Groundwater

Technical Commentary/

Drawdown "Triggers": A Misguided Strategy for Protecting Groundwater-Fed Streams and Springs

by Matthew J. Currell

Introduction

There is increasing recognition of the importance of groundwater to the survival and function of terrestrial ecosystems (e.g., Ribeiro et al. 2013), which has grown from understanding of the intimate connections between groundwater and surface water (Winter et al. 1998). In this context, management strategies that can protect groundwater-dependent ecosystems (GDEs) such as springs and groundwater-fed streams are of critical importance. One strategy being adopted in some cases is the use of "drawdown triggers." This involves specifying an amount of acceptable drawdown relative to baseline at a particular monitoring point, which if exceeded, triggers a management response. This technical commentary examines this strategy, highlighting potential pitfalls. There are important aspects of the response of groundwater and connected springs and streams which may be overlooked if drawdown triggers are adopted as the primary strategy for GDE protection. A case study of a recently approved mining project is discussed and some additional and/or alternative approaches proposed.

Capture, Depletion, and Pitfalls of Drawdown Triggers

In a recent example (discussed further below), a "maximum allowable drawdown" at a springs complex was set as a key monitoring criteria and approval condition for a mining project in Australia. This section explains why using "drawdown triggers" in this way to protect springs and gaining streams can be problematic. At a practical level, drawdown in response to a new activity can be difficult to assess, as water levels in springs, streams, and monitoring wells nearly always vary due to a range or influences (e.g., climate, existing pumping, and plant water use). As such, establishing the drawdown related to a particular activity (such as abstraction for mining) relative to a baseline can be difficult. More importantly, the use of drawdown triggers ignores fundamental principles of how aquifers respond to abstraction—first outlined in C.V. Theis' classic paper (Theis 1940), and more recently in contributions to *Groundwater* (e.g., Alley and Leake 2004; Bredehoeft and Durbin 2009; Konikow and Leake 2014). Conceptually, it can be shown that during groundwater abstraction, a significant impact on spring or stream flow can begin to take place with minimal drawdown at the point of groundwater discharge (Figure 1), due to a reversal of groundwater flow direction. This means that drawdown triggers, particularly if monitored at the point of impact (e.g., the spring or stream itself) may not detect a significant effect on flux before it arises. This highlights the key point that aquifers respond in two ways to abstraction—through storage depletion and capture; the latter of which is not well quantified or monitored using a drawdown trigger.

In 1940, Theis set out the fundamental principles behind assessing impacts of groundwater abstraction on hydrological systems (Theis 1940). He first noted that all water taken by wells is "balanced by a loss of water somewhere"; intuitive to any hydrologist familiar with

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Article impact statement: Protecting groundwater-dependent ecosystems near mining developments requires more than setting drawdown "trigger levels."

[The copyright line for this article was changed on August 30, 2016, after original online publication]

Received December 2015, accepted March 2016.

doi: 10.1111/gwat.12425

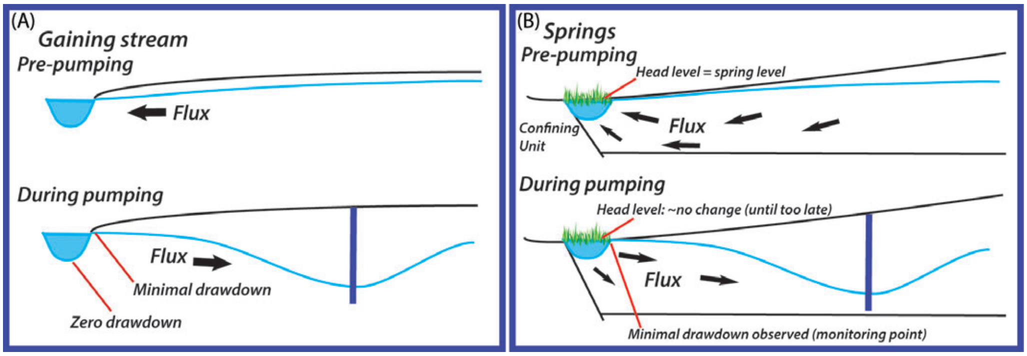

Figure 1. Conceptual scenario showing potential impact of groundwater abstraction on a gaining stream or spring, and the relationship with observed drawdown.

a water balance. Theis elaborated that water pumped for a groundwater development is always balanced by a combination of three possible sources:

1. An increase in recharge (e.g., incorporation of "rejected recharge")
2. A decrease in discharge (e.g., reduced flux to springs or streams)
3. Depletion of water in storage (e.g., manifest as declining groundwater levels)

