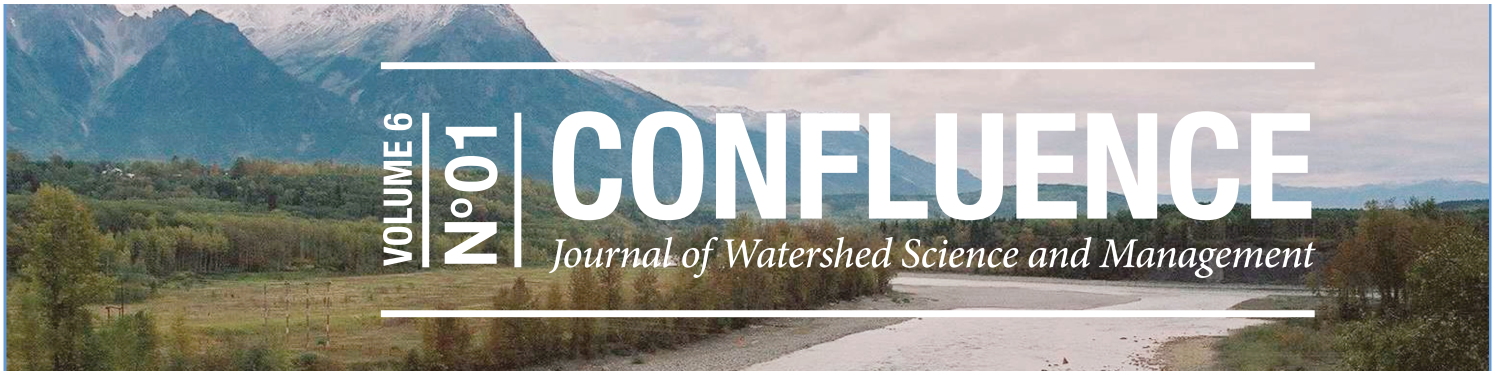

VOLUME 6 Nº01 CONFLUENCE
Journal of Watershed Science and Management

Groundwater Resource Allocation in British Columbia: Challenges and Ways Forward

Diana M. Allen, *Simon Fraser University*
Tom Gleeson, *University of Victoria*

Abstract

Groundwater allocation in British Columbia is facing several important challenges. Groundwater is licensed under the *Water Sustainability Act* and potentially included in modern treaties. These challenges include acknowledging the importance of groundwater in supporting environmental flow needs and human water use, the uncertainty and misconceptions surrounding annual recharge estimates, and the under-appreciated importance of aquifer drainage, while tackling cumulative impacts in watersheds using adaptive management with clear sustainability goals. This article summarizes these challenges and suggests ways forward so that we can more robustly, holistically, and sustainably allocate groundwater resources. This includes some evidenced-based suggestions that are already being implemented partially or in some regions. Not implementing these suggestions risks permanent over-allocation of groundwater resources that would impact stream ecology, endanger rural livelihoods, and challenge reconciliation with First Nations.

Keywords: *groundwater allocation, groundwater resources, water management, water policy, climate change*

The context

We are at a watershed moment (pun intended) for groundwater resources in British Columbia (B.C.). The *Water Sustainability Act* (WSA) and ongoing Indigenous treaty negotiations have both led to unprecedented questions of how to allocate groundwater resources. The WSA licenses groundwater for non-domestic users for the first time and modern treaties often include specific water allocations (Gullason, 2018).

Groundwater processes in B.C. have much in common with other jurisdictions; groundwater is highly connected to surface water, renewed by recharge, crucial for domestic and agricultural purposes, and monitored with an insufficient monitoring network (Curran et al., 2023). Yet, groundwater in B.C. is unlike many other jurisdictions because the aquifers are typically small and highly responsive to climate and hydrological forcing. While much has been learned about the complex hydrogeology of B.C., groundwater allocation remains challenging. A requirement of the WSA is that new water use licence applicants must consider environmental flow needs (EFNs), defined as the volume and timing of water flow required for the proper functioning of the aquatic ecosystem of the stream (BC FLNRORD & BC ECCS, 2022). Groundwater recharge or water budget estimations are considered important for directly or indirectly supporting or informing allocation decisions (e.g., Kohut, 2021). But seeking a recharge estimate or a watershed budget estimate may prove to be a complicated, fruitless pursuit for water allocation decisions due to misconceptions about recharge and how it is related to groundwater discharge.

Recharge and water budgets can be explained using a simple bucket conceptual model, where the "bucket" is an aquifer (since this analogy is focused on groundwater allocation, whereas the "bucket" for water budget methods is most often a watershed or basin). In B.C., single or multiple aquifers can be within one watershed and aquifers can cross watershed boundaries, especially small watersheds. As with any conceptual model, it is important to define terms:

- Recharge is the renewing flow of water into the aquifer.
- Groundwater discharge is the flux out of the aquifer to surface water bodies or springs, seepage to the land surface, or evapotranspiration to the atmosphere.
- Groundwater pumping is sometimes considered groundwater discharge but, for clarity, herein is simply called "groundwater pumping."
- Drainage is a natural change in stored groundwater that manifests as a change in the water level and leads to groundwater discharge (herein evapotranspiration and groundwater pumping are not included in drainage).
- Baseflow is the slow flow component of streamflow (i.e., generated by glacier melt, reservoir release, groundwater discharge, release of water from lakes and wetlands), but often and herein we use this term to exclusively represent the groundwater contribution (groundwater discharge) to streams.

Recharge is commonly misconceptualized as replenishing a bucket, simply adding to the volume of water stored in the bucket (Figure 1a). Shown in Figure 1 is an unconfined aquifer with the water table rising until the bucket is full. However, this conceptualization is missing the "hole" in the bucket. The hole in the bucket can function as a one-way valve (Figure 1b), gradually releasing groundwater sourced from recharge to a stream year-round. This type of aquifer is classified as recharge-driven (Allen et al., 2010). Alternatively, the hole in the bucket can function as a two-way valve, allowing for bi-directional flow of water between the stream and the aquifer. When the stream stage is higher than the water table (e.g., during the spring freshet), water flows from the stream to the aquifer, recharging the aquifer and causing the water table to rise. When the stream stage lowers, the flow direction is reversed and groundwater discharges to the stream. This type of aquifer is streamflow-driven (Allen et al., 2010). Provincial groundwater observation wells across B.C. have been classified as recharge- or streamflow-driven based on the relationship between the groundwater level hydrograph and the stream hydrograph (Gullacher et al., 2021). Unconfined and confined aquifers may be recharge-driven or streamflow-driven.

This article considers the unique aquifer systems (small and generally rapidly responding) and the hydroclimatology (rainfall- and snowmelt-dominated) of B.C. We focus primarily on unconfined, recharge-driven aquifers, as illustrated in Figure 1b, but note that confined aquifers may be recharged by both mechanisms and groundwater can discharge to streams if the aquifer is hydraulically connected. We discuss groundwater discharge from the bucket that supplies streams with water year-round and supports EFNs, especially essential water in the low-flow periods (Section 2.1). The hole in the bucket is a fundamental component of the recharge process (Section 2.2) that may significantly change the calculated recharge or water budget of a watershed if not accounted for (Section 2.3). Simply, we argue for the importance of this hole in the bucket, and the problems that can arise if groundwater allocation decisions are based on the recharge amount rather than discharge.

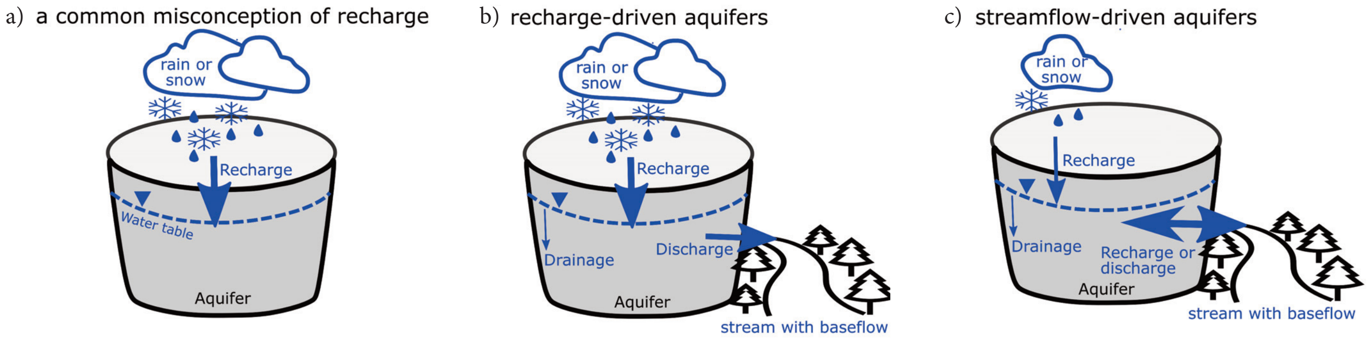

Figure 1. Visualizing groundwater recharge, drainage, and contributions to EFNs with bucket-style conceptual models of an unconfined aquifer. a) A common misconception of recharge whereby water from rain or snowmelt is simply added to storage. More holistic conceptual models incorporate temporary aquifer storage, continued drainage, discharge, and baseflow are shown for b) recharge-driven aquifers and c) streamflow-driven aquifers. Graphics developed using "rain bucket" and "river" from noun project.

