KGS RESEARCH SPOTLIGHT | 1
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Quantifying streamflow depletion from groundwater pumping: A practical review of past and emerging approaches for conjunctive water management

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What is streamflow depletion and why do we care?

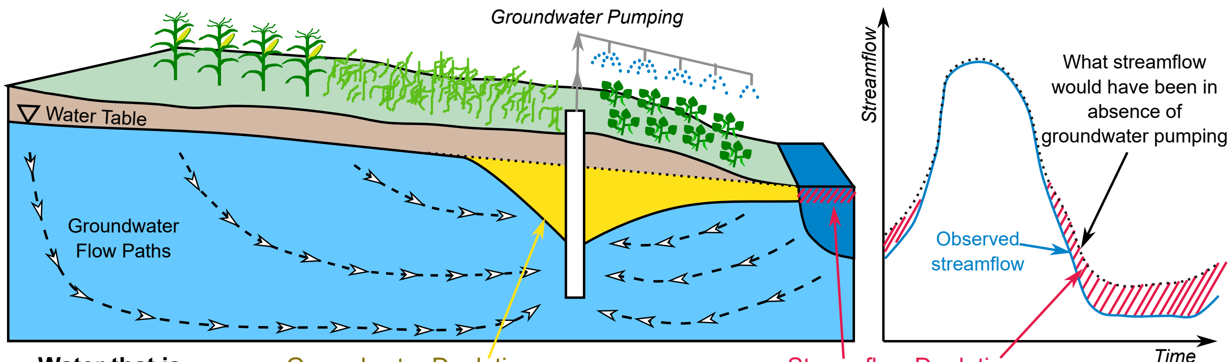
Streamflow depletion is a **reduction in the amount of water flowing in a stream caused by groundwater pumping.** Streamflow depletion occurs when wells capture groundwater that otherwise would flow from the aquifer to the stream or when wells lower the water table and increase the rate of loss when water infiltrates, or seeps in to, soil or porous rock through the streambed. Streamflow depletion can occur whether streams are gaining (inflow from groundwater to the stream) or losing (outflow from the stream to groundwater).

Estimates of streamflow depletion are often needed to answer three broad categories of water management questions:

1. **Attribution:** Does pumping contribute to decreases in streamflow and, if so, how do the effects of pumping compare to those caused by other factors that affect streamflow?
2. **Impacts:** What are the implications of streamflow depletion for water users, ecosystems, and society?
3. **Mitigation:** How can negative impacts of streamflow depletion be minimized?

How can I estimate streamflow depletion?

Streamflow depletion is challenging to quantify because the effects of pumping are hidden by variability in streamflow caused by weather or other human activities (such as surface water diversions or reservoir operations) and the time lag between when pumping occurs and when streamflow is reduced can be substantial. Streamflow depletion can be directly estimated at the scale of a stream reach, or section of stream between two specific points, using detailed field measurements, but this can require intensive effort and is not feasible for scales beyond a single stream. For estimation on a regional scale, approaches fall into one of three categories: analytical, numerical, and statistical models.



Water that is pumped from a well comes from two sources:

Groundwater Depletion
Pumping reduces groundwater storage.
This can be quantified by measuring changes in groundwater levels.

Streamflow Depletion
Pumping captures groundwater that would have flown into the stream and/or induces infiltration from the stream into the aquifer.
This cannot be directly measured and is challenging to estimate.

▶Analytical models

Analytical models use simplifying assumptions (such as assuming that a stream is linear, not curved, and that conditions in an aquifer are consistent across its extent instead of variable) to derive a mathematical equation for streamflow depletion. Analytical models tend to be the cheapest and easiest approaches to implement.

Example Tools

Glover model
Hunt model
semi-analytical models
analytical depletion functions

Real-World Application

Michigan Water Withdrawal Assessment Tool

▶Numerical models

Numerical models estimate changes in water storage and flux associated with groundwater pumping across a variety of scales and are often considered the gold standard of streamflow depletion assessment. They often involve creating a gridded representation of the landscape and are able to simulate complex stream-aquifer geometry and differences in aquifer characteristics as well as processes such as surface water management and flow of water through unsaturated soil above the water table. As a result, they tend to require the most expertise and time to develop.

Example Tools

MODFLOW
FEFLOW
ParFlow
HydroGeoSphere

Real-World Application

Republican River Basin

▶Statistical assessments and models

Statistical assessments and models attempt to infer streamflow depletion by analyzing the relationships between different variables such as streamflow, precipitation, and groundwater pumping. Statistical approaches are highly flexible in allowing different input data and target metrics but are challenging to attribute the causes of streamflow change to specific factors like pumping. They can be broadly divided into statistical assessments, which attempt to document streamflow change, and statistical models, which attempt to relate change in streamflow to potential predictor variables such as groundwater use and precipitation. The time and expertise requirements of different statistical approaches can vary widely.

