Quantifying groundwater's contribution to regional environmental flows in diverse hydrologic landscapes

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Abstract

Increasing recognition of the importance of ecosystem services in water resources management has accelerated the development and applications of environmental flows requirements for lotic ecosystems which are often dependent on groundwater. However, most environmental flows management focuses on water infrastructure, like dams or diversions, without explicitly taking groundwater into account and ignoring the importance of groundwaters' contribution to environmental flows. Here, we introduce two methods for estimating groundwater contribution to environmental flows: 1) a groundwater-centric method, which proposes that high levels of ecological protection are maintained if 90% of groundwater discharge is preserved and 2) a surface water-centric method, which quantifies groundwater's contribution to environmental flows from streamflow using region-specific streamflow sensitivity metrics and local environmental flows policies. The two methods are tested in British Columbia, Canada, which has a diverse, complex, and highly coupled groundwater-surface water systems. The two methods gave comparable results in different hydrogeoclimatic settings. Though the two methods are demonstrated using British Columbia as a case study, this framework can be implemented across different spatial and temporal scales for different regions and globally in data-scarce, hydrologically complex landscapes. Application of these methods can aid in a robust and holistic assessment of environmental flows, taking into account the often missing groundwater component.
Keywords: Groundwater, Environmental flows, British Columbia, Surface water centric method, Groundwater centric method

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Key Findings

- Two novel methods for estimating the groundwater contribution to environmental flows are developed which can be applied across scales.
- Results from the two methods were in agreement at regional, biogeoclimatic and hydrozone scale in a hydrologically diverse study area.
- The groundwater contribution to environmental flows is larger in the drier, snow-melt dominated regions in British Columbia, Canada.

Plain language summary

A growing recognition of the importance of ecosystem services to the development and management of water resources has spurred the development and application of environmental flows requirements. Despite the importance of groundwater in maintaining the freshwater ecosystem, groundwater is seldom taken into consideration in environmental flows allocation and management. In this study we develop two methods for estimating groundwater contribution to environmental flows: 1) a groundwater-centric method and 2) a surface water-centric method. The two methods are demonstrated using the western province of Canada,

British Columbia as a case study. The framework presented in this study can be implemented across different spatial and temporal scales for different regions and globally, in data-scarce, hydrologically complex landscapes. Application of these methods can aid in a robust and holistic assessment of environmental flows, taking into account the often missing groundwater component.

Abstract

Increasing recognition of the importance of ecosystem services in water resources management has accelerated the development and applications of environmental flows requirements for lotic ecosystems which are often dependent on groundwater. However, most environmental flows management focuses on water infrastructure, like dams or diversions, without explicitly taking groundwater into account and ignoring the importance of groundwaters' contribution to environmental flows. Here, we introduce two methods for estimating groundwater contribution to environmental flows: 1) a groundwater-centric method, which proposes that high levels of ecological protection are maintained if 90% of groundwater discharge is preserved and 2) a surface water-centric method, which quantifies groundwater's contribution to environmental flows from streamflow using region-specific streamflow sensitivity metrics and local environmental flows policies. The two methods are tested in British Columbia, Canada, which has a diverse, complex, and highly coupled groundwater-surface water systems. The two methods gave comparable results in different hydrogeoclimatic settings. Though the two methods are demonstrated using British Columbia as a case study, this framework can be implemented across different spatial and temporal scales for different regions and globally in data-scarce, hydrologically complex landscapes. Application of these methods can aid in a robust and holistic assessment of environmental flows, taking into account the often missing groundwater component.

Keywords*: Groundwater, Environmental flows, British Columbia, Surface water centric method, Groundwater centric method*

1 Groundwater, the forgotten contribution to environmental flows

Groundwater is a critical resource supporting human well-being (Aldaya, 2017; Konikow & Kendy, 2005), freshwater ecosystems (Barlow & Leake, 2012; Constantz, 1998; Noorduijn et al., 2018), irrigation and thus for food security and other economic activities (Dalin et al., 2017; Siebert & Döll, 2010; Wada et al., 2012). As groundwater and surface water systems are hydrologically interconnected in most parts of the world, groundwater plays a pivotal role in contributing to environmental flows that are defined as "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems." (Arthington et al., 2018). Groundwater contributions also influence water quality, geomorphic evolution, and the character and composition of riparian zones, all of which are essential for maintaining a healthy aquatic ecosystem (Currell et al., 2012; Malcolm et al., 2004; Maxwell & Condon, 2016). Despite groundwater being critical to a myriad of aquatic ecosystems, and broadly impacted, groundwater contributions to streamflow have not been directly considered or quantified in the current environmental flows literature (de Villiers et al., 2008). Environmental flows studies so far focused on surface water alterations such as dams, impoundments, and stream dependent water diversions (Poff & Zimmerman, 2010) even though, the role of groundwater in ecosystem maintenance is long understood at local and regional scales (Barlow & Leake, 2012; Famiglietti, 2014; Konikow & Kendy, 2005). Like other hydrologic systems, groundwater resources are stressed by unsustainable water pumping to meet the growing demands. Groundwater pumping, which is a direct manifestation of human interference, could impact the groundwater discharge and eventually environmental flows in hydrologically connected streams and wetlands (Acreman et al., 2014; Barlow & Leake, 2012; Bierkens & Wada, 2019; de Graaf et al., 2019; Hendriks et al., 2014). Therefore, for environmental flows assessment to be comprehensive, the groundwater's contribution needs to be explicitly accounted for (Gleeson & Richter, 2018).

Baseflow (the portion of streamflow that is not directly generated from the excess rainfall during a storm event and often generated through delayed sources), usually sustains the low flows which partially or completely becomes environmental flows. Though baseflow can originate from various sources like groundwater, snowpack, or glaciers, groundwater discharge is often the most common and volumetrically significant portion (Cartwright et al., 2014; Costelloe et al., 2015). Groundwater pumping can have a significant impact on the environmental flows and this impact could vary drastically depending on the length and intensity of pumping (de Graaf et al., 2019). In a natural gaining stream (water flows from groundwater system to streams), groundwater discharge is directly supporting the environmental flows particularly during low flows. Groundwater pumping, however, reduces the groundwater discharge, thereby decreasing the available water to meet environmental flows. Additionally, prolonged pumping widens the cone of depression until all groundwater pumped is derived from streamflow, further reducing environmental flows (Bierkens & Wada, 2019). More than half of watersheds around the world may reach their environmental flows limits before 2050 due to excessive groundwater pumping, as evidenced by a substantial number of watersheds already reaching the limits (de Graaf et al., 2019). As the human dependence on groundwater resources is not likely to decline any time soon and may even increase in the future (due to an increase in demand and climate change), it is crucial to estimate the groundwater contribution to environmental flows scientifically for sustainable water resource management.

Scientific literature supports environmental flows regimes as essential to sustain freshwater and estuarine ecosystems and the human livelihood (Acreman et al., 2014; Gleeson & Richter, 2018; Harwood et al., 2014; Zektser et al., 2005). However, few methods have been proposed in the literature to quantify groundwater's contribution to environmental flows (Gleeson & Richter, 2018; de Graaf et al., 2019). Quantifying groundwater's contribution to environmental flows has multiple possible applications, such as, in aquifer stress evaluation and efficient water allocation. For instance, groundwater stress is often approached as a ratio between groundwater use and availability, where availability is represented as the mean annual groundwater recharge (Richey et al., 2015; Van Beek et al., 2011; Wada et al., 2012). This approach does not consider the environmental needs and overestimates the groundwater available for human use and underestimates the pressure on groundwater systems. An alternate approach for groundwater stress estimation was proposed by Gleeson et al. (2012) considering the difference between recharge and groundwater environmental contribution as the total groundwater availability. Gleeson et al. (2012) used Q_{90}, the monthly streamflow that exceeded 90% of the time during the study period as the groundwater contribution to environmental flows. Though this method works well for streams with low to moderate flow variability, the fixed percentage of 90% throughout the year may not be accurate for streams with highly variable flow. It is therefore necessary to develop methods to estimate groundwater contribution to environmental flows that are more detailed and have more temporal/flow specific discretization. Additionally, none of the existing environmental flows 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.