Throughout this article we question what the recharge and water budget estimates mean andthen how we can use these values in water allocation decision-making, ultimately to determine how much groundwater is available for our use. We also explore the difficulties of cumulative impacts and water budgets (Section 2.4) and adaptive management and sustainability goals (Section 2.5). Unfortunately, determining the amount we can *sustainably or safely use* without causing undue harm to the aquifer, and the ecosystems supported by natural groundwater discharge, presents several challenges to groundwater professionals and managers. We summarize these as five challenges for groundwater allocation in B.C. based on a review of existing publicly accessible provincial water allocation policies,1 *BC Water Science Series* reports, informal conversations with provincial employees, and our observations:

1. Groundwater is critical in supporting EFNs and human water use yet is considered implicitly rather than explicitly in the current EFN policy.
2. Misconceptions about recharge and the role of drainage can have significant implications for water allocation.
3. Annual recharge and water budget estimates are highly uncertain and are largely irrelevant to groundwater allocation.
4. Cumulative impacts in watersheds are crucial but water budgets are fraught with uncertainty.
5. Adaptive management with clear sustainability goals is essential.

Many provincial employees, consultants, and non-governmental organizations are working hard to protect and better manage B.C. groundwater resources. We hope to support and elevate these efforts by suggesting potential ways forward to address these challenges so that we can more robustly, holistically, and sustainably allocate groundwater resources. Some of the proposed ways forward are based on sound science and could be implemented immediately (and may be already implemented partially or in some regions) whereas some need more research. Not implementing these ways forward may risk permanent over-allocation of groundwater resources that would impact stream ecology, endanger rural livelihoods, and challenge reconciliation with First Nations. Throughout this article we consistently ground ourselves in decades of research in B.C. hydrogeology, often funded by the B.C .government and conducted in collaboration with B.C. government scientists. This research has often been in the “quest for recharge” or aiming to “quantify the water balance,” which we now see as largely misaligned with groundwater allocation in this province. This article is timely since 1) EFNs assessments are required for all water licence or use approval applications on a stream or on an aquifer that is hydraulically connected to a stream, except where exempted (BC FLNRORD & BC ECCS, 2022), 2) groundwater licence applications and decisions are technically challenging (Todd et al., 2020), and 3) modern treaties and ongoing treaty negotiations often include specific water allocations (Gullason, 2018).

Challenges for groundwater allocation in B.C.

Groundwater is critical in supporting environmental flow needs (EFNs) and human water use, yet is considered implicitly rather than explicitly in the current EFN policy

Groundwater is crucial to supporting EFNs especially in small, unregulated streams across the province. This fact has been emphasized in government science (Province of British Columbia, 2016), academic literature (Middleton & Allen, 2017; Gleeson & Richter, 2018), and the WSA itself. The BC EFN policy now applies to groundwater allocations from aquifers that are reasonably likely to be hydraulically connected to a stream. However, the groundwater contribution to EFNs is considered implicitly (as part of low flows) rather than explicitly in the current EFN policy. For example, the word “groundwater” does not appear in the current BC EFN policy (2022). Broadly speaking, none of the existing EFN estimation methods explicitly consider groundwater components (Pastor et al., 2014) due to the lack of adequate groundwater discharge data. Thus, there is a research and management requirement to develop methods to estimate groundwater contribution to environmental flows.

Groundwater is most important to streamflow during low flows when groundwater discharge supports baseflow in streams (Figure 2). Streamflow recession often lasts for months, and groundwater discharge may be the only source of water to the stream. In B.C., the timing of low flows is controlled by the diverse hydroclimatology across the province (Figure 3). In rainfall-dominated regions, the lowest flows are in late summer or early autumn. In cold, snowmelt-dominated regions, the lowest flows are during the winter or early spring, sometimes with a secondary low-flow season in late summer or early autumn. The regions in B.C. of greatest water scarcity (Gower & Barroso, 2019) or groundwater stress (Forstner et al., 2018) are generally in Thompson-Okanagan, West Coast, South Coast, Kootenay-Boundary, and Skeena. Both rainfall-dominated and snowmelt-dominated hydroclimatic regimes are found in the regions of greatest water scarcity and groundwater stress. In both hydroclimatic regimes, low flows often occur in late summer and these baseflow periods are often sustained by groundwater discharge. Unfortunately, the importance of groundwater to streamflow coincides with peak water use for irrigation in many regions, so summer is often the period when both ecological and human water use needs are highest.

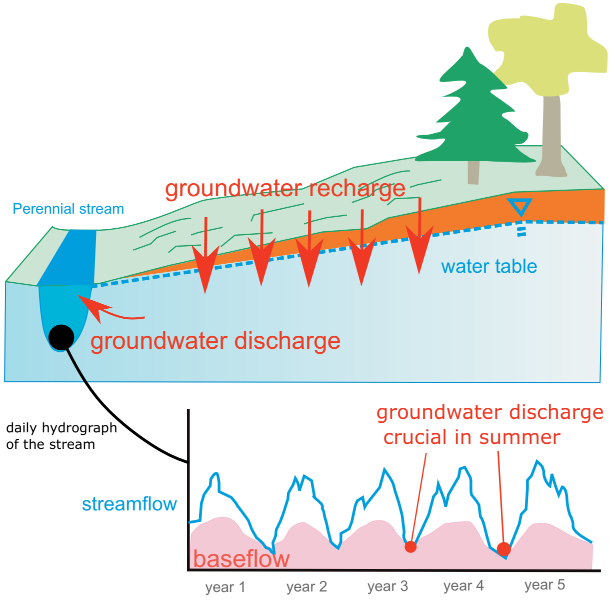

Figure 2. Groundwater contribution to streamflow as baseflow through discharge (modified from Gleeson & Richter, 2018). Here, focusing on a rainfall-dominated hydroclimatology where low flows occur during the summer.

Groundwater allocation in B.C. faces a series of challenges considering the importance of summer low flows and EFNs. First, the different processes, timing, and controls of groundwater discharge versus other streamflow generation mechanisms are not explicitly considered when applying the EFN policy; the current EFN policy only considers groundwater contribution to EFNs implicitly. Second, much of the streamflow monitoring network in B.C. focuses on major streams and rivers, making monitoring groundwater-surface water interactions in small tributary streams and rivers challenging. Third, groundwater pumping can impact EFNs by decreasing the flux of groundwater to streams, yet quantifying the impact of pumping in complex stream networks and aquifer systems is challenging (Rathfelder, 2016; Gleeson & Richter, 2018). The effect of groundwater pumping on EFNs is most often quantified using analytical models based on pumping of a single well (e.g., Hunt, 1999). While some numerical models have been used to assess the impact of pumping on streams (e.g., Foster & Allen, 2015), rarely have these models been for water allocation purposes (Li et al., 2020; Li et al., 2021).

Overall, we argue that culturally and legally, British Columbians and the province care much more about salmon and aquatic habitats that are supported by EFNs than the recharge flux (Section 2.2). So, although recharge seems important to groundwater allocation decision-making since it is the source of aquifer renewal, we suggest it is much more important to focus on the streams that are supported by the hole in the aquifer bucket (Figures 1b and 1c) rather than the recharge to the bucket.

