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SPECIAL FEATURE: ORIGINAL ARTICLE

The Reality of Transdisciplinary Processes

Practicing the science of sustainability: the challenges of transdisciplinarity in a developing world context

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Abstract Questions related to how we practice sustainability science remain salient in the face of the failure to achieve broad-scale sustainability objectives. Transdisciplinarity is an essential part of sustainability science. Transdisciplinary conceptual scholarship has been more prevalent than empirical scholarship or applications, especially in developing world contexts. In a single case study of a multiyear project addressing water security issues in HaMakuya, South Africa, we used a framework for assessing transdisciplinary objectives to facilitate more systematic learning for those who practice sustainability science. We found that defining the problem and assembling our team were easier than the co-creation of solution-oriented knowledge and the reintegration and application of this new knowledge. Our singular case study speaks to the potential challenges related to building relationships and co-creating knowledge in an epistemologically diverse setting. Other case studies appear to have negotiated these issues in developing country contexts, and this leaves room further investigation for how to practice transdisciplinarity under these conditions.

Keywords Sustainability science · Integration · Transdisciplinarity · Interdisciplinarity · Multidisciplinarity · Water security · South Africa

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Introduction

The urgency of global problems including growing income inequality, climate change, threats to water security, loss of species, and the intensification of urbanization suggest that the aspirations for sustainable development that were laid out in the late 1980s and early 1990s have largely not been met (Rockström et al. 2009; Gross 2012). Failures in conventional science to address these pressing problems and better serve society have led to calls for practicing a different kind of science (Lubchenco 1998; Gallopín et al. 2002; Ascher et al. 2010)—one that can lead to the goal of a more ecologically sustainable and equitable quality of life (Kates et al. 2001; Kates 2011; Kueffer et al. 2012; Miller et al. 2014). A recommended path forward to achieve this kind of science is for researchers to participate in problem-oriented, co-designed, interdisciplinary,[1] and transdisciplinary[2] work that can contribute to this vision (Brewer 1999; National Research Council 1999; Kates et al. 2001; Kates 2011; Hackmann and Clair AL 2013; Kueffer et al. 2012; Van Kerkoff 2014; Wiek et al. 2011, 2014; Miller et al. 2014).

The challenge is that while we have a vision of where we would like science to go, we do not have a clear road map that can get us there. The problem lies less with the articulation of the conceptual goals and more with how to execute or implement a sustainability science vision on the ground (National Research Council 1999; National Academies Press (NAP) 2004; Kueffer et al. 2012; Lang et al. 2012; Van Kerkoff 2014). This raises the important question: how do we practice sustainability science so as to reduce inequality, promote health and psychological well-being, reduce environmental degradation, and secure livelihoods?

This article builds on a framework that can facilitate more systematic learning in how we practice sustainability science. Spangenberg (2011) makes a distinction about science for sustainability (conducting science to understand specific sustainability phenomena) and science of sustainability (a discussion about how we actually practice and integrate understanding for sustainability science). In this article, we build on how we practice the science of sustainability. We drew upon the transdisciplinary literature to identify an appropriate framework for advancing the collective learning of sustainability science practitioners. We then assessed our project and how it measured up according to the framework. This assessment revealed strengths and weaknesses in our practice of sustainability science. Reflexive practice of this kind contributes to the adaptive cycle of social learning that is essential for the development of a science of sustainability (Spangenberg 2011; Lang et al. 2012). By way of example, we demonstrated how we and others might use this framework to deliver insights into their own projects while also fostering more systematic learning to enhance the practice of sustainability science at large. Our findings also speak to some of the challenges of practicing transdisciplinarity in a developing world context.

Systematic learning and the practice of sustainability science

The literature on sustainability science has grown enormously since the 1980s (Bettencourt and Kaur 2011; Pooley et al. 2013). A cohesive field has been established in terms of collaboration and citation, but it is unclear how much systematic learning by scholars, practitioners, and students is taking place (Lang et al. 2012; Van Kerkoff 2014). While there is considerable work on the barriers and obstacles to the practice of sustainability science (Brewer 1999; National Academies Press (NAP) 2004; Weichselgartner and Kasperson 2010; Lang et al. 2012; Anderson et al. 2013; Roy et al. 2013; Scholz and Steiner 2015b), we are less clear on how we can learn to overcome such barriers.

Efforts to systematize learning—especially as it relates to transdisciplinary sustainability science, a subcategory within sustainability science—are emerging (Lang et al. 2012; Wiek et al. 2012, 2014; Miller et al. 2014; Scholz and Steiner 2015a, b). From our perspective, systematic learning is facilitated by building ontology- and/or taxonomy-based knowledge systems (Rossman and Rallis 2011; Babbie 2015). By creating stable categories, language, and expectations around categories in a given knowledge system, we can codify what we learn in context-specific ways and share lessons more broadly. In this way, patterns are identified among the community of practitioners which advance collective learning across different projects (Jennex 2008; Bengtsson 2012; al-Shehri et al. 1993; Babbie 2015) and facilitate the blending of learning to a macro level (Gurung and Wilson 2013).

[1] We take our definition from the National Academies report (2004:2) on Facilitating Interdisciplinary Research: “Interdisciplinary research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding to solve problems whose solutions are beyond the scope of a single discipline or area of research practice”.

[2] We adopt here the Zurich 2000 definition which was derived from a conference of over 500 researchers and 300 practitioners: “transdisciplinary aspires to the efficient use of knowledge by relating different epistemics (i.e. ways of knowing) when dealing with a complex, societally relevant real-world problem” Scholz and Steiner 2015a: Scholz and Steiner (2015a) in this issue include a more extensive history of this definition.

Sustainability problems are characterized by potentially irreducible uncertainty and conflicting value demands which contribute to their complexity (Rittel et al. 1973; Funtowicz and Ravetz 1993; Miller et al. 2014). To address complexity, we need to establish integrative practice across disciplines and spatial and temporal scales, as well as between academics and non-academics, and knowledge and action (Van Kerkoff 2014). We have different methods that triangulate on similar characteristics that allow for integrating across these multiple dimensions and, by extension, are also important for practicing the science of sustainability. These include community-based, participatory, integrative, and/or transdisciplinary research approaches (Lang et al. 2012; Miller et al. 2014). Arguably, there is convergence in the transdisciplinary literature on a set of "ideal" principles and processes for what constitutes a stable set of transdisciplinary practices (Scholz et al. 2006; Scholz 2011; Lang et al. 2012; Scholz and Steiner 2015a). Transdisciplinarity is a research paradigm that is seen as appropriate for those practicing research in support of sustainability because it involves both scientists and relevant non-science stakeholders in the process of developing and implementing "socially robust knowledge" as a basis for "socially robust orientations", while also creating a foundational knowledge for the practice of sustainability science (Scholz 2011; Scholz and Steiner 2015a).

For this article, we adopted and adapted the framework developed by Lang et al. (2012: 27–29) who identified a process comprised of three phases: Phase A: problem framing and team building; Phase B: co-creation of solution-oriented transferable knowledge; and Phase C: re-integrating and applying the produced knowledge in both scientific and societal practice, as detailed in Table 1. Phase A intends to be problem focused, both in terms of how the problem was defined and in how the research was designed and carried out (Lang et al. 2012). This initial focus capitalizes on the consensus in sustainability science for research to be problem oriented (Brewer 1999; National Academies Press (NAP) 2004; Kates 2011; Spangenberg 2011; Kueffer et al. 2012; Mooney et al. 2013; Lang et al. 2012). A challenge of deriving research from a problem-oriented perspective is that knowledge is intended to be user-friendly for both the stakeholders who define the problems and the scientists participating in the research. This places demands on the knowledge produced to be both scientifically credible as well as relevant for the diverse audiences using it (Cash et al. 2003; Clark et al. 2011; Lang et al. 2012). Ideally, the process of crafting the problem definition should be inclusive of diverse perspectives so as to be salient and relevant for those who will ultimately use it (Kates et al. 2001; Cash et al. 2003; Lang et al. 2012; Weichselgartner and Kasperson 2010).

