct meaning from course materials) and teaching presence (the ability of teachers to facilitate cognitive and social presence) are also necessary for rich educational experiences (Garrison 2016; Tan et al. 2020). As with social presence, special considerations are needed to maintain cognitive and teaching presence online. Ensuring that educational programs continue to equip students with transferable skills, meaning the skills that are useful for students in future employment, was highlighted by Ng and Harrison (2021), who found that multi-modal teaching approaches and student self-reflection journals helped maintain student motivation. A multi-modal approach can include both synchronous (real-time) and asynchronous (self-guided) activities to maximize social engagement while providing additional flexibility (Bao 2020).

More generally, courses should be adapted and evaluated to promote learning objectives (Bryson and Andres 2020), which may be best facilitated through different teaching modes. Asynchronous and synchronous activities can support each other, facilitating extensive and intensive learning encounters, respectively (Bryson and Andres 2020). Students are more likely to gain satisfaction from activities that they perceive as purposeful; therefore, the importance of activities to the course's learning objectives should be emphasized. Overall, consideration of the CoI and maintenance of social, teaching, and cognitive presence can strengthen efforts to evaluate online course adaptations. For this reason, this paper suggests the application of SWOT analysis informed by the CoI framework, as described above. This analysis framework is demonstrated through a case study shown below.

Case Study - The MSc in IWRM Program at McGill University Québec, Canada

Overview of the Program

McGill University in Montreal, Canada, canceled in-person classes on Friday, March 13, 2020. Two weeks later, emergency remote teaching commenced, challenging instructors and students to adapt quickly. While most classes returned to in-person or hybrid instruction as of Fall 2021, many remain online, and the evolving situation may necessitate a return to a remote approach. The situation impacted classes and degree programs, including the IWRM Master's program at McGill. The one-year, 45-credit, Master of Science (MSc) in IWRM aims to foster future water professionals. The shift online in March 2020 impacted the 2019-2020 cohort mid-program. For 2020-2021, the program was offered entirely online.

Outside of the COVID-19 pandemic, the IWRM program is delivered entirely in person, providing an opportunity to study the biophysical, environmental, legal, institutional, and socioeconomic aspects of water use and management in an integrated context. Annually, the program accepts between 25 and 40 applicants, coming to Montreal from diverse locations (e.g., Mexico, Brazil, United States of America, United Kingdom, France, Germany, India, Bangladesh, Rwanda, Nigeria, Australia, New Zealand, etc.) and backgrounds (e.g., humanities, science, engineering, law). The networks that students develop with their peers, professors, and guest speakers are a benefit of the program. Furthermore, the diversity of candidates provides a multitude of perspectives that expose cohorts to a range of global water issues and governance strategies.

Students end their degree by completing a 13-week, full-time internship on an integrated water management project; thus, students graduate with theoretical and practical knowledge to support them in their careers. Over 300 students have graduated from the program, obtaining positions in industry, consulting, academia, government, politics, and non-government organizations (NGOs) worldwide (e.g., United Nations, European Union, Food and Agriculture Organization, Oxfam, Environment and Climate Change Canada, AECOM, SNC-Lavalin, WSP).

Emergency Shift to Online Teaching

When McGill shifted courses online during the Winter semester of 2020, lecturers had only two weeks to adapt their ongoing in-person courses to an online format. Students continuing their studies or starting a new program were informed that the University would continue operating online. To compensate for the lack of in-person courses, McGill and the IWRM program quickly adopted the Zoom app as the main technology to facilitate online lecturers, seminars, and meetings. By the summer of 2020, Zoom was integrated with McGill's pre-existing learning management system, MyCourses, the online portal for students to access class documents, assignment submissions, grading, groups, quizzes, and discussion boards.

To support instructors, McGill's administrators quickly published frequently asked questions (FAQ) by instructors and training opportunities to support online teaching. The administration emphasized that lecturers should reflect on their courses' objectives, and how best to achieve them online. This was done for the core MSc in IWRM courses, which helped guide online adaptation.

Core Courses in the MSc in IWRM Program

The IWRM program includes a mix of compulsory and elective courses, totaling 45 credits; this paper analyzes the adaptation measures of the five courses that are compulsory to the program. Each course is described briefly in terms of topic, format, learning outcomes, and online adaptation. The courses are shown in Table 1, including short-form names used in this paper.

Water Policy (BREE 503: Water: Society, Law and Policy)

Water Policy is a one-semester course to familiarize students with water policy issues and equip them with the transferable skills needed to understand, discuss, and analyze water problems and policies. Topics include transboundary water management, IWRM, Canadian water policy, ethics, public involvement, Indigenous water issues, and international water governance.

The course, which includes one three-hour lecture per week, has three modules in which students (1) write and present a review of two journal articles (from pre-selected papers), (2) prepare a paper on an issue of choice, and (3) complete a written review of an assigned water policy book. Typical classes begin with student presentations, followed by lectures by guest speakers; roundtable discussions follow both. Given this format, the course puts a greater emphasis on peer-to-peer learning than traditional lecturing. The instructor acts as a facilitator, guiding dialogue about the policy issues associated with student presentations. Students are required to contribute to roundtable class discussions.

Adapting Water Policy to an Online Format. To adapt Water Policy online, specific issues needed to be addressed. The basic structure of the course could be maintained through Zoom if students could participate synchronously. However, as the MSc IWRM program was offered online in 2020-2021, some students stayed in different countries and time zones, creating challenges for scheduling. The 2020-2021 class was comprised of 17 students: three from Africa (Rwanda, Ghana, and Nigeria), two located in the U.S., and the rest from across Canada.

A short questionnaire was prepared and sent to students a month before the course to ascertain their expectations, availabilities, and technological capacities. The questionnaire was crucial to designing the adapted course, as it confirmed that everyone was capable of synchronous participation. If not, students could have participated asynchronously through pre-recorded presentations or class recordings.

Class materials, such as PowerPoints and readings, were uploaded to MyCourses in weekly modules, and students were encouraged to email the instructor with questions. Selection of the journal articles to review is easier in person, as it ensures that students have equal opportunity to select papers of interest while guaranteeing that

Table 1. Overview of the courses analyzed in this research.

Shortform Name	Full Course Name	Course Code	Semester	Credits
Water Policy	Water: Society, Law and Policy	BREE 503	Fall	3
Water Management	Watershed Systems Management	BREE 510	Fall	3
Research Visits	IWRM Research Visits	BREE 655	Winter	3
IWRM Internship	IWRM Internship	BREE 630	Summer	13
IWRM Project	IWRM Project	BREE 631	Summer	6

there are unique presentations each week. Despite coordination challenges, this process was carried out successfully via email. Most students gave presentations using Microsoft PowerPoint through the Zoom share-screen function. Class recordings were uploaded on MyCourses for students to review.

A weekly reflection journal was added to the online format, where students were asked to comment on each class and make suggestions for improvements. Full class roundtable discussions were difficult to manage online, therefore, the breakout room feature in Zoom was adopted to create more manageable discussions. Post discussion reports were provided by a group representative to the class. The lecturer entered and exited breakout rooms to check on and facilitate discussions.

To replace traditional office hours, private Zoom meetings were available for students; these meetings also replaced the typical informal conversations before and after in-person class. While the grading scheme was not changed, all assignments were graded electronically. The journals were semi-voluntary; marks could be deducted if students failed to submit any material. Weekly feedback participation was almost always 100% and was easy to read and track due to the small class size (17 people).

Water Management (BREE 510: Watershed Systems Management)

Water Management is a weekly three-hour class covering the purpose, content, and implementation of two main water management frameworks, IWRM and Adaptive Management (AM), and highlighting specific aspects of the planning processes including stakeholder engagement, modeling techniques, planning across jurisdictions, and monitoring and evaluation. The class is larger (40-60 students), as it is also open to senior undergraduate students. Case studies are used, along with guest speakers who differ from the guests in Water Policy. The course helps equip students to analyze water resource management issues and design appropriate water resource and AM plans. Transferable skills include problem analysis, strategic planning, data collection, synthesis, and teamwork.

Water Management follows a lecture-style format; PowerPoint presentations on the weekly topic are given, often followed by a guest lecture and question and answer session. Mandatory readings are provided online. Students are evaluated on the following: (1) an individual journal-style article about a water issue of choice, (2) class participation, and (3) a group watershed study and presentation. In the group project, students study a watershed and make recommendations to improve management and governance, and are encouraged to interview various watershed stakeholders. Students also perform a group participatory model-building activity, giving them insight into this unique stakeholder engagement tool.

Emergency Adaption of Water Management Online. Similar to Water Policy, the structure of Water Management lent itself to being adapted online. The class relies heavily on readings (asynchronous learning) and lectures (usually synchronous), which were easily transferred to the Zoom platform.

One main challenge was adapting the participation grading methods as some students could not participate synchronously due to time zones. As such, attendance was not recorded and participation grades were assigned based on the student's group project peer reviews. The size of the watershed project groups was also reduced from 4-8 members to 3-6 members to improve the ease of coordinating online. During lectures, students were asked to use the "raise hand" button in Zoom or to post in the chat to ask questions.

The submission and evaluation processes were moved to MyCourses, while communication was arranged through emails (and sometimes Zoom). A discussion board was created for each weekly topic to facilitate ad-hoc discussions. The participatory model-building activity was completed individually online, rather than in groups.

Research Visits (BREE 655: IWRM Research Visits)

Research Visits is a course consisting of class visits to firms and agencies working in the realm of IWRM, as well as guest lectures given by experts from the field. Under normal circumstances, students have field trips during alternate weeks. During other weeks, the professor leads class discussions revolving around current issues and trends in water resources management. Examples of regular speakers include staff from Environment Canada, the International Joint Commission, the United Nations, many NGOs (e.g., Winrock International), AECOM, SNC-Lavalin, Hydro-Quebec, local water and wastewater treatment plants, and professors from diverse universities (e.g., Alberta, Waterloo, Texas A&M).

While guest speakers are an integral component of other IWRM classes, this class goes further, providing students with insights regarding future career prospects. The lectures and shadowing experience provide students with networking opportunities and a better understanding of which career path would be best for them based on their interests, skills, and desired work environment.

Emergency Adaptation of BREE 655 Online. Unlike Water Management and Water Policy, the Research Visits course structure was negatively impacted, as COVID-19 restrictions canceled class visits. Instead, the classes comprised of guest speakers only and facilitated discussions through Zoom. Like the previous classes, assignment submissions were handled online. To resemble in-person courses, students were encouraged to ask questions to guest speakers through the chat or with the raised hand function. Finally, classes were recorded to accommodate others in various time zones.

IWRM Internship (BREE 630) and IWM Project (BREE 631)

IWRM Internship and associated IWRM Project courses are critical components of the IWRM program. Although the internship and project occur in the program's final semester, students are oriented to the requirements and expectations of the internship from the beginning. The internship involves placement in a government, university, or private sector agency/organization full-time for thirteen weeks, where students must work on a research project related to water resources and prepare a formal report on the research performed. Students are responsible for finding their placements. The IWRM Project requires students to write a research paper or 'plan of action' regarding the work done in their internships.

IWRM Internship and Project aim to teach students how to transfer the knowledge they obtained throughout their MSc degree to real-world applications. Additionally, the classes give the students practical experience working within the realm of IWRM, emphasizing soft skills such as project management, teamwork, communication, professionalism, and knowledge acquisition and mobilization.

Emergency Adaption of IWRM Internship/Project Online. These classes were also heavily impacted by the pandemic in both format and results. Many of the 2019-2020 cohort students found their internships being canceled or significantly reduced in scope. As a result, the requirements for the internship and project were more flexible, with many students working independently on a research project under the supervision of their original host institution or a professor from McGill University.

Results and Discussion

The SWOT framework was applied using the observations of the authors who were directly responsible for teaching and adapting these courses online to analyze the strengths, weaknesses, opportunities, and threats of the online adaptation efforts described above. The adaptation of each class is discussed together to aid comparisons and glean insights.

Strengths

A strength of the online format is that it allows students to study from wherever they are, lowering relocation costs (Watermeyer et al. 2021). The formatting of both Water Policy and Water Management made online adaptation simple to design and implement, ultimately preserving learning outcomes. In both classes, asynchronous learning was facilitated through readings and lecture recordings, which helped accommodate students experiencing poor internet connections or time zone differences. A greater diversity of guest speakers was possible in Water Policy, Water Management, and Research Visits, as travel to McGill University was not required for participation. The online format offered students options to engage speakers, participants, and classmates through the chat function or video. Course evaluations revealed that students were enthusiastic about the guest speakers.

The overall reduction in class interactions proved to have some benefits. For example, in Water Management, the less interactive format benefitted students who faced technical difficulties; recorded lectures allowed students with unstable internet access to access class content they otherwise would have missed after the live sessions. Furthermore, these recordings allowed all students to revisit class content, which can be beneficial for students with learning disabilities (Maccini et al. 2002) as they can replay videos at slower speeds or multiple times, better facilitating cognitive presence. Finally, the pandemic situation established a new precedent for course recordings, even when in-person lectures returned.

The online format caused students to increasingly ask questions with email, which caused answers to be recorded, unlike in impromptu conversations. Students could also schedule one-on-one Zoom meetings, allowing them to ask numerous questions, facilitating student-to-instructor learning and teacher presence. For Water Policy, breakout rooms were integral for maintaining peer-to-peer learning and cognitive presence. Breakout rooms also gave students a space to socialize and form peer networks like in traditional classrooms. Furthermore, the weekly feedback forms helped to maintain student-to-instructor learning. For the IWRM Internship and Project courses, while students in the 2019-2020 cohort lost opportunities due to travel restrictions and the impossibility of in-person work, many students gained skills in working independently. Additionally, some students were able to work remotely with a university or organization that they otherwise may have been unable to work with due to financial considerations (e.g., travel to a foreign university).

Weaknesses

A significant weakness of online delivery was the lack of opportunities for impromptu face-to-face discussions. Some students felt uncomfortable asking questions in Zoom classes, limiting teacher-to-student interactions. Similarly, the online environment reduced impromptu socialization opportunities at the beginning and end of classes with peers and guest speakers. This is especially relevant as interactions with guest speakers often assist students in finding internships. Similarly, many students preferred to have their cameras off, which reduced social connection and corresponding social presence (Castelli and Sarvary 2021).