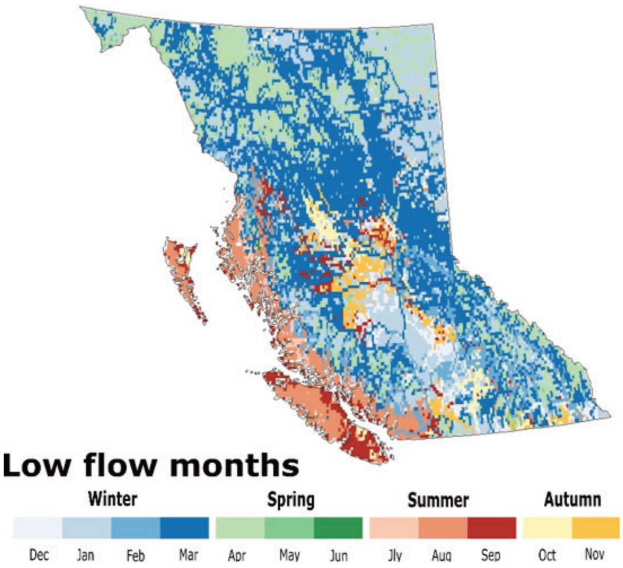

Figure 3. Hydroclimatic variability across the province that is important to groundwater allocation. The lowest flow month varies across the province (modified from Mohan et al., 2022).

Misconceptions about recharge and the role of drainage can have significant implications for water allocation

A classic hydrograph from the South Coast of B.C. is useful for illustrating recharge processes and some misconceptions surrounding recharge. Consider a groundwater level hydrograph for a shallow well (B.C. Observation Well 357) screened (17–19 m depth) in an unconfined aquifer in coastal B.C. (Figure 4a). The groundwater level is shown as a depth below ground surface (in metres) with the dates corresponding to the start of the water year (October 1). First, notice that the maximum groundwater levels are relatively consistent from one year to the next, at approximately 9 m deep, suggesting that aquifer recharge over the fall and winter months is relatively consistent from year to year. Similarly, the minimum groundwater levels are relatively consistent from year to year, at approximately 11 m deep, with the notable exception of summer 2021. The range in groundwater level is relatively consistent inter-annually (approximately 2 m); however, the timing of the maximum and minimum groundwater levels is variable. Minimum groundwater levels typically occur in October when the recession ends and the rainy season starts, while maximum groundwater levels occur as early as February and as late as mid-April.

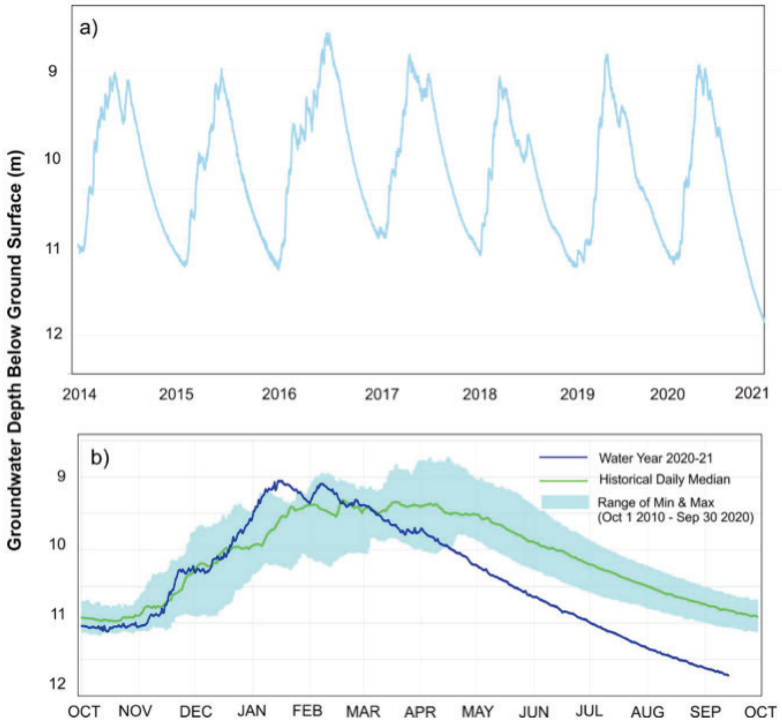

Figure 4. a) Groundwater level hydrograph for B.C. Observation Well 357 (October 1, 2014–September 30, 2021) and b) statistical hydrograph (October 1, 2010–September 30, 2020) showing the range (turquoise band), the historical daily median (green line), and the hydrograph for water year 2020–2021.[2]

Groundwater level hydrographs differ in character depending on the hydroclimatology of the region. The hydrograph shown in Figure 4a is characteristic of wells in the south B.C. coast region, which is dominantly a rainfall regime. Recharge occurs primarily in the late fall and winter and into the spring. In the interior of B.C., groundwater hydrographs reflect a snowmelt regime, peaking during the spring freshet in late spring to mid-summer. In addition to seasonal differences in the groundwater level hydrographs in rainfall and snowmelt regimes, the interaction between aquifers and streams influences the relative timing of the peaks and troughs. Observation wells across B.C. have been classified according to their response mechanism, which identifies whether the groundwater level responds before streamflow (recharge-driven) or lags the streamflow response (streamflow-driven) (Gullacher et al., 2021). Many observation wells across B.C. are classified as streamflow-driven, meaning that the peak in groundwater level (at least near the observation well) lags the streamflow peak throughout the year. In these streamflow-driven systems, the aquifer is more strongly influenced by focused recharge from the stream than by diffuse recharge (recharge-driven system). Such interactions between aquifers and streams are not accounted for in most recharge estimation methods. Importantly, groundwater level hydrographs for wells classified as streamflow-driven should not be used for diffuse recharge estimation because the groundwater levels are being dominantly controlled by the stream.

Figure 4b exemplifies how variable the timing of the peak groundwater level can be. The 2020–2021 water year was a significant deviation from the historical record. The peak water levels in 2021 occurred 108 days after the start of the water year, which was 30 to 90 days earlier than other years (except 2018, which was 101 days after the start). The timing of the peak in 2021 was quite different even though the peak groundwater level was much the same as historical peaks. The timing of the peak is important because it determines when the recession begins. An earlier peak may logically translate into a longer recession period and result in the lowest groundwater levels being reached earlier in the summer as shown in Figure 4b. Thus, it doesn't necessarily matter how much recharge occurred prior to the peak groundwater level, since most groundwater level hydrographs have similar magnitude peaks each year (see Figure 4a). What is important is the timing of the peak and the rate of recession.

The reason the water table rises is that the rate at which water is added to the aquifer is greater than the rate at which the aquifer is draining. This drainage represents the hole in the bucket (Figure 5). If the rate of replenishment is greater than the natural drainage rate, the water level rises (Figure 5a). If the rate of replenishment is the same as the natural drainage rate, the water level will not rise and fall—it will remain stable (Figure 5b). Once the rate of replenishment declines sufficiently so that it is less than the drainage rate or stops altogether, the water level in the bucket continues to decline (Figure 5c).

The concept of continued drainage from an aquifer is fundamental to understanding what the calculated recharge means. Some recharge estimation methods explicitly take drainage into account; for example, the water table fluctuation (WTF) method, if used correctly by incorporating drainage (Cuthbert, 2010) and integrated hydrological models or coupled land surface-subsurface models (e.g., MIKE SHE). Other methods do not; for example, land surface water budget approaches implemented in a geographic information system (GIS) (e.g., Dyer, 2019), which only incorporate precipitation and evapotranspiration and typically ignore overland flow and subsurface flow. Therefore, the choice of recharge estimation method and how it is used dictates whether drainage is accounted for or not. This raises the question of the value of recharge estimates for water allocation decisions if recharge estimation methods differ, with some ignoring drainage and others not. What do these recharge estimates mean?

