Groundwater Sustainability: Towards a Common Understanding

Report Summary of
Workshop, held May 12, 2009

Sponsored by
Water Resources Center, University of Minnesota
St. Paul, MN
and the Freshwater Society
Excelsior, MN

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Introduction and Purpose of Workshop

This report summarizes the discussion and outcome of a workshop held on May 12, 2009 at the University of Minnesota on the Sustainable Management of Groundwater. This was the second of two workshops held on this subject sponsored by the Water Resources Center of the University of Minnesota and the Freshwater Society[1], to foster communication and understanding about the quantity of Minnesota's groundwater resources, and what technical considerations are needed to manage it sustainably.

Groundwater is a vitally important resource. About 90 percent of Minnesotans get some or all their drinking water from the aquifers that lie beneath almost every part of the state. Agriculture and many of the other industries that sustain the state's economy consume tens of billions gallons of groundwater every year. Groundwater also feeds lakes, streams and wetlands. Without the regular discharge they receive from aquifers, many streams would dry up in the winter and in summer droughts. Humans have a huge, and growing, impact on aquifers and the water flowing through them. Human decisions and actions affect both the quality of groundwater in the aquifers and the quantity of it that is available to support natural ecosystems or provide for human use.

The two workshops grew out of two recent recommendations:

- The Statewide Conservation and Preservation Plan, prepared by the University of Minnesota, Bonestroo, and CR Planning for the Minnesota Legislature in 2008 that urged that groundwater resources be assessed for their sustainability.
- A 2008 Freshwater Society report, *Water Is Life: Protecting A Critical Resource for Future Generations*, that reported a lack of consensus among groundwater experts on the sustainability of current patterns of water use and called for a scientifically rigorous study of sustainability.

Approximately 70 invited technical experts in hydrology, geology, aquatic chemistry, aquatic biology, and aquatic ecology attended the May workshop. Participants debated the shortcomings of existing research practices and management policies involving groundwater. After a presentation by Professor Calvin Alexander on the process used by Texas to determine groundwater management units, participants broke into small groups and were asked to address a series of questions based on a simple groundwater scenario (single withdrawal, single shallow aquifer):

- What information is needed to understand the system?
- What tools are most appropriate to describe the system?
- What data are needed to maximize these tools, and at what scale?

[1] The Water Resources Center provides leadership in freshwater management through cutting-edge research, educational opportunities for students and professionals and community outreach. It is affiliated with the College of Food, Agriculture, and Natural Resources Science and Minnesota Extension of the University of Minnesota. The Freshwater Society is a 41-year-old Minnesota-based nonprofit that works to educate and inspire people to value, conserve and protect all water resources.

Participants were then asked to consider a much more complex groundwater scenario (multiple uses, potential for development, multiple aquifers of different scales) and answer:

- What additional or different data and tools are needed to understand this system?
- What external drivers on the system would lead to changes in management, now or in the future?
- What are the obstacles to managing groundwater sustainably?

Much of the information that was obtained during this workshop was synthesized into a separate report, *Guidance for Developing a Sustainable Management Plan for Groundwater*. This document is attached as an Appendix to this summary. The Guidance is intended for water scientists, planners and managers with the responsibility for defining management areas and for making decisions regarding how much groundwater they can -- and should -- pump, and how much they should leave untouched to support ecosystems and to protect groundwater from contamination.

The Guidance is not a proscriptive or prescriptive list of rules or a cookbook with recipes for every situation. Rather, it is a call to action for everyone who has responsibility for groundwater decisions to:

- Think broadly about all aspects of the hydrologic cycle and to plan for the use and protection of groundwater at a scale that matches the extent of underground aquifers.
- Plan proactively to protect groundwater from pollution, rather than relying on ever-more-expensive treatment strategies to mitigate contamination after it occurs.
- Recognize and advocate for ecosystems' need for sustaining groundwater.
- Increase the research and modeling devoted to understanding groundwater flows, and widely share the data and knowledge produced by that research.

The authors of this guide are indebted to those workshop participants who generously gave their energy and diverse expertise in an atmosphere of collegial give-and-take, and we gratefully acknowledge their contributions. Any omissions or errors are the responsibility of the steering committee that oversaw the workshops and attempted to reflect and assimilate the participants' work in this report.

Considerations for Managing Groundwater Sustainably

The amount of water on our planet is finite, and the natural hydrologic cycle moves water to the atmosphere by evaporation, and returns it to land and ocean surfaces by precipitation. The water that falls on land runs off to rivers, streams, and lakes, and infiltrates to aquifers, to complete the cycle. Human use of water can interfere with this cycle by redistributing water, or by degrading water quality. Much of our fresh water is stored as groundwater, and because of the long times (years to decades) needed to replenish water that is withdrawn from groundwater, it is particularly vulnerable to disruptions in the hydrologic cycle and to degradation of water quality by chemical and microbiological contamination. Also, groundwater use affects surface water stream flows and the ecological services provided by those streams.