The objective of this study is to develop two novel methods for estimating the groundwater contribution to environmental flows and demonstrate these methods in a case study area (British Columbia (BC)) with a diverse hydrologic and hydrogeologic setting. The first method is a groundwater-centric method from the application of the groundwater presumptive standard defined by (Gleeson & Richter, 2018), Gleeson and Richter (2018) suggest that high levels of ecological protection are maintained if 90% of groundwater monthly averaged discharge is preserved. The second method is a surface-water centric method developed in this study, which quantifies groundwater's contribution to environmental flows from streamflow using region-specific streamflow sensitivity metrics and local environmental flows policies. It is important to emphasize that the applicability of the two methods in this paper is not limited to the modeled data or scale used here, which are only meant as a first example application. Both the methods can be applied across different spatial and temporal scales based on data availability and application requirements. At smaller scales, these methods can be used with higher resolution model data or field-based data.

2 Methods and Data

2.1 Groundwater contribution to environmental flows

The groundwater contribution to environmental flows can be estimated either by adopting a groundwater-centric method or by using a surface water-centric method. In the groundwater-centric method, groundwater-supported environmental flows are estimated using modeled groundwater discharge to the streams. Whereas, in the later, the low flows in the streams are used based on the assumption that the entire low flows in the streams are supported by groundwater. Both methods can be applied at varying temporal and spatial scales. In this study, however, the methods are demonstrated using monthly simulated data (1960 to 2010) and the results are presented as annual aggregates. The slow nature of groundwater discharge and the regional extent of this study makes this choice reasonable. The two methods were systematically compared at different spatial scales (regional scale, biogeoclimatic zones and hydrozones) both statistically (using Kolmogorov-Smirnov test) and graphically. The difference between the two methods was determined to assess the comparability of the estimates, and multiscale aggregation was applied to test how these differences vary with different hydroclimatic conditions. Additionally, the methods were applied separately in rainfall dominant regions and snowfall dominant regions (described in Section 2.2).

For the current case study, the streamflow and groundwater discharge outputs from a global-scale groundwater and surface water model were used. For a detailed model description, we refer to de Graaf et al (2017, 2019), a summarized description is given below. The model consists of a coupling between the hydrological model PCR-GLOBWB2.0 (Sutanudjaja et al. 2018) and a groundwater flow model based on MODFLOW (de Graaf et al. 2019). This coupled groundwater and surface water model runs at high spatial resolution (5-arcminutes globally) at a daily to monthly time step. The model simulates groundwater and surface water storages and fluxes and interaction between groundwater, surface water, soil moisture, and atmosphere. Unique of this model is the dynamic coupling between groundwater and surface water resources via groundwater drainage and river infiltration (de Graaf et al 2019) and the globally detailed parameterization of the sub-surface, including the simulation of groundwater flow for confined and unconfined conditions (de Graaf et al 2015, 2017). For this study, model outputs of a historical human run (i.e., including human water uses) were used (de Graaf et al 2019).

One could argue that a regionally or locally calibrated model outputs or observed data would be more accurate to use in a regional study. The intention of this paper, however, is to develop and compare two methods for estimating groundwater contribution to environmental flows. The current model inputs are used for demonstration purposes. Therefore, these methods could be forced with streamflow/groundwater discharge data from a well parameterized regional or local model, if and when it is available. In this study, however, global-scale modeled data were chosen, because of the unavailability of uniformly gridded data with adequate temporal range, particularly for groundwater discharge. Additionally, even at a larger scale, a reliable non modeled groundwater discharge dataset does not exist for the required spatial and temporal scale.

2.1.1 Groundwater centric method

The groundwater centric method (presumptive standard method) is based on the Sustainability Boundary Approach ((Richter, 2010)), which involves restricting hydrologic alterations to within a percentage-based range of natural or historical flow variability (Fig. 1.a). The groundwater presumptive standard is a standard for managing groundwater pumping appropriate for maintaining environmental flows by explicitly including the potential impacts of groundwater pumping over long temporal scales. The groundwater presumptive standard suggests that high levels of ecological protection will be provided if groundwater pumping decreases monthly natural baseflow by not less than 10% through time (Gleeson & Richter, 2018). The groundwater presumptive standard of 10% should be considered nested within and part of current EF frameworks for streamflow rather than additional 10%. This presumptive standard is intended to provide estimation of environmental flows where detailed scientific assessment of environmental flows cannot be undertaken. The groundwater presumptive standard is estimated as:

$$E_{GW} = 0.9 \cdot Q_{dis} \qquad 1)$$

where

E_{GW} is groundwater's contribution to environmental flows based on the groundwater centric method [m yr^{-1}]

Q_{dis} is groundwater discharge, the flux from the aquifer to the stream [m yr^{-1}]

Spatially distributed estimates of annual groundwater discharge (aggregated from monthly estimated groundwater discharge routed along the stream network) for 51 years (1960 to 2010) were derived from the global hydrological model (as described in section 2.1). More specifically, and relevant for the groundwater centric method, is the interaction between groundwater and surface water and related boundary conditions. Namely, large lakes and the ocean are represented as a Dirichlet boundary condition, where the ocean groundwater head was set to 0 m, and water levels of the lakes were set at elevation levels provided by the HydroSHEDS digital elevation map (Lehner & Grill, 2013). The groundwater body and surface water body interactions are incorporated in the groundwater model through MODFLOW's river (RIV) and drain (DRN) packages. Three levels of groundwater-surface water interactions are represented in the model (de Graaf et al., 2017; de Graaf et al., 2015): (1) large rivers, wider than 10 m, (2) smaller rivers, smaller than 10 m, and (3) springs and streams higher up in the valley. A summarized description of how these interactions is simulated is given below, for a more detailed description we refer to de Graaf et al (2017).

For large rivers, water is drained from the groundwater system to the river when the simulated groundwater head is above the river head. When modeled groundwater heads drop below the river head, river water infiltrates the groundwater system. This flux, Q_{riv_large}, is calculated in the RIV-package and is positive for infiltration (water entering the system groundwater) and negative for drainage (groundwater leaving the groundwater system). In smaller rivers, the riverbed is assumed to be at the surface elevation, and the groundwater is drained into the river when the simulated groundwater head lies above the riverbed. This flux (Q_{riv_small}), is also calculated in the RIV-package. Runoff, generated by snowmelt, surface runoff, interflow, and groundwater discharge, is routed along the river network to the ocean, lakes, or wetlands using a kinematic wave routing (Sutanudjaja et al., 2018).

