DEVELOPMENT OF AN OPERATIONAL GROUND WATER MANAGEMENT POLICY BASED ON SAFE YIELD

MINNESOTA DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS

DEVELOPMENT OF AN OPERATIONAL GROUND WATER MANAGEMENT POLICY BASED ON SAFE YIELD

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ABSTRACT

Minnesota's Public Water Resources Rules specify that approval for appropriation from ground water shall be limited to the safe yield of the aquifer and that impacts on surface water should be considered where connection between surface and groundwater exists. An operational policy for the application of these rules must be developed. This paper outlines the issue and suggests an operational management policy.

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INTRODUCTION

The Legislative Commission on Minnesota's Resources made funds available for the development of an operational definition or policy to be used in the management of the ground water resource based on *safe yield*. Such a policy will help in the identification of areas where potential water conflicts may arise and in the assessment and ranking of data needs. This paper represents one segment of a larger project which focuses on Swift County, Minnesota. The project includes modeling of ground water flow and a regional assessment of groundwater quality.

Minnesota is dependent on ground water for a variety of uses, including individual domestic wells, public water supplies, agricultural irrigation, and commercial and industrial water use. The Division of Waters of the Department of Natural Resources has been given the authority to grant permits for appropriation from ground water. Where a permit would be required, it is subject to a priority system which ranks users and it is subject to limitations intended to reduce negative impacts on the resource and on higher priority users. The goal is wise, efficient and optimal management of Minnesota's water resources.

Stress on the ground water resource in a given area increases with decreased precipitation. Public interest in and controversy over appropriation permit decisions and water issues in general also increase during drought periods and in areas affected by ground water contamination. There is a need to enhance the water appropriation decision-making process within the legal framework of Minnesota Statutes (MS) and Minnesota's Public Water Resources Rules. In addition, contingency and emergency planning must be carried out so that possible solutions to problems are available if the problems materialize. The Division will then have the ability to deal with severe climatic conditions and ground water contamination both of which affect the quantity of available water while minimizing disruption of an area.

The appropriation process has been characterized by Bittinger (1980) as an interaction between three concerned sectors, each of which influences the final implementation of any operational policy for water resources management in Minnesota:

1. law and policy makers who develop the legal framework for the appropriation process.
2. interested public user groups.
3. technical decision makers who are responsible for processing individual appropriation requests.

The criteria we have chosen for the evaluation of any potential operational policy include:

1. impacts on the quantity and quality of the resource
2. definition of constraints imposed on the policy by the legal framework
3. administrative feasibility
4. economic efficiency
5. equity

LEGAL FRAMEWORK

The approval of an appropriation permit is subject to limits set up to safeguard aquifers and protect surface water supplies. As stated in the Public Water Resources Rules for the Appropriation and Use of Water (Rules) 6115.0670:

> 'C (1). The amounts and timing of water appropriated shall be limited to the *safe yield* of the aquifer to the maximum extent feasible and practical.'
>
> 'C (2). If the commissioner determines, based on substantial evidence, that a direct relationship of ground and surface waters exists such that there would be adverse impact on the surface waters through reduction of flows or levels below protected flows or protection elevations the amount and timing of the proposed appropriation from ground water shall be limited.'
>
> 'C (3). Appropriation of ground water shall not be approved or shall be issued on a conditional basis in those instances where sufficient hydrologic data are not available to allow the commissioner to adequately determine the effects of the proposed appropriation. If a conditional appropriation is allowed, the commissioner shall make further approval, modification, or denial when sufficient hydrologic data are available.

Definitions for *safe yield* are provided in the Rules (6115.0630):

> 'Subp. 15 *Safe yield for water table condition* means the amount of ground water that can be withdrawn from an aquifer system without degrading the quality of water in the aquifer and without allowing the long term average withdrawal to exceed the available long term average recharge to the aquifer system based on representative climatic conditions.'
>
> 'Subp. 16 *Safe yield for artesian condition* means the amount of ground water that can be withdrawn from an aquifer system without degrading the quality of water in the aquifer and without the progressive decline in water pressures and levels to a degree which will result in a change from artesian condition to water table condition.'

These definitions imply that a protected level may be determined for an aquifer which will act as an indicator for the *safe yield*. Aquifers are assumed to have certain idealized characteristics and are assumed to fall into one of two distinct categories, either artesian (confined) or water table (unconfined). Methods of estimating the protected level for a given aquifer system must be outlined and decisions must be made about the action to be taken when it is anticipated that withdrawals will soon cause water levels to drop below the protected level. The application of these principles must be regional in nature and is limited by existing hydrologic data.

