# Groundwater resource allocation in British Columbia: challenges and ways forward

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## Abstract:

Groundwater allocation in British Columbia is facing a number of important challenges as 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 irrelevance of annual recharge estimates, and the under-appreciated importance of aquifer drainage, while tackling cumulative impacts in watersheds using adaptive management with clear sustainability goals. We summarize these challenges and then suggest ways forward so that we can more robustly, holistically and sustainably allocate groundwater resources. Some of the proposed ways forward are based on sound science and are already being implemented partially or in some regions. Not implementing these ways forward 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

# 1. Groundwater allocation challenges in BC

We are at a watershed moment (pun intended) for groundwater resources in British Columbia (BC). The recently passed *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 can include groundwater reserves in perpetuity. To date, no area-based limits on allocation have been applied, such as limiting groundwater licensing in areas where streams are known to be overallocated (called over-recorded in BC), for example, in parts of the Okanagan. Moreover, the licensing of single wells or well fields may not adequately evaluate the cumulative effects of pumping within an aquifer or watershed.

Groundwater processes in BC 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. Yet groundwater in BC 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 BC,  groundwater allocation remains challenging.  An additional new element in the WSA is that new use licences 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 Ministry of Forests, Lands, Natural Resource Operations and Rural Development & BC Ministry of Environment and Climate Change Strategy, 2022). Groundwater recharge or water budget estimations are considered important for directly or indirectly supporting or informing allocation decisions. 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 (or bank account) conceptual model. For clarity herein we consider the 'bucket' to be an aquifer since we are focused on groundwater allocation, but it is important to note that the 'bucket' for water budget methods is most often a watershed or basin (Figure 1). In BC, single or multiple aquifers can be within one watershed and aquifers can cross watershed boundaries, especially smaller order watersheds. As with any conceptual model, it is important to define terms:

- recharge is the renewing flow of water into the top of the bucket which in this case is an aquifer;
- groundwater discharge is the flux out of aquifers to surface water bodies or springs, as seepage to the land surface or evapotranspiration to the atmosphere;
- groundwater pumping is sometimes considered groundwater discharge but for clarity herein simply called 'groundwater pumping';
- drainage is a natural change in stored groundwater which manifests as a change in the water table and leads to groundwater discharge (herein groundwater pumping is not included in drainage);
- aquifer exchange is the flux between aquifers; and
- baseflow is the slow flow component of streamflow (i.e. generated by glacier melt, reservoir release, groundwater discharge, etc.), but often and herein we use this term to exclusively represent the groundwater contribution (groundwater discharge) to streams.

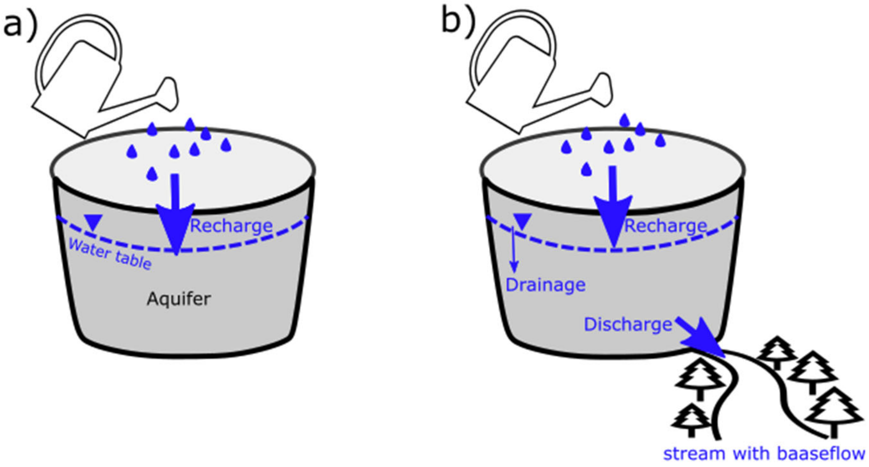

**Figure 1. Visualizing groundwater recharge, drainage and contributions to EFNs with a bucket-style conceptual model. a) the conceptual model often used in recharge estimates and b) a more holistic conceptual model that incorporates aquifer drainage, discharge and baseflow** (graphics developed using 'rain bucket' and 'river' from noun project)