The first two terms can be collectively called "capture"—water that was previously external to, or leaving the aquifer system (Konikow and Leake 2014). In most arid and semiarid environments, rejected recharge is minimal. Hence, the major water balance terms that change following development are capture of discharge and depletion of storage. While storage depletion can be readily measured and quantified by the amount of drawdown experienced (if storativity is known), capture of discharge is related to drawdown only indirectly. While it is true that the total extent of the area from which water is sourced by a development will experience some drawdown, the amount of water level change at the extremities may be minimal (Figure 1), and difficult to distinguish from baseline variability. As long as there is surface water available to be captured by pumping—that is, the system is not "capture constrained" (Konikow and Leake 2014)—drawdown at the point of discharge itself (e.g., streambed or spring outlet) will in fact remain negligible. Hence, monitoring the amount of drawdown in the vicinity of these features (a drawdown trigger) is not a good predictor of the impact of abstraction on the flux, and hence spring or stream flow.

Quantifying the relative importance of capture and storage depletion through time is required to correctly understand the impacts of groundwater abstraction on water balances (Bredehoeft 2002; Alley and Leake 2004; Bredehoeft and Durbin 2009; Konikow and Leake 2014). Both will occur in some combination in response to groundwater abstraction in almost all cases, and their importance depends on the context. For example, in an aquifer where pumping takes place close to other groundwater users, storage depletion may leave others unable to pump (e.g., Walton 2014). On the other hand, capture is of greatest concern where springs, waterholes, and streams depend upon groundwater discharge (or rejected recharge) to maintain flow.

When groundwater is pumped, as Theis and many others have since have proved, the most immediate effect is typically a decline in storage near the point of extraction. This manifests as drawdown in proportion to the aquifer's storativity and transmissivity. In the long term, drawdown tends to stabilize, storage depletion becomes less important, and the water extracted is increasingly balanced by capture of discharge that would otherwise reach the surface at springs or streams (Alley and Leake 2004; Konikow and Leake 2014). This is of course related to the drawdown—but only to the extent that the shape of a drawdown cone is relatable to groundwater levels, which dictate the hydraulic gradients, flow directions, and hence discharge fluxes. Hydraulic parameters also control the relationship between water levels and flux, meaning smaller or larger changes in water level can have variable effects on the flux. What is therefore important to recognize is that the capture of discharge (a flux) is not accurately predicted by measuring the amount of drawdown. A drawdown trigger is therefore likely to be an unreliable monitoring strategy, particularly if set at the point where discharge reaches the landscape. Only very minor drawdown need occur at this point for the flow direction to reverse, depriving springs or streams of flux (Figure 1).

Konikow and Leake (2014) showed that capture, not storage depletion, is the largest ultimate source of water derived from pumping in most major groundwater systems of the United States. They highlight, just as Theis and others since have, that capture of discharge is an inevitable long-term effect of pumping, which arises over a longer time period than the immediate (and often temporary) loss of storage. Their analysis is consistent with analytical models developed to estimate impacts of pumping on stream depletion, based on Theis' subsequent paper in 1941 (Theis 1941; Glover and Balmer 1954; Barlow and Leake 2012). These models demonstrate that for aquifers with typical ranges of transmissivity and storativity, "residual" effects on streamflow—for example, years after pumping ceases—can be significant. Konikow and Leake (2014) also introduced the idea of "capture constrained" systems, in which the amount of capture is limited by available surface flow. In these cases, storage depletion may temporarily re-emerge as pumping goes on (akin to a boundary effect during a pumping test). Most spring systems are likely to be capture-constrained, and thus highly sensitive to reduced groundwater discharge, as this is their only water source. They may therefore suffer a rapid loss of flux, with little advance warning in the form of a drawdown response.

Case Study: The Carmichael Mine

Recently, the Australian Minister for the Environment gave approval to the Carmichael Mine in central Queensland. If built (there remain financial hurdles and legal challenges may yet halt the project), it would extract approximately 5 to 12 million cubic meters of groundwater per year, for 60 years (GHD 2013). Within approximately 10 km of the proposed site boundary are two groups of springs—the Mellaluka and Doongmabulla Springs Complexes (GHD 2014). As part of the approval, the Minister imposed conditions to mitigate the mine's impact on the environment (Department of Environment 2015a, 2015b), including a 20 cm drawdown trigger at the Doongmabulla springs:

> I took a precautionary approach by imposing a drawdown limit of 20 cm at the Doongmabulla Springs Complex (condition 3d), to ensure that there are no unacceptable impacts to the springs. Department of Environment (2015b)

If the trigger is exceeded, the mine operators are required to adopt mitigation measures (GHD 2014). Similar triggers are adopted as monitoring criteria for the Mellaluka Springs and Carmichael River—a groundwater-fed stream in the area. As outlined in the Capture, Depletion, and Pitfalls of Drawdown Triggers section, this approach has a number of potential pitfalls. Most importantly, it ignores the importance of conducting a detailed water balance, including assessment of the capture and storage depletion that will occur in response to mining through time. The 20 cm drawdown trigger may in fact not be a good predictor of changes in flux at the springs. In practice, it is also likely to be difficult to monitor drawdown at the springs and distinguish it from natural variability, to the required level of accuracy.