Minnesota's Public Water Resources Rules for the Appropriation and Use of Water define water use conflicts (Rules 6115.0740):

> Subpart 1. 'For the purpose of these rules a conflict occurs where the available supply of waters of the state in a given area is limited to the extent that there are competing demands among existing and proposed users which exceed the reasonably available water. Existing and proposed appropriations could in this situation endanger the supply of waters of the state so that the public health, safety and welfare would be impaired.'

The evaluation of a conflict includes analyzing the following (Rules 6115.0740 Subpart 2):

> 'B(1). the reasonableness for use of water by the proposed and existing users;'
>
> 'B(2). the water use practices by the proposed and existing users to determine if the proposed and existing users are or would be using water in the most efficient manner in order to reduce the amount of water required.'
>
> 'B(3). the possible alternative sources of water supply available to determine if there are feasible and practical means to provide water to satisfy the reasonable needs of proposed and existing users.'

If the conflict cannot be resolved by modifying the appropriations of the proposed and existing users, permits will be modified, issued or terminated on the basis of priorities (MS 105.41, Subd. 1a) established by the legislature:

> 'First priority. Domestic water supply, excluding industrial and commercial uses of municipal water supply.'
>
> 'Second priority. Any use of water that involves consumption of less than 10,000 gallons of water per day. For purposes of this section "consumption" shall mean water withdrawn from a supply which is lost for immediate further use in the area.'
>
> 'Third priority. Agricultural irrigation, involving consumption in excess of 10,000 gallons per day, and processing of agricultural products.'
>
> 'Fourth priority. Power production, involving consumption in excess of 10,000 gallons per day.'
>
> 'Fifth priority. Other uses, involving consumption in excess of 10,000 gallons per day.'

Within priority groups, users shall be treated as equals. The requirements of higher priority users are satisfied first. If any water remains, it is apportioned to users within the lower priority group. The priority system provides varying degrees of protection from interference to domestic well users and the domestic use portion of public water supplies; interference (as distinguished from water use conflict) is related directly to well construction, proximity to other user, or lack of reasonable capture rather than to overuse of the water resource. Well interference problems are investigated and mediated by the Department according to Rules 6115.0730.

HYDROLOGIC PRINCIPLES

The development of the legal framework for ground water management required the adoption of simplified definitions for complex natural features and processes. Ground water is not isolated; surface water and ground water supplies are connected through the process of recharge and by discharge of ground water to surface water. Water withdrawn from ground water is derived from decreased natural discharge or from a decrease in the amount of water in storage. Maximum long term yield from a ground water system is obtained when natural discharge is minimized or eliminated. The natural discharge which then becomes available for ground water withdrawal is termed *captured discharge.*

Ground water can be considered a renewable resource to the extent of actual recharge; the total physical quantity of ground water, which does not increase with time, is considered nonrenewable and thus subject to depletion. This depletion is termed ground water mining. The magnitude of development depends on the hydrologic effects tolerable within the basin at a given time. These hydrologic effects may include land subsidence, well failure, well interference, and water quality degradation.

Water quality impacts caused by ground water withdrawals are primarily due to infiltration into the aquifer of lower quality water than the original water in the aquifer. Water quality impacts can be due to the capture of waters from a stream or lake, to the infiltration of agricultural chemicals and fertilizers, to multiaquifer wells, to landfills and hazardous waste storage, and to the intrusion of waters from an aquifer dissolved solids, high salinity and ionic concentration, chemical or bacterial contamination and temperature changes.

Initiation of, or a change in, ground water withdrawals disturbs the existing equilibrium (equilibrium exists when inflow and outflow balance over a period of time). Establishment of a new equilibrium requires an indefinite period of adjustment. Equilibrium is reached more rapidly under confined conditions than under unconfined or water table conditions. The rate at which the hydrologic system can be brought into equilibrium depends on the rate at which discharge can be captured. The full implications of a change in ground water appropriations may not be apparent for some period of time. The time for establishment of a new equilibrium and the water levels under the new regime must be predicted and considered when determining ground water appropriation amounts and timing.