Recharge estimates, however, ignore drainage (Figure 1a). This is essentially missing the hole in the bucket, which in this context, supplies streams with water year-round and supports EFNs (Figure 1b), especially essential water in the summer (Section 2.1). If the hole in the bucket is not considered in recharge estimation, the amount of groundwater that can be allocated may be grossly overestimated (Section 2.2) and may significantly change the calculated water budget of a watershed (Section 2.3). Put in simple terms: we argue for the importance of this missing hole in the bucket, and the problems that can arise if groundwater allocation decisions are based on recharge or water budget methods. Throughout we also question what do the recharge and water budget estimates actually mean? How do we use these values in water allocation decision making? Ultimately, we aim to answer the question: 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 a number of challenges to groundwater professionals and managers. We summarize these as five challenges for groundwater allocation in BC based on informal conversations with Provincial employees and our own observations:

1. Groundwater is most important in summer to support environmental flow needs (EFNs) and human water use;
2. Annual recharge and water budget estimates are highly uncertain and are largely irrelevant to groundwater allocation;
3. Aquifer drainage rates and the timing of the peak in a groundwater hydrograph are crucial for determining summer conditions;
4. Cumulative impacts in watersheds are crucial but water budgets are fraught with uncertainty; and
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 BC 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 risks permanent over-allocation of groundwater resources that would impact stream ecology, endanger rural livelihoods and challenge reconciliation with First Nations. Throughout this opinion piece, we consistently ground ourselves in decades of research in BC hydrogeology, often funded by the BC government and conducted in collaboration with BC 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. We consider the unique aquifer systems (small and generally rapidly responding) and the hydroclimatology (rainfall- and snowfall- dominated regions in Figure 2). This Perspective is timely since EFNs assessments are required for all licence applications after March 2022, ongoing water licence applications and decisions are challenging, and ongoing Treaty negotiations are using conventional water budget calculations.

# 2. Challenges for groundwater allocation in BC

## 2.1 Groundwater is most important in summer to support environmental flow needs (EFNs) and human water use

Groundwater is crucial to supporting EFNs especially in smaller, unregulated streams across the province. This fact has been emphasized in government science (Province of British Columbia, 2016), academic literature (Middleton and Allen, 2017; Gleeson and 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 environmental flow needs 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). Groundwater is most important to streamflow during low flows when groundwater discharge supports baseflow in streams (Figure 1b). In BC, the timing of low flows is controlled by the diverse hydroclimatology across the Province. In rainfall-dominated regions, the lowest flows are in late summer or early autumn whereas in snowfall-dominated regions the lowest flow month is often in the winter or early spring (Figure 2).

The regions in BC of greatest water scarcity (Gower and Barroso, 2019) or groundwater stress (Forstner et al. 2018) are generally in the Thompson-Okanagan, West Coast, South Coast, Kootenay-Boundary and Skeena and often coincide with rainfall-dominated hydroclimatic regimes and lowest flows in summer (Figure 2). Thus, for the regions of greatest water scarcity and groundwater stress, low flows occur in late summer and these 'baseflow' periods are often sustained by groundwater discharge (Figure 3). In these regions, the groundwater contribution as a percentage of total streamflow is greatest in the summer and hence groundwater is most important in summer. Unfortunately, the importance of groundwater to streamflow coincides with peak in water use for irrigation in many regions, so summer is often the pinch period when both ecological and human water use needs are highest. Groundwater pumping can impact EFNs which is most often quantified by analytical models, although some numerical models have been used, but not for water allocation purposes (Li et al., 2020; Li et al., 2021).

Groundwater allocation in BC faces a series of challenges considering the importance of summer low flows and environmental flow needs. First, the different processes, timing and controls of groundwater groundwater discharge vs. other streamflow generation mechanisms are not explicitly considered when applying the EFN policy;  the current EFN policy only considers groundwater contribution to environmental flow needs implicitly. Second, the current streamflow monitoring network in BC mostly covers larger, regulated streams and lacks long-term records of smaller, non-regulated streams where the role of groundwater is even more important. Thus, quantifying the groundwater contribution to EFNs is difficult especially given the likely inherent time and space scales of monitoring. Third, quantifying the impact of pumping in complex stream networks and aquifer systems is challenging.

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 (Figure 1b) rather than the recharge to the top of the bucket (Figure 1a).