While Minnesota is rich in groundwater, our supplies are not inexhaustible, especially in the context of a state population that is projected to grow by 1.2 million people – more than 20 percent – by 2035. The Metropolitan Council recently produced a water plan that predicted about 60 percent of the region's communities could face some negative impact – a significant lowering of water levels in wells, private wells rendered unusable because of pumping by higher-capacity municipal wells, draw-downs of close-to-the-surface water tables that support lakes and wetlands – if they tried to maintain current water use patterns in the face of the expected population growth. Thus there is a critical need to plan for the future, to develop a water management strategy that will be implemented today to ensure that our use of our water resources is done sustainably. We embrace the following definition:

> ***Sustainable waters are those that meet people's needs, safeguard ecosystem function, preserve water quality and provide sustainable water for future generations. Water use is sustainable when the use does not harm ecosystems, degrade water quality or compromise the ability of future generations to meet their own needs.***

To achieve our goal of water resource sustainability, a systems approach must be taken that is integrated, comprehensive, recognizes the clear linkage between groundwater and surface water, and considers quantity as well as quantity. We must be proactive in this approach, and prioritize the areas of the state in terms of assessment, management and implementation.

Findings from Workshop: Barriers to Progress

Throughout the workshops, participants noted the challenges to understanding groundwater and planning for a future in which the needs of both humans and ecosystems can be met. Those challenges include:

- **The perception of abundance.** There is no question that Minnesota has lots of groundwater. That fact contributes to a mindset that we do not, and may never, have to engage in the kind of water supply planning that many other states actively practice. But, in fact, groundwater is very limited in some parts of the state and future shortages could occur in some Twin Cities communities.
- **A lack of a sense of urgency.** A crisis is a terrible thing to waste, and a severe drought that afflicted Minnesota from late 1987 into 1989 was not wasted. The drought provoked a flurry of legislative interest in conserving water and spurred enactment of a law phasing out the wasteful practice of once-through air conditioning. Since then, though, mostly above-normal precipitation has dulled policy-makers' commitment to conservation. At the workshops, several participants said another serious drought could be beneficial because it would provoke renewed interest in researching, protecting and managing groundwater.

- **Lack of a professional consensus on what can, and should, be done.** Groundwater science is difficult. The water in hidden in layers of sand, gravel and rock, often hundreds of feet beneath the land. It flows into and out of surface waters, and it fluctuates in response to precipitation and pumping. In Minnesota, groundwater scientists and managers have never reached consensus on how much water is available for human use. The question of how much water should be left for ecosystems – whether too much already has been diverted, whether it is permissible to sacrifice wetlands and streams to support future human population growth – involves philosophical and political issues, as well as hydro-geologic concerns. Disagreement persists on how to research groundwater: Do you focus on the container, the geological formations through which the water flows? Or can you construct satisfactory groundwater models by studying the flow into and out of aquifers?
- **Limited access to data.** In the workshops, participants called for sustained funding for long-term data collection, better sharing of data among agencies and easier access to existing data collections for researchers and members of the public. Some called for the collection of new data on land use, climate and transpiration.
- **Lack of public understanding.** Until wells run dry or become contaminated, most citizens show little interest in groundwater. Workshop participants commented on the need for better education for children and adults about water.
- **Lack of an interdisciplinary team approach to research.** Workshop participants criticized barriers – some institutional, some personal – that they said often keep scientists from different disciplines from working together. But in their interaction at the workshops, they demonstrated a desire to work with other physical scientists, as well as social scientists. Values, not science, drive tough choices about sustainability, one participant said of the need to include social scientists in the debate.
- **Limitations of the current legal, governmental structure.** Some workshop participants called for more political leadership, at the state and local levels, on groundwater issues, such as the siting of ethanol plants.
- **Erosion of expertise by attrition.** Some workshop participants said there has been a decline in the expertise of some water professionals due to the high number of retirements occurring in natural resource agencies.
- **Failure to internalize costs.** At present, water is essentially free. Users pay only the cost of pumping it, treating it and piping it to their homes and businesses. Putting a price on water would inspire conservation.

Conclusions from Workshop

These conclusions are summarized from the group discussions, and do not represent a consensus from the group.

- **Need for a paradigm shift.** Rather than managing groundwater primarily as a supply problem driven almost exclusively by human needs, people making decisions about groundwater should consider the chemistry of the water, the ecosystems it feeds and the human activities and land use choices that protect or degrade water.