SAFE YIELD

A technical definition of *safe yield* is the amount of water which can be withdrawn from a ground water basin without causing any undesirable effect. Potential undesirable effects are:

- declines in water levels
- increased pump lift
- conflicts between and among users
- intrusion of lower quality water
- land subsidence
- depletion of available ground water (mining)
- streamflow depletion
- reduced lake levels
- economic impacts, e.g. lack of water or increased costs of obtaining water
- social impacts, e.g. degradation of recreational value of streams and lakes at reduced levels

The term *safe yield* is generally criticized. It has been redefined numerous times and many similar concepts have been created in an effort to find a term which would find general acceptance. These alternatives include:

- sustained yield
- permissive yield
- optimal yield
- practical yield
- perennial yield
- basin yield

The absence of the word *safe* in the above terms avoids the implication, inherent in the term *safe yield*, that this yield is certain or guaranteed. Opposition of ground water professionals to the term *safe yield* arises in part from the potential misconceptions involved and in part from the implication that a number can be determined for *safe yield* which will apply over a period of time.

The direct application of the rules based on *safe yield* is difficult because of a universal lack of information about ground water systems. In most cases actual values for recharge are unknown. Even if current values for recharge were known, the information could not be used directly to predict future recharge values due to climatic changes. Hydraulic communication (or leakage) between aquifers is complex and the current level of understanding of resultant induced infiltration is limited. Information about the interconnection between specific surface water sources and ground water supplies is seldom available. A practical evaluation of the rules must take this into account.

It is imperative that the policy implemented provide the flexibility necessary to accommodate regional differences in the geologic, hydrologic, social and economic framework. Any quantity or number associated with the *safe yield* of an aquifer cannot be considered rigid or exact; it can only represent the estimate based on best available data and it will include errors. The reliability of the estimated *safe yield* is dependent upon the validity of any assumptions used in the analysis, upon the existing data available for the area in question, and the money, time and personnel dedicated to making *safe yield* determinations. The estimate must be subject to revision as more information becomes available.

GROUND WATER MANAGEMENT IN OTHER STATES

Management of the ground water resource in other states has been investigated. The results are summarized in this section. The legal framework within which each state's water resource managers operate dictates the options open to them; however, Minnesota hopes to learn from the successes and avoid the failures of others.

Many states, particularly in the western part of the country, have considered or implemented ground water management controls to deal with declining water levels and increased development, and to avoid land subsidence and increased numbers of conflicts between ground water users. The legal framework in which the ground water resource is to be managed will determine the controls exercised. The tolerance of the users for the negative effects of management and of overuse and misuse of the resource will also influence management decisions.

Eastern states are relatively water-rich. These states have traditionally defined ground water rights based on common law, with the reasonable use doctrine currently most widespread. This doctrine allows any traditional beneficial use of water on the overlying land without regard to impacts on adjacent landowners. Due to the general abundance of water, conflicts are more likely to arise over water quality issues. Many states have replaced or augmented the common law system with some form of permitting, but in the absence of conflict over water use, permitting may become a mere formality rather than a management tool.

States with permit systems may impose limits on water use: how water is used, how much water is used, how long water can be used. Connecticut, Delaware, Florida, Georgia, Iowa, Kentucky, Maryland, Minnesota, New Jersey, North Carolina, New Jersey, Oklahoma, South Carolina, Virginia, and Wisconsin are among the states which have adopted some form of ground water use permitting program (Cox and Shabman, 1982; Miller and Powers, 1984).

Specific areas which face problems needing more intensive management may be designated and administered differently than the rest of the state. Such areas may be called critical areas, capacity use areas, aquifer protection areas, restricted use areas, or ground water management areas (Miller and Powers, 1984). Ground water management districts have been formed in most Western and Midwestern states (as well as some Eastern states) to manage the specific problems and concerns unique to the area managed. Management plans can be initiated on a local level or state level; administration and funding may also be local, state or joint. A number of ground water management policy options are listed in Table 1. Current policies of other states consist of a patchwork of these policies; they are outlined in Table 2. Several types of ground water management policies in effect in other states are discussed.

One reality all ground water management policies must deal with is the current unreliability of drought forecasting. Many proposed temporary restrictions must be imposed very early in a drought period to prevent water scarcity and to allow the available water to be allocated optimally. Forewarned, farmers can plan to plant less water-demanding or early maturing plants or opt to let part of their land lie fallow. Industry can plan production to coincide with water availability and power companies can plan purchases from utilities in areas not experiencing drought.