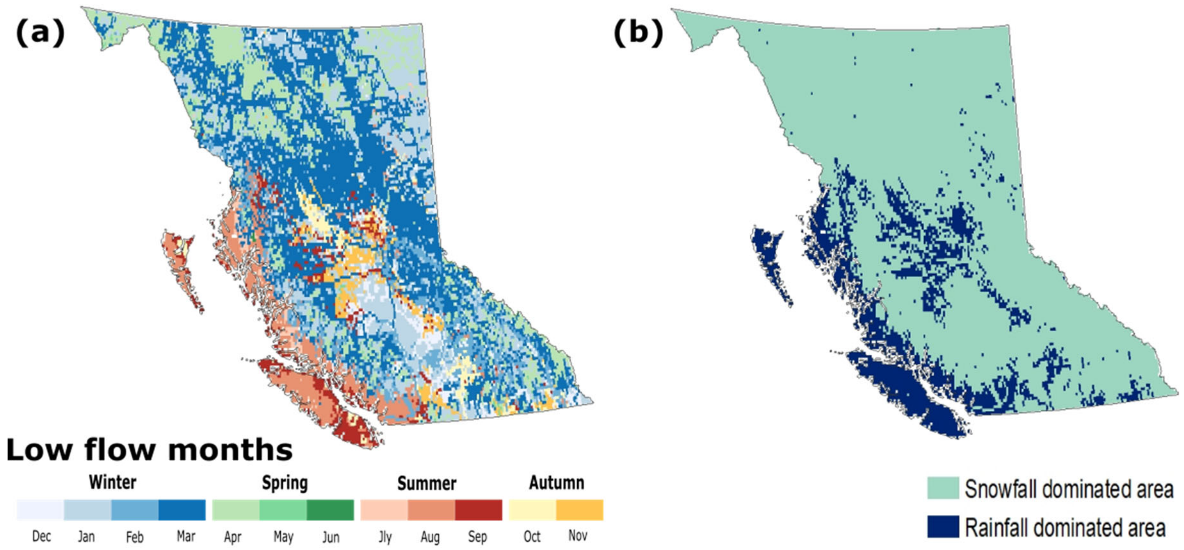

**Figure 2. Hydroclimatic variability across the province that is important to groundwater allocation. a) the lowest flow month varies across the province and b) streamflow hydrographs differ between snowfall dominated areas and rainfall-dominated areas (modified from Mohan et al. submitted).**

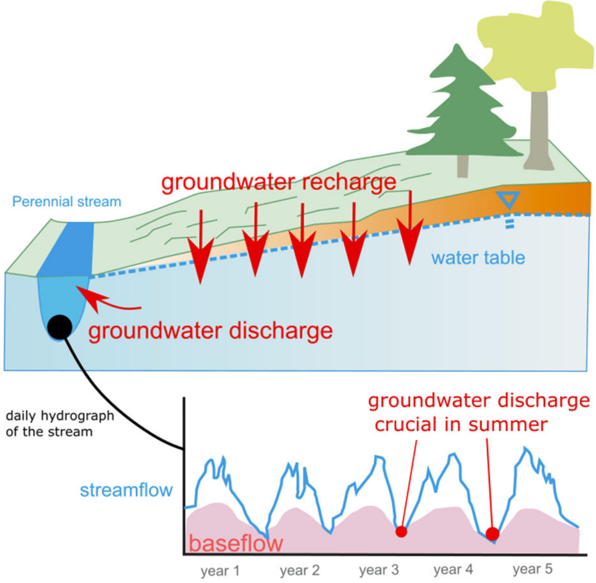

**Figure 3. Groundwater contribution to streamflow as baseflow through discharge (modified from Gleeson and Richter, 2018)**

## 2.2. 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 one of the most important components of groundwater studies, it is also one of the least understood, largely because recharge rates vary widely in space and time (Healy, 2010). Practically speaking, we still have no idea 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 4, which shows the spatial variability of mean annual recharge and seepage on Gabriola Island (Burgess and Allen, 2016), simulated using a physically-based integrated hydrological model (MIKE

SHE software; DHI, 2022). The software is used internationally for modeling 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 recharge was 199 mm (average of ~20% of mean annual precipitation, range of 17-26% across all years)(Burgess and Allen, 2016). For comparison, the average annual recharge to the Cowichan Watershed was estimated at ~17% of mean annual precipitation using the same software (Foster and Allen, 2015). In stark contrast, Foweraker (1974) estimated recharge on Mayne Island at 25.4 mm or ~3% of the average annual precipitation of 838 mm using the water table fluctuation method and 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% using spatially varying 1D vertical percolation models. Thus, even within the Gulf Islands, recharge estimates have ranged from 0.1 to 45%, pointing to the extremely high range of uncertainty given that all the methods were appropriate and had been used in studies elsewhere.

The modeled recharge estimates above 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 4, 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. Approximately 30% of the island area is represented by seasonally persistent recharge areas (i.e. always recharge throughout the year), and 4% is represented by seasonally persistent seepage (i.e. always seepage). Due to the seasonality of precipitation in this coastal region, 66% of the island area experiences both recharge and seepage variably throughout the year. Importantly, many areas receive little to no recharge.