In Phase B, the research is carried out and knowledge is co-produced (Lang et al. 2012). The complexity of sustainability issues necessitates the incorporation of multiple ways of knowing the problem that is faced and a skill set for conducting integrative research (Van Kerkoff 2014). Ultimately, problems are nested in a social context so appropriately defining who should be involved in addressing them is a key aspect in sustainability science (Miller et al. 2014). These multiple perspectives come in two forms: diverse disciplines and diverse stakeholders. Diverse disciplines, including the natural and physical sciences, humanities, engineering, and social sciences, are needed to fully understand human-environment interactions (National Research Council 1999; Spangenberg 2011; Kueffer et al. 2012). Explicit discussion among disciplinary researchers about research design, methodology, and implementation is undertaken in this stage. In some cases, research may also be co-designed in collaboration with stakeholders or community partners. The involvement of salient stakeholders increases the opportunities for broader social learning so that science can actually inform decision-making and policy (National Research Council 1999; Kates et al. 2001; Cash et al. 2003; Angelstam et al. 2013; Wiek et al. 2014). Balancing these competing expectations and demands associated with disciplinary and stakeholder involvement can be very challenging (Weichselgartner and Kasperson 2010; Angelstam et al. 2013; Roy et al. 2013). As observed by Van Kerkoff (2014) the execution of this integrative research ideal has been more successful conceptually than in practice.

The final Phase C entails using the research results to inform both societal and scientific practice (Lang et al. 2012). Because researchers are often enmeshed in the sustainability problem with which they are researching, the assumptions typically associated with a traditional research may not hold. The conventional research process of identifying a research question and appropriate methodology, collecting data, conducting analysis, and identifying findings and conclusions imperfectly fits the dynamic research setting in which sustainability problems are embedded (Van Kerkoff 2014). This means researchers must be committed to reflexivity and likewise to changing research plans and practices as new insights are gained (Spangenberg 2011; Van Kerkoff 2014). As such, findings will inform not only what is salient for addressing the sustainability problem and its solutions, but will likewise inform the iterative process of adapting research design and execution. On the social side, results are connected back to partners, community members, and others so that the problem is addressed in alignment with action-based research (Van Kerkoff 2014; Miller et al. 2014).

Sustainability scientists and practitioners do not have much empirical evidence of the efficacy of transdisciplinary approaches or the lessons learned from them. Literature has tended to focus more on the conceptual aspects

Table 1 Ideal characteristics for transdisciplinary aspects of sustainability science (adapted from Lang et al. 2012)

Ideal characteristics	As implemented in IMAGINE project
Phase A: problem framing and team building	
Build a collaborative research team	Prior to the arrival in country PI Melissa McHale assembled an interdisciplinary research team and facilitated connections to the local community
Create joint understanding and definition of the sustainability problem to be addressed	2011—The IMAGINE program intended to focus on a socio-ecological problem that was to be defined from the community's perspective. 2012/13—Water security became the primary focus once we took direction from the community. Beyond the integrative originality of the research, the science is more applied than theoretical
Collaboratively define the boundary/research object, research objectives as well as specific research questions and success criteria	2011—Asset mapping was identified as a culturally appropriate boundary methodology to define the research problem from the community's perspective. 2012/13—Research questions and objectives shifted in response to learning from the community and iterative stages of data collection as we learned what worked and what did not in how to collect relevant data
Design a methodological framework for collaborative knowledge production and integration	2012/13—A research design that capitalized on understanding community water quality, quantity and reliability aspects from a biophysical and social science perspective was created. We anticipated to triangulate on how the objective biophysical data matched local perceptions. Opportunities for novel, scientific insight were minimal
Phase B: co-creation of solution-oriented transferable knowledge	
Assign and support appropriate roles for practitioners and researchers	2012/13—Biophysical scientists were tasked with conducting water quality and quantity studies. Social scientists were tasked with collecting perception data about water quality, quantity and availability. A local non-profit organization was engaged to facilitate interaction with the community. Community-based translators assisted in data collection while helping us communicate with local participants
Apply and adjust integrative research methods and transdisciplinary settings for knowledge generation and integration	2013—We created greater alignment between sites where biophysical data were being collected and perception data were being collected. We needed to adjust for spatial and temporal challenges in data collection. We created the opportunity to hire and leverage community based monitors to facilitate additional data collection opportunities
Phase C: re-integrating and applying the produced knowledge in both scientific and societal practice	
Realize two-dimensional integration	2012/13—We had numerous discussions about how to best integrate our data, the significance of the data and how it could be used effectively to deal with the water problems faced by the community and how it could be published
Generate targeted products for both parties	2013—We developed Fig. 2, which served as a better communication tool for the researchers than the community. In person meetings with simple descriptions of what we found were more effective ways to convey knowledge. Finding appropriate framing to allow for peer reviewed publication has been challenging
Evaluate scientific and societal impact	This is an ongoing process. Scientific impact is unclear. Data have been used to advance an argument for increased water storage capacity and inform decision making, as well as educate members of the community. Conveying results back to the individual villages has been delayed

of practice rather than the empirical lessons, but the literature and evidence are growing. Evaluative literature on the practice of inter- and multidisciplinary practice exists, but there is little empirical work on transdisciplinarity. Additionally, much more is known about the efficacy of interdisciplinary, multidisciplinary, and transdisciplinary practice in the developed world compared to the developing world. For instance, Roy et al. (2013) conducted a survey of 323 North American sustainability professionals to identify key challenges and obstacles they faced in interdisciplinary environmental research. Pooley et al. (2013) identified key themes from a bibliographic analysis of the literature related to challenges of multiple disciplinary collaboration, but these were not project or geographically specific. Lang et al. (2012: 35) identified challenges and "coping strategies" derived from transdisciplinary projects in both developed and developing world contexts. Angelstam et al. (2013) categorized 14 transdisciplinary problem-solving cases primarily located in the developed world to infer barriers and bridges for participants. Wiek et al. (2014) unpacked three case studies to identify lessons learned for sustainability scholars, including a case study related to bioenergy production in Zambia and Tanzania. More recently, Scholz and Steiner (2015b) reviewed 40 mid- and large-scale transdisciplinary projects undertaken by ITdNet (http://www.uns.ethz.ch/translab/itdnet). Three of these focused on developing countries. Most case studies have a European and/or industrial focus (Scholz and Steiner 2015b).

We seek to contribute to the literature on the practice of sustainability science and especially transdisciplinary aspects by focusing on an in-depth case study of a multi-year effort in rural South Africa. Given the state of knowledge related to transdisciplinary practice, there is scope for detailed, in-depth case studies to help uncover the challenges in different cultural contexts as we continue to strive for more generalized learning. These cases are needed to allow for a greater depth of appreciation for "complexity, multilayeredness of tradeoffs and conflicts, uncertainty and incompleteness" as part of learning how to practice transdisciplinarity (Scholz and Steiner 2015a: XXX). Our single case study offers depth of experience, but is limited in its generalizability.

Importantly, our project did not begin as a practice of transdisciplinarity; rather we set out to do integrative research with an explicit problem focus in a developing world context (Van Kerkoff 2014). Only later did we realize that our approach fit into a broader set of practices best characterized as transdisciplinary research. Consequently, our evaluation has been post hoc so we could begin to see how our effort measured up to the practice of sustainability science, with special emphasis on transdisciplinarity. As such, we did not follow from the start the processes laid out by Scholz and Steiner (2015a) and elsewhere (Scholz et al. 2006).

Methods and research context

To understand our process and how well we adhered to a transdisciplinary "ideal", we adopted the three phases from Lang et al. (2012) to structure our understanding (Table 1). We recognize that there are common roots among the many researchers who work in the transdisciplinary field (Scholz et al. 2006; Stauffacher et al. 2006; Lang et al. 2012), but settled on Lang et al. (2012) due to the concreteness of the review criteria.

Reflexivity is an important part of the practice of the science of sustainability (Spangenberg 2011) and our research team self-assessed at various stages from 2011 to 2015. Meetings and exchanges would take place in person, via email, and Skype. One-on-one meetings would take place as would sub-group and full-group meetings. Key points for interaction included planning for each trip to conduct field work, analyzing findings, working through dissemination and knowledge transfer activities, and writing this manuscript. The iterative process of manuscript writing has become a key boundary[3] tool for us to understand our own process and the relative strengths and weaknesses of how we are practicing the science of sustainability.