The groundwater-surface water interactions estimated for large and smaller rivers are the main components of the estimated groundwater discharge. At the 5-arcminutes resolution, however, local springs, and streams higher up in the mountain are not represented well enough by larger and smaller rivers only. Therefore, it is assumed that groundwater drainage above the floodplain level can be tapped by local springs, which are represented as a linear storage-outflow relationship. This flux, Q_{drn}, is calculated in the DRN-package. The total groundwater discharge, Q_{bf}, is thus calculated as:

$$Q_{bf} = Q_{riv-large} + Q_{riv-small} + Q_{drn} \qquad 2)$$

where

Q_{bf} s the total groundwater discharge [m^3 d^{-1}]

$Q_{riv\text{-}large}$ is the groundwater drainage or infiltration from groundwater to the surface water estimated for large rivers (width > 10 m) [$m^3 d^{-1}$]

$Q_{riv\text{-}small}$ is the groundwater drainage from groundwater to surface water estimated for small rivers (width < 10 m) [m^3 d^{-1}]

Q_{drn} is the is the groundwater drainage representing drainage by local sags, springs, and streams higher up in the mountain [m^3 d^{-1}]

For this study, Q_{bf} was converted to annual fluxes, m^3y^{-1}. Also, for the methods developed in this study we focused on groundwater drainage only and cells where the yearly sum is 'infiltration' were ignored in the analysis.

2.1.2 Surface water centric method

During low flow conditions, groundwater is often the sole source of river water, and is a critical flux particularly in montane environments which sustains downstream water supplies and provide other ecosystem services (Frisbee et al., 2011). Low flows are often identified using Q_{90} or Q_{80} rule, where flows lower than the 90th or 80th percentile respectively, equate to low flow conditions (Pastor et al., 2014). This method uses a surface water centric position to identify groundwater fluxes from streamflow hydrographs and explicitly considers surface water EF metrics (Fig. 1.b). The environmental flows metrics in this study are based on the environmental flows policy (BC EF policy) for British Columbia (Province of British Columbia 2016b) (similar methodologies are used globally (Pastor et al., 2014)). The stream sensitive classification (Table 1) based on BC EF policy is used here to estimate the proportion of annual streamflow reserved for environmental flows. With the use of BC EF policy, the final estimates will be at annual scale but alternatively, a monthly or daily methodology could be developed by applying a similar logic to the flow sensitivities. In the following, a method for calculating the annual contribution of groundwater is described but alternatively, sub-annual contributions could be calculated if the role of groundwater contribution during high flow months was understood.

Groundwater's contribution to environmental flows (E_{SW}) based on this method can be described as:

$$E_{SW} = k_{EFN} \cdot Q_{GW} \qquad 3)$$

where

E_{SW} is groundwater's contribution to environmental flows based on surface water centric method [$m^3\ yr^{-1}$]

k_{EFN} is the coefficient representing the proportion of annual streamflow reserved for EF [-]

Q_{GW} is mean annual groundwater supported streamflow [$m^3\ yr^{-1}$]

In order to derive the mean annual groundwater supported streamflow (Q_{GW}), each month is classified into low, moderate, and high sensitivity months using Mean Monthly Streamflow (MMF) data (Table 1). The high sensitivity months are assumed to represent a low flow season that is primarily supported by groundwater. The maximum monthly flow during low flow conditions was used as a representative MMF (Q_{LF}) to provide a conservative estimate of groundwater's contribution to streamflow. For major streams which never enter low flow conditions, the representative MMF is the lowest monthly flow within the intermediate or high flow conditions. The mean annual groundwater supported streamflow (Q_{GW}) is derived using the extrapolation of the representative MMF (Q_{LF}) based on the sensitivity classification. Groundwater discharge to streams increases during high flow conditions, and therefore, using such an annual extrapolation would in some cases yield an underestimation of annual groundwater supported streamflow.

Q_{GW} represents groundwater's annual contribution to streamflow normalized by grid cell area:

$$Q_{GW} = \frac{12 \cdot f_{local} \cdot Q_{LF}}{A_{cell}} \qquad 4)$$

where

Q_{GW} is mean annual groundwater supported streamflow [m^3 yr^{-1}]

f_{local} is the ratio of locally derived streamflow (from grid cell area) to total streamflow [-]

Q_{LF} is the representative MMF [m^3 yr^{-1}]

A_{cell} is area of the grid cell (~100 km^2) [m^2]

The surface water discharge generated within a grid cell was calculated by subtracting the upstream routed discharge from the cell's discharge. The local additions equate to the sum of discharges into the stream from the local cell area, such as baseflow, runoff, interflow. The ratio of local additions to streamflow, f_{local}, are derived as follows:

$$f_{local} = \left(1 - \frac{Q_{LF,\ upstream}}{Q_{LF}}\right) \qquad 5)$$

where

f_{local} is the ratio of locally derived streamflow (from grid cell area) to total streamflow [-]

$Q_{LF,\ upstream}$ is the upstream flow of the representative MMF [m^3 yr^{-1}]

Q_{LF} is the representative MMF [m^3 yr^{-1}]

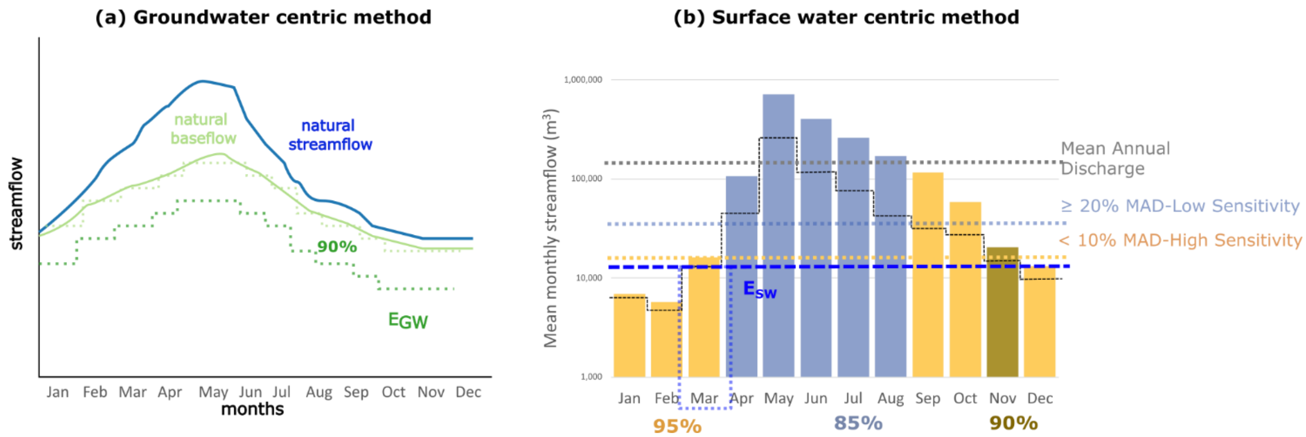

Fig. 1 Conceptual diagram of a) Groundwater centric method and b) Surface water centric method for estimating groundwater contribution to environmental flows

Note: MAD = Mean Annual Discharge; See Table 1 for the definition of High and Low Sensitivity

Table 1. Classification of flow sensitivities based on BC EF policy using mean monthly flows and mean annual discharge values.

Hydrologic season	**Stream classification**	**Criteria**	k_{EFN}
Low flow	High sensitivity	<10% MAD	95%
Intermediate flow	Moderate sensitivity	10-20% MAD	90%
High flow	Low sensitivity	>20% MAD	80%

Note: MAD – Mean Annual Discharge

2.2 Hydrology of British Columbia

This study uses British Columbia (BC), Canada as an example study area to demonstrate the groundwater centric and surface water centric methods (See section 2.1). British Columbia (total area = 944735 km^2) is one of the most hydro-climatically diverse regions in North America, consisting of around 14 distinct biogeoclimatic zones that have been previously mapped. It lies in Western Cordillera of North America bordered by the Pacific Ocean in the western side and Rocky Mountain ranges in the east. The northeastern part of the province, however, extends beyond the Rocky ranges into the Alberta Plateau (Pike et al., 2010). The study area is characterized by a wide variety of terrain types and hydrogeological materials, from mountain peaks exceeding 4000 m in elevation to broad plateaus and alluvial valleys at sea level. The annual precipitation received in British Columbia varies widely from around 4100 mm/yr on the coast to 320 mm/yr in the arid interior, largely determined by the mountain ranges along the coast and the eastern border (Pike et al., 2010).

