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Key Points:
- First global comparison of methods to calculate the environmentally critical contributions of groundwater to streamflow
- The methods identified similar hotspots of historic violations of environmentally critical groundwater discharge
- The utility of the methods depends on whether an environmental flow assessment is important for all flow seasons or only low-flow periods

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
B. P. P. Marinelli,
bryan.marinelli@wur.nl

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Author Contributions:
Conceptualization: I. E. M. de Graaf
Formal analysis: B. P. P. Marinelli
Funding acquisition: I. E. M. de Graaf
Methodology: B. P. P. Marinelli, I. E. M. de Graaf
Project administration: I. E. M. de Graaf
Software: B. P. P. Marinelli
Supervision: C. Mohan, T. Gleeson, F. Ludwig, I. E. M. de Graaf
Visualization: B. P. P. Marinelli
Writing – original draft: B. P. P. Marinelli
Writing – review & editing: C. Mohan, T. Gleeson, F. Ludwig, I. E. M. de Graaf

Comparing Global Violations of Environmentally Critical Groundwater Discharge Thresholds

B. P. P. Marinelli[1], C. Mohan[2,3,4], T. Gleeson[3,5], F. Ludwig[1,6], and I. E. M. de Graaf[1]

[1]Earth Systems and Global Change Group, Wageningen University & Research, Wageningen, The Netherlands, [2]Waterplan, San Francisco, CA, USA, [3]Department of Civil Engineering, University of Victoria, Victoria, BC, Canada, [4]Global Institute for Water Security, University of Saskatchewan, Saskatoon, SK, Canada, [5]School of Earth and Ocean Science, University of Victoria, Victoria, BC, Canada, [6]International Water Management Institute, Colombo, Sri Lanka

Abstract Groundwater is a crucial resource to support surface water bodies via groundwater discharge. In this study, we applied two methods of estimating global environmentally critical groundwater discharge, defined as the flux of groundwater to streamflow necessary to maintain a healthy environment, from 1960 to 2010: the Presumptive Standard stipulates that a standard proportion of groundwater discharge should be maintained at all timesteps, while the Q^* is a low-flow index that focuses on critical periods. We calculated these critical flow thresholds using simulated natural groundwater discharge, and estimated violations of the thresholds when human-impacted groundwater discharge dropped too low. Our global assessment of the frequency and severity of violations over all timesteps in our study period showed that the Presumptive Standard estimated more frequent and severe violations than the Q^*, but that the spatial patterns were similar for both methods. During low-flow periods, when the relative importance of groundwater to support streamflow is greatest, both methods estimated similar magnitudes of violation frequency and severity. We further compared our results to a method of estimating environmentally critical streamflow, Variable Monthly Flow, which does not explicitly consider groundwater. From the differences in violation frequency between these groundwater-centric and surface water-centric methods, we evaluated the influence of including groundwater contributions to streamflow in environmental flow assessments. Our results show that including groundwater in such assessments is particularly important for regions with high groundwater demands in the drier climates of the world, while it is less important for regions with low groundwater demands and more humid climates.

Plain Language Summary We used two global methods of estimating the necessary flow of groundwater to surface water to protect environmental health. One method (Presumptive Standard) is designed to maintain environmental flows over the whole year, while the other method (Q^*) focuses on low-flow periods when groundwater plays a larger role in supporting surface water. We estimated historic violations of these environmentally critical flow thresholds and found that they estimated similar spatial patterns (although at different magnitudes). We then compared the violations to a method of estimating environmentally critical streamflow (Variable Monthly Flow), which does not directly consider groundwater. Here, we found that considering groundwater contributions to surface water affects the estimated environmental impacts of water use, particularly in river basins that are dry, have high amounts of agriculture, and are densely populated. From this study, we conclude that including groundwater in environmental flow assessments is important in regions with significant groundwater use, and that the choice of method should depend on the period of focus.

1. Introduction

Groundwater serves as a vital source of freshwater for rivers, streams, lakes, and wetlands, and is vital to support human well-being, mainly through irrigation (e.g., Famiglietti, 2014; Konikow & Kendy, 2005; Mohan et al., 2023; Siebert & Döll, 2010; Wada et al., 2012). During times of low precipitation, groundwater flows support aquatic ecosystems by helping to maintain water levels, temperatures, and oxygen concentrations in surface water bodies, as well as to dissolve nutrients and pollutants (de Graaf et al., 2019; Gleeson & Richter, 2018; van Vliet et al., 2023). Current environmental flow management programs, however, tend to focus on sustaining sufficient surface water flow, and often do not explicitly consider groundwater contributions (Pastor et al., 2014). Although the importance of groundwater to healthy environments is known, as are the impacts of human interactions on groundwater availability, current environmental flow analyses do not explicitly account for groundwater contributions to streamflow (e.g., Huggins et al., 2023; Mohan et al., 2023; Pastor et al., 2014;

Scanlon et al., 2023; Virkki et al., 2022). These contributions should, therefore, be directly considered for comprehensive environmental flow assessments (Gleeson & Richter, 2018).

Groundwater discharge, which is the flow of groundwater into rivers or streams, directly supports environmentally critical streamflow, defined here as the quantity of river discharge required to support aquatic ecosystems (which is decided politically at local-scales, but informed scientifically; Arthington et al., 2018). Due to groundwater pumping, however, water tables drop and, consequently, groundwater discharge decreases, thereby reducing the available groundwater to support environmentally critical streamflow (de Graaf et al., 2019; Gleeson & Richter, 2018). Prolonged pumping may then lead to river infiltration, further decreasing the available water to support environmentally critical streamflow (Bierkens & Wada, 2019; de Graaf et al., 2019). In a recent study, it was estimated that 20% of globally abstracted groundwater is pumped at the expense of river discharge (de Graaf et al., 2024). Additionally, one-third of river basins worldwide (where groundwater is pumped) have already reached their limits of environmentally critical streamflow due to excessive groundwater pumping, and, if current practices continue, this share is expected to rise to more than half by 2050 (de Graaf et al., 2019). As human water demands continue to increase, it is crucial to comprehend the current and future impacts of groundwater pumping through assessments of environmentally critical contributions of groundwater to streamflow.

There are, however, few currently existing methods of quantifying this relationship. Gleeson and Richter (2018) developed the concept of environmentally critical groundwater discharge, and de Graaf et al. (2019) tested and evaluated an environmentally critical groundwater discharge limit using simulated estimates of groundwater discharge. Furthermore, groundwater components have only been explicitly considered in estimates of environmentally critical streamflow at the regional-scale (Mohan et al., 2023), but not in any currently available global methods (Pastor et al., 2014). The clear difference between the inclusion or exclusion of groundwater contributions in estimates of environmentally critical streamflow illustrates the uncertainty and knowledge gap concerning environmentally critical groundwater discharge.

Quantifying the contribution of groundwater to environmentally critical streamflow has multiple possible applications, including advanced assessments of current and future aquifer stress and water allocation, and could enable a shift towards more sustainable groundwater management. The aim of this study, therefore, was to evaluate the contribution of groundwater to environmentally critical streamflow by comparing three methods of estimating environmentally critical flow (one surface water-centric and two groundwater-centric). The overall objective of the comparison was to identify similarities and differences in the levels of environmentally critical flow violations between estimates, and, thus, to identify where and when it is crucial to explicitly consider groundwater in assessments of environmentally critical streamflow.

2. Methods and Data

2.1. Simulating Environmentally Critical Flow

In this study, we estimated environmentally critical flow following two approaches: surface water-centric (environmentally critical streamflow) and groundwater-centric (environmentally critical groundwater discharge). We adapted and compared results of one surface water-centric method, using simulated streamflow, and two groundwater-centric methods, using simulated groundwater discharge (i.e., the contribution of groundwater to streamflow). Details are provided in Sections 2.1.1 and 2.1.2.