Our project is part of a long-term research program that emphasizes graduate student training in interdisciplinarity. As such, it fits within the scholarly tradition of working with students in real, problem-based settings to advance the key competencies students will need to participate constructively in sustainability science (Van Kerkoff 2014; Wiek et al. 2011, 2014; Schmidt et al. 2012). The IMAGINE (International Mentoring of Advanced Graduates for INterdisciplinary Excellence) program was initiated in 2011. From 2011 to 2013 the program officially incorporated 21 graduate students, two undergraduate students, and two post docs from South Africa and the United States, as well as over 15 scientists from South Africa, the United States, and Canada. These individuals came from multiple disciplines, including educational psychology, rural livelihoods, conservation and ecosystem ecology, cultural anthropology, environmental history, environmental policy, hydrology, environmental technology, political science, and tourism studies. Due to space limitations in this article, we report only on findings that emerged from perceptual studies on water quality, quantity, and availability, as well as data collected on biophysical aspects of water quality, quantity, and availability. The IMAGINE program continues to extend beyond these disciplinary areas to include an examination of how communities cope with and adapt to environmental challenges and analyses that support a conceptual understanding of socio-ecological resilience. Studies on rural livelihoods and the ecosystem services people receive from the surrounding communal areas and their personal properties are also being implemented in the villages of HaMakuya. Finally, the IMAGINE program aims to incorporate a political and cultural history of the region to embrace the full complexity of sustainability problems in the region.

The focus for our research was HaMakuya, a set of 20 villages with an estimated total population of 9678, with 2054 households (DWA 2011) located in Mutale Local Municipality in the Vhembe District of Limpopo Province, which is situated near the South African borders of

[3] Boundary objects are concrete or abstract tools that facilitate the translation, sharing and use of knowledge across disciplinary and organizational cultures (Star and Griesemer 1989; Guston 2001; Crona and Parker 2012). They facilitate knowledge co-production and use in community, research, and policy settings.

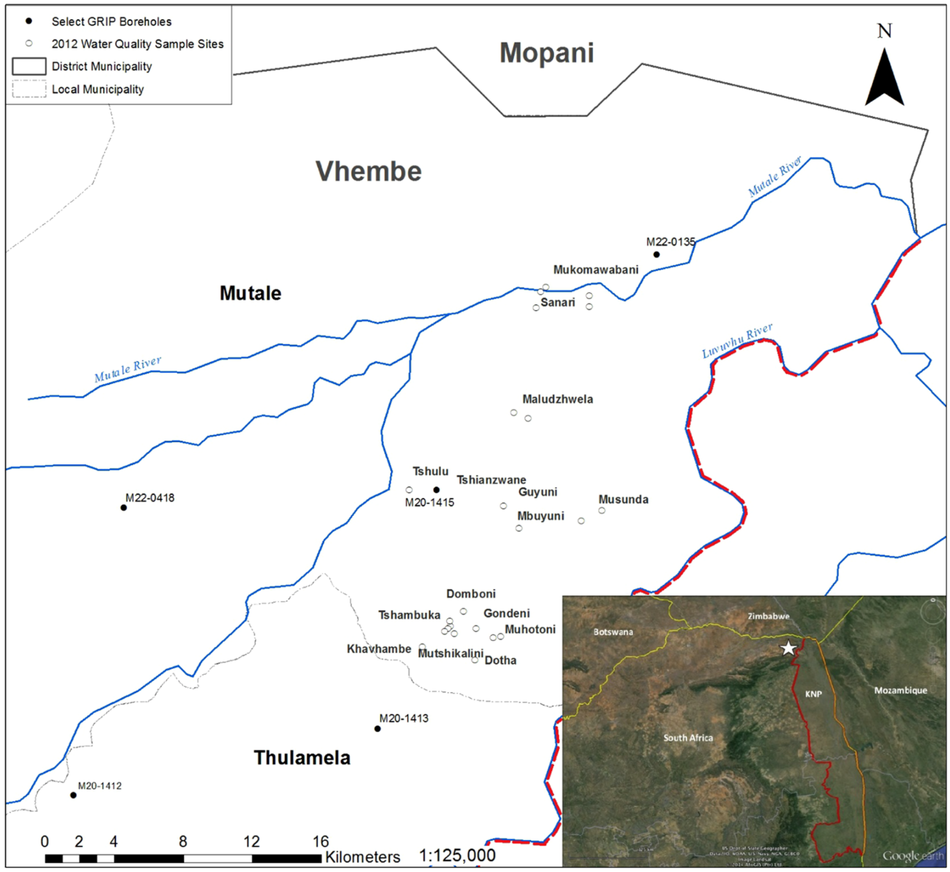

Fig. 1 HaMakuya villages 2012 water quality sampling sites (*white circles*) (with local and district municipalities, MDB 2005) and select boreholes (*black circles*) used by the South African Department of Water Affairs for regional groundwater monitoring (GRIP LIMPOPO accessed June 2013). The Luvuvhu River to the east of the HaMakuya villages is the border with Kruger National Park (*red line*, see also *inset*)

Zimbabwe and Mozambique (Fig. 1). HaMakuya is a region where traditional authority combines with new political structures and communal land tenure. Located in the former apartheid homeland of Venda, it has poor infrastructural investment and limited economic development that provides an important context for the practice of sustainability science. Mutale Local Municipality had a population of 91,870 in 2011 with a total of 23,751 households (Statistics South Africa 2013). Female-headed households made up the majority (54.8 %) of the total households in 2013, which had on average 3.8 people. Nearly 87.7 % of these households lived in formal dwellings, up from 63 % in 2001, and 64 % owned their own dwelling. Only 5.8 % of the households had piped water inside their dwelling, but 83.3 % had electricity, up from 39.9 % in 2001. The percentage of population aged 20 and older without any schooling was 18.8 %. The unemployment rate in 2011 was 48.8 %, down from 56.8 % in 2001 (Statistics South Africa 2013).

Findings

We leverage the phases of the ideal transdisciplinary process as articulated by Lang et al. (2012). Table 1 summarizes our experience in HaMakuya to date.

Phase A: problem framing and team building

An interdisciplinary research team was assembled by Primary Investigator Melissa McHale in 2011. Individuals were chosen based on their areas of expertise and willingness to participate in interdisciplinary, integrative research project. McHale's contacts in HaMakuya facilitated the necessary connections with the local community; Tshulu Trust, a local non-profit organization that helps to administer research in the villages of HaMakuya, is a key partner.

To create joint understanding of the problem, we worked with local community members to understand their concerns. Asset mapping was identified as an appropriate boundary methodology given language and cultural constraints. The work to identify an appropriate exploratory boundary method was undertaken by the primary researchers prior to arriving in country. In May 2011, we conducted a participatory asset-mapping project in country aimed at understanding key problem definitions in the HaMakuya villages. Four focus groups stratified by age and gender (older women, younger women, older men, younger men) were created and participants were asked to describe and draw maps of what they perceived to be physical, social, and cultural assets, in their respective villages. Once each of the four focus groups had identified their assets, they were then discussed within each group. The focus groups comprised forty adult participants aged 20 to elders from the villages of Guyuni, Mbuyuni, Tshianzwane, and Musunda. Participants were selected through a partnership with Tshulu Trust. In addition to helping identify participants, Tshulu Trust recruited qualified local translators to assist with the focus groups. After the four individual groups completed the interview and mapping sessions, the groups reconvened in a plenary, open-ended question and answer session for the purpose of identifying key problems faced by the village and what information they would like to receive from researchers and what their expectations were going forward. All focus groups and plenary sessions were audio-recorded and field notes were taken.

The outcome of the asset-mapping exercise and the plenary group discussion was a focus on the importance of water as an asset within the communities. Out of all assets identified in the focus groups, 77 % were natural resource assets, including water, agriculture, eco-tourism, and fuel wood, and 23 % were social assets, which included meeting areas, sites associated with spiritual and physical well-being, education, and recreation. More than 50 % of all participants indicated the importance of water as an asset in the community. During the plenary session, water availability, especially from boreholes with taps, was identified as one of the greatest concerns. This concern had been documented previously in other studies and reports categorizing the challenges faced by local communities. Research led by the Association of Water and Rural Development (AWARD) showed similar results in villages much further south of HaMakuya along the border of the Kruger National Park (Cousins et al. 2007).

Informed by the focus groups and asset mapping exercise, our team designed a research approach that could address their concerns. In 2012 and 2013, our research team returned to HaMakuya with the objective of more comprehensively understanding water issues in the villages. Research focused on groundwater hydrology (availability and quantity), water quality (chemistry and biology), and perceptions of water availability, quantity, and quality. Researchers took the lead in defining the research tools and protocols. These were refined over time with input from our partners. The aim of the research was to triangulate on local perceptions and physically collected water quality and availability data.

Phase B: co-creation of solution-oriented transferable knowledge

Our approach has been more problem oriented than solution oriented to date. This has been necessary to fully understand existing complexities before we attempted to address solutions. Our intention is for our project to lead to solution-oriented action, but this is a continuous practice. The distance (for some team members) from our research site and cultural dissimilarity affect many operating assumptions in our working environment that would not apply to work in a developed, industrialized setting. At present, we are taking incremental steps as we collect data and establish relationships to build trust and community engagement that will lead toward more noteworthy results. Additionally, researchers and partners need to build our collective capacity to work together to identify solutions so that they are politically feasible and practically implementable in the long run.

Water quality sample collections occurred between 1st and 7th June, 2012, and June 28th through July 1st, 2013 at all available water sources.[4] General water quality parameters were collected, and water samples were collected for certified analysis of nitrate ($NO_3 + NO_2$) concentrations, stable water isotopes of hydrogen and oxygen, and for *Escherichia coli* testing using standard field methods, quality assurance, and quality control procedures. Most communities utilized groundwater from boreholes that are stored in above-ground tanks and then distributed to public taps. Hand pumps, natural springs, and surface water sources required water collection directly at the source.

To understand local perceptions about water, a total of 34, in-person surveys were conducted in the three villages of Sanari (14 surveys), Maludzhawela (11), and Mukomawabani (9) between 1st and 7th June 2012. Survey questions were devised from a literature review ahead of in-country field work. The survey tool was revised by our research team members who were from South Africa. Survey questions were then pilot tested with local community members outside the target communities. Revisions were made based on this iterative process to create a tool with greater face validity given our cultural context. Surveys were conducted in-person with translator assistance with heads of households in the study villages to gauge their perceptions on water consumption, quality, reliability, and availability. In addition, focus groups were held with members from the villages of Maludzhawela, Musunda, Mbuyuni, and Sanari. In 2013, another 30 surveys were again completed between March 6th and 8th in Sanari (15), Maludzhawela (5), and Mukomawabani (10). Community-based translators assisted in data collection for both the water quality and quantity sampling and local perception data collection. Community-based water quality monitors were hired and trained in 2013 to supplement data collection.

Water quality emerged again as a major concern for the respondents. Half of our 2-year sample did not believe their water was safe and 30 % did not know whether their water

[4] This included surface waters, borehole to tap, municipal storage to tap, and individual hand pumps (borehole).

was safe. 40 % of respondents rated their current water quality as awful or unpleasant, and 61 % of our respondents indicated that the quality of water had not changed or had become worse over the past 15 years. Sanari's respondents were more likely to believe their water was safe than those surveyed in the other communities (57 %). Participants from Maludzhawela (73 %) reported feeling less sure about the safety of their water compared to the other communities (56 % in Mukomawabani and 29 % in Sanari). In describing the reasons for potentially unsound water quality, residents discussed infrastructural problems, contamination issues, and not knowing the water source.

Water quality at 33 locations was assessed during two collection events in 2012 and 2013. Water quality results support the perceived concerns of community respondents. Water quality parameters often did not meet primary or secondary drinking water standards per South African standards (Tredoux and Talma 2006). For example, participants from Maludzhawela have access to groundwater from an older hand pump (primarily used for watering cattle), a more recent borehole and tap system in the village itself, and a seasonal spring near to the tap system. All three sources had higher concentrations of salts (salinity) than the acceptable secondary drinking water standard concentrations of 0.25 parts per thousand (ppt) or 250 mg/L total dissolved solids. Of the three water source systems, the newer borehole/tap system and seasonal spring had nitrate and chloride concentrations that exceeded the primary drinking water standard concentrations of 10 mg/L nitrate and 250 mg/L of chloride (aesthetic quality). The seasonal spring tested positively for the presence of *E. coli*, an indicator of potential human or animal waste contamination. The older hand pump borehole used for cattle was slightly brackish with a salinity of 0.7 ppt, but nitrate (0.01 mg/L) and chloride (104 mg/L) concentrations were well below primary and secondary standards, respectively, which indicated they were safe. If residents relied mainly on the newer borehole/tap and/or seasonal spring for drinking water use, then water quality data supported participants' concerns about sanitation and health consequences from these sources.

Across HaMakuya, 10 of the 33 locations had brackish waters (salinity between 0.5 and 30 ppt) and/or indications of high nitrate or *E. coli* contamination. One hand pump and one borehole to tap system did test positive for *E. coli*. Although the remaining locations in HaMakuya appear to have water with acceptable nitrate, chloride, and salinity concentrations for potable water, many water sources were "hard" with high alkalinity and high conductivity due to the presence of various Na^{+}, Cl^{-}, K^{+}, Mg^{2+}, and carbonate ions. In general, community residents' perceptions of water safety were substantiated by the biophysical data collected; however, consistent water quality data for each village are needed to match perceptions of water quality and reliability at the village scale. Additionally, their explanations of why the water was unsafe, including reference to infrastructural problems and contamination, were supported by the physical data collected. Consistent seasonal testing is necessary to better understand water quality variability and risk in this area. IMAGINE team members are involved in ongoing efforts with local community participants to more frequently monitor water quality at locations of concern.

Water availability was less of a concern among household survey respondents than water quality. A high proportion of our sample indicated that enough water was available to meet their needs, although there were significant differences among villages. Nearly three quarters (73 %) of our 2-year sample indicated that water was available to meet their household needs "all the time", while 17 % said it did sometimes, and 9 % said water was not available. Our respondents also indicated that for 66 % of them, water was always available at their main source, while 31 % indicated that water was sometimes available at their main source (which for 56 % is a village tap). Sanari residents perceived inadequate supplies more often than the other villages with only 32 % indicating they had water availability that met their household needs "all the time". This difference persisted with Sanari when asked about main sources of water. Water for Sanari respondents was more likely to be "sometimes" or "rarely" available than in the other villages.

Groundwater data supported the variable perceptions about water availability. Inadequate supplies in some communities may result from a combination of issues, including the number of wells per unit area or number of people and limited potential of subsurface aquifers to meet the current water demands. Existing groundwater wells located in the communities vary in daily abstraction rates anywhere from 2 to 259 m^3/day (GRIP Limpopo accessed June 2013), suggesting that some individual wells do not meet a $\sim$5 m^3/day typical rural water supply demand (Macdonald et al. 2005). At one school, staff indicated water was not sufficient to meet both drinking and garden uses. Discussion with a local worker managing one of the community wells indicated that the drawdown experienced during continuous well pumping required significant shut down time to allow for water level recovery to avoid damaging the pump. Shut down time for water recovery is an often-cited reason in these communities for water limitations at the government-supplied taps. Further, documentation on individual well status (GRIP database) indicates pumping equipment failures and fuel shortages as other potential reasons for wells not functioning. Again these data have been supported by comments in our surveys, which suggest there are a multitude of reasons why any well may be out of service. These results are similar to those of other studies in villages in the region (Cousins et al. 2007).

When asked about past and future water trends related to water availability, respondents were split between those who believed there was no change in the amount of water from the past (36 %) and those who thought there was less water in the past (33 %). Alternatively, when asked about future water availability, more survey respondents were likely to indicate they expected declines in water availability (42 %). In subsequent surveys and interviews, respondents identified decreased precipitation as one reason for a reduction in water availability over time (McHale, unpublished data). Interestingly, in these interviews decreased amount of rain can be attributed to anything from climate change to loss of traditions and a dwindling population of "rainmakers". On the other hand, when people believed there would be more water available in the future, increased infrastructure provided by the government, rather than a changing climate, was a cited mechanism.

Physical data supported perceptions of decreasing water availability over time. Over the past 9 years (Oct-04 to Sept-13), groundwater monitoring wells in the region (e.g. ~75 km radius of HaMakuya communities) show overall water level drops on the order of 1–8 m (GRIP Limpopo database). Both well observations and stable water isotope signatures of groundwater collected from community wells during the 2012 and 2013 surveys suggest fractured hard rock aquifers are recharged by rainfall and/or episodic river recharge (Van Wyk 2010; IAEA GNIP, International Atomic Energy Agency, Global Network of Isotopes in Precipitation, Accessed 18 Aug 2012; Ridell, personal communication). Contributing factors to local water level declines could include changes in recharge (rainfall or riverflow) and/or local-scale withdrawals. As noted by Odiyo et al. (2015), recent studies specific to the Luvuvhu River catchment have quantified changes in land-use (reducing indigenous forest to bare ground) possibly resulting in changes to recharge (Griscom et al. 2010). Both local (Odiyo et al. 2015) and national scale analysis (Kruger 2006) have found decreasing trends in rainfall for the region. Considering all of these results, it is not surprising that officials in the HaMakuya Tribal Authority do not perceive groundwater as a reliable source for the long term, indicating they have had to drill to deeper depths for community water supplies, and they are in negotiations with regional and national governing agencies to install a dam on the Mutale River (HaMakuya Tribal Authority, personal communication, June 2013).

We experienced challenges in how to collect data and needed to adapt our research design to facilitate the opportunity for better data integration. In this initial phase of the program, the social and ecological methods and results did not overlap in a way that allowed for simple comparisons. Due to time constraints, challenges experienced in the field, and specific requirements and standards for each discipline's work to be accurate and publishable, integrating the social and ecological results was a challenge. For instance, our water quality results extended across numerous villages, while the survey data focused on three of the northern villages in HaMakuya. The water quality analysis required a high sample size distributed across the community and centered on schools since nitrates in water are specifically a health concern for children. Alternatively, for the survey data we needed high sample sizes within villages to account for variability that exists in perceptions in each place. Each village can have very different perceptions based on the water points located in close proximity to their households. Often the water is not available when we are in the field collecting data and, therefore, it has been difficult to assess water quality at all the water points in each village.

We have also learned that as researchers we needed to invest in reworking our survey tools to accurately capture the context sensitivities of place, framing, and culture. Partnerships with longer term residents helped to fill in gaps in our knowledge and data. Input from our partners and participants led us to realize that adjustments in wording, phrasing, and framing have been needed to maintain face validity of the survey tools. This meant a trade-off between absolute consistency of the tool used over time, relative to improvements in the validity of the data collected.

Data from the research project are featured in a local resource and education center and are used by local environmental monitors within the community in an effort to develop and promote a community-based learning and the monitoring system. In 2013 and 2014 the environmental monitors were able to present preliminary results to the Tshulu Trust Board and the HaMakuya Tribal Authority. Also, in 2014 the IMAGINE team produced a summary report for the Tribal Authority to review and utilize in negotiations with regional and national governing agencies surrounding the provisioning of water to HaMakuya's residents. Future data and analyses will be featured at the Tshulu Trust's resource center and presented to the individual villages of HaMakuya.

Phase C: re-integrating and applying the produced knowledge in both scientific and societal practice

We had numerous conversations as a research team about the significance of the findings, their relevance to the local community and how we could effectively communicate them. We had misgivings in the first year of data collection

(2012) because trends indicated that water quality might be detrimental to health, but we did not feel confident enough in 1 year's worth of data to go back to the community and potentially create a problem or a crisis. Instead, we elected to collect data for one more year, and we were more confident communicating our results after the second year of data collection. Although we were able to share preliminary data with the Tribal Authority, we have yet to be able to share this information with the residents of HaMakuya. This is partially because our data set included a dispersed group of 30 different water distribution systems across the 21 villages of HaMakuya. Our team has recently expanded their analyses, sampling all water distribution systems in 2013–2015 in over seven villages so we can provide a clearer picture to each village of the trends regarding water quality and their available water resources.

As a problem-oriented project, a key goal was to be responsive to the community's concern about water. One of the greatest challenges associated with conducting transdisciplinary research is in integrating data and finding ways to effectively communicate complex information to diverse audiences (Cash et al. 2003; Clark et al. 2011). To assess potentially important linkages between people's perceptions and water quality and availability we developed Fig. 2, which combined perceptual and biophysical data about water quality, quantity, and availability into one tool. The traffic light design in Fig. 2 is intended to be interpreted by the colors (green = good, red = bad, yellow = caution/data deficient) while also conveying some of the specifics included in the data collected that could be helpful to research participants and decision makers. Figure 2 indicated that water security was more of an issue for the villagers in the second year (i.e., more red lights on our traffic light diagram). The villagers who were interviewed the second year listed more varied water sources (column 1), had poorer water quality (column 2), declared less awareness of the National Water Act (column 3), and had more negative perceptions of water access and quality (columns 5, 6).[5]

Once data were blended, we were faced with knowledge mobilization challenges. Developing peer-reviewed publications from this work has been challenging. Time differences and distance constraints between South Africa, the United States, and Canada made meeting in person and via Skype challenging. Identifying clear niches in contribution to cumulative knowledge has been difficult with the variety of disciplines practiced individually among our team. The science created is more directly relevant to addressing the applied problem of our community partners than for academic audiences. Additional knowledge mobilization challenges were faced when relaying the blended data to the community members.

We had hoped that the traffic light tool would also help us communicate the scientific results to a diverse audience, but the staff at Tshulu Trust indicated that this tool was not intuitive for them, since traffic lights are not familiar elements of rural HaMakuya. Furthermore, when the local Tribal Authority requested a summary of the results, our trained environmental monitors (hired in 2013 to conduct water sampling, analysis, and data management in the HamaKuya area) preferred a bulleted summary statement and a table indicating the results to date. Although the traffic light figure was useful for the researchers to discuss the results in an interdisciplinary way, and to plan for future more integrated field methods, a more locally relevant visualization tool will have to be developed with the community members' involvement in the future.

It has taken five years of cumulative work (two years beyond the processes documented in this article) to have both the data and relationships to move beyond a problem orientation toward a more action-oriented stage. The project continues to navigate and build the relationships necessary with key stakeholders, including existing and new partners, and more attention is now being paid to the communities in the Limpopo by national government. Turnover in political appointees and elected officials necessitates the continuous building and then re-building of relationships. The potential for national government action could converge with the availability of our data and existing work to lead catchment scale action. At this stage, we have not yet achieved what we would like in terms of solutions, but we are on a path to do so. The knowledge that has been created has been used by the Tribal Authority and the rural municipality to push for a dam. Our partners have taken the knowledge and moved it forward. But the dam has not been realized, so the solution is incomplete. The water quality knowledge has not been used because we have been less confident in what the data meant, so we, as researchers, have not achieved what we would like to see in terms of solutions. Those solutions need to be generated by the Tribal Authority and rural municipality based on the knowledge created. So we, as researchers, are not yet satisfied in what the entire process has yielded, but we are confident that

[5] Symbols and colors were derived through collaboration among the research partners so equivalent scales of 'goodness' or 'badness' of the data could be produced. Green circles in column 2 indicate that safe quality and quantities of water were found using laboratory testing. Yellow triangles mean caution is needed in the interpretation because of data deficiencies. Yellow diamonds mean a poor quality or quantity finding such as the presence of *E Coli*. Red squares mean serious quality or quantity issues are present. For columns 3–7, green circles were used when *more than* half of participants at each site indicated positive perceptions of having knowledge of the NWA, water meeting household needs, consistent water supply, and a positive outlook for the future. Yellow diamonds mean 20–50 % of the sample perceived those findings. Red squares mean that more than half of the sample had negative perceptions of water safety, reliability, or quality, or less than 20 % of the sample had knowledge of the NWA.

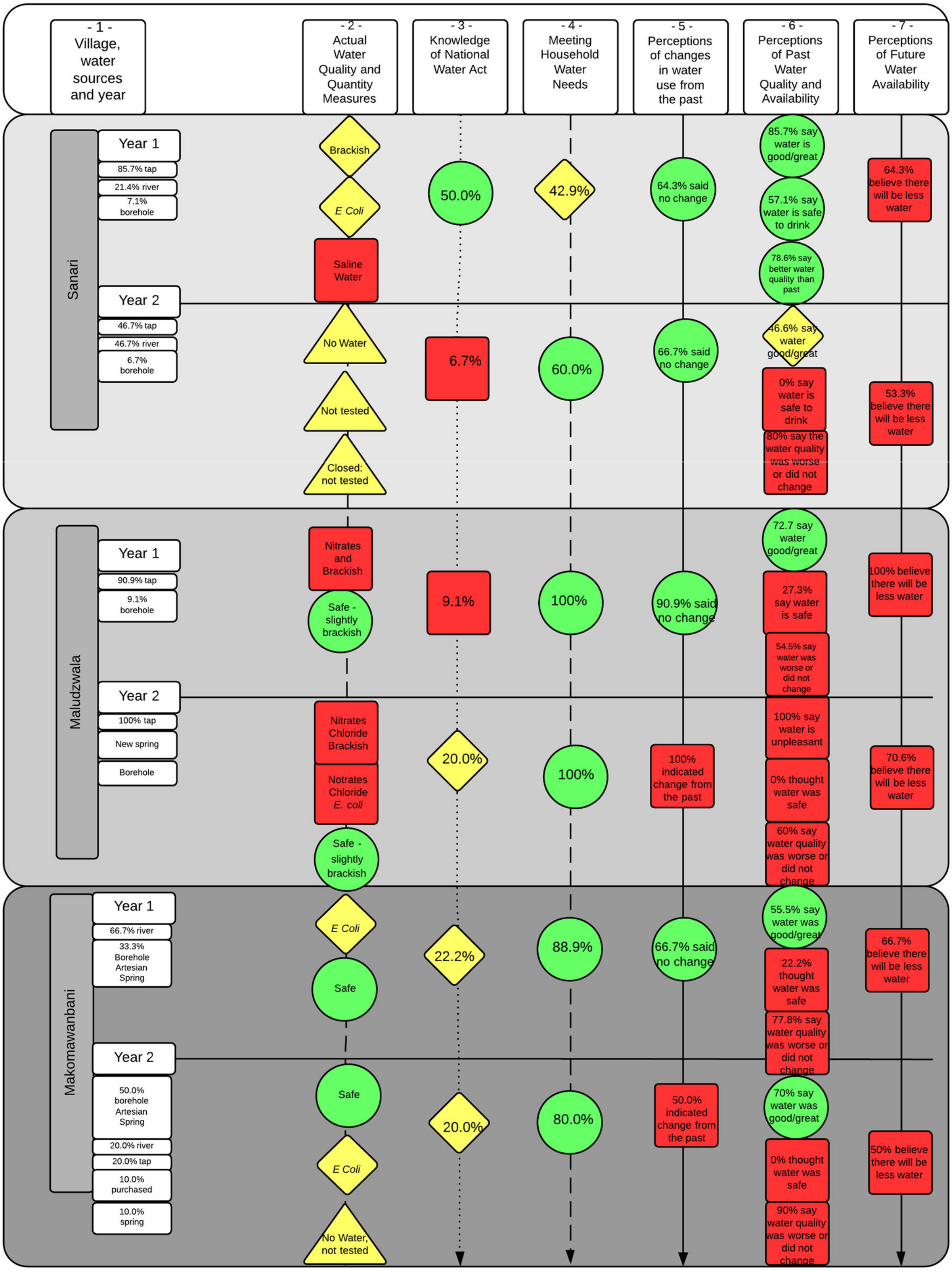

Fig. 2 Traffic light diagram: integrated data from water quality, quantity, and reliability research

additional time will yield gratifying results for all involved. Our goals have been to help the community understand their problems so we can jointly advocate for solutions. Solutions to water availability (more wells or build a dam) and water quality (discontinue use of some wells due to water quality or dilute the water from those wells if it is chemically polluted) require understanding the constraints on both issues. Our research during 2011–13, as documented here, was part of the larger effort to validate community perceptions and document water quality and availability problems. These data enable key stakeholders to advocate for solutions, as in the case made for the dam. We have been more circumspect with the data related to water quality and availability due to concerns about validity. The water quality solutions are beyond the scope of this manuscript at this time and our efforts could be interpreted as colonial or patronising if offered without building a consensus solution with our in-country partners.

Discussion

The value of the framework developed by Lang et al. (2012) comes from a wider scale application of case studies and projects to help fully understand where the systematic strengths, weaknesses, opportunities, and threats are to the practice of sustainability science. As such, we adopt their framework for evaluating the challenges faced by transdisciplinary projects to categorize where our project experiences obstacles (Table 2). In this section, we detail our challenges with an eye toward building this knowledge, especially as it relates to practicing sustainability science in a developing world context. While we have faced numerous challenges, we have also been creative in identifying coping strategies to deal with them, as detailed in Table 2. In short, we found that defining the problem and building our team have been easier than co-creating solution-oriented knowledge and reintegrating and applying this new knowledge in scientific and social practice back to the community at large, designing the research, and integrating the findings, especially given the demands for peer-reviewed science.

As suggested by Phase A: problem framing and team building, a problem-oriented approach recommends that sustainability scientists should focus their work as defined by human experience and expectation, not by researcher curiosity (Brewer 1999; National Academies Press (NAP) 2004; Kates 2011; Spangenberg 2011; Kueffer et al. 2012; Mooney et al. 2013; Lang et al. 2012). Lang et al. (2012: 33) identify three key barriers in this stage: (1) lack of problem awareness or insufficient problem framing; (2) unbalanced problem ownership; and (3) insufficient legitimacy of the team or actors involved. These were not significant challenges for our project, as documented in Table 2.

Problem framing was not a significant obstacle for our project. Our research team took direction from the asset mapping and focus groups in 2011 to explore issues related to water. We operationalized this to investigate concerns about water quality, quantity, and availability. Some reframing and reflexivity have been necessary along the way to refine our focus as we continue to drill deeper in terms of what water security means for the community. As recognized in Lang et al. (2012) one of the obstacles encountered in this phase of transdisciplinary research included insufficient problem framing. In our case, problem formulation has been a prolonged, iterative process of identifying different dimensions of the broader problem related to water security and then figuring out how to address them. As we learned about our context, we had to shift our assumptions about what would constitute effective research. Our work is firmly rooted in place—HaMakuya. Our data collection efforts had been piloted, refined, and revisited through an iterative process that continues to take into account specific local conditions and culture. However, translational and cross-cultural assumptions were not always valid and influenced our progress. As we grew to understand the complexity of problems we faced, we needed to address additional aspects. For instance, we are now incorporating different spatial scales, including different scales of catchment hydrology, different case study sites to understand the overall water systems, and we have a growing appreciation for the complexities of water governance in HaMakuya, Mutale Municipality, Vhembe District, and Limpopo Province within the broader framework of the South African system. Maps of elevated nitrate in groundwater for northern Southern Africa (Maherry et al. 2008) indicate a long running phenomenon that may not have easy solutions—this broader context is essential to understanding the decision space for taking relevant action.

Ownership of the problem has been unbalanced. Initially, the specific aspects of scientific data collection were left up to the researchers. Researchers and students initially dominated data collection. To address this challenge, national government funding was secured for a community-based monitoring program to help build credible longitudinal data sets for scientists as well as inform political discussion about the need to take action related to water quality, reliability, and availability concerns. Two local residents have been trained as environmental monitors and are now full-time employees involved in water sampling, analysis, and data management in the HaMakuya area.

We have experienced underrepresentation of stakeholders involved in the effort. Researchers have been more dominant that others involved, such as the Tribal Authority, municipal government, federal officials and agencies, and local non-profit organizations. Turnover in positions has been a problem, which leads to rounds of successive engagement, education, and involvement. Continuous efforts are made to engage these stakeholders and broaden the coalition working toward water security. Involvement is getting stronger over time.

As documented in Table 2, Lang et al. (2012) identify five key challenges associated with Phase B: the co-creation of solution-oriented transferable knowledge. These

Table 2 Challenges and coping strategies in the IMAGINE project (adapted from Lang et al. 2012)

Challenges	Description	IMAGINE project	Coping strategies
Phase A: problem framing and team building			
Lack of problem awareness or insufficient problem framing	Issues are not perceived as problematic	2011—focus groups based on asset mapping in the community. Communities identified water as a key asset and indicated they would like follow up work on water security. We need to revisit the appropriate scales at which the problem is conceptualized	Engaging in reflexive practice to ensure problem definition continues to be relevant. The problem has been refined iteratively based on on-going discussion with partners, community members and decision makers. New methods and approaches have been adopted as needed
Unbalanced problem ownership	Dominance of scientist or actors from practice in defining the joint boundary/research object and research objectives	Specific aspects of investigation were not well defined by the community, but left up to researchers to detail initially. As such, we focused on water quality, availability, reliability and perceptions. Researchers initially dominated data collection	Community–based monitors have been hired to collect data and build local capacity for understanding water quality. Surveys have been re-designed based on input from partners and local community members
Insufficient legitimacy of the team or actors involved	Underrepresentation of relevant actor groups in the research process	Researchers were more dominant than other stakeholders in the project initially. A broader coalition of groups has been developed over time	Continuous efforts are made to broaden stakeholder representation as new aspects of the problem are re-framed
Phase B: co-creation of solution-oriented transferable knowledge			
Conflicting methodological standards	Conflict between scientists and researchers regarding suitable methods	Research was primarily atheoretical and defined by methodological approaches from different disciplines (hydrology, ecotoxicology, and social science). Data are primarily focused on biophysical and perceptual aspects of water quality and availability. Data sets are small and limited to 2 years which makes it weak from a scientifically peer reviewed standpoint. Adapting to the needs of the community for better data collection has created issues related to standardized longitudinal data collection	We have had to identify creative opportunities for publishing to satisfy granting organizations that look for peer reviewed publications. We are publishing more about the process rather than the results
Lack of integration	Lack of integration across knowledge types, organizational structures, communicative styles, or technical aspects	Multiple disciplines (hydrology, ecotoxicology, social science) have been involved to create a greater understanding of how the parts contribute to the whole. This is best described as additive multidisciplinarity at this stage. Publication word limits constrain the ability to present complex, multidisciplinary work. Other disciplines involved in this project have not been well integrated (history, livelihoods, psychology) due to various obstacles (time, distance, disciplinary cultural divides, leadership). Identifying useful boundary crossing tools for communicating scientific findings that integrate our work has been challenging. Our initial Fig. 2 failed	We have identified publishable units that document smaller aspects of the broader research effort. We have adapted to respond to the kinds of findings/formats more useful to our partners
Discontinuous participation	Barriers for researcher and partners from practice to participate in transdisciplinary processes	Limited time in country for some of us and at the field site has led to discontinuous participation by researcher and disjointed interaction with on-site stakeholders. Community-based environmental monitors have presented data to other key stakeholders. Other opportunities to participate have been limited to date. There has been no easy solution to this given the distance from the site for all researchers	We maintain contact by email, Skype and in-country visits. We created a reflective experience with local leaders in HaMakuya, researchers, the Tshulu Board and local Tribal Authority to meet and discuss water issues in the region

Table 2 continued

Challenges	Description	IMAGINE project	Coping strategies
Vagueness and ambiguity of results	Different interpretations of results conceal potential conflicts	Results have not led to conflict. Findings have been conveyed to limited stakeholders, but not back to the community. We have created findings for stakeholders and scientists. These findings were used by HaMakuya Municipality in 2013 and 2014 to advocate for a dam. Findings have not been used beyond this	We have collected more data to create greater confidence in our results. We have conveyed some findings to key stakeholders and delayed conveying other findings to the broader community until clearer trends are apparent on which realistic solutions can be recommended
Fear to fail	Pressure leads to retreat to pre-packaged solutions	Did not apply to our case	N/A
Phase C: re-integrating and applying the produced knowledge in both scientific and societal practice			
Limited, case-specific solution options	Lack of transferability and scaling-up of results	Transferability is limited. The research is highly context sensitive at the local level—the villages of HaMakuya. Our confidence in trends is limited by the number of years of data collection. We see the context sensitivity of the work as strength, not a weakness of it. This creates greater challenges in peer-reviewed publishing, but creates greater face-validity for the findings for our local partners	We continue to collect more water quality, quantity and reliability data over time to assess temporal trends to create greater confidence in trends. We are now moving to understand the overall water systems hydrologically and politically. Scientific credibility of the data set will grow with time and a larger and longer data set
Lack of legitimacy of transdisciplinary outcomes	Friction between transdisciplinary projects and political processes	In terms of water governance, overlapping authorities at different scales (village headmen, ward councillors, district officials) affect attitudes related to the reliability of water provision. We are constrained in offering solutions until the Tribal Authority, municipal government and national government are ready to take action. Turnover in political appointees and elected officials has been a challenge	We continue to build research-informed constituencies that will help to direct researchers. We maintain a long-term, on-the-ground presence
Capitalization on distorted research results	Results are misused to legitimate actions that were not included	Results have been limited to date and so this did not apply to our case	N/A
Tracking scientific and societal impacts	Difficulties to assess scientific and social impacts due to characteristics of transdisciplinary research	No formal assessment has taken place at this time. We anticipate having challenges assessing impacts formally. Informal assessments are more likely	N/A

include (1) conflicting methodological standards; (2) lack of integration; (3) discontinuous participation; (4) vagueness and ambiguity of results; and (5) fear to fail. Our project experienced more challenges in Phase B relative to Phase A.

We have employed different methodological strategies based on the disciplines needed to understand both the biophysical and social processes related to water quality, reliability, and availability and this has led to difficulties integrating our findings. Interviews, surveys, focus groups, conventional scientific monitoring of ground water and water quality, community-based monitoring, historical archival analysis, participant observation, and listening have been some of the many ways of knowing what have been integrated in this project. Because the methods were not integrated when the research was initiated, we have had to find creative ways to integrate post-data collection. For this specific article, we could present only a small subset of data and, therefore, involved a limited number of our research colleagues. Furthermore, the complexity of the project and its applied focus has led to challenges in finding peer-reviewed outlets where we can publish, which is important to our funders (but not the community). We have focused on publishing about our process rather than the results. This article is an example of this strategy.

Full disciplinary and transdisciplinary integration has not occurred. These shortcomings arise out of the difficulties of crossing disciplinary divides and cultural borders. However, we see this as a long-term process and our program is young. Initially, in 2011 and 2012, we worked within our own disciplinary boundaries and our effort can best be described as additive and multidisciplinary rather than interdisciplinary—a problem not unfamiliar to other researchers in practice in projects of these kind (Roy et al. 2013). Although graduate students were engaged in all activities regardless of their disciplinary studies, their individual projects focused on one particular method associated with each discipline we engaged. We created a tool (Fig. 2) to integrate our interdisciplinary results. This tool has not been as effective as we would have liked it to be in terms of communicating with local decision makers and community members. Irrespective of the usefulness of Fig. 2, the knowledge is credible in terms of scientific standards and has use for local participants. For instance, the reports we created have been used to assist stakeholder interactions with municipalities for water capacity expansion, enabling them to make the case for surface water reservoirs.

Discontinuous participation has also been an issue for us. Temporal inertia is a challenge as most of us are on the ground in HaMakuya on a temporary basis so making progress is slow. Some researchers are in-country as full or part time residents, while others only come for a week or two at a time during field season. Interaction with key partners and stakeholders occurs episodically, based on when researchers are visiting. While distance, time, and labor intensity have restricted our ability to work more integratively as collaborators, significant steps were taken in 2013 and 2014 to be more transdisciplinary. For instance, we developed a reflective experience with local leaders in HaMakuya where researchers from the IMAGINE team and members of the Tshulu Board and local Tribal Authority met to discuss water issues in the region. Instead of the scientists presenting graphs with preliminary data, the meeting was a facilitated discussion in which participants described their own understanding of water availability and quality in the region, thereby building capacity for understanding the problems. This formal sharing of information was meant to reinforce our primary objective of working alongside the community to interpret and understand results from these analyses and plan future research activities. Other opportunities to participate have been limited to date. Overall, there has been no easy solution for discontinuous participation. We remain in contact via email, Skype, and with site visits.

Results have been ambiguous to date, but this has not led to political conflict. Data have been used to advocate for building a water reservoir. The water quality and availability data have not been used to advocate for solutions. As researchers, more data and comprehensive coverage would give us greater confidence in the trends we are identifying in water quality, quantity, and availability. Decision makers would like our data, so we must be responsive in terms of timeliness to meet their expectations. The trade-offs between comprehensiveness and timeliness are a challenge for sustainability scientists (Miller et al. 2014; Van Kerkoff 2014; Ascher et al. 2010). Unpredictable events need consideration. In only 2 years of study (2012–2013), we experienced a flood event that dramatically affected our results and created challenges for interpreting data. This has given us greater insight into the complexities of interacting stressors across scales and the consequences this can have on social perceptions as well as biophysical processes. Various government agencies and non-profit organizations are present and working on water quality and availability. Finding an appropriate and constructive niche for our work is politically sensitive.

