Groundwater

Technical Commentary/

# Aspects of Groundwater Supply Sustainable Yield

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## Introduction

Groundwater supply sustainable yield is herein defined as how much water can be withdrawn from an aquifer system, where and for how long, with acceptable physical, economical, environmental, social, cultural, institutional, and legal consequences. The purpose of this Technical Commentary is to focus on the following technical aspects of groundwater supply sustainable yield that are sometimes overlooked: bounded supply, supply evaluation difficulties, aquifer system response time, supply management considerations, supply uncertainties, and needed supply evaluation and management improvements. These hydraulic and hydrogeologic aspects of aquifer development and management should be considered, along with political, social, and economic aspects, to successfully achieve a sustainable groundwater supply.

## Bounded Supply

Groundwater supply is bounded because precipitation and aquifer systems are bounded. There are five supply components as follows (see Bredehoeft 2011):

1. aquifer system storage;
2. discharge to and recharge from aquifer system surface water bodies;
3. evapotranspiration discharge from aquifer systems;
4. potential recharge being rejected in areas with shallow aquifer system water tables; and
5. capture of groundwater from adjacent basins in connection with groundwater divide movements.

Full capture of these supply components may not be feasible. Supply withdrawals cannot increase indefinitely because aquifer dimensions and interactions between aquifer layers are bounded, supply wells often only partially penetrate an aquifer, and large decreases in saturated thickness of aquifer layers with development result in rapid declines in supply well yields.

Because groundwater supply is bounded, special care must be taken in evaluating, managing, and utilizing the resource. Various groundwater sustainable supply sustained yield evaluation difficulties and uncertainties discussed below complicate optimized utilization and management of available resources. However, available sophisticated techniques and groundwater modeling tools may be employed to reduce these difficulties and uncertainties.

## Evaluation Difficulties

Available modeling tools for evaluating groundwater supply components with which the authors are most familiar are: MODFLOW for estimating head, drawdown, and budget data (Harbaugh 2005); models for estimating groundwater recharge (Rutledge 1998); models for simulating climate, land use, and supply availability (Markstrom et al. 2008); models for estimating evapotranspiration discharge (Scanlon 2005); models for estimating rejected infiltration and recharge in areas with shallow water tables (Niswonger et al. 2006); models for evaluating exchanges of water between the land surface and aquifer systems (Niswonger and Prudic 2005); and models for evaluating subsidence and aquifer system compaction (Leake and Galloway 2007).

Despite this impressive list of modeling tools available, supply evaluation is difficult and approximate because aquifer systems are heterogeneous, data bases are limited, and there is some degree of nonuniqueness in aquifer system conceptualization and modeling (Doherty 2011). For example, many difficult complications in modeling arise when heavily concentrated development results in portions of source and confining layers becoming unsaturated thereby restricting vertical flow due to the several order of magnitude decreases in hydraulic conductivity. Modeling the effects of unsaturated portions of multilayer aquifers is difficult and approximate because unsaturated conductivity is uncertain, there is a several order of magnitude increase in the storativity of unconfined versus

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Received May 2012, accepted October 2012.



doi: 10.1111/gwat.12001

confined layers, partial reversal of flow occurs from and into layers, and there are delays in vertical flow to and from layers.

Modeling potential recharge from induced infiltration of streamflow is also difficult for the following reasons. Induced recharge from surface bodies of water varies with the surface body dimensions and the temperature of the surface water (Rorabaugh 1956). During periods of high streamflow, streambeds are scoured and the leakance increases (Nortz et al. 1994). During periods of low streamflow, fine materials are deposited in streambeds and streambed leakance decreases (Norris 1983a,1983b). When groundwater levels are lowered below a streambed underlying materials become unsaturated and seepage loss from a stream is restricted by the reduced vertical hydraulic conductivity of the underlying materials (Niswonger and Prudic 2006).

## Management Considerations

The time frames of groundwater supply management planning are usually constrained by the difficulties and uncertainties of future withdrawal projection. Aquifer system response time may appreciably exceed the planning time frame, especially if the aquifer system has a large areal extent (see Gleeson et al. 2012). In addition, locating supply wells as close as possible to aquifer system surface water recharge areas such as streams minimizes the equilibrium time after a change in groundwater withdrawals. Response time can increase greatly with supply wells located at increasing distances from recharge areas (Sophocleous 2002).

In multilayered aquifer systems, the aquifer system response time depends upon whether withdrawals are from shallow layers, deep layers, or both. Evaluation of future withdrawal impacts in aquifer layers, especially the uppermost unconfined layer, based on model studies and planning time frames can differ appreciably from evaluations based on aquifer system response time frames. The acceptability of possible impacts beyond the specified planning time frames and at least some preliminary planning for coping with these impacts need to be addressed.

Initially, when supply is abundant in relation to withdrawals the criteria commonly used to determine the yield and spacing of supply well fields is primarily based on cost effectiveness concepts. Consideration of maximized and optimized development concepts (Theis 1940; Spitz et al. 2008) increases as demand approaches supply. Maximized development results when supply wells are distributed as uniformly as possible in withdrawal areas and throughout the aquifer system and, in certain settings, located as close as possible to surface waters. Maximized development avoids excessive dewatering of aquifer system layers but does not necessarily minimize the potential impacts of development on in-stream uses and aquatic and riparian ecosystems.

Optimized development (see Ahlfeld et al. 2009) employs optimization and groundwater flow modeling to determine optimal supply locations and withdrawals. This approach sets constraints, modifies current supply withdrawal schedules and configurations, and then evaluates the impacts of future supply development patterns subject to these constraints instead of extrapolating withdrawals with existing patterns of supply wells and evaluating their impacts. Strategy options for optimization include limiting groundwater level declines or streamflow depletions; practicing artificial recharge, conservation, and reuse; and conjunctively using groundwater and surface water resources.

## Evaluation and Management Improvements

In estimating sustainable yield, it should be more fully recognized that the sustainable yield of a groundwater supply depends partly on the location and partial penetration of supply wells; that full capture of surface recharge by deeply partially penetrating wells may not be possible; and that in-stream uses and aquatic and riparian ecosystem impacts (Alley et al. 1999; Galloway et al. 2003; Niswonger and Prudic 2005) can be minimized but not eliminated.

Further, additional attention should be given to estimating water budgets for all aquifer and confining layers, appraising the possibility of upconing of poor quality groundwater, using production well pumping water levels as a planning constraint, incorporating the concept of aquifer system response time in supply modeling, translating water level declines into quantifiable environmental impacts, and discovering and adopting ways and means of coping with supply modeling uncertainty (Nilsson et al. 2007, Doherty 2010) including, most importantly, planned periodic groundwater supply sustainable yield post audit validation, revision, and refinement (Hassan 2004).

Finally, as discussed in recent studies (Kinzelbach et al. 2003; Goesch et al. 2007; Singh et al. 2010), concepts such as "uncertainty quantification" and "planning under uncertainty" could be more fully incorporated into sustainable groundwater supply management programs to ensure that uncertainty does not unduly hinder continuing progress toward improved management.

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