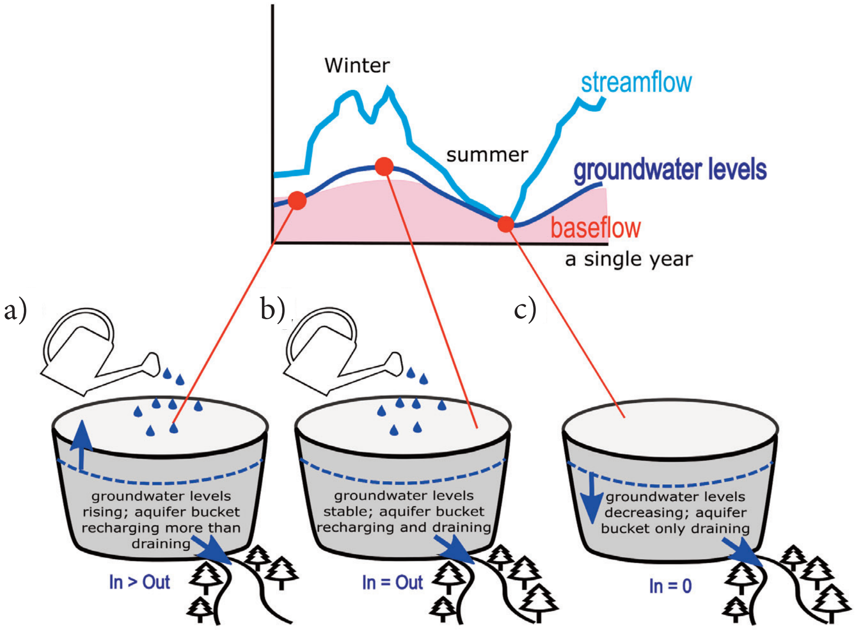

Figure 5. Streamflow, groundwater levels, and baseflow throughout a single representative year in a rainfall-dominated regime with the aquifer bucket a) recharging, b) stable, and c) draining for a recharge-driven aquifer.

Annual recharge and water budget estimates are highly uncertain and are largely irrelevant to groundwater allocation

Although recharge (i.e., the rate at which an aquifer is replenished) is an important component of some groundwater studies, it is also one of the most difficult parameters to estimate, largely because recharge rates vary widely in space and time (Healy, 2010). Practically speaking, it is difficult to determine whether recharge estimates are accurate because recharge cannot be measured directly (Healy, 2010), nor is there a widely applicable method for accurately quantifying how much precipitation reaches the water table (Scanlon et al., 2002; Healy, 2010). Even if we employ different methods and obtain roughly the same values, this does not necessarily mean that the values are accurate.

Consider Figure 6, which shows the spatial variability of mean annual recharge and seepage on Gabriola Island (Burgess & Allen, 2016), simulated using a physically based integrated hydrological model (MIKE SHE software; DHI, 2022). The software is used internationally for modelling the various components of the water cycle (interception, ponding, overland flow, infiltration, groundwater flow, streamflow, and exchanges between aquifers and streams) and estimating watershed water budgets. The model for Gabriola Island used actual climate data for a 10-year period from October 1, 1995, to September 30, 2005, and so the results represent a period of historical recharge on the island. Average annual precipitation (over the 10-year period) was ~984 mm and average annual simulated recharge was 199 mm (average of ~20% of mean annual precipitation, range of 17–26% across all years) (Burgess & Allen, 2016). For comparison, the average annual recharge to the Cowichan Watershed on Vancouver Island was estimated at ~17 percent of mean annual precipitation using the same software (Foster & Allen, 2015). In contrast, Foweraker (1974) estimated recharge on Mayne Island at 25.4 mm or ~3 percent of the average annual precipitation of 838 mm using the water table fluctuation (WTF) method, accounting for drainage. Similarly, Hodge (1995) estimated recharge for Salt Spring Island between 1.0 mm and 43.2 mm (0.1–5%) using a specific yield, Sy = 10^{-4}, but noted that recharge rates would increase by one order of magnitude if Sy increased to 10^{-3}. At the other extreme, Surette et al. (2006) estimated recharge at ~45 percent using spatially varying 1D vertical percolation models that include drainage. Thus, even within the Gulf Islands, recharge estimates incorporating drainage have ranged from 0.1 to 45 percent, pointing to the extremely high range of uncertainty given that all the methods were appropriate and had been used in studies elsewhere. This is not to suggest that different methods cannot yield similar values, but simply points to the high level of uncertainty that can arise if different recharge estimation methods are used.

The modelled recharge estimates above for Gabriola Island were extracted from the water budget and calculated either as daily or monthly estimates, and then summed annually and averaged. The recharge represents a spatial average, which is a common way to report recharge. However, as shown in Figure 6, the recharge is highly spatially variable. Positive values (in blue and green) represent areas where recharge occurs on an average annual basis, while negative values (in red) represent seepage areas, where groundwater discharges to the land surface. Based on the model, approximately 30 percent of the island area is represented by seasonally persistent recharge areas (i.e., always recharge throughout the year), and 4 percent is represented by seasonally persistent seepage (i.e., always seepage). Due to the seasonality of precipitation in this coastal region, 66 percent of the island area experiences both recharge and seepage variably throughout the year. Importantly, many areas receive little to no recharge. This example serves to illustrate that both recharge and discharge occur across the aquifer, so the water budget is different for different areas. The rates also vary seasonally and interannually, so the water budget varies temporally (Burgess & Allen, 2016). Consequently, land surface-based estimates of recharge such as those implemented in a GIS or estimates based on some fraction of precipitation applied to the entire aquifer surface can be inaccurate both spatially and temporally.

Regarding climate variability and climate change, how recharge might change in the future is uncertain. Climate data produced from equally plausible global climate models (GCMs) can introduce significant uncertainty in recharge estimates (Allen et al., 2010). Moreover, potential changes in the hydrological regime (from snowmelt-dominated to rainfall-dominated), and changes in the intensity and frequency of heavy rain events may significantly alter recharge processes.

Groundwater allocation in B.C. faces a significant challenge if water allocation decisions are reliant on recharge and water budget estimates (which require estimates of recharge), considering their significant uncertainty. Regardless of the method used and whether recharge is spatially varying or not, the uncertainty is huge. Even if we acknowledge the uncertainty and accept a range of values, how do we use the values in water allocation decisions, particularly given the uncertainty of future climate? While quantifying the natural rate of groundwater recharge has been considered "imperative" for efficient groundwater management (Simmers, 1990), more recently it is well recognized that allocating groundwater resources based on recharge is flawed (Bredehoeft, 2002), although others have argued that recharge is part of the assessment of safe yield or sustainable yield (Zhou, 2009; Pierce et al., 2013). While the recharge rates are important for determining sustainable yields in many aquifer systems, the recharge rates by themselves are not sufficient for determining sustainability (Bredehoeft, 2002); this is the "water budget myth." The effects of changes in groundwater levels on groundwater discharge (i.e., accounting for the hole in the bucket) and aquifer storage must be considered. This means that allocating some percentage of annual or seasonal recharge can lead to unsustainable groundwater use, because the amount of available groundwater is overestimated due to an overestimate of the recharge.

Volume 6 No. 01 Allen & Gleeson. (2023). Groundwater Resource Allocation in British Columbia: Challenges and Ways Forward
http://confluence-jwsm.ca/index.php/jwsm/article/view/49/7 . doi:10.22230/jwsm.2023v6n1a49