- **"One hydrosphere" as a multidisciplinary intellectual framework.** We need a system of thinking about water that looks at it in all its physical forms – fresh and saline, ground and surface, vapor, liquid, ice – and embraces the connections between them. Individual researchers and managers must challenge themselves to move beyond their sometimes narrow niches of expertise within the big picture.
- **Need to view water from a systems perspective.** The systems approach bridges the interactions and feedback between the natural and earth sciences with the social and behavior sciences. It acknowledges groundwater – surface water interactions, and incorporates chemistry, ecology, economics, human behavior and values and stressors to develop both conceptual and modeling approaches.
- **Need to evaluate and modify legal and political frameworks that narrowly regulate only certain aspects of the hydrosphere.** If current laws and modes of regulation fail to recognize the complexity and connections between the various forms of water, the laws and regulations should be changed.
- **Importance of communicating issues, educating citizens.** Participants in the workshops called for scientists, schools and the media to do a better job of helping citizens understand the way groundwater works and expand their use of modern forms of communication.
- **Necessity of integrated, easily accessible and transparent data and information systems.** Workshop participants repeatedly said that even scientists often do not know about and have ready access to some types of data that already have been collected. The most common recommendation voiced by the participants was a call for agencies to use shared standards in the collection and indexing of their data, and that agencies widely disseminate their research.

APPENDIX A

Guidance for Developing a Groundwater Management Plan

November, 2009

Sponsored by
Water Resources Center, University of Minnesota
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The need for a groundwater management plan may be evident from long-recognized conflicts between the demand and the supply of groundwater; from data that show falling water levels, diminished flows, or declining quality; or it may be triggered by a proposal for new groundwater use of a magnitude that requires regulatory review and decision-making. All three situations occur in Minnesota, and the intersection of growing water demand with a finite resource will certainly increase the need for management plans. Plans should take into account human and ecosystem needs including anticipated future needs. Goals should be defined that meet regulatory requirements and build on the values of the community. It is imperative that the finite nature and inherent value of water resources are recognized. A management plan is an active process intended to monitor the health of the hydrologic system and to determine what changes to the groundwater system can be implemented without degrading the resource, the habitat it supports, and its long-term sustainability.

Presented herein are guidelines for developing a sustainable management plan for groundwater, aimed at water managers who are responsible for developing such plans. Because details of these plans vary depending on the water use, the geographical scale, and the complexity of the system, these are generic guidelines that focus on the overall process and the considerations of designing a sustainable plan. Figure 1 provides an overall process flow diagram.

The report results from input gathered at two workshops attended by about 70 invited scientists, engineers, and water planners. The workshops, held November 11, 2008, and May 12, 2009, were sponsored by the University of Minnesota's Water Resources Center and by the Freshwater Society. This document was developed to provide guidance to local water planners, counties, regional and State agencies, and other parties who are responsible for managing groundwater.

I. Involve Stakeholders

Stakeholder involvement is key to developing as successful groundwater management plan. Identifying and engaging the appropriate stakeholders should be a priority. Potential stakeholders include:

- Local units of government
- County, regional, and State agencies
- Commerce and industry representatives
- Land owners
- Water-resource and other technical professionals

These stakeholders should be brought together to define management or protection goals and processes for developing, implementing, and evaluating the planning efforts. A process for ongoing engagement and communication with stakeholders should be set up early in the plan development.

II. Develop a Conceptual Model

A necessary first step in the development of a management plan is the development of a conceptual model of the hydrologic system. Development of the conceptual model is necessary to define the management area, determine what types of data need to be collected, and select appropriate analysis methods. The conceptual model can start very basic based on available information such as:

- aquifer geometry (depth, thickness, etc.)
- aquifer and confining layer characteristics (hydraulic conductivity, preferred flow paths, etc.)
- general groundwater-flow directions
- connection to surface-water features
- recharge characteristics

It is likely that the conceptual model will change as data are collected and the framework of the system becomes more apparent.

III. Define a Management Area

Sustainable management of groundwater is based on the premise that while groundwater in storage can be used to bridge relatively short-term droughts, groundwater use over the long-term cannot exceed the rate at which new groundwater is added minus that portion needed to support surface-water bodies and ecosystem needs. That "management by budget" is most effective when the management area includes natural boundaries to surface and groundwater flows such that inputs and outputs can be measured or adequately estimated. A management boundary that includes only a portion of an aquifer complicates this budgeting because water can readily flow from one part of an aquifer to another. Regional aquifers that extend for hundreds of miles make this concept difficult, and it is likely that they will be managed in smaller units bounded by regional discharge features, such as rivers, or flow divides where the direction and magnitude of flow can be well-defined.