In regard to 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 BC faces a significant challenge if water allocation decisions are reliant on recharge and water budget estimates, 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 recognised in the ‘water budget myth’ that allocating groundwater resources based on recharge is flawed (Bredehoeft, 2002). Allocating some percentage of annual or seasonal recharge is the water budget myth.

In the following section, we more deeply examine recharge process and some of the misconceptions about recharge. We explain how allocating based on recharge implicitly under-represents (or even disregards) the importance of groundwater discharge illustrated in Figure 1b.

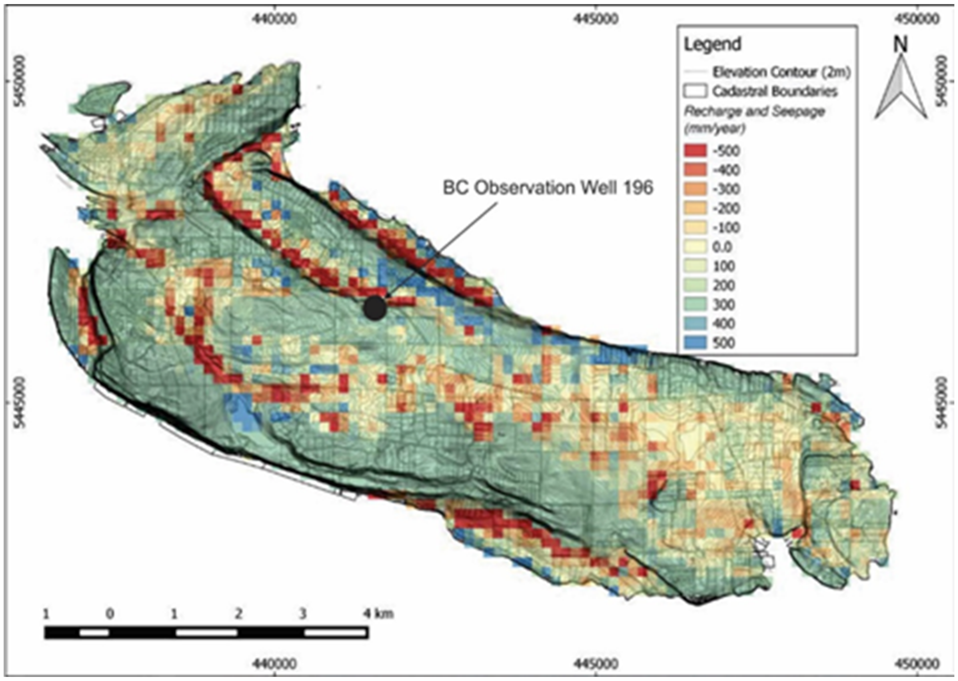

**Figure 4. Gabriola Island, British Columbia, Canada showing modeled average annual recharge and seepage (mm/year). The scale shows positive and negative numbers. Positive numbers represent recharge areas on an average annual basis, while negative numbers represent discharge zones on an average annual basis. Values close to zero are neither recharge nor discharge areas. From Burgess and Allen (2016).**

## 2.3 Aquifer drainage rates and the timing of the peak in a groundwater hydrograph are crucial for determining summer conditions

A classic hydrograph from the South Coast of BC is useful for illustrating recharge processes and some misconceptions surrounding recharge. Consider a groundwater level hydrograph for a shallow well (BC Observation Well 357) screened (17-19 m depth) in an unconfined aquifer in coastal BC (Figure 5a). The groundwater level is shown as a depth below ground surface (in meters) with the dates corresponding to the start of the water year (October 1). The first thing to notice is that the maximum groundwater levels are relatively consistent from one year to the next, at approximately 9 m depth, 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 depth, 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.

Groundwater level hydrographs differ in character depending on the hydroclimatology of the region. The hydrograph shown in Figure 5a is characteristic of wells in the south BC 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 BC, 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 BC have been classified according to their response mechanism, which identifies whether the groundwater level response leads the streamflow response (recharge-driven) or lags the streamflow response (streamflow-driven) (Gullacher et al., 2021). Many observation wells across BC are classified as streamflow-driven, meaning that the peak in groundwater level (at least near the observation well) follows the streamflow peak. This means the aquifer is responding more to what is happening in the stream than from diffuse recharge across the aquifer surface. Such interactions between aquifers and streams are not accounted for in most recharge estimation methods.