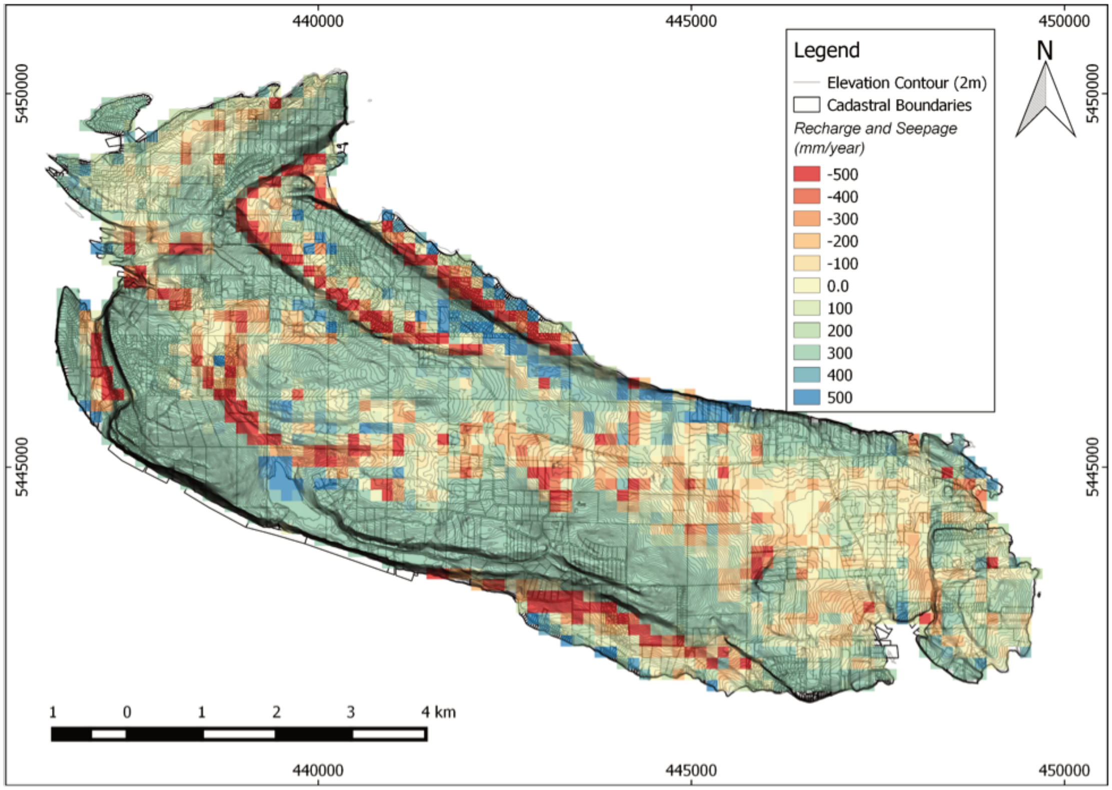

Figure 6. Gabriola Island, British Columbia, Canada, showing modelled average annual recharge and seepage (mm/year). The scale shows positive and negative numbers. Positive numbers represent recharge areas on an average annual basis, while negative numbers represent discharge zones on an average annual basis. Values close to zero are neither recharge nor discharge areas (from Burgess & Allen, 2016).

Cumulative impacts in watersheds are crucial but water budgets are fraught with uncertainty

Since EFNs are a key component of current groundwater allocation in B.C., considering and managing the cumulative impact of water use, land use, and climate change at the scale of watersheds is paramount. Two recent initiatives in B.C. are heightening this awareness: the new Ministry of Water, Land and Resource Stewardship and the BC Watershed Security Strategy and Fund. While only a handful of observation wells across the province (~15%) hint at localized long-term groundwater depletion problems, it is important to note that most aquifers across the province are not being monitored routinely. In fact, B.C. has a lower density of observation wells compared with many Canadian provinces and American states even though there is a great hydrogeologic and hydroclimatic diversity across the province (Curran et al., 2023). Of the 121 examined observation wells, 85 percent have water levels that are stable or increasing (with nine wells showing increasing trends), 6 percent of wells show a moderate rate of decline in water levels, and 9 percent show a large rate of decline in water levels (Environmental Reporting BC, 2019). These statistics point to the overuse of groundwater in some aquifers, likely due to the cumulative effects of pumping.

When wells are pumped, groundwater comes from both groundwater storage (ideally replenished annually by recharge) and the capture of streamflow, both of which can lead to streamflow depletion. Since there are few cases of long-term groundwater depletion in unconfined aquifers, most pumped groundwater is likely coming from seasonal streamflow depletion or seasonal storage loss (rather than long-term groundwater depletion over years or decades; see Gleeson et al., 2020). The seasonal nature of pumping effects can impact the recession of the groundwater hydrograph (Section 2.2) and, potentially, EFNs (Section 2.1).

Groundwater allocation in B.C. faces a series of challenges considering cumulative impacts and water budgets. First is the inherent uncertainty of water budgets: if recharge uncertainty is high (Section 2.3) and discharge is largely unmeasured across the province (Section 2.1), it is doubtful that meaningful water budgets can be derived that are useful for water allocation. Kohut (2021) developed a Groundwater Allocation Methodology (GWAM) for estimating available quantities of groundwater for allocation purposes based on simplified water budget equations for known aquifers in B.C. or areas where groundwater is of interest. Kohut acknowledged the large degree of uncertainty in estimating various components of water budgets and recommended the estimates of groundwater use from the water budget tool be refined before allocating any significant groundwater quantities for future use. We emphasize that regardless of how "refined" a water budget is, there remains considerable uncertainty in water budget components, particularly recharge, and this uncertainty is compounded in data-poor regions where both aquifer and stream monitoring are limited. Additionally, the temporal scales are challenging due to intra- and inter-annual variability. An annual or long-term/steady state water budget is commonly used as the basis for aquifer scale assessments of groundwater stress, which can be useful for giving an overall picture of the rate of aquifer development if the components of the water budget can be trusted (based on the description above, this is doubtful, but this may not be universally true for all aquifers and settings in B.C.). Finally, licence applicants may argue there is enough uncertainty in any method that the impacts from their proposed allocation will not be distinguishable from the fuzziness of the answer (at least for small diversions).

Adaptive management with clear sustainability goals is essential

All the technical methods and hydrologic processes described above are uncertain, suggesting adaptive management is essential, which, importantly, is being acknowledged in the new BC Watershed Security Strategy and Fund. This is even more true given the uncertainties of increased development of water resources, changing climate, and evolving practices in acknowledging the Indigenous rights to water. Yet, groundwater allocation decisions are effectively made in perpetuity, with terms of the licence only reviewed after 30 years (Section 23 of the WSA). Practically, the usefulness of any technical method may be the context within which an allocation decision is made. Maybe any specific method should not lead directly to a yes or a no, but trigger other actions to happen (within a regulatory context), like modelling the aquifer, measuring actual use, checking for unauthorized uses, monitoring during operation to verify actual behavior, using the results to facilitate community discussions within a water sustainability plan (like restricting access to water for new, large uses), etc. Overall, getting better answers on groundwater availability only has meaning if it is part of the overall effort that allows adaptive management to occur to achieve B.C.'s sustainability goals.

Surprisingly, although "sustainability" is in the name of the Act and an inherent motivation for the WSA, sustainability is not clearly defined or no sustainable goals or targets have been explicitly developed. The WSA and related regulations and policies do not define groundwater sustainability but herein we suggest this definition: maintaining dynamically stable groundwater levels, flows, and quality with 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., 2020). This general definition of groundwater sustainability is generally agreed upon by greater than 1300 signatories of the Global Groundwater Statement[3] (Gleeson et al., 2019; Gleeson 2020). It can be made more specific for a certain watershed or region as part of a water sustainability plan or for setting water objectives as set out in the WSA.

Ways forward

Finding ways forward is challenging because recharge and water budget approaches are well established in professional practice, management, and research. For each challenge in Section 2, we suggest possible ways forward that are meant to be seeds for broader future discussions. Some of these ways forward may be already implemented partially or fully in some regions and are not meant as a final recommendation or prescription, but rather the beginning of conversations.

Summer low flows and environmental flow needs

The BC EFN policy now applies to groundwater allocations from aquifers that are reasonably likely to be hydraulically connected to a stream, so the focus of groundwater allocation decisions is shifting towards the output of groundwater systems (discharge/baseflow) rather than on the input (recharge). We support and hope to elevate this shift so that all groundwater allocation decisions start by focusing on summer baseflows and the role of pumping on impacting EFNs. This can be done in three ways: 1) Conducting more fieldwork on the impact of pumping on EFNs of streams in different hydrogeologic environments in B.C. This has started, for example, in the Fraser Valley where joint university-government research studied the effects of controlled pumping of an unconfined aquifer on streamflow depletion (Allen et al., 2020). 2) At the well scale, analyzing the impact of pumping using analytical depletion solutions and functions (Li et al., 2020), which are not perfect but can help predict the impact and timing of pumping on discharge/baseflow. It is important to remember that analytical depletion functions are uncertain and potentially misused if the aquifer setting is inappropriate or hydraulic parameters are unknown. 4) At the aquifer scale, we have developed two methods for quantifying the groundwater contribution to EFNs (that are consistent with international literature) and applied these methods for all the unconfined aquifers in B.C. (Figure 7, a & b). All this research has been provincially funded and could be more fulsomely and directly used in decision-making by systematically using analytical depletion functions and estimates of groundwater contributions to environmental flows as well as quantifying groundwater contributions using fieldwork. In the long term, there is a need to revise the BC EFN policy so that it explicitly considers the role of groundwater in supporting low flows explicitly rather than implicitly.