Aside from the internship, the present authors also observed that roundtable discussions after presentations in Water Management, Water Policy, and Research Visits were less animated than previous years. However, the use of breakout rooms in Water Policy helped remediate this issue. Furthermore, in a larger class such as Water Management, it was difficult for the instructor to lecture, moderate the chat for questions, and look for "hands up" among over 40 individuals. As a result, some questions were missed during the lecture time. Some students found the three-hour lecture format to be tiring and wanted it to be more interactive. Multiple students felt the pandemic increased their workload, especially given the required reading for Water Management. Finally, while the Water Management discussion board had good intentions, students rarely used it, likely because participation was not mandatory.

In Research Visits, a lack of in-person site visits reduced students' exposure to different workplaces. While guest speakers partially made up for this, presentations are less interactive than physical visits. Additionally, students were less inclined to ask questions over Zoom than when taking a site tour.

The online presentations by students in both Water Management and Water Policy – a key aspect of both courses – were more challenging than in-class presentations due to technical challenges, internet connectivity issues, and maintaining overall focus. The quality of presentations was also slightly diminished; some students resorted to reading off slides instead of speaking naturally.

Regarding the internship, there were two identified challenges. The majority of students could not travel to their intended internship destination and missed out on in-person benefits such as close collaboration with the host and networking. In some instances, funding for the internship was no longer provided since the students were not 'on-site.'

Opportunities

Within many of the weaknesses, there are opportunities. For example, a solution for poor connectivity or time zone differences is to pre-record presentations; however, this may take away from live presentation skill development. As was shown in Water Policy, having frequent breakout rooms and informal weekly reflections led to high levels of engagement in the class that rivaled in-person delivery. Given that students and instructors are now more experienced with online applications, there are additional opportunities to enhance class discussions. In Water Management, the use of interactive components, such as polls, quizzes, breakout rooms, and other technologies (e.g., online whiteboards), could reduce the monotony of the lecture-based class and improve engagement (Gewin 2020; Pather et al. 2020). However, as Water Management is a larger class, it would benefit from a teaching assistant to help with chat moderation and other interactive components. Adding more frequent short breaks could also help break up the class and keep people attentive.

Remote classes open opportunities for a greater variety of guest speakers, a key component of the program. Guest speakers can deliver presentations from anywhere, allowing for speakers from farther parts of Canada and the U.S. However, remote guest lectures could be continued if in-person classes resume.

Finally, remote learning may create opportunities for people to join the program who could not afford both the tuition and living costs in Montreal, allowing more students to partake in a ‘virtual global education’ without barriers to immigration and travel (Krishnamurthy 2020). This is important, as water issues impact every area of the globe and necessitate a diversity of water resources practitioners. Furthermore, having the program online could help the program build international connections, giving students more opportunities to find internships in their own communities while helping them build impactful networks close by. Remote learning can also facilitate accessibility; for example, some workplaces visited during Research Visits, such as wastewater treatment plants, may not have been wheelchair accessible, potentially excluding students from participating.

Threats

Simultaneously, unequal global information technology threatens the participation of some students (Aristovnik et al. 2020). Furthermore, if offered remotely, some potential applicants may question whether the tuition fees match the value derived online. Therefore, the program directors and McGill must either reconsider tuition costs or redesign program components to ensure that the value is maintained remotely, presenting a logistical and marketing challenge. A key aspect of this value is networking, both with peers and guests; however, this could be facilitated online through Zoom or an interactive software.

While remote learning can reduce barriers to participation, it can also reduce the quality of student participation. For example, it was easier online for students to not participate fully in group projects, class size limited group discussion, and student questions could get lost in the chat. Without proper adaptations, such as teaching assistants for larger classes, cognitive presence can be limited and students may be left with a poorer understanding of the material. During the internship, the professor and teaching assistant noted that students had difficulties staying self-motivated, falling short of expectations, and highlighting the need for greater engagement and accountability. However, most of these threats can be dealt with by minding key considerations, as discussed below.

Key Insights

Through the application of SWOT analysis, as informed by the CoI framework and its three components (teaching, social, and cognitive presence), to evaluate the rapid adaptation of the IWRM MSc program online, various broadly relevant key insights were discovered.

To facilitate cognitive presence and set expectations, it is important for students to have early access to a **Course Outline** that reflects the course’s remote delivery. This requires careful modifications to the in-person Course Outline from previous years. In all aspects of course delivery, including the outline, clear communication of requirements and expectations is vital and should be provided well in advance. Expectations should be reinforced periodically through lectures, emails, and class announcements.

It is also important to quickly reach out to students in a **personal way,** which facilitates student-to-instructor learning and teaching presence.

Moreover, providing ample opportunities for one-on-one meetings through scheduled office times or personal Zoom meetings is helpful, especially for struggling students (Hart et al. 2018).

It is often easier to engage students in person than online. Therefore**, demonstrating enthusiasm** for the course material cannot be overemphasized. Beyond adopting an enthusiastic demeanor, efforts are needed to ensure lectures are not monotonous. For example, slides can be modified to include more pictures and video clips. Exercises, such as group discussion or writing prompts, can be used to break up long lectures. Interactive software can also be used to facilitate group work and the co-creation of diagrams. Giving a varied course experience can help students avoid developing online learning fatigue, improving cognitive presence (Pather et al. 2020).

Feedback, through regular journal entries, feedback forms, or a mid-course questionnaire, is helpful to determine how the course is being received and what issues need to be addressed, especially since instructors do not receive the same social cues and informal feedback online as occurs in person (Desai et al. 2009; Gewin 2020).

To facilitate social presence and student-to-student interactions, smaller group discussions like **breakout rooms** can provide students with opportunities to socialize with their peers (Wut and Xu 2021). Students are often more willing to participate in smaller groups, facilitating greater engagement (Kim 2013). As students may not have the same peer support networks online as in person, it is important to be considerate of **psychological issues and direct** students to the university's mental health services. Program directors can further facilitate social presence by offering online events, such as meet and greets.

Overall, when transitioning an academic program to an online format, it is best to **expect the unexpected**; students will sometimes have technical difficulties, requiring rescheduling of presentations to future weeks. Preparation and foresight are key to handling these situations, which are almost guaranteed to arise. For example, if possible, having a backup guest speaker is beneficial.

Breaks are also important for both the lecturer and the students, especially if the class is three hours long. Students clearly communicated that it was important for them to have two breaks, one after each hour. Sufficient breaks are also an important aspect of avoiding online learning fatigue (Shoshan and Wehrt 2021).

Although it is preferred, not every student chooses to use the **video aspect** of online communication, and it is not possible to require them to do so. As a result, each class is likely to be a mixture of students appearing on camera and others not, with their screens black. This should be accepted; the most important indicators of student engagement are presence and participation, neither of which require video.

Finally, **prioritize student engagement online.** If students are not engaged (e.g., not asking or responding to questions), it can be useful to call on specific students. Consequently, students may be more alert since they are anticipating being called on. If certain students are not participating at all, it is important to reach out to them individually to establish a teaching presence through student-instructor interaction. Peer evaluation can also be used to encourage student-student interactions when working on group projects.

Conclusion

While many of the IWRM classes have now returned to an 'in-person' format, the rapid adaptation of the program online has shown that remote learning, or a hybrid approach, may be a feasible future for the program. Indeed, classes such as Water Policy continued to be offered online for the Fall 2021 semester. However, if online or hybrid classes are going to become a permanent fixture of the IWRM MSc program (or any MSc program), it will be important to build on the findings of the literature and SWOT analysis to ensure course objectives are met and transferable skills are preserved.

As was found in this study, remote teaching of water management can create opportunities for students to participate globally, eliminating the need for (often high) translocation costs. Similarly, online delivery can allow for a wider range of guest speakers, providing a more enriching experience and exposing students to greater career options. However, additional efforts must be taken to preserve processes that facilitate learning. In many cases, the standard lecture-style format must be amended to include more breaks and varied activities. Furthermore, instructors need to pay attention to facilitating peer-to-peer interactions (and networking) online through, for example, breakout rooms. From a program perspective, it is important to rework not only classes but also other components (such as social activities) to preserve value and student experience. In the case of the IWRM MSc program, more work is needed to ensure that the internship experience is valuable for students participating remotely. Program administrators have determined that in-person internships remain a priority as these tend to give the students the most value, though they can take place globally.

While this paper focused on one water management program, both the information uncovered through the literature review and the evaluation tool combining SWOT with the CoI are widely applicable to other post-secondary programs. The developed framework is a particularly useful methodology for evaluating the adaptation of in-person classes to online formats, helping to identify areas of excellence and improvement and preserve transferable skills. Overall, this type of analysis is crucial to understand successes and areas for improvement, to maintain educational standards for both students and professors in future scenarios when courses are adapted to an online format.

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South Texas Water Resource Mental Models: A Systems Thinking, Multi-stakeholder Case Study

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Abstract: The Coastal Bend (CB), Lower Rio Grande Valley (LRGV), and Wintergarden (WG) subregions of south Texas co-exist in similar socio-economic contexts but rely on markedly different water sources (CB: precipitation; LRGV: surface water; WG: groundwater). This has led to unique agricultural practices and municipal policies and reinforced mental models adapted specifically to each subregion, both of which are critical to understanding structural causes behind current water use and future water sustainability. To better stakeholder mental models in each subregion, semi-structured interviews were conducted with individuals with a significant stake in water resource use and management. Results indicated near unanimous consensus among farmers and other stakeholders that water supply is limited and will be increasingly stressed under continued urban population growth. Farmers expressed concern that it will become more difficult to continue farming if additional water resources are not available, while each subregion expressed their own unique concerns: growing bureaucratic oversight and growing population problems (CB), lack of inflows, poor water quality, and international disputes with Mexico (LRGV), and political subdivision, declining groundwater levels, and information technology costs (WG). Mental models were synthesized based on dominant themes expressed by respondents; we synthesized these into two systems thinking archetypes: Tragedy of the Commons and Success to the Successful. Though it is unreasonable to create blanket region-wide policies, the adoption of under-utilized conservation practices coupled to stakeholder outreach remains unexplored leverage points, given most stakeholders are unaware of the feedback processes continuing to threaten south Texas water resources.

Keywords: *water management, mental models, systems thinking, stakeholder analysis, Texas*

South Texas is a major agricultural region reliant upon three distinct water sources: precipitation in dryland cropping systems in the Nueces River watershed and surrounding Coastal Bend (CB) plains; surface water flows for ditch irrigation that are generally low quality in the Lower Rio Grande Valley (LRGV) (Vargas 2019); and groundwater sources for pivot sprinkler irrigation in the Wintergarden (WG) area (Figure 1). Each subregion is stressed by water availability and quality fluxes that are often exacerbated by management of cropping and irrigation system decisions as well as drought conditions which limit crop productivity, streamflow, and groundwater recharge (Figure 2). Additionally, each subregion faces unique water quality challenges, such as nutrient loading and urban stormwater runoff problems, leading to excessive aquatic plant growth and potential disease transmission pathways in the LRGV, or perennial salinity issues due to poor soil quality and declining groundwater tables (CB and WG). Each subregion is additionally stressed by population growth and economic development (which compete with agriculture for both land and water), including water sharing agreements with Mexico (CSIS 2003; Fischhendler et al. 2004; Carter et al. 2017) and escalating effects of climate change (Seager et al. 2007). Cumulatively, these threats put the sustainability of south Texas water resources at risk, escalating pressure on agricultural

Research Implications

- Stakeholder mental models expressed more concern than optimism and contained unrecognized vicious feedbacks connecting to other stakeholders.
- These mental models and feedbacks must be recognized if adaptive water management is to succeed.
- Collaboration and better communication are high-leverage strategies needing investment for improved water resource management.

stakeholders to minimize water losses, which often requires investments or tradeoffs too costly for many irrigation districts or producers to consider (e.g., relining ditches or replacing failing pipe systems in the irrigated areas, or investing in alternative nutrient management or cropping systems in the dryland areas). Research from similar contexts around the world has shown that attempting to solve any one of these issues in isolation has led to far-reaching, unintended ecologic, hydrologic, or economic consequences (e.g., reduced ecosystem services as result of effort to minimize conveyance loses; greater per capita water use in the face of water rationing policy; increasing investment in agricultural land and therefore irrigation demand as a result of investment in maximizing irrigation efficiency) (Gohari et al. 2013; Breyer et al. 2018; Di Baldassarre et al. 2018; Grafton et al. 2018).

Such complex, dynamic trade-offs have increasingly led investigators to adopt a systems approach to problem-solving (reviewed in Turner et al. 2016a, with exemplary case-study examples in Stave 2003 and Gunda et al. 2018). For all these reasons, holistic water management research is becoming increasingly important in this semi-arid region facing increasingly frequent and severe droughts. Unfortunately, decision-making models integrating hydrologic, ecological, agronomic, and socio-economic structures (similar to Turner et al. 2016b and Gunda et al. 2018) specific to south Texas, needed to compare tradeoffs from various coping strategies or their impact to other ecosystem goods and services requiring conservation and enhancement, are not available.

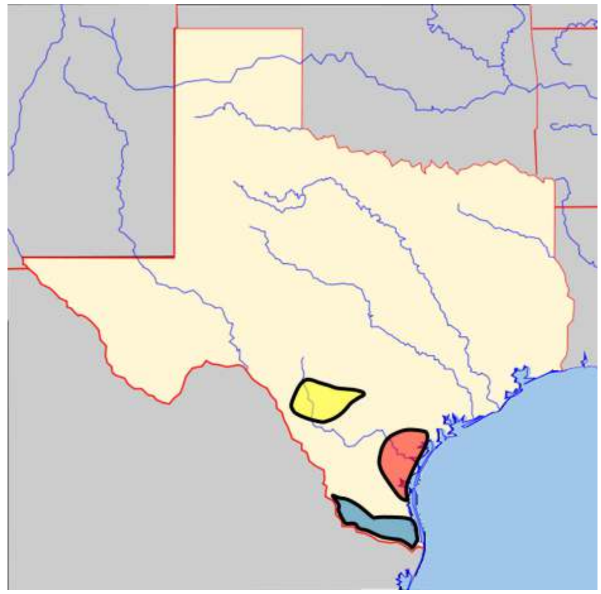

Figure 1. Map of south Texas illustrating the three project study areas: Wintergarden (yellow shaded), Coastal Bend (red shaded), and Rio Grande Valley (blue shaded). Modified "Blank map of Texas" by "Angr" is licensed under CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0/deed.en).