The distance between the mine and springs in question also makes the use of drawdown triggers problematic. Capture of discharge will likely emerge after some time, due to this distance (depending on the hydraulic diffusivity). By the time noticeable drawdown has occurred at the springs, mitigation measures may come too late—for example, reducing pumping 10 km away may have little effect. However, due to the constrained amount of available water, once the mine begins to capture discharge, the decline in flows is likely to be rapid.

The Doongmabulla springs are in a topographic low point, fed by discharge from one the underlying Permian or Triassic sedimentary rock units (Bradley 2015). In fact, there is still uncertainty over the source aquifer providing flow to the springs. The mining company's experts propose that flux is likely sourced from shallow Triassic aquifers, separated from the layer targeted by mining by an aquitard (e.g., Bradley 2015). An alternative view proposes that the springs are fed by flux from deeper Permian units (possibly the unit targeted by mining), through weaknesses and/or faults in the aquitard (Webb 2015). Capture of discharge from the source aquifer will determine the level of impact to spring flow. As such, this uncertainty is concerning, and establishing the source aquifer through methods such as tracer studies and/or isotope sampling should be a priority. This would allow water level mapping, flux estimation (e.g., using well transects and monitoring of spring flow rates), and water balance assessment in this aquifer. Only then can accurate assessment of future changes (e.g., capture and storage depletion) be conducted through modeling. Regular mapping of water level patterns and measurement of flow rates at the springs could then provide a more effective monitoring approach during mine development, rather than relying on a drawdown trigger.

Additional/Alternative Approaches to Drawdown Triggers

In place of, or in addition to drawdown triggers, more comprehensive assessment and monitoring programs for GDEs generally should include the following:

1. Establishing the source aquifer for springs and/or groundwater-fed streams. This can be conducted using tracer studies, seepage meters, and other techniques (Rosenberry and La Baugh 2008);
2. Water level monitoring in the source aquifer (and other related aquifers), to establish flow patterns and baseline variability;
3. Monitoring of fluxes at springs (and if possible, groundwater-fed streams), including variability under predevelopment conditions;
4. Water balance analysis, including assessment of the relationship between water levels and fluxes, and assessment of future water balance changes—that is, capture and storage depletion—using modeling.

In terms of monitoring and assessment, "trigger levels" are still an important part of GDE monitoring programs. However, ideally triggers should be for specified water levels (not drawdown), determined to be critical for maintaining fluxes required for ecosystem function. Combining water level triggers and flux-based criteria (e.g., spring flows) can provide a more complete picture of water balance evolution and provide advance warning of impacts as they arise. This hybrid approach involving conjunctive use of trigger and flux-based management has been demonstrated to be an effective approach to protecting coastal aquifers from sea water intrusion (e.g., Werner et al. 2011).

It is important to note the difference between a *water level* trigger and a *drawdown* trigger. A water level trigger (e.g., minimum water level which triggers a management response) is a much clearer and more easily measured criterion than a drawdown trigger. As discussed earlier, drawdown triggers require deconvolution of drawdown related to the activity in question from other influences—often a difficult task. On the other hand, if a minimum water level can be determined on the basis of steps 1 to 4 above, on the understanding that it represents a threshold to maintain flux and/or GDE health, then this is a much more practical monitoring indicator. Water level triggers should also not be set (only) at the location of springs or streams themselves, but rather at a series of monitoring points with some set-back distance, to allow for time-lags in response to water balance changes.

At Carmichael mine, some aspects of this strategy, such as water level monitoring at wells between the mine and springs, will be adopted (e.g., URS 2014). However, the use of the drawdown trigger at the springs will still be the key metric used to decide whether management intervention is required. An alternative approach, based on the steps outlined above, would provide greater assurance that these GDEs can be effectively protected. The loss of springs could be of great consequence, as they are of high environmental significance and cultural value to indigenous and other Australians (Fensham et al. 2015).

Concluding Remarks

The discussion above highlights potential pitfalls of using drawdown triggers for monitoring and protection of GDEs, and proposes alternative strategies that are broadly applicable. It is important that these concepts are understood by the water and environmental management profession, and that the hydrogeology community ensures they are taken into account by decision makers, so that appropriate monitoring and assessment criteria are adopted to protect GDEs worldwide.

Author's Note: The author does not have any conflicts of interest or financial disclosures to report.

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