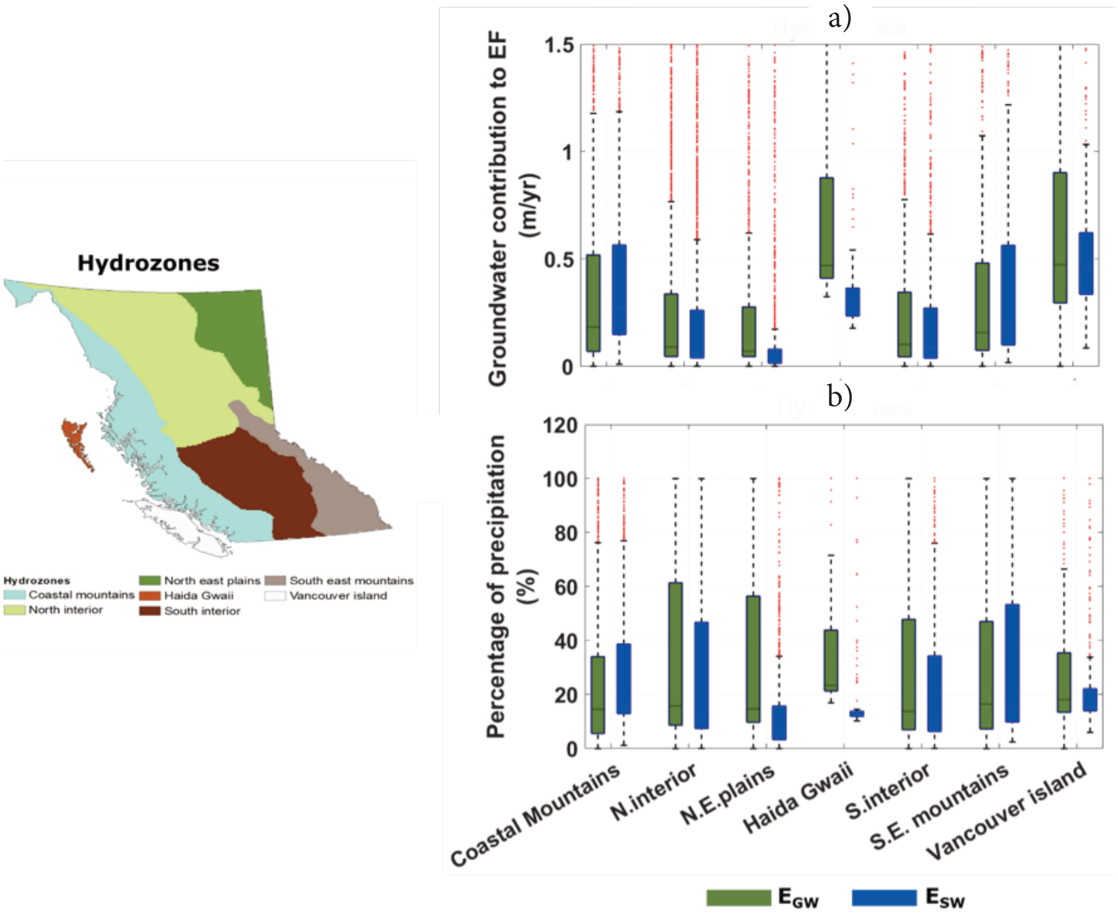

Figure 7. Estimates of E_{GW} and E_{SW} (respectively, the groundwater and surface water contributions to environmental flows) by hydrozones (from Mohan et al., 2022).

Recharge and water budget estimation and cumulative impacts

In recent years, there has been a growing interest in mapping groundwater recharge potential and developing water budgets (e.g., Islands Trust, 2021) in water sustainability initiatives across B.C. Unfortunately, there are no provincial standards that we are aware of that speak to estimating recharge or preparing water budgets. A review of published Water Science Series reports[4] attests to the wide range of methods that are currently used. A provincial technical guidance document, like the *Guidance for Technical Assessments in Support of an Application for Groundwater Use in British Columbia* (Todd et al., 2020), would be a tremendous benefit for practitioners. Given the uncertainty in recharge estimates, particularly annual recharge estimates, and more importantly the fact that some recharge estimation methods ignore the drainage rate of the system, it is strongly recommended that assessments significantly reduce emphasis on or eliminate altogether annual recharge and annual water budget estimation, and not use these directly in allocation, such as for groundwater reserves. We particularly caution against using some percentage of recharge for groundwater allocations because most of the recharge occurs before the recession and has been draining from the system throughout the recharge period. Even allocating a small percentage of the annual recharge may compromise the sustainability of groundwater resources and the baseflow contribution during the summer when the aquifer is not being replenished. Ultimately, the usefulness of recharge for assessing water security is part of the "water budget myth" (Bredehoeft, 2002) and is misaligned in a strongly seasonal hydroclimatology when protecting EFNs is important.

Recharge estimates can be useful for assessing the potential impacts of climate change on water budgets, but certainly not annual recharge estimates. Most of the recharge occurs during the wet (or freshet) seasons when groundwater levels are already at their maximum, so any increase in recharge at this time will not necessarily translate into higher baseflow during the summer. Therefore, at a minimum, monthly recharge estimates are needed to anticipate a) whether and by how much recharge might be reduced during the summer months, b) whether or how much earlier the onset of the groundwater level recession will occur (as illustrated in Figure 5b for water year 2021), or c) whether a regime shift (snowmelt- to rainfall-dominated) may occur in different regions across the province. A shift in the temporal pattern of streamflow, such as earlier freshet, lower late summer and early fall flows, and higher early winter flows, has already been observed (Leith & Whitfield, 1998).

Recharge estimates can also be useful for assessing the potential impacts of land cover change on water budget, for example, the impact of a change in land cover such as tree removal or identifying recharge areas that should be protected. Obtaining recharge estimates for confined aquifers, while challenging, is important because these aquifers can undergo significant depletion if overdrawn (e.g., Aquifer 33, West of Aldergrove[5]). Aquifer 33 is rated as moderate demand, and provincial Well 415 shows clear evidence of a long-term decline in groundwater level due to the cumulative impacts of pumping. While recharge to a confined aquifer can be estimated using the annual rise in groundwater level multiplied by the storativity—a parameter that is more "easily" estimated from pumping test data compared to specific yield—it is still important to consider the drainage of that aquifer, which may be through exchange with another aquifer or possibly to a surface water body.

Groundwater drainage and hydrographs

Considering EFNs, it is really the drainage rate, particularly sustaining the drainage rate, that is important for water allocation decisions. Examination of Figure 4b suggests that the drainage rate is approximately linear over most of the recession period (almost a straight line) and there is not much variability in the rate of recession from one year to the next. From a conceptual perspective, this is because: 1) the transmissivity of the aquifer does not change much throughout the year or from one year to the next, 2) the stage in the discharge area (stream, lake, ocean, seepage) is maintained at a relatively constant level compared to topography, and 3) the maximum groundwater level is relatively consistent from year to year. Given (2) and (3), the hydraulic gradient remains roughly the same; although it is important to note that the gradient does, in fact, lessen near the end of the recession (see Cuthbert, 2014).

The relative constant of rate of recession from year to year is illustrated in Figure 8 by the parallel recession lines for a normal year and a dry year. we argue that the timing and amplitude of the peak (i.e., the onset of recession) and the rate of recession (i.e., the slope of the recession curve), which are directly observable, should be the focus of analysis rather than the rate of recharge when trying to estimate how much water might be available for use. Importantly, if the maximum groundwater level occurs earlier in the year, then, because the slope is relatively constant, the recession period is much longer, and minimum groundwater levels are lower (Figure 8). This assumes the fall rainy season commences at the same time each year, with October 1 as the conventional start of the water year.

Also consider the fact that B.C. is generally not water limited in the fall and winter (and spring) months. Intense water use is normally during the summer months, during the period of recession (of groundwater levels and streamflow). What we really need to be concerned about is the summer and early fall water use (assuming a relatively short lag between streamflow impacts due to seasonal pumping), because once the rate of drainage of the aquifer exceeds the rate of replenishment, then we only have as much water available as the system can drain. What if there was no more replenishment after this peak groundwater level? How quickly does the aquifer drain?