British Columbia consists of around 1130 mapped aquifers, with 36% (404 aquifers) being unconfined and 64% (726 aquifers) being confined in nature (Berardinucci & Ronneseth, 2002). The aquifers in British Columbia are categorized into six major types based on hydrogeology: 1) unconfined fluvial/glaciofluvial aquifers: sand and gravel aquifers that are generally shallow, unconfined, and occur along river or stream valleys (e.g., Chilliwack-Rosedale aquifer along the Fraser River, aquifers along the Cowichan River on the east coast of Vancouver Island, aquifers along the Kettle River at the Southern Interior), 2) unconfined deltaic aquifers: sand and gravel aquifers that are shallow, unconfined, and which form deltas at the mouth of rivers and streams (e.g., the Scotch Creek aquifer at Shuswap Lake), 3) unconfined alluvial or colluvial aquifers: sand and gravel aquifers that form alluvial fans or are of colluvial origin near the land surface (e.g., Vedder River Fan aquifer at the City of Chilliwack), 4) aquifers of glacial or pre-glacial origin: identified in well records as occurring at depths underneath till or glaciolacustrine deposits, and glaciomarine sand, sand and gravel aquifers (e.g., Abbotsford-Sumas Aquifer in Cordillera Region, Quadra Sand in Georgia Depression, aquifers in low-lying areas in the Fraser Lowland), 5) sedimentary bedrock aquifers: consists of fractured sedimentary rocks and karstic limestone rocks (e.g, Nanaimo group) and 6) crystalline bedrock aquifers: consists of flat lying to gently dipping volcanic aquifers and fractured crystalline rocks (e.g., large volcanic bedrock aquifer in the Central Interior, aquifer underlying the Saanich Peninsula). Each of these categories of aquifers had its unique characteristics in terms of development and vulnerability that requires unique ways of sustainable management. This heterogeneity allows the proposed methodology to be tested in multiple settings. In similar fashion to the hydrogeologic diversity, the stream flow sensitivity to groundwater discharge is also very heterogeneous in British Columbia. Accounting for this difference in the stream sensitivity is crucial in formulating environmental flows regulations.

Streamflow in British Columbia is highly seasonal and controlled by localized climatic influences. Based on the dominant source of the streamflow, the regions in British Columbia can be classified into rainfall dominant areas, snowfall dominant areas and mixed regions (Fig. 2) (Allen et al., 2010). As the name implies, in the rainfall dominant regions, precipitation in the form of rainfall is the largest contributor to the streamflow. These regions are characterized with early winter (November - December) high flows and late summer (July - August) low flows. Rain dominated systems are found primarily in the coastal lowland areas and at lower elevations on the western Coastal Mountains. These regions are strongly influenced by precipitation intensity with relatively little smoothing or lagging evident in stream hydrographs. In contrast, the snow dominant regions of the interior plateau and mountain areas at higher elevations have streamflow more derived from melting snow with highest flows in spring (April - June) and low flows during the winter months. These systems integrate precipitation inputs over the winter and spring within the snowpack then release the stored water during spring-summer melt.

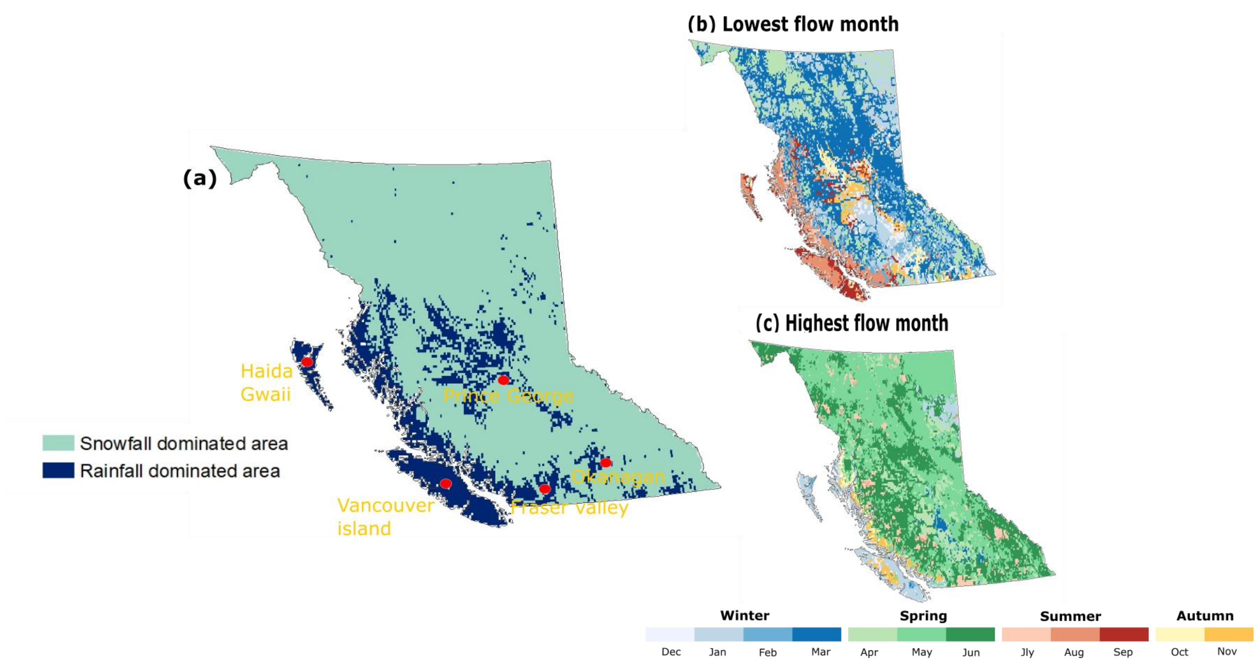

Fig. 2 a) Rainfall dominant and snowfall dominant areas in BC along with (b) lowest and (c) highest flow months.

3 Results

3.1 Estimated role of groundwater in maintaining environmental flows in British Columbia

In British Columbia, the average groundwater contribution to environmental flows was estimated as 25 and 27% of mean annual precipitation by groundwater centric method (E_{GW}) and surface water centric (E_{SW}) method, respectively. Both the methods produce higher groundwater contribution estimates in regions with significant hydraulic connection (mostly along the major rivers) (Fig. 3). The Fraser River that flows from Fraser pass in Rocky Mountain to Strait of Georgia near Vancouver was estimated to have the highest groundwater contribution in British Columbia, by both the methods (Fig. 3) followed by the Okanagan region. When the mean annual fluxes of groundwater contribution to environmental flows for the entire study area were compared, the snowfall dominated regions were having higher contribution than the rainfall dominated regions. The mean contribution in the rainfall dominated region was approximately three times less than that of snowfall dominated region (Fig. SI 1).

In general, the groundwater contribution to environmental flows is higher in the drier biogeoclimatic zones (Bunchgrass (BG), Ponderosa Pine (PP) and Interior Douglas-fir (ID)) than the more wetter zones (Fig. 4a), except for Interior Cedar Hemlock (ICH) (Fig. 4b). In most hydrozones the two methods have very similar results except in Haida Gwaii where the groundwater centric method was estimating higher values compared to the surface water centric method. In drier regions in particular, the groundwater contribution to environmental flows was almost or slightly greater than 100% of the total precipitation received in these regions. This is likely due to the upstream flow contribution to the grids during the routing process.