Although identifying farm- and catchment-scale drivers may reveal dynamic linkages between uplands with irrigated landscapes previously not emphasized, a better understanding of water resource stakeholders' decision-making goals, constraints, and mental models (by which decision-makers process information) is vital to improve model realism, quality, and adoption and use by stakeholders.

Objectives

The primary focusing question of our case study was the following: why do south Texas stakeholders struggle to balance the current water needs of diverse users with conservation efforts for everyone's long-term benefit? The goal or objective was to uncover the predominant mental models of individuals who maintain a high stake in water resource management in the CB, LRGV, and WG areas of south Texas. By doing so, this work aims to more usefully inform regional scientists currently developing improved quantitative management models for decision-support purposes; without capturing valuable mental model information,

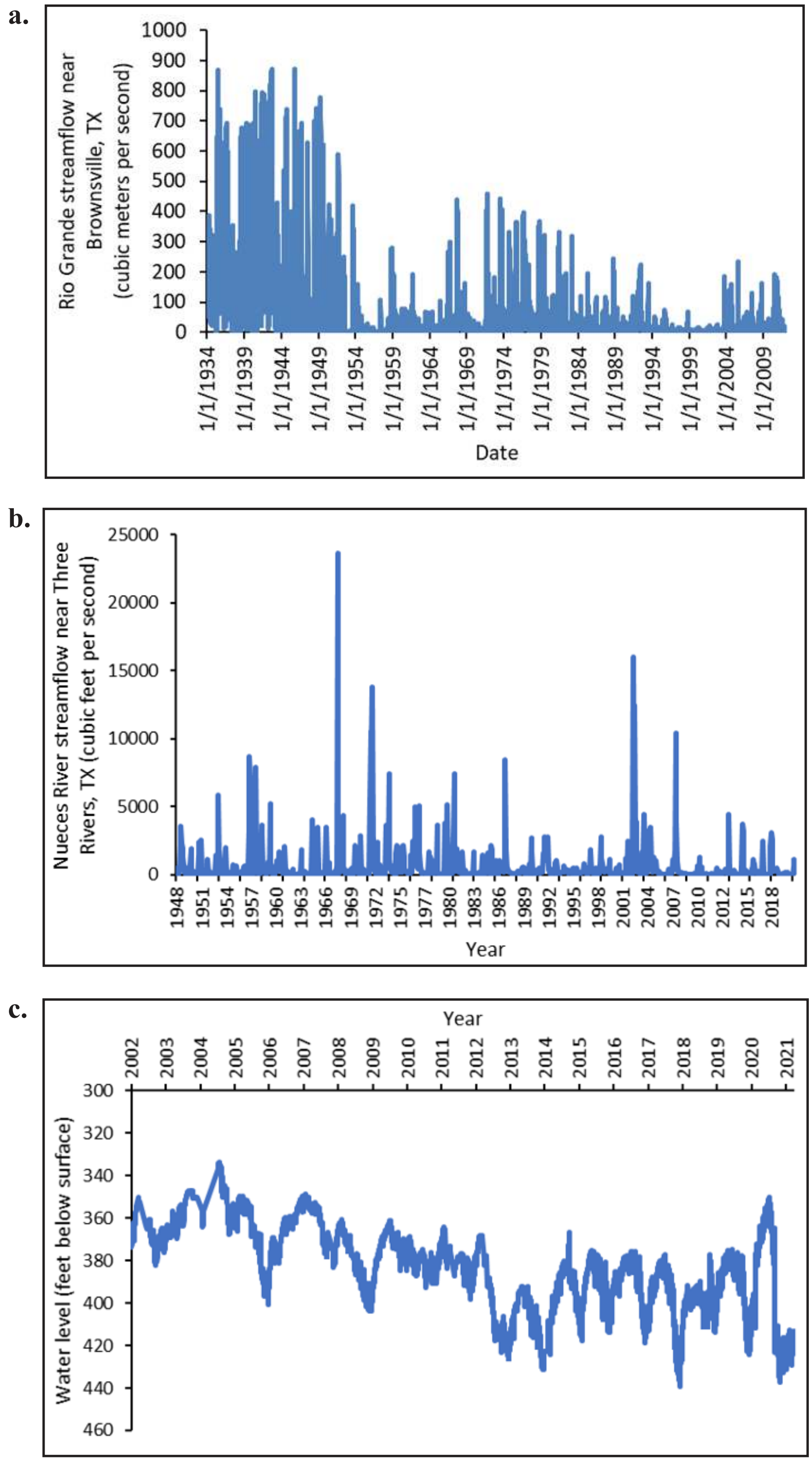

Figure 2. Illustration of stressed water supply sources in south Texas. (a) Rio Grande streamflow near Brownsville, TX, 1934-2021 (IBWC n.d.). (b) Nueces River streamflow near Three Rivers, TX, 1948-2021 (USGS 2022). (c) Carrizo-Wilcox groundwater levels near La Pryor, TX, 2002-2021 (Texas Water Development Board 2022).

important conceptual considerations, objective function assumptions, and/or modeled feedback processes may not be representative of decision-maker considerations in practice, therefore running the risk of disseminating decision-support tools of limited utility. Mental models tend to be accessible and enduring, albeit limited, conceptual representations about the world around us and how it works (Senge 1990; Doyle and Ford 1998).

To begin, we outline the general background policy context of Texas and the characteristic water sources used in each subregion: CB, LRGV, and WG, respectively. We then describe a qualitative data collection process using semi-structured interviews to elicit mental models of water resource stakeholders in each subregion. Analysis of interview responses is then presented. Finally, using concepts from the systems thinking methodology (Senge 1990; Sterman 2000), we generate integrated mental model descriptions of each stakeholder group and synthesize their high-level observations and concerns into causal loop diagrams (CLD), which illustrate the pressing water resource challenges using structural feedback mechanisms. The case study concludes with management and policy implications and questions for future investigations needed to find tangible solutions that are both socially acceptable and economically feasible.

Background Case Study Information

Policy Context

Water rights and resource use in Texas have historically been driven predominantly by economic forces, grounded in private property or "right of capture" legislation (Texas State Library and Archives Commission 2016). Given the variability of water fluxes (described below) and the multitude of stakeholders involved, this approach has made water sharing difficult, which is exacerbated during droughts (Sturdivant et al. 2007).

Legislation has evolved to reserve portions of current water storage or reduce pumping volumes for times of water scarcity (where municipalities and irrigation and groundwater districts have instituted such measures), although in many cases surface rights holders maintain their "right of capture." Texas began issuing water rights for surface water stakeholders in the 1890's (Texas State Library and Archives Commission 2016), but did not recognize the importance of protecting water for the conservation of aquatic ecosystems until 1985 (Sansom 2008).

Texas groundwater regulation is severely lacking relative to its surface water counterpart. Groundwater ownership is predominantly still regulated by the right of capture. The creation of groundwater districts is the exception to the rule of the right of capture. In applicable areas, groundwater districts develop and manage groundwater resource plans, address conservation, and adopt rules of procedure for their respective districts (Texas A&M University 2014).

Bordering both Mexico and the USA, the Rio Grande River has its own unique set of policy characteristics. Because it is both a water source and international border, distribution of water rights is determined by international treaty, the most recent of which was agreed to in 1944. Besides specifying water rights and delivery obligations, the treaty also dictated that both countries construct and operate dams along the main channel of the Rio Grande (IBWC 2021). Populations in south Texas and northern Mexico have grown and precipitation has decreased due to more frequent droughts, resulting in failures to meet 1944 treaty agreements and rising tensions between the two countries.

Sources of Water Supply and Its Variability

The CB, WG, and LRGV subregions rely on different water sources for agricultural, industrial, and municipal use, despite their close proximity.

Coastal Bend. In the CB, precipitation is the primary water source for agriculture, groundwater being too saline, while municipalities rely on surface water storage on the Nueces River. Due to the scale of row-crop agriculture (primarily cotton and sorghum) in the CB plains, limited surface water flow and storage potential on the Nueces River, and demand for water in Corpus Christi and surrounding municipalities, the majority of CB surface and groundwater supplies are owned by the City of Corpus Christi and the Nueces River Authority and reserved for municipal and industrial use (Coastal Bend Regional Water Planning Group 2015). Historical rainfall varies in range from 13.6

to 35.7 cm per year and predicting precipitation is not reliable (Murdock and Bremer 2016). Therefore, agricultural stakeholders must manage water resources during droughts differently compared to WG and LRGV areas (primarily through crop insurance rather than water sharing agreements).

Wintergarden. The WG area produces fruit and vegetable crops and relies predominantly on groundwater for both agricultural and municipal use. Major aquifers include the Edwards, Trinity, Edwards-Trinity, and Carrizo-Wilcox. The mean water depth for the area from 1940 to 2021 was 37.58 feet below land surface with a standard deviation of 15.14 feet (Texas Water Development Board 2021a). The Uvalde County Groundwater District predicts that future demands are going to continue to outpace inflows of supplies for the area, with the City of Uvalde taking the largest net deficit (UCUWCD 2015).

Lower Rio Grande Valley. The LRGV is well-known for diverse fruit, vegetable, and row-crop production and relies on surface water for irrigation. Rio Grande flows are stored at Falcon Reservoir, located southeast of Laredo, Texas. Irrigation districts order water from the reservoir and then divert via pumping from the river to canals that deliver to both farms and municipal providers. The Falcon reservoir has a 2,646,813 acre-feet conservation storage potential, of which 59% is allocated to Texas (lifetime mean actual storage = 1,550,632 acre-feet, standard deviation = 821,892 acre-feet; Texas Water Development Board 2021b). The average Rio Grande flow below the Falcon reservoir from 1958-2011 was ≈88 cubic meters per second with a standard deviation of about 118 meters per second. The Rio Grande flow near Brownsville/Matamoras from 1934-2011 was ≈44 cubic meters per second with a standard deviation of about 95 meters per second (IBWC n.d.).

Materials and Methods

Stakeholder Analysis

Stakeholder analysis is a method for understanding stakeholders' reasons, purpose, regard, and behavior and how the relationships between those factors would influence their resource use and decision-making (Brugha and Varvasovszky 2000). Stakeholder analysis is a useful approach to identify convergent (reinforcing) or divergent (destabilizing) economic, social, and ecological problems confronting stakeholders (Moodley et al. 2008). Whereas stakeholder analysis has a longer history in social or corporate management situations (Preston 1975; Carroll 1991), its use in agriculture and natural resources areas is growing, including in natural resources management (e.g., Mayagoitia et al. 2012; Turner et al. 2014). In this study, formal interviews were conducted with various stakeholders involved in south Texas water use. For analysis purposes we grouped participants into two categories: those directly involved in management of production agriculture (e.g., farmers and ranchers; denoted as x_f), and those involved in the management or use of water resources but not directly production agriculture (e.g., irrigation district managers, extension agents, urban managers; denoted as x_s).

Interview Methods

Data were collected using semi-structured interviewing methods, where the researcher starts the interviews with a fixed set of questions for the interviewee to answer but permits the discussion to diverge depending on the discussion (Hancock et al. 2007). An advantage of utilizing semi-structured interviews is that it gives the researcher the ability to identify in-depth insights into stakeholder ideals and relationships, as well as the ability to link sources together (Reed et al. 2009). Due to health concerns stemming from the COVID-19 pandemic, no face-to-face interviews were done. Interviews took place either over-the-phone or through a video conference medium (e.g., Zoom) at the individual participant's discretion.

The interview guide consisted of a total of 15 open-ended questions per stakeholder (summarized in Table 1). However, questions were broken up and were varied between different stakeholders in different fields (i.e., dryland vs. irrigation reliant farmers, producers vs. industry stakeholders). The audio from the interviews were recorded and transcribed for further analysis.

Coding Procedures

Open coding was used to define stakeholders' problems and their boundaries, and to distinguish

Table 1. Interview sections with example questions.

Interview Sections	**Sample Question(s)**
Enterprise and water resource description	• How would you describe the nature and scope of your operation? • In terms of water sources, are you most dependent on surface water, groundwater, or precipitation? • In your area, what do you consider the most pressing issues or problems regarding water resources and their use?
Current tradeoffs and long-term insight	• In your area, is there a particular irrigation system (furrow/flood, sprinkler, drip) that you rely on for water delivery? If so, what are the advantages and disadvantages of that particular irrigation system? • Do you foresee any long-term economic or environmental consequences of current irrigation practices in your area (e.g., water quality degradation)?
Public policy and resource conservation	• In your area, how is water shared amongst user groups? Have there been any conflict or frustration among users due to these agreements or lack thereof? • In your area, how influential is local or state water policy in your water use or water management decisions? • In terms of water resource sustainability, what steps, if any, have been made in water conservation efforts to sustainably manage water in your area?
Personal perspective and emerging technology	• From your perspective, what emerging technologies and/or management practices hold the best promise for improving water resource sustainability conservation in your area? • From a personal perspective, how would you describe your own personal values that guide your management of and advocacy for improved water resource management?

apparent variables and mental models as they relate to other factors relevant to south Texas. Each transcribed interview was read and color-coded based on sustainable water-use related factors. For example, water inflows and outflows were colored blue. Environmental externalities were colored green. Urban water factors were colored grey. International issues were colored red. Agriculture management, technology, and traditions were colored purple. Lastly, any other miscellaneous factors were colored yellow.

Axial coding is the process where disparate data from various respondents are aggregated by common trends and patterns among the different categories of code, as described above. This process is similar to knowledge mapping, which also utilizes semi-structured interviews to help recognize different variables from stakeholder interviews (Reed et al. 2009). Memoing was used widely throughout axial coding to describe implicit structure, sub-factors within a given color code (e.g., commodity prices or input costs within the open coded "economics" theme), general observations, and sometimes questions to be reflected upon later.

After the coding procedures were complete and interview data were processed, a systems thinking perspective was applied to synthesize the stakeholder responses into a conceptual model (Sweeney and Sterman 2000; Kim and Anderson 2012), in this case an archetype-based CLD, that best reflected the problematic water resource dynamics of concern in south Texas. By doing so, we made explicit causal connections of the feedback processes at work that stakeholders are subject to, and that they identified during the interview process. This approach has been used in other domains where interview data were directly converted in a CLD (Kim and Andersen 2012), including agricultural and natural resources (Turner et al. 2014). In this case, due to the responding categories from open coding, we examined the responses as a whole to identify commonly occurring descriptions of feedback, and then illustrated those in the form of systems thinking archetypes (Senge 1990).