Table 1: Ground water management policy options (modified from Keller *et al.*, 1981)

Renewable Resource	Allow use of that portion of ground water which is renewable on a long-term basis to avoid depletion and its negative effects. Set water levels below which withdrawals are not allowed. Determine the theoretical sustained yield for the basin and allocate among users.
Limited Use	Limit the kind of crops irrigated. Limit irrigation to the most efficient systems or to the most suitable land. Limit the number of permits available for a region or aquifer system.
Prioritization	Rights of earliest users supersede more junior rights. Stop development of new irrigated land, do not limit present irrigators. Irrigation ranked with other uses before water is allocated; higher use priorities given water first.
Taxation	Pump tax. Irrigation acreage tax. Funds dedicated to securing alternate water supplies for those impacted by the beneficial use others have made of the water.
Metered Use	Meter water used and charge a user fee.
Well Spacing	Adopt rules to govern well density which will apply to all new high capacity wells.
Apportioning	Allocate water in proportion to acreage owned or irrigated. Allocate water in proportion to amounts used in the past.
Rationing	Allow specified withdrawals at specified times to reduce peak use.
Conservation	Allow irrigation only after specific need is determined. Focus on dry land farming. Require use of most efficient technology. Use local tax incentives to encourage use of water conserving equipment.
Mining	Allow planned aquifer depletion over a given number of years. Allow overdrafts to occur during sufficient time for the operator to recover the initial economic investment. Allow partial mining of the aquifer, reserving forever a given volume or portion of the aquifer for high priority uses.
Preserve Quality	Establish water quality threshold, limit withdrawals when threshold is reached.
Alternate Supply	Where the economic value of ground water mining overwhelms the value of domestic water wells, arrangements may be made to provide water to those impacted by the ground water mining. Rural water districts, tank trucks and bottled water delivery may be solutions.

Table 2: Outline of the ground water management strategies of other states.

State	Summary of Management Strategy[1]
Alabama	No statutes governing ground water.
Alaska	USGS ground water model used to guide well spacing. Permits granted only upon receipt of well log and aquifer test results.
Arizona	Four management areas have set sustained withdrawal as a long term management goal; well spacing requirements enforced for new wells pumping more than 35 gpm.
Arkansas	No statutes governing ground water.
California	Ground water basins designated by state mandate but managed locally. Pumping may not exceed recharge over a 28 to 35 year cycle; continued overdraft is not allowed.
Colorado	The connection between surficial aquifer and streamflow is recognized. Within designated ground water basins a local vote may establish a ground water management district. Permits may be denied if other users will be affected. Planned depletion over 25 years will allow a 40 percent decline in water levels. Well spacing criteria are used within a three mile circle.
Florida	Ground water control areas are initiated, administered and funded jointly by state and local authorities.
Georgia	Allocation system gives industry and cities priority over agricultural use. Well spacing restrictions, use rotations, metering and allocations are imposed statewide where necessary.
Hawaii	Pumping is not allowed to exceed the sustaining yield in state-administered and funded control areas. In other areas overdrafts are allowed if water levels do not significantly deviate from the 40-year average. Water quality emphasis because of salt-water intrusion problems.
Idaho	Critical ground water areas declared when supply is inadequate. Reasonable pumping levels are used to guide policies.
Illinois	Water resources management area apportions Lake Michigan withdrawals; ground water availability is considered. Conservation and monitoring part of official water management program.

Table 2 cont.: Outline of the ground water management strategies of other states.

State	**Summary of Management Strategy**[1]
Iowa	Permit system based on priority of use category and time of application for permit. Irrigation withdrawals are limited based on the crop planted. State has authority to create ground water management area.
Indiana	State has the authority to designate a ground water management area within which a permitting system would be implemented.
Kansas	Ground water management districts use a combination of planned depletion, well spacing controls, and sustained yield management.
Louisiana	Locally funded and administered ground water control areas. No state statute governs ground water.
Maine	No statutes governing ground water.
Massachusetts	Ground water protection strategy based on water quality concerns.
Michigan	No statutes governing ground water.
Mississippi	Capacity use areas designated, controls may include metering, rotations, well spacing requirements and drilling restrictions.
Missouri	No statutes governing ground water.
Montana	Ground water management in control areas uses sustained yield principle. Control measures may include closing an area to further development, pumping rotations and restrictions.
Nebraska	Natural resource districts can allow ground water mining over 25 years, can impose well drilling moratoria, well spacing requirements, pumping rotations and quantity limitations.
New Hampshire	No statutes governing ground water.
Nevada	Nearly all usable ground water has been designated for management. Ground water with drawals 30 percent in excess of perennial yield can be permitted. Well spacing case by case, 1 mile in desert.
New Jersey	Department of Environmental Protection manages a permit system. Critical area rules have been proposed.
New Mexico	Ground water basins can be mined over 40 years; one third is reserved in perpetuity for domestic use. Well spacing case by case.