Effective management boundaries have the following considerations:

- Where practical, the management area should include the entire aquifer, and preferably all of the land area that contributes groundwater inputs to the aquifer;
- Where multiple aquifers exist in a vertical sequence, there are advantages to a management area that includes the entirety of all aquifers, and preferably the land areas that contribute groundwater to these aquifers;
- If a management area is chosen that does not include the entire aquifer or sequence of aquifers, the management area should be defined by no-flow boundaries, boundaries that are monitored such that gradients or discharges are measureable, or boundaries that can be characterized with reasonable assumptions;

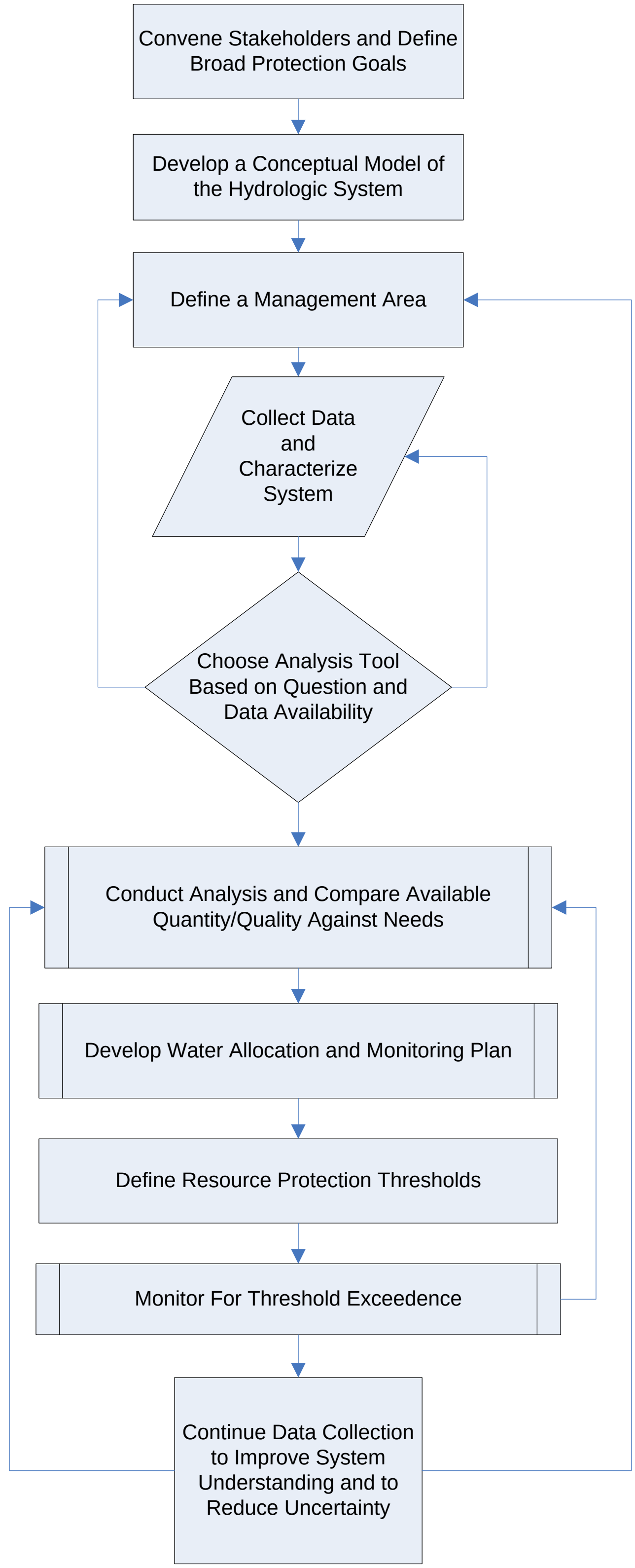

Figure 1. Process diagram for developing a sustainable management plan for groundwater.

- For management of an area that only includes part of an aquifer, it must be recognized that if gradients change across the boundaries of the management area then all flux estimates will also change;
- Management may require multiple, overlapping models to address multiple aquifers or management goals; and
- As data are collected and understanding of the geology and hydrology of the area is improved, it may be useful to change the management area boundaries to fit the new conceptual model.

IV. Collect the Necessary Data

Maintaining sustainable groundwater resources is a function of many factors including minimizing reductions in groundwater storage, maintaining streamflow and lake levels, minimizing the loss of wetlands and aquatic ecosystems, and maintaining groundwater quality. A key challenge for achieving groundwater sustainability is to predict the hydrologic implications of various alternative management strategies such that appropriate management decisions can be made. This analysis requires data and hydrologic tools of sufficient complexity to address questions about sustainability.

