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ARENA PAPER

How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers

T. Gleeson[1] | B. Richter[2]

[1] University of Victoria, Victoria, British Columbia, Canada

[2] The Nature Conservancy, Charlottesville, VA, USA

Correspondence
Tom Gleeson, Department of Civil Engineering and School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada.
Email: tgleeson@uvic.ca

Abstract

Groundwater is a critically important source of water for river, wetland, lake, and terrestrial ecosystems, yet most frameworks for assessing environmental flows have ignored or not explicitly included the potential impacts of groundwater pumping on environmental flows. After assessing the processes and existing policies for protecting streamflow depletion from groundwater pumping, we argue that a new groundwater presumptive standard is critical as a placeholder to protect environmental flows in rivers lacking detailed assessments. We thus extend the previous presumptive standard to groundwater pumping, a different and important driver of changes to streamflow. We suggest that “high levels of ecological protection will be provided if groundwater pumping decreases monthly natural baseflow by less than 10% through time.” The presumptive standard is intended to be a critical placeholder only where detailed scientific assessments of environmental flow needs cannot be undertaken in the near term. We also suggest a new metric, the environmental flow response time, that allows water managers to quantify the timescales of the impacts of groundwater pumping on the loss or gain of environmental flows.

KEYWORDS

aquifers, ecological flows, ecology, ecosystems, environmental flows, groundwater use, rivers, streamflow depletion

1 | WHY A PRESUMPTIVE STANDARD FOR GROUNDWATER PUMPING?

Groundwater is a critically important source of water for river, wetland, lake, and terrestrial ecosystems, helping to maintain water levels, temperature, oxygen content, and chemistry required by plants and animals (Bradley, Streetly, Farren, Cadman, & Banham, 2014; Brown, Bach, Aldous, Wyers, & DeGagné, 2010; Brunke & Gonser, 1997; Dugdale, Bergeron, & St-Hilaire, 2015; Eamus, Froend, Loomes, Hose, & Murray, 2006; Kennen, Riskin, & Charles, 2014; Kurylyk, MacQuarrie, Linnansaari, Cunjak, & Curry, 2015; Power, Brown, & Imhof, 1999). For example, groundwater commonly supplies or supplements summer flows with cool, oxygenated water and creates focal areas of groundwater discharge that provide important localized habitats crucial to the survival of certain species or aquatic food webs in warm summer rivers. Unfortunately, groundwater pumping reduces the flow of groundwater to many aquatic and riparian ecosystems over timescales ranging from days to centuries and can even intercept streamflow in severe cases (Barlow & Leake, 2012). Environmental flow management programs usually focus on the operations of water infrastructure, such as dams or diversion structures, and often do not explicitly consider groundwater contributions. Groundwater pumping is a fundamentally different cause of hydrologic alteration than surface water alterations, because groundwater pumping only lowers streamflow and does not affect its timing and often occurs over much longer timescales than other hydrologic alterations. Additionally, groundwater is often thermally and chemically distinct from surface water, making groundwater baseflow nonsubstitutable: a reduction of flow from groundwater pumping sometimes cannot be suitably substituted by releasing water from reservoirs to maintain the same ecological conditions. As a fundamentally distinct and important driver impacting river hydrology and ecology at different spatial and temporal scales, groundwater pumping needs to be considered explicitly in environmental flow assessments. Although environmental flow assessments often consider baseflow and low flows (Poff et al., 2009; Richter, Davis, Apse, & Konrad, 2012; Richter, Mathews, Harrison, & Wigington, 2003), “groundwater,” “groundwater pumping,” or “groundwater abstraction” have only recently been considered in environmental flow management programs (e.g., Acreman et al., 2014; Sanz, Calera, Castaño, & Gómez-Alday, 2016).

Environmental flows have been assessed in a number of frameworks with varying levels of sophistication, stakeholder involvement, and required data and investment. For instance, the ecological limits of hydrologic alteration (ELOHA) is a robust framework for assessing regional relationships between hydrologic alterations and ecological responses that can help in designing hydrologic management strategies to protect and sustain the structure, composition, and function of ecological communities (Poff et al., 2009). The ELOHA framework is focused on developing flow alteration–ecological responses, based upon existing hydro-ecological literature, expert knowledge, and field studies, and applies these in an adaptive management framework where stakeholders and decision makers make risk-based consensus decisions. The ELOHA framework has been applied in a number of settings around the world (The Nature Conservancy, 2017), but it can be time-consuming and expensive to implement as it requires significant data gathering, analysis, and community involvement. Alternatively, “presumptive standards” have been proposed that restrict hydrologic alterations to within a percentage-based range around natural or historic flow variability (Richter et al., 2012). These simpler and more easily applied presumptive standards are intended to be adopted only where detailed scientific assessments of environmental flow needs cannot be undertaken in the near term, which is the case for many rivers worldwide (Richter et al., 2012). Richter et al. (2012) argued that presumptive standards can be critically important as placeholders for protecting environmental flows in the absence of detailed scientific studies. The presumptive standard proposed by Richter et al. suggested that a high level of ecological protection is provided when daily streamflow alterations are no greater than 10%. We extend this presumptive standard concept to explicitly include the role of groundwater pumping, based upon the same arguments: groundwater pumping is potentially impacting streamflow in many areas around the world with no or scant protection of environmental flows on those rivers.