Table 2 cont.: Outline of the ground water management strategies of other states.

State	Summary of Management Strategy[1]
New York	Permits and restrictions on Long Island only.
North Carolina	Capacity use areas designated, controls may include metering, rotations, well spacing requirements and drilling restrictions.
North Dakota	Surficial aquifers are managed for sustained yield; small declines are allowed as they reduce losses to evapotranspiration. Leaky artesian systems are managed for limited declines in induce additional recharge.
Oklahoma	Ground water managed for a basin life of 20 years; users are given equal shares based on maximum aquifer yield (not sustained yield). Well spacing criteria used. Local Irrigation Districts may petition to be allowed to limit well sizes, withdrawal rates and well spacing.
Oregon	Maximum beneficial use of aquifer takes precedence over protection of water levels. Critical ground water areas have been designated.
Pennsylvania	No statutes governing ground water. Ground water protected area established by Delaware and Susquehanna River Basin Commission.
Rhode Island	No statutes governing ground water.
South Carolina	Capacity use areas designated, controls may include metering, rotations, well spacing requirements and drilling restrictions.
South Dakota	Cumulative withdrawal cannot exceed average annual recharge. Aquifer protections are applied to supply (does not include pressure on artesian systems or well construction conditions). State has the authority to designate a ground water control area, recommend well spacings.
Texas	Planned depletions over certain periods of time. Management districts may require well spacing but may not determine the amount pumped. Local Underground Water Conservation Districts locally initiated, administered, and funded.
Utah	Administrative policy: No applications approved if mining will result. Much of the state is limited to small domestic wells or is completely closed to new development. Water users pay fees.
Vermont	No statutes governing ground water.

Table 2 cont.: Outline of the ground water management strategies of other states.

State	Summary of Management Strategy[1]
Virginia	Ground water management areas issue permits.
Washington	Ground water management areas regulate withdrawals, 30 feet in three years is the allowable depletion rate.
West Virginia	No statutes governing ground water.
Wisconsin	Ground water use permits.
Wyoming	Ground water control areas have been designated. Administrative policy: Sustained yields. Controls include allocations, metering, well spacing, rotations, drilling moratoria, and regulations based on priority.

1/ compiled from:
Cox and Shabman, 1982
Krane, 1985
Miller and Powers, 1984
Wald, 1982

Conservation

Wise use of the water resource is a necessary part of any rational water management program. The amount of sacrifice the water users can tolerate will limit the conservation effort to relatively convenient measures during times of abundant precipitation; only during drought periods can widespread compliance be planned on. New equipment purchases can be made with water conservation in mind; old equipment can be modified to waste less water. Alternative irrigation methods may be considered (for example drip irrigation on fruit and vegetable crops). Tax incentives can encourage water conservation in the same ways they encourage energy conservation.

Minnesota's Rules require that conservation be a part of conflict resolution and emergency and contingency planning.

Well Spacing

Well spacing requirements determine the minimum spacing between new high capacity wells and existing wells. This distance may be dependent on the proposed pumping rate or diameter of the new well, the aquifer in which the well is screened, the priority of the existing well, or some combination of these factors. Well spacing can control high capacity well development and may prevent direct interference with surrounding wells. Spacing criteria are relatively easy to administer. However, only new wells are controlled; existing conflicts and excessive withdrawals will still exist. Individuals who have not yet developed a water supply are at a disadvantage and may incur higher water access costs due to forced locations of new wells. Well spacing requirements may pose possible constitutional challenges where the right to water is considered a property right (Aiken and Supalla, 1979).

Well spacing restrictions might be useful in outwash plains and alluvial aquifers where yields are relatively uniform. A good understanding of the aquifer characteristics is required. Spacing restrictions are too arbitrary to be useful in crystalline rock, drift areas and in most buried aquifer systems. In Minnesota the site of a well must be determined by the geology; test holes sometimes reveal very good producing wells and 'dry holes' in close proximity.

Pumping Rotations

Pumping rotation is a method for timing withdrawals from the aquifer. The timing of permissