A coupled-systems framework for reducing health risks associated with private drinking water wells

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ABSTRACT
Privately owned wells are vulnerable to contamination and as such pose a significant public health threat to those who rely on them for domestic water use. While a myriad of studies have sought to individually examine well water quality or the stewardship behaviours among well owners and users, few have effectively explored the intersection between private groundwater contamination and human behaviour. Even hydrosciology, socio-hydrology, and socio-hydrogeology, which make cases for an integrated, transdisciplinary approach to water-related challenges, do not appropriately describe the full range or complexity of interactions between the hydrological, geological and human systems necessary for effective public health interventions. To respond to this gap, a novel framework is proposed within the Canadian context, building upon ecohealth principles, and applied to an exposure framework developed for private wells. This framework improves upon current hydrologically based approaches and provides a comprehensive coupled (social and physical) systems framing of risk within the context of private well ownership. Application of this conceptual framework may be employed to support both transformative public health responses and effective stewardship by well owners.

Introduction
Human activities have resulted in a multitude of anthropogenically induced changes in the environment, such as climate change, land-use changes, and the increased emergence of zoonoses (Whitmee et al. 2015). There is a growing body of research that recognizes humans as dynamic and interactive actors within hydrological systems, whereby aspects of human behaviour need to be considered (e.g. Bloschl et al. 2015; Renaud and Schuster-Wallace 2017). Specifically, within the context of private drinking water wells, humans both create and control
groundwater issues and solutions. This body of research is emerging in parallel with the growing need to conceptualize public health threats as complex issues that require a coupled-systems approach that recognizes the relationship between the health of humans and the broader environment (Bogardi et al. 2011). Therefore, there is a need to re-examine public health challenges in a comprehensive and integrated fashion, in which environmental and hydrogeological issues are viewed in a broader, interactive context and as indicators of a once healthy ecosystem that has lost its ‘wellness’ (Bunch 2016). This is essential moving forward in the Anthropocene epoch, where humans have a central and vested role in the health and integrity of the environment.

Waterborne enteric illnesses, or acute gastrointestinal infections (AGI), continue to be a threat to public health globally (UN Water 2018), with untreated groundwater being a major source of enteric disease (Murphy et al. 2017). A recent study estimated that approximately 78,073 cases of AGI per year in Canada could be attributed to untreated private well water (Murphy et al. 2016). *Giardia* has been identified as a primary causative agent in numerous groundwater outbreaks and has been isolated from groundwater supplies in North America (Murphy et al. 2017). In Canada, for example, there were approximately 2500 laboratory-confirmed cases of giardiasis associated with contaminated private drinking water sources (surface and ground) in 2011 (Public Health Agency of Canada 2013). Moreover, laboratory confirmed cases likely under-represent the actual number of cases in the Canadian population, given not all ill persons seek medical care or submit samples for laboratory testing (Flint et al. 2004). The Walkerton, Ontario, tragedy of 2000 underscored the potential health risks associated with groundwater contamination, with seven deaths and 2300 illnesses in a town with a population of less than 5000 (Ontario Ministry of the Attorney General 2002). In Canada the majority of private water systems utilize groundwater, and 4.1 million (11.7%) people are reliant on private wells (Murphy et al. 2017).

**Purpose and aim**

Complex social-ecological relationships are often viewed in silos and analyzed as separate social and physical systems. However, coupled-systems thinking considers the complex relationships and interactions between these two systems (Berkes and Folke 1998). A coupled-systems approach moves beyond interdisciplinarity to transdisciplinarity, recognizing the interactions between disciplines rather than merely working between them (Waltner-Toews and Kay 2008). The concept of complex relationships between humans and ecosystems as a coupled system (Berkes and Folke 1998) stems from the application of a variety of ecosystem approaches to planning and management (Lee et al. 1982; Kay and Schneider 1994). The idea of a research approach that couples issues between society and the environment in the context of ecosystems has most notably been discussed in Kay and Regier (2000), Forget and Lebel (2001), Regier and Kay (2001), and Waltner-Toews et al. (2008), who advanced ecosystem approach frameworks such as the adaptive ecosystem approach (AEA; Kay et al. 1999; Bunch 2001; Waltner-Toews and Kay 2008) and the adaptive methodology for ecosystem sustainability and health (AMESH; Waltner-Toews et al. 2004).

