ground water

Issue Paper/

Defining and Managing Sustainable Yield

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Abstract

Ground water resource management programs are paying increasing attention to the integration of ground water and surface water in the planning process. Many plans, however, show a sophistication in approach and presentation that masks a fundamental weakness in the overall analysis. The plans usually discuss issues of demand and yield, yet never directly address a fundamental issue behind the plan—how to define sustainable yield of an aquifer system. This paper points out a number of considerations that must be addressed in defining sustainable yield in order to make the definition more useful in practical water resource planning studies. These include consideration for the spatial and temporal aspects of the problem, the development of a conceptual water balance, the influence of boundaries and changes in technology on the definition, the need to examine water demand as well as available supply, the need for stakeholder involvement, and the issue of uncertainty in our understanding of the components of the hydrologic system.

Early Concepts of Sustainable Yield

Before the broader implications of ground water consumption were more completely understood, sustainable yield was generally confused with the simple concept of aquifer yield. In a practical sense, this meant defining how much water could be extracted from the aquifer based on the hydraulic characteristics of the aquifer itself. The gradual expansion of the concept of sustainable yield from simple aquifer yield to the more complex idea that the term sustainability represents has a long history. Alley et al. (1999) and Alley and Leake (2004) provide an excellent description of the historical development of the concept of sustainability from the original safe-yield concepts derived from water supply engineering studies through the more recent concept of sustainability. Bredehoeft (2002) demonstrates that sustainable pumping rates are better defined by equating the capture of water by pumping to the change in the natural rates of ground water recharge and discharge (usually to rivers, lakes, or the ocean). His point is that estimating natural recharge is relatively unimportant to defining sustainable pumping rates. It is the natural pattern of discharges, as well as the changes that occur to recharge and discharge caused by ground water pumping, that matter.

Sophocleous (1997, 1998, 2000) pointed out the significant gap between what is known about safe yield and what is applied, and called for bridging the gap between research and practice. The American Society of Civil Engineers (ASCE) Task Committee for Sustainability Criteria (1998) proposed an inclusive definition of sustainability. Their definition, "Sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity," represents a broadening of the concept to include societal, ecological, and environmental needs (Loucks et al. 2000). It is a reasonable starting point in an attempt to stop trying to "determine a fixed sustainable yield . . . [but] recognize that yield varies over time as environmental conditions vary" (Sophocleous 1997).

A Practical Approach to Defining Sustainable Yield

The following considerations are intended to provide guidance in developing a practical, working definition of sustainable yield. If sustainable development must be all-inclusive, as the ASCE definition implies, the idea that

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there exists a single, correct number representing sustainable yield must be abandoned. In fact, it may not be possible to completely address the full complexity of the concept of sustainability in many situations. Much can be gained, however, by an organized approach toward developing a working definition, coupled with an adaptive management approach. The principal considerations in defining sustainable yield are discussed here.

Understand the Spatial Aspects of the Problem

Pay attention to the spatial aspect of the problem. Spatial scale must be understood and defined, or the concept of sustainable yield becomes meaningless. For example, defining the sustainable yield over a relatively large area may result in seemingly low rates of withdrawal per square kilometer. Total use of ground water, when compared to total recharge and discharge, may suggest little worry and a sustainable situation. This ignores more local effects of ground water pumping that might heavily influence an important ecosystem (e.g., a wetland, a scenic stretch of river, a first order stream), cause localized salt water intrusion, or degrade a sensitive plant community that is dependent on a certain water table depth. Thus, understanding where withdrawals can best be made and identifying areas where impacts are to be minimized (or maximized) are critical considerations in defining sustainable yield. Define sustainable yield on a scale small enough to address important local impacts, but large enough to recognize the ability of aquifer systems to adjust to pumping stress.

Develop a Conceptual Water Budget

A good way to stimulate a discussion on sustainable yield among stakeholders is to develop a water budget that represents the relationship between the natural watershed system and human intervention in the water cycle. The water budget will emphasize an important point—defining sustainable yield of an aquifer system can no longer be limited to just ground water. Both the ground water and surface water systems must be considered, along with constructed systems such as water supply, waste water treatment, and storm water collection. Through quantifying each component in the water budget, the building blocks of a definition of sustainable yield are developed through the easily understood concept that water "in" must equal water "out." The components of the water budget also help organize the necessary data collection, analysis, and modeling that often is needed to develop estimates of each of the terms of the water budget.

