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PAPER

# Applying a science-forward approach to groundwater regulatory design

**Deborah Curran**[1] · **Tom Gleeson**[2] · **Xander Huggins**[3,4]

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## Abstract

Groundwater sustainability is challenged by the difference between legal and scientific understanding of groundwater, as well as the lack of focused attention to regulatory design in the literature on groundwater institutions, governance and management. The purpose of this paper is to use the scientific characteristics of groundwater to direct the necessary elements of regulatory design for this unique element. Developing interdisciplinary language that could be applied in any jurisdiction or region, the article describes seven groundwater characteristics as processes, functions, qualities, physical sustainability, scale, information and data, and physical state. Using these characteristics of groundwater embeds the scientific understanding of groundwater into regulatory design and enables the expression of new values such as Indigenous rights to water. Applying these scientific characteristics to a case study of new groundwater regulation in a subnational jurisdiction in the Global North—British Columbia (BC), Canada—highlights the failure of regulatory design even in a well-resourced jurisdiction where environmental regulation is the norm. Groundwater in BC is extremely heterogeneous in process and function, with low observation density and undefined sustainability goals where regulations are applied uniformly. Looking forward, three recommendations can be drawn using the scientific characteristics of groundwater to improve regulatory design in BC: defining sustainability goals and ecological thresholds; regionalizing and prioritizing; and long-term planning. This science-forward and interdisciplinary approach has implications for states with customary water entitlements and multiple legal orders. It also provides practitioners with an interdisciplinary language that can be useful for assessing current and future regulatory design.

**Keywords** Groundwater management · Groundwater protection · Regulatory design · Indigenous authority · Canada

## Introduction: regulatory design as a missing ingredient in groundwater sustainability

> Oversimplification of our design options is dangerous since it hides more of the working parts needed to design effective, sustainable institutions than it reveals. And, it reduces our awareness of the need to monitor outcomes and improve them over time through better processes of learning and adaptation (Ostrom 2005, p. 256).

Since the 2000s, the conversation about the sustainability of groundwater has increasingly turned to issues of governance. Noting the disproportionate research focus on groundwater science and technology that ignores the people involved (Mukherji and Shah 2005), water scholars and experts ascribe the crisis in water to a failure in governance (Global Water Partnership 2000). More generally, environmental governance, which includes regulatory design (defined in the Appendix) for groundwater, is not simply a technical endeavour but involves complex socio-ecological processes both within and beyond the state (Harris 2017; Taylor 2015). Socio-ecological systems approaches acknowledge the dynamic and reactive interdependence between humans and natural systems (Gain et al. 2021).

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✉ Deborah Curran
dlc@uvic.ca

[1] Faculty of Law and School of Environmental Studies, University of Victoria, Victoria, Canada

[2] Department of Civil Engineering and School of Earth and Ocean Sciences, University of Victoria, Victoria, Canada

[3] Department of Civil Engineering, University of Victoria, Victoria, Canada

[4] Global Institute for Water Security, University of Saskatchewan, Saskatoon, Canada

Groundwater management and regulation is equally about social change where hydrosocial processes also shape waterscapes (Delgado-Serrano and Borrego-Marin 2020; Nygren 2021). Therefore, scholars are calling for a shift in the focus of groundwater management as a purely technical science or legal endeavour to a governance that accounts for multiple scales, actors and approaches needed (Mukherji and Shah, 2005). Such a shift would allow for more authentic expression of Indigenous or customary water rights and responsibilities (Marshall and Kirby 2017; Craft and King 2021).

Placing more emphasis on governance and the social aspects of groundwater through water resources policy, administration and law necessitates an interdisciplinary approach (Caponera and Nanni 2019). Groundwater regulation is a key tool for policy implementation and structuring governance arrangements (Mechlem 2016; De Stefano and Lopez-Gunn 2012), as well as for adapting uses and protecting water from the impacts of climate change (Nanni 2012; Cullet and Stephan 2017). While regulatory design is challenged by uncertainty (Jones 2007; Muchmore 2016), it is important to take an integrated approach that values groundwater science, social relations and institutional structures (Mukherji and Shah 2005).

This evolving context for the complexity of groundwater governance reveals at least two challenges for advancing groundwater sustainability. The first is that legal views about groundwater often differ fundamentally from scientific understanding of the scope and qualities of groundwater such that legal distinctions “bear no resemblance to geological reality” (Nelson and Quevauviller 2016). Groundwater regulatory design as part of water resources regulation for the extraction of groundwater continues to be preoccupied with allocating use entitlements and property rights in water (Bosch and Gupta 2023; De Stefano and Lopez-Gunn 2012). The second challenge is that the significant literature on groundwater institutions, governance and management lack focused attention to regulatory design. Articles dealing with regulatory design, in general, do not define the term (Muchmore 2016; Jones 2007), and scholars tend to focus on the features of policy and regulatory design such as flexibility, predictability and incentives (Pettersson and Söderholm 2014) and their failure (Koski 2007). Authors have examined how dependent structures, such as institutions, should have an impact on regulatory design (Araral 2014). In the case of water, regulatory design is not just about creating a permit system for water users but includes how the law enables the features of the entire regime for water protection and management from creating planning mandates to diverse institutions that may reflect customary and state responsibilities and rights through which decisions are made.

Groundwater regulation literature includes technical, case study, and interdisciplinary synthesis approaches. Technical research includes examining the relationship between well drilling, abstraction and regulation (November et al. 2021; Naber and Molle 2017), as well as modeling or testing how different regulations will affect a stated issue (Liao and Hsiang-Wei 2016; Guo et al. 2015; Missimer et al. 2014; Rinaudo et al. 2012). Case studies of special status or place-specific groundwater regulation abound (Knorr et al. 2021; Turco and Petrov 2015; Cullet 2014; Apaydin 2011) and include optimal regulation to achieve a specific outcome (Aarnoudse et al. 2017; Ling et al. 2020; Li et al. 2018), and compliance (Holley et al. 2020). Interdisciplinary syntheses have evaluated the social, political and economic factors that influence the success or failure of groundwater regimes and noted trends, challenges, or established practices (Mukherji and Shah 2005; Theesfeld 2010; FAO 2016; Mechlem 2016; Nelson and Quevauviller 2016; Molle and Closas 2020a). Noting that most quantitative groundwater regulation regimes fail, Molle and Closas (2020b) identified strengths and weaknesses in political will, the extent of quantification of the resource, institutional capacity, and social norms, including how the attributes of aquifers affect policy implementation through institutions. While few examples exist of regulation that achieves quantitative groundwater sustainability, authors note that the relative successes demonstrate aquifer-specificity (rather than national or regional approaches), wells that are easily defined (either small in number or managed by a defined user group), users that can be identified by their physical plant (such as farms), social homogeneity among the primary users (i.e. farmers) or equality of access to licensing, and the state can effectively exercise authority to identify wells, control drilling and take enforcement action (Molle and Closas 2020a). Most recently groundwater governance scholars are calling for a return to Ostrom’s principles of institutional design for common pool resources (2005), to examine its ongoing utility for informing groundwater governance (Seward and Xu 2019).

Returning to the challenge of legal intention failing to reflect hydrological processes, there is a contemporary research gap in considering how the scientific characteristics of the thing being regulated, in this case groundwater, impact regulatory design. Scholars have noted the importance of building from the characteristics of groundwater and aquifers (Theesfeld 2010; Caponera and Nanni 2019); however, studies do not examine whether a regulatory regime meets this precondition that regulatory design must reflect the unique qualities of groundwater. Posing this fundamental question continues the important inquiry into the connection between regulatory design and groundwater sustainability, and also begins to formulate a new interdisciplinary language through which natural and social scientists can explore the complexity of groundwater governance. In addition, this approach permits new or unrecognized socio-ecological elements, such as the rights of Indigenous peoples in legally pluralistic jurisdictions that may also hold legal entitlements under state law or Indigenous or customary legal orders and have their own knowledge traditions, to gain expression within the regulatory and research realms (Curran 2019).