Example Tools

trend analysis
regressions between streamflow and potential drivers
time series analysis
metamodels using machine learning

Real-World Application

Statistical methods have not been widely used for streamflow depletion estimation, though a mixed numerical-statistical approach is used in the Murray-Darling Basin

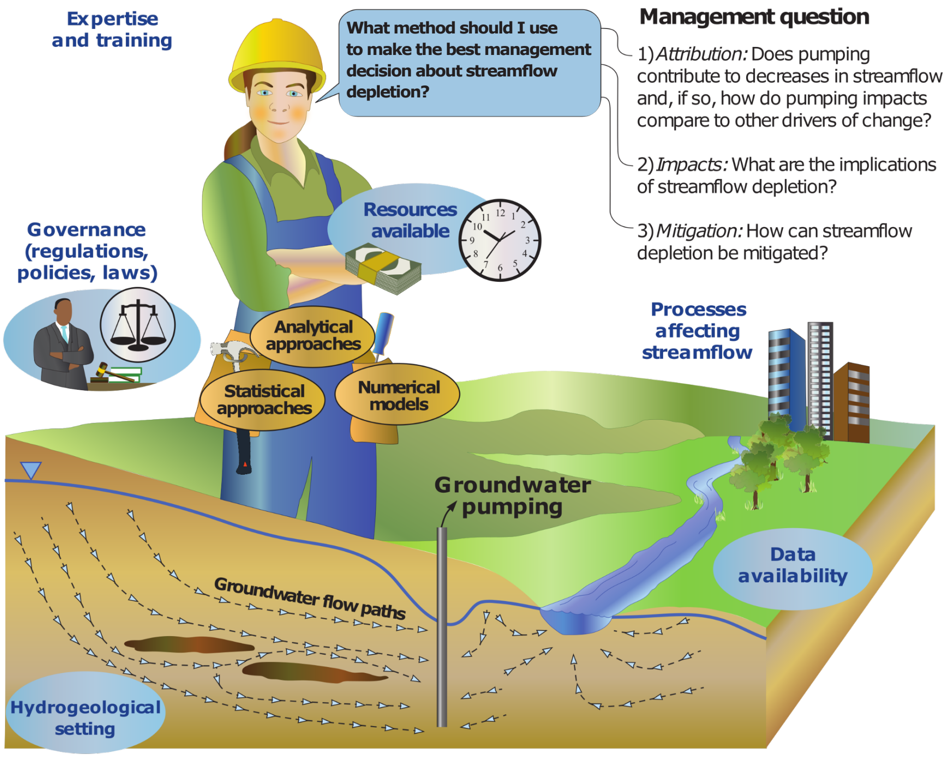
Strengths	Weaknesses
Analytical models	
• Easy to use: low data, expertise, and computational requirements • Able to quickly explore different pumping scenarios • Useful as a screening tool to prioritize further investigation with other approaches	• Reliant on many simplifying assumptions • Limited in capability for scenario analysis due to inability to represent many processes • Not available for many systems — typically calculate impacts of one well on a single stream
Numerical models	
• Physics-based representation of many processes in up to three spatial dimensions through time • Able to assign/test causation and explore different scenarios • Able to provide solutions for both flux (streamflow depletion) and storage (groundwater depletion) • Able to estimate prediction uncertainties • Guided by model physics, which may make predictions outside training conditions more reliable	• Data-, expertise-, and time-intensive • Computationally costly in large domains • Challenging/impossible to validate • Subject to mass balance numerical errors that can overwhelm pumping signal • Realistic in appearance even when errors are large
Statistical assessments and models	
• Adaptable to a wide range of information sources and target metrics • Not dependent on hard-to-collect subsurface data • Generally less computationally and expertise-intensive compared to numerical models • Well suited for analysis and simulation of long records	• Rarely capable of assigning causation • Not created at suitable space/time resolution for some management questions • Designed for specific objectives with challenges moving outside of that objective • Dependent on large datasets for training

How should I choose?

Streamflow depletion is challenging to quantify, and no approach is one-size-fits-all. Each method has strengths and weaknesses (see table on page 2), and the appropriate method will depend on numerous study-specific factors, such as the question of interest, resources available, processes affecting streamflow, hydrogeological setting, and the governance or regulatory situation.

Regardless of the specific quantitative tool used, the analysis should be:

- **well-suited to local conditions,** meaning that it can account for other potential influences on streamflow, and associated uncertainty, within the domain of interest;
- **actionable,** meaning that it can provide an estimate within an acceptable margin of error with input data that either already exist or can be obtained so that you can weigh costs, benefits, and risks of decision options;
- **transparent,** meaning that the logic behind the choice of the method is clear to those who will be affected by the streamflow depletion estimates, including the strengths, weaknesses, assumptions, and uncertainties; and
- **reproducible,** meaning that the necessary data files, inputs, calibration data sets, code, and sufficient documentation are available for others to reproduce your analyses.



When streamflow depletion estimates are meant to serve a management decision, it is critical to calculate and communicate the uncertainty in estimates (even though the true value of streamflow depletion can never be known) so that costs, benefits, and risks of given decisions can be weighed. This is particularly true when extrapolating any approach beyond the conditions in which the model was developed (i.e., testing different management scenarios). By being transparent about strengths, weaknesses, and uncertainties, affected parties and the public will better understand the logic behind decisions. Increased engagement with these groups can serve as a bridge to participatory approaches to streamflow depletion estimation that can enhance both scientific quality and societal impact around water management issues that can often turn contentious.

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The KGS has no regulatory authority and does not take positions on natural resource issues. The main headquarters of the KGS is in Lawrence in the West District of the University of Kansas, and the Kansas Geologic Sample Repository of the KGS is in Wichita.

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