Stakeholder Factor Analysis

A structured approach, identifying sub-factors within each theme from open coding, was used to characterize the level of stakeholder interest across responses. A stakeholder-factor matrix, following Moodley et al. (2008), was constructed to quantify priorities of each response group and understand any interactions or divergences among regions or major themes. The matrix was created by counting the number of instances certain responses or arguments were raised from each respondent group within the aggregated (axial) coding. The matrix allowed for relatively rapid identification of the most important sub-factors for each response group.

Author Involvement and Sampling of Interviews

The amount of time the author spent with each participant varied between stakeholders. Most interviews were kept within an hours' time; however, the amount of time spent with each participant differed due to individual schedules and logistics. Students enrolled in an undergraduate agribusiness class, Decision Support Tools in Agriculture, were employed to collect some but not all of the interview data for this project, with the first author completing the remainder. All interviewers completed Collaborative Institutional Training Initiative (CITI) training for human subjects research. All of the interviews conducted by the first author and student assistants occurred either through a video streaming medium (e.g., Zoom) or through a recorded phone call. Although the physical appearance, attitude, and domain experience of the interviewer is known to influence interviewee responses (see discussion in Turner et al. 2014 for example), it was assumed that these were marginal given the method of interaction. Other contextual factors, such as when and where the respondent chose to answer questions, likely outweighed any potential bias introduced from the interviewer. However, the lack of physical presence may have had other consequences on responses, such as how respondents perceived the importance of their responses, given the lack of personal interaction and non-verbal ques with interviews. This was evidenced by a shorter than expected average interview time (around 30 minutes). In total, 30 participants were interviewed (4 WB, 7 CB, and 19 LRGV; Figure 1).

Results and Discussion

Open Coding

As expected, the recorded perspectives about water resource management and allocation evaluated in the CB, WG, and LRGV subregions were distinct from another. While some common themes did emerge from reviewing the transcripts, including water quality concerns and the role of government programs (Table 2), there was not enough evidence to suggest that a wide range of high-level water resource management issues were shared between the regions.

Water Supply and Quality. Stakeholders referred to the Texas State Soil and Water Conservation Board (TSSWCB), the United States Department of Agriculture (USDA), and the Texas Commission of Environmental Quality (TCEQ) when regarding the minimum quality standards that must be met for public drinking water. On the other hand, water that is intended for agriculture use utilizes different standards. Key stakeholders delineated the difference between raw and treated water uses in that raw water is extracted from its source, not put through any filtering process, and is the primary source for agriculture use. Responses about the quality of raw water varied greatly from region to region (e.g., raw water could potentially have high levels of salts and other chemicals). Being that irrigated agriculture enterprises predominantly utilize raw water, issues regarding raw water effects on soil health and eventual crop productivity were of interest to respondents.

The CB, WG, and LRGV subregions each have their own bureaucracies in place to manage their water resources. While there are primarily dryland farmers and ranchers in the CB subregion, there are small groups of producers who rely on groundwater

Table 2. Open coding resulted in two themes: water quantity and water quality. Additional concerns are labeled region-specific. Responses are noted (S) for stakeholders, (F) for farmers, or (S and F) for congruent responses, although only one quotation is used.

Open coding theme	Coastal Bend (n = 7)	Wintergarden (n = 4)	Rio Grande Valley (n = 19)
Water quantity and quality	"Water would probably be the number one limiting resource." (F)	"Counties that haven't managed their supplies very well and they're going to get to a point where they're going to be out of water and it's going to be a nightmare for those areas." (S)	"When you don't have the ability to create rain whenever you want, it's definitely the most limiting factor." (F)
	"I think it's going to get much more expensive, I mean, I think its supply and demand." (S)	"Water gets in big demand. You know we live in a fragile environment in south Texas, and we've all got to do what we've got to do to conserve water." (S)	"There's no concrete, nothing, no liner or anything to be able to keep the water from evaporating or seeping and losing the water so the constant pressure that we need to provide to a canal system." (S)
	"Reliable or drought resistant types of water resources; we're getting to a population size and as a region…we need to think of having multiple water sources and not being afraid to see that investment put in not just for the day but for tomorrow." (S)	"You're talking about ground water through irrigation under the Edwards Aquifer Authority." (S)	"The other pressing issues is maybe water quality or like water treatment for treating the water once you get it to the surface." (S and F)
	"Seawater desalination project that the city of Corpus Christi is actively pursuing. We're looking at constructing a 20 mgd expandable 30 mgd seawater desalination plant that could provide a resistant water situation to our growing needs for the future." (S)	"People don't necessarily understand why we develop the way we do. You know, you can't just build a water supply project for five thousand acre-feet of water because that's all you need, but ten years later you need twenty acre-feet." (S)	"I guess it's probably more the river being overutilized further upstream." (S)
	"Utilizing our wastewater as a potential source of water." (S)	"We have environmental issues as far as drought that'll take our alluvial water away and take those shallow wells away." (S)	"Water is just not available when farmers are ready to irrigate. You know, the water is just not available or they may be restricted on the number of waters that they can do within a given season." (S and F)

Table 2 (continued).

Open coding theme	Coastal Bend (n = 7)	Wintergarden (n = 4)	Rio Grande Valley (n = 19)
Region-specific	"I get a little worried when groundwater conservation districts start to dictate what a landowner can and cannot do with their water." (F)	"The state has developed these groundwater districts, they are not necessarily designed for the aquifers benefit, they're designed for the political subdivision." (S)	"Make it accessible to have these technologies communicate at an affordable price…that even goes for row crop farming or farming where you could have these sensors that communicate over rural internet access." (S)
	"Other challenges for the strip-till and no-till kind of perspective, as opposed to other parts of the country, we don't freeze, or when we do freeze it's kind of a rare event. We have to control weeds chemically all year long." (F)	"The amount of exotic species, they're not as efficient at putting water in the ground as are rangeland plants are." (S)	"If we're in a severe drought and water is allocated, agriculture is going to get cut off first. No trade-off, it's just a reality." (S)
	"It's kind of hard to teach an old dog new trick, and so it's kind of like well we've always done things like this. I think the key is getting new blood in…getting individuals that are educated." (F)	"Industry and environmental flows all take precedence over the farmers and the ranchers which has resulted in extreme dissatisfaction during periods of extreme drought." (S)	"Of course, we have a treaty between Mexico and the United States, Mexico tends to fall back on their commitment or the responsibilities that the 1944 treaty calls for." (S)
	"Water resources and how things grow in this area, it goes hand in hand. As population and industry grows, population growth rate accelerates even more." (S)	"Biggest problem would be the municipalities trying to set the rules…to how reallocate water and how it is used." (S)	"If we could get what's supposed to be delivered to us by the treaty, most likely we wouldn't have our issues, but we don't control the source of the water another country does." (S and F)
	"Economic protection comes in the form of crop insurance and of course crop insurance is both purchased at the private level and you're paying your share of it, but it's also subsidized by the government…we can't operate the way we operate without having crop insurance." (S and F)	"[Municipalities] making the rules where it's more difficult to farm, the farmers will be pushed." (S)	"I know that locally, they're not really enforcing very much as the moment… not much is being done to conserve water." (S and F)

for their production. This minority of groundwater-dependent CB area mangers expressed fear that groundwater districts will strip them of their "right of capture" on their properties, and thus, their means of production. Stakeholders in the WG area feared that the groundwater districts were not designed to benefit their respective aquifers, given that multiple groundwater districts have access to the same aquifer, yet have different mandates based on the political subdivisions of the region rather than needs of the underlying groundwater source. Along the LRGV, multiple municipalities, farmers, and ranchers rely on Rio Grande surface water for their residents and agricultural production. Stakeholders in the LRGV were worried about water quality/salinity issues and international disputes about Mexico's water supply obligation to the United States. Therefore, in the eyes of the LRGV stakeholders who heavily rely on consistent surface water availability, negotiations between representatives of the United States and Mexico are increasingly necessary.

Almost every stakeholder and farmer from each region agreed that sustaining a steady supply of clean water is necessary for the continued growth and vitality of their respective subregions. Nevertheless, water resource issues between the three subregions varied widely (Table 2). Attempting to adopt a single solution on a state level would not give each subregions' water resource issues the respect and attention they deserve. Many stakeholders and farmers expressed concerns over urbanization. Farmers indicated increased agricultural land sales in their area due to the lack of profitability in agriculture caused by unpredictable water resources availability. The fragmentation and urbanization of agricultural land could become even worse in these conditions if farm subsidies and insurance were not available.

Coastal Bend-centric Issues. Farmers and ranchers in the CB area indicated continued reliance on precipitation both now and into the future, given no current organization for irrigation districts and relatively low groundwater district interventions. Regarding conservation agriculture, some respondents mentioned the use of reduced tillage practices, but most respondents had a negative disposition toward the use of conservation practices (e.g., no-tillage, efficient irrigation methods, and high intensity/low frequency grazing), often citing that conservation agriculture methods are costly, labor intensive, and do not provide enough short-term benefits to their production. Farmers also noted that, due to the extreme precipitation variability in the area, they heavily rely on subsidized crop insurance to stay in business.

Fears over a growing population were also prevalent. Key stakeholders in the area did not believe that current politicians and water resource managers were doing enough to ensure a steady supply of quality water for future generations. However, despite public backlash, the Corpus Christi city council recently budgeted a desalination plant proposal (Kovar 2021). While there was no standalone question regarding desalination in the predesigned survey instrument, several of the stakeholders and farmers mentioned desalination with a positive connotation and none expressed any backlash or concerns to the idea of desalination investment to support future water supply sustainability.

Wintergarden-centric Issues. As opposed to the CB subregion, the residents in the WG area were acclimated to having a groundwater district and the division of their water rights. Consistent with other areas, WG respondents indicated that managers allocate more water toward industry and municipalities during times of drought. Farmers and ranchers in this subregion feared that shifting local politics and urbanization will make operations more difficult (and therefore less profitable), which may force some farmers to leave the area or go out of business.

Stakeholders for the WG subregion expressed desire to have more money invested toward information technology (e.g., groundwater monitoring sensors, infrared drone technology, soil moisture sensors). They believed readily available information will help the groundwater districts be more prepared for drought conditions. Stakeholders also stressed the need for more public outreach about issues regarding water sustainability, water supply, and water conservation strategies (e.g., relying on native species who are already adapted for the climate and soil conditions). The biggest fear that stakeholders in the WG area maintained was the poor design of the groundwater districts, given that multiple groundwater districts could share an aquifer, yet apply different policies to the same aquifer (a form of a transboundary water problem exhibited in many geographic contexts where stakeholders in diverse socio-economic systems and policy contexts are reliant on a single groundwater source; Uitto and Duda 2002; Earle 2013) . However, other entities, such as the Edwards Aquifer Authority, could alleviate some of these stresses.

Lower Rio Grande Valley-centric Issues: Akin to the WG subregion, LRGV farmers and ranchers desired greater investment in information technology, including at the farm-scale, to improve water management for the sake of improved operations. They also expressed concerns over agriculture businesses not receiving water allocations during droughts or inadequate water supply. Farmers described missing irrigation windows dependent on the status of the river and irrigation district. Water quality issues (e.g., salinity, salination, miscellaneous minerals) caused by upstream water over-utilization were also a concern. Concerns over water availability, supply, and quality were further amplified by statements pertaining to the fact that Mexico has historically not fully met its annual water supply obligations to the United States on a regular basis, as per the 1944 treaty. All stakeholders (farmers, ranchers, and others) believed that all their current resource supply issues would be relieved if Mexico met their obligations as intended.

On a local level, respondents believed that there is not enough water scarcity pressure endured by everyday residents in the LRGV to incentivize local politicians and stakeholders to create or enforce more water conservation efforts. It was suggested by respondents that very little is being done to conserve water in the LRGV area. However, concerns over inadequate water flows into the Gulf of Mexico were raised, indicating environmental concern from stakeholders. They expressed concern that aquatic life in the bays and estuaries and the vegetation along the Rio Grande are not getting the supply they need to survive and thrive in their environments; these concerns were juxtaposed against comments pertaining to the volume of water being utilized by irrigation districts and municipalities before it can reach the Gulf of Mexico.

Axial Coding

A total of five subthemes and factors were identified and analyzed (i.e., Water Supply, Bureaucracy, Water Conservation, Water Quality, and Environmental). The subthemes and factors synthesized from the open codes were then split up into "concerns" and "optimisms" (Table 3). The transcripts were reviewed for content within the five categories and were counted and sorted to be a "concern" or an "optimism." The threshold on whether water supply was a "concern" or "optimism" was dependent on the respondents' regard to current water demands being met. Bureaucracy was evaluated on the governmental agencies perceived roles, functions, and necessity in the opinions of the respondent. Water conservation "optimisms" were counted based on applied agriculture or water conservation strategies and their "concerns" were counted based on the externalities of, or the perceived costs, of implementing conservation strategies. Water quality was measured based on the references to the drinkability of water or if there were any concerns utilizing it as irrigation water. Environmental "concerns" were measured based on answers regarding current practices that lead to any negative environmental externality of the lack of water availability and quality, while environmental "optimism" referred to current practices that lead to positive environmental externalities.

Overall, interviewed farmers and stakeholders expressed many more water conservation concerns rather than optimisms (Table 3). While the overall differences for average concerns and optimisms between the farmers and stakeholders were marginal, farmers expressed more optimisms and stakeholders expressed more concerns per interview. On a per-interview basis, stakeholders mentioned water supply concerns more than farmers ($\bar{x}_s = 4.94$ mentions/interview compared to $\bar{x}_f = 3.46$), but overall, stakeholders and farmers expressed over three times the number of concerns than they did optimisms (139 observed water supply concerns compared to 39; Table 3). Farmers seem to also have more bureaucratic concerns and hold much less optimism ($\bar{x}_f = 1.31$ mentions/interview vs. 0.38, respectively), than stakeholders ($\bar{x}_s = 1.06$ mentions/interview vs. 1.35, respectively). In terms of water conservation strategies and concerns, farmers and stakeholders seem to be

Table 3. Results from axial coding highlighting similarities or differences in response rates between farmers and stakeholders. Total responses per stakeholder group are shown with mean number of responses per respondent in parentheses.

Subtheme Factors	Farmers n=13	Stakeholders n=17
Concerned/Problematic		
Water Supply: "Water, if it isn't already, is going to be our next gold."	45 ($\bar{x}_f = 3.46$)	84 ($\bar{x}_s = 4.94$)
Bureaucracy: "We have this underground water district now, we don't know where that's going …"	17 (1.31)	18 (1.06)
Water Conservation: "I think we have to try to conserve; we're using more and more water and we don't have a whole lot of it."	38 (2.92)	39 (2.29)
Water Quality: "The most pressing issues I would say is water quality. The water we get from the canals are high in salts at certain times of the year."	11 (0.85)	26 (1.53)
Environmental: "The river does not have any allocation for the environment. So if the river goes dry, the environment's going to suffer…"	32 (2.46)	27 (1.59)
Total	**143 (11)**	**194 (11.41)**
Optimistic		
Water Supply: "Business and politicians are aligned to a certain extent. They want to make sure that there is a stable supply of water."	14 (1.08)	25 (1.47)
Bureaucracy: "I think one year, we did have a drought but because we belong to a water district that had plenty of water allocated to them we never suffered from not having enough water."	5 (0.38)	23 (1.35)
Water Conservation: "We have a water conservation plan we are continuously reviewing and updating; it's not a static document."	68 (5.23)	55 (3.24)
Water Quality: "I think these irrigation districts test them (canals) weekly and they would know where the salt levels are."	0 (0.00)	5 (0.29)
Environmental: "[We do] everything from brush management, if you're reclaiming areas to range planting utilizing native species for maximum effect."	8 (0.62)	9 (0.53)
Total	**95 (7.31)**	**117 (6.88)**
Concerned Responses (% of Total)	60.1%	62.4%

confident in the fact that the ability and techniques used to conserve water are available, but still maintain some degree of reservation regarding current water conservation practices and economic limitations (38 and 39 concerned responses compared to 68 and 55 optimistic responses; Table 3). However, water quality concerns are primarily specific to the LRGV subregion. Overall, very few concerns or optimisms were expressed for water quality (37 observed water quality concerns compared to 5; Table 3). There seem to be many more environmental concerns than optimisms from both stakeholders and farmers (59 observed environmental concerns compared to 17; Table 3), in response to the environmental externalities of current water management practices, or lack thereof (Table 3).

Mental Model Descriptions

Peoples' management responses (or heuristics) for routine decisions are often a function of their underlying mental models (broad mental pictures or world views developed through experience and tradition); in many cases such heuristics lead to desirable outcomes. However, people often apply heuristics in response to complex problems or issues that may lead to undesirable outcomes (Kahneman 2011) contrary to what their underlying mental model inferred about the situation. Unfortunately, heuristic use in complex, feedback-driven problems can have devastating long-term consequences, potentially making the initial issue more destructive (Turner et al. 2016a; 2020a). Given the complexity of water resource systems and their overlapping connectivity to agricultural, industrial, and municipal systems, it is critical to understand heuristic responses and the mental models of stakeholders they are embedded in, prior to generating up-to-date decision-support tools.

The farmers and stakeholders interviewed maintained a variety of mental models regarding complicated issues and the proper management of water resources. To better communicate mental model insights and crystallize their potential role in developing decision-support tools, we synthesized the results of open and axial coding into the following brief descriptive quotes representing each respondent group:

Coastal Bend

- Farmers: "We are hoping for a timely rain for our production. We are worried about groundwater conservation districts interfering with our ability to stay profitable."
- Stakeholders: "Water resources are going to continue to get more expensive. We must find new sources of water and conserve what we have for future generations."

Wintergarden

- Farmers: "Farming is becoming more difficult because of urbanization and the lack of water rights for farmland."[1]
- Stakeholders: "Utilizing soil-health principles and techniques in agriculture are necessary for the long-term sustainability of our natural resources."

Rio Grande Valley

- Farmers: "Working with irrigation districts can be difficult and irrigation timing has to change depending on water availability."
- Stakeholders: "Mexico owes the United States the water resources they promised in the 1944 treaty. All of our water resource issues would be resolved if Mexico met their obligations."

Discussion and Implications

Given Texas' size and complex land and water resource features, it would be impossible to assign widespread blanket policies to problems at any scale. On the other hand, supporting and maintaining water conservation policies and plans that are well-adapted to specific regions seems more appropriate. Questions concerning whether policies should be based upon political, economic, cultural, or geological boundaries should be asked. Either way, the role of government (both local and state) will be vital for information generation and public outreach and education regarding current water supply levels and water conservation efforts.

[1] No farmers were interviewed. Mental model was synthesized from stakeholder responses regarding farmers during interviews.

The Role of Mental Models in Agricultural Systems

Mental models are defined as cognitive representations of how individuals view the world (Levy et al. 2018). Mental models tend to be very accessible and lasting; however, they are limited in scope in abstract and complex systems (Doyle and Ford 1998). Mental models are prevalent in every aspect of society, but, managing dynamic and complex variables in the environment makes it difficult for agriculturalists who are balancing several and often conflicting responsibilities (e.g., increase production, minimize inputs and runoff, etc.; Wilmer et al. 2020). Being part of extremely dynamic systems, agriculturalists can find themselves anywhere between considering themselves either the "controller" of nature or simply a "member of it" (Wilmer and Sturrock 2020). Although subjective, the general implications of environmental ethics assume that individuals in agriculture will adopt less environmentally damaging behaviors based on intrinsic values, care ethics, and land ethics (Turner et al. 2014; Batavia et al. 2020). Previous research suggests that many agriculturalists make "middle-ground" decisions to hedge themselves for ecological or economical risk (Wilmer et al. 2020). However, the definitions of sustainability should be grounded in practitioners' viewpoints, particularly farmer goals and concrete strategies for achieving those goals, for improved relevance for academics and policy makers pursuing sociological, economical, and ecological aspects of sustainability (Hoffman et al. 2014). Rural communities are key to understanding the relationships between land-based resources and the society that manages them (Mayagoitia et al. 2012). Water resources in agriculture are important for healthy soil and plant relationships. However, decades of relatively accessible water resources in agriculture have led to irrigation methods that maintain low standards of irrigation efficiency.

By articulating stakeholder mental models surrounding water use we gained greater appreciation for the complex dynamics driving current and emergent challenges in the region (e.g., urbanization and population growth, segmented groundwater conservation efforts, international boundary and water quality issues, among others). In order to inform future efforts to craft sustainable and actionable solutions, emerging hydrologic and socio-economic models must incorporate stakeholders' perspectives, goals, and values. Without doing so, emergent models run the risk of missing critical feedback linkages that, when unaccounted for, can lead to unintended consequences (Sterman 2000; Turner 2020b).

Our mental model syntheses highlighted several key feedback interrelationships existing below the surface of awareness that will influence emerging water management challenges. For example, in the CB subregion, stakeholders concerned with the rising cost of water expressed explicit interest in utilizing new water sources, such as groundwater. This may be viewed as a threat to agricultural producers relying on precipitation, since groundwater recharge is partly a function of effective rainfall (i.e., rainfall minus runoff). If land use and management were shown to reduce recharge potential, then creation of groundwater management areas may lead to unintended frustration among stakeholder groups. Or consider the LRGV, where farmers are some of the first stakeholders that must adapt during times of water scarcity. Frictions may arise between irrigation district members and managers, since irrigation districts also provide water to municipalities. Relationships must be managed to minimize erosion of trust over time and ensure adequate resources are allocated to much needed investment in irrigation upgrades, which may seem undesirable if farmers do not perceive a positive return on investment. On the other hand, non-agricultural stakeholders, who identify water scarcity as a political issue as well as an environmental one, are incentivized to keep demand growing in order to mount evidence for international responses. Pressure on growth fuels water demand in both sectors, which reinforces scarcity-induced frustration amongst users, and makes coordinated international effort more fragmented.

Integration through Systems Thinking

Systems thinking archetypes are visualizations of complex issues, made up of balancing and reinforcing feedback loops, that illustrate structural relationships underlying significant events and behaviors over time (Senge 1990; Kim 1992; 1994; 2000). Balancing loops move toward an equilibrium condition or goal whereas reinforcing loops lead to an exponential increase (i.e., virtuous) or decline (i.e., vicious). Unique combinations of balancing and reinforcing loops, along with commonly occurring problem descriptions or stores, constitute individual systems archetypes (Senge 1990).

One systems archetype identified in our responses was "Tragedy of the Commons" (TOC). The story of TOC revolves around constrained growth due to resource limitations shared by multiple stakeholders, who through competition to acquire and utilize the resource accelerate its depletion or degradation (Senge 1990; Kim 1994). In our case, the common resource shared by stakeholders is water, that, regardless of source (precipitation, surface water, or groundwater), is supply-constrained. Given fluctuating weather patterns that make water inflows or recharge rates extremely variable, as well as domestic (e.g., water rights structures) and international issues (e.g., water quality degradation), stakeholders face mounting pressure to secure and use available water for their respective operations. For example, Figure 3 highlights the stake that both farmers and municipalities have for water resources in the LRGV. Municipalities rely on water for continued growth and development, while farmers need water for their enterprise to be profitable. Frustration around water resource limitations was highlighted by one of the interviewees, who stated "When you don't have the ability to create rain whenever you want, it's definitely the most limiting factor," (Table 2). Both parties extracting from the same source,

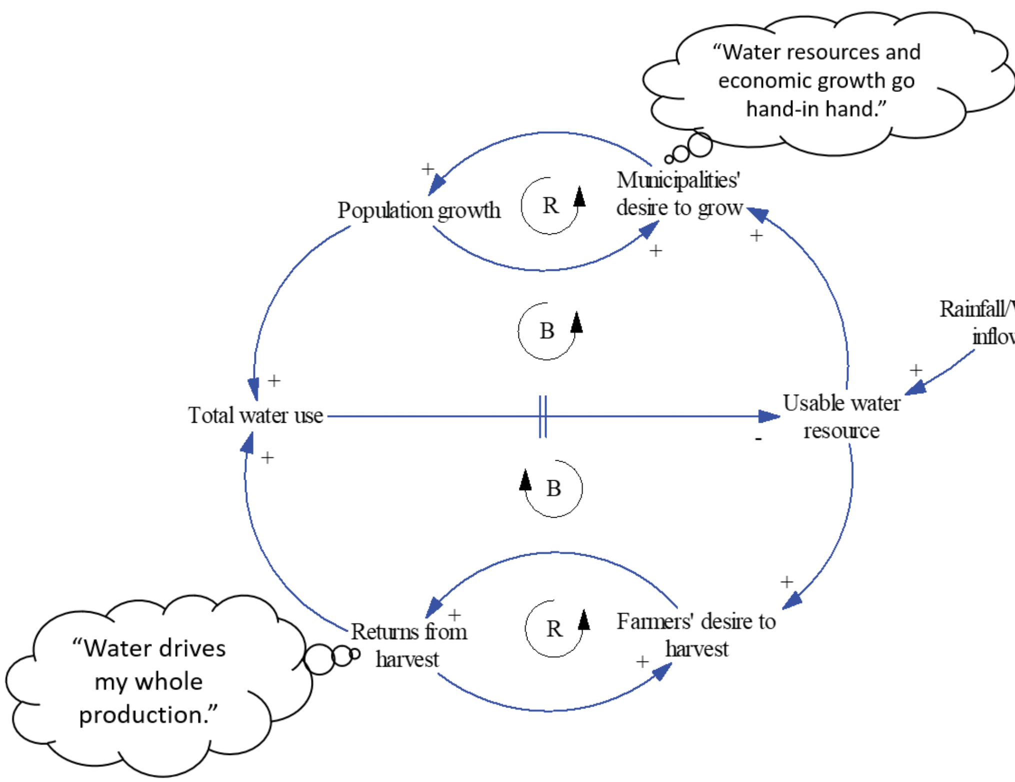

Figure 3. Tragedy of the Commons archetype. Positive "+" links indicate the effect variables at the arrow head move in the same direction as the cause variables at the arrow tail, negative "–" links indicate effect variables move the opposite direction as the cause variables, "R" indicates a reinforcing process, "B" indicates a balancing process, and double-hash marks across causal links represent time-delays. Given that rainfall and water inflows are limited, the total amount of usable water for agriculture and cities are also limited. Both cities and agriculture have their own intended goals and reasons for utilizing water. Agriculture wants to make a return on their investments, while cities desire more growth and output. However, both utilizing the resource without regard for the other will lead to the totality of the resource declining. Their actions unchecked can lead to a decline of water supply and quality. Text in the thought bubbles provide mental model descriptions of stakeholders based on survey responses.

without any regard for negative externalities or other stakeholders, will lead to eventual water supply and quality issues as supplies become increasingly stressed in the long-term.

The second identified archetype was "Success to the Successful" (S2S), which is the story of self-fulfilling prophecies. Success to the Successful begins when, in the face of competition between users of a given resource, one party is given an unfair or disproportionate competitive advantage over another, who then becomes more competitively disadvantaged over time as the initial "winner" garners more and more success (Senge 1990; Kim 1994). For example, Figure 4 highlights the stories heard regarding the fight for water rights between municipalities and farmers. Municipalities, who are given priority for water resources during times of stress, utilize those resources to maintain growth and development, with farmers receiving what remaining water allocation is available (if any remains). As one respondence said, "[Municipalities] make the rules where it's more difficult to farm, the farmers will be pushed [out]," (Table 2). Farmers argue that cities are harming the agriculture industry by means of urbanization and by buying more water rights, making it extremely difficult if not impossible to justify expansion of farm sizes or the number of farm operations as water supplies for agriculture get tighter and tighter.

Implications for Tragedy of the Commons. Given that water is a shared resource needed by all, its allocation and extraction is highly valued. While water resources are considered renewable, they are limited by their natural inflows and recharge rates. Water resources may not seem limiting immediately, yet south Texas farmers and water resource stakeholders have felt the pressure of living with limited water during drought and anticipate future shortages. Some common high leverage interventions for TOC include: finding a central point for resource management, developing a shared vision to guide individual and collaborative actions, developing a central information database that tracks resources over time, or employing a final mediator who allocates the resource dependent on the needs of the whole system (Ostrom 1990; Ostrom et al. 1994; Dietz et al. 2003).