The purpose of this paper is to use groundwater science to direct the necessary elements of regulatory design for the unique scientific characteristics of groundwater behaviour, use, and users. In this paper, the focus of regulatory design is on regulation of the extraction or use of groundwater and not on groundwater quality. It is important to note that evaluating how groundwater should inform regulatory design does not address many of the weaknesses of groundwater management and governance, namely equal access, justice, community stability and economic sustainability. However, an underlying condition for the success of regulatory design such that other policy, funding and management levers can address those values is regulation that is grounded in the scientific characteristics of groundwater.

In orienting the regulatory analysis around the nature of groundwater itself, this inquiry is opportune for two reasons. First, the sustainability of groundwater relies equally on natural and social sciences. Though interdisciplinary groundwater science is increasingly being conducted (Barthel and Seidl 2017), disciplines and their different approaches to knowledge do not yet have a common language through which to examine whether groundwater governance is appropriately designed or succeeding. Using the characteristics of groundwater embeds the scientific understanding of groundwater into the regulatory design structure. Second, international norms such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) (United Nations General Assembly 1993) and national and subnational legal orders are directing meaningful attention to Indigenous peoples as an unaccounted user (or governing bodies) in state water regimes (Province of BC 2020). While many state water law regimes, including in BC, do not acknowledge Indigenous rights to water, expression of those rights by Indigenous governments underscores the characteristics of groundwater and the need to sharply correct state regulatory design for groundwater (Macpherson 2017).

Using the scientific characteristics of groundwater described in section ‘Groundwater science and regulation: finding a common language’, the paper is an examination of whether new groundwater regulatory design in British Columbia (BC), Canada, reflects these characteristics, and thus orients the regulatory infrastructure to long-term groundwater sustainability. The case study of BC (Fig. 1) offers a contemporary example of an entirely new groundwater regulatory design in a relatively homogenous state legal context—no groundwater licences, institutions or governance fora existed, the common law of groundwater applied to existing uses, no state-recognized Indigenous right to water exist, and there were no formal legal conflicts between users. [A case law search of conflicts relating to groundwater in BC yielded notable attention to groundwater contamination but not to allocation (see, e.g. Gehring v Chevron Canada Ltd. 2006 and 2007), assertions of aboriginal rights to groundwater (see, e.g. Halalt First Nation v BC, 2012), and protection of groundwater resources (see, e.g. Highlands District Community Association v BC, 2020).] The state government had consolidated ownership and control over water in 1909, as is typical of modern state groundwater regimes (Nelson and Quevauviller 2016), however, had not explicitly included groundwater in law until 1995 (Water Protection Act 1995). Legislated drilling parameters for wells have been in place since 2004 but registration of new wells was not mandatory.

Underlying that assertion of ownership and thus regulatory authority over groundwater are state-recognized aboriginal rights and title (Constitution Act 1982, section 35), with many pre-existing Indigenous legal orders establishing responsibility for land and water relations through Indigenous territories throughout the province (Napoleon 2009). This means that for each region and aquifer, there may be multiple legal orders that apply. The conflict between state and Indigenous authority or responsibility for water is demonstrated in the stark example of the issuance of a water licence in support of hydraulic fracturing activities in the northeast of the Province of BC on the Fort Nelson First Nation’s territory. The First Nation appealed the water licence alleging faulty science and that it infringed its treaty rights (Gale v BC 2015). Noting that the licensee had withdrawn one-third of the volume of a lake, the Appeal Board overturned the licence as “fundamentally flawed in concept and operation” (para 337) citing errors in scientific methodology, modelling and field data, as well as erroneous conclusions about lack of significant impacts on fish, riparian wildlife and the riparian environment, which are the foundation of the First Nation’s treaty rights (paras 337–338).

Finally, like many state jurisdictions, the hydrogeology of BC and groundwater’s interaction with surface water and the broader environment is complex, and some of the motivation for licensing groundwater uses stems from concern about maintaining adequate flows for aquatic species, especially fish (Province of BC 2010). While not in extreme groundwater crisis, a conservative estimate places 20% of aquifers in BC under stress from water extraction (Forstner et al. 2018). The new licensing process for groundwater, commenced in 2016, is displaying many of the weaknesses or failures of other groundwater regimes across the globe but in a context where the main structural determinants of good environmental regulation, green advocacy and governance capacity, are strong (Blohmke et al. 2016). Rather than examining BC’s groundwater regulation as a regulatory design exercise that is embedded within a history of natural resource rights allocation (Scott 2008), the legal approach that continues to fail groundwater regulation, the present study focuses on what scientific characteristics of groundwater itself require specific types of regulatory responses.

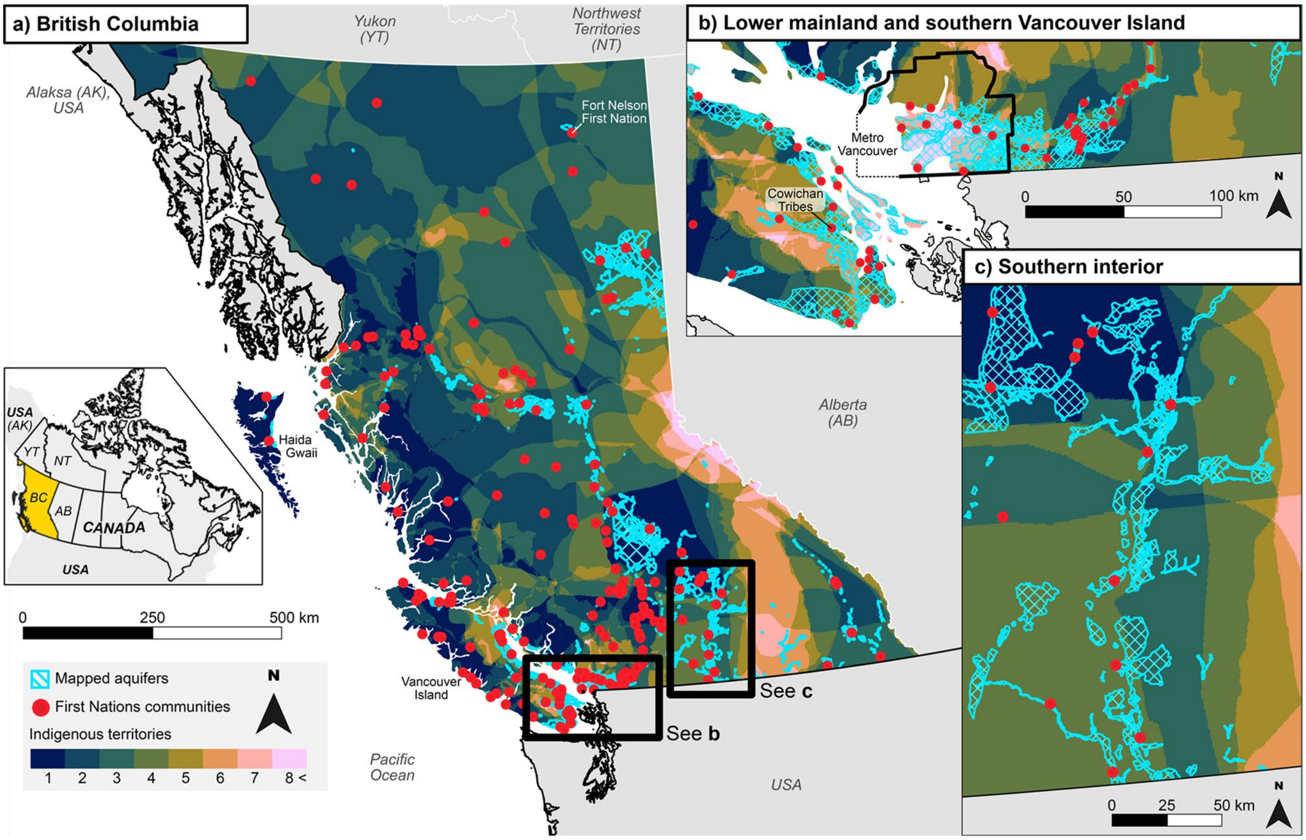


**Fig. 1** Mapped aquifers, First Nations communities, and Indigenous territories in British Columbia, Canada (data sources: mapped aquifers – Province of BC 2023c; First Nations communities – Government of Canada 2023; Indigenous territories: Native Land 2023). The number of Indigenous territories denotes the claimed territory of different nations, highlighting that much of BC is shared territory between multiple First Nations