The development of tools and collection of data are concurrent processes. As more information is collected, different tools may be brought to bear. Conversely, the development of tools will highlight the need for additional or different types of data collection. A successful management strategy will recognize the importance of choosing the right tool for the job and be dynamic so that other information can be collected and tools can be implemented as needed. This section focuses on the data collection, and the following section focuses on the tools.

Groundwater hydrologists are challenged continually to provide greater refinement to analyses and to address new problems and issues. The foundation of groundwater analysis is the availability of high-quality data. Some data, such as precipitation data, generally are available and relatively easy to obtain. Other data and information, such as geologic and hydrogeologic maps, can require years to develop. Still other data, such as the history of water levels in groundwater systems, requires foresight in order to obtain measurements over time. A key starting point for assuring sustainability for groundwater systems is the development of comprehensive hydrogeologic databases. Geographic Information Systems (GIS) typically are an integral part of database systems needed to assist in organizing, storing, and displaying this information.

A. Physical Framework Data

- Topography (maps showing the stream drainage network, surface-water bodies, landforms, cultural features, and locations of structures and activities related to water);
- Geology (maps of surficial deposits, bedrock, and soil);
- Hydrogeology (maps showing extent and boundaries and tops and bottoms of aquifers and confining units);

- Aquifer vulnerability/sensitivity;
- Saturated-thickness maps of unconfined (water-table) and confined aquifers;
- Hydraulic conductivity (maps for aquifers and confining units) and transmissivity (maps for aquifers);
- Porosity and permeability;
- Maps showing variations in storage coefficient for aquifers; and
- Characteristics of confining beds.

B. Hydrologic Data

- Precipitation data;
- Evaporation data;
- Streamflow data, including measurements of gain and loss of streamflow between gauging stations;
- Maps of the stream drainage network showing extent of normally perennial flow, normally dry channels, and normally seasonal flow;
- Estimates of total groundwater discharge to streams;
- Measurements of discharge from springs;
- Measurements of surface-water diversions and return flows;
- Quantities and locations of interbasin diversions;
- History and spatial distribution of water withdrawals from aquifers;
- Amount of groundwater consumed for each type of use (municipal, industry, private) and spatial distribution of return flows;
- Well hydrographs and historical hydraulic head (water-level) maps for aquifers; and
- Projections of water needs.

C. Chemical Framework Data

The chemistry of groundwater is a function of natural and human influences. The natural geochemical characteristics of earth materials vary both areally and with depth and they affect the chemistry of groundwater that resides within them or flows through them. Exchange with surface water also can affect the chemistry and quality of groundwater systems. Understanding the chemical changes in water from the point of recharge to the point of discharge allows water scientists to establish residence time and the pathways by which the water traveled. Important data include the following:

- Geochemical characteristics of earth materials and naturally occurring groundwater in aquifers and confining units. It is essential to establish baseline chemical characteristics to allow recognition and understanding of changes that occur over time;
- Spatial distribution of water quality in aquifers, both areally and with depth;
- Temporal changes in water quality, particularly for contaminated or potentially vulnerable unconfined aquifers;

- Sources and types of potential contaminants;
- Chemical characteristics of artificially introduced waters or waste liquids; and
- Streamflow quality (water-quality sampling in space and time), particularly during periods of low flow.

D. Ecosystem Framework Data

Beyond managing groundwater for human needs, there are ecosystem services provided by aquatic environments that should be explicitly recognized and protected. These ecosystem services are defined in the UNEP Millennium Report (*http://www.millenniumassessment.org/en/Framework.aspx*) as the benefits people obtain from ecosystems. These include "provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling." For water resources, ecosystem benefits include services such as the water filtering and nutrient removal provided by wetlands as water flows through them, or fishery habitat provided by emergent vegetation. Groundwater must be managed to maintain surface-water bodies and groundwater discharge features that support these ecosystems. Given the immense complexity of biological communities and their overall structure and functions, it is important to identify the specific services that are most critical and manage minimally for these (for example, threatened species habitat and temperature effects of protected cold water fishery streams).

Basic information needed to evaluate ecological services includes the following:

- Identifying the ecosystem services; and
- Identifying the threshold levels necessary to maintain ecosystem functions (for example, flow, temperature, and chemistry)

V. Determine the Tools and Methods Appropriate for the Questions, and the Data

Groundwater scientists need to provide information for decisions about groundwater sustainability. These decisions need to be made using data, tools, and methods that allow for predictions of the consequences of groundwater appropriations and the timeframe of changes that may occur as a result of those appropriations. As previously mentioned, the selection and use of tools may change as more information is collected and different questions are asked.