We used simulated streamflow and groundwater discharge data from a physically based global-scale groundwater and surface water model (de Graaf et al., 2017, 2019). The model consists of the global hydrological model PCR-GLOBWB 2.0 (Sutanudjaja et al., 2018), which is dynamically coupled via groundwater recharge/capillary rise and groundwater discharge/river infiltration to a two-layer groundwater flow model based on MODFLOW (de Graaf et al., 2019). In the groundwater flow model, groundwater heads, dynamics, and interactions are simulated for both confined and unconfined aquifers. We used model results at 5-arcminute spatial resolution (∼10 km at the equator) and monthly timesteps. In addition to groundwater and surface water storage, the model simulates dynamics between groundwater, surface water, soil, and the atmosphere. A dynamic water demand and water use module is included which allocates sectoral water demands (domestic, industrial, irrigation, livestock) to available water resources and takes return flows of unused (withdrawn) water into account (de Graaf et al., 2014; Sutanudjaja et al., 2018). The model has been tested, evaluated, and validated in several previous studies (de

Table 1
Overview of Updated Variable Monthly Flow Classifications and Calculations

Hydrological season	Determination of hydrological season	Environmentally critical streamflow
Low-flow season	$MF \leq 0.4 * AAF$	$LFR = 0.6 * MF$
Intermediate-flow season	$0.4 * AAF < MF \leq 0.8 * AAF$	$IFR = 0.45 * MF$
High-flow season	$MF > 0.8 * AAF$	$HFR = 0.3 * MF$

Note. MF represents the monthly flow, AAF the mean annual flow, and LFR, IFR, and HFR the low-flow, intermediate-flow, and high-flow requirements, respectively. These calculations were carried out for each modeled timestep and gridcell. This table is derived from Pastor et al. (2014).

Graaf et al., 2014, 2015, 2017, 2019; Sutanudjaja et al., 2018; Wada et al., 2010, 2014, 2016), and currently provides the only global-scale model results including groundwater dynamics and interactions with surface water affected by human impacts.

For this study, we used outputs from two model runs, a natural run and a human-impacted run, from 1960 to 2010 (de Graaf et al., 2019). We used estimates of streamflow and groundwater discharge from the natural run to formulate environmentally critical flow thresholds of each (Sections 2.1.1 and 2.1.2), and then compared these thresholds to the model results of the human-impacted run to assess the impacts of groundwater pumping (Sections 2.2-2.4). The methods applied in this study are global estimates of environmentally critical flow derived from simulated output from a global model and are not based on local environmental flow assessments.

2.1.1. Surface Water-Centric Approach

As environmentally critical streamflow is often assessed at the river basin-scale, Pastor et al. (2014) developed the Variable Monthly Flow method (VMF) to be globally applicable. The VMF method is defined as a global-scale parametric method to estimate environmentally critical streamflow. This method follows the natural variability of river discharge by defining environmentally critical streamflow at a monthly basis, adjusted to the flow season (Pastor et al., 2014). The flow seasons and environmentally critical streamflow thresholds that are defined are: low-flows, when 60% of the mean monthly flow (MMF) is reserved; intermediate-flows, 40% of the MMF is reserved; and high-flows, 30% of the MMF is reserved.

For the purposes of our study, we have adapted the application of VMF. Rather than calculating the hydrological seasons and environmentally critical streamflow using long-term averages, we used monthly flow (MF) and average annual flow (AAF), and updated the classifications accordingly (Table 1, Figure 1a). In this manner, we determined hydrological seasons based on the values in each specific year, and environmentally critical streamflow was based on the monthly streamflow. This avoided any situations where the natural streamflow was inherently less than the environmentally critical streamflow, thereby eliminating the possibility of naturally occurring violations.

2.1.2. Groundwater-Centric Approaches

The first groundwater-centric method we evaluated was the Presumptive Standard (PS; Gleeson & Richter, 2018). The PS assumes that high levels of ecological protection will be provided if the natural groundwater discharge does not deviate (increase or decrease) by more than 10% for any given moment in time (Gleeson & Richter, 2018). Based on the simplicity, applicability, and level of protection provided by presumptive standards in hydrology (both for surface water and groundwater), a specific strength of the PS method is that it can be used globally, including in regions where detailed, local estimates of environmentally critical groundwater discharge are not available (Gleeson & Richter, 2018; Richter et al., 2012).

In our study, we focused on using the PS method only for groundwater contributions dropping below the environmentally critical groundwater discharge, rather than deviations both above and below the natural flows (Figure 1c). Effectively, this meant that the PS threshold was 90% of the natural simulated groundwater discharge. Furthermore, in the case of negative simulated natural groundwater discharge values (river infiltration), the PS was set as the simulated natural groundwater discharge value itself (Equation 1). This was done so that no human

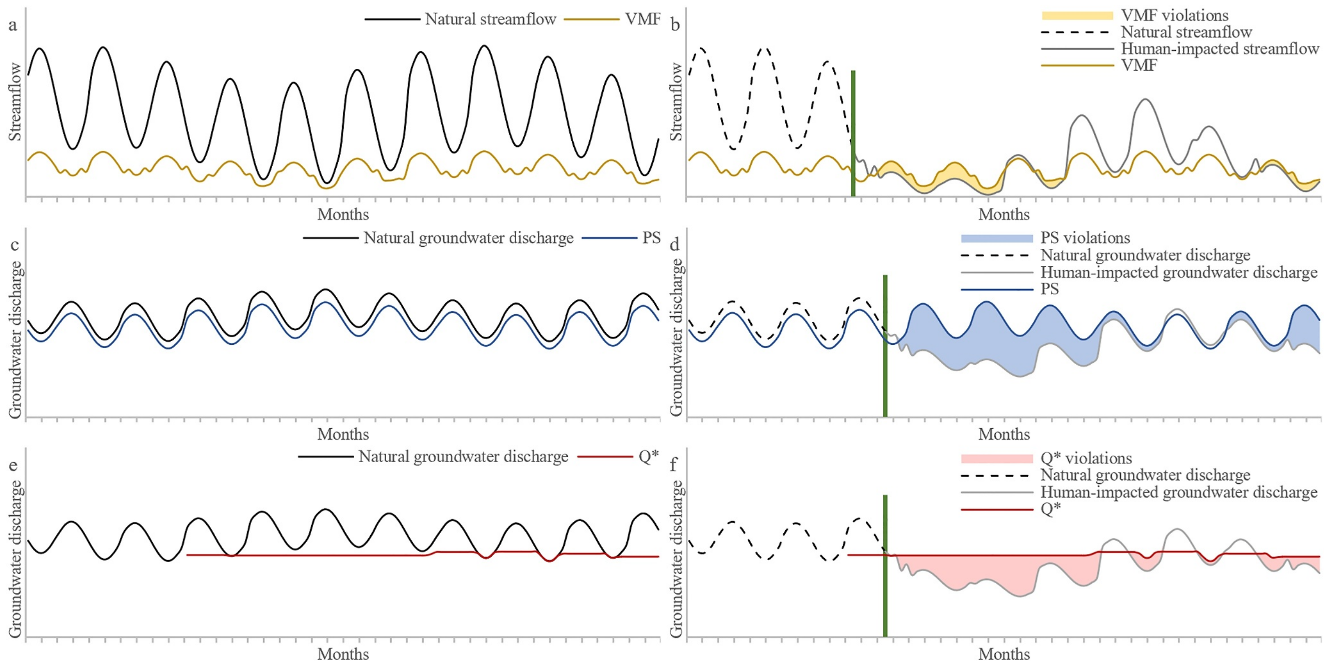

Figure 1. Schematic representations of the different methods used to estimate environmentally critical flow that were evaluated in this study. Presented are the VMF threshold as calculated from the natural streamflow (a) and the PS and Q^* thresholds as calculated from the natural groundwater discharge (c, e). Additionally, violations of these environmentally critical flow thresholds are shown when pumping starts (green) and causes the human-impacted streamflow to drop below the VMF threshold (b) or when pumping causes the human-impacted groundwater discharge to drop below the PS and Q^* thresholds (d, f).

intervention would be necessary to ensure environmentally critical groundwater discharge was maintained (i.e., inducing more river infiltration).

$$\mathrm{PS}(t,x) = \begin{cases} 0.9 * Q_{\mathrm{GW,natural}}(t,x) \; if \; Q_{\mathrm{GW,natural}}(t,x) > 0 \\ Q_{\mathrm{GW,natural}}(t,x) \; if \; Q_{\mathrm{GW,natural}}(t,x) \leq 0 \end{cases} \tag{1}$$

Calculation of the Presumptive Standard, PS, per each timestep, t, and location (gridcell), x, where $Q_{\mathrm{GW,natural}}$ refers to the natural groundwater discharge.