The last issue identified by Lang et al. (2012) in this Phase, Fear to fail, was not an issue for our project. Our commitment to the HaMakuya community means long-term engagement that over time is likely to result in numerous failures and successes. We accept this will be part of our process.

The final Phase C—re-integrating and applying new knowledge as part of our scientific and social practice—has four major challenges associated with it. These include (1) limited, case-specific solution options; (2) lack of legitimacy of transdisciplinary outcomes; (3) capitalization on distorted research results; and (4) tracking scientific and societal impacts.

Our results have been case specific and transferability is limited. We began work at the local scale and are now moving into understanding the overall water systems hydrologically and politically. The research is highly context-sensitive and targeted to the villages of HaMakuya. We would like to have more water quality, quantity, and availability data over time to assess temporal trends to create greater confidence in the trends we think we see. We see the context sensitivity of our work as a major strength, not a weakness or challenge. The case-specific focus has limited our ability to publish in peer-reviewed journals, but will hopefully provide us with greater confidence in the problem definition which will lead ultimately to more robust solutions.

We have had great concern about the lack of legitimacy in our outcomes. Importantly, this article represents a "moment" in a long-term project, and the co-creation of knowledge associated with this phase (2011–2013) involved extensive engagement with the community. Water quality, quantity, and availability are by far the most significant issue in the lives of these communities, and for that reason they are also the most politically volatile, cutting across age, gender, class, and traditional authority asymmetries. Reporting early unconfirmed results to villages, without being able to offer pathways to solutions, could be counter-productive to our larger effort in the long run. In this observation, we agree with Scholz and Steiner's (2015b) comments about the tensions for protected discourse and the responsible release of results. Our effort is a long-term process of building research-informed constituencies that help to direct researchers in the trajectory of their further research, through a long-term, on the ground presence.

Capitalization on distorted research results has not been a concern for us. Data about water quality, quantity, and availability have not been communicated more widely so there has been no opportunity to distort results. Additionally, tracking scientific and societal impacts has not been given formal attention through the project at this stage. Our informal assessment leads us to conclude that we are building capacity among some of the stakeholders to understand the science and the dynamics associated with water quality and availability. Community-based environmental monitors and the Tribal Authority have been using the data to advocate for change; data have been used by the Tribal Authority to advocate for a reservoir. We have not yet communicated results back to the communities at large, and we have had significant challenges in establishing a niche for the originality of the science. There have been no plans for a formal assessment.

Conclusions and implications

For this article, we adopted the frameworks developed by Lang et al. (2012) to provide systematic insight into a case study about the practice of the science of sustainability. Our hope was to build on the practice of transdisciplinarity, since the field is still young and we have much to learn. At this time, we appear to know more about interdisciplinary and multidisciplinary practice relative to transdisciplinary practice.

Our finding that Phase A was easier and more effective than B and C is interesting, but it will be more noteworthy if this pattern continues over time or if it existed more broadly in other case studies. More in-depth case studies could be helpful in this regard. Are these patterns of practice common in transdisciplinary work in developing world contexts? Or are they reflective of how we practiced our version of transdisciplinarity? Future comparative research could help begin to address these questions.

Taking a transdisciplinary approach has been a simultaneously frustrating and satisfying issue for us. We needed to adhere to sound scientific processes while being responsive to a community that does not always understand or appreciate the need for scientific standards; these are issues not unique to our project (Wiek et al. 2014; Cash et al. 2003). Crossing cultural divides created communication challenges for what qualified as an effective boundary object. The opportunities to build community-based environmental monitoring and empower community resilience through citizen-based science are encouraging but challenging in terms of data quality, data dissemination, and data use. Trade-offs are necessary, but it is unclear where the thresholds are for what constitutes sound sustainability science, including transdisciplinarity, in these contexts.

How prescriptive should be we in understanding what can be labeled as a transdisciplinary process? Scholz and Steiner (2015a) suggest an ideal pathway, and it is clear that our project would not fit cleanly into this framework. Does that mean our work is not transdisciplinary?

Our experience differs from other transdisciplinary studies featured in this special issue. Our timeline has been longer and we have had to cultivate relationships and capacity for engagement along the way. In this issue, Scholz and Steiner (2015b) document obstacles at different stages in the transdisciplinary process. An important point they raise is whether the situation is ready for a transdisciplinary process. In our case, nearly 5 years have been spent building capacity to continue to engage in a transdisciplinary process. Scholz and Steiner observe that the projects on which they worked took 9–30 months (2015b). Our project clearly does not adhere to this ideal. Co-leadership, one of primary determinants of transdisciplinarity for Scholz and Steiner (2015a), has not been conventional in our case. We have had forms of collaboration during problem definition, data collection, and the search for solutions, but we have not had a stable set of co-leaders throughout the whole process. Does that invalidate our approach as transdisciplinary? These are important areas for continued discussion and research.

We feel that our singular case study speaks to potential challenges related to building relationships and co-creating knowledge in an epistemologically diverse and culturally foreign setting. Other case studies appear to have negotiated these issues in developing country contexts (MAC-COC Project 2011; Njoroge et al. 2015), and this leaves room for further investigation. What fundamental assumptions and practices differed in these cases? In our project, we have had to build our own capacity to engage both culturally and politically, which have been impediments to a more timely transdisciplinary process. Time, travel, distance, language, custom, and culture influenced what was possible for us. Transmission and use practices that applied in the developed world did not translate easily to our context. Were these functions failing to practice transdisciplinarity or were they part of creating capacity to practice transdisciplinarity? More research is needed to understand the opportunities for and limits of transdisciplinarity.

Scholz and Steiner (2015b) acknowledge that certain antecedents may need to be met before transdisciplinarity can be practiced. This raises provocative questions about when and where transdisciplinarity practice starts and how capacity for transdisciplinary research is cultivated. Community-based, participatory, and integrative research approaches triangulate on similar methods (Lang et al. 2012; Miller et al. 2014). Where does transdisciplinarity begin and the others end? Others have advocated for exploring bottom-up, adaptive transdisciplinary processes. We see our work contributing to this continued dialogue.

If we are going to tackle complex sustainability problems through transdisciplinary methods, then we need to educate students to deal with these approaches and techniques (Miller et al. 2014; Van Kerkoff 2014; Wiek et al. 2011; Wiek et al. 2014; Schmidt et al. 2012). Our project was targeted to educate and expose graduate students to the complexity of sustainability science. Key competencies such as teamwork and scaffolding (Schmidt et al. 2012), problem- and project-based learning (Wiek et al. 2014; Schmidt et al. 2012), and systems thinking and interpersonal competence (Wiek et al. 2011) were emphasized. Our process illustrated how messy these problems are, which can be difficult for students to understand and appreciate. While most students embraced the experience, some wanted a more sanitized, streamlined educational experience. Not all students prefer this type of work given its uncertainties. Coming to these insights in the field in a developing country is harder, but is it possible to understand sustainable complexities and challenges without these experiences?

We conclude there is great room left for improvement in practicing science of sustainability. Creating a community of practice for sustainability science practitioners is one way of capitalizing on our collective lessons learned and enhancing social learning on a meta-sustainability science level. As Lang et al. (2012) suggest, we need to work toward evidence-based principles for success that draw on individual and meta studies. We need to promote social and institutional learning at the project level (Miller et al. 2014), while also recognizing that we need to create the social infrastructure among sustainability scholars to learn from each other. Lang et al. (2012) framework helps us advance this agenda.

Contributing to the Lang et al. (2012) framework, we participate in the reflective practice that is essential for social learning in the adaptive management cycle (Spangenberg 2011; Miller et al. 2014). Our hope is to contribute a dialogue among those practicing sustainability science so that we might learn how to deal with the challenges we face within our own projects. Our example demonstrated the possibility for more systematic learning in how we might enhance the practice of science of sustainability on the ground. In this way, we can learn from one another and hopefully move towards achieving sustainability science goals.

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