A water budget is crucial because it requires that the entire flow system of the aquifer is well understood. This includes understanding the change in the amount of water in storage and the amount naturally recharging and discharging from the aquifer, the amounts taken or recharged through human intervention, as well as the hydrogeologic properties governing where and how much water can practically be withdrawn. In most situations, such an understanding can be gained only by simulating the aquifer system with numerical flow models.

Understand the Boundaries of the System

The boundaries of the aquifer system under consideration are often critical to defining the water budget and sustainable yield. Boundaries can represent water lost or gained from over- or underlying aquifers, areas of direct recharge, areas of subsurface discharge to coastal areas or lakes, and discharges to streams as base flow. For example, some systems are essentially nonrenewable resources (e.g., deep confined aquifers with limited recharge, fresh water trapped offshore during periods of low sea level). The whole concept of sustainable yield breaks down in those situations. In other situations, the recharge of the aquifer might vary depending on the amount of water withdrawn. Well systems near a lake or river are typical examples of this.

Understand Water Needs

The water budget includes man's intervention in the water cycle, i.e., ground water pumping and recharge, as well as surface water discharge and withdrawals. The extent and timing of future water needs must be understood. This includes an understanding of where demand will occur, how much water will be required, and when it will be needed. Because defining sustainable yield will inevitably require tradeoffs, understanding demand growth, attitudes toward risk, and the limits and opportunities for demand management are critical to developing a working definition of sustainable yield. This question was addressed recently by Howard (2002). Howard's idea is that water resource sustainability must be considered within a framework of probability. Sustainable yield as measured by risk has three main components—probability of water supply shortages, the costs when shortages occur, and the level of acceptability of the risks. Thus, sustainable yield also must consider reliability and cost of failure. This makes sustainable yield dependent on the probability of certain occurrences, and a consensus on the acceptability of risk of failure. According to Howard, sustainability must be defined as "a system that maintains acceptable risk over an indefinite time horizon." The risk is a function of uncertainty in both supply and demand, as well as their interaction in time and space. The risk associated with supply is increased when one considers that significant uncertainty exists in estimating almost all the terms in the water balance, resulting in a range of probability for any calculation of sustainable yield.

Consider the Temporal Aspect of Sustainable Yield

Bounding the problem is not only an issue of space, but also of time. Pumping, recharge, and ecological response are all time dependent, changing over varying periods (days, seasons, multiyear trends, etc.). Thus, sustainable yield must be defined over a specific time period. Do we wish to minimize impacts under average conditions, or during droughts? Can we vary withdrawal according to the availability of water? Can we manage demand differently according to season or water availability? Several regulatory agencies in New England already use seasonally varying base flow in streams as one approach to assessing sustainable yield.

Consider Effects of Changing Technology

Another consideration might be the effects of changing technology on future need and availability. In other words, future definitions of sustainable yield may change as technology places new sources within reach, or makes old unusable sources once again available for use. Examples might include coastal areas where desalination technology makes brackish zones a viable source of drinking water, or areas that are currently contaminated but can now be remediated by emerging soil and ground water treatment technologies. Such considerations may alter our concept of intergenerational fairness when considering sustainable yield, and should be considered in defining sustainable yield.

Work with Stakeholders to Understand Tradeoffs

Tradeoffs between impacts are inevitable. One tradeoff that often arises is finding a balance between meeting demands for potable water and maintaining a healthy aquatic ecosystem. The current debate between Georgia and Florida on the use of water from the Apalachicola-Chattahoochee-Flint river basin essentially entails a debate on the tradeoff between aquifer pumping for agriculture in Georgia against the need for sufficient flows of fresh water into Apalachicola Bay to maintain an estuarine ecosystem. Another tradeoff is between current water supply needs vs. future needs. For example, a coastal aquifer may have a large body of fresh water stored offshore. Should this water be extracted using coastal wells to meet current needs? Should it be preserved for future generations? Perhaps it can be used judiciously over an agreed upon period of time, thus bridging a current crisis and providing time for alternative sources to be found. This is one issue facing coastal Georgia, where significant nonrenewable offshore fresh water resources are being tapped through pumping near Savannah.

Recognize Limits to Our Knowledge

There are inherent uncertainties in our understanding of the components of the hydrologic system that must be taken into account in our definition of sustainable yield. However, a broader definition introduces additional elements of uncertainty. Simply striving to understand the hydrology of the aquifer system is no longer sufficient to address the issue of sustainable yield. The ASCE definition implies much more. We must now understand the impacts of pumping and its effect on the ecosystem. A recent article on ecohydrology put it as follows.