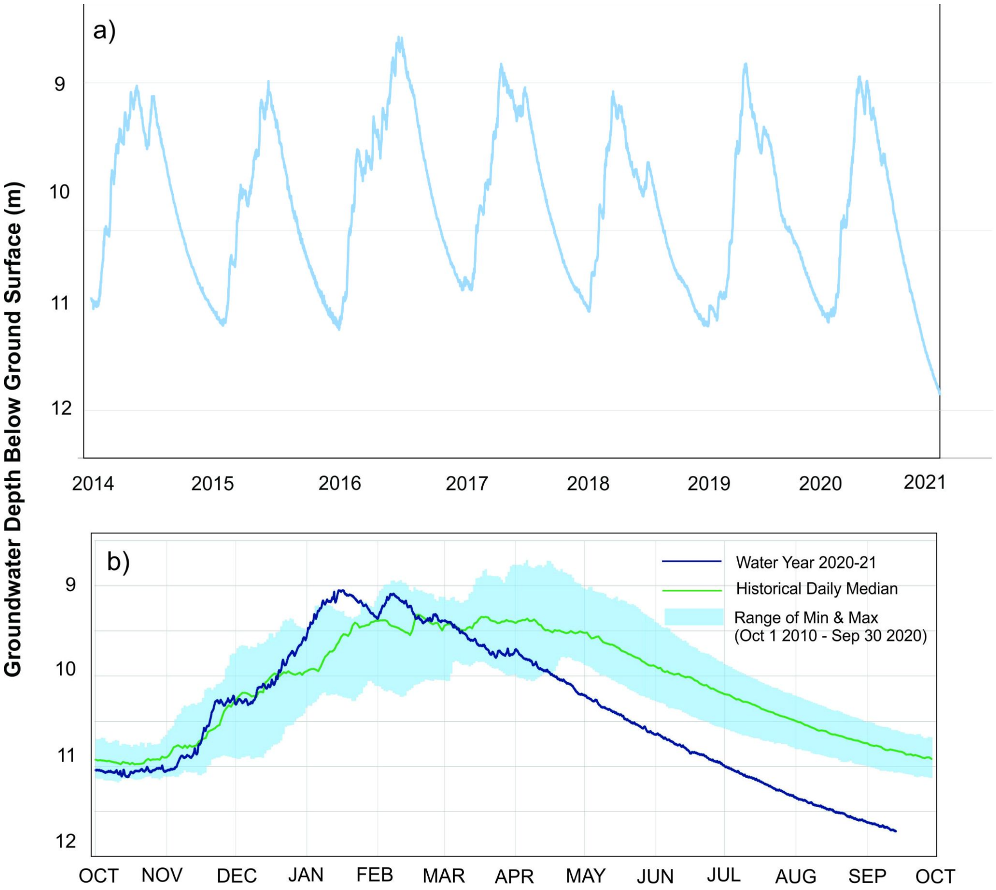

**Figure 5. a) Groundwater level hydrograph for BC Observation Well 357 (October 1, 2014 - September 30, -2021) and b) statistical hydrograph (October 1, 2010 - September 30, 2020) showing the range (turquoise band), the historical daily median (green line) and the hydrograph for water year 2020-21.**

Figure 5b exemplifies how variable the timing of the peak groundwater level can be. The 2020-21 water year was a significant deviation from the historical record, suggesting that the timing of the peak 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 5b. Thus, it doesn’t matter how much recharge occurred prior to the peak groundwater level. 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 6). If the rate of replenishment is greater than the natural drainage rate, the water level rises (Figure 6a). 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 6b). Once the rate of replenishment declines or stops altogether, the water in the bucket continues to drain (Figure 6c). The concept of continued drainage from an aquifer is fundamental to understanding what the calculated recharge means. Effectively, when we estimate recharge, we are only estimating the filling rate (Figure 1a). But, it is the continued drainage from the system that allows recharge to continue during the recharge season - if we kept adding water and there was no drainage, the ground would flood. This raises the question of the value of recharge estimates for water allocation. Given the continual drainage of water from the system, is it realistic to estimate recharge, particularly annual recharge, and use that number in an annual water budget?

In regard to EFNs, it is really the drainage rate, particularly sustaining the drainage rate, that is important. Thus, it is not a question about how much water we keep adding to the leaky bucket because most of that water has already drained from the system before the summer low flow period even begins. Examination of Figure 5b suggests that the drainage rate is fairly constant over the recession period (almost a straight line) and that there is not much variability in the rate of recession from one year to the next. This is because: 1) the hydraulic conductivity of the aquifer does not change, 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 gradient remains roughly the same. Due to interannual variability in recharge, we argue that the rate of recession, which is 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.

