Too many streams and not enough time or money? New analytical depletion functions for rapid and accurate streamflow depletion estimates

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Abstract

Groundwater pumping can cause streamflow depletion by reducing groundwater discharge to streams and/or inducing surface water infiltration. Analytical and numerical models are two standard methods to predict streamflow depletion. Numerical models require extensive data and efforts to develop robust estimates, while analytical models are easy to implement with low data and experience requirements but are limited by numerous simplifying assumptions. We have pioneered a new approach that balances the shortcomings of analytical and numerical models: analytical depletion functions, which include more empirical functions expanding the applicability of analytical models for real-world settings with complex hydrogeologic landscapes and stream networks. Specifically, analytical depletion functions combine analytical models with stream proximity criteria used to determine which stream segments are most likely to be affected by a pumping well and a depletion apportionment equation which is a geometric method to distribute depletion among the affected stream segments. The accuracy of analytical depletion functions has been tested by comparing against a variety of numerical models from simplified, archetypal models to sophisticated, calibrated models in both steady-state to transient conditions. Estimates of streamflow depletion from analytical depletion function generally agree with estimates from numerical models, suggesting analytical depletion functions are an accurate tool for the streamflow depletion assessment over diverse hydrogeological landscapes and scales. Analytical depletion functions are rapidly and easily implemented and have low data requirements like analytical models but have significant advantages of better agreement with numerical models and better representation of complex stream geometries. Relative to numerical models, analytical depletion functions have limited ability to explore non-pumping related impacts and incorporate subsurface heterogeneity. Analytical depletion functions can be used as a stand-alone tool or part of decision-support tools as preliminary screening of potential groundwater pumping impacts when issuing new and existing water licenses while ensuring streamflow meets environmental flow needs.

1. The importance of streamflow depletion

Groundwater pumping has caused dramatic groundwater storage depletion globally over the past decades, and anticipated growing demands from agricultural irrigation and other human activities can further stress groundwater sustainability (Döll et al., 2014; Gleeson et al., 2020; de Graaf et al., 2019; Rodell et al., 2018; Wada et al., 2014; Wada et al., 2012). In addition to declines in aquifer storage, groundwater pumping affects surface water by reducing the groundwater discharge to surface water and/or inducing surface water infiltration, which together are defined as “streamflow depletion” (Barlow & Leake, 2012; Gleeson & Richter, 2018; Konikow & Leake, 2014; Theis, 1940). At the onset of pumping, most of the pumped water is from groundwater storage (Figure 1a). As pumping continues, an increasing proportion of water comes from capture rather than storage (Leake, 2011; Leake et al., 2010) (Figure 1b). Assuming pumping has limited effects on groundwater recharge or non-stream discharge (e.g., groundwater evapotranspiration), pumped water inevitably depletes streamflow in aquifers that are hydraulically connected to surface water features, but the timing and magnitude of streamflow depletion depend on local hydrogeological conditions and well location and pumping rate (Bredehoeft & Durbin, 2009; Walton, 2011). In extreme cases, streamflow depletion can lead to the disconnect between the surface and groundwater systems and even dry up streams (Barlow & Leake, 2012; Bierkens & Wada, 2019). Preliminary studies have proven that streamflow depletion threaten environmental flow needs (defined as volume and timing of water flow required for the proper functioning of the aquatic ecosystem) and thus affect the health of the aquatic ecosystem at watershed (Essaid & Caldwell, 2017; Zeng & Cai, 2014; Zipper et al., 2019a), regional (Forstner & Gleeson, 2019; Maxwell & Condon, 2016; Reba et al., 2017), and global scales (de Graaf et al., 2019; Konikow & Kendy, 2005; Tang et al., 2019; Wada et al., 2012). Therefore, understanding streamflow depletion is critically important for conjunctive water management, particularly for regions with intensive groundwater consumption.

The main objective of technical note is to introduce the novel *analytical depletion functions* (ADFs) for streamflow depletion prediction as an effective and efficient new tool in the water sustainability toolbox for researchers, consultants and industry. For ease of use, ADFs have been implemented in the open-source ‘streamDepletr’ package for R (Zipper, 2019), but can be calculated in a relatively straightforward manner in any programming language. In this note, we show the

workflow of a single ADF which has performed best across multiple domains as an example, although we have tested more than 50 ADFs and other ADFs may be more effective in other hydrogeological settings. This methods note briefly reviews the methods that have been used for streamflow depletion assessment (Section 2), highlights the workflow for analytical depletion functions (Section 3), and reviews the performance of analytical depletion function in tested domains with diverse hydrogeological settings to enhance the confidence of applying ADF (Section 4). Finally, we discuss recommendations for using numerical models to study the impacts of groundwater pumping on streamflow since ADFs might be applied as a preliminary screening tool that could lead to developing numerical models for a region (Section 5).

Figure 1 a) Streamflow depletion and groundwater depletion caused by a groundwater pumping well. b) Status of streamflow depletion since the start of pumping: decreased groundwater discharge or induced infiltration of water from the river. c) Source of pumping groundwater from streamflow depletion and groundwater depletion through time since the start of pumping. Figures from Gleeson & Richter (2018).

2. Methods to quantify streamflow depletion

In practice, it is not feasible to quantify streamflow depletion in the field because (1) sufficient monitoring networks are often lacking, and natural flow variability creates challenges for isolating the changes in flow from pumping (e.g., Flores et al., 2020); (2) where measurement can be taken, streamflow depletion must be a significant fraction of streamflow so that changes in streamflow by pumping can be measured (Barlow & Leake, 2012; Flores et al., 2020); and (3) it may take days to decades for a well stress to be manifested in a stream depending on local hydrogeological condition, surface water and groundwater interaction, and distance between streams and well (Alley et al., 1999; Barlow & Leake, 2012; Bredehoeft & Durbin, 2009; Konikow & Leake, 2014; Walton, 2011). Thus, field measurement of streamflow depletion is only feasible for localized sites at a reach scale (e.g., Sophocleous et al., 1988; Hunt et al., 2001; Kollet & Zlotnik, 2003). Often the knowledge gained from a small scale cannot directly be applied at large watershed/regional ones due to the spatial heterogeneity in hydrological conditions.

Therefore, streamflow depletion is evaluated with a variety of non-field-based methods from local experts' guesses to advanced numerical models (**Figure 2**). Local experts guess can provide a rough estimates of streamflow depletion – for example, one could assign all streamflow depletion to the nearest stream segment with no time lags between the pumping the impact on the stream but this does not represent the spatial or temporal differences in pumping impacts on streamflow (therefore assumed to be low accuracy in Figure 2). Numerical groundwater models and analytical models are the two most common approaches to quantify streamflow depletion (Barlow & Leake, 2012). Numerical models are often considered the standard or ideal method for quantifying streamflow depletion as they are widely used for site-specific assessment and have a more sophisticated representation of the subsurface and the spatial and temporal differences in pumping impacts on streamflow compared to analytical models (Ahlfeld et al., 2016; Feinstein et al., 2016). Streamflow depletion estimates from numerical models are considered as the “gold standard” method for generating predictions, but they are often limited by data availability, and human and financial resources to develop, calibrate, and validate them (Rathfelder, 2016). In general, numerical models are calibrated for study sites based on historical field observations which is treated as a baseline scenario. To assess streamflow depletion, pumping scenarios can be simulated by either turning off existing pumping wells, changing their pumping schedules/volumes, and/or adding new

pumping wells. Streamflow depletion due to groundwater pumping can then be calculated as the difference in streamflow and stream-aquifer exchange between the pumping and baseline scenarios.

Conversely, analytical models are relatively easy to implement with low data and experience requirements (Flores et al., 2020; Reeves et al., 2009). Analytical models for a myriad of subsurface conditions and stream geometry types have been derived [see the details in review paper of Huang et al. (2018)]. For instance, analytical models have developed for confined (Theis, 1941; Glover and Balmer, 1954; Hunt, 1999; Chen & Yin, 2004; Sun & Zhan, 2007; Singh, 2009), unconfined (Huang et al., 2011; 2012), and leaky aquifers (Hunt, 2003; 2008; Butler et al., 2007; Zhan & Park, 2003) with zero- and finite-width stream, respectively. Among them, the most analytical models include one stream, while only Sun & Zhan (2007), Huang et al., (2014), and Huang et al. (2016) consider more than one stream but only design for two parallel streams. In practice, when implementing analytical models, practitioners may assign all streamflow depletion to one stream segment or the nearest stream segments experience a similar magnitude of streamflow depletion leading to overestimation. As such, the spatial impacts of pumping on streams cannot be evaluated which may be more pronounced when multiple pumping wells exist in the study domain. To our best knowledge, there is lacking literature in analytical models in complex, sinuous stream networks (Huang et al., 2014; 2018). It is commonly accepted that the accuracy of analytical models is generally lower than numerical models due to their simplifying assumptions. For instance, the commonly used Glover model (Glover & Balmer, 1954) assumes an infinite horizontal aquifer bounded by a single linear stream with full penetration of the aquifer. Therefore, there is an apparent gap between analytical and numerical models and a need to advance analytical models for the real-world settings with a complex stream network of multiple and meandering stream segments to improve the prediction accuracy potentially.

Figure 2 Diagram showing methods and accuracy in assessing streamflow depletion in conjunctive water management. Accuracy in this figure refers to the method that can estimate the streamflow depletion best in real-world settings with multiple streams.

3. Analytical depletion functions

To date, limited work has been done to advance analytical models' application in real-world settings with multiple sinuous stream segments. Before we developed analytical depletion functions (ADFs), to our best knowledge, the Michigan Water Withdrawal Assessment Tool (Reeves et al., 2009) is the only study that integrates the concept of depletion apportionment to distribute the depletion by a pumping well to adjacent stream segments. This method was tested in a single watershed for a single timestep. Inspired by this concept, Zipper et al. (2018) tested five depletion apportionment equations across wide ranges of stream networks in British Columbia and concluded the depletion apportionment with consideration of stream geometry performed best against the numerical model. Thereafter, Zipper et al. (2019b) developed more than 50 ADFs, in which different combinations of (1) *stream proximity criteria* used to determine which stream segments are most likely to be affected by a pumping well; (2) *depletion apportionment equation* which is a geometric method to distribute depletion among the affected stream segments; and (3)

analytical models are adopted to calculate the amount of depletion for all impacted stream segments based on the previous two components. Streamflow depletion predicted by ADF is significantly different from analytical models alone, and below in Section 4 we evaluate the performance of ADFs relative to numerical models (Zipper et al., 2018; 2019b; 2020; Li et al. 2020). Here, we first use the best performing ADF as an example to show the workflow of ADF.

3.1. A practitioner's workflow of analytical depletion functions

3.1.1. Data Acquisition

Geospatial data including stream network and well locations are the two primary input parameters, which are often available from government agencies and remotely sensed products [e.g., MERIT Hydro-a new global flow channel map at a spatial resolution of 90 m (Yamazaki et al., 2019)]. The availability of hydrostratigraphic units (i.e., hydraulic conductivity, water table depth, and storativity) are highly variable across global regions for various spatial scales. For small scales, the ideal estimates of hydrostratigraphic properties are derived from field data, such as pumping tests at specific study sites. For large regions, global data compilation of permeability and porosity [e.g., GLobal HYdrogeology MaPS, *GLHYMPS* (Gleeson et al., 2014; Huscroft et al., 2018)], for instance, can provide useful inputs for the ADFs. The choice and resolution of data should be consistent with research and management objectives, as the quality and scale of this data will strongly influence streamflow depletion predictions.

Figure 3. Diagram showing workflow to implementation of analytical depletion functions, which include (a) stream proximity criteria, (b) depletion apportionment equations, and (c) analytical model.

3.2. Data processing for analytical depletion function

The selection of the best performing ADFs is the key to calculate streamflow depletion. The preliminary assessments showed that the choice of depletion apportionment equation has the largest impact on streamflow depletion estimates with ADFs, followed by stream proximity criteria, and analytical model, which highlights the importance of ADFs over standalone analytical models (Zipper et al. 2019b). Zipper et al. (2019b) compared 50 ADFs concluding that a combination of “*adjacent + expanding*”, “*web squared*”, and *Hunt analytical model* (Figure 3) performed best in a case study in the Navarro River Watershed, California, USA and two different hydrologic landscape in British Columbia, Canada (Li et al., 2020). Thereafter, Zipper et al. (2020) further validated this conclusion in the Republican River, the USA with a different streamflow network and hydrogeological conditions, comparing results there with a calibrated numerical model as part of an inter-state water management compact related to managing streamflow. Since the best performing ADF was only tested in limited sites, it should be noted that other ADFs may have a better estimate in other regions. We, therefore, suggest the more case studies are needed to advance the application of ADFs.

The best stream proximity criteria for ADFs is “***Adjacent+Expanding***” (Zipper et al. 2019b; 2020). It selects any stream segment that is in a catchment adjacent to the well or is within the maximum radial distance where depletion would be at least 1% of the pumping rate at a given time step. Depletion apportionment equations calculate the fraction of total depletion allocated to each stream segment. The ***Web Squared*** depletion apportionment equation splits each stream segment into a finite number of points (e.g. space between each point is 5 meters) and apportion depletion based on the square of the inverse distance of each stream segment to the well as shown in Eqn. (1).

$$f_i = \frac{\sum_{p=1}^P \frac{1}{d_{i,p}^2}}{\sum_{j=1}^n \sum_{p=1}^P \frac{1}{d_{j,p}^2}} \quad (1)$$

where f_i is the depletion fraction of total streamflow depletion from a well apportioned to a stream segment, P is the total number of points which a stream segment is divided into the web squared equation, d is the distance from a well to a stream segment, and n is the total number of stream segments meeting the stream proximity criteria.

In the current “streamDepletr” package, the Glover (Glover & Balmer, 1954) and Hunt analytical models (Hunt, 1999) are included due to the simplicity of implementation. These two models have different assumptions of stream and aquifer interaction, which allows ADFs that can be applied in settings with variable hydrogeologic characteristics and data availability. Specifically, the Glover model assumes that streams fully penetrate the aquifer, i.e., no resistance to flow through the streambed, while the Hunt model assumes the streams partially penetrate the aquifer with a streambed clogging layer of finite thickness (b_r) and hydraulic conductivity (K_r) impede water exchange between the aquifer and streams. The volumetric streamflow depletion rate, Q_a of a stream segment can be calculated by Eqns. (2) and (3) for the Glover model and Hunt model, respectively.

$$Q_a = Q_w * \operatorname{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) \quad (2)$$

$$Q_a = Q_w * \left(\operatorname{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right) \operatorname{erfc}\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{4Tt}\right)\right) \quad (3)$$

Where , Q_w is the pumping rate (L^3/T); t is the time since the start of pumping (Time); d is the well-stream distance (L). S is the aquifer storage coefficient (e.g., specific yield in an unconfined aquifer, unitless); T is aquifer transmissivity ($L^2/Time$). Theoretically, T and S are the effective values averaged between pumping wells and affected stream segments. Zipper et al. (2018; 2019b; 2020) used the weighted average values of T and S of the shortest distance between well and stream segments while Li et al. (2020) adopted T and S at the well locations. As a result, two ways of calculations provided consistently accurate estimates of streamflow depletion. In Appendix, we introduced the method in detail to calculate the effective T and effective S for homogenous and heterogenous conditions. λ is the streambed conductance. The streambed conductance is defined as $\lambda = w_r * \frac{K_r}{b_r}$, where w_r is the width of the stream segments (L). It should be noted that λ in the Hunt model has a unit of $Length^2/Time$ and can be interpreted as the conductance per unit length of a stream (Li et al., 2020).

3.3. Potential applications, output analysis, and data visualization

The output of streamflow depletion can be used in various ways. *i)* ADFs can be used as a pre-screening tool that can help prioritize areas for more detailed further study using field study and/or numerical models and can save the cost for developing a local numerical model. *ii)* Based on the spatial impacts of streamflow depletion, watershed maps, for example, with different sensitivity of streamflow depletion can be developed to identify the most sensitivity stream segments to groundwater pumping to facilitate a target management approach. Also, the “capture maps”, which is similar to the one in Leake et al. (2010), can identify spatial impacts of depletion potential of a well. *iii)* The simple implementation of ADFs serves as a basis for developing the decision support tool. For instance, Huggins et al. (2018) demonstrated that ADFs were adopted to develop the conjunctive water management tool in British Columbia, Canada. *iv)* The importance of streamflow depletion has been well-recognized in water research and management communities. For instance, the *Sustainable Groundwater Management Act* (2014) in California, USA, identifies the depletion of interconnected surface waters as one of six core undesirable results. Similarly, the *Water Sustainability Act* (2016) in British Columbia, Canada mandates that groundwater pumping must not reduce streamflow below the environmental flow needs where they are hydraulically connected. Therefore, ADFs offer water managers a useful tool to consider streamflow depletion

when considering new applications for groundwater rights. v) This tool also allows users to define various scenarios, such as various pumping schedules (e.g., pumping rate and well depth), well-stream distance, and sensitivity tests of local hydrogeological parameters to understand local hydrogeological conditions.

4. Performance of analytical depletion functions in tested domains and future research

The performance of ADF has been tested across a wide variety of hydrologic landscapes, streamflow networks, and spatial scales in four watersheds (**Table 1**). The accuracy of ADFs has been tested by comparing against numerical models from archetypal (Zipper et al., 2018) to calibrated ones (Li et al., 2020; Zipper et al., 2020), from steady-state (Zipper et al., 2018) to transient conditions (Zipper et al., 2019b; Li et al., 2020), and have been adopted for theoretical tests (Zipper et al., 2018) to decision-support tools (Huggins et al. 2018; Li et al., 2020). Here, we consider three metrics that can comprehensively assess ADF performance: 1) *correct identification of most affected streams*, which is shown as the percentage of the most affected stream identified by ADFs and MODFLOW are the same; 2) *mean absolute error (MAE) for most affected stream segments normalized by pumping rate*, which is the MAE between the ADF and numerical model for the most affected streams; 3) *MAE for all affected streams normalized by pumping rate*, which quantifies the overall accuracy of ADF for all affected stream segments.

As shown in **Table 1**, ADFs can capture all most-affected streams in a small watershed (BX Creek) with simple hydrostratigraphic units and stream networks, while its capability reduces to more than 50% in large watersheds with complex hydrostratigraphic units and stream network (Republican River). In addition, the MAE of most affected streams is less than 15% of the pumping rate, indicating that ADF can accurately identify and predict the streamflow depletion for the most affected streams. Furthermore, the MAE for the affected streams is less than 5% of the pumping rate, which is much smaller than those of most-affected streams as streams experiencing small depletion and hence deriving small errors are included in the assessment. Based on the above summary, *the performance of ADFs proves that ADF is an accurate tool for the streamflow depletion assessment over the diverse hydrogeological landscapes and scales tested to date.*

Despite the overall acceptable performance of the ADFs in a limited number of studies, we also found that their performance varies with different hydrogeological factors.

1) ADFs had small errors with continuous pumping schedule in Navarro River watershed. Similarly, they had a good performance for the intermittent pumping, and tended to perform better during the pumping season than the non-pumping season in three domains (Zipper et al., 2019b; Li et al., 2020). Moreover, the performance of ADFs is insensitive to the pumping rate in the Republican River domain. Altogether, ADFs can be applied for both continuous and intermittent pumping schedule, but are more suitable for the pumping season when streamflow depletion is often larger.

2) Transmissivity and storativity are the two primary hydrostratigraphic input parameters for both analytical models and ADFs. Studies showed analytical models and ADFs are more sensitive to transmissivity than storativity (Zipper et al., 2018; Li et al., 2020). Furthermore, transmissivity and storativity play a more dominant role than other landscape factors such as distance to surface water, indicating that these model input parameters should be carefully selected to ensure the accuracy of streamflow depletion. However, variation in ADFs in response to transmissivity is not consistent. For example, ADF performed better in higher conductivity (transmissivity) areas in the BX Creek and Republican River domains, while the inverse trend was shown in the Peace region (Table 1), which is likely due to the differences in hydrological conditions.

3) Distance between affected streams and wells is the key variable to water management. In BX Creek and Peace region domains, better performance is found for wells within ~2 kilometers of a stream. Further, the best-performed areas are detected within 3 km in the Navarro River watershed. However, it should also acknowledge that ADFs performance in these areas is also variable as these regions often have higher streamflow depletion predictions and therefore higher uncertainties in an absolute sense. Therefore, the uncertainties within a few kilometers between stream and wells should be considered in the decision-making process.

4) Streambed conductance is an input included in the ADFs with Hunt model. In the Navarro River watershed, considering streambed conductance can improve the accuracy of ADFs, while streambed conductance may not be a significant factor that leads to the differences between Glover and Hunt model in both BX Creek and Peace region domains. Therefore, the choice of ADFs with different analytical models should consider local stream and hydrogeological conditions, while acknowledging that streambed conductance is an exceedingly difficult parameter to measure in the

field (Christensen, 2000). 5) Other landscape parameters can also affect the performance of the ADFs, which adds another layer of uncertainty in applying ADFs in the real-world settings. In BX Creek, Navarro River, and Republican River domains, ADF performed the best in small topographic relief where a shallow water table exists. Conversely, we detected inconsistent responses in the Peace region. Besides, Zipper et al. (2018) showed that ADF performance decreased with increases in drainage density and recharge rates. Therefore, our synthesis highlights that response of streamflow depletion to hydrogeological characteristics could be region-specific and additional testing in other hydrogeological environments is needed.

Here, we suggest the focus of future testing can be prioritized for the following issues.

- 1) Evaluate ADFs against actual field measurements of streamflow depletion, potentially from past experiments that have been conducted (e.g., Flores et al., 2020) in addition to further comparisons against numerical models.
- 2) Evaluate ADFs in hydrologic landscapes that have not yet been examined specifically, such as playas, coastal terrain, and hummocky terrain (Winter, 2001). As shown in Table 1, the previous assessments have focused on certain hydrologic landscapes (mountain valley, plateau and highlands and riverine valley).
- 3) Examine the appropriateness of the assumption of many analytical models that groundwater recharge and phreatophytic evapotranspiration do not change over the pumping period. Groundwater evapotranspiration and recharge have not considered in the preliminary assessment of the performance of ADFs. Groundwater pumping, however, can alter groundwater hydrological processes in the regions with substantial phreatophytic evapotranspiration. Zipper et al. (2020) found lower agreement between ADFs and a calibrated MODFLOW model when pumping was occurring near cells with phreatophytic ET.
- 4) Examine the cumulative impacts of multiple pumping wells on streamflow depletion rather than one-well-at-a-time, like most of our current assessments of ADF performance.

Table 1 Summary of the performance of analytical depletion function over the tested domains.