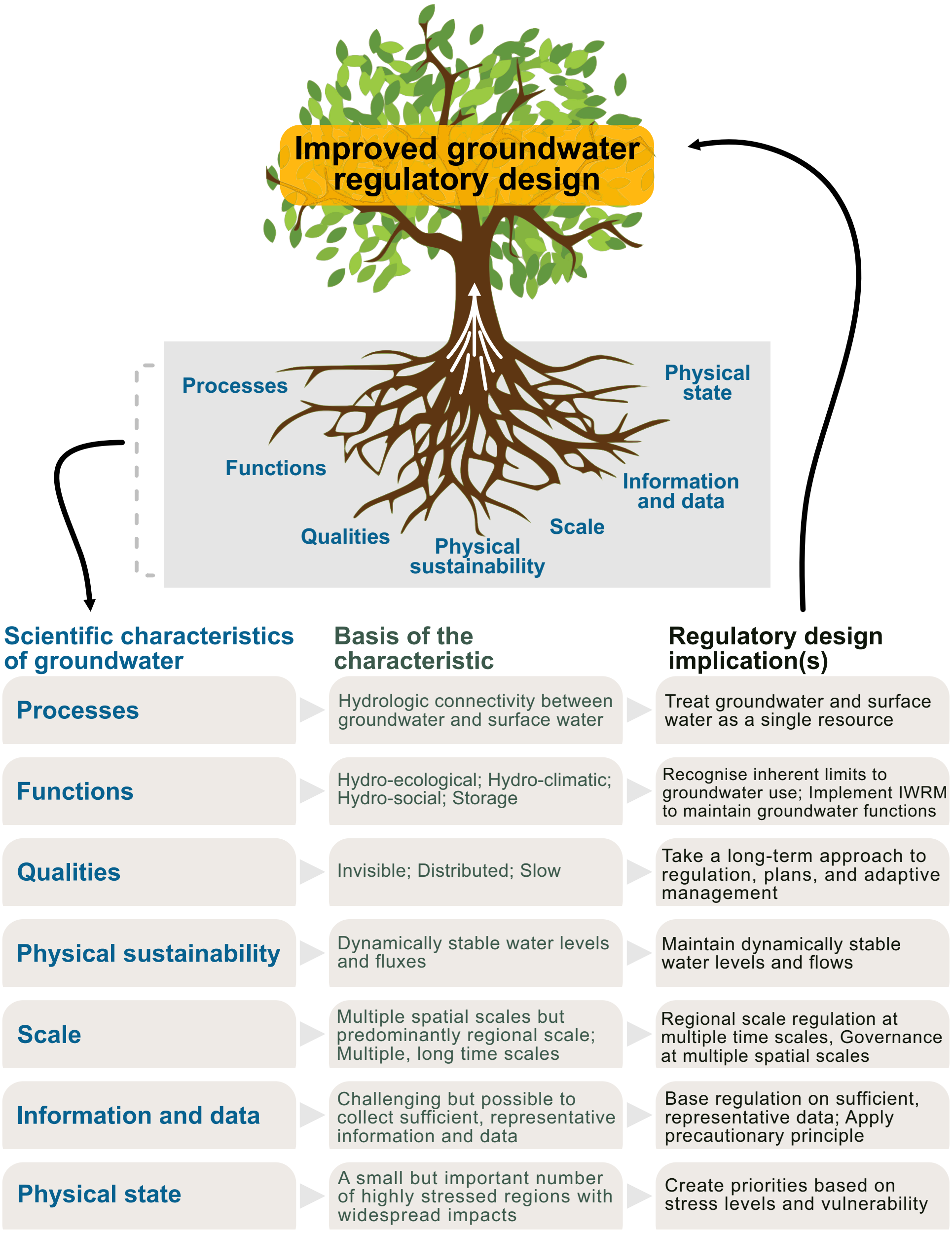
Using both natural and social sciences perspectives, section 'Groundwater science and regulation: finding a common language' explores the scientific characteristics of groundwater (processes, functions, qualities, physical sustainability, scale, information and data, and physical state) and its regulation to identify some common language for groundwater governance (see also the Appendix for key terminology). The focus is on improving regulations for groundwater allocation which usually do not consider groundwater quality or contamination. Therefore, it is important to note that 'qualities' herein refer to the physical qualities of groundwater (invisible, distributed and slow), as previously described by Vilholth and Conti (2017), rather than chemical quality or contamination of groundwater. The discussion in section 'New opportunities in groundwater regulation: the case of British Columbia, Canada' applies this interdisciplinary categorization to the new experience of groundwater regulation in BC from 2016 onwards to assess whether it meets the precondition of responding to the scientific attributes of groundwater. Concluding that this new regulatory design does not respond to the scientific characteristics of groundwater, section 'Implications for future regulatory design and recommendations' reflects on the synergies between hydrogeological processes, best practices in groundwater governance, and how these characteristics begin to formulate an interdisciplinary language for groundwater scholars, particularly when newly visible interests, such as the rights of Indigenous peoples, are introduced into the socio-hydrological system.

## Groundwater science and regulation: finding a common language

As this paper is a collaboration of natural and social scientists, finding a common language is important but challenging, which is a frequent observation in interdisciplinary research (Bracken and Oughton 2006; Freeth and Caniglia 2020) accentuated across multiple knowledge systems. For the authors of this paper's experience, the interdisciplinary conversations were fruitful and led to a shared understanding that will be useful for other interdisciplinary collaborations. Some of this language or description of concepts may be simple or obvious to people within a discipline (such as hydrogeology), but in preparing this paper, the authors have found it important to be as clear as possible in order for interdisciplinary conversations to leverage new ways of thinking and move towards solutions. The authors argue that the scientific characteristics of groundwater have regulatory design implications, and thus are essential to improved groundwater regulatory design (Fig. 2). Therefore, first these scientific characteristics are listed and then followed by their regulatory implications, using the shared interdisciplinary language of 'characteristics' and the key terminology provided in the Appendix.

Before turning to the scientific characteristics of groundwater, a note about jurisdiction. Water is largely under state (national and subnational) authority, with local government responsibilities for water focused on drainage or stormwater management and delivering potable water. Except in states that lack this national/subnational state structure, such as New Zealand, local governments, such as municipalities, typically do not have jurisdiction for water allocation, watershed management or impacts beyond their local borders such that they receive water in a quantity and quality dictated by land and water uses surrounding them. While municipalities increasingly take a source protection approach to drinking water and take into account the scientific characteristics of groundwater as much as possible, full implementation of those characteristics is prevented by the boundaries of municipal scale and limited regulatory jurisdiction (Plummer et al. 2010). In short, "…water's disrespect for all human boundaries" defies the political margins imposed by

**Fig. 2** Visualization of an improved approach to regulatory design. The roots are the hydrogeologic characteristics of groundwater which each have regulatory design implications



| Scientific characteristics of groundwater | Basis of the characteristic | Regulatory design implication(s) |
|---|---|---|
| Processes | Hydrologic connectivity between groundwater and surface water | Treat groundwater and surface water as a single resource |
| Functions | Hydro-ecological; Hydro-climatic; Hydro-social; Storage | Recognise inherent limits to groundwater use; Implement IWRM to maintain groundwater functions |
| Qualities | Invisible; Distributed; Slow | Take a long-term approach to regulation, plans, and adaptive management |
| Physical sustainability | Dynamically stable water levels and fluxes | Maintain dynamically stable water levels and flows |
| Scale | Multiple spatial scales but predominantly regional scale; Multiple, long time scales | Regional scale regulation at multiple time scales, Governance at multiple spatial scales |
| Information and data | Challenging but possible to collect sufficient, representative information and data | Base regulation on sufficient, representative data; Apply precautionary principle |
| Physical state | A small but important number of highly stressed regions with widespread impacts | Create priorities based on stress levels and vulnerability |

most states (Gray et al. 2016, p. 4). In Canada, for example, it is presumed that the constitution reposes jurisdiction over water in the subnational provincial government along with land (Brandes and Curran 2016). Water allocation is the responsibility of the provincial and territorial governments with local governments having statutory roles as water purveyors and providing approvals for local land development that may impose conditions relating to impacts on water.