Implications for Success to the Successful. Local government can play several important roles in a community, for example providing protection (law enforcement), supporting and maintaining public infrastructure and utilities, and incentivizing business development to improve standards of living, among other roles. Being that water is a limiting resource for the further development of municipalities, major city stakeholders have reason to allocate water inflows to current and future development projects intended to increase the cities growth and prosperity. However, rural

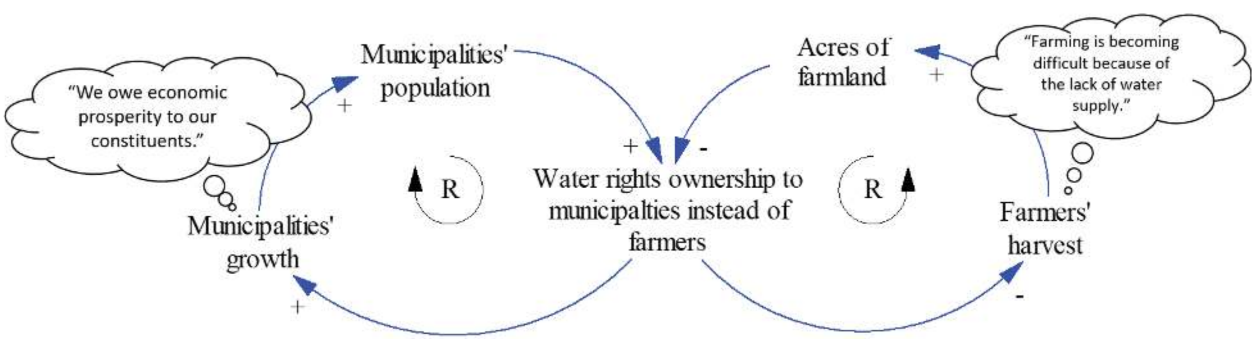

Figure 4. Success to the Successful archetype. Positive "+" links indicate the effect variables at the arrow head move in the same direction as the cause variables at the arrow tail, negative "–" links indicate effect variables move the opposite direction as the cause variables, "R" indicates a reinforcing process, "B" indicates a balancing process. Farmers have a fear that municipalities will continue to encroach on agriculture production. As municipalities have the desire to grow, they will continue to buy more water resource rights to help their internal development. Given that cities and residents are given priority to water resources and that water is considered a finite resource at any given point in time, farmers fear that the further urbanization of rural land will leave them with less water resources for their production, and eventually make their enterprise unprofitable. Text in the thought bubbles provide mental model descriptions of stakeholders based on survey responses.

communities who traditionally relied on agriculture will begin to suffer as local cities rapidly develop, fragmenting agricultural land, and increasing urbanization. As water resource allocations pivot toward municipalities, farmers' total harvests will decrease, and may eventually lead to less acres allocated for agriculture production. Some potential high leverage intervention points, originating from the generic points in Senge (1990), include: looking for overarching goals for all parties involved (e.g., municipal-supported investment in on-farm water storage to facilitate precision irrigation, reduce total agricultural water use, and free up supplies for municipal use); locating supplementary resources if all activities warrant investment (e.g., water reuse infrastructure); reducing or eliminating competition (e.g., water-use efficiency or water reuse); and allocating resources based on the total potential benefits of each activity, not just economic utility (e.g., valuing non-provisional ecosystem goods and services from agricultural water use, such as habitat support and recreation fishing from surface water systems).

Risks of Limited Water Resources to other Regional Challenges

Outside of consistent water supply, the CB, WG, and LRGV areas each have their own unique water-resource problems. Systems archetypes can help key stakeholders and academics identify relationships in highly dynamic and complex systems. However, concerns about or limitations of the aforementioned leverage points could include competency of management and lack of incentives to change and innovate, the role of government that guides adaptive management, and the time and effort needed to update current underlying mental models to incorporate a wider array of potential management pathways. In any case, the inherent risks of not conserving existing water resources or finding new sources will yield accelerated loss of agriculture production, environmental externalities to water quality, and increased stress as water supply shortages become more widely felt among all community members.

Conclusions

The goal of this research was to uncover and articulate mental models surrounding sustainable water use in south Texas. We found that, in general, stakeholders were more concerned than optimistic about the current state of water resource issues in the region with the largest concerns being water supply availability (for all uses) and environmental quality loss. The most optimistic or favorable area for stakeholders was conservation given existing surface- and ground-water organizations leading adaptive conservation efforts. Mental models, useful for identifying and interpreting possible decision-making rules, were synthesized from coded transcript data, that, combined with axial coded factors, yield several systems thinking archetypes, including TOC and S2S. Understanding the regional structures and forces that shape these archetypical behaviors, stakeholder mental models, and decision-making rules is vital to understanding and identifying high points of leverage in south Texas water conservation and sustainable management efforts, which themselves will largely depend on how farmers and other stakeholders (industrial and municipal) *interact* collaboratively (rather than combatively) in creative ways conducive to finding and sustaining novel practices and relationships that to-date have gone unexplored. Improved collaboration and communication ensure everyone is aware about the current state of their water and the economic and social impact that a lack of water resources (of extreme fluxes) will have on local communities. Given the tightly-coupled nature of soil processes and water conservation, emerging evidence in soil health management at field and farm scales presents novel opportunities to connect immediate productivity goals in agriculture to broader societal interests beyond food production. Technologically, on-farm information systems (e.g., real-time moisture and climate monitoring) will shorten the delay between water stress and management response. Each subregion in our case was unique; water management decisions should therefore be made on a local-level through collaboration of policy makers, stakeholders, and farmers, using the best information available for their area in attempts to avoid the cascading feedback impacts that will contaminate sustainable management efforts over time.

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Total Maximum Daily Loads and *Escherichia coli* Trends in Texas Freshwater Streams

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Abstract: Fecal indicator bacteria are routinely used to assess surface water sanitary quality. The State of Texas uses Total Maximum Daily Loads to address water bodies that exceed the allowable fecal indicator bacteria criteria. The effectiveness of these processes in decreasing the fecal indicator bacteria concentrations has been debated due to the diversity and nature of fecal indicator bacteria sources. We assessed actual and flow-adjusted trends in measured *Escherichia coli* (*E. coli*) concentrations at 721 freshwater stream sites from 2001 through 2021. We also compared odds of statistical improvement of *E. coli* concentrations at sites before and after the adoption of Total Maximum Daily Loads (adopted from 2008 through 2014). Results indicate non-significant differences in the odds of statistically detected improvements in *E. coli* concentration between pre-Total Maximum Daily Load and post-Total Maximum Daily Load sites. Although the State of Texas and numerous watershed stakeholders have made efforts to address water quality impairments, these results join a body of evidence that water quality improvements are stagnating in the state. Furthermore, this study leverages water quality data used for state water quality standards assessment purposes and highlights that robust monitoring program design is needed to effectively assess the progress of water quality planning efforts.

Keywords: *Total Maximum Daily Load, indicator bacteria, water quality, trend test*

Elevated fecal indicator bacteria (FIB) concentrations are responsible for approximately 40% of water quality impairments in the State of Texas (TCEQ 2019). *Escherichia coli* (*E. coli*) and enterococci are non-host specific bacteria typically present in the gut of warm-blooded animals and utilized as FIB to indicate the potential for recent fecal contamination of water bodies. *E. coli* and enterococci concentrations are evaluated using numeric criteria based on U.S. Environmental Protection Agency (EPA) studies that positively correlated the incidences of gastrointestinal illnesses with concentrations of *E. coli* or enterococci at recreational beaches with known point source sewage discharges (Dufour 1984; Fujioka et al. 2015). While substantial improvements in point sources of FIB (end of pipe discharges such as municipal or other wastewater facilities) have been achieved through the Clean Water Act and its amendments, non-point sources have remained a substantial challenge (National Research Council 2001; Benham et al. 2008). Potential non-point sources of FIB are generally diffuse across a watershed and can include domestic

Research Implications

- Despite substantial efforts, only 7.4% of water quality monitoring stations had statistically decreasing *Escherichia coli* concentrations after adoption of a Total Maximum Daily Load (TMDL).
- We observed no evidence of a difference in the odds of detecting statistically decreasing *Escherichia coli* concentrations between stations before a TMDL and after a TMDL.
- Additional research is called for to understand the commonalities in successful water quality planning efforts and to identify challenges in the existing state water quality planning and implementation framework.

livestock, wildlife, septic systems, pets, and any other potential source of fecal contamination in a watershed. Furthermore, sediments and algal communities can harbor and potentially allow *E. coli* to naturalize in the environment (Ishii and Sadowsky 2008). The diffuse nature of non-point sources of FIB, background contributions from wildlife, and potential for naturalization in the environment present considerable challenges for entities involved in improving impaired waterbodies.

Federal, state, and local government agencies and stakeholders have devoted substantial resources to address the sources of these impairments. Through July 2018, the Texas Commission on Environmental Quality (TCEQ) has developed and approved 187 Total Maximum Daily Loads (TMDLs) that define the FIB load allocations for water bodies not meeting state water quality standards. In addition to TMDL development, the TCEQ and Texas State Soil and Water Conservation Board provided funding and support for the development of 34 accepted watershed-based plans by local stakeholders through July 2018. From 1998 through 2015, the U.S. Department of Agriculture contributed over $171 million in cost-share payments to Texas agricultural producers to implement best management practices that protect or improve water quality (Environmental Working Group 2016). Local and regional governmental entities are also working to address non-point source driven impairments through updated codes and design guidance that promote low impact development. Notable examples include green stormwater infrastructure design criteria adopted in Harris County, low impact design guidance from the San Antonio River Authority, and the City of Austin's watershed protection ordinance among others (Storey et al. 2011; Dorman et al. 2013; Kip 2016).

Achieving in-stream FIB reductions is challenging because of strong influences of land cover on FIB concentrations and the wide diversity of potential point and non-point indicator bacteria sources amongst watersheds (Smith and Perdeck 2004; Mallin et al. 2009). Observed improvements in non-point source degraded water quality are hindered by water quality response lag times, shifts in climate and streamflow that obscure impacts of improved land management practices, changes in land use and land cover, and the difficulty in translating site-scale runoff and pollutant reductions to watershed-scale water quality improvements (Meals et al. 2010; Tomer and Locke 2011).

TMDLs and watershed-based plans are the two primary tools available to the State of Texas for addressing water quality impairments, with the former being most used. TMDLs identify the total pollutant load that a water body can assimilate and still meet water quality standards. TMDLs also assign portions of the pollutant load to point and non-point sources. Alongside a TMDL, an Implementation Plan (I-Plan) is developed using stakeholder input to identify how TMDL allocations will be achieved (Benham et al. 2008). Historically, TMDLs were treated as desktop modelling exercises and generally considered well suited for point-source driven impairments that can be easily modeled as steady-state systems (Haith 2003). However, there are concerns about the effectiveness of the approach for non-point source dominated systems, especially in agriculturally dominated watersheds that do not fall under state or federal stormwater regulations (Laitos and Ruckriegle 2012).

One indication that collective efforts are beginning to work is a decrease in the number of FIB impaired water bodies from 320 segments in 2010 to 237 segments in 2018 (TCEQ 2019). While water body de-listings are one metric of improvement, further insight can be gleaned to provide appropriate context of the relative impacts (or lack of impacts) from TMDLs. For example, a water body that is orders of magnitude above the standard may see significant water quality improvement but remain on the list of impaired water bodies. Conversely, an unimpaired water body may see undesired increases in bacteria loads but not enough to trigger an impairment listing. Furthermore, the number of listings is a flawed metric due to administrative reasons for removal such as changes in water body classification (lengthening or shortening of the assessed water body) or changes in water quality criteria.

With nearly 200 completed TMDLs addressing bacteria impairments in the State of Texas, there is an opportunity to assess the effectiveness of TMDLs in achieving detectable water quality improvements. Trends in water quality can be masked by natural variation in precipitation and discharge because of the correlation between pollutant concentration and flow. Therefore, flow-adjustment methods can provide insight into whether pollutant concentration trends are driven primarily by changes in streamflow or on the ground practices (Helsel and Hirsch 2002; Stow and Borsuk 2003). This study intends to (1) describe actual and flow-adjusted indicator bacteria trends across the state, and (2) assess the effect of TMDLs on indicator bacteria trends.

Methods

Data

The TCEQ Surface Water Quality Monitoring (SWQM) stations and associated *E. coli* monitoring data were obtained from the Water Quality Portal (https://www.waterqualitydata.us/) using the "dataRetrieval" package in R version 4.2.1 (De Cicco et al. 2018; R Core Team 2022). Data were retrieved for all stations between January 1, 2001 through December 31, 2021. The time period was chosen to evaluate at least seven years of data before and after adoption of FIB TMDLs adopted from January 1, 2008 through December 31, 2014. A seven-year period was chosen because it aligns with the assessment period length used to evaluate compliance with water quality criteria.

Apriori power analysis by Monte Carlo simulation of *E. coli* data sets at median variance indicated that the modified Mann-Kendall test has a power of 0.63 to detect a 40% change in concentration over seven years with three samples per year and $\alpha = 0.10$ (Schramm 2021a). The statistical power increased to 0.79 with four samples per year. Here, the statistical power refers to the probability that the Mann-Kendall test rejects the null hypothesis (no-trend) when there is an actual trend in the data at a particular site and is a function of some pre-assigned significance level, effect size (percent decrease in concentration), sample size, and variance.

In order to maximize sample size, and in consideration of within site variation of annual sampling effort, we retained stations with a median three or more samples per year for analysis. Justification for this filtering criteria is further explained in the limitations section of the discussion. The actual statistical power of the modified Mann-Kendall test at an individual station will vary based on the number of samples and sample variance at that station. Schramm (2021a) provides further discussion on implications of designing monitoring approaches for stakeholders interested in detecting smaller effects.

Mean daily streamflow data from United States Geological Survey (USGS) stream gages were downloaded from the National Water Information System using the "dataRetrieval" package in R. The TCEQ SWQM stations were linked to the nearest upstream or downstream USGS streamflow gage using the NHDPlus National Seamless database (Moore and Dewald 2016) and the "nhdplusTools" package in R (Blodgett 2018). SWQM stations and data without a stream gage within 4 km on the same stream were removed from analysis. Since we assessed *E. coli* concentrations and not loads, co-located streamflow data were not necessary. The 4 km threshold was deemed adequate to capture streamflow variation for flow-adjustment procedures based on visual inspection of gages and stations in an attempt to balance maximizing stations with streamflow data and accurate streamflow data.