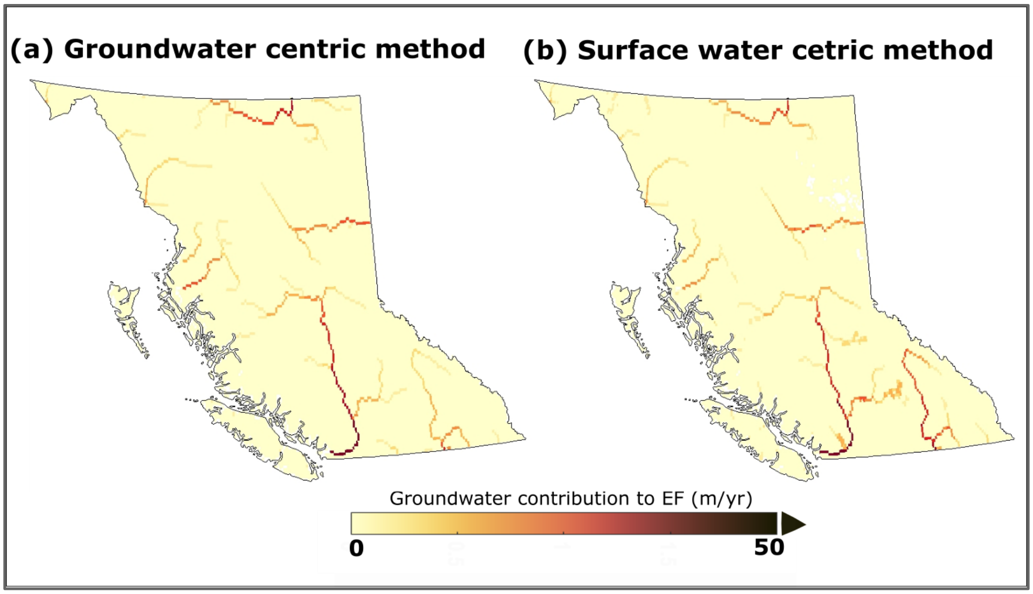

Fig. 3 Spatial map of mean groundwater contribution to environmental flows in BC calculated using (a) groundwater centric method and (b) surface water centric method.

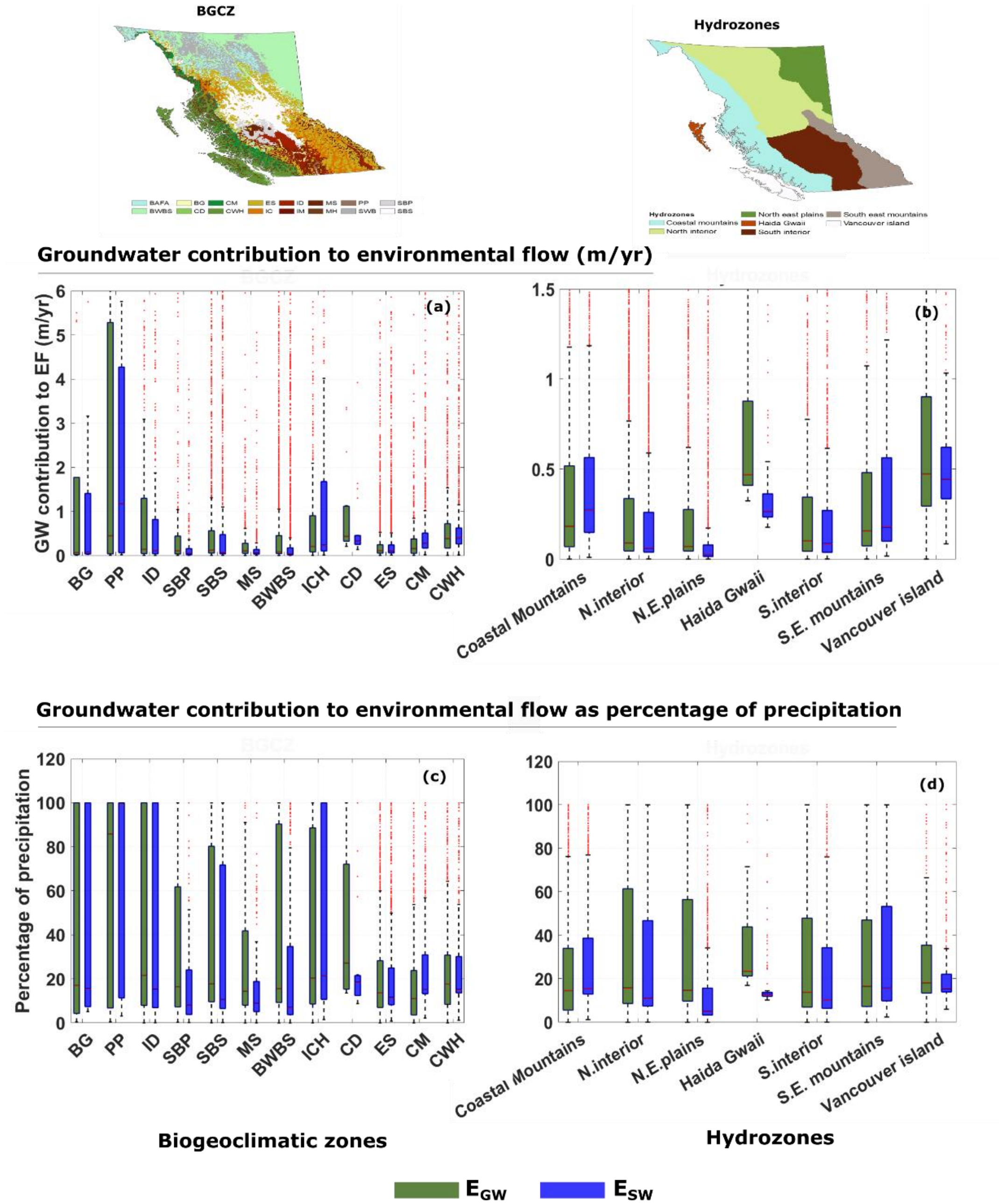

Fig. 4 Estimates of E_{GW} and E_{SW} by (a) biogeoclimatic zones (driest on the left and wettest on the right), (b) hydro zones; along with E_{GW} and E_{SW} as percentage of precipitation in different (c) biogeoclimatic zones and (d) hydrozones.

Note: CM-Coastal Mountain-heather Alpine, IM-Interior Mountain-heather Alpine, MH - Mountain Hemlock, SBS-Sub-Boreal Spruce, BAFA-Boreal Altai Fescue Alpine, ICH-Interior Cedar -- Hemlock, PP-Ponderosa Pine, SBP-Sub-Boreal Pine -- Spruce, MS-Montane Spruce, ES-Engelmann Spruce -- Subalpine Fir, ID-Interior Douglas-fir, CWH-Coastal Western Hemlock, BG-Bunchgrass, SWB-Spruce -- Willow -- Birch, BWBS-Boreal White and Black Spruce, CD- Coastal Douglas-fir

3.2 Comparison between two methods to estimate groundwater contribution to environmental flows

When the two methods are compared using graphical and statistical methods (results given in supplementary information, see Table S2), the surface water centric method gives higher estimates compared to groundwater centric method along most of the major rivers in British Columbia, except in the Okanagan region (Fig. 5). However, the difference between the two methods is low when averaged over British Columbia (average difference = 0.32 m/yr). In general, the groundwater centric method was producing slightly higher estimates along the Coastal Mountains, Central Vancouver Island and Okanagan region. Despite the difference, when aggregated to the hydrozone level or the biogeoclimatic zones, the median difference between the two methods becomes negligible (close to zero) (Fig. 5 b,c). The statistical difference between the two methods was found significant in most biogeoclimatic zones and hydrozones (see Table S2 in supplementary information). The graphical method is however more reliable in this case as the estimates in each of the zones were having non normal distribution (see Table S3 and S4 in supplementary information).