Decisions about appropriating groundwater have historically been addressed by monitoring groundwater responses to determine effects of new uses. Technology has advanced and we now have the opportunity to predict outcomes and to evaluate the reliability of those predictions. Over time, as methods continue to improve, it should be possible to develop policies and rules that allow appropriation decisions to increasingly be based on data and documented conditions.

There are a range of tools that can be used to evaluate the data. The choice of the tool(s) depends on many factors including scale of management area, available information and data, management goals, risks and consequences of failure, and available financial resources and time. The tools discussed herein are not mutually exclusive, and in some cases, information from one type of analysis can be used to conduct a different type of analysis. Potential tools include the following:

- Water budget, flux, and recharge estimates;
- Basic drawdown calculations;
- Monitoring programs; and
- Computer groundwater models.

Water Budget, Flux, and Recharge Estimates:
Groundwater budgets recognize that the rate of change in water stored in an area, such as an aquifer, is balanced by the rate at which water flows into and out of the aquifer. An understanding of water budgets can provide the foundation for effective groundwater sustainability planning and management. They can provide an estimate of the amount of water that is entering or leaving a system under various climatic and land-use conditions, providing information on how much water may be available under different scenarios. Water budget information also is very useful for computer groundwater models. These methods, however, do not provide a prediction of the effects of discrete withdrawals on the specific resources within the system.

Because water that is used must come from somewhere, human activities—such as irrigation, groundwater withdrawals, and land-use changes—affect the amount and rate of movement of water in the system, entering the system, or leaving the system. Depending on the use of the water that is pumped, some of it may be returned to the aquifer (return flows from irrigation, seepage from individual sewage treatment systems, storm water ponds, and others). However, other infrastructure systems may affect the budget by transporting the water from the location where it was obtained, and possibly from the management area entirely, to other locations (for example, through wastewater collection and treatment that routes water from an area of groundwater withdrawal to treatment plants that discharge to surface-water bodies elsewhere). If the volume of water pumped is an important factor in the water budget, then the transport of the same water out of the management area also must be an important factor. Mass movements of water across confining layers, or across watershed boundaries or groundwater contributing area boundaries should be evaluated carefully and accounted for in models.

The calculation of groundwater flux provides an estimate of the total amount of groundwater than can be sustainably appropriated within the management area boundary. It is based on a budget that measures the movement of water into and out of the management area. Although this is useful in identifying areas of concern and prioritizing them for further, more detailed analysis, it does not predict the effects of pumping, and does not identify potential negative effects even if the amount of groundwater deemed available in the management area is not exceeded. Pumping effects are not necessarily uniform across an area, and pumping decisions need to be supported by other tools and information. The flux method can be applied at various levels of resolution. For example, developing flux budgets for individual aquifers will improve predictions of pumping effects. The choice of management area boundaries also greatly affects the usefulness of this method as described above.

A key component of the water budget for evaluating groundwater sustainability is groundwater recharge. Recharge is the amount of water that replenishes a groundwater system. It can be used as an estimate of how much recharge is available over a broad area and is an important input to computer groundwater models. The following methods are available for estimating groundwater recharge:

- Surface-water methods
  - Water balance method—groundwater recharge is calculated as the residual of the water balance;
  - Base-flow method—measured base flow is assumed to be equal to the recharge over the watershed contributing to the streamflow;
  - Watershed modeling method—the model is calibrated to match surface-water fluxes in streams and find the recharge rate that gives the best match; gives an estimate over the representative hydrologic units;
  - Seepage meters;
  - Heat tracers; and
  - Chemical tracers.
- Unsaturated zone methods
  - Lysimeters method;
  - Zero-flux plane method;
  - Darcy's law method;
  - Chemical tracers—historical (isotopes from nuclear bomb testing) or applied chemicals;
  - Heat tracers; and
  - Unsaturated zone modeling method—the model is calibrated to match measured moisture content and water pressure profiles along with known fluxes at the land surface; limited to point estimation.
- Saturated zone methods
  - Water-table fluctuation method—uses measured water-table fluctuations with the specific yield of the aquifer material;
  - Soil water balance method (U.S. Geological Survey)—takes land use, topography, soils, and climate into consideration to arrive at groundwater recharge;
  - Watershed characterization—undertakes a systems analysis of water fluxes and uses the water-balance analysis to derive estimates of renewable flux at multiple scales;
  - Regional regression recharge (RRR) method (U.S. Geological Survey)—relates estimated recharge, derived from base-flow recessions, to precipitation, growing degree days, and specific yield of the soil overlying the aquifer;
  - Chemical tracers—historical (isotopes from bomb testing) or environmental chemicals; and

- Groundwater modeling—the model is calibrated to match water table or piezometric heads; can give a distribution of recharge over the area of interest.