The second groundwater-centric method we evaluated was the Environmental Limit method, designed by de Graaf et al. (2019), to estimate where and when environmentally critical streamflow was reached for the first time due to groundwater pumping. Using a threshold of natural monthly low-flows estimated from a 5-year running average, this method sets the required contribution of groundwater discharge to streamflow to maintain healthy ecosystems (de Graaf et al., 2019). The natural monthly river discharge is above this threshold during 90% of months. This is the first, and so far, only, method of quantifying environmentally critical groundwater discharge globally.

In this study, we adapted the Environmental Limit method for low-flow periods. As the threshold of the original method is set as the 90th percent exceedance (10th percentile) of the natural monthly discharge, the estimated environmentally critical groundwater discharge (i.e., the low-flow threshold) lies above the natural monthly low-flow during 10% of months. For these months, we adjusted the threshold to be the natural flow itself (Q^*; Figure 1e). This means, for those 10% of months, the natural situation is not inherently violated, but as these low-flow months represent periods when the environment is naturally in a vulnerable state, any decreases in groundwater discharge below the natural flow are assumed to cause environmental harm. Lastly, we took the same assumption (as we did when calculating the PS threshold) regarding negative simulated natural groundwater discharge–the Q^* threshold was set as the negative value itself during these instances (Equation 2).

$$Q^{*}(t,x) = \begin{cases} \min\begin{cases} Q_{90}(t,x) = \dfrac{P_{90}(t,x) - N_{60}(t,x)}{100} \\ Q_{\mathrm{GW,natural}}(t,x) \end{cases} & \mathit{if}\ Q_{\mathrm{GW,natural}}(t,x) > 0 \\ Q_{\mathrm{GW,natural}}(t,x)\ \mathit{if}\ Q_{\mathrm{GW,natural}}(t,x) \leq 0 \end{cases} \quad (2)$$

Calculation of the Q^*, per timestep and location where Q_{90} represents the low-flow threshold, P_{90} represents the 90th percent exceedance (10th percentile) of natural groundwater discharge, and N_{60} represents the 60-month moving window (from t-60 to t-1, inclusive) over which the running percentile is calculated.

2.2. Evaluating Violations of Environmentally Critical Flow

We assessed the impacts of human water use by comparing the estimated environmentally critical flow thresholds of the three methods with the human-impacted flows (Figures 1b, 1d, and 1f). We calculated violations at each gridcell and for each (monthly) timestep over the model period (1960–2010). We noted whether violations occurred (Equation 3), and the corresponding magnitudes of those violations. For the groundwater-centric methods, we focused our calculations on locations with significant groundwater pumping (greater than 0.01 m/y), to isolate the impacts of groundwater pumping specifically.

$$v(t,x) = \begin{cases} 1\ \mathit{if}\ Q_{\mathrm{human}}(t,x) < \mathrm{EFR}(t,x) \\ 0\ \mathit{if}\ Q_{\mathrm{human}}(t,x) \geq \mathrm{EFR}(t,x) \end{cases} \quad (3)$$

Calculation of environmentally critical flow violations, v, per timestep and location where a value of one indicates a violation occurred and a value of 0 indicates no violation occurred. Q_{human} refers to the human-impacted streamflow (for VMF) or human-impacted groundwater discharge (for PS and Q^*) and EFR refers to a specific environmentally critical flow threshold used (either VMF, PS, or Q^*).

We initially analyzed violations of environmentally critical flow from two perspectives: frequency and severity (Virkki et al., 2022). Here, violation frequency refers to the proportion of violated months from the modeling period (Equation 4) and violation severity refers to the magnitude of the violations (how far the human-impacted flows dropped below the environmentally critical flow; Equation 5).

$$v_{\mathrm{frequency}}(x) = \frac{\sum_{t=1}^{n_{\mathrm{timesteps}}} v(t,x)}{n_{\mathrm{timesteps}}} \quad (4)$$

Calculation of violation frequency, $v_{\mathrm{frequency}}$, per location where $n_{\mathrm{timesteps}}$ refers to the total number of timesteps over our study period. Missing values were ignored in these calculations.

$$v_{\mathrm{severity}}(x) = \begin{cases} \dfrac{\sum_{t=1}^{n_{\mathrm{timesteps}}} \begin{cases} \mathrm{EFR}(t,x) - Q_{\mathrm{human}}(t,x)\ \mathit{if}\ Q_{\mathrm{human}}(t,x) < \mathrm{EFR}(t,x) \\ 0\ \mathit{if}\ Q_{\mathrm{human}}(t,x) \geq \mathrm{EFR}(t,x) \end{cases}}{\sum_{t=1}^{n_{\mathit{timesteps}}} v(t,x)} & \text{if } \sum_{t=1}^{n_{\mathrm{timesteps}}} v(t,x) > 0 \\ 0 \text{ if } \sum_{t=1}^{n_{\mathrm{timesteps}}} v(t,x) = 0 \end{cases} \quad (5)$$

Calculation of violation severity, v_{severity}, per location. Missing values were ignored in these calculations.

The gridded PS and Q^* violation frequency and severity, as well as the VMF violation frequency, were averaged over sub-basins (HydroSHEDS level 6 customized with lakes; Lehner & Grill, 2013). Since the modeled streamflow data was routed, however, the gridded VMF violation severities were taken at the outlet of each sub-basin. These values represented the accumulated result per sub-basin. As we did not directly compare the values

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of VMF violation severities with those of either the PS or Q^* violation severities, this difference in methodology did not impact our analysis.

First, we compared the basin-scale results of estimated violation frequency and severity from the two groundwater-centric methods. This comparison served to assess the impact of using a more conservative approach (PS) or a less conservative approach (Q^*), focusing on regions at high-risk for violations of environmentally critical groundwater discharge. Second, we compared the PS and Q^* violation schemes to the VMF violation schemes. These comparisons showed where violations of environmentally critical flow were accruing and evaluated the impact of including groundwater contributions in assessments of environmentally critical streamflow.

2.3. Low-Flow Conditions

The contribution of groundwater to streamflow is relatively largest and most relevant during low-flow conditions to meet environmental and anthropogenic water demands (de Graaf et al., 2019). Additionally, as groundwater discharge fluctuations have lesser magnitude than streamflow fluctuations over the year, groundwater discharge often dominates streamflow composition during low-flow periods (Gleeson & Richter, 2018). Therefore, we specifically focused our analysis on these low-flow periods. Groundwater low-flows were defined as groundwater discharges below the low-flow threshold calculated in the Q^* method (Equation 6).

$$\mathrm{LF}_{\mathrm{GW}}(t,x) = \begin{cases} 1 \; if \; Q_{\mathrm{GW,natural}}(t,x) \leq Q_{90}(t,x) \\ 0 \; if \; Q_{\mathrm{GW,natural}}(t,x) > Q_{90}(t,x) \end{cases} \tag{6}$$

Calculation of groundwater low-flow periods, $\mathrm{LF}_{\mathrm{GW}}$, per timestep and location. A value of one indicates there is a low-flow period, while a value of 0 indicates there is not a low-flow period.