When looking at stream order, the groundwater centric method estimates higher values along higher order streams in the southeastern and southwestern part of the study area. Whereas the surface water centric method was giving comparatively higher estimates along the higher order streams for the rest of the province (Fig. 5). On the other hand, when it comes to lower order streams, the groundwater method was giving slightly higher estimates along the Coastal mountain and South eastern region and groundwater centric method was giving slightly higher estimates for the rest of the study area. The comparative performance of the two methods were similar in rainfall dominated and snowfall dominated areas of the province.

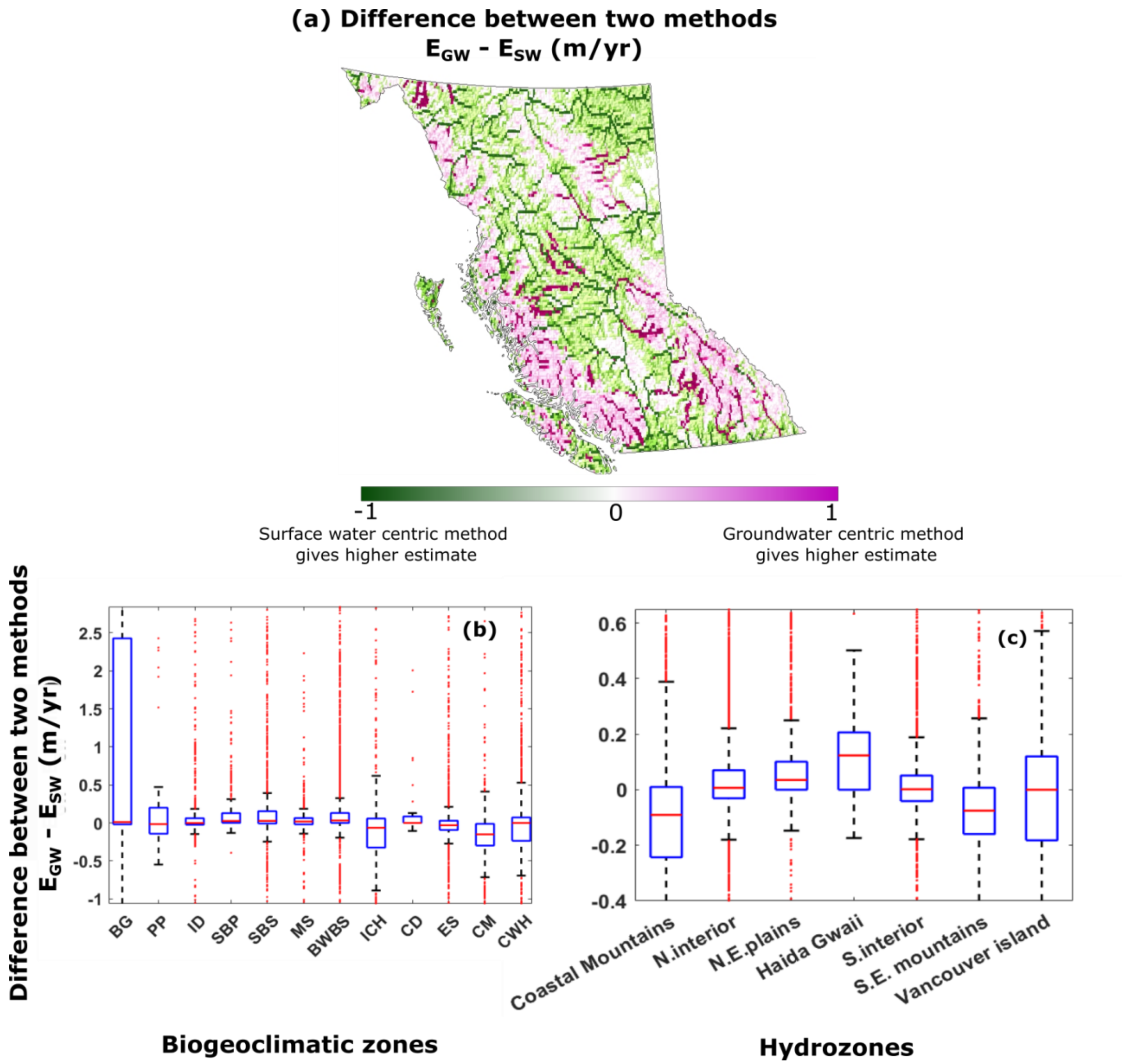

Fig. 5 (a) Map showing difference between the groundwater centric method and surface water centric method for estimating the groundwater contribution to environmental flows and the difference is also categorized for (b) BGCZ and (c) Hydrozones

4 Discussion - the need and limitations of new methods

Regional to local scale methods of estimating groundwater contribution to environmental flows are critical for groundwater management, allocation licenses, and mitigation of stream supported ecosystem deterioration. In a future with increased demand for water from all sources, it is essential to have integrated management to ensure sustainable water availability to both humans and ecosystems. Herein, two methods for estimating groundwater contribution to environmental flows, which could be a key addition to the integrated management toolkit are discussed.

4.1 The need for quantifying groundwater contribution to environmental flows

To the best of the knowledge of the authors, there are no scientifically robust methods available to estimate the groundwater part of environmental flows. Consequently, few or no environmental flows policies consider groundwater in the allocation process. This elimination could lead to the underestimated environmental flows allocation in regions where rivers are hydraulically connected to overexploited aquifers. There are several examples around the world where stream depletion and ecosystem degradation can be directly linked to groundwater pumping (Alley et al., 2018). By excluding groundwater in environmental flows estimation, not only is the quantity of flow underestimated, but also its quality. Groundwater part of environmental flows plays a key role in regulating the temperature adequate to maintain a high quality functional aquatic habitat (Lapides et al., 2022). In such scenarios where an integrated groundwater-environmental flow management is essential, the use of the proposed methods can give firsthand information on when and where the streams are sensitive to groundwater contribution and thus prioritize the conservation efforts.

The methods developed in this study can have multiple applications. These methods could be made use in the groundwater informed environmental flows policies formulation process and/or to set ecologically informed groundwater availability limits for human development. In general, methods for quantifying aquifer development capacity are solely based on recharge and will over allocate groundwater resources for human needs, possibly leading to detrimental effects on local ecosystems. Additionally, the unaccounted groundwater hydraulic connectivity could lead to an over or under allocation of environmental flows in heavily managed aquifer- river systems. Therefore, with the application of either of the proposed methods, the underestimation of the environmental flows and the overestimation of groundwater availability for human use can be eliminated.

Advantages and disadvantages exist for both methods. Namely, E_{GW} is advantageous as it is more aligned with groundwater stress management and represents a peer-reviewed approach to evaluating environmental flows. However, validating groundwater discharge estimates especially at larger scales is inherently difficult (Smakhtin, 2001; Tallaksen, 1995), therefore, uncertainty exists in using modeled groundwater discharge values. In contrast, the E_{SW} method quantifies groundwater contribution to EF using streamflow data, however, the surface water centric approach does not consider groundwater fluxes explicitly. Advantages of the surface water centric approach include being able to apply a regionally specific value to represent k_{EFN} based on stream sensitivity and streamflow data is often more abundant and measurable compared to groundwater discharge data.