Given the potential magnitude of, and uncertainty associated with, AGI incidence in people using private wells in Canada, the first aim of this paper is to develop and utilize a coupled (social and physical) systems approach to identify the potential contamination pathways and factors associated with the use of private wells, thereby creating a comprehensive conceptual framework for associated risks and interventions (see the section ‘Deconstruction of exposure pathways of well contamination’). The second aim is to highlight the current limitations of previous approaches, described subsequently in this paper (‘A systems approach – bridging hydrology and humans’), as the authors suggest that the next area of innovation for transdisciplinary action is to appropriately acknowledge and analyze social, political, geological and hydrological systems together. The complexity of the relationships that exist between these systems requires a comprehensive framing (see the section ‘Framing the human–water interface within a coupled-systems approach through a public health lens’) to provide a process of inquiry and research for private drinking water wells. Thus, the third aim is to propose a framing that utilizes a coupled-systems approach to place human health and society within both the problem and the solution, while working across disciplines and methodologies to understand the behaviours (social) and elements (physical) that mitigate human health risk (see the section ‘Framing the human–water interface within a coupled-systems approach through a public health lens’). While focused on Canada, the findings are applicable to other geographic contexts and other water-related health threats. Moving forward, the proposed framework is intended to be used as the basis for the design of data collection and decision support tools,
Deconstruction of exposure pathways of well contamination

Identification of contamination sources and pathways is vital to the implementation of appropriate mitigation strategies that aim to minimize human health risks associated with groundwater systems. A coupled system combines the hydrogeological system with social and physical systems to account for environment, groundwater source, pathogen, human behaviour and regulation, as well as feedback loops that mediate (for better or worse) human risk. As such, a multi-dimensional exposure framework has been developed (Figure 1) describing the potential for adverse human health outcomes (e.g. AGI) associated with contaminated groundwater in private wells. Although enteric pathogens are the focus of this exposure framework, it could be argued that this framework is applicable to other contaminants.

The exposure pathway begins with one or more pathogen reservoirs, be it a host (final or intermediate), vector or the environment, initiating the contamination pathway (Figure 1, top left). An extensive global review covering over six decades, from 1948 to 2016, identified norovirus, Campylobacter, Shigella, hepatitis A and Giardia as the pathogens associated with most groundwater outbreaks (Murphy et al. 2017). In Ontario, Campylobacter, Cryptosporidium, Giardia, norovirus and Escherichia coli O157 have been used as index pathogens to determine the health risks associated with private groundwater sources (Murphy et al. 2016).

Temperature, which changes over space and time and is impacted by climate change, is an important factor in determining pathogen survival, virulence and proliferation (Patz et al. 2003). Precipitation mobilizes pathogens on the ground surface and transports them to water bodies through runoff or to the subsurface through infiltration (Blaustein et al. 2016). Thus, changes in intensity, duration, frequency and
distribution of precipitation will ultimately affect pathogen transport (Blaustein et al. 2016). Pathogens can enter a well directly (i.e. surface runoff) or indirectly through an aquifer (i.e. recharge) (Pandey et al. 2014). This highlights the importance of well location in pathogen transport, as the threat to groundwater in developed countries is primarily a result of private and municipal wastewater treatment systems, livestock grazing and farming practices (e.g. fertilization and irrigation) (Hynds et al. 2014). In a review of groundwater contamination in Canada and the US by enteric pathogens, almost 50% of extracted records from private domestic wells reported septic tanks or sewage systems as the most likely pathogen source (Hynds et al. 2014). This relationship is moderated by location and distance to contamination sources, as the presence of enteric pathogens in well water associated with AGI rose as distance to contamination sources, such as septic tanks, decreased (Murphy et al. 2017). Additionally, the direct connection between surface water and groundwater, referred to as groundwater under the direct influence of surface water (GUDI), is recognized as an important transport pathway for contamination to enter both aquifers and private wells (Nnadi and Fulkerson 2002).