Domains	Domain size (km ²)	Elevation range (meter)	Hydrologic landscapes (Winter 2001)	Hydraulic conductivity ranges (m/s)	ADFs performance		
					Correct identification of most affected stream (%)	Mean absolute error (%) for most affected streams	Mean absolute error (%) for all affected streams
BX Creek Watershed, Canada (Li et al., 2020)	165	350~1850	plateau and highlands	$1 \times 10^{-8} \sim 1 \times 10^{-5}$	100	14	5
Navarro River watershed, USA (Zipper et al., 2019b)	816	0~211	mountain valley	1×10^{-5}	70	<15	-
Peace Region, Canada (Li et al., 2020)	1952	440~1580	riverine valleys	$7.7 \times 10^{-12} \sim 3 \times 10^{-3}$	83	7.6	2.3
Republican River watershed, USA (Zipper et al., 2020)	77868	450~1800	plateau and highlands	$3.5 \times 10^{-5} \sim 1.1 \times 10^{-3}$	>54	4.8	0.4

5. Recommendation of numerical models in simulating streamflow depletion: lessons from comparing streamflow depletion between analytical depletion functions and numerical model

In this note, we consistently compared ADFs to MODFLOW models, and also foresee ADFs as a useful tool for preliminary screening of potential groundwater pumping impacts, which in some cases might lead to developing a MODFLOW model for a region. Streamflow depletion can be modelled in a number of different ways in MODFLOW as well as other numerical models such as HydroGeoSphere (Brunner and Simmons, 2012) and ParFlow (Maxwell & Condon, 2016) as is outlined in textbooks such as Anderson et al. (2015) and Kresic (2006). In making multiple comparisons between ADFs and numerical models, we have learned some hard-won lessons about how to evaluate and develop numerical models effectively for estimating streamflow depletion that was not explicitly discussed in previous literature. Many of these lessons came when trying to compare ADFs against numerical models that had been previously developed and calibrated for purposes other than streamflow depletion. Although some of these lessons appear obvious (and

are to us in hindsight), they were not obvious to us from the start so we share these here, in the hopes that they may save others from having to find them on their own.

(Lesson 1) Numerical models used for streamflow depletion assessment should be designed for exploring surface and groundwater interactions. Each numerical model is developed for a specific purpose. When it is not designed to simulate the surface and groundwater interactions, and then transformed to study streamflow depletion by groundwater pumping wells, large and significant errors may be expected. Therefore, stream-aquifer exchange in both pumping and non-pumping conditions need to be included as part of the model calibration and evaluation process in order for a numerical model to be considered reliable for streamflow depletion. In the absence of field based objective assessment of the performance of the numerical models for calculating streamflow depletion, sufficient high-quality data is needed to fully realize the benefit of numerical models.

(Lesson 2) Small domain size is preferable for streamflow depletion assessment. Small domain size allows stream features that can be designed at fine spatial scale for each calculation unit (e.g., finite difference or finite element unit) in the numerical model so that the surface water and groundwater interactions can be well represented and thus pumping impacts on stream segments can be quantified accurately (Mehl & Hill, 2010; Brunner et al., 2010).

(Lesson 3) Mass balance error of numerical models should be minimized. To calibrate numerical models, mass balance error (the difference between total flux in and out of aquifer) should be minimized, otherwise these errors can overshadow the impacts of pumping on stream segments when pumping rates are much smaller than the mass balance. The same issue has been addressed in Leake, (2011), and mass balance errors tend to be larger in larger domains, lending further support to lesson 2.

(Lesson 4) Stream features in numerical models need to be properly selected for streamflow depletion assessment. To represent real-world surface water features, many types of flow boundary conditions have been proposed and developed. The correct selection of flow boundary conditions is the key to the success of streamflow depletion simulation. We suggest flow boundary conditions should be physically consistent to local conditions and aligned with the numerical model settings (Brunner et al., 2010; Li et al., 2020).

(Lesson 5) All components of capture (e.g., groundwater recharge and evapotranspiration) should be included. Streamflow depletion is only one component in the capture since groundwater

pumping can induce groundwater recharge and/or reduce evapotranspiration depending on local hydrogeological conditions, such as local water table, soil properties, evapotranspiration extinction depth (Kim et al., 2008; Maxwell & Condon, 2016). These components can be included in the numerical models, e.g., recharge (RCH), evapotranspiration (EVT), and unsaturated zone flow (UZF) packages in MODFLOW (Harbaugh, 2005; Niswonger et al., 2006).

6. Conclusions

Quantification of groundwater pumping on streamflow depletion is critical for water sustainability and management. In this note, we introduced an emerging approach, analytical depletion functions, which include capabilities that expand the utility of analytical models for real-world settings to evaluate the spatial and temporal groundwater pumping effects on streamflow depletion. The performance of analytical depletion functions has been tested by comparing them against the numerical models in different hydrological landscapes and stream networks. We conclude that analytical depletion functions can provide comparable accurate estimates of streamflow depletion to numerical models while requiring less data and experience to implement. This does not imply that analytical depletion functions can replace numerical models, but we see the potential benefits of using analytical depletion function as a preliminary screening tool to identify where the numerical model is needed to address the environmental issues resulting from streamflow depletion. Therefore, we highly recommend that water management can put analytical depletion functions in their toolbox to assess the potential environmental impacts of streamflow depletion on water resources sustainability, environmental flow needs, and aquatic functioning.

Conflict of Interests

The authors declare no conflict of interests.

Authors' Contribution

T.G. and L.Q. and S.Z. proposed idea for this note and conceptualize the figures. L.Q. wrote the first draft of the manuscript and drew the figures. S. Z. and T.G. developed the methods and figure for Appendix. All authors contributed to the writing.

Appendix***Calculating effective transmissivity and storativity in heterogeneous conditions***

Transmissivity (T) and storativity (S) are the two primary hydrostratigraphic inputs for the ADFs. Zipper et al. (2020) stressed that accurate inputs are the key to ensure robustness of streamflow depletion estimation. In homogeneous conditions, the T and S from any point, such as the location of the well, can be used as inputs for the ADFs. In the presence of subsurface heterogeneity, multiple hydrostratigraphic units, and/or variable aquifer thickness, the estimation of appropriate T and S values is more complicated (Figure 4). Hence, the effective transmissivity (T_E) and effective storativity (S_E) are typically used to represent the integrated hydrostratigraphic conditions between the well and affected streams.

In practice, there are often a mixture of datasets with different spatial resolutions within a domain. A typical case may be a gridded global dataset available in raster data format, and some regions also have localized data (e.g., aquifer boundary) with finer discretization than the global data. To facilitate the calculation of appropriate input parameters for ADFs, we explain here an approach to calculate T_E and S_E in heterogeneous conditions, including mixed-resolution input data. In our description, we assume that all input data are in raster format. For regions with finer localized polygon data, they should be rasterized at an appropriate resolution (i.e., resolution should not be finer than the data source used to derive the polygon) and intersected into the coarser dataset (Figure 4b).

To derive the T_E and S_E , we first calculate cell effective transmissivity (T_C , Eqn. A1) and cell effective storativity (S_C , Eqn. A2) for each raster cell intersected by a straight line between the well and the stream (inclusive) using the assumption of flow parallel to layering following Kollet and Zlotnik (2003).

$$T_C = (m_1 + m_2 + \dots + m_n) \left(\frac{K_1 m_1 + K_2 m_2 + \dots + K_n m_n}{m_1 + m_2 + \dots + m_n} \right) \quad (\text{A1})$$

$$S_C = \frac{S_1 m_1 + S_2 m_2 + \dots + S_n m_n}{m_1 + m_2 + \dots + m_n} \quad (\text{A2})$$

where, m and K are the thickness and hydraulic conductivity, respectively, of layer n at that grid cell. We then can calculate S_E as the arithmetic mean of all S_C between well and stream, and T_E

as the average of T_C (Eqn. A3) using the assumption of lateral flow perpendicular to the cells
(Domenico and Schwartz 1998)

$$T_E = \frac{\sum_{C=1}^{C_T} d_C}{\sum_{C=1}^{C_T} T_C} \quad (A3)$$

where C_T is the total number of cells between the well and the stream and d_C is the width of each cell C .

This approach allows calculations to take advantage of any available data source, regardless of resolution, and can also be used to calculate the T_E and S_E when comparing the ADFs to numerical models.

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