Basic Drawdown Calculations

Using information or estimates of aquifer characteristics (hydraulic conductivity, thickness, storage), basic calculations can be made to estimate spatial drawdown from proposed withdrawals. Although this is not the most robust method, it can provide a sense of whether or not drawdowns from proposed pumping will intersect other groundwater users or surface-water features. Basic drawdown calculations combined with a monitoring program provide the most basic approach to managing groundwater withdrawals.

Monitoring Programs

The data and information collected, such as those listed in Section IV, part B, should be used to design a continuing and evolving monitoring program that will likely be a component of any management plan. However, at a minimum, an appropriate monitoring program can be used alone as a tool to evaluate the effects of withdrawals. This will result in reactive management, that is, changes in management are made after a problem is shown by monitoring data, but may be appropriate where the risks are low. More discussion about the use of monitoring to ensure resources are protected is provided in Section VII.

Computer Simulations of Groundwater Flow and Solute Transport (Models):

Groundwater models provide a predictive method for analyzing the sustainability of groundwater use. They require more data and more effort than the other tools, and thus incur higher costs. However, the output includes estimates of water levels everywhere within the modeled area, and such output can be calculated for specific timeframes. This makes it possible to envision the effects of pumping in time and space and to predict the effects on surface-water and groundwater levels. The limitations to computer models must be recognized. All models are simplifications of systems with multiple variables.

Models attempt to represent the essential features of groundwater systems by means of a mathematical counterpart. Although forecasts of future events that are based on model simulations are imprecise, they nevertheless represent the best-available decision-making information at a given time. Computer simulation models have value beyond their use as purely predictive tools. They commonly are used as learning tools to identify additional data that are required to better define and understand groundwater systems. Furthermore, computer models have the capability to test and quantify the consequences of various errors and uncertainties in the information necessary to determine cause and effect relations and related model-based forecasts. This capability, particularly as it relates to forecasts, may be the most important aspect of computer models in that information about the uncertainty of model forecasts can be defined, which in turn enables water managers to evaluate the significance, and possibly unexpected consequences of their decisions.

VI. Policy Considerations: Using Technical Results

No single statewide policy or guidance currently exists to aid State and local planners in determining the optimal amount of groundwater that can be withdrawn to ensure sustainability. Thus, a process and the factors to be considered in lieu of set policy or guidance are presented herein. The process is complicated by varying perspectives, values, and goals of stakeholders, citizens, and users.

A basic process could include the following steps:

1. Allocate portions of the groundwater to existing uses,
2. Determine the future desired uses,
3. Develop consensus on how much is actually available, and
4. Determine which uses (current and future) may move forward and which may need to be reduced or eliminated through a process of prioritization.

Decision-making and policy development in a management area rely on technical analysis of water availability, effects of its use, and ultimate disposal of the withdrawn water. The more complex analysis is determination of priorities for uses and the point at which withdrawals will no longer support a long-term supply of groundwater and surface water. Further complicating the decisions about groundwater use and long-term sustainability is the fact that groundwater and surface water interact, so it is necessary to consider surface-water conditions in the same body of policy. In setting priorities, it is important to include the current and future uses for surface water, and to consider ecosystem services in such decisions. For example, to what extent would a groundwater appropriation for drinking water be curtailed or prohibited if it had an undesirable effect on an ecosystem?

Water availability should be included in all planning exercises, not only plans focused on groundwater. This is especially true for plans that affect the distribution of population, land use, community development, and other water intensive activities. Similarly, planning should evaluate the effects on water quality as well as on the quantity.

Appropriations from local, shallower, less-confined sources (aquifers or surface-water features) may be desirable for the following reasons:

- Their effects are realized more quickly and adjustments can be made;
- Preserves the highest quality water in storage and encourages management of shallow water quality;
- Easier to monitor;
- Less expensive to produce;

On the other hand, the following are disadvantages to appropriating from shallow sources:

- Fewer regional aquifers; therefore, incentive to distribute use (sprawl);
- More vulnerable to drought—requires deeper storage backup system;
- More vulnerable to water quality degradation from activities at the land surface.

Water uses that return more and higher quality water to the system should be favored.

Water availability is fixed, but more can be done with the same volume of water through conservation and reuse. Some uses could be supported with reused water, lower quality water, or wastewater. Stormwater retention and use might also be a useful component.

Some uses may be deemed to be unnecessary and prohibited, or appropriate uses of water might be assigned on the basis of water quality (for example, no lawn watering with pristine, fresh water, but permissible with gray water).