Better integration of knowledge among the sciences of groundwater hydrology, ecology, and environmental flows, as well as water policy and management, is urgently needed. The processes and timing of streamflow depletion from groundwater pumping are quite well understood within the hydrologic science community (Alley, Healy, LaBaugh, & Reilly, 2002; Barlow & Leake, 2012; Konikow & Leake, 2014; Leake, Reeves, & Dickinson, 2010), and models have been developed to predict localized streamflow depletion (Hunt, 1999; Reeves, Hamilton, Seelbach, & Asher, 2009; Singh, 2009; Sophocleous, Koussis, Martin, & Perkins, 1995), as well as global hydrologic models that consistently show that groundwater pumping is depleting many aquifers and potentially impacting environmental flows in rivers (de Graaf, Sutanudjaja, van Beek, & Bierkens, 2014; de Graaf et al., 2017; Döll, Müller Schmied, Schuh, Portmann, & Eicker, 2014; Gerten et al., 2013; Hoekstra, Mekonnen, Chapagain, Mathews, & Richter, 2012; Konikow, 2011; Pastor, Ludwig, Biemans, Hoff, & Kabat, 2014; Wada, van Beek, & Bierkens, 2012; Wada, Wisser, & Bierkens, 2014). The ecology community has identified and argued for the importance of protecting groundwater-dependent ecosystems (Eamus et al., 2006; Fisher, 2015; Kløve et al., 2014; Lewis, 2012; Murray, Zeppel, Hose, & Eamus, 2003). Meanwhile, the environmental flow community has developed excellent tools for quantifying streamflow alteration and connecting this with the mechanisms of hydrologic alteration such as dam operations but has inadequately focused on groundwater discharge as an integral component of streamflow regimes (e.g., Poff et al., 2009; Richter et al., 2012) that could potentially help meet community and stakeholder objectives in environmental flow assessments (Jackson, Pollino, Maclean, Bark, & Moggridge, 2015). In many areas globally, the water policy and management communities have recognized the need to quantitatively assess the ecological importance of streamflow depletion from groundwater pumping (e.g., European Union, 2015), but to our knowledge, a universal standard has never been clearly articulated that would protect environmental flows from groundwater pumping on rivers lacking river management plans or detailed environmental flow studies.

Our objective is to propose a standard and a metric for managing groundwater pumping appropriate for maintaining environmental flows, which will help bridge these gaps in the science, policy, and management communities. We assess the processes and existing policies for protecting streamflow depletion from groundwater pumping and, then, offer two specific contributions: (a) we modify the presumptive standard to explicitly incorporate the potential impacts of groundwater pumping, and (b) we provide a metric for managing the impacts of groundwater depletion on ecosystems through time. We hope that these contributions can be used by the environmental flow community to address concerns about groundwater use; by groundwater hydrologists who are concerned about impacts of groundwater alterations on streamflow; and by international river scientists, managers, and decision makers who are interested in integrated water resource management, conjunctive use of groundwater and surface water, meeting community and stakeholder objectives in environmental flow assessments, and evaluating regional to global impacts of groundwater use. By developing a standard and metric for protecting environmental flows from groundwater pumping, we hope to diversify the tools available to river scientists, managers, and decision makers. Although groundwater pumping can impact diverse terrestrial and aquatic groundwater-dependent ecosystems, herein, we focus on environmental standards to protect streamflow as a first, tractable step towards comprehensive environmental standards for groundwater pumping on other hydrologic environments. We acknowledge that for some groundwater-dependent ecosystems, factors such as water table depth may be more important than streamflow (Aldous & Bach, 2014) and, thus, terms such as “ecological water requirements” might be more useful than “environmental flows” (Acreman et al., 2014). For consistency here, we use the terms *environmental flows*, which has also been called environmental flow needs, instream flows, environmental flow requirements, or ecological flows; *streamflow*, which is sometimes referred to as discharge; *groundwater discharge*, which is the flux of groundwater to surface water; *rivers*, which could include any lotic ecosystems in streams, channels, and brooks.

2 | BASEFLOW AND STREAMFLOW DEPLETION

Baseflow is generally defined as "the portion of flow that comes from groundwater or other delayed sources" (Hall, 1968; Tallaksen, 1995) whereas low flows are the "flow of water in a stream during prolonged dry [but non-drought] weather". Here, we provide only a cursory introduction to baseflow and low flow hydrology, because detailed reviews are available elsewhere in review articles and textbooks (e.g. Hall, 1968; Smakhtin, 2001; Tallaksen, 1995).

Baseflow can originate from groundwater, lakes, reservoirs, snowpack, or glaciers, but here, we focus on groundwater-derived baseflow (herein called *baseflow* for simplicity), which is the most common and volumetrically significant portion of the delayed water sources in many, but not all, rivers. Groundwater-derived baseflow is driven by groundwater tables that slope and flow towards the river, eventually discharging into the river—this is called a gaining river because the river is gaining flow from groundwater (Figure 1a). Baseflow is generally quantified using baseflow separation (Figure 1b), where the delayed component of the hydrograph (a graph of measured streamflow through time) is separated from the nondelayed component of the hydrograph using graphical or mathematical algorithms (Halford & Mayer, 2000; Hall, 1968; Smakhtin, 2001; Tallaksen, 1995); techniques based on heat, physical measurement, or chemical tracers (Cook, 2013; Kalbus, Reinstorf, & Schirmer, 2006); or from groundwater numerical models (Barlow & Leake, 2012; Sanz et al., 2016). Baseflow often dominates the flow of rivers during low-flow periods, which can be seen on the long-term average daily hydrograph of Figure 1c. Low-flow statistics and metrics can be derived from a flow duration curve, which shows the relationship between any given streamflow value and the percentage of time that this streamflow is equalled or exceeded, or in other words, the relationship between magnitude and frequency of streamflow (Figure 1d). For example, one common way to characterize low-flow conditions is to assume that Q90 or Q80, the streamflow that is exceeding 90% or 80% of the time, respectively, equates to low flow. Although some authors and policies consider low-flow metrics a surrogate approximation or equivalent to baseflow, using flow duration curves to derive baseflow can be problematic because low flow metrics do not distinguish the source of the water (i.e., surface water vs. groundwater).