## Key scientific characteristics of groundwater as a resource

Groundwater is a dynamic component of the hydrological cycle whose *processes and functions* play important roles in supporting ecosystems, ecosystem services, Earth system dynamics, and society. The *processes* are the fundamental physical hydrologic processes (groundwater discharge, streambank infiltration, etc.) that lead to the connections between groundwater and other parts of the water cycle. Herein, the focus is on groundwater and surface-water systems that are often hydraulically connected (Winter et al. 1998), though the distribution of groundwater and the configuration of its flow systems are invariably a product of local and regional geology, topography, climate, and increasing human activity (Margat and van der Gun 2013, Abbott et al. 2019). *Functions* of groundwater can be summarized using the broad categories of: hydro-ecological regulation, hydro-climatic regulation, hydro-social services and storage (Gleeson et al. 2020b). Hydro-ecologically, groundwater discharge to surface watercourses provides critical baseflow which sustains wetlands and streamflow during low-flow months, necessary for the health of aquatic and riparian ecosystems (Barlow and Leake 2012). Groundwater also supports groundwater-dependent ecosystems, which depend on groundwater variously through groundwater/surface-water interactions, ecologically accessible groundwater, or as ecosystems which exist within groundwater bodies themselves. Hydro-climatically, water-table depth serves as an important control on the land-atmosphere energy balance and dictates whether groundwater-climate interactions are unidirectional or bidirectional (Kollet and Maxwell 2008; Cuthbert et al. 2019). Hydro-socially, groundwater provides freshwater for a wide array of human activities from drinking to agricultural irrigation to supporting recreational activities and is in many regions a resource of cultural significance (Griebler and Avramov 2015; Gleeson et al. 2020a, b; Kreamer et al. 2015; Moggridge 2020). Finally, groundwater represents the largest store of liquid freshwater (Shiklomanov 2000; Gleeson et al. 2016; Ferguson et al. 2021). Fluctuations and trends in this storage have important implications on sea-level rise, riparian forest loss, land subsidence, flooding, and soil salinization.

Groundwater has been characterized as a unique natural resource due to its set of distributed, slow, and invisible *qualities* (Villholth and Conti 2017). Ubiquitously distributed, the water table is located anywhere from intersecting with to hundreds of meters below the ground surface depending on the regional setting (Fan et al. 2013). The combined distributed and slow nature of groundwater necessitates that many spatial (well to global) and temporal (seasons to centuries) *scales* are relevant when developing sustainability strategies (Aeschbach-Hertig and Gleeson 2012; Gleeson et al. 2020a). The most common scales of consideration are regional watersheds or aquifers and multiannual (i.e. 1–20 years) timescales (Gleeson et al. 2010). In part because its subsurface existence challenges *information and data* collection, the invisible quality of groundwater may be its most difficult characteristic. Data sparsity in groundwater research has been identified as an example of ‘science lagging behind policy’ (Elshall et al. 2020). Although recent decades have witnessed the emergence of remote sensing applications in tracking regional-scale groundwater-storage trends, and improvements in the ability to model groundwater across continental to global scales (e.g. Reinecke et al. 2019; de Graaf et al. 2017), coarse-scale global data are often insufficient for the needs of watershed management (Taylor et al. 2013; Gleeson et al. 2020a) in the absence of aquifer-scale numerical models or dedicated monitoring well networks which are underdeveloped or underutilized in most regions of the world (IGRAC 2020).

While many have asserted the *state* of groundwater resources constitutes a global crisis (Famiglietti 2014), there is significant regional variation in groundwater dependence and rates of depletion (Wada et al. 2010). Yet, over half of the major aquifer systems of the world are being depleted (Richey et al. 2015). Groundwater sustainability is dependent on *physical sustainability* (see Appendix). Groundwater dependence and depletion rates are greatest in agricultural regions and arid to subhumid climates, though pressures on groundwater resources are increasing globally as hydrological extremes intensify and surface-water availability becomes more variable and less reliable under climate change (Taylor et al. 2013). Existing groundwater use has led to environmental flow thresholds being already transgressed in ~20% of basins where groundwater pumping exists, which could grow to >50% by 2050 (de Graaf et al. 2019). This serves as one example to suggest that not only are groundwater resources in stressed states around the world, but that this state is already leading to a cascade of impacts through social, ecological, economic, and Earth systems.

## Implications for groundwater regulatory design

Mapping the trends and best practices of groundwater regulation onto the scientific (hydrogeological) characteristics of groundwater demonstrates how the unique qualities of groundwater create regulatory preconditions for its sustainability. Here, the authors translate each of the seven groundwater characteristics discussed in section 'Key scientific characteristics of groundwater as a resource' into their implications for regulatory design. The authors then use this list of implications as criteria to evaluate the current groundwater regulatory environment in BC in section 'New opportunities in groundwater regulation: the case of British Columbia, Canada'—a process which can be repeated for other jurisdictions around the world.

The hydrological processes that underpin hydrological connectivity between groundwater and surface-water resources require that regulation treats ground and surface water as one resource (Villholth 2021; Theesfeld 2010). These hydrological processes are also central to the hydro-ecological, hydro-climatic, hydro-social, and storage functions of groundwater. These functions are characterized by nonlinear behaviour with inherent (natural), system-specific thresholds such as environmental flow requirements, maximum water-table depths at which root water uptake can occur, or the preserving of functions of cultural significance (Anderson et al. 2019). These thresholds should be reflected in the regulatory environment, such as through environmental flow regulations or restrictions on yield that prioritize sensitive, critical, or inherently valued areas (Davies et al. 2021), which could respond meaningfully to Indigenous interests and responsibilities. Treating groundwater and surface water as one resource and managing groundwater to protect its core functions calls on regulatory implementation of the integrated water resources management (IWRM) paradigm (Hassing et al. 2009). Implementing IWRM links groundwater and surface-water regulatory design considerations with other activities affecting the water cycle such as sanitation, land use, agriculture, energy, and other subsurface uses (Van der Gun et al. 2016).

Groundwater's distributed and slow qualities impart a number of considerations for regulatory design. Its distributed nature is accompanied by significant physical and functional heterogeneity which necessitates place-specific solutions (Mukherji and Shah 2005), such as special management zones where groundwater abstraction is restricted or prohibited (Caponera and Nanni 2019; Mechlem 2016). Attention to what uses of groundwater are valued and permitted also would be more specific—for example, an "industrial" use would be categorized in multiple subcategories according to impact (Molle and Closas 2020a). Place-specific responses could also respond to Indigenous values and responsibilities creating more fine-grained regulatory approaches where Indigenous territories and aquifers intersect. Groundwater's slow behaviour also must be reflected in regulatory design. This can be achieved through implementing long-term management plans which also require adaptive management elements. Adaptive management enables regulatory approaches to be changed over time depending on evolving aquifer conditions (Caponera and Nanni 2019), which is increasingly necessary as groundwater systems are under increasing pressure from human use and climate change.

*Sustainability* and the precautionary principle are the foundational goals and policies, respectively, informing groundwater regulation (Mechlem 2016). To achieve physical sustainability in groundwater systems, allocation decisions must take into account recharge rates and discharge to surface water (i.e. groundwater/surface-water fluxes, Mechlem 2016) such that groundwater levels, fluxes, and quality remain dynamically stable. These outcomes, however, are not possible by constraining management approaches to allocation decisions alone and must be incorporated into larger integrated management plans.