The locations of water bodies with FIB TMDLs adopted from 2008 through 2014 were obtained from EPA Assessment, TMDL Tracking, and Implementation System (ATTAINS) database (https://www.epa.gov/waterdata/attains) using the "rATTAINS" package in R (Schramm 2021b). Water body locations and TMDL classification were spatially linked to the NHDPlus database and SWQM station data set to classify SWQM stations as located within or outside a TMDL water body.

Trend Analysis

Prior to assessing trends in *E. coli* concentration, data were grouped into: (1) pre-TMDL stations, (2) post-TMDL stations, and (3) stations without a TMDL (no-TMDL). Pre-TMDL stations include FIB and flow data prior to TMDL adoption. Post-TMDL stations include FIB and flow data after TMDL adoption. The no-TMDL stations include stations that do not have a FIB TMDL adopted from 2008 through 2014. The data for sites without a TMDL were restricted to the seven-year period from 2015 through 2021 for appropriate comparison with post-TMDL stations. Stations that had a TMDL adopted after 2015 were excluded from this analysis.

We assessed the presence of upward or downward monotonic trends in log-transformed *E. coli* concentrations using the modified Mann-Kendall test and Sen slope at each station (Helsel and Hirsch 2002; Yue and Wang 2002). The Mann-Kendall test is a non-parametric, two-sided test, with trends considered upward or downward based on the value of the Sen Slope with a predetermined α of 0.1. Typically, substantial variance in *E. coli* concentration can be explained by natural changes in stream discharge, precipitation, and hydrology. However, decision-makers are more often concerned with human influence on changes in *E. coli* concentration. The modified Mann-Kendall test for trend can be adjusted to account for variation in streamflow by applying the test to the regression residuals between streamflow and *E. coli* concentration (Helsel and Hirsch 2002). Residuals were obtained from a Generalized Additive Model (GAM) of form:

$$log(y) = \beta_0 + tp_1(log(x)) + \varepsilon \qquad \text{(equation 1)}$$

where y is *E. coli* concentration, β_0 is the intercept, x is streamflow, and ε is the error term assumed to be normally distributed around mean zero. tp_1 is a smoothing function that utilizes reduced rank versions of thin plate splines (Wood 2003). GAMs were fit using the "mgcv" package in R which utilizes generalized cross validation to estimate the optimal splines in the smoothing function (Wood 2011). While GAMs are increasingly used for water quality assessment and trend detection, our primary interest was to obtain the residuals from the model and assess the likelihood of a monotonic improvement in flow-adjusted *E. coli* concentrations across a wide number of sites (Beck and Murphy 2017; Murphy et al. 2019).

Relationship between TMDLs and FIB Trends

A binary presence-absence outcome variable was created for each SWQM station to indicate significant improvement in *E. coli* concentration based on the modified Mann-Kendall test. The outcome variable was coded as zero if the Sen slope was positive or Mann-Kendall test p-value $\geq$ 0.1 or one if the Sen slope was negative and Mann-Kendall test p-value < 0.1. The odds ratio of the outcome variable was calculated for pre-TMDL SWQM stations and stations without a TMDL (no-TMDL) using post-TMDL streams as a reference group. This design allows comparison of SWQM stations before and after TMDLs are adopted, as well as to stations that do not have a TMDL at all. Odds ratios and 95% confidence intervals were calculated using the GLM function in R.

Results

A total of 721 SWQM stations were included in the unadjusted analysis (Table 1); however, not all stations that had TMDLs had sufficient data to be included in both pre-TMDL and post-TMDL groups. The station sample size (n = 196) decreased drastically for the flow-adjusted analysis due to fewer stations located proximate to a USGS stream gage. On average, the number of sampling events at SWQM stations with TMDLs were higher than SWQM stations without a TMDL. As expected, the *E. coli* geometric mean concentrations at SWQM stations with a TMDL were on average higher than SWQM stations without a TMDL.

Trend Analysis

Of the 164 post-TMDL stations, 7.3% showed significant decreases in *E. coli* concentrations (Figures 1, 2; Table 2). In comparison, 11% of the pre-TMDL SWQM stations and 9.2% of no-TMDL stations showed significant decreases in *E. coli* concentrations. When adjusted for flow, concentrations significantly decreased at 17.4%, 10%, and 4.7% of post-TMDL, pre-TMDL, and no-TMDL sites, respectively.

We report the results for flow-adjusted concentrations, but caution readers to limit drawing broad conclusions due to reduced sample size and possibility of selection bias. There is indication that geometric mean concentrations are typically lower at the subset of sites included in the flow-adjusted analysis compared to the full set of sites in the unadjusted analysis. Since proximity to a USGS gage is the major filter on this data, we are likely biasing selection to stations near urbanized areas or on larger tributaries and rivers that justify long-term streamflow monitoring.

Table 1. Summary statistics of SWQM stations and *E. coli* data (collected between 2001-2021). Total values do not represent the sum of the individual categories but of the total unique SWQM stations used in the analysis. Not all stations had sufficient data to include in both the pre-TMDL and post-TMDL categories.

	SWQM Stations (n)	Mean *E. coli* Samples per Station (n)	Geometric Mean *E. coli* Concentration (MPN/100 mL)	Geometric SD *E. coli* Concentration (MPN/100 mL)
Unadjusted Data				
All Stations	721	50.03	178.81	3.04
No-TMDL	552	34.55	131.77	2.62
Post-TMDL	164	63.45	409.26	2.57
Pre-TMDL	146	45.18	766.90	3.27
Flow-Adjusted Data				
All Stations	196	51.06	140.15	2.89
No-TMDL	148	40.10	97.56	2.44
Post-TMDL	46	75.70	439.59	2.37
Pre-TMDL	10	59.10	382.30	2.80

The proportion of pre- and no-TMDL stations with significant decreases in *E. coli* decreased after the flow adjustment procedure was applied (Figure 1). The proportion of post-TMDL stations with significant decreases in *E. coli* increased after the flow-adjustment procedure. This difference suggests that local changes in streamflow may have masked improvements in *E. coli* concentration in post-TMDL stations. However, a single-sided paired t-test on the unadjusted and flow-adjusted slopes at post-TMDL SWQM stations suggested an increase in mean slope when the flow-adjusted procedure was applied (t = 6.196, df = 45, p-value < 0.01). When the flow-adjustment procedure is applied, some individual stations shifted from significant decreases in *E. coli* concentration to no detectable trend (Figure 2). Again, limited conclusions can be drawn from the flow-adjusted results, but the results highlight the importance of the flow-adjustment procedure, particularly when evaluating trends at individual sites.

Relationship between TMDLs and FIB Trends

The difference in the odds of a significant improvement in *E. coli* concentrations occurring between post-TMDL and pre-TMDL SWQM stations (OR = 1.56, 95% CI [0.72, 3.49]) or between post-TMDL and no-TMDL SWQM stations (OR = 1.29, 95% CI [0.69, 2.59]) was statistically non-significant (Table 2). When adjusted for flow, the difference in odds was also statistically non-significant between post-TMDL and pre-TMDL SWQM stations (OR = 0.53, 95% CI [0.03, 3.45]) (Table 3). The difference in the odds of significant improvement in flow-adjusted *E. coli* concentrations between post-TMDL and no-TMDL SWQM stations was statistically significant (OR = 0.24, 95% CI [0.08, 0.70]).

Discussion

This work provides an exploratory analysis of the effectiveness of TMDLs within Texas for addressing FIB impairments by comparing the odds of statistically significant trends. The results indicate that the difference in the odds that significant improvements in *E. coli* concentrations were observed between post-TMDL stations and pre-TMDL stations were statistically non-significant. The odds of statistical improvement between post-TMDL and no-TMDL stations were also statistically non-significant. When adjusted for flow, significant improvements were observed in a high proportion of post-TMDL sites. The difference in the odds of improvement between the post-TMDL and pre-TMDL station categories remained statistically non-significant. However, the post-TMDL sites had statistically higher odds of *E. coli* improvements than no-TMDL sites, when adjusted for flow. The flow adjustment procedures indicate

Table 2. Cross classification table of TMDL categories and detected improvements in *E. coli* concentrations from the modified Mann-Kendall test on unadjusted *E. coli* concentrations.

	---------------------TMDL Category---------------------		
Outcome Variable	**Post-TMDL**	**Pre-TMDL**	**No-TMDL**
No Improvement	152	130	501
Statistical Improvement	12	16	51
Total	164	146	552
Odds Ratio	1	1.56	1.29
95% CI	—	(0.72, 3.49)	(0.69, 2.59)
Log Odds	0	0.44	0.25

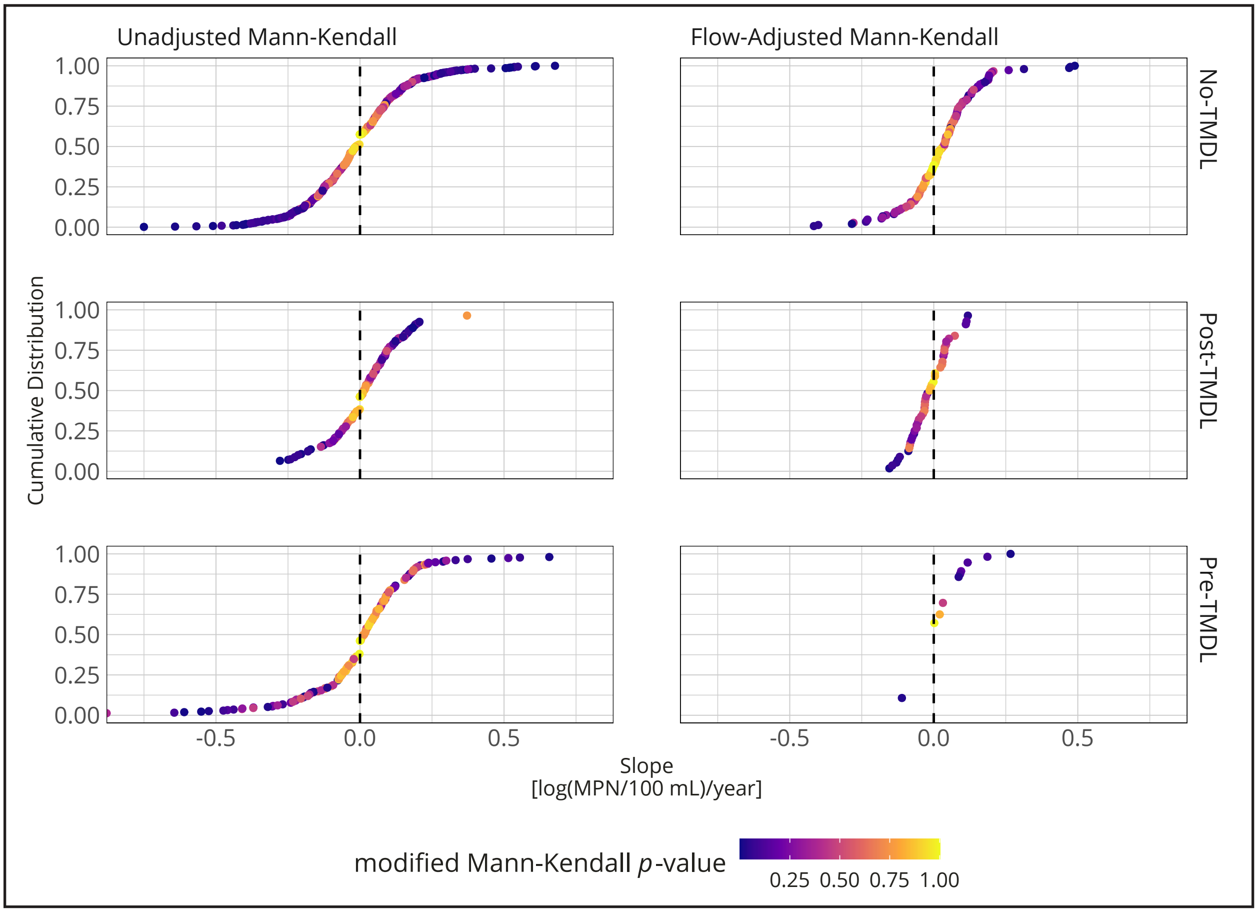

Figure 1. Cumulative distribution of Sen slope and associated p-values from the modified Mann-Kendall test on unadjusted and flow-adjusted *E. coli* concentrations at individual monitoring stations.

that changes in flow masked some improvements in *E. coli* concentrations over the sampled time period at some stations. Our expectations are that pre-TMDL stations would have significantly lower odds of improvement compared to post-TMDL stations, if broad-scale improvements in water quality occurred following TMDLs. We attempt to account for variations in flow with the flow-adjustment procedure in our analysis, but it drastically reduced the overall sample size and limits the conclusions that can be drawn. Other confounders, such as changes in land-use, variation in sources, and variance in local watershed groups are not included in this project but discussed below. Overall, this provides some evidence that improvements in *E. coli* concentrations have not been achieved at a broad scale despite TMDL efforts. While the results indicate some individual sites have seen improvement following TMDLs, the odds that they occur are not any higher than before TMDLs were implemented.

There have been limited comprehensive assessments of water quality trends in Texas for comparison. Some coastal assessments in Texas point to increasing trends of water quality exceedances or degradation. Powers et al. (2021) revealed statistically increasing rates of enterococci bacteria exceedances at Texas recreational beaches over a similar timeline. These exceedances were correlated with population increases and sea level rise that might impact the effectiveness of source-controls, such as septic systems and sanitary sewer

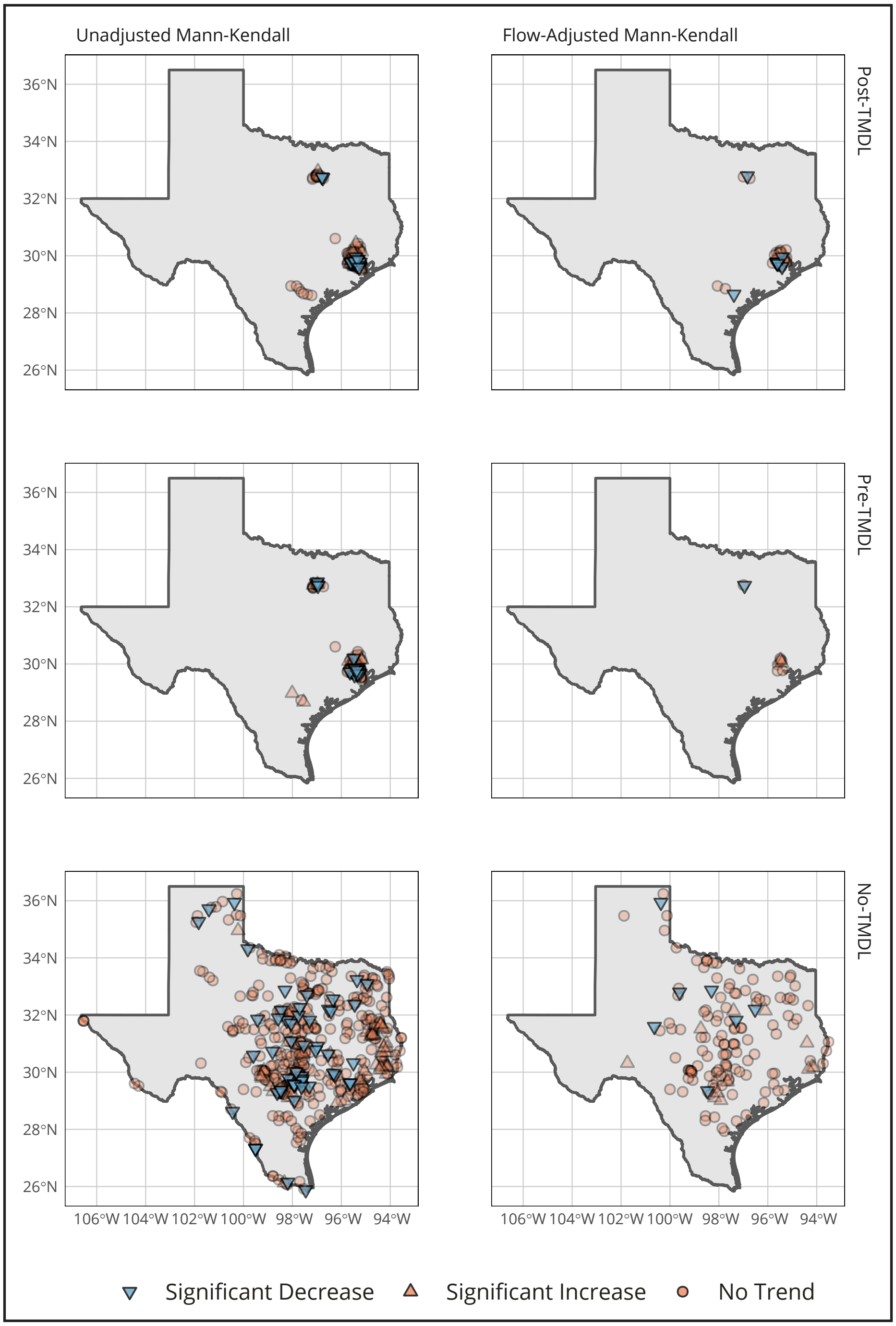

Figure 2. Map of individual monitoring stations and associated modified Mann-Kendall test results for unadjusted and flow-adjusted *E. coli* concentrations.

Table 3. Cross classification table of TMDL categories and detected improvements in *E. coli* concentrations from the modified Mann-Kendall test on flow-adjusted *E. coli* concentrations.

	---------------------TMDL Category---------------------		
Outcome Variable	**Post-TMDL**	**Pre-TMDL**	**No-TMDL**
No Improvement	38	9	141
Statistical Improvement	8	1	7
Total	46	10	148
Odds Ratio	1	0.53	0.24
95% CI	—	(0.03, 3.45)	(0.08, 0.70)
Log Odds	0	-0.64	-1.44

systems in coastal systems (Powers et al. 2021). Bugica et al. (2020) present evidence that both point and non-point sources were contributing to declining estuarine water quality and increasing risk of eutrophication on the Texas coastline between 1996 and 2016. Kuwayama et al. (2020) investigated trends in multiple water quality parameters and indices in Texas river basins and concluded that water quality improvements within the state have largely stagnated over the last 30 years. While substantial regulatory and voluntary efforts have been made to address *E. coli* and other impairments in Texas, this analysis adds to the limited but growing evidence that improvements are not being achieved on a broad scale in the state.

Many of the FIB water quality impairments and TMDLs in the state have been in and around urbanized centers such as Houston, Dallas, and San Antonio. In 2008, the first major FIB TMDL effort in the state (referred to as the Bacteria Implementation Group, or BIG) resulted in the development of 72 different TMDLs and associated I-Plans for impaired waterbodies in the Houston area (HGAC 2020). Similar groups have been formed in San Antonio, Dallas, and Austin, Texas. While these groups report on some individual successes in implementing projects and some reductions in bacteria, achievements in overall water quality goals have not been met. The negative impact of urbanization and imperviousness on hydrologic processes and water quality is well established and likely contributes to limited observations of significant improvements in *E. coli* concentrations (Handler et al. 2006; DiDonato et al. 2009; Mallin et al. 2009; O'Driscoll et al. 2010). Previous studies on fecal coliform and *E. coli* concentrations in Houston, Texas area watersheds indicated initial decreases in FIB concentration following wastewater plant improvements in the 1980s, which was followed by a period of no statistical improvements in *E. coli* concentrations coinciding with high rates of urbanization (Petersen et al. 2006; Desai et al. 2010). Within the Houston, Texas area watersheds, increased urbanization was associated with lower attenuation of wet-weather related *E. coli* concentration spikes, and relatively high *E. coli* concentrations under baseflow and stormflow conditions (compared to less developed watersheds), despite major improvements in point-source discharges. Brinkmeyer et al. (2014) found streambed and bank sediments account for up to 90% of daily *E. coli* and enterococci loads in two highly urbanized Houston, Texas waterbodies with chronically elevated FIB concentrations, and suggest that naturalized background FIB will prevent attainment of water quality goals. This evidence suggests that as urbanized centers grow in Texas, achieving water quality improvements will be increasingly difficult. In anticipation of continued land use development, improved integration of land-use planners and water managers is required to manage and plan around the interconnections between land and water (Stoker et al. 2022).

While substantial regulatory and voluntary efforts have been made to address *E. coli* impairments in Texas, we did not find broad-scale evidence that rates of improving *E. coli* concentration differ after TMDLs are implemented or from non-TMDL stations. While there are specific stations that demonstrated improvements in *E. coli* concentrations, it is beyond the extent of this project to dive into site specific data. However, we do call on a need for further research and data collection to identify the implementation efforts, funding, stakeholders, and other characteristics that might contribute to successful improvements in water quality. Previous studies indicate that the outcome of water quality planning and implementation efforts are a function of financial resources invested, stakeholder engagement, institutional capacity, and norms. Scott (2015; 2016) provides evidence that collaborative watershed management groups (like the BIG) can drive improved water quality outcomes. However, instituting a truly collaborative and effective watershed management effort is a challenge due to institutional silos, stakeholder perceptions, resource availability, and presence of cooperative networks (Lubell 2004; Imperial 2005; Koontz and Newig 2014).

Agricultural non-point sources such as livestock also contribute to FIB impairments throughout Texas and livestock management objectives are often identified in TMDL I-Plans (see HGAC 2020 for an example), presenting additional challenges for water quality planning. The agricultural associated non-point source reductions identified in I-Plans rely on voluntary implementation of best management practices achieved through outreach, education, and Farm Bill financial incentive programs. The voluntary implementation of best management practices faces major barriers such as the economic investments required of landowners, and landowners' limited trust in government programs and initiatives (Kay et al. 2008; Jordan et al. 2011; Guo et al. 2019). The mandatory implementation of agricultural best management practices is both legally and politically fraught (Laitos and Ruckriegle 2012). Due to the voluntary nature of these practices and confidentiality agreements with agencies, numerous knowledge gaps remain related to tracking and evaluating the effectiveness of agricultural best management practices implemented at the watershed scale (Batie 2009).

Partially in response to these challenges, the EPA developed guidance for the development of watershed-based plans as a local stakeholder-driven option to identify and address water quality concerns (U.S. EPA 2013). Under the watershed-based plan concept, local stakeholders drive the identification of issues and desired outcomes, increasing the likelihood of engagement, implementation, and successful outcomes (Koontz and Newig 2014). Agencies that lead these collaborative planning efforts often face difficulties shedding institutional and bureaucratic norms and enabling the flexibility required for successful collaborative governance regimes (Biddle 2017). However, agencies can also add administrative capacity and financial and technical resources, and compel participation that may lead to improved outcomes (Biddle 2017; Bitterman and Koliba 2020). Since addressing water quality challenges requires agency involvement and funding as well as strong local watershed organizations, additional research is needed in Texas to clearly identify the challenges and capacity for state institutional and local watershed groups in developing and implementing plans and projects that lead to improved water quality outcomes.

Limitations

The modified Mann-Kendall test on *E. coli* data has limited power to detect trends in *E. coli* data sets at typical monitoring frequencies (Schramm 2021a). For a station with a median population variance of *E. coli* concentration, monthly sampling is required to obtain 0.71 power for detecting a 20% change in *E. coli* concentration. Monthly sampling is the best-case scenario for most stations. Quarterly sampling is a more typical scenario for stations across the state. At four samples annually, a 40% change in *E. coli* concentration is required to achieve approximately the same power. However, for the stations in this analysis, our assumption is that most sites require relatively large percent reductions to achieve water quality standards (Table 1 indicates the overall geometric means require 67-84% reductions to meet standards, although individual sites will vary). The power of the Mann-Kendall test for detecting effects of this magnitude over seven years is sufficient with three to four samples annually.

The number of stations with adequate data limited exploratory analytic approaches, such as logistic regression, that would permit exploration of the influence of additional covariates. For unadjusted *E. coli* trends, 95 of the 134 stream assessment units with FIB TMDLS adopted from 2008 through 2014 were included in the analysis. However, for flow-adjusted *E. coli* trends, only 34 of 134 stream assessment units with FIB TMDLs were included in the analysis. SWQM stations lacking a proximate stream gage, without adequate data samples, or with only enterococci data, were excluded from analysis. This sample size restricts extending our analysis to include additional explanatory covariates such as land-use, implementation funding, and spatial dependencies that could provide desired insight. The number of SWQM stations throughout the state without a proximate stream gage severely restricted sample size, and as noted earlier, potentially introduces some sampling bias in location and stream size. Future work may consider the use of proxies for streamflow (such as precipitation) which have substantial effect on pollutant loading, and possibly allow the inclusion of more SWQM stations (Sinha and Michalak 2016). While further insights could also be gleaned by assessing financial resources invested, the types of projects implemented, and stakeholder involvement following TMDL development (Scott 2015; 2016), this data is not readily available across the study area.

The shortcomings of using changes in FIB as a metric deserve some discussion. As noted, there are numerous potential sources of FIB within a watershed and this regional level exploratory study does not parse out the possible background-level *E. coli* conditions or the feasibility of reducing *E. coli* concentrations at individual sites. We do not know if actual human health risk from water quality contact has changed following TMDL implementation. TMDLs within Texas currently do not utilize microbial source tracking (MST) to parse out potential contributors and sources of FIB within TMDLs. Nationally, efforts have been made to quantify the risks associated with FIB and integrate findings in watershed decision-making. Using FIB to assess human health risk in freshwater streams presents certain challenges. FIB can survive outside of the host and become naturalized in the environment effectively increasing baseline concentrations (Ishii and Sadowsky 2008). Furthermore, these FIB are not always host specific and may overestimate the risk relative to FIB originating from human sources, such as raw sewage, bather shedding, or treated effluent. The ability and desire to manage or mitigate non-human sources such as wildlife can be costly with uncertain effectiveness and limited impact on reducing potential risk for human health.

MST and Quantitative Microbial Risk Assessment (QMRA) are potential cost-effective frameworks that are increasingly recommended to assist resource managers with management practice selection and translation of FIB concentrations into human health risk (U.S. EPA 2014; Goodwin et al. 2017). QMRA studies have consistently indicated that FIB from non-human and non-cattle sources likely result in a lower risk for a gastrointestinal infection and illness than from FIB resulting from human sources (Schoen and Ashbolt 2010; Soller et al. 2010; Gitter et al. 2020). The presence of fecal pathogens in streams, as indicated by monitoring the FIB concentrations, can be influenced by pathogen source. A management approach that relies solely on the concentration of FIB and not the contributing sources can potentially mischaracterize the human health risk associated with recreation in a specific water body. The use of MST and QMRA provides an opportunity for regulators and stakeholders to establish goals and track progress for realistic water quality improvements based on actual human health risk, as opposed to the current single water quality criterion.

Conclusions

Our analysis indicates that there was no significant difference in the odds of statistically significant reductions of *E. coli* concentration, at an effect size broadly relevant across sites in the state, between pre- and post-TMDL stations. To an extent, sampling sizes restrict the ability of the analysis to detect smaller improvements that might be identified as relevant to local stakeholders. However, this analysis supports similar published findings that water quality improvements have largely stagnated across the state. While the state's TMDL and I-Plan efforts fulfill federal regulatory requirements, the lack of significant difference between pre-TMDL and post-TMDL trends suggests that further work is needed to identify locally successful planning mechanisms and build upon those efforts. It is likely the TMDL planning processes have evolved over time and space as response to administrative changes, stakeholder feedback, and capacity of local stakeholders to lead efforts. In-depth assessment of the processes would provide valuable insight when attempting to link outcomes to process. This study highlights the importance of a robust monitoring to assess program effectiveness and linkages to environmental outcomes, especially in light of continued efforts to develop additional TMDLs to address other impaired streams.

Data Availability Statement

Data and code generated or used during the study are available online at https://doi.org/10.5281/zenodo.4321728.

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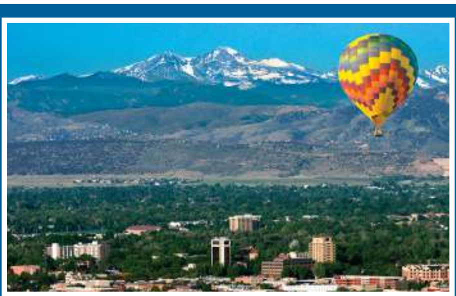

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