Also consider the fact that BC is 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). This suggests that what we really need to be concerned about is the summer (Section 2.1) and early fall water use 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 BC faces a significant challenge if water allocation decisions ignore the draining rate of the aquifer. This rate of drainage is reflected in the groundwater recession, not the recharge. Therefore, the quest for estimating recharge rates is misaligned with water allocation. As we explore in the following section, water budgets are increasingly being developed for aquifers, catchments and watersheds as a means to address cumulative effects, and arguably recharge is an essential component of a water budget. But does knowing the recharge get us any closer to addressing cumulative effects?

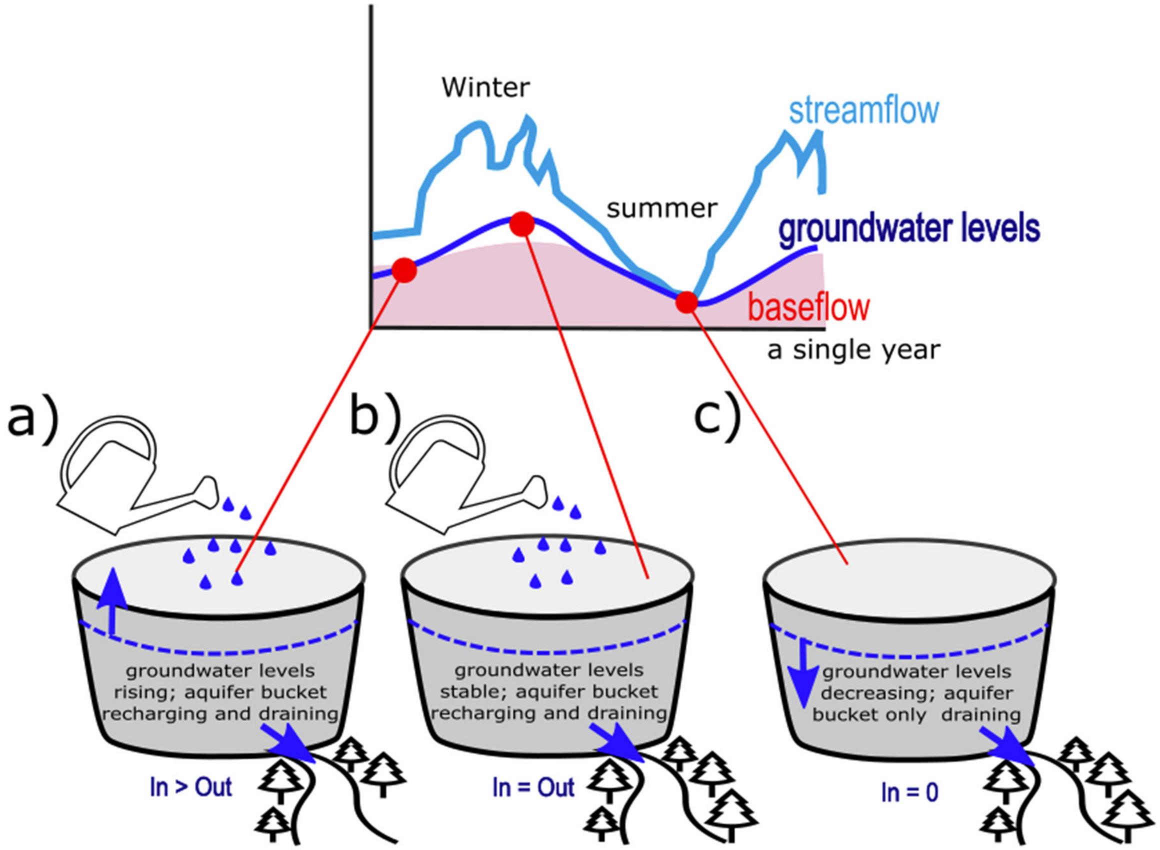

**Figure 6. Streamflow, groundwater levels and baseflow throughout a single, representative year with the aquifer bucket a) recharging, b) stable and c) draining.**

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

Since EFNs are a key component of current groundwater allocation in BC, 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 BC are heightening this awareness: the new Ministry of Land, Water and Resource Stewardship and the BC Watershed Security Strategy and Fund. Unfortunately, observation wells across the province hint at localized long-term groundwater depletion problems (although it is important to note that the vast majority of aquifers across the province are not being monitored routinely). Of the 121 examined observation wells, 85% have water levels that are stable or increasing (with 9 wells showing increasing trends), 6% of wells show a moderate rate of decline in water levels, and 9% show a large rate of decline in water levels (ref). 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 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 2.3) and potentially EFNs (Section 2.1).

Groundwater allocation in BC 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 2.2) and discharge is largely unmeasured across the province (Section 2.1), we highly doubt that meaningful water budgets can be derived that are useful for water allocation. Second, this uncertainty is compounded in data poor regions where both aquifer and stream monitoring is limited. Third, 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 overall picture of rate of aquifer development if the components of the water budget can be trusted (based on the description above we doubt this but this may not be universally true for all aquifers and settings in BC). Finally, license applications 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 smaller diversions).

## 2.5 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 often made in perpetuity with no ‘off ramps’. 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 triggers other things to happen (within a regulatory context), like modeling 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 BC'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 (that is also generally agreed upon by signatories of the Global Groundwater Statement): 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 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.

# 3. 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 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 are 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: a) conducting more fieldwork on the impact of pumping on EFNs of streams in different hydrogeologic environments in BC. 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). b) At the well-scale, one can analyze the impact of pumping using analytical depletion solutions and functions (Li et al., 2020) which are not perfect 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. c) 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 BC (Figure 7). All of 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, we argue for the need to revise the BC EFN policy so that it explicitly considers the role of groundwater in supporting low flows explicitly rather than implicitly.

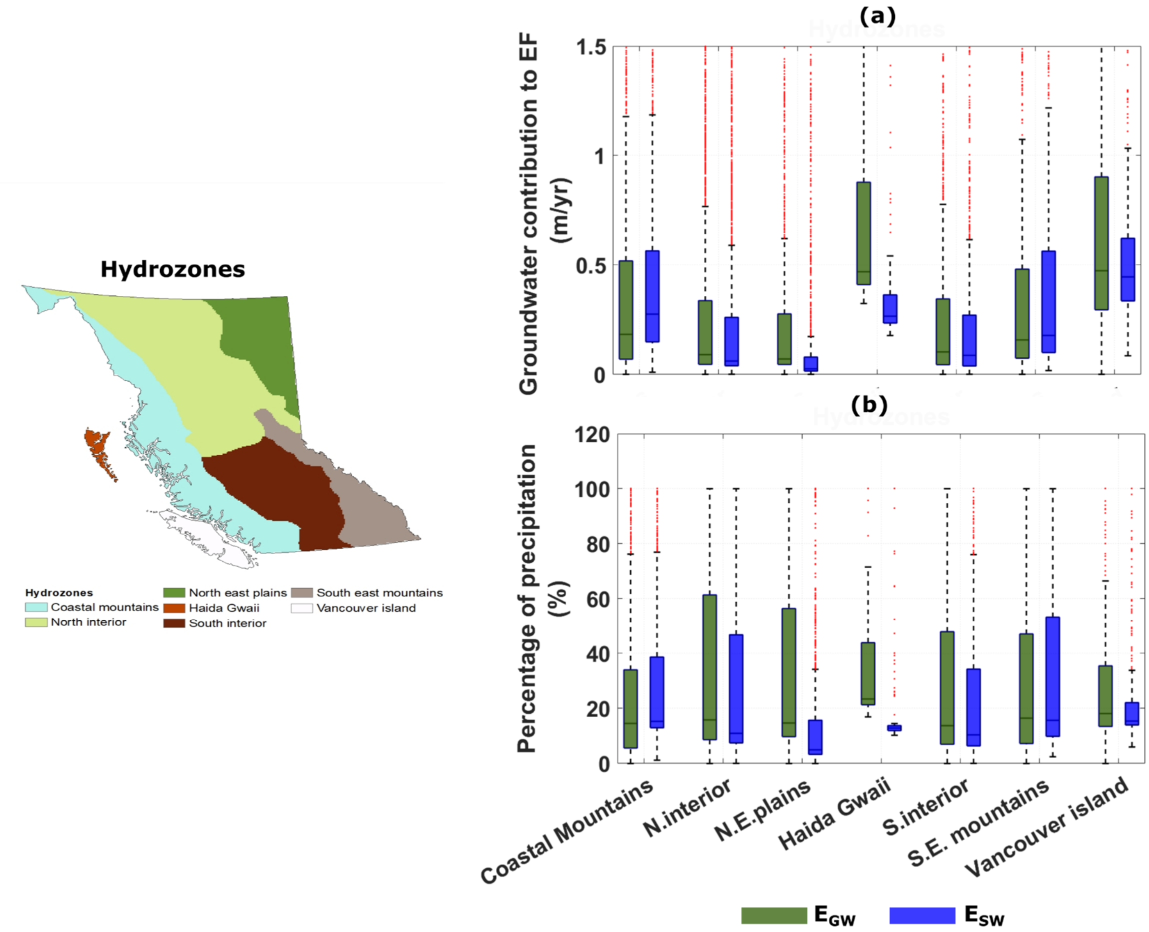

**Figure 7. Estimates of $E_{GW}$ and $E_{SW}$ (respectively, the groundwater and surface water contributions to environmental flows) by hydrozones (from Mohan et al. submitted).**