Here, we followed a similar methodology to our analyses over the full study period. We compared the PS and Q^* violation schemes during low-flows to gain insight into how the similarities and differences between approaches varied during these periods. Furthermore, we compared the PS and Q^* violation frequencies with those of the VMF to better understand the influence of including low-flow groundwater contributions in estimates of environmentally critical streamflow.

2.4. Violation Timing in Selected Basins

All the analyses described above were performed globally and at the sub-basin level. To obtain better insights into regional dynamics of violations, and to enable a regional comparison of the globally applicable methods used in our study, we highlighted four specific basins based on high levels of irrigated agriculture, groundwater use, and environmental flow violations (Aeschbach-Hertig & Gleeson, 2012; Rodell et al., 2009, 2018). Within these basins, delineated using HydroSHEDS (levels 3 and 4 customized with lakes), we analyzed the timing of violations at gridcell resolution (Lehner & Grill, 2013). Here, violation timing refers to the proportion of violated gridcells per basin (Equation 7). Furthermore, instead of using temporally averaged violations, we used the monthly results to specifically obtain more insight into how violations have progressed over time in each of these vulnerable regions.

$$v_{\mathrm{timing}}(t,y) = \frac{\sum_{x=1}^{n_x} v(t,x)}{n_x} \tag{7}$$

Calculation of violation timing, v_{timing}, per timestep and each river basin, y, where x refers to the specific locations (gridcells) within each basin and n_x refers to the total number of gridcells within each basin. Weighted means, based on the area of each gridcell, were used in the case of basin extents intersecting with gridcells. Missing values were ignored in these calculations.

We calculated the timing of violations over all the months in our study period, as well as the multi-year trends for each month, to assess long-term inter-annual and intra-annual trends of overexploitation of water resources. Furthermore, we compared these trends between methodologies to better understand the temporal fluctuations in violations.

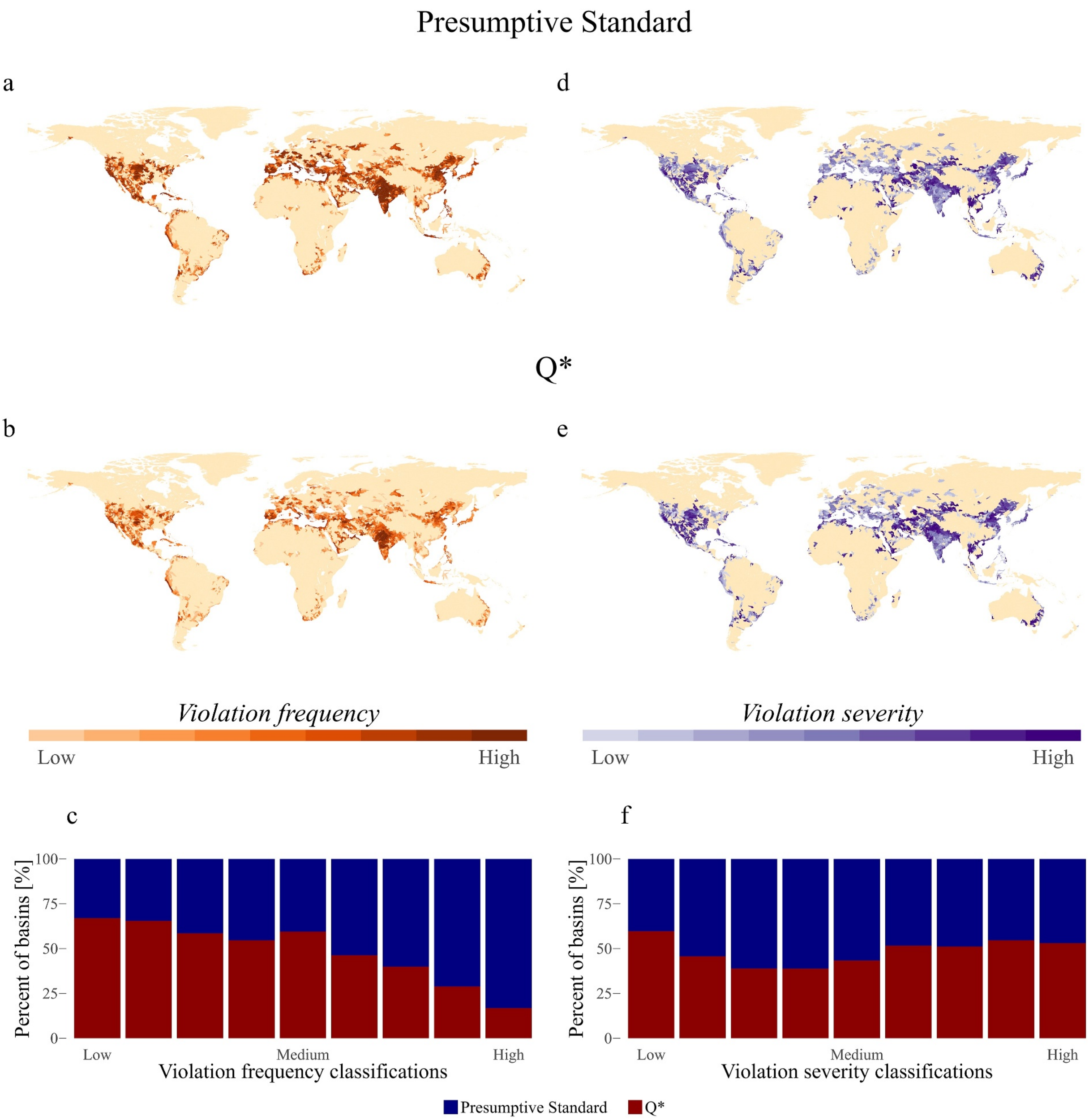

Figure 2. Estimated violations of environmentally critical groundwater discharge. Estimated violation frequency and severity for the PS (a, d) and Q^* (b, e), averaged per sub-basin. All basins with groundwater pumping less than 0.01 m/y are colored beige. The global distribution of violation frequency and severity classifications between the PS and Q^* schemes are presented as stacked barplots (c, f).

3. Results

3.1. Comparison of Estimated Environmentally Critical Flow Thresholds

Globally, all three methods estimated that violations of environmentally critical flow were most frequent in drier climates and densely populated regions (e.g., south Asia, Middle East, north Africa, southern Europe, central and western North America; darker orange in Figures 2a, 2b and 3a). Note that an equal number of basins are represented in each classification between low and high for both the violation frequency and severity in Figures 2 and 3. Violations were clearly estimated to be more widespread, more frequent, and more severe using the surface water centric-approach compared to the groundwater-centric approaches. The violation frequencies ranged from

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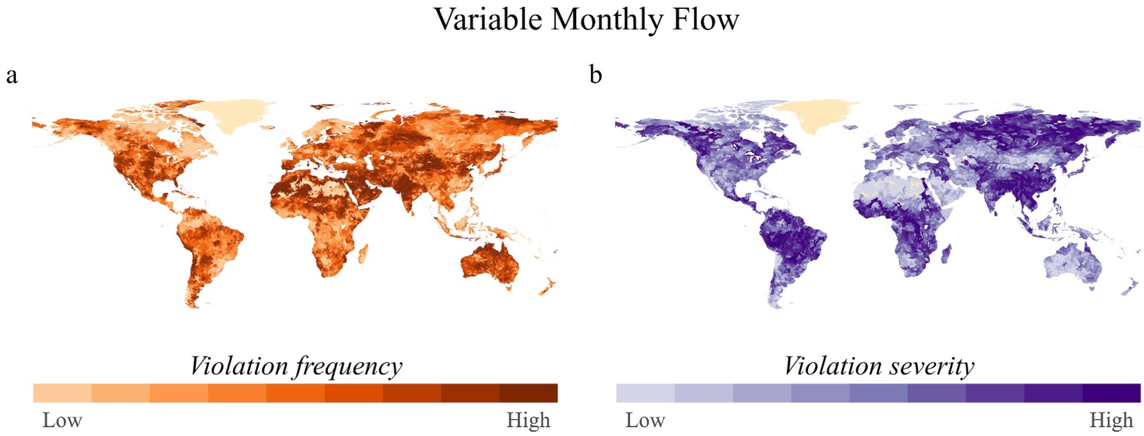

Figure 3. Estimated violation frequency (a) and severity (b) of environmentally critical streamflow using the modified VMF method, averaged per sub-basin. Beige basins had no violations.

1.6e−13% to 81%, with a median of 0.78%, for the groundwater-centric approaches, and from 7.9e−6% to 99.6%, with a median of 3.1%, for the surface water-centric approach.

With the two groundwater-centric methods, estimated violations were most severe in the drier climates of the world (Figures 2d and 2e). For the surface water-centric method, estimated violations were most severe in major river networks, such as the Amazon, Ganges, or Congo (Figure 3b). The violation severity ranged from 2.5e−8 to 0.4 m/y, with a median of 6.7e−3 m/y, for the groundwater-centric approaches and, from 9.5e−9 to 7,422 m^3/s, with a median of 18.5 m^3/s, for the surface water-centric approach.

Overall, the spatial results of the two groundwater-centric methods look generally similar. When comparing estimated magnitudes of violation frequencies (and, to a lesser extent, severities), however, the differences are clearer. Notably, PS violations were estimated to occur more often than Q^* violations (Figure 2c), and with slightly greater severity (Figure 2f). Despite the differences in magnitude, however, the two groundwater-centric methods do highlight the same basins with the most frequent and severe violations, often in regions with major agricultural production (e.g., Indus basin, North China Plain, High Plains, Central Valley).

3.2. Focus on Periods of Groundwater Low-Flows

We specifically focused on low-flow periods when groundwater contributions to streamflow are relatively the largest. During such periods, the PS and Q^* methods estimated very similar violation frequency and severity (Figure 4). Note that Figure 4 shows combined classes of frequency and severity, and that an equal number of basins appear in each of the low, medium, and high classifications (although all nine categories are not necessarily equally represented). Similar to the results covering the full period, the PS and Q^* highlighted the same regions as having the most frequent and severe violations. The differences are even smaller when focusing on low-flows, as indicated by the minor variations in estimated violation frequencies and severities (Figure 4c). Q^* violations were more frequent in all cases, however, as well as slightly more severe for any given timestep. The violation frequencies ranged from 3.1e−11% to 68.3%, with a median of 1.7%, and the violation severities ranged from 2.5e−8 to 0.39 m/y, with a median of 7.2e−3 m/y.

Furthermore, the same relationship between methods was found when comparing estimated PS and Q^* violation frequencies to the results using the VMF method during these low-flow periods. Although violations of environmentally critical streamflow were more predominant globally, including groundwater contributions using either groundwater-centric method produced similar results (Figure 5): 81.4% of basins had more frequent VMF low-flow violations than PS low-flow violations; 80.5% of basins had more frequent VMF low-flow violations than Q^* low-flow violations. Interestingly, regions where VMF violations were more frequent included the Indus River basin and North China Plain, two regions with very high levels of groundwater discharge violation frequency during low-flows. Exceptions were western and central Europe, central India, and western North America (Figures 5a and 5c). Additionally, the median difference between groundwater discharge and streamflow violation frequency over all global basins was 3.9% (Figures 5b and 5d).

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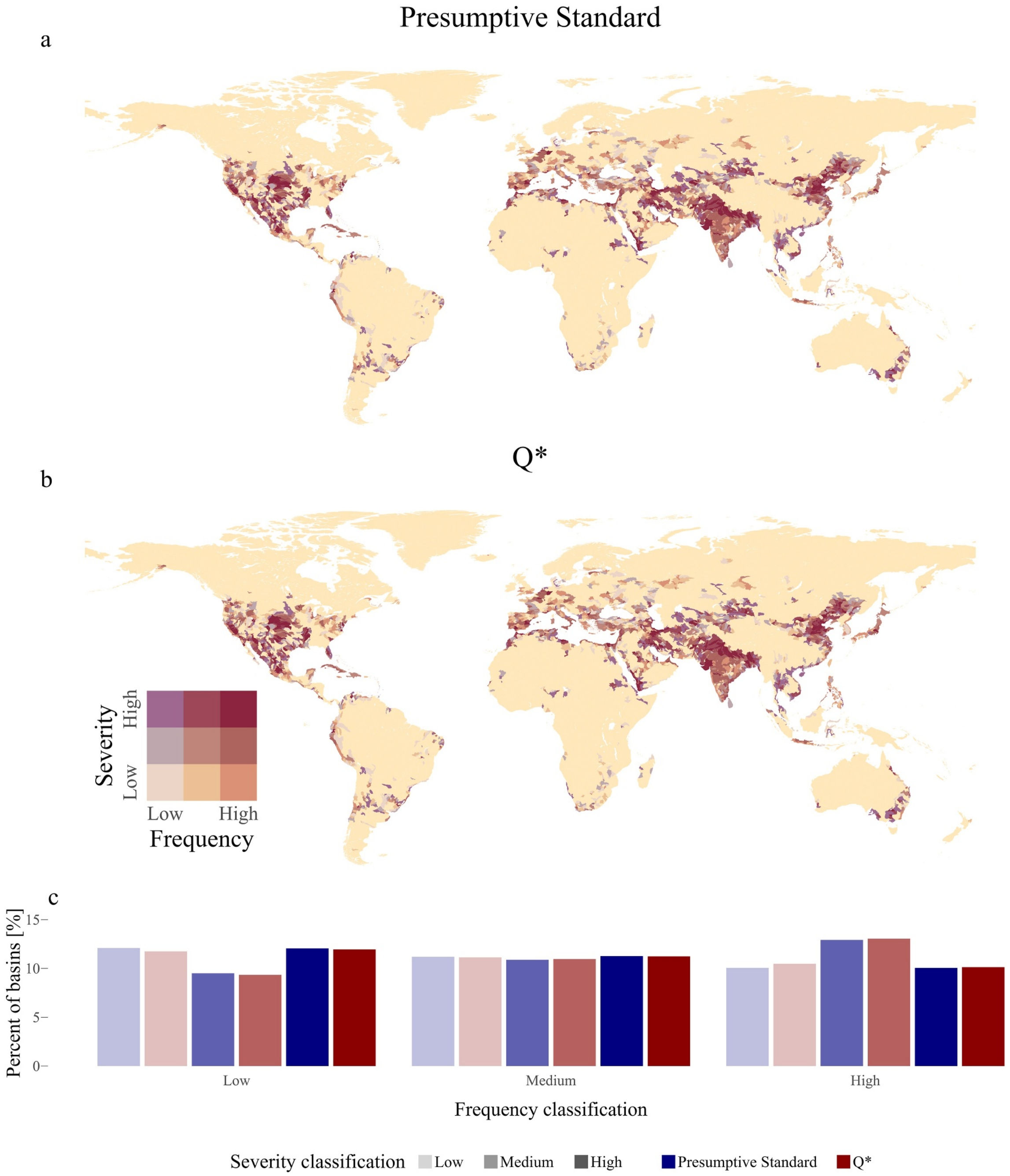

Figure 4. Estimated violations of environmentally critical groundwater discharge during low-flow periods. PS (a) and Q^* (b) violation frequencies and severities are compared per sub-basin, including the distribution of frequency and severity classes for each method (c).