A pathogen’s ultimate route into a private well is highly dependent on local (hydro)geology and the physical integrity of the well, which is mediated by well characteristics (including type of well – dug or drilled) and maintenance (Wallender et al. 2014). Geology and soil type determine the size and distribution of transportation pathways for pathogen contamination and therefore whether or not contaminants reach the well and whether they are still viable pathogens (i.e. able to induce illness). Fractures facilitate rapid transport of pathogens in subsurface environments, with contamination events frequently occurring in regions underlain by karst and fractured bedrock (Berger 2008). In Canada, 70% of the regional aquifers exist in fractured formations (Rivera 2014). Overburden when present, such as sandy soils, provides some pathogen removal through filtration, while competent (i.e. unfractured) clay aquitards are relatively impermeable, thereby preventing the migration of pathogens.

In addition, the physical integrity of the well influences pathogen ingress. The construction (i.e. age, type of well, depth, presence and integrity of a casing and grout seal) and maintenance (i.e. uncovered wellheads and cracked jointing) of a well are important factors in mitigating the risk of contamination, as poorly designed or constructed wells are the most likely pathway for contamination by enteric pathogens (Hynds et al. 2014). These factors may provide a ‘rapid bypass mechanism’ for contaminants to directly enter the well, leading to potentially more pervasive threats to water supply than aquifer pathways (Howard et al. 2003).

Beyond the ecological perspectives that frame the exposure framework, the systems approach requires integration of the social pathways that contribute to human health risk (Figure 1, right side). The true extent to which a well owner’s knowledge, attitudes and practices (KAP) contribute to the likelihood of contamination has yet to be appropriately addressed in exposure risk assessments for drinking water wells. Previous studies have shown a paucity of well stewardship behaviour (e.g. well maintenance, testing, treatment) among private well owners and users, which is likely associated with poor engagement, communication and policy (Jones et al. 2006; Summers 2010; Kreutzwiser et al. 2011; Hynds et al. 2013; Roche et al. 2013). Water testing frequency has previously been employed as an indicator of stewardship behaviour (Kreutzwiser et al. 2011); however, among well users from Ontario municipalities, almost 90% failed to submit the three recommended samples per year (Maier et al. 2014). Similarly, low uptake and use of appropriate water treatment methods has been found among approximately 50% of well users in various municipalities across Canada (Jones et al. 2006; Roche et al. 2013). Perhaps more concerning are the pervasive inconsistencies between groundwater risk and knowledge of groundwater contamination among private well owners, which indicate a low level of perceived risk (Summers 2010; Kreutzwiser et al. 2011). Well owners are often unable to recognize potential sources of contamination, such as agricultural activities and presence of a septic sewer system (Hynds et al. 2013). In the absence of this awareness and with the consequent limitations of risk perception, well owners believe it is best to forgo testing unless a problem arises (Summers 2010).

A coupled-systems framing recognizes the need for the engagement of multiple stakeholders that influence decisions, policies and practices (Figure 1, top right). Although guidelines and legislative tools exist provincially and municipally across Canada regarding groundwater use, private and public drinking water systems, including wells, are not analogously regulated. In Ontario, the Ontario Safe Drinking Water Act (2002) and the Ontario Clean Water Act (2006) set out guidelines for public drinking water systems. Although the construction of a private well is
regulated under the Ontario Water Resources Act (1990), responsibility for the condition and maintenance falls on the well owner. While national guidelines exist for maximum allowable levels of specific pathogens and chemicals, the lack of regulation for private wells means that individual well owners are entrusted with managing their own water quality, well maintenance and testing.

Ultimately, the human health risk of exposure to waterborne enteric pathogens is contingent on exposure factors (Figure 1, bottom right), which include water uses or contact, and consumption volume (affecting pathogen dose). Some segments of the population are more vulnerable than others, including the immunocompromised, the elderly and children (<5 years). Children in particular are at an increased risk of AGI from consuming private groundwater sources, primarily as a result of their increased likelihood of exposure (i.e., bathing and recreation, lack of hygiene; Dickin et al. 2016), an overall lower dose–response (threshold dose) to pathogens, and higher water volume ratio per unit body weight, which increases dehydration risk (UNICEF and WHO 2009).

A systems approach – bridging hydrology and humans

Several interdisciplinary approaches to researching water-related issues have emerged over the past four decades, primarily due to a major shift in water resources research. The growing recognition of the interplay between people and water systems (e.g. Gorelick and Zheng 2015) has resulted in numerous notable studies recommending that the social, health and natural sciences be combined within the context of water research in response to the convergence of several disciplines, starting with Falkenmark (1979).

These shifts in perspective have given rise to frameworks that strive to integrate the interactions between humans and water, the earliest of which was the hydrosocial cycle, followed by socio-hydrology, and most recently socio-hydrogeology. Although these frameworks may seem synonymous, in reviewing their epistemology and research paradigms the differences become evident, in particular how each approach differs with respect to how it captures the risk pathways of well water systems for the people using them, and in its application of scientific knowledge in providing solutions to water issues.

The hydrosocial cycle is described as a ‘dialectic relationship’ between water and society, where social relations and power (i.e. level of influence or authority) are inherent parts of the water cycle (Linton and Budds 2014). It should be noted that the hydrosocial cycle was never intended to address health. Derived from Marxism, power and water are so closely related in the hydrosocial cycle that these two entities are seen as hybrids and cannot be viewed separately from one another (Wesselink et al. 2017). This dynamic relationship between power and water represents not only how water is engineered socially and physically, but also how water shapes social relations (Linton and Budds 2014). The hydrosocial cycle is used within the hydrosocial approach as a means to depart from merely scientific concepts, and to view water ‘as a social construct with political consequences’ (Wesselink et al. 2017, p. 8). As such, the concept of water and society shifts from a linear process to a dialectic cycle in which social relations and water co-evolve, ‘making and remaking each other’ (Linton and Budds 2014, p. 171). Therefore, society and power have remained the focal point of the hydrosocial approach, in which an analysis starts with society and ends with recommendations. A challenge to the hydrosocial approach is whether the use of in-depth social and power theorizing can actually provide superior case descriptions (e.g. the application of the hydrosocial cycle in describing the social and political definition of water in the European Union, as described in Zurita et al. 2015), compared to other, less theoretically dense approaches (Wesselink et al. 2017). Moreover, the emergence of the hydrosocial approach from the social sciences means that the language used in the hydrosocial literature can be limiting for most hydrogeologists, and its use of theoretical terminology can restrict its use among non-hydrosocial researchers.