The generic nature and the scale independence makes these methods suitable for local to global scale depending on the data availability. For instance, in resource limited situations, these methods can be forced with a high resolution global/regional hydrological model to identify the regions with higher groundwater- environmental flows sensitivity and to prioritize the regions for further detailed evolution. Or if a finer resolution well parameterized local model outputs are available for a region, it can be used along with these methods as well. In addition, these methods are not limited to the modeled output, but can also be used in conjunction with observed streamflow data. To be able to apply these methods to other areas, it is crucial to constrain uncertainty and limitations of the analyses. If the methods are applied with modeled data, comparing the model input parameters of permeability to aquifer permeability values would help constrain the model's ability to simulate aquifer/local scale processes. Moreover, the surface water centric method only considers the low flow months (high flow is considered only if there are no low flow months) in the estimation, which makes the estimates more conservative, particularly in regions with non-uniform annual precipitation. Therefore, this method is most suitable for regions where the intra annual precipitation deviation is low. In addition, further investigation into how the model performs in diverse hydro-ecologic settings would be crucial to properly constrain the limitations in the groundwater's contribution to environmental flows.

4.3 Method limitations

The groundwater centric method which uses a presumptive standard is a peer reviewed volumetric allocation approach that is easily implemented, readily understood, and provides a stable and reliable basis of maximum allowable abstraction on an annual basis. However, the groundwater centric method is limited by data availability, and therefore, the estimates are dependent on modeled values of groundwater discharge. In addition, the fixed value of 10% tolerance does not necessarily account for regionally specific environmental flows policies, nor does it account for variable stream sensitivity to groundwater fluxes, seasonal variability for habitat. However, from a groundwater standpoint, it does provide a conservative metric for protecting the long-term effects of pumping on groundwater's contribution to environmental flows.

The surface water centric approach to quantifying groundwater's contribution to EF, is similarly a volumetric allocation method, however with an emphasis on protecting low flows. Low flow periods are often supported by groundwater processes (Barlow & Leake, 2012; Poff et al., 1997; Smakhtin, 2001), however, in diverse hydrologic environments, this assumption is often invalid. For example, at high elevations, influences of meltwater on the hydrograph can decrease the ratio of groundwater to surface water supporting low flows. With the streamflow sensitivity classification and flexible proportion of annual streamflow reserved for EF (k_{EFN}), streams with variable flows, such as those at headwaters, can be protected better. This approach is less conservative for low sensitivity streams, as allocations increase in these areas, which does not explicitly protect against the long-term effects of groundwater abstraction, but rather sets a limit on maximum abstraction mitigating low flow deterioration. Though the methods presented in this paper have multiple applications in water management, authors acknowledge the need for considering the local heterogeneity and complexities including effects of non-hydrologic facets like temperature, water chemistry and aquatic responses for understanding actual EF needs. In addition, these methods do not account for the quality of water discharged into the streams. Further research would be required to fully understand the implications of applying these methods in integration with water quality signatures at different scales. Though the model data is only used for the demonstration purpose in this study, we acknowledge the limitations in the application of a relatively coarse resolution model in hydrologically complex and heterogenous environments. The resolution of this study is not useful or appropriate for water resource or allocation decisions at the scale of individual aquifers but is valuable for examining the patterns of spatial and statistics trends across this heterogeneous landscape. Therefore, the results in this paper are presented as provincial-scale maps or aquifer-scale statistical plots rather than displaying or discussing results from individual aquifers.

5 Conclusion

The main object of this study was to develop two methods to quantify groundwater contribution to environmental flows and to demonstrate it using a Canadian study area (British Columbia). The first method is a groundwater-centric method from the application of the groundwater presumptive standard defined by Gleeson and Richter (2018), which suggests that high levels of ecological protection are maintained if 90% of baseflow is preserved. The second surface-water centric approach is a novel method which quantifies groundwater's contribution to environmental flows, with streamflow as input and using region-specific streamflow sensitivity metrics and local environmental flows policies. The developed methods are scale independent and can be used from local to global scale at diverse temporal resolution if there is adequate data available. The estimation of groundwater contribution to environmental flows can have a profound impact on formulating a holistic environmental flows policy and allocation. In conclusion, this paper contributes valuable knowledge on groundwater resources in British Columbia, and additionally, provides methods which can be further applied in data scarce hydrologically complex landscapes worldwide.

Author Contribution

TG, TF and CM devised the conceptual framework of this study with inputs from JSF and IG. IG provided the global-scale modeled data for the analysis and rest of the data are jointly compiled by CM and TF. CM performed the analysis required for this manuscript with help from TF. CM produced the results and visualization shown in the study, and the interpretation of the results was done with help from TG, IG, JSF and TF. CM took the lead in writing the manuscript with major contributions from TG and IG. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Compelling Interests

The authors declare no competing interests.

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Data availability

All data needed to reproduce the analysis done in this manuscript will be made available via University of Victoria data repository, Dataverse after the paper is accepted. Additionally, all the codes used in this study are also made available via. GitHub.

Data for reproducing the results of this study is temporarily provided via. Google drive for the review purpose. Link to data:
https://drive.google.com/drive/folders/1EOqS46_fHQq8J-eF2yia68p5ZyYdqm8E?usp=sharing

Supplementary Information

Supplementary information is submitted as a separate document.

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S1 Groundwater contribution to environmental flows estimation in snowfall dominated and rainfall dominated regions in British Columbia

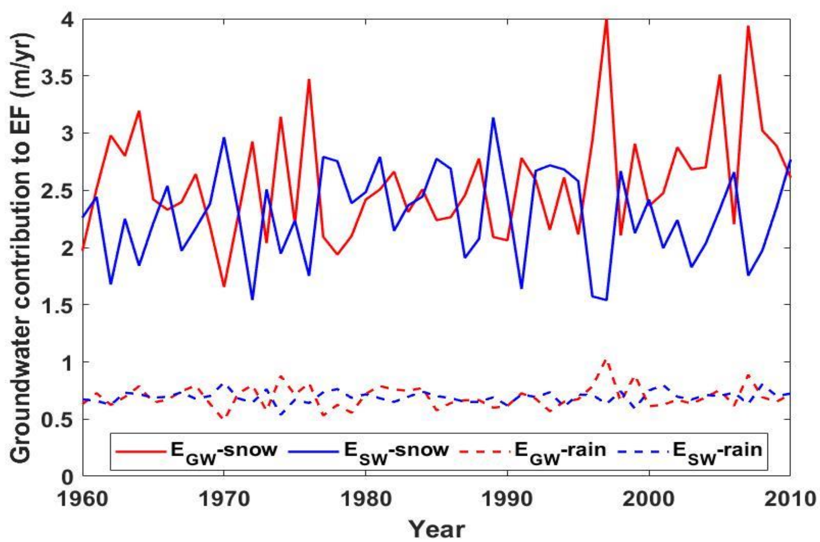

Fig. SI1 Mean annual groundwater contribution to environmental flows in snowfall dominant areas (E_{GW}-snow, E_{SW}-snow) and rainfall dominant areas (E_{GW}-rain, E_{SW}-rain) in British Columbia

S2 Groundwater contribution to environmental flows as percentage of annual precipitation