3.3. Focus on Select Basins

To better understand the regional influence of including groundwater discharge in estimates of environmentally critical streamflow, we selected four regions to focus on, namely the Indus, Yellow, Rhine, and Arkansas River basins (Figure 6). In each of these basins, Q^* violations were the least frequent over the entire study period. Q^* violations also stayed relatively constant, compared to the PS and VMF violations (with the exception of Q^* violations in the Yellow River basin, which did steadily increase in small increments). In the Indus and Yellow River basins, VMF violations occurred most often, but in the Rhine and Arkansas River basins, PS violations occurred most often.

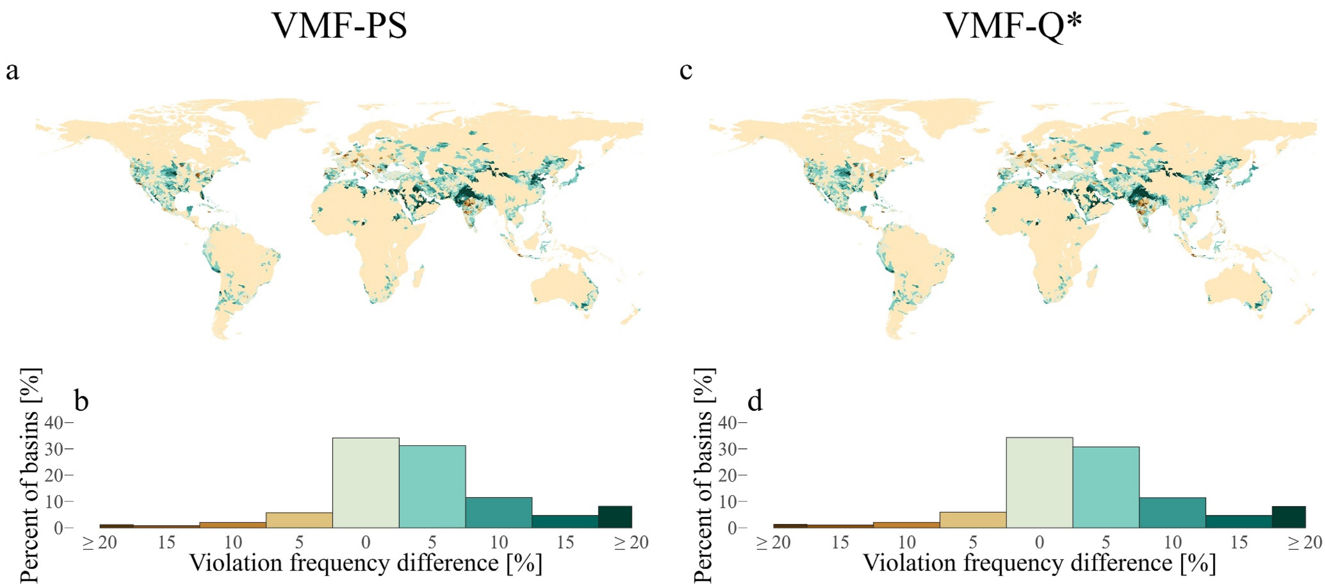

Figure 5. Comparison of estimated environmentally critical flow violations due to the inclusion or exclusion of groundwater contributions during low-flow periods. The differences between VMF and PS violation frequencies (a) and VMF and Q^* violation frequencies (c) per sub-basin, including histograms (b, d). Browner basins had more frequent violations when including groundwater discharge contributions, greener basins had more frequent violations when excluding groundwater discharge contributions, and beige basins had groundwater pumping less than 0.01 m/y.

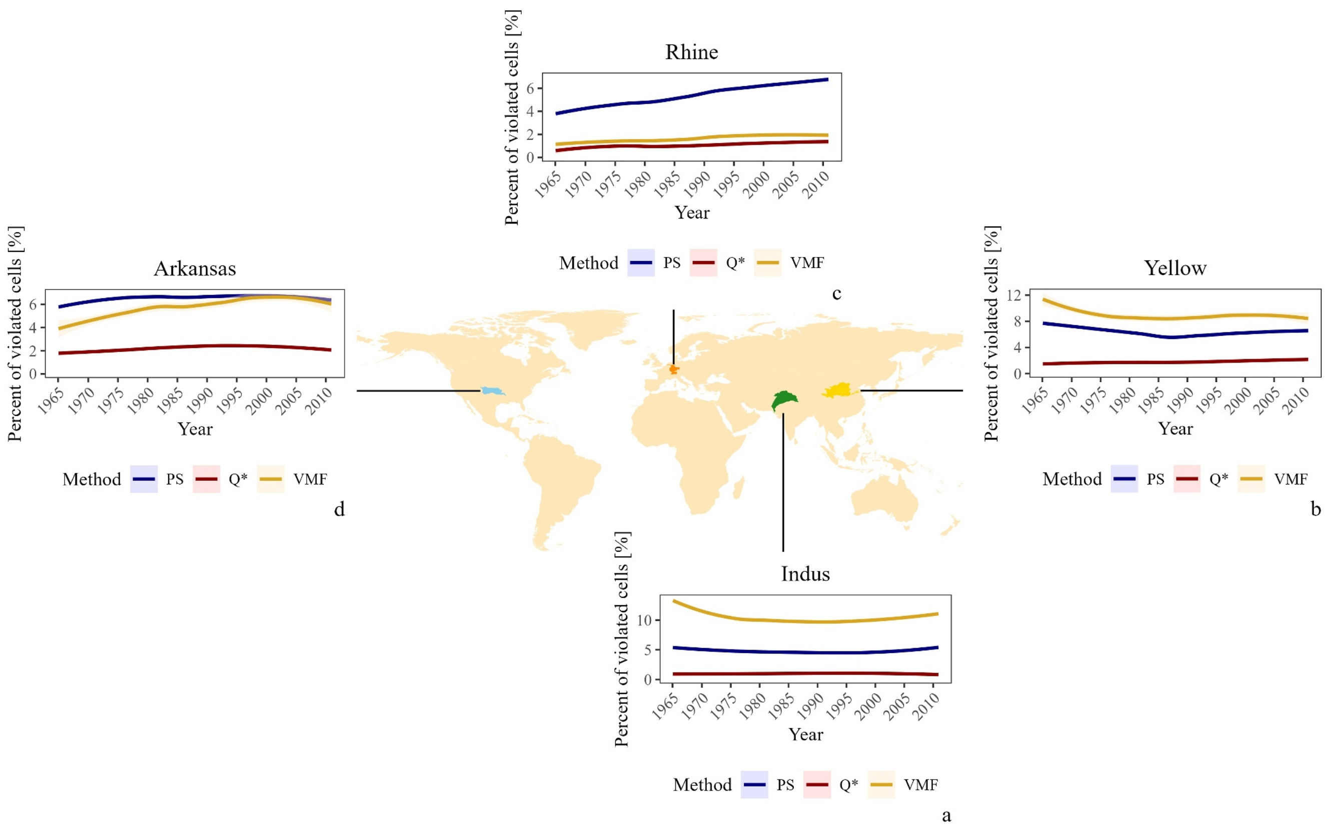

Figure 6. Violation timing trends of the selected basins used in this study. Green: Indus River basin (a); gold: Yellow River basin (b); orange: Rhine River basin (c); blue: Arkansas River basin (d). The 95% confidence intervals are included for each of the trendlines.