> The questions that society asks often are not simply focused on hydrology, but are more encompassing; for example, "what is the effect of pumping on this spring/lake/trout stream/wetland?" The hydrologist can collect hydrogeological data, construct a model, and develop a defensible estimate of water level declines and flux reduction. However, that is not what was asked. The public cares about the effect on things it can relate to—plants, birds, fish, or other animals of interest. So the hydrologist is not expected to stop at reporting the water level and flux declines, but is expected to relate the declines to the biotic components in the environment. Unfortunately, this is the abyss. There are few studies linking the abiotic effects hydrologists know well to the ecological community the public holds dear (Hunt et al. 2003).

These are precisely the issues facing us on the Flint River in Georgia. How does agricultural pumping impact the aquatic life in the river? What, exactly, is the most sensitive component in calculating sustainable yield? Cooperative research between hydrologists, ecologists, biologists, and limnologists is occurring, and will need to bear significant fruit before the links between hydrologic impacts, habitat, and biological impacts can be fully integrated into our assessment of sustainable yield.

Adaptive Management: Dealing with Uncertainty

Our knowledge on how to quantify the causes of impacts is limited. Our perception of risk can change over time. Our priorities with regard to the acceptability of tradeoffs can change as our knowledge and situation change. All these factors have led to the concept that water resource management must be adaptive and flexible. Recent trends in resource management focus on the concept of adaptive management. Adaptive management treats management policies and actions as experiments, not fixed policies. Management must continually improve by learning from the ecosystems being affected. Adaptive management links science, values, and the experience of stakeholders and managers to the art of making management decisions. Some fundamental ideas for adaptive management can be found in Ludwig et al. (1993). They suggest a set of prescriptions for practicing adaptive management as follows.

- Include human motivation and responses as part of the system to be studied and managed.
- Act before scientific consensus is achieved. Calls for additional research may be delay tactics.
- Rely on scientists to recognize problems, but not to remedy them. Scientists and their judgments are subject to political pressure and their disciplinary training.
- Question claims of sustainability.
- Confront uncertainty. Consider a variety of plausible hypotheses about the world, consider a variety of possible strategies, and favor actions that are robust to uncertainties.
- Favor actions that are informative, probe and experiment, update assessments, and favor actions that are reversible.

The concept of adaptive management appears to be the only viable approach in dealing with the uncertainties in knowledge and the variability of societal attitudes toward the resource. Yet it also presents an important dilemma. Defining sustainable yield implies some form of control of water use, usually resulting in the requirement for withdrawal permits for water suppliers and other users. Permittees seek consistency and stability in permit conditions. Stability and consistency are needed to make long-term planning and capital investment possible, and to be able to plan and/or guarantee supply to users for the period of time for which the permit is issued. The inherent tension between the need for consistent permit terms and the requirements laid out in the adaptive management approach is real, and must be an explicit part of the applied management process.

Adaptive management must be a collaborative and consensus-seeking approach. It is our responsibility as scientists and engineers to investigate as many of the impacts as possible, share the results with stakeholders, and help them make the management decisions that maximize benefits and minimize negative impacts. This requires a stakeholder-supported decision process in which all considerations relevant to the specific problem are addressed or at least discussed. The disparate tradeoffs must be clear, and stakeholders must understand what they are trading.

A Sampling of Approaches

There are no perfect examples of how to define sustainable yield; nevertheless, it is interesting to note how this problem has been addressed in various places. Several recent examples are provided here to illustrate some of the complexities inherent in the recommended approach. For each example, a summary box (Tables 1 through 3) is provided illustrating how some of the relevant considerations were handled.

Nassau and Suffolk Counties, New York

Nassau and Suffolk counties are both located on Long Island and share the same glacial outwash aquifer system. The aquifers are sand and gravel, with three distinct aquifer systems separated by confining units. Nassau County, adjacent to New York City, developed earlier than Suffolk County, with a rapid expansion of housing during the 1950s. With an area of ~500 km^2 and a population of ~1.3 million people, it is a fairly densely populated suburban county. During the 1970s and 1980s, with nitrate concentrations increasing due to on-lot septic system discharges, ~90% of the county was sewered, with ocean outfalls used for treated effluent disposal. As a result, the consumptive use of ground water (water pumped out of the aquifer and not returned through recharge or on-lot septic systems) rose to ~250 Mm^3/yr. The water table declined until, after a period of ~10 to 15 yr, a new equilibrium was reached. The principal response of the aquifer system to sewering was a reduction in the natural discharge of ground water, either to streams or to the ocean, by an amount almost equal to the increased consumptive use. Is the current consumption of ground water sustainable? Modeling and monitoring show that it is; however, a de facto decision was made to allow the streams to dry up in exchange for improved ground water quality (Nassau County Department of Public Works 1990).