Socio-hydrology was first introduced by Sivapalan et al. (2012) as a term to describe the feedback loops between hydrological and social processes to better address the aspects of human alteration of water systems, as this had previously been ignored. Socio-hydrology researchers have branded this discipline the ‘science of people and water’, a discipline intended to provide an understanding of the ‘co-evolution of coupled human–water systems’ (Sivapalan et al. 2012, p. 1271). Again, health is not an explicit domain of socio-hydrology. Socio-hydrology is conceptually derived from classical sociological and ecological theories (Pande and Sivapalan 2017). However, socio-hydrology separates itself from these theories and case-specific research, such as integrated water resources management. It draws from scenario-based studies, but rather than providing solutions to water
management issues, socio-hydrology utilizes social and physical dimensions within predictive models to better understand the coupled system (Sivapalan and Blöschl 2015). However, the complexity of studying the co-evolution of human processes over time and spatially relevant scales to construct models is still not well understood in socio-hydrology’s application (Troy et al. 2015). Socio-hydrology distinguishes itself by attempting to understand the co-evolution of humans and water systems by capturing these interactions through mathematical equations in the form of predictive models for hypothesis generation (Sivapalan and Blöschl 2015). However, upon analysis of the current existing socio-hydrologic models, Troy et al. (2015) determined that these models must do more than generate hypotheses. Rather, they must ‘become formal quantitative tools that can be used for hypothesis testing and for general advancement of the foundations of socio-hydrology’ (Sivapalan, 2015, p. 4804).

Recently derived from the socio-hydrology approach as a sub-discipline, socio-hydrogeology has been proposed to recognize human impacts on groundwater systems (Re 2015; Re et al. 2017). Compared to socio-hydrological models, socio-hydrogeology brings attention to a ‘hidden’ water resource and separates itself by recognizing the need to integrate local knowledge, and bring solutions to society through knowledge sharing and scientist–society engagement (Re 2015; Limaye 2017). It can be interpreted as an evolution of both the hydrosocial approach (recognizing the importance of power in water issues) and socio-hydrology, incorporating end users throughout the process. It is purposed that involvement with local stakeholders and final knowledge users of hydrogeological research improves sustainability and effectiveness of water management solutions (Re 2015). Closing the gap between researcher and end user has been postulated as the key to bringing science to society (Limaye 2017), and has been suggested as the mechanism to provide changes among society, pushing hydrogeologic investigations beyond the bounds of academic journals and predictive models (Re 2015). Although other approaches recognize the social dimensions of water issues, socio-hydrogeology attempts to integrate it. Bir Al-Nas (Bottom-up IntegRated Approach for sustainaBLe grouNdwater mAnagement in rural areaS) (Re 2015; Re et al. 2017) was the initial case study incorporating socio-hydrology into groundwater investigations and solutions in the Grombalia Basin in North-East Tunisia. Its focus on stakeholder and social analyses separates itself within hydrogeological assessments, but similar to the aforementioned approaches, still lacks a vital component – health.

In attempting to identify and understand the strengths and weaknesses of these approaches, the exposure framework (Figure 1) was examined from the perspectives of hydrosociology, socio-hydrology and socio-hydrogeology. While together these approaches identify most of the critical pathway elements, their epistemologies and disciplinary roots emphasize different parts of the exposure framework (Table 1). Specifically, the hydrosocial approach, with its emphasis on power differentials, is useful in deconstructing the policy/practice interface, but it stops short of solutions in a broad field of water research that emphasizes their implementation (Wesselink et al. 2017). Socio-hydrology provides a mechanism to model water–human interactions. However, despite its intentions to understand the interaction between humans and water systems, the way in which socio-hydrology conceptualizes this two-way feedback system is difficult to validate and requires application across multiple locations (Troy et al. 2015). The ability to observe and record human processes involved with water issues is difficult to quantify, subjecting much of the data to the interpretation of the researcher. A call for a more decentralized approach to socio-hydrology, which includes translating knowledge to decision makers and incorporating local knowledge with science, may provide the best way forward (Gober and Wheater 2015).

Further, modeling human behaviour presents a significant challenge, requiring large amounts of data across and within varying demographics, regions and timeframes. Even if the evolution of humans and

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<tr>
<td>Contamination source</td>
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<td>Pathogen transport</td>
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water systems can be predicted, it is likely that the dynamics of other societal dimensions, such as economics and culture, are not transferable to other water issues or models (Troy et al. 2015). Socio-hydrogeology, as the most recent approach, is consequently the most underdeveloped but it provides perhaps the most advanced social assessment of the three approaches. Socio-hydrology emphasizes the relationship between researchers and end users and the imposition of science on people, rather than the behaviours and practices that provide critical insight to mediation of enteric pathogen risk. The positioning of hydrogeologists at the forefront of socio-hydrogeology appears to be a logical and effective use of hydrogeologists as educators and mediators in hydrogeological investigations. However, it is also a major limitation as the inclusion of social elements into hydrogeological research is likely to lie outside the expertise of many hydrogeologists. A truly transdisciplinary approach involving hydrogeologists, social scientists and local stakeholders would serve to strengthen the realization of socio-hydrogeology.