Temporal and physical scales for regulation and governance are crucial to consider—aquifer- or basin-scale data, planning and agencies support state government planning and protection mandates (Council of Canadian Academies 2009). As success (e.g. 80% of water users) in achieving licensing can take 20 years (Molle and Closas 2020a, 1970), groundwater regulation must have appropriately phased and sequential implementation commitments that target resources to basins in order of priority to optimize the use of human resources for user registration and planning (Mukherji and Shah 2005). Linking a diversity of water resources institutions at different scales through IWRM enables integrated planning and the ability to respond locally to new problems and emergencies (Caponera and Nanni 2019; Mechlem 2016; Theesfeld 2010; Mukherji and Shah 2005). The scale of governance through time must also align with the physical, jurisdictional and social boundaries: "This involves an appreciation of three effective levels of *integration,* integration within the hydrological cycle (the physical processes), integration across river basins and aquifers (spatial integration) and integration across the overall social and economic fabric at national and regional levels" (Burke et al. 1999, p. 308). Such a conjunctive use approach is best embedded within an overall planning framework at the aquifer, watershed or basin scale (Mechlem 2016; Theesfeld 2010) that is separate from special protected areas that respond to an identified need (Caponera and Nanni 2019).

There is wide consensus, as highlighted in the case of the Fort Nelson First Nation, that reliable groundwater *information and data* are precursors to effective groundwater governance. This prerequisite applies both to understanding the state of the resource itself (Mukherji and Shah 2005; Van der Gun 2007) and to creating a common understanding of groundwater processes so that the public, groundwater users, Indigenous communities and state governments can act based on collaborative learning and groundwater protection

(Theesfeld 2010). High-quality data, which are challenging to obtain, require state support for groundwater and Indigenous organizations to develop, coordinate, and integrate community-based and participatory efforts with state run and public research initiatives that employ a diversity of methods to collect and analyze hydro-geological and related data. This data collection should include the monitoring of groundwater use and groundwater system states (Mechlem 2016) but could also include the monitoring of indicators of the role of groundwater in supporting its core hydro-climatic, hydro-ecological, and hydro-social functions.

Therefore, the state of groundwater requires regulation that is place-specific, adaptive and imposes limits on abstraction to maintain the functions of groundwater, which are regulatory approaches that can better reflect Indigenous territorial responsibilities toward water that go beyond extractive potential (Macpherson 2019). Typically expressed first in management plans, different terms denote restrictions on groundwater use and include "sustainable diversion limits" (Australia), "good groundwater status" (European Union) and "safe yield" (western United States; Nelson and Quevauviller 2016, p. 178). Such limits must not just apply to individual licences (volumetric) but must consider aquifer-wide, cumulative impacts (Molle and Closas 2020a; Mechlem 2016; Nelson and Quevauviller 2016). While state governments often set these overall governance policies, a network of groundwater-dependent actors, including aquifer management organizations, have a role in creating policies and plans, as well as ongoing implementation and data collection leading to "more effective and legitimate forms of groundwater governance" (Elshall et al 2020; Theesfeld 2010, p.139; Lopez-Gunn 2009; Caponera and Nanni 2019; Mechlem 2016), including recognizing the unique status of customary or Indigenous water rights in the hydro-social regime (Caponera and Nanni 2019). Given that groundwater systems exist across a range of states of stress and vulnerability, the implementation of regulations should be sequenced based on a prioritization scheme that reflects an intra-jurisdictional gradient that evaluates impacts from existing and projected stress.

## New opportunities in groundwater regulation: the case of British Columbia, Canada

The Province of BC set out its modern policy framework for water in 2009 (Province of BC 2009). Titled "Living Water Smart", it included a commitment to protect the connection between ground and surface water by regulating "groundwater use in priority areas and large groundwater water withdrawals" by 2012 (Province of BC 2009, p. 49), which followed on the heels of the Groundwater Protection Regulation aimed at protecting groundwater quality and quantity by creating well drilling and construction standards. The Province of BC then put into motion a Water Act modernization process that included a discussion paper (Province of BC 2010a), policy proposal (Province of BC 2010b) and legislative proposal (Province of BC 2013). All these documents signaled groundwater sustainability as a key concern and motivating policy objective. For example, the discussion paper identified BC's water law as having a "key role in ensuring the sustainability of BC's water resources" (Province of BC 2010a, p. 1) and the policy proposal noted aquifer sustainability as one of the motivations for the policy directive to regulate groundwater use (Province of BC 2010b, p. 10). These specific policy outcomes are important to evaluating the regulatory design for groundwater in BC in section 'Implications for future regulatory design and recommendations' as is done after setting the stage with the state of scientific knowledge about groundwater (section 'State of knowledge about groundwater in British Columbia') and describing the Water Sustainability Act and groundwater regulation (section 'Water Sustainability Act and groundwater regulation 2016–2020). Although resulting in a new regime for groundwater regulation, the regulatory design failed to take a science-forward approach and ignored territory-specific Indigenous authority over water.

## State of knowledge about groundwater in British Columbia

British Columbia's highly variable environment, climate, and geology yield a complex set of hydrogeological systems across the province, with regional variation in aquifer types, groundwater functions, and system states. Figure 3 maps core groundwater and groundwater-related variables across the province based on the seven characteristics of the resource listed in Fig. 2 and section 'Key scientific characteristics of groundwater as a resource'. Where feasible, the authors also compare the distribution of these variables within BC to other subnational jurisdictions around the world or across North America to situate BC in a broader context.

A key family of groundwater processes is the well-recognized connectivity between groundwater and surface water (Winter et al. 1998). This interdependent relationship is highly variable as shown through quantification of the groundwater contribution to environmental flow across the province (Fig. 3a). Major contributions are visible on Vancouver Island, the Haida Gwaii archipelago, and in the Coastal Mountains, yet are low throughout much of the province's interior. These environmental flow contributions also highlight the hydro-ecological function of groundwater.

There is also significant spatial variability in the hydro-climatic functions of groundwater. British Columbia has a