Suffolk County is very similar to Nassau County, but is > 2000 km^2 in area, and has a population only slightly higher than that of Nassau County. Aquifer recharge on a per unit area is the same; however, sewering in Suffolk County accounts for < 70 Mm^3/yr of consumptive use. As a result, most streams in Suffolk County still have relatively unchanged base flow. Suffolk County, unlike Nassau County, chooses to protect its streams and wetlands, and monitors changes in the aquifer system and the wetland areas very closely (Suffolk County Department of Health Services 2003). Should declines occur at key surface water features, protection measures have been planned.

Nassau County, with dry streams and areas of salt water intrusion, set a strict consumptive yield ceiling on ground water pumping in cooperation with New York State. This was a reactive approach, responding to impacts that had already occurred, with the intent of avoiding further, undesirable consequences. Although a formal definition of sustainable yield has not been made in Suffolk County (i.e., a defined, maximum level of ground water consumption), the acceptable impacts to streams have been defined. This will have a profound effect on the allowable amount of ground water consumption in the future. Permissible sustained yields have been tentatively defined in water budget areas as percentages of the average recharge rates in order to control salt water intrusion. During the next phase of water resource planning, the sustainable yield of the aquifer in Suffolk County will be further modeled and, it is hoped, defined with extensive stakeholder participation. It is very clear from the planning objectives, however, that the definition of sustainable pumping intensity (ground water withdrawal rates per square kilometer) will be several times lower in Suffolk County than the comparable sustainable

Table 1
Long Island Sustainable Yield Example

Spatial aspect	Countywide analysis (500 to 2000 km^2), with smaller regional analyses where required. On peninsulas and islands, salt water intrusion is a concern; separate sustainable yields were needed on a smaller scale.
Conceptual water balance	Hydrologic mapping, aquifer testing, three-dimensional, transient ground water and salt water intrusion modeling.
System boundaries	Recharge was estimated, flow system included discharge to stream and underflow to surrounding salt water bodies.
Water demand	Disaggregated water demand analysis based on population, household, and economic trends.
Temporal aspects	Analysis of salt water intrusion over decades to centuries; consumptive use controls applied on an annual basis.
Stakeholder interaction	Limited to technical advisory committee, public information distribution.
Primary concern	Meeting drinking water demand (Nassau County); maintaining stream base flow and wetlands (Suffolk County).

pumping intensity in Nassau County. This simply illustrates the importance of the chosen definition of sustainability.

Chester County, Pennsylvania

Chester County is a developing area west of Philadelphia. It still has a mix of suburban, rural, and protected open space, with a dense network of streams and rivers that very much define the character of the county. In 2002, the Chester County Water Resources Authority (CCWRA) developed a comprehensive water resources plan (Chester County Water Resources Authority 2002); one of the largest issues addressed was sustainable yield. In this case, a large and active stakeholder task force participated in the entire planning process and many discussions (and compromises) were directed at settling on a workable definition of sustainable yield. The task force considered many definitions of sustainable yield and many ways of measuring it. Eventually, stream base flow was selected as the standard against which ground water pumping would be measured because it represents exposed ground water, thus providing the link between the ground water system and the streams that are so important to the county. The standard by which the health of the ground water/surface water system is measured is stream base flow under drought conditions, because base flow maintenance during droughts is critical to aquatic habitats in many sensitive areas. The task force selected the 1 in 25 yr annual average low flow as the standard, both for practical reasons (it fit in best with current regulatory tools), as well as to forge a compromise between more stringent low flow numbers (such as the 7Q10 flow to protect aquatic habitat) and the need to accommodate population growth.

The CCWRA funded an extensive study on water budgets in each of the 21 watersheds and 78 subwatersheds in the county, and estimated the 1 in 25 yr annual low flow from unit discharges from each of the geologic formations found in the area. Much discussion focused on the scale at which the standard would be applied, with the eventual decision to apply the standard at a subwatershed level (~25 to 130 km^2). Additional restrictions were placed at a smaller scale in certain areas to protect first order streams. As a result, total ground water consumptive use within each subwatershed will be restricted to the 1 in 25 yr annual low flow or to half that number in certain, designated sensitive subwatersheds.