The following is a partial list of laws and rules that govern water use and protection in Minnesota:

- Minnesota Rules 6115.0630 Safe Yield for Confined and Unconfined Aquifers;
- Minnesota Statute 103G.271 Appropriation and Use of Waters—permits, Mt. Simon Hinckley aquifer limitations, once through cooling prohibition, lake level maintenance, fees;
- MS 103G.291 Water Conservation and Water Supply Plan;
- MS 103G.265 Water Supply Management;
- MR 6115.0730 Well Interference;
- MR 6115.0770 Water Conservation;
- MS 103G.223 Calcareous Fens;
- MS 103G.285 Surface Water Appropriations—trout streams;
- MR 6115.0810 Water Appropriation and Use Management Plans;
- MS 103G.261 Water Allocation Priorities; and
- MS 103H. Groundwater Protection.

VII. Application and Analysis of the Results

When the tools and information collected through the steps identified previously are compared to the policy considerations and protection goals, allowable withdrawals and thresholds can be established to ensure the resource protection goals are met.

A. Establish resource protection thresholds that protect water resources and ecosystems.

   These thresholds should be based on the information gathered as described previously. For example, the following information could be used in establishing thresholds:

   - Water levels or water-level trends in wells (for example, a water level should not drop below a certain elevation in a particular monitoring well or there should not be a downward trend in water levels over 12 consecutive months);
   - Water levels in surface-water features (this could be as measured at a stream or lake gauge);
   - Flows in springs or streams (for example, using historical flows and ecosystem needs, what minimum flow must be maintained?); and
   - Water withdrawals (for example, if withdrawals exceed some specified amount).

B. Use appropriate models and methods to predict the effects of projected uses on the system.

Using tools described in Section V, an analysis should be conducted to determine acceptable withdrawal scenarios that do not result in adverse effects to resources or exceed the resource protection thresholds. The analysis should consider the volumes available based on the estimation of available flux as well as how withdrawals can be made without exceeding resource protection thresholds, i.e., various pumping schedules, well placement, etc. The models and tools should be appropriate in cost and data availability, and with explicit descriptions of reliability, accuracy, consequences of risks, and proper application.

C. Consider how external drivers could affect management of water quantity and water quality now and in the future.

Depending on the tools and information available, consideration of external drivers could be used to build in safety factors in resource protection thresholds and contingency plans or also may be used to focus ongoing data collection and analysis. The following are examples of external drivers:

- Land-use changes—development and agricultural production changes;
- Demographic changes, both increases and distribution changes by culture, age, etc.;
- Climate change (temperature effects, eco-region migration, change in precipitation, change in severity of precipitation);
- Impervious surface changes;
- Tile drainage changes;
- Economic changes;
- Changes in societal priorities;
- Changes in our understanding of the water system;
- Change in valuation and/or value of water including commoditization;
- Changes in energy use and demand; and
- Changes in technologies.

D. Develop a plan to monitor thresholds.

An appropriate monitoring program to measure the effects of withdrawals should be developed. It should consider the protection thresholds and all available information and analyses. Development of a monitoring program will include the following:

- Installation or identification of available monitoring wells and surface-water stations; and
- Establishment of appropriate monitoring frequency and parameters to be monitored.

E. Develop a mitigation plan.

A mitigation plan should be developed and implemented if thresholds are exceeded due to withdrawals or changes in external drivers or if thresholds are changed on the basis of new information or understanding of the system. The extent to which the mitigation measures are developed should be proportional to the estimated potential for thresholds to be exceeded and consequences of their exceedance. Potential mitigation measures include the following:

- Water demand management (demand reduction, conservation);
- Adjust pumping rates, schedules;
- Use alternative sources; and
- Cease withdrawals.

F. Reevaluate allocations, thresholds, and mitigation measures based on additional information as it becomes available.

VIII. On-going Improvements and Feedback to Management Plan

All successful management plans must be living documents and allow for improvement through adaptation and feedback. It is important that management plans recognize the possibility that things will change on the basis of new and better information, and be designed to incorporate iterative improvements. Specifically:

- Develop a data collection approach that will reduce uncertainty—Design data collection activities to be comprehensive, but also strategic in terms of spatial coverage, density, and temporal coverage so that measurements or variables that have high uncertainty and high sensitivity to modeling and decision making have sufficient data collection to reduce that uncertainty.

- Ensure that all data that are collected at all levels of jurisdiction are accessible—The State agencies are continually enhancing the accessibility of State agency data; however, data collected by local governments, Federal agencies, and other involved groups also must be made available. A plan to make this data and information easily accessible will be a benefit to ongoing analysis.

A dynamic, adaptive, transparent process that is supported by active stakeholder engagement is necessary for ensuring an increasing likelihood of success in achieving sustainable water resources for the future.