Groundwater allocation in B.C. faces a significant challenge if water allocation decisions ignore the draining rate of the aquifer and instead focus on recharge rates. Groundwater allocation should be based on an understanding of groundwater drainage rather than groundwater recharge. However, additional research is needed to better understand a) the controls on groundwater recession in different aquifers and in different regions of B.C. and how the recession relates to the baseflow, b) if the cumulative effects of pumping in an aquifer might change the natural drainage rate, and c) how climate variability, such as low snowpack or summer drought, may impact groundwater recession rates. Figure 8 is a somewhat simplified conceptualization, and indeed recession rates are not always linear. Cuthbert (2014) identified three recession phases: the linear phase, a transition phase, and an exponential phase after some critical time, which is independent of the position of the monitoring point. Cuthbert defines the critical time as ~ 0.15 L^2 S/T, where L is the distance from a groundwater divide to a constant head boundary such as a stream, S is the storativity which is equivalent to the specific yield of an unconfined aquifer, and T is the transmissivity of the aquifer. He notes that the critical time is in the range of tens to hundreds of days for all but the most hydraulically diffusive or small aquifers. Diffusivity (T/S) estimates reported by Rathfelder (2016) for unconfined, unconsolidated aquifers in B.C. (subtypes 1a, 1b, 1c, 2, 3 and 4a) range from 13000 m^2/day (1b) to 22500 m^2/day (1a) and many aquifers are very small (< 1 km^2), suggesting short critical times (see Figure 4 in Cuthbert, 2014). However, many observation wells in B.C. have approximately linear recessions, which may aid in interpreting groundwater recessions and the factors that influence the drainage rates.

Recent research by Gullacher et al. (2023) identifies various climate and hydrological variables (e.g., snow water equivalent and spring maximum temperatures) as being strongly associated with summer groundwater levels. These predictor variables could be used in combination with groundwater level hydrographs from provincial observation wells and/or dedicated monitoring wells in specific aquifers to anticipate the minimum groundwater levels at the end of the summer, simply by considering the timing of the beginning of the recession and knowing the average rate of recession.

If we are concerned with maintaining environmental flows, then we first need to estimate how the drainage rate (in mm per day) translates into the baseflow contribution. This could perhaps be done empirically by comparing the calculated drainage rates with the streamflow when there is no precipitation input (i.e., the baseflow). We may possibly derive indicators based on how rapidly streamflow or groundwater levels are declining during the recession period. The next, and perhaps the most challenging, step would be to estimate what the reduction in drainage rate would be if groundwater was pumped from the aquifer. How to do this is uncertain, because there is a time delay between the start of pumping (i.e., use in the summer for irrigation) and the initiation of streamflow depletion. Estimating the potential impact of groundwater pumping on streamflow (e.g., streamflow depletion) poses challenges for all but the simplest systems.

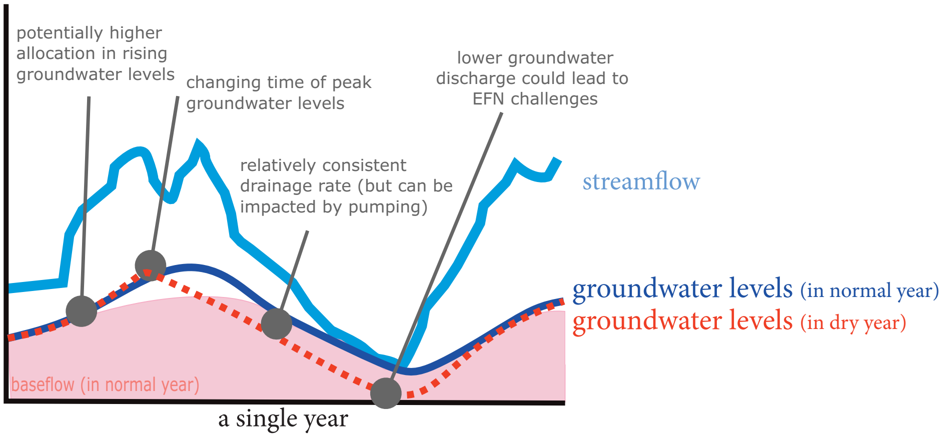

Figure 8. Conceptualization of a groundwater level hydrograph in a normal year (dark blue) and during a dry year (red dashed) relative to the total streamflow (light blue) and baseflow during a normal year (pink). The rate of recession during a normal year and a dry year are much the same. Therefore, during a dry year, the peak groundwater level occurs earlier and the minimum groundwater level is much lower, potentially reducing the late summer groundwater contribution to baseflow.

Volume 6 No. 01 Allen & Gleeson. (2023). Groundwater Resource Allocation in British Columbia: Challenges and Ways Forward
http://confluence-jwsm.ca/index.php/jwsm/article/view/49/7 . doi:10.22230/jwsm.2023v6n1a49

The proposed recession approach will involve focusing our attention on measuring streamflow and groundwater fluxes into streams and lakes during the summer low-flow period, and this will present challenges because streamflow is particularly difficult to measure when the flow is small. Rating curves thus tend to be less accurate for low flows. Nevertheless, a focus on collecting data during the recession period is recommended.

Adaptive management and sustainability

Given the manifold uncertainty of groundwater allocations and the generally unmet "sustainability" intentions of the WSA, we argue that significantly elevating adaptive management and sustainability is critical (e.g., Gleeson et al., 2012). We are basing water allocation decisions today on what the "natural" system was, at a time when that natural system had a very different climate than today. Moreover, we are ignoring how climate change will impact the system norm. There is no norm anymore. So, how can we make decisions on how much water to allocate with changing baselines? An Adaptive Management Framework with clear provincial-level guidelines and practice approaches is critical. This framework could include audits on licence decisions, with the possibility of altering the licence conditions, and the possibility of licensing off-ramps. Such a framework would allow us to learn more about how climate extremes and climate changes may manifest in aquifer-stream systems. Further, we are making water allocation decisions without any clearly communicated sustainability goals, either provincially or regionally. The general definition of groundwater sustainability (Gleeson et al., 2020) can be made more specific for a certain watershed or region as part of a water sustainability plan or setting water objectives as set out in the WSA. These goals or definitions could include defining desired physical states (stable groundwater levels, flows, and quality) as well as governance and management goals (equitable, effective, and long term).

A parting invitation

We hope this article will stimulate discussion. Some of these ways forward may already be implemented in some regions but, as academics outside of government, we had difficulty teasing out the exact practices and workflows of how allocation decisions are made and how groundwater reserves are being established in modern treaties. As we move forward, we encourage ongoing transparency and building connections across government, academia, and consulting.

Ackowledgements

We thank many provincial employees for their hard work and passion to protect and better manage B.C. groundwater resources. We thank Mike Wei, Sylvia Barroso, Mark Cuthbert, and David van Everdingen for thoughtful conversations that helped shape our thinking. We also thank Chinchu Mohan for help with the figures as well as members of the UVic Groundwater Science and Sustainability research group for their useful suggestions. Any errors, omissions, or opinions are entirely the responsibility of the authors.

Notes

1. Available at https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-licensing-rights/water-policies.
2. Data accessed through the BC Groundwater Level Data Interactive Map, available at: https://governmentofbc.maps.arcgis.com/apps/webappviewer/index.html?id=b53cb0bf3f6848e79d66ffd09b74f00d.
3. Available at https://www.groundwaterstatement.org/.
4. Available at https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-science-series.
5. See https://apps.nrs.gov.bc.ca/gwells/aquifers/33.

References

Allen, D.M., A.J. Cannon, M.W. Toews, & J. Scibek. 2010. Variability in simulated recharge using different GCMs. *Water Resources Research 46:*W00F03. doi:10.1029/2009WR008932

Allen, D.M., B. Johnson, A. Garnet, K. Howe, M. Lepitre, & M. Simpson. (2020). Assessment of aquifer-stream connectivity related to groundwater abstraction in the Lower Fraser Valley: Phase 2 field investigation at Otter Park, Langley. Water Science Series 2020-03, Province of British Columbia, Victoria, B.C.

BC FLNRORD & BC ECCS [BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development & BC Ministry of Environment and Climate Change Strategy]. 2022. Environmental Flow Needs Policy, January 11, 2022. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/water-rights/efn_policy_jan-2022_signed.pdf [June 13, 2023].

Bredehoeft, J.D. 2002. The water budget myth revisited: Why hydrogeologists model. *Groundwater 40*:340–345. doi:10.1111/j.1745-6584.2002.tb02511.x

Burgess, R., & D.M. Allen. 2016. *Groundwater recharge model for Gabriola Island. Final report submitted to Regional District of Nanaimo*. Simon Fraser University, Burnaby, B.C.

Curran, D., T. Gleeson, & X. Huggins. 2023. Applying a science-forward approach to groundwater regulatory design [accepted for publication]. *Hydrogeology Journal*. 1–19. doi:10.1007/s10040-023-02625-6

Cuthbert, M.O. 2010. An improved time series approach for estimating groundwater recharge from groundwater level fluctuations, *Water Resour. Res. 46*:W09515, doi:10.1029/2009WR008572

DHI. (2022). *MIKE SHE: User guide and reference manual*. https://manuals.mikepoweredbydhi.help/2020/Water_Resources/MIKE_SHE_Print.pdf [June 13, 2023].