Gaza Strip

The Gaza Coastal Aquifer is the single most important natural source of water in the Gaza Strip. With a population of ~1.1 million and one of the highest birth rates in the world, the water resources of the Gaza Strip are under considerable strain and future predicted demands far exceed available supplies. Overexploitation of the coastal aquifer has resulted in continuous lowering of regional water levels and a gradual worsening of water quality. The greatest threats to existing water supplies are sea water intrusion and upconing of deep, fossil brines. There are more than 4000 municipal and agricultural wells pumping ~140 Mm^3/yr from the coastal aquifer. The estimated net water balance of the Gaza Coastal Aquifer is negative; i.e., there is a water deficit. Manifestations of the water deficit are lowering of water levels and a documented deterioration of water quality. In some wells, documented rates of salt water intrusion are resulting in chloride increases of nearly 10 mg/L/yr. The rate of reduction in aquifer storage is estimated to be ~5 Mm^3/yr (Moe et al. 2001).

Unlike the two examples in the United States, issues of aquatic habitat and stream base flow are not part of the sustainable yield discussion. This is primarily because perennial streams do not exist there and the need for potable supply is so overwhelming. Ground water modeling has been carried out, and consumptive use and natural recharge have been estimated. The situation is serious, with consumptive use of ground water of 140 Mm^3/yr far exceeding the estimated long-term average natural recharge rate of ~40 Mm^3/yr. Plans for alternative sources of water, with reductions in ground water pumping to equal natural

Table 2
Chester County Sustainable Yield Example

Spatial aspect	Surface subwatersheds used as basis for analysis. Subwatersheds of 25 to 130 km^2.
Conceptual water balance	Water balances developed on the basis of permitted discharges and withdrawals, well pumping estimates, estimates of septic system discharges, stream base flow analysis, and precipitation records.
System boundaries	Subwatershed boundaries developed from USGS watershed delineation. Ground water basins assumed to be the same. Fractured bedrock ground water system, streams as primary discharge boundaries.
Water demand	Demand projections for 20 yr horizon based on population growth projections. Considerable population and water demand growth anticipated.
Temporal aspects	Analysis of drought condition impacts on streams on weekly and annual basis; consuptive use controls applied on an annual basis.
Stakeholder interaction	Extensive, with monthly Technical Advisory Committee meetings, public hearings, Web site, and monthly newsletter.
Primary concern	Maintaining stream base flow and aquatic habitat while meeting reasonable growth in population and water demand.

Table 3
Gaza Strip Sustainable Yield Example

Spatial aspect	Countrywide analysis (ca. 400 km^2).
Conceptual water balance	Hydrologic mapping, aquifer testing, development of three-dimensional ground water and salt water intrusion models.
System boundaries	Recharge of aquifer and subsurface discharge to Mediterranean Sea.
Water demand	Planning for meeting current needs overwhelming. Immediate demand is primary focus.
Temporal aspects	Analysis of salt water intrusion over decades; consumptive use analysis on a seasonal and annual basis.
Stakeholder interaction	Extensive, with public meetings, interviews with households, and a government advisory council.
Primary concern	Meeting immediate health concerns due to inadequate quantity and quality of drinking water.

recharge, are being developed. In Gaza, sustainable yield is being defined as almost equal to natural recharge of the aquifer on an average annual basis because the intent is to maximize withdrawals by eliminating all but the minimum subsurface discharge to the ocean needed to minimize salt water intrusion.

Conclusions

These brief examples show that sustainable yield is a flexible concept, one that must take account of the hydrologic system, the concerns and needs of the inhabitants, the potential impacts to ground water quality, and environmental side effects. In most cases, a definition of sustainable yield is never formally discussed when water resource management is attempted, and even fewer examples exist of formal adoption of limits to ground water consumption. It can be instructive, however, to back calculate the de facto sustainable yield definition that exists in a given area and to reopen the discussion. In more recent studies, explicitly defining sustainable yield is becoming more commonplace, though the true complexity of the concept is usually avoided. One conclusion might be that consensus can never be reached on a firm number representing the sustainable yield of an aquifer system. This is particularly true when trying to consider the ecological impacts of ground water consumption. Nevertheless, the discussion is critical, and an explicit process of bounding the problem, analyzing tradeoffs, and interacting with stakeholders can lead to a workable definition of sustainable yield.

There is an inherent tension between the fixed definition of sustainable yield needed to provide regulatory certainty to water users, and the concept that sustainable yield concepts can evolve and must be monitored and adjusted over time. This second approach is the essence of adaptive management, the recommended approach for water resource management.

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