In summary, while all three approaches integrate the social and physical systems of water to some degree, none can claim to be comprehensive. Humans have impacted water resources and courses, but it is the fundamental need for water in life, health, and economic growth that serves to drive these impacts. As such, the lack of recognition of or emphasis on human health and wellbeing in any of these approaches is a major drawback to their use in this context.

**Framing the human–water interface within a coupled-systems approach through a public health lens**

The field of ‘ecosystem health’ emerged in the 1990s as an interface between the social, natural and health sciences (Rapport et al. 1999). The ecosystem approach to health, or ecohealth, was pioneered in the 1990s by the International Development Research Centre (IDRC) (Forget and Lebel 2001; Lebel 2003). This ‘ecosystem approach to human health’ was based on three methodological pillars: transdisciplinarity, participation and equity (Lebel 2003). These were later expanded to the current six principles that ground the theory to inform ecohealth research, namely systems thinking, transdisciplinary research, participation, sustainability, gender and social equity, and knowledge to action (Charron 2012).

The ecosystem approach to health, or ecohealth, was identified as being flexible and comprehensive, and therefore a more robust approach to addressing human–water challenges. Unlike the previously proposed approaches, ecohealth places human health at the center of both improving and managing the environment (Lebel 2003). From a research perspective, ecohealth provides a transdisciplinary approach that is grounded in *systems thinking*, harnessing *participatory* action methods, and emphasizing gender and social *equity* (Charron 2012). An ecosystem approach draws from a multitude of disciplines, including public health science (Forget and Lebel 2001; Parkes et al. 2005), systems ecology (Parkes et al. 2003), veterinary medicine and ecosystem management (Charron 2012).

Ecohealth differentiates itself from the aforementioned approaches by focusing on the co-benefits of both humans and the environment. The approach is rooted in the ideology that human health must be understood within the context of the interrelationship between coupled human and socio-ecological interactions (Waltner-Toews 2009). The approach is also based on the need to protect ecosystems and improve environments to ensure human health, along with social and environmental *sustainability*. However, the principles of sustainability in ecohealth are not always practiced through the implementation of technologies, but rather through ‘a process of learning and investment in local governance’ (Webb et al. 2010, p. 440). The approach is explicit in its application to translate *knowledge into action*. Much of what this approach tries to explain is beyond the traditional sciences, and is used in situations where there are multiple competing causes and interconnected relationships (Bunch 2016), such as the case of private drinking water wells.

A comprehensive conceptual framing for well water contamination must encompass the following criteria, and which ecohealth most adequately fulfills:

1. Utilize a coupled-systems approach (i.e. social and physical systems) [socio-hydrology, socio-hydrogeology, ecohealth];
2. Place human health at the center [ecohealth];
3. Incorporate a humanistic approach (i.e. examine issues through both the eyes of the observer and the individual/community) [ecohealth];
4. Integrate qualitative methods with traditional quantitative approaches in order to better understand human behaviours in water systems [socio-hydrology, socio-hydrogeology, ecohealth]; and
5. Disaggregate into specific elements and behaviours and avoid over-generalization [hydro-sociology, socio-hydrology, socio-hydrogeology, ecohealth].