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In the Indus River basin, PS violations stayed relatively constant, although there was a dip during the middle of the study period (Figure 6a). Despite the increase in groundwater abstractions during this time frame, neither the Q^* nor PS method estimated a notable increase in violations (Figure S3a in Supporting Information S1). Lastly, there were minimal intra-annual differences in the timing of environmentally critical groundwater discharge violations (Figure S2a in Supporting Information S1). VMF violations, on the other hand, initially decreased sharply, but then increased toward the end of the study period (Figure 6a). As with the Q^* and PS, the VMF violations also stayed relatively constant within each year (Figure S2a in Supporting Information S1).

In the Yellow River basin, PS violations slightly decreased during the first half of the study period, then slightly increased during the second half (Figure 6b). Notably, this trend differs from the groundwater abstractions over time in the Yellow River basin (which increased at the start of the study period, and decreased toward the end; Figure S3b in Supporting Information S1), signaling a different driving force was influencing the violations. Q^* violations, on the other hand, steadily increased along with the groundwater abstractions. VMF violations, on the whole, decreased over the study period (Figure 6b). Intra-annually, there were seasonal spikes in violations for each of these methods (Figure S2b in Supporting Information S1). Q^* violations spiked in June and July, while PS violations peaked in the winter months. The increases in Q^* violations coincide with decreases in violations of environmentally critical streamflow. VMF violations decreased during these summer months, although the end of the study period signaled a sharp increase in VMF violations in July.

In the Rhine River basin, while the VMF violations increased over time, they occurred at a similar frequency as Q^* violations (Figure 6c). PS violations, on the other hand, increased steadily over time, and occurred far more often. The increase in PS violations appears to have been driven by sharp increases in groundwater abstractions in the basin (Figure S3c in Supporting Information S1). Intra-annually, there is a slight inverse correlation between the occurrences of Q^* and VMF violations, with Q^* violations being more frequent in the summer and VMF violations being more frequent in the winter (Figure S2c in Supporting Information S1). PS violations always occurred most frequently and did not experience much seasonality.

In the Arkansas River basin, both PS and VMF violations initially increased, and then ultimately decreased toward the end of the study period (Figure 6d). PS violations generally occurred more often than VMF violations, although toward the end of the study period the difference was much smaller (and even flipped, briefly). While the initial increase in PS violations corresponds with increases in groundwater abstractions, the change in the trend is likely attributed to the stagnation of these groundwater abstractions toward the latter half of the study period (Figure S3d in Supporting Information S1). Within each year, violations of environmentally critical groundwater discharge remained relatively stable, but violations of environmentally critical streamflow were much more seasonal: VMF violations decreased greatly during the summer months (Figure S2d in Supporting Information S1).

4. Discussion

4.1. Patterns of Estimated Violation Frequency and Severity

We compared two approaches of estimating environmentally critical flow: surface water-centric (streamflow) and groundwater-centric (groundwater discharge). Globally, the similarities and differences in the spatial distribution of estimated violation frequency and severity between the surface water-centric and groundwater-centric approaches were evident (Figures 2 and 3). Violation frequencies from both approaches were greatest in drier regions, as were violation severities from the groundwater-centric approach, but violation severities from the surface water-centric approach were greatest in major river basins. These differences can be explained by the two groundwater-centric methods focusing on basins with groundwater pumping, while the surface water-centric method includes impacts routed along the drainage network. Furthermore, the surface water-centric approach estimated higher violation frequencies because surface water stores are often used before groundwater stores and are quicker to respond to changes in both groundwater and surface water abstractions.

For the groundwater-centric approach, the differences between the two methods we applied (PS, Q^*) were less pronounced. Both methods highlighted similar basins with frequent and severe violations, often in regions with drier climates, major agricultural production, and high population density. The Indus Basin, North China Plain, High Plains, and Central Valley experienced such trends due to high groundwater demands causing abstraction rates to exceed groundwater recharge (Figure 2). Despite the similarities in spatial violation distribution, PS violations were more frequent and severe than Q^* violations. This was an expected outcome, as the PS threshold is generally higher, and, therefore, more restrictive, than the Q^* threshold. Due to such differences in the thresholds, the PS tended to require smaller amounts of groundwater abstractions for violations to occur. Then, when violations did occur, they would usually drop farther below the PS threshold than the Q^* threshold.

VMF violations were most frequent in drier climates (Figure 3a). This is due to the relatively higher levels of surface water use in these regions with limited access to groundwater stores. Furthermore, there is less replenishment of the natural system to offset the removal of water for human needs. VMF violations were most severe near major river networks (e.g., Amazon, Ganges, Congo) due to larger possible fluctuations in streamflow and the necessary decreases to cause violations to occur (Figure 3b). Large rivers where groundwater use is high also stood out with severe VMF violations (e.g., Nile, Indus).

Similar differences between the surface water-centric and groundwater-centric approaches were evident during low-flow periods, when groundwater contributions to streamflow are generally largest (Figures 4 and 5). The VMF method estimated the largest violation frequencies, including in basins with high PS and Q^* violation frequencies (e.g., Indus, Yellow River basins; explained by the dry climate and high groundwater demands in these regions). This overlap in regions with high frequencies of VMF, PS, and Q^* violations during low-flow periods emphasizes the connection between the groundwater and surface water systems, and that the two cannot be separately managed. During low-flows, Q^* violation frequencies and severities had slightly higher magnitudes than those of PS violations. This is explained by the methodological differences between the two, where the Q^* threshold is more conservative than the PS threshold during low-flow periods. The differences are small, however, and akin to the results considering the full model period, in that they highlight similar regions with high vulnerability to groundwater pumping.

Including groundwater contributions to streamflow in environmental flow assessments can have notable impacts on the estimated violations of environmentally critical flow thresholds. In several regions globally, violations of environmentally critical groundwater discharge were far more frequent than violations of environmentally critical streamflow, emphasizing that it is crucial to consider the groundwater system in these areas to protect the environment (e.g., central India, southern Italy, parts of northern Europe; brown basins in Figure 5). In these locations, the differences between the surface water-centric and groundwater-centric approaches, as well as their impacts on estimating violations of environmentally critical flow, are clear. Additionally, there are basins where the estimated violations of environmentally critical streamflow were far more frequent than those of groundwater discharge (e.g., Indus River basin, North China Plain, High Plains; green basins in Figure 5). Here, the differences between the surface water-centric and groundwater-centric approaches are again very noticeable, but the inclusion of groundwater contributions to streamflow reduces the estimated frequency of violations. This further emphasizes the importance of including groundwater in environmental flow assessments, as it provides a store of useable freshwater to meet high demands.

Alternatively, there are several regions where the inclusion of groundwater contributions to streamflow do not play a major role in estimating violations of environmentally critical flow (e.g., Turkey, Greece, western France; neutral basins in Figure 5). In these locations, the frequency of estimating violations of environmentally critical streamflow and groundwater discharge were very similar. This implies that the surface water-centric and groundwater-centric approaches function very similarly in these areas. Furthermore, there are several basins that were masked out due to insignificant groundwater abstractions (less than 0.01 m/y), but were included in the analysis of VMF violations (beige basins in Figure 5). These are basins where groundwater does not play a major role in meeting freshwater demands, and, thus, are regions where it is not vital to include groundwater contributions to streamflow in environmental flow assessments.