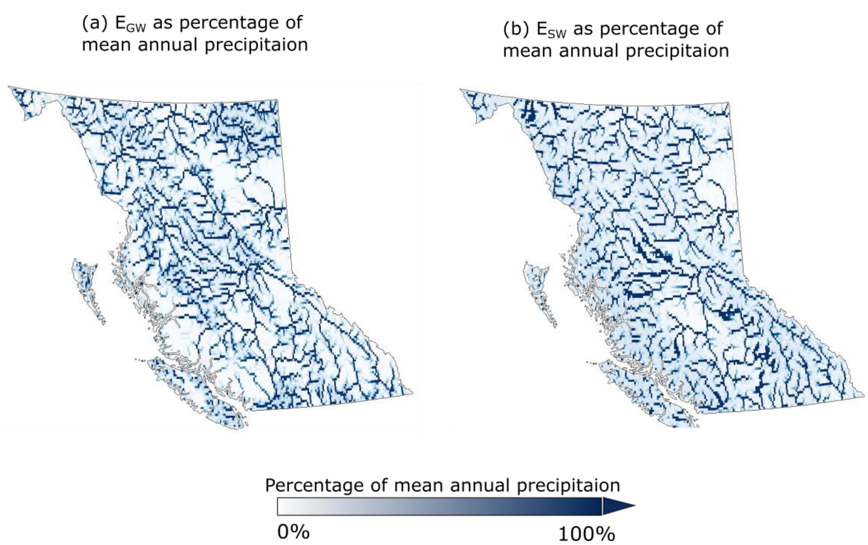

Fig. SI2 Annual groundwater contribution to environmental flow (a) groundwater centric method and (b) surface water centric method as percentage of mean annual precipitation

S3 Groundwater contribution to environmental flows estimates in different biogeoclimatic zones and hydrozones in British Columbia

Table S1. Results for derived values of EF contribution from groundwater in British Columbia using groundwater centric method and surface water centric method.

Groundwater contribution to EF (m/yr)	Mean	Median	Max	Min	Mean	Median	Max	Min
	E_{GW}				E_{SW}			
Full BC	2.27	0.09	232.11	0.00	1.99	0.13	285.62	0.00
Bio-geo climatic zones (BGCZ)								
BG	2.79	0.07	18.11	0.00	1.88	0.08	17.37	0.02
PP	4.79	0.45	39.58	0.00	2.79	1.17	17.96	0.02
ID	1.93	0.14	23.25	0.00	1.54	0.10	17.65	0.00
SBP	0.74	0.10	15.02	0.00	0.41	0.05	11.51	0.00
SBS	1.71	0.12	40.33	0.00	1.31	0.07	19.74	0.00
MS	0.59	0.10	23.57	0.00	0.47	0.06	17.63	0.00
BWBS	1.16	0.08	27.57	0.00	0.78	0.04	18.80	0.00
ICH	1.76	0.20	33.51	0.00	2.08	0.23	18.77	0.01
CD	1.37	0.43	9.54	0.20	0.68	0.33	3.92	0.13
ES	0.51	0.10	28.78	0.00	0.56	0.10	19.32	0.01

CM	0.53	0.15	20.41	0.00	0.82	0.28	14.18	0.02
CWH	0.97	0.38	19.40	0.00	1.17	0.39	15.59	0.01
Hydrozones								
Coastal Mountains	0.94	0.18	30.96	0.00	1.07	0.27	19.32	0.01
N.interior	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N.E.plains	1.15	0.09	40.33	0.00	0.87	0.06	19.74	0.00
Haida Gwaii	0.83	0.07	21.33	0.00	0.43	0.02	11.38	0.00
S.interior	1.05	0.47	13.32	0.32	0.48	0.27	4.64	0.18
S.E.mountains	0.98	0.10	39.58	0.00	0.98	0.09	17.96	0.00
Vancouver island	0.92	0.16	33.51	0.00	1.09	0.18	18.57	0.02

S4 Statistical evaluation of the difference significance between two methods of estimation

Table S2. Kolmogo- Smoirnoff test results to evaluate the statistical significance of the difference between estimates from two methods.

Zones	Kolmogorov-Smirnov test	
	p value	Difference significant
Bio-geo climatic zones (BGCZ)		
BG	0.26	False

PP	0.44	False
ID	0.10	False
SBP	0.00	True
SBS	0.00	True
MS	0.00	True
BWBS	0.00	True
ICH	0.00	True
CD	0.25	False
ES	0.00	True
CM	0.00	False
CWH	0.00	False
Hydrozones		
Coastal Mountains	0.00	True
N.interior	NaN	NaN
N.E.plains	0.00	True
Haida Gwaii	0.00	True
S.interior	0.00	True
S.E.mountains	0.00	True

Vancouver Island	0.00	True

S5 Statistical evaluation of the normality

Normality of the E_{GW} and E_{SW} was tested using 10 different statistical methods. Namely, test1 - Kolmogorov-Smirnov test; test 2-Stephens Method; test 3- Marsaglia Method; test 4-Lilliefors test; test 5- Anderson-Darling (AD) test; test 6-Cramer-Von Mises (CvM) test; test 7-Shapiro-Wilk (SW) test; test 8-Shapiro-Francia (SF) test; test 9-Jarque-Bera (JB) test; test 10-D'Agostino and Pearson (DAP) test. In Table S3 and S4, 1 indicate normal disctibution and 0 indicate not normal distribution

Tabe S3. Normality test results for E_{GW} for different biogeoclimatic zones and hydroones

Results for E_{GW}	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**	**Test 10**
Bio-geo climtaic zones (BGCZ)										
BG	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0
ID	0	0	0	0	0	**1**	0	0	0	0
SBP	0	0	0	0	0	**1**	0	0	0	0
SBS	0	0	0	0	0	**1**	0	0	0	0
MS	0	0	0	0	0	**1**	0	0	0	0
BWBS	0	0	0	0	0	**1**	0	0	0	0

ICH	0	0	0	0	0	**1**	0	0	0	0
CD	0	0	0	0	0	0	0	0	0	0
ES	0	0	0	0	0	**1**	0	0	0	0
CM	0	0	0	0	0	**1**	0	0	0	0
CWH	0	0	0	0	0	**1**	0	0	0	0
Hydrozones										
Coastal Mountains	NaN	0	0	0	0	0	0	0	0	0
N.interior	0	0	0	0	0	0	0	0	0	0
N.E.plains	0	0	0	0	0	**1**	0	0	0	0
Haida Gwaii	0	0	0	0	0	**1**	0	0	0	0
S.interior	0	0	0	0	0	**1**	0	0	0	0
S.E.mountains	0	0	0	0	0	**1**	0	0	0	0
Vancouver island	0	0	0	0	0	**1**	0	0	0	0

Tabe S4. Normality test results for E_{SW} for different biogeoclimatic zones and hydroones

Results for E_{SW}	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**	**Test 10**
Bio-geo climtaic zones (BGCZ)										

BG	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0
ID	0	0	0	0	0	**1**	0	0	0	0
SBP	0	0	0	0	0	**1**	0	0	0	0
SBS	0	0	0	0	0	**1**	0	0	0	0
MS	0	0	0	0	0	**1**	0	0	0	0
BWBS	0	0	0	0	0	**1**	0	0	0	0
ICH	0	0	0	0	0	**1**	0	0	0	0
CD	0	0	0	0	0	0	0	0	0	0
ES	0	0	0	0	0	**1**	0	0	0	0
CM	0	0	0	0	0	**1**	0	0	0	0
CWH	0	0	0	0	0	**1**	0	0	0	0
Hydrozones										
Coastal Mountains	NaN	0	0	0	0	0	0	0	0	0
N.interior	0	0	0	0	0	0	0	0	0	0
N.E.plains	0	0	0	0	0	**1**	0	0	0	0
Haida Gwaii	0	0	0	0	0	**1**	0	0	0	0

S.interior	0	0	0	0	0	**1**	0	0	0	0
S.E.mountains	0	0	0	0	0	**1**	0	0	0	0
Vancouver island	0	0	0	0	0	**1**	0	0	0	0

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