***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. Freshwater Sustainability - Programs - Islands Trust) in water sustainability initiatives across BC. Given the uncertainty in recharge estimates, particularly annual recharge estimates, and more importantly the fact that such estimates ignore the drainage rate of the system, we strongly recommend significantly reducing emphasis or eliminating altogether annual recharge and annual water budget estimation, and not using 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 where 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. Annual recharge will likely increase across BC due to climate change, but remembering that most of the recharge occurs during the wet (or freshet) seasons when groundwater levels are already at their maximum will not help to inform water allocation decisions. 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 whether a regime shift (snowmelt- to rainfall-dominated) may occur in different regions across the Province. A shift in the temporal pattern of streamflow - earlier freshet, lower late summer and early fall flows, and higher early winter flows has already been observed (Leith and 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 1144 - Hopington C). Aquifer 1144 is rated as high demand, and provincial observation 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 specific storage - 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***

Groundwater allocation should be based on an understanding of groundwater drainage rather than groundwater recharge. Ultimately, it doesn't matter how much recharge occurred prior to the peak groundwater level. What is important is the timing of the peak (i.e. the onset of recession) and the rate of recession. The rate of recession (i.e. the slope of the recession curve) is relatively constant from year to year as illustrated in Figure 8 by the parallel recession lines for a normal year and a dry year. Importantly, if the maximum groundwater level occurs earlier in the year, then because the slope is 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; we assume October 1 as the conventional start of the water year.

Additional research is needed to better understand a) the controls on groundwater recession in different aquifers and in different regions of BC, b) 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. Recent research by Gullacher et al. (submitted) identified 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 to 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.

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.

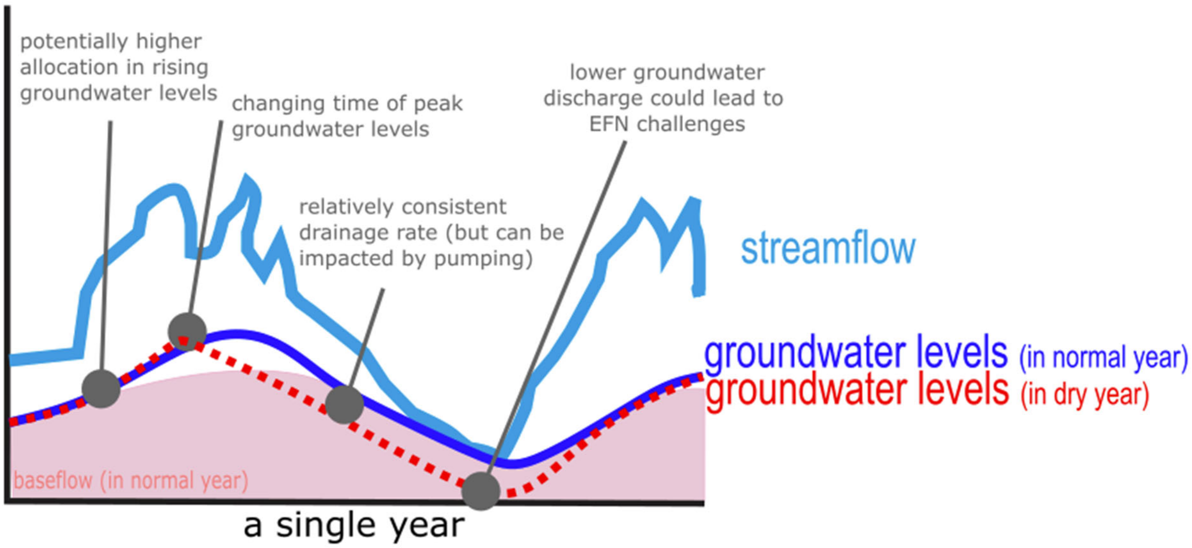

**Figure 8. Conceptualization of a groundwater level hydrograph in a normal year (dark blue) and during a dry year (red dashed) relative to the total streamflow (light blue) and baseflow during a normal year (pink). The rate of recession during a normal year and a dry year are much the same. Therefore, 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.**

### *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. 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 'norm' of the system. There is no norm anymore. So, how can we make decisions on how much water to allocate when we have changing baselines? An Adaptive Management

Framework with clear provincial-level guidelines and practice approaches is critical. This framework could include post-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 Perspective 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.

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