Specifically, an ecohealth approach addresses all elements identified as necessary for a comprehensive framework, as detailed below.
Ecohealth’s focus on health (both human and ecological health)
Defining health within the context of ecohealth has been described in a metaphorical rather than literal sense, and is attributed to more than just human health (Charron 2012). The health of humans and the environment are closely intertwined in ecohealth. Bunch et al. (2011, p. 2) stated, ‘human health and well-being are important outcomes of effective ecosystem management’, which reinforces the need for multi-sectorial collaboration that brings together human health and the environment. Further, ecohealth can be defined as an approach to both understand and promote human health, specifically within the context of social and environmental issues (Waltner-Toews 2009). Unlike other approaches, ecohealth places humans as internal rather than external to the system; that is, human health is not the consequence of what occurs in the system, but rather reflects the role of humans as participants in the system.

Ecohealth’s focus on the human–environment relationship in the face of a changing environment
Ecological approaches to human health consider the determinants of health, to investigate the interactions between social factors and the environment in order to generate a more comprehensive understanding of human health within the context of the environmental issues (Webb et al. 2010). Within the discipline of ecohealth, the idea of population health is considered, and as a result of physical, social, and political hierarchies within the biosphere (Webb et al. 2010).

Ecohealth’s focus on systems thinking
Systems thinking stresses individual system components, non-linear interactions and feedback loops between several complex components (e.g. Figure 1), and the ability to integrate multiple systems.

Building upon the AMESH framework (Waltner-Toews and Kay 2008), Figure 2 articulates a coupled-systems framing of private drinking water well risks and responses. In a desire to articulate and understand the health risks to private well owners (in this case from pathogens), it is critical to describe and analyze the core elements of both the social and physical systems, as well as points of interaction between the two. As illustrated in Figure 1, in the case of pathogen contamination, the physical system risks are represented by weather and climate change, pathogen sources, local hydrogeology, and local well descriptors. The social system risks (Figure 2) are realized through human behaviours, knowledge, perceptions and access to resources, infrastructure and information. The main cross-system feedback mechanism affecting risk (Figure 2) exists between knowledge, attitudes and practices and the condition of the well, for reasons articulated earlier.

Once these drivers of risk have been identified, it is possible to derive risk profiles for specific groups within the system (Figure 2), including which system they impact upon or impacts upon them and therefore which identified intervention in which system confers the greatest risk reduction for the investment made. In this manner, intervention scenarios can be deconstructed in terms of target for impact, degree of risk reduction, and feasibility. For example, a concerted, well-defined public health campaign to increase well inspections and well water testing might confer similar risk reduction to far more complex and largely unfeasible individual well source water protection plans that apply to lands not under the control of the well owner themselves, depending on which is the greater driver of risk. Other potential

Figure 2. Framing a coupled-systems approach to mitigating microbial health risks for private well owners.
interventions might include additional access to water testing laboratories or a septic tank assessment protocol.

It should be noted that application of the framework requires a qualitative and quantitative approach to analyzing and describing the impacts of physical and social factors on risk profiles as they pertain to different segments of the population. The resulting assessment of risk levels and pathways facilitates iterative collaborative learning and informed action that cannot simply rely on physical interventions, but must also include behavioural interventions (including policy) across key stakeholders.

Conclusions

While the recognition of the importance of interactions between humans and the hydrological system through the emergence of these new approaches (i.e. hydro-sociology, socio-hydrology and socio-hydrogeology) should be lauded, it is important to recognize potential limitations and pitfalls. When attempting to use these approaches that bridge hydrology and humans to characterize health risks associated with private well ownership, it becomes clear that health and wellbeing (of both humans and the environment) is a critical gap. Moreover, as a result of epistemological roots, each approach emphasizes particular elements as compared with a more comprehensive coupled-systems framing. Ecohealth provides the missing elements (especially the historical context and human behaviour) articulating not only the exposure pathway, but also a framing to guide transdisciplinary research investigations for the development of tools. These tools, in turn, work to enhance knowledge and understanding of risks, threats and preventive actions among all stakeholders, ultimately impacting the health of private well users.

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