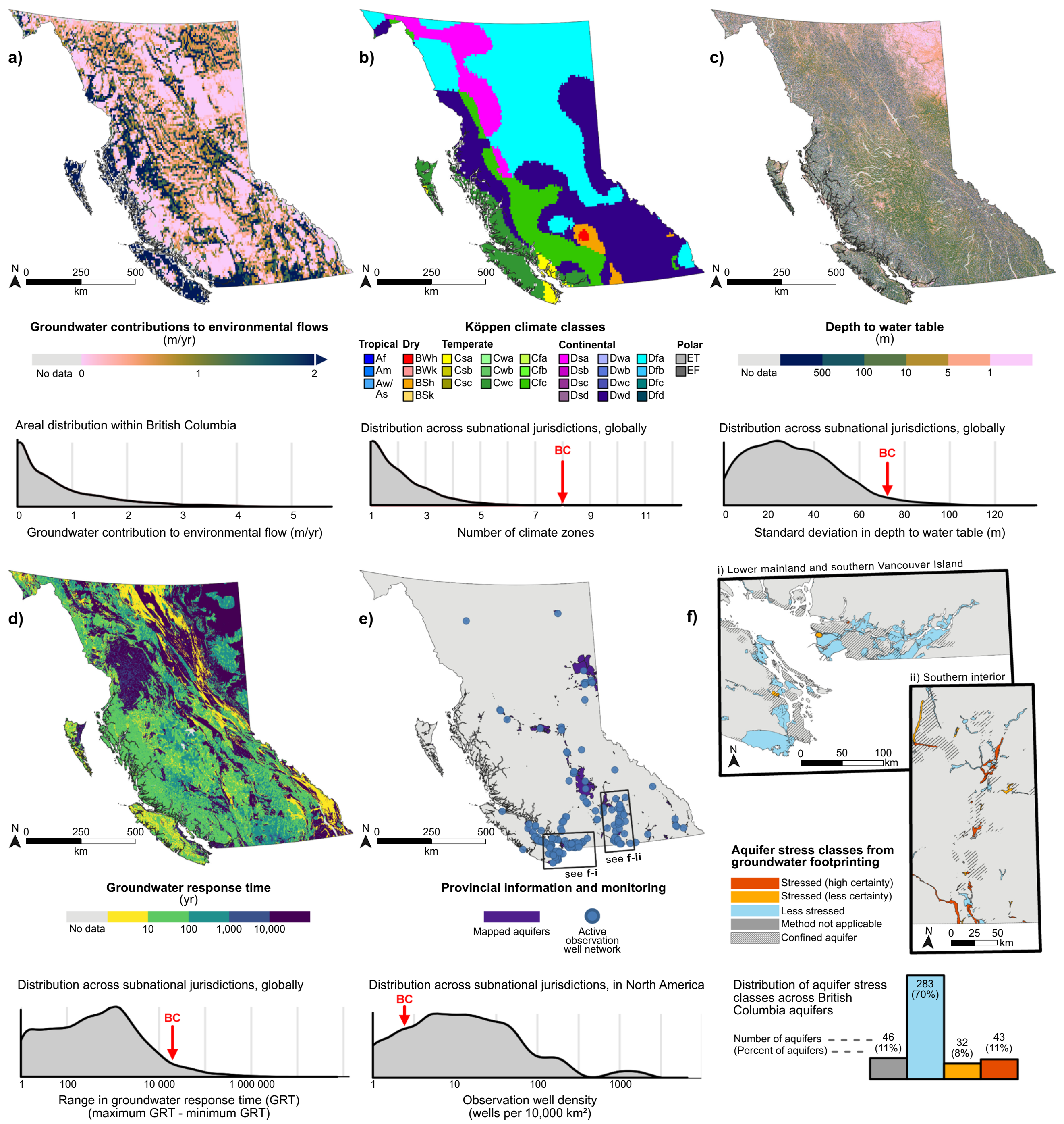


**Fig. 3** Characteristics of groundwater within British Columbia, and in comparison to other state, provincial, or equivalent (subnational) jurisdictions. **a** Groundwater's contribution to environmental flows, and the distribution of this contribution across British Columbia. **b** Köppen climate zones within BC, and the distribution of the number of climate zones across subnational jurisdictions globally. **c** Depth below the ground surface to the water table, and the distribution of standard deviation of depth to the water table in all subnational jurisdictions globally. **d** Groundwater response time, and the range (maximum–minimum) in response times within all subnational jurisdictions globally. **e** Mapped aquifers and observation wells, and the density of observation wells in all subnational jurisdictions in the contiguous United States and Canadian provinces. **f** Aquifer stress classification, and the distribution of stress classes across applicable unconfined aquifers in British Columbia. Figure 3 data sources: **a** Mohan et al. (2022), **b** Peel et al. 2007, **c** Fan et al. 2013, **d** Cuthbert et al. 2019, **e** Aquifers: Province of British Columbia 2023b, c, observation wells: Province of British Columbia 2023b, c, **f** Forstner et al. 2018

significant regional variability in climate (Fig. 3b) with eight Köppen Climate Zones within the province. This makes BC one of the most climatically diverse subnational jurisdictions in the world, and contributes to the four major hydro-climatic regimes within the province: pluvial, nival, hybrid, and glacierized (Allen et al. 2014; Eaton and Moore 2010). BC is not only hydro-climatically diverse but this variation can occur over short distances: hot semi-arid climates in the province's southern interior are located just ~400 km from coastal temperate climates.

Significant geological heterogeneity, diverse landforms, and climate variability all contribute to highly variable groundwater qualities—for example, water-table depths vary across the province from anywhere between <1 to >500 m below the ground surface (Fig. 3c). Similar to its climate, this variability in depth to the water table is an outlier among other subnational jurisdictions globally. This variation in water table depth has important implications for groundwater-climate and groundwater/surface-water interactions. Another example of BC's groundwater heterogeneity is the range of groundwater response times (Fig. 3d). Groundwater response times, or the time required for the groundwater system to re-equilibrate to a change in boundary conditions, ranges from less than 10 years to over 10,000 years within the province. This range of >10,000 years (maximum–minimum) in groundwater response times is also among the largest within a single subnational jurisdiction globally. This slow quality of groundwater, coupled with its extreme variability, highlights the challenges of managing groundwater in BC as groundwater systems function in fundamentally different ways and over radically different time scales depending on the location within the province.

The physical sustainability of groundwater can be examined using water level data although this is a major challenge based on the information available as described below. In 2019, the Province of BC conducted a trend analysis of water levels in 121 observation wells that have been monitored for over 10 years. Of these wells, 85% were found to have stable or increasing water levels while 15% are experiencing moderate to large rates of decline (Province of BC 2019a). These changes in water levels reflect changes in groundwater storage in BC's aquifers, and this subsurface storage of freshwater is one of groundwater's core functions (Gleeson et al. 2020b).

The information and data on groundwater within BC are summarised in Fig. 3e. Over 1,100 aquifers have been mapped in the province, with a total surface area coverage of over 30,000 km$^2$ (Province of BC 2023c). Groundwater provides water for a variety of user groups including private domestic (~30% of British Columbians rely on groundwater for their drinking water), industrial, irrigated agriculture, and finfish aquaculture (Forstner et al. 2018). However, public hydrogeologic data are based on a groundwater observation well network of just 220 wells (Province of BC 2023b). Unlike its physiographic variability, where BC is a global outlier, the province has among the least dense observation well networks when compared to other subnational jurisdictions within North America (i.e. the 48 contiguous United States and the other nine Canadian provinces).

The physical state of groundwater is characterized by a number of 'hot spots' within the province where aquifers are stressed and groundwater levels are dropping. Seventy-five (~20%) of the mapped aquifers of the province have been identified as being in stressed condition (Fig. 3f). These estimates are based on available data, and the existing limitations on hydrogeological data within BC constrain the ability to measure groundwater use and quantify aquifer stress with greater specificity (Forstner et al. 2018). The stressed aquifers of the province concentrate throughout the dry interior, but are also found in the more populated regions of lower Mainland, within the limits of Metro Vancouver, and on Vancouver Island's east coast.

In summary, groundwater in BC can be understood as extremely heterogeneous in its characteristics and functions, poorly monitored due to a low observation well density, and in conditions of stress in a number of 'hot spots' which are predominantly located in populated and arid regions. Together, this reality emphasizes the importance and challenge of robust groundwater management in the Province.

## Water Sustainability Act and groundwater regulation 2016–2022

Within this hydrologic and hydrogeologic diversity, the Province of BC significantly modernized the century-old water law in 2014 with the new law coming into force in 2016. It is an understatement to say that BC followed the "laissez faire mode" of groundwater management (Kemper 2007): a key feature of the new law was to regulate groundwater for the first time. The Water Sustainability Act mandated groundwater licences for all nondomestic users across the entire jurisdiction (sections 6 and 140; Water Sustainability Regulation section 55), some 20,000 anticipated licences (Province of BC 2023a), with the possibility of including domestic users in all or parts of the province in the future (section 136). The Province of BC gave existing groundwater users 3 years to apply for a licence and included two incentives: Applications would be at no cost; and The Province of BC would recognize valid applications during this period within the 'first in time, first in right' priority system (Province of BC 2016a and 2023a) and irrespective of Indigenous claims. This means that groundwater licences for existing uses would receive priority of use within the current surface-water licence regime as of the proven date of first use of groundwater. Attempting to integrate surface and groundwater regulation, any existing groundwater users who did not apply within the 3-year period would be required to pay an application fee and would lose their priority of use and be treated as applications for new groundwater abstraction. Groundwater licensees would also pay the same water rental rates as surface-water users, the rate for which the Province of BC doubled to (only) \$2.25/1,000 m$^3$ for commercial and industrial uses as part of the new law (Province of BC 2016b; Province of BC 2016c)

Other features of the Water Sustainability Act provide additional context to this new regulatory design for groundwater. Also, for the first time, any decisions about new entitlements such as licences must consider environmental flows in streams, including in relation to “an aquifer the decision maker considers is reasonably likely to be hydraulically connected” (section 15). However, applications for existing nondomestic groundwater uses are exempt from an environmental flow needs analysis (Water Sustainability Regulation section 55), and the province-wide environmental flow needs policy does not elaborate on methodologies for assisting decision makers to evaluate aquifer impacts (Province of BC 2022a). The new law requires decision makers to consider applications for licensing existing groundwater uses even where regulations designate an aquifer as having insufficient water (section 135).