The processes and timescales of streamflow depletion from groundwater pumping are the focus here, because these are most relevant for developing new standards and metrics. Models and methods for quantifying streamflow depletion from groundwater pumping are useful for the implementation of these standards and tools, as reviewed elsewhere (Barlow & Leake, 2012; Hunt, 1999; Reeves et al., 2009). Figure 2 shows the impact of groundwater pumping on rivers, illustrating that groundwater can impact streamflow in very different ways and over differing time spans. Real conditions are likely significantly more complex (Rushton, 2002) but usually include some combination or modification of these generalized endmembers. The shape and timing of the impacts of groundwater pumping shown on each of the graphs in Figure 2 are generalized and are dependent on a number of variables, such as aquifer characteristics, water table gradients, the proximity of surface water bodies, and the streambed conductance (how permeable and thick the river bottom sediments are). When pumping is near the river, the impacts of groundwater pumping can be quite limited temporally to specific days, months, or seasons when the pumping is actually occurring, and limited spatially to the area around the well (Figure 2a; Bredehoeft & Kendy, 2008; Kendy & Bredehoeft, 2006). In some cases, the water table can entirely recover in-between periods of pumping such that there is effectively no long-term groundwater depletion. When the well is further from the stream, seasonal changes in pumping can be attenuated, such that the streamflow depletion from pumping is relatively consistent throughout the year (Figure 2b; Wallace, Darama, & Annable, 1990). For wells at significant distances from the stream, the impact of

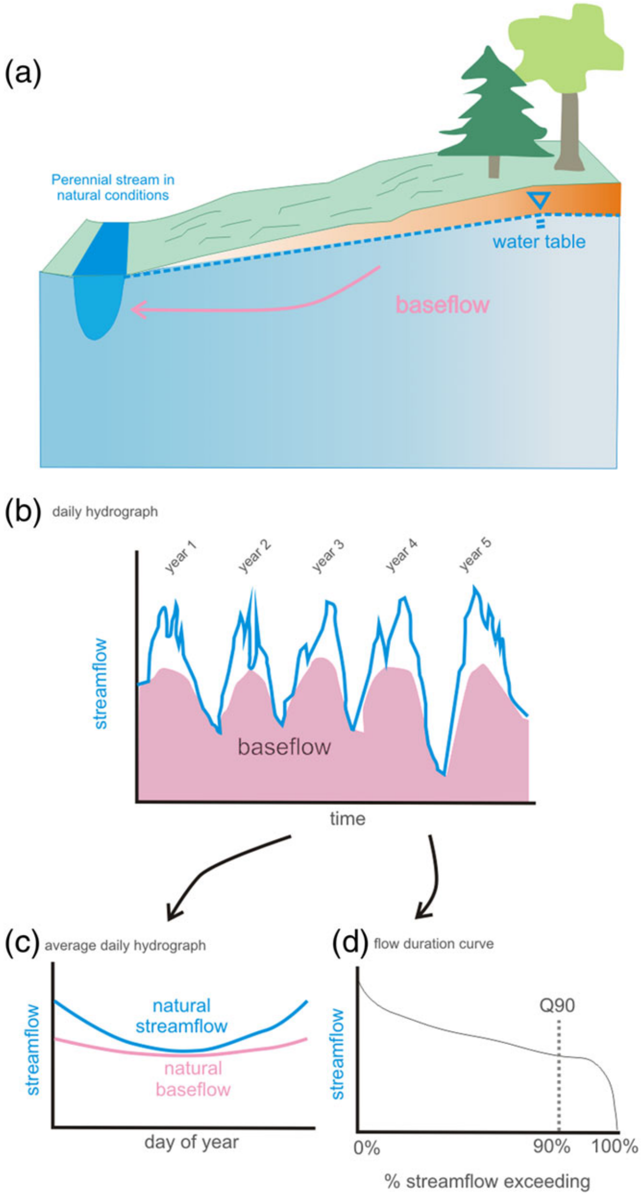

FIGURE 1 (a) Baseflow is the streamflow contribution from groundwater that sustains many perennial rivers (modified from Leake and Barlow 2012). (b) Baseflow can be separated from measured streamflow with a number of techniques. Long-term baseflow statistics can be quantified either (c) for each day of the year or (d) as a statistical long-term average using flow duration curves (i.e., flows lower than the 90th percentile or Q90 is commonly assumed to be baseflow) [Colour figure can be viewed at wileyonlinelibrary.com]

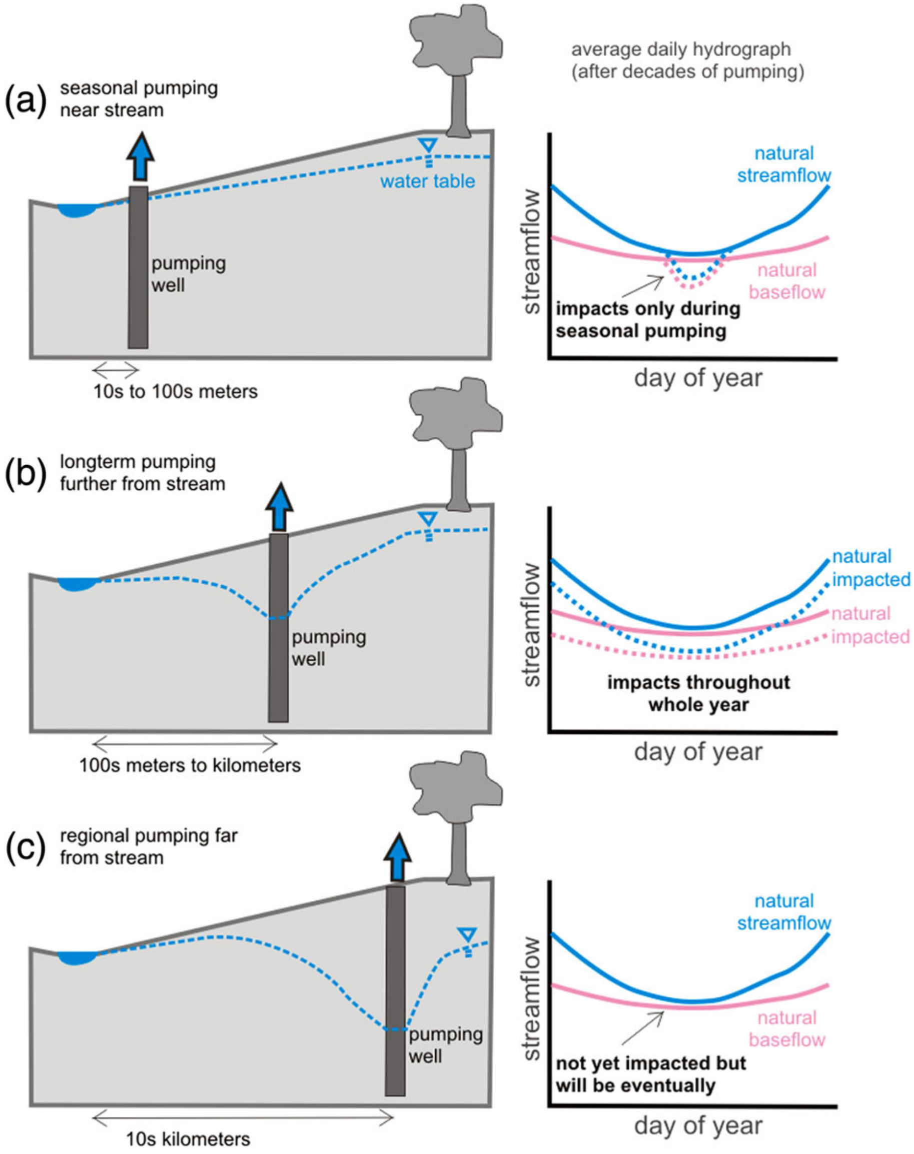

FIGURE 2 The impacts of pumping on streamflow are highly variable through time and space. (a) Seasonal pumping near a stream can potentially only impact part of the daily hydrograph. (b) Long-term pumping further from the stream could impact through the whole year. (c) Regional pumping far from stream could potentially not significantly impact the stream for decades after the start of pumping. These scenarios show the effect of pumping at different distances from the stream for average aquifer parameters, but the response to pumping depends on not only time and space parameters but also pumping rate, climate, topography, and aquifer characteristics [Colour figure can be viewed at wileyonlinelibrary.com]

pumping may not be observable even after decades of pumping (Figure 2c). One of the challenging implications of Figure 2b,c is the long timescales over which the impacts of groundwater pumping can appear at the stream, which is often beyond the normal timescales used in water planning and management (Gleeson et al., 2012).

When a well is pumped at a constant rate, initially most of the groundwater comes from storage as the water table around the well in lowered in a "cone of depression" (resulting in long-term groundwater depletion, unless water tables are allowed to recover from short-term pumping) that expands laterally through time, eventually reaching the river. When the lowering of the water table reaches the river, significant streamflow depletion begins, with more and more of the groundwater coming from capture of groundwater discharge or streamflow, rather than groundwater storage (Figure 3). which has profound implications for the river. Assuming the river does not become dry, which is called "capture-constrained" by Konikow and Leake (2014), and recharge from precipitation does not change (Bredehoeft, 2002), all pumping eventually leads to a reduction in streamflow and the majority of the pumped groundwater is streamflow depletion (decreased groundwater discharge or induced infiltration from the river as shown in Figure 3c).

All pumped groundwater comes either from stored groundwater which lowers the water table, increased aquifer recharge from precipitation, or decreased baseflow to streams, lakes, wetlands, or the ocean (Figure 3; Theis, 1940; Bredehoeft, 2002). Permanent lowering of the water table is called "groundwater depletion," that is, the permanent loss of stored groundwater (Aeschbach-Hertig & Gleeson, 2012). Increased recharge and decreased baseflow

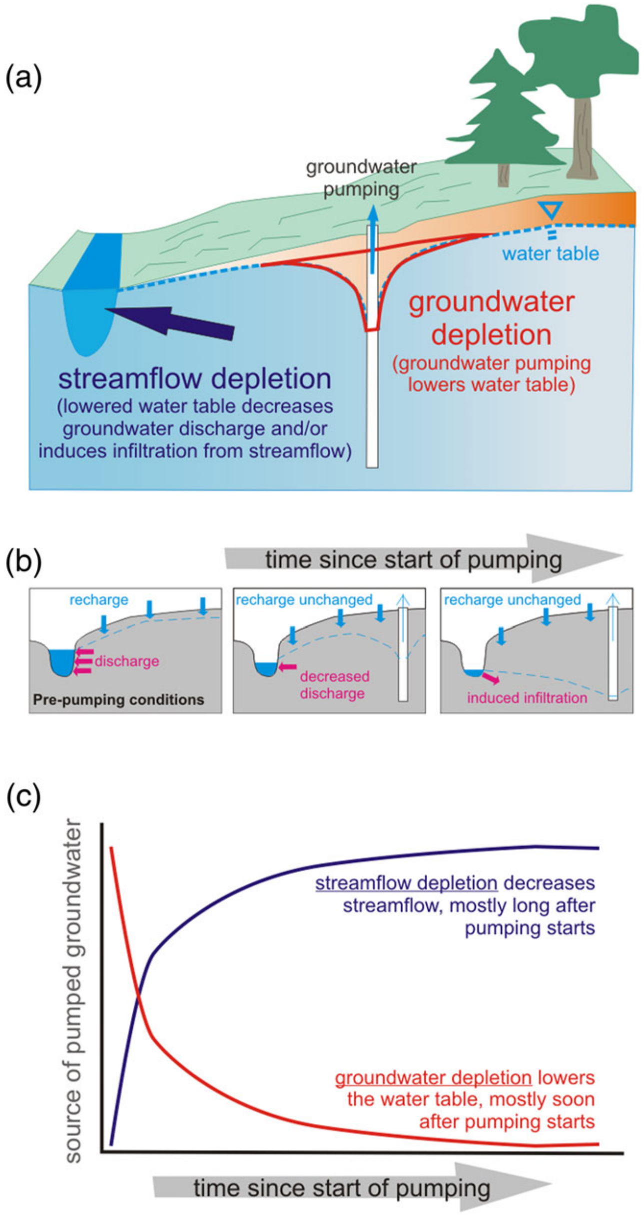

FIGURE 3 (a) The relative importance of streamflow depletion and groundwater depletion changes significantly through time. (b) Decreased groundwater discharge or induced infiltration of water from the river leads to streamflow depletion. (c) Relative importance of streamflow depletion and groundwater depletion through time since the start of pumping. Graphics modified from (Alley, Reilly, & Franke, 1999; Barlow & Leake, 2012; Konikow & Leake, 2014) [Colour figure can be viewed at wileyonlinelibrary.com]

are together called "capture" (Lohman, 1972). Recharge is often considered to not change significantly (Bredehoeft, 2002), so in practice "capture" usually means decreased contribution of groundwater to streamflow (Figure 3b), called "streamflow depletion," which is due to either decreased discharge from the aquifer to the river (due to lowered water table gradients) or induced infiltration from the river to the aquifer (resulting from lowering of the water table below the streambed level, causing a reversal in the water table gradient near the river which shifts the river from a gaining to a losing condition; Barlow & Leake, 2012; Reeves et al., 2009). Either streamflow depletion mechanism leads to a reduction in streamflow relative to prepumping conditions. One of the challenging implications of Figure 3 is that setting limits on the lowering of groundwater levels (sometimes called "drawdown triggers") may not often be effective because streamflow can become significantly depleted with minimal drawdown at or near the stream or spring (Currell, 2016).

Examination of a number of large aquifers in the United States in diverse hydrologic and geologic environments indicates that the ratio between streamflow depletion and groundwater depletion is highly variable in time and space but that overall 85% of long-term pumping is derived from stream capture (Konikow & Leake, 2014). The exact shape of the lines in Figure 3c, as well as the timing of transition between the predominance in groundwater depletion and surface water depletion, is dependent on a number of variables such as aquifer characteristics, water table gradients, and proximity of surface water bodies (Barlow & Leake, 2012). The severity of the streamflow depletion may be insignificant relative to environmental flows (if the pumping rate is insignificant relative to streamflow), or the streamflow depletion may occur on very long time frames (hundreds to thousands of years). Therefore, the critical question is the timing and severity of streamflow depletion relative to environmental flows, which we address below.

Unlike surface water alterations such as dam operations, which generally are easy to detect in streamflow records, the impacts of groundwater pumping may be much more difficult to detect due to the fact that they occur over a wide variety of timescales and may not be as large in volume as direct surface water depletions. Hydrogeologists use a number of assessment techniques to quantify these changes, such as by plotting the source of water to a well through time (e.g., Figure 3), or the rate of streamflow depletion through time (Barlow & Leake, 2012). For example, Barlow and Leake (2012) quantify the "time to reach (streamflow) depletion-dominated," which is when the two lines on Figure 3c cross, indicating that the source of pumping to a well is predominantly streamflow depletion. Or the ratio of streamflow depletion divided by the pumping rate can be mapped for a region (Leake et al., 2010). Another approach is to evaluate the "streamflow depletion factor" (Jenkins, 1968), which is the time at which the ratio of volume of streamflow depletion to volume of water pumped is a standard value. Also important is the "aquifer system response time" or "time to full capture," which quantifies the time for water levels and storage changes to become negligible after a change in pumping (Bredehoeft & Durbin, 2009; Walton, 2011). Finally, the time to "sustainable capture thresholds" has been proposed (Davids & Mehl, 2015) that, unlike all the above metrics, does explicitly include environmental flows but does not recommend actual thresholds. Each of these metrics could be useful for examining temporal aquifer dynamics and/or the impacts of streams on pumping, but when considering environmental flows, the percentage of pumped groundwater that comes from the river is in itself unimportant to lotic ecosystems, and the rate of streamflow depletion may be insignificant relative to the environmental flows. What is important is the change in streamflow (Figure 3) or baseflow (Figure 4) relative to environmental flow needs, which is rarely plotted in the hydrogeology literature. This is a subtle but important shift from being aquifer centric to river centric, which is important for evaluating environmental flows.

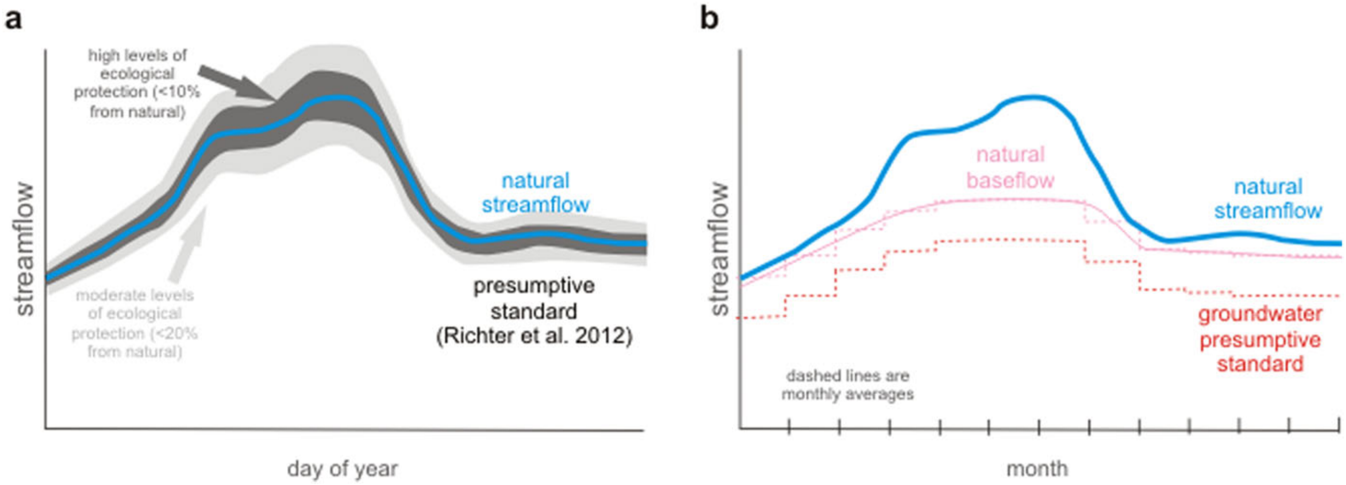

FIGURE 4 (a) The presumptive standard for protecting streamflow (adapted from Richter et al., 2012) and (b) the groundwater presumptive standard for protecting baseflow from the impact of groundwater pumping [Colour figure can be viewed at wileyonlinelibrary.com]

3 | EXISTING POLICIES, REGULATIONS, AND MANAGEMENT PLANS

A number of jurisdictions have developed policies, regulations, and management plans to reduce streamflow depletion or otherwise protect streamflow from the impact of groundwater pumping. The following case studies highlight the breadth of efforts to limit streamflow depletion from groundwater pumping, which form the basis for the more generalized standard articulated below.

The province of Ontario, Canada, has established “technical rules” as part of the Clean Water Act passed in 2006 to limit streamflow reduction from groundwater pumping (MoE, 2008). These rules stipulate that an area is assigned a risk level of “moderate” if groundwater discharge to an aquatic habitat that is classified as a cold water stream is (a) at least 10% of the existing estimated streamflow that is exceeded 80% of the time (Q80) or (b) at least 10% of the existing estimated average monthly base flow of the stream. An example of how this has been implemented comes from the region of Waterloo, where regional-scale groundwater models were developed and show that under all reasonable future scenarios of groundwater consumption, cold water streams in the region will not be impacted (Wotten, 2014).

The state of Michigan in the United States enacted legislation in 2008 requiring high-capacity wells to be reviewed to prevent reduced streamflow and changes in stream ecology (Reeves, Seelbach, Nicholas, & Hamilton, 2011). Significant scientific research and policy development led to a risk-based system of ecological response curves and modelled groundwater-surface water interaction (Reeves et al., 2009). Although the legislation and the related online decision support tools do not explicitly set a universal standard for environmental flows, in a related research project Watson, Mayer, and Reeves (2014) used Q90 as basis for the environmental flow limits, arguing that this low-flow statistic represents the summer baseflow, a flow critical to ecosystem function in this region (Zorn, Seelbach, & Rutherford, 2012).

The European Union Water Framework Directive discusses the impact of groundwater pumping on environmental flows (European Union, 2015). In order to achieve good groundwater quantitative status, pumping should not cause a failure in environmental objectives for associated surface waters, although methods for quantifying environmental flows or the impacts of groundwater on environmental flows are not specified for any country in the European Union. As an example from the United Kingdom, Bradley et al. (2014) demonstrate statistically significant relationships between in-stream ecological condition based upon macroinvertebrate populations and the hydrological effect of groundwater abstraction on streamflow. Ecological impacts occurred when the effect of abstraction exceeded 60% of Q75 flows regardless of water quality, habitat or seasonal effects. Streetly et al. (2014) combine this ecology–streamflow–groundwater pumping relationship with a calibrated regional groundwater model within an ELOHA framework to assess river reaches that are likely to be ecologically impacted by pumping and might consequently be at risk of failing to meet European Union Water Framework Directive standards.

A number of jurisdictions have made policy to reduce the impacts of groundwater pumping on baseflow without quantifying baseflow directly. For example, in the Upper Ovens Valley of Australia, where irrigation pumping during summer low flows is the most significant ecological concern, pumping from the alluvial aquifer adjacent the stream was shown to quickly and significantly impact streamflow, whereas there was a significant time lag between pumping and streamflow impacts from the adjacent fractured rock aquifer. As a result, the managers divided groundwater licences based on different aquifers with different lag times between pumping and streamflow impacts, to limit pumping during critical periods (Goulburn-Murray Water, 2012).

In sum, these policies include a diversity of approaches to limiting the impact of groundwater pumping on environmental flows. Some approaches attempt to limit baseflow directly (Australia). Other approaches are based more on low flow metrics (Michigan, United Kingdom), or both low flow metrics and percentage of baseflow (Ontario).

4 | PROTECTING ENVIRONEMENTAL FLOWS THROUGH TIME WITH A PRESUMPTIVE STANDARD AND METRIC

On the basis of the case studies above, the presumptive standards previously proposed for streamflow (Richter et al., 2012), and acknowledging the importance of groundwater-derived baseflow and the processes of streamflow depletion, we suggest that “high levels of ecological protection will be provided if groundwater pumping decreases monthly natural baseflow by less than 10% through time” (Figure 4). For rivers with existing surface water alterations, this “groundwater presumptive standard” of 10% should be considered nested within and part of the presumptive standards for streamflow rather than an additional 10%. Like the broader presumptive standards (Richter et al., 2012), we intend for this standard to be a critical placeholder only where detailed scientific assessments of environmental flow needs cannot be undertaken in the near term.

It is important to clarify the specific wording in the presumptive standard. By “high levels of ecological protection,” we mean the natural structure, composition, and function of the riverine ecosystem will be maintained with minimal changes (Richter et al., 2012). This assumes that ecosystems are well adapted to natural flow hydrographs, which may not be a reasonable assumption for novel ecosystems (Hobbs et al., 2006) in regions with significant ecological alteration. We suggest “monthly” because the impacts of groundwater pumping on streams are usually realized over longer (i.e., annual to decadal) timescales, but policies could include monthly, weekly, or daily thresholds of groundwater alteration in some jurisdictions if deemed appropriate, especially with seasonal pumping such as for irrigation from wells near streams (Figure 3a). By “natural,” we mean baseflow before human alteration such as pumping. By “baseflow,” we mean groundwater-derived baseflow. We recommend deriving baseflow using baseflow separation, because as described above, low flow metrics derived from flow-duration curves do not distinguish the source of the water (surface vs. ground water). Some authors and policies discussed above consider low flow metrics a surrogate, approximation or equivalent to baseflow, which may be appropriate in certain settings. We suggest “less than 10%” because (a) groundwater maintains sensitive components of freshwater ecosystems that depend on the stability and reliability of groundwater; (b) this is precautionary because streamflow depletion can be easy to miss (due to streamflow variability), can be very delayed (past the normal management time horizon), and can be very slow to recover (Barlow & Leake, 2012); (c) groundwater is sometimes nonsubstitutable; and (d) this level of protection is already the practice in some jurisdictions (see above). On the basis of the hydrology, policy, or regulations in some regions, an alternative value above or below 10% may be more appropriate but we argue that 10% is a precautionary value for regions where detailed scientific assessments of environmental flow needs cannot be undertaken in the near term. Finally, in the presumptive standard, we purposefully added “through time” because the impacts of groundwater pumping can significantly be delayed. The ideal timescale to consider with respect to impacts from groundwater pumping is the aquifer system response, but we acknowledge this may often be longer than normal groundwater management horizons.

Because the severity of the impact may be insignificant relative to environmental flow needs, or this impact may happen on very long time frames, a metric may be useful for assessing the timing and importance of streamflow depletion relative to environmental flows. Other metrics discussed above (time-to-reach-streamflow-depletion-dominated, streamflow depletion factor, aquifer system response time, and sustainable capture thresholds) do not explicitly examine the temporal impact of groundwater pumping on environmental flows. This new metric allows water managers to quantify the timescales of the impacts of groundwater pumping on the loss or gain of environmental flows. Therefore, we suggest a new metric, the environmental flow response time (EFRT), which is the duration from the start of pumping to the loss of environmental flows, called EFRT$_{\text{loss}}$ (in this case, the groundwater presumptive standard) or conversely, the duration of restoration or gaining environmental flows after the cessation of pumping, called EFRT$_{\text{gain}}$ (Figure 5a). On the y-axis of Figure 5 is baseflow, with the top being a nonimpacted, natural river and the bottom being a river where the baseflow has disappeared due to groundwater pumping, making this an ephemeral river. After a duration of time, called EFRT$_{\text{loss}}$, ground pumping causes baseflow to decrease below the groundwater presumptive standard. Conversely, the EFRT$_{\text{gain}}$ can be considered as the time after the cessation of pumping at which baseflow rises above the presumptive standard (Figure 5a). Note, EFRT$_{\text{loss}}$ generally does not equal EFRT$_{\text{gain}}$ because the impacts of pumping are nonlinear (Figure 3). Figure 5b shows that depending on the pumping rate, the proximity of a well to the river, and the geology, topography, and hydrology of the system, the EFRT can be very short (hours to months) to very long (decades or centuries), or have an environmentally sustainable capture that never crosses the groundwater presumptive standard (EFRT$_{\text{loss}} = \infty$). The shorter the EFRT, the more rapidly pumping impacts environmental flows. Large impacts to environmental flows on short time frames are problematic, especially

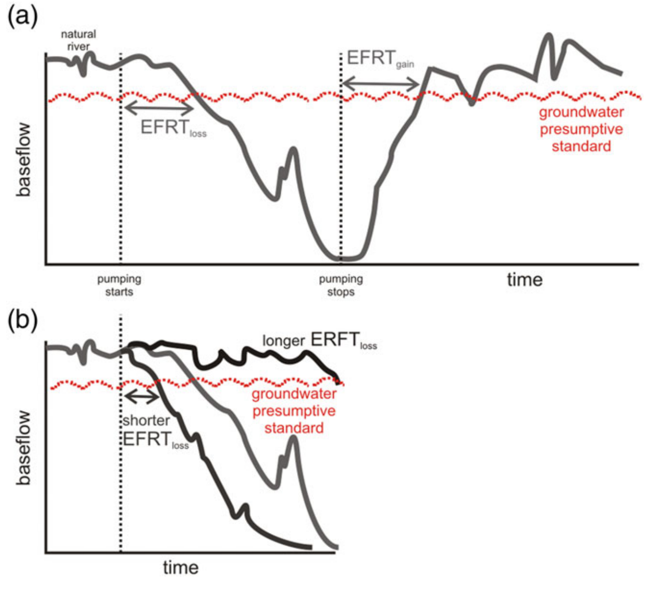

FIGURE 5 Environmental flows response time (EFRT) reveals the timescales associated with impacts from groundwater pumping (a) shows the loss and gain of EFRT in a region with a moderate EFRT. (b) shows the loss of EFRT in three regions with shorter, moderate and longer EFRT [Colour figure can be viewed at wileyonlinelibrary.com]

during summer low flow periods or periods of drought. However, a short EFRT implies impacts would be also quick to recover if pumping is stopped or decreased. A long EFRT (i.e., > > 100 years) may be a useful objective for minimizing the effects of groundwater pumping on streams over long time periods. However, a long EFRT also implies the system will take a long time to recover.

5 | TOWARDS POLICIES, REGULATIONS, AND MANAGEMENT INCLUDING THE PRESUMPTIVE STANDARD

Barlow and Leake (2012) argue that "managing the effects of streamflow depletion by wells is one of the most common and often one of the most challenging aspects of conjunctively managing groundwater and surface-water systems." By developing a standard and metric for protecting environmental flows from groundwater pumping, we hope to diversify the toolkit available to river scientists, managers, and decision makers—here, we examine methodology, challenges, and solutions for applying this new standard.

The methodology for applying the new presumptive standard and a new metric, the EFRT, will vary depending on the hydrologic setting, policy objectives, management structures, and so forth. In some cases, the groundwater presumptive standard could be applied alone, such as to groundwater-only environments such as springs. But generally, the presumptive standard for groundwater (Figure 4b) should be applied in conjunction with the presumptive standard for streamflow (Figure 4a) because together, they provide a more holistic protection of streamflow to multiple threats and at multiple timescales. As mentioned above, the presumptive standard for groundwater pumping should be considered nested within the presumptive standards for streamflow for rivers with existing surface water alterations. We suggest a monthly timescale for the groundwater presumptive standard whereas Richter et al. (2012) suggested a daily timescale for the presumptive standard. Therefore, ideally, the two standards should be applied concurrently. Applying the groundwater presumptive standard necessitates quantifying, estimating, or modelling baseflow using baseflow separation, chemical tracers, or groundwater numerical models, as described above.

Implementing the presumptive standard for groundwater could face a number of challenges, which we discuss below along with some potential solutions:

1. Large range of timescales of impacts. Bredehoeft and Kendy (2008) suggest different management strategies based on short, medium, or long timescale "stream depletion factors." In a similar way, different management strategies might be appropriate for wells with short-, medium-, or long-term EFRT. Therefore, a first step in applying this methodology may be calculating the EFRT for wells in the region. For example, in the example of the Upper Ovens in Australia discussed above, aquifers have been divided based on the response time between groundwater pumping and streamflow impacts.
2. Long timescales. One of the important messages of Figure 3 is that the impact of groundwater pumping on environmental flows can be very long, much longer than typical water management time horizons. Gleeson et al. (2012) suggested backcasting and setting multigenerational goals as possible water management tools to mitigate the impacts of the long times of groundwater pumping.
3. Hydrologic variability. Monitoring streamflow depletion at the watershed scale can be difficult because of the inherent hydrologic variability, which can exceed the signal of baseflow changes. For rivers where baseflow is highly uncertain, an alternative and pragmatic standard may be a "measurable" difference from natural conditions. In some cases, the uncertainty in baseflow contribution to a river may be greater than 10%; in these cases, a more realistic limit may be a measurable difference from prepumping conditions, although as we discuss, quantifying baseflow can be difficult. In all rivers, hydrologic and climatic data can be collected over a period of many years to determine whether changing streamflow conditions can be correlated to long-term groundwater pumping, which has been successful in a few cases of significant groundwater pumping (Barlow & Leake, 2012). One example of hydrologic systems with significant hydrologic variability are rivers that lack streamflow at some time in the seasonal cycle, and include ephemeral, intermittent and episodic streams, which have been called "temporary streams" (Buttle et al., 2012). In the cases of temporary streams, the groundwater presumptive standard for some months may be zero.

6 | CONCLUSIONS

In quantifying environmental flows, streamflow has been described as the "master variable" because of its strong influence on many critical physiochemical characteristics of rivers, including water temperature, geomorphology, and in-channel and off-channel habitat diversity (Poff et al., 1997). Streamflow has, even more creatively, been called the "maestro" of the river orchestra (Walker, Sheldon, & Puckridge, 1995); in this metaphor, groundwater is the backbone of the maestro, consistently supporting streamflow with baseflow. Yet most frameworks for assessing environmental flows have ignored or not explicitly included the potential impacts of groundwater pumping on environmental flows, in essence neglecting the backbone of environmental flow. We assess the processes and existing policies for protecting streamflow depletion from groundwater pumping, which contributes to a better integration of knowledge among the sciences of groundwater hydrology, ecology, and environmental flows, as well as water policy and management. Our key findings are as follows:

1. Pumping groundwater decreases river flows, which can in turn impact ecosystems, especially at ecologically sensitive times such as during summer low flows.
2. The impacts of groundwater pumping on river flows can take place over decades, so we need long-term planning, management, and laws.
3. The science, policy, and management of groundwater pumping to protect environmental flows are poorly understood and fragmented.

On the basis of these findings, we argue that a new groundwater presumptive standard is critical as a placeholder to protect environmental flows in rivers lacking detailed assessments. We thus extend the presumptive standard of Richter et al. (2012) to groundwater pumping, a different and important driver of changes to streamflow. We suggest that "high levels of ecological protection will be provided if groundwater pumping decreases monthly natural baseflow by less than 10% through time." We intend for this standard to be a critical placeholder only where detailed scientific assessments of environmental flow needs cannot be undertaken in the near term.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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