Our analysis of the timing of violations in select river basins shows the effects of including groundwater components in estimates of environmentally critical flow over the study period. Notably, there are differences in the prevalence of environmentally critical flow violations based on the inclusion or exclusion of groundwater contributions to streamflow. In the Rhine and Arkansas River basins, for instance, violations of environmentally critical flow were more frequent when considering groundwater use, thereby exemplifying that more harm has been done to the environment than previous assessments (ignoring groundwater contributions) would have estimated (Figure 6). Alternatively, in some regions, this analysis shows that environmental harm may have been less prevalent than previous assessments estimated due to the ability of available groundwater stores to supply freshwater to meet local demands (as seen in the Indus and Yellow River basins). The large differences between

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the surface water-centric method and the groundwater-centric methods exemplifies the major role that groundwater contributions to streamflow play in supporting environmental flows. Groundwater is a store which can supplement surface water to provide more available freshwater to meet demands, but its use must also be carefully regulated to ensure that it is not overexploited, which can itself lead to environmental harm. This analysis of the progression of violations over time serves as a regional comparison of global methods and is not meant to inform policy or water management decisions in these basins.

Regarding the methods we applied that consider groundwater contributions to streamflow, there is a notable distinction in their applicability. The PS is equally restrictive at all times (Gleeson & Richter, 2018), while the Q^* is more restrictive during low-flow periods (de Graaf et al., 2019). Due to this difference, they serve different purposes in estimating environmentally critical groundwater discharge. If all timesteps are to be considered, then the choice of method will affect the thresholds, and, therefore, the violations, of environmentally critical groundwater discharge; PS violations were more frequent and more severe than Q^* violations over the full historic period. If only low-flow periods are to be considered, when the relative importance of groundwater to support environmental needs is greater, the choice of method does not have a great effect on the thresholds and violations of environmentally critical groundwater discharge.

Environmentally critical flow violation frequencies and severities are dominantly driven by climatic conditions and water demands (e.g., Indo-Gangetic Plain, North China Plain, Central Valley). The interactions between groundwater and regional drainage to maintain river flows, and the dependency on groundwater to meet water demands, are relatively more important in drier climates than in wetter climates. The impacts of groundwater pumping are, therefore, most notable in these drier regions. This does not, however, mean that regions in wetter climates are not impacted by groundwater pumping. In Europe, for example, all three methods applied in our study estimate violations of environmentally critical flow, albeit to lesser extents than violations in drier climates. This does, however, highlight the vulnerability of the environment to groundwater pumping, as global climate change and population growth are expected to increase the pressure on groundwater systems in the future, and a large share of the world population already lives in regions with frequent and severe violations of environmentally critical flow. Furthermore, our findings emphasize the need to consider both environmentally critical streamflow and groundwater discharge, as environmental protection can only be achieved when they are considered in the context of each other. A full understanding of their relationship is necessary to quantify the current and future impacts of groundwater pumping on aquifer stress and water allocation, as well as to set proper thresholds of environmentally safe groundwater pumping, leading to improved, sustainable global groundwater management. Our assessment, therefore, serves to inform users of the benefits of implementing each of the methods applied, and can be used to inform global groundwater pumping limits aimed at ensuring environmental protection.

4.2. Uncertainties and Limitations

In our study, we used modeled global data for natural and human-impacted water use and availability (de Graaf et al., 2019). Although this data is not observed, and limited by data availability, model assumptions, and model uncertainties, it is nonetheless the best available globally applicable data set for the purposes of our study. Spatially, this data set covers the entire global land surface at uniform gridcell extent, and temporally, it covers the entire duration of our study period in uniform timesteps. Additionally, by using a coupled groundwater-surface water modeling framework, the modeled groundwater discharge and streamflow data are linked, and, therefore, have the same uncertainties. The use of this global data also emphasizes that the results provided in this study are estimates of violations of environmentally critical flow, and do not serve as local environmental flow assessments.

All three of the methods utilized in this study provide global estimates of environmentally critical flow. This means, however, that they are simplified for applicability across a multitude of regions and climates. The VMF methodology is validated globally, but still generalized (Pastor et al., 2014). The PS methodology is globally uniform, and thus not expected to provide regionally specific information (Gleeson & Richter, 2018). It does, however, provide a conservative metric for protecting long-term impacts of groundwater pumping on the environment (from the groundwater perspective). All three of the methods were implemented at large-scales (globally) to provide first-order estimates of environmentally critical streamflow and groundwater discharge. To be more regionally relevant, a more reliable regional method could be applied to smaller scales.

We had to adapt the VMF and Q^* methods to avoid naturally occurring violations. Such measures were necessary for the purpose of our study to assess where, when, how often, and how severely human water use caused environmental harm. Furthermore, we had to account for the influence of river infiltration with the dynamically coupled model by adjusting both groundwater-centric methods when the natural groundwater discharge flux was negative. This led to situations where the PS and Q^* thresholds were equal, and any decreases to the natural groundwater discharge caused violations. As such, the violation severity comparison between the PS and Q^* (Figure 2f) levels off for classifications 6–9 because many severe violations occurred when the natural system was already in a state of extreme low-flows. The difference in violation severity between methods, therefore, is more evident for classifications 1–5.

In this study, we applied thresholds of environmentally critical flow, which can be used to estimate when the environment may be impacted. This contrasts with previous studies which applied limits of environmentally critical flow to estimate when the environment may be impacted to the point that actions will be taken to prevent further environmental harm (e.g., de Graaf et al., 2019). Both techniques provide valuable information for environmental protection and can have applicability for strategic water resources management and policy makers. Ultimately, such assessments of environmentally safe operating spaces of global groundwater use can ensure that sufficient and sustainable water is provided for both environmental and human needs.

5. Conclusion

To inform more sustainable water resources management at large-scales, we conducted a comparison of three methods of estimating environmentally critical flow (one following a surface water-centric approach, two following a groundwater-centric approach). Following these methods, we made first-order global estimates of environmentally critical streamflow (VMF) and environmentally critical groundwater discharge (PS, Q^*), using simulated data over the historic period (1960–2010). From our analyses of violations of these critical flow thresholds, we have highlighted the importance of including groundwater contributions to streamflow in environmental flow assessments. Such assessments generally do not directly account for groundwater discharge, but, as our results show, there are major implications for this exclusion, as the surface and subsurface systems are intrinsically and dynamically connected. We found that there were noticeable differences in violations of environmentally critical flow depending on the approach applied. When groundwater contributions were explicitly considered, the estimated prevalence of environmental harm was altered. In many regions, including the Rhine River basin and High Plains, we estimated (using the PS or Q^*) that the historic environmental harm has been worse than previous estimates, excluding groundwater contributions, would have found (e.g., VMF). Ignoring groundwater contributions in environmental flow assessments, on the other hand, misses out on both the environmental impacts caused by overexploiting groundwater resources (e.g., central India), as well as the capacity for groundwater to serve as an additional store of freshwater to meet growing demands (e.g., northern India). Therefore, the global differences exemplified by our comparison of the surface water-centric method with the groundwater-centric methods emphasize the importance of including groundwater in environmental flow assessments in regions with significant groundwater abstractions.

When groundwater contributions are included in environmental flow assessments, the choice of method (PS or Q^*) can lead to differing violation schemes. This difference is dependent on the period of focus, as the PS was designed for assessments over the whole year, and the Q^* was designed for critical periods of low-flows. For an assessment over the whole year, applying the PS method results in a more conservative threshold of environmentally critical groundwater discharge than applying the Q^*. For an assessment that is focused on low-flow periods, the two methods estimate similar violation schemes.

During these low-flow periods, we also estimated an overlap in regions with frequent violations from all three methods (VMF, PS, Q^*). This highlights the interconnectedness of the groundwater and surface water systems, and emphasizes that the two systems cannot be separately managed. Using freshwater from one store will invariably affect the other and reduce the remaining available water to meet the needs of the environment. Therefore, it is crucial for future research to build on estimates of environmentally critical groundwater discharge by quantifying environmentally safe groundwater pumping limits to ensure ecological protection now and in the future.

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Data Availability Statement

All data necessary to evaluate the findings of this study are publicly available from Marinelli (2024).

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