The new law expanded on a water planning mechanism to permit regional or watershed-specific water sustainability plans, the implementation of which can address conflicts about water use (section 65), bind identified statutory decision makers in other sectors such as forestry (section 76) and change existing use entitlements (section 79). Plan implementation can also restrict or prohibit the use of land and resources (section 78), well construction and groundwater use (section 83). There are ongoing discussions with several First Nations about water sustainability planning processes (Curran 2019; Province of BC 2020), and the Province of BC has just committed to one in partnership with Cowichan Tribes for the Koksilah watershed (Province of BC 2022b).

Finally, the new groundwater regulations do not consider the impact of aboriginal and treaty rights and customary laws on existing and new licenses, as well as the entire water balance in a watershed. While the Provincial government has a duty to consult First Nations on licensing decisions (Curran 2017) the new groundwater regime’s automatic insertion of existing groundwater uses into the priority system alongside surface water uses absent sufficient data, ignores cumulative impacts to Indigenous interests and prevents meaningful assessment of aquifer sustainability (Curran 2019; “Yahey v BC” 2021).

This regulatory design, a 3-year window for applications for nondomestic uses for groundwater across the entire province, resulted in less than 10% of nondomestic groundwater users applying for a licence by the 3-year application deadline in February 2019 (Parfitt 2021). The Province of BC’s response was to extend the period of eligibility for applications for another 3 years to 2022 (Province of BC 2019b; Water Sustainability Regulation 2016, section 55). However, despite a last-minute rush in applications, about 60% of existing users missed the March 1, 2022 deadline and risk losing their access to water (MacLeod 2022). Now the majority of nondomestic groundwater is out of compliance and achieving meaningful groundwater regulation is challenging. The Province of BC’s choice to “enforce” the new law by extending the deadline for applications replicates the experience of other jurisdictions, which underscores the need for regulatory design that mandates basin- or aquifer-specific approaches that include local governance mechanisms such as water or aquifer management councils (Wester et al. 2011).

## Implications for Future Regulatory Design and Recommendations

### Assessing the current regulatory design in British Columbia

The authors begin by applying the characteristics of groundwater regulatory design to the case study of BC to assess whether the new groundwater regulations were designed according to the lessons learned internationally, and consistent with the characteristics of groundwater itself (Table 1). The Water Sustainability Act regulates both streams and aquifers so current regulations are consistent with processes. The current regulatory design is partially consistent with the functions in that an environmental flow policy suggests risk-based processes to assess hydroecological functions, but importantly, the current policy does not explicitly consider groundwater or apply to existing users. While the new Water Sustainability Act requires decision makers to consider environmental flows where aquifers are hydrologically connected, the law exempts licence applications for existing groundwater uses from that analysis. In practice the new regime locks in existing unregulated use of groundwater without any overarching ecosystem standards or adaptive management mechanisms.

Similarly, groundwater qualities are partially consistent; licences without end dates are certainly long-term but this same permanence makes adaptive management challenging. The new regulatory design applied to all non-domestic users and their use entitlement status automatically fits into the existing surface-water regime for priority of use. No basin or aquifer analysis assessing recharge or sustainable withdrawal informed this priority scheme, and regulators did not undertake a cumulative effects assessment to determine whether any specific aquifer could sustain current use. Regulators fell prey to what Molle and Closas (2020a) term the “licensing

**Table 1** Evaluating current and potential use of regulatory design implications in British Columbia

| Regulatory design implication | Current use in BC regulations? | Potential use in BC regulations |
|---|---|---|
| *Processes*: Water as a single resource | *Yes*: streams and aquifers are both regulated under the Water Sustainability Act | Water has value beyond extraction as a resource (for example, Syilx Okanagan Nation declaration 2014);<br>Apply environmental flow policy consistently |
| *Functions*: Inherent limits to groundwater use; and integrated water resource management to maintain functions | *Partially*: environmental flow policy suggests risk-based process to assess hydroecological functions; current policy does not explicitly consider groundwater or apply to existing users | Regulations at a regional scale to maintain hydro-ecologic, hydro-climatic and storage functions and include groundwater;<br>Limits to use based on responsibility to land/water in Indigenous territory;<br>Mandatory environmental flows based on Indigenous knowledge and western science;<br>Integrated water resource through water sustainability plan mechanism |
| *Qualities*: Importance of long-term regulatory approach, plans and adaptive management | *Partially*: licenses are long term but permanent licensing makes adaptive management challenging | Long-term, ecosystem-based water sustainability plans with built-in adaptive cycles;<br>Collaborative governance with Indigenous communities;<br>Licensing that is adaptive to changing conditions |
| *Physical sustainability*: Regulation based on maintaining water levels, flows and quantity | *No*: no current regulations based on maintaining levels, flows, or quantity | Regional Water Sustainability Plans and implementing regulations mandating water levels, flows and quantity;<br>Triggers for protection and emergency orders located with both Indigenous governing bodies and state governments;<br>Cumulative effects across Indigenous Territories and within watersheds monitored and drive adaptation |
| *Scale*: Regulation and governance at multiple spatial (watershed/region) and temporal scales | *No*: regulations applied over whole province with short licensing application period | Place-based widespread planning, data generation and licencing in targeted regions (phased implementation);<br>Ecological and Indigenous boundary scales |
| *Information and data*: Regulatory design based on sufficient, representative and accessible data; Application of precautionary principle when dealing with sparse or limited data | *No*: unclear connection between regulations and monitoring data, which are sparse, and not representative of all aquifers | Directly connect regulatory processes and more representative monitoring data;<br>Collaborative data generation with Indigenous and non-Indigenous communities accounting for OCAP |
| *State*: Regional prioritization schemes based on stress levels | *No*: regulations applied over the whole province without considering highly stressed regions | Prioritize highly stressed regions or regions with unique hydrological cultural values |

policy dilemma" (at p. 1970) where licensing without justification and licensing once over abstraction has occurred will result in regulatory failure.

Although 'sustainability' is in the name of and an inherent motivation for Water Sustainability Act, sustainability is not clearly defined and no sustainable goals or targets have been explicitly developed. For example, there are no current regulations or plans based on maintaining groundwater levels, flows or quantity. The Province of BC operationalized groundwater licensing for non-domestic uses at the scale of the whole province irrespective of intensity of use or vulnerability of the aquifer. The temporal and institutional scales were similarly monochrome. The Province of BC extended the unrealistically short 3-year timeframe for applications for existing users to 6 years when it became evident that a very small number of users subject to the new regulation would apply. Institutionally, all regulation and governance remained at the broad subnational provincial scale. This acontextual blanketing of provincial jurisdiction occurred without the direction of basin, watershed or aquifer plans that reflect the challenges of and objectives for a hydrological region. There is no obvious or stated connection between available information and data and regulations. For example, regulations are the same regardless of where monitoring data, which is sparse and may not be representative of all aquifers, are available. While there is sufficient information to justify groundwater regulation for several threatened aquifers or where they are hydrologically connected to vulnerable fish-bearing watercourses (Halstead 2018), this information has not been publicly integrated into the regulatory design. Finally, the state of regulations was applied over the whole province without considering highly stressed regions.

Two additional priorities of the Province of BC that operate alongside the new groundwater regulatory regime underscore the need to rescale to local governance for ground and surface water. First, in 2019 the Province of BC enacted the Declaration on the Rights of Indigenous Peoples Act (2019c), through which that government commits to ensuring consistency between provincial law and UNDRIP. While it is beyond the scope of this paper to assess what UNDRIP will mean for groundwater regulation, the principle of free, prior and informed consent is of central importance to First Nations (White 2019). Consent requires more than consultation (Moore et al. 2017) and watershed- or territory-based water governance is expected. Second, the Province of BC has entered into several memoranda of understanding with Indigenous governments to pursue Water Sustainability Plans. Acknowledging longstanding low-flow issues, the state government is showing a willingness to develop watershed-specific plans and governance structures to address conflicts in water use (Province of BC 2020; Curran 2019). While regulatory design for groundwater formally remains at a provincial scale, more fine-grained planning and governance processes are proceeding by agreement.

Overall, the evidence from applying the characteristics of groundwater indicates that the Province of BC largely failed to design its new groundwater regime according to the lessons learned internationally, and pursuant to regulatory design that attends to the characteristics of groundwater itself (Table 1). In the context of BC, where the state demonstrated its ability and willingness to implement groundwater regulation by creating a new regime from the aquifer up, the regulatory design approach of province-wide application to broad user categories was a mismatch to groundwater's requirement for more nuanced watershed-specific attention that meaningfully links surface and groundwater regulation. The short time and broad geographic scales mean that the financial resourcing for this project was spread thinly across the entire province instead of concentrated first in the areas of greatest groundwater stress. Finally, by inserting existing groundwater users into the existing 'first in time, first in right' priority system in BC, the provincial government missed an opportunity to assess the sustainability of both surface and groundwater use in each watershed and establish local watershed governance mechanisms that could be a venue for also addressing customary or Indigenous laws and outstanding aboriginal rights and title.

## Implications for regulatory design in British Columbia

These critiques and considerations point to how the characteristics of groundwater could potentially be used to improve regulatory design (Table 1), leading to the recommendations in the following subsection. In the future, even more social-ecological processes could be included, such as by considering that water could have value beyond extraction as a resource—for example, the Syilx Okanagan Nation water declaration positions water as a relation towards which Syilx people have responsibilities (2014). Given the hydrogeologic and hydroclimatic variability across the province (Fig. 3), the functions of groundwater could be more robustly included in regulations at a regional scale to maintain hydro-ecologic, hydro-climatic and storage functions, as well as limits to use based on responsibility to land/water in Territory, potentially through water sustainability plans (which could operationalize integrated water resource management). The qualities of groundwater suggest the importance of long-term ecosystem-based water sustainability plans with built-in adaptive cycles, collaborative governance with Indigenous communities, and licensing that is adaptive to changing conditions (Curran and Brandes 2019).

Physical sustainability could be enhanced through regional water sustainability plans that implement regulations that mandate water levels and flows. These could be strengthened by triggers for protection and emergency orders located with both

Indigenous governing bodies and state governments as well as assessments of cumulative effects across territories and within watersheds. The importance of scale to future groundwater licensing points to place-based widespread licencing in targeted regions (phased implementation) ideally using ecological and/or Indigenous territory as the relevant scales. Regulatory processes need to be more directly connected to information and data such as representative monitoring data and collaborative data generation with Indigenous and non-Indigenous communities accounting for ownership, control, access and possession of data, called OCAP or data sovereignty (First Nations Information Governance Centre 2023) is crucial. Finally, it is important to emphasize prioritizing highly stressed regions where the physical state of groundwater is most at risk.

## Recommendations for regulatory design

Groundwater regulations are still relatively new to BC and there is still time to course correct. The authors identify three overarching yet integrated and specific recommendations based on the common themes described previously regarding how the characteristics of groundwater could be used to improve regulatory design: (1) defining sustainability goals and ecological thresholds; (2) regionalizing and prioritizing regulatory action for groundwater; (3) planning for the long term and adaptively. Defining sustainability and ecological thresholds depends on scaling-up groundwater data collection and use of those data in priority watersheds with the involvement and knowledge of local authority holders (Indigenous communities) and stakeholders. The Province of BC can reorient the implementation of groundwater licensing and planning attention to those areas identified as having the highest priority aquifer and connected surface-water stress with the watersheds and Indigenous territories having secondary precedence clearly marked for action within a specific timeframe. Water sustainability plans should explain the adaptive mechanisms for those goals and thresholds, as well as distributed governance and priorities for water management and use that rely on ongoing review mechanisms (e.g. every 5 years). Regulations under the Water Sustainability Act can implement the mandatory aspects of the watershed agreement expressed through water sustainability plans.

Across these three recommendations, the emphasis is on the importance of a distributed, collaborative and Indigenous-led approach. Practically, these three recommendations can all be implemented by quickly identifying a small number (<5) of priority watersheds, aquifers or regions in which to concentrate groundwater licensing, and redeploy regulatory efforts in those areas. These may be in locations where there are existing agreements between Indigenous governing organizations and the provincial government. In these locations, it is paramount to define sustainability goals and ecological thresholds and accurately assess surface and groundwater sustainability to establish an adequate, even if shifting, picture of hydrology, hydrogeology and water use. Meanwhile, initiate (or augment if already underway) a water sustainability planning process in each location to create a watershed-specific mechanism for continuing to implement groundwater management, adapt water use, and evaluate the long-term sustainability of groundwater. By concentrating efforts in a few locations that can be expanded as earlier planning processes conclude, provincial staff can marshal the resources to not only implement groundwater regulation but establish watershed-specific governance processes to integrate surface and groundwater use over time using an adaptive approach. Such a longer-term integrated and resource-specific approach addresses the invisible, slow and distributed qualities of groundwater that necessitate a more careful regulatory design.

This approach has implications for regulatory design in common law states with legal pluralism as well as states with customary water entitlements, and regardless of a legal system for practitioners seeking useful interdisciplinary language. The context in Canada of state-acknowledged aboriginal and treaty rights, alongside the provincial government's commitment to implementing UNDRIP, reinforces the need for regulatory design that attends to the scale and other qualities of groundwater. Each First Nation continues to govern within a specific territory that has a unique combination of hydrogeological, social and economic conditions and relationships with water. These Indigenous territories also express specific legal and political scales that necessitate a territorial- or watershed-based approach to groundwater regulation. The design of those regimes will be defined or supported by plans and policies, such as for environmental flows (Jackson et al. 2015), that are informed by the local Indigenous legal order. In a country such as Canada where multiple legal orders are entangled, successful groundwater regulatory design cannot remain solely a centralized state endeavour. The characteristics of groundwater itself and the multiple legal orders have specific behaviours within a territory that will establish parameters for sustainable groundwater governance.

Finally, as alluded to in section 'Key scientific characteristics of groundwater as a resource', the authors have found it useful to develop and use a common language between the social and natural sciences for exploring groundwater sustainability. This enhanced the clarity and robustness of the analysis while staying grounded in a science-forward approach to regulatory design.

While there is broad agreement that "the analysis comes back to questioning the state's *ability* to deploy regulatory authority on the ground and its *willingness* to do so" (emphasis in the original, Molle and Closas 2020a, p. 1972), the endeavour in this paper is to highlight that in a jurisdiction where the state's ability and willingness are evident, its regulatory design must match the scale and distinctive physical parameters of groundwater for ultimate success in meeting its sustainability goals.

## Appendix: Key terminology

- *First Nations*: Métis and Inuit are the political organizations of Indigenous communities that interact with the state in Canada. First Nations are the principal Indigenous organization in BC.
- *Governance*: How decisions are made (who makes decisions, how, and at what scale). In policy science, governance has moved beyond the state into many institutions and processes that include civil society, markets, transnational bodies and local organizations as well as state governments (Chandhoke 2003 p. 2957).
- *Groundwater sustainability*: Maintaining dynamically stable groundwater levels, flows, and quality using equitable, effective, and long-term governance and management to sustain water, food, and energy security, environmental flows, and groundwater-dependent ecosystems, infrastructure, social well-being, and local economies for current and future generations (Gleeson et al. 2020a). The focus herein is on how the physical components of sustainability (maintaining levels and flows) relate to regulatory design (Fig. 2).
- *Indigenous communities*: Self-identified groups of Indigenous peoples.
- *Integrated water resources management(IWRM)*: A process that promotes the co-ordinated development and management of water, land, and related resources to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Hassing et al. 2009).
- *Regulatory design*: The sum total of choices of legal approaches and strategies that result in a regulatory infrastructure intended to meet specific policy outcomes.
- *Scale*: An encompassing term that represents the basic spatial, temporal, and power dimensions of a system, or of an analysis of a system (Vervoort et al. 2012).

## Declarations

**Conflicts of interest** The authors declare no conflicts of interest.

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