Dyer, J.M. (2019). A GIS-based water balance approach using a LiDAR-derived DEM captures fine-scale vegetation patterns. *Remote Sensing 11*(20):2385. https://people.ohio.edu/dyer/WB/Water%20Balance%20Tool%20v3.0.2%20User%20Manual.pdf [June 13, 2023].

Environmental Reporting BC. 2019. Long-term trends in groundwater levels in BC. https://www.env.gov.bc.ca/soe/indicators/water/print_ver/envreportbc_gwl_March2019.pdf [June 13, 2023].

Foster, S., & D.M. Allen. 2015. Groundwater—Surface water interactions in a mountain-to-coast watershed: Effects of climate change and human stressors. *Advances in Meteorology, Special Issue on Hydrological Processes in Changing Climate, Land Use and Cover Change 2015*:861805. doi:10.1155/2015/861805

Forstner, T., T. Gleeson, L. Borrett, D.M. Allen, M. Wei, & A. Baye. 2018. Mapping aquifer stress, groundwater recharge, groundwater use, and the contribution of groundwater to environmental flows for unconfined aquifers across British Columbia. *Water Science Series*, WSS2018-04. Prov. B.C., Victoria, B.C.

Foweraker, J.C. 1974. Groundwater Investigations on Mayne Island, Report No.1: Evaluation, development, and management of the groundwater resource on Mayne Island. Groundwater Division, Water Investigation Branch, B.C. Department of Lands, Forests and Water Resources, Victoria, B.C., p. 54.

Gleeson, T. 2020. Global groundwater sustainability. *Groundwater 58*:484–485 doi: 10.1111/gwat.12991

Gleeson, T., M.O. Cuthbert, G. Ferguson, & D. Perrone. 2020. Global groundwater sustainability, systems and resources in the Anthropocene. *Annual Review of Earth and Planetary Sciences 48*:431–463. doi:10.1146/annurev-earth-071719-055251

Gleeson, T., & B. Richter. 2018. How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. *River Research and Applications 34*:83–92. doi:10.1002/rra.3185

Gleeson, T., W.M. Alley, D.M. Allen, M.A. Sophocleous, Y. Zhou, M. Taniguchi, & J. Vandersteen. 2012. Towards sustainable groundwater use: Setting long-term goals, backcasting, and managing adaptively. *Ground Water 50*:19–26. doi:10.1111/j.1745-6584.2011.00825.x

Gleeson, T., K. Villholth, R. Taylor, D. Perrone, & D. Hyndman. 2019. Groundwater: A call to action. *Nature 576*:213. doi:10.1038/d41586-019-03711-0

Gower, T., & A. Barroso. 2019. Tapped out: A special report on water scarcity and water solutions in British Columbia. Watershed Watch Salmon Society, Coquitlam, B.C., 24 pp. https://watershedwatch.ca/wp-content/uploads/2019/09/2019-09-24-Tapped-Out-RGB.pdf [June 13, 2023].

Gullacher, A., D.M. Allen, & J. Goetz. 2023. Indicators of groundwater drought in British Columbia. *Water Science Series*, WSS2023-01. Prov. B.C., Victoria, B.C.

Gullacher, A., D.M. Allen, & J. Goetz. 2021. Classification of groundwater response mechanisms in provincial observation wells across British Columbia. *Water Science Series*, WSS2021-03, Prov. B.C., Victoria, B.C.

Gullason, K. 2018. The Water Sustainability Act, groundwater regulation and Indigenous rights to water: Missed opportunities and future challenges. *Appeal: Rev. Current L. & L. Reform*, *23*, 29.

Healy, R.W. 2010. Estimating groundwater recharge. Cambridge University Press, Oxford, U.K.

Hodge, W.S. 1995. Groundwater conditions on Salt Spring Island. Government of British Columbia. https://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/library/saltspring/saltspring.html [June 13, 2023].

Hunt, B. 1999. Unsteady stream depletion from ground water pumping. *Ground Water 39*(1):98–102.

Islands Trust. 2021. Islands Trust freshwater sustainability strategy, December 2021. https://islandstrust.bc.ca/document/freshwater-sustainability-strategy/ [June 13, 2023].

Kohut, A. 2021. Estimating groundwater availability for allocation in British Columbia. *Water Science Series*, WSS2021-07, Prov. B.C., Victoria, B.C. https://a100.gov.bc.ca/pub/acat/documents/r59189/GWAM_ReportFinal_1623175838412_271537D15D.pdf ([June 13, 2023].

Leith, R.M. & P.H. Whitfield. (1998). Evidence of climate change effects on the hydrology of streams in south-central BC. *Canadian Water Resources Journal 23*(3):219–230.

Li, Q., S.C. Zipper, & T. Gleeson. 2020. *Analytical depletion functions and response times of groundwater pumping impacts on environmental flow. A report prepared for the B.C. Ministry of Environment and Climate Change Strategy*. Department of Civil Engineering, University of Victoria, Victoria, B.C.

Li, Q., T. Gleeson, S.C. Zipper, & B. Kerr. 2021. Too many streams and not enough time or money? New analytical depletion functions for rapid and accurate streamflow depletion estimates. *Groundwater*. doi:10.1111/gwat.13124

Middleton, M.A., & D.M. Allen. 2017. Assessment of hydraulic connectivity related to groundwater extraction on selected sensitive streams: Stream vulnerability mapping. *Water Science Series*, WSS2017-04, Prov. B.C., Victoria, B.C.

Mohan, C., T. Gleeson, T. Forstner, J.S. Famiglietti, & I. de Graaf. 2022. Quantifying groundwater's contribution to regional environmental flows in diverse hydrologic landscapes. *Authorea*. doi:10.1002/essoar.10511792.1

Pastor, A. V., Ludwig, F., Biemans, H., Hoff, H., & Kabat, P. (2014). Accounting for environmental flow requirements in global water assessments. *Hydrology and earth system sciences, 18*(12), 5041–5059.

Pierce, S. A., J.M. Sharp, H. Joseph, A. Guillaume, R.E. Mace, & D.J. Eaton. 2013. Aquifer-yield continuum as a guide and typology for science-based groundwater management. *Hydrogeology Journal 21*(2):331.

Province of British Columbia. 2016. Determining the likelihood of hydraulic connection—Guidance for the purpose of apportioning demand from diversion of groundwater on streams. Version 1.0. *Water Science Series*, WSS2016-01, Prov. B.C., Victoria, B.C. https://a100.gov.bc.ca/pub/acat/documents/r50832/HydraulicConnectMW3_1474311684426_4310694949.pdf [June 13, 2023].

Rathfelder, K. 2016. Modeling tools for estimating effects of groundwater pumping on surface waters. *Water Science Series,* WSS2016-09, Prov. B.C., Victoria, B.C. https://a100.gov.bc.ca/pub/acat/documents/r51878/tools4streamdepletion_1484093475019_4092907088.pdf [June 13, 2023].

Scanlon, B.R., R.W. Healy, & P.G. Cook. 2002. Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal 10*:18–39.

Simmers, I. 1990. Aridity, groundwater recharge and water resources management. In: *Groundwater Recharge. A Guide to Understanding and Estimating Natural Recharge. International Contributions to Hydrogeology*, vol. 8, D.N. Lerner, A.S. Issar, & I. Simmers (Eds.), Hanover, Verlag Heinz Heise, pp. 3–22.

Surette, M., E.K. Appaih-Adjei, & D.M. Allen. 2006. Quantifying recharge to fractured aquifers using a discrete fracture network approach. In: *Proceedings of Canadian Geotechnical Society—International Association of Hydrogeologists Joint Conference*, Sea-to-Sky, B.C., October 1–4.

Todd, J., M. Lepitre, D. Thomson, J.A. Ishikawa, M. Wade, & C. Beebe. 2020. Guidance for technical assessments in support of an application for groundwater use in British Columbia, Version 2. *Water Science Series*, 2020-01, Province of British Columbia, Victoria, B.C.

Water Sustainability Act. SBC 2014 c 15. https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/14015 [June 13, 2023].

Zhou, Y. 2009. A critical review of groundwater budget myth, safe yield and sustainability. *Journal of Hydrology 370*(1-4):207–213. doi:10.1016/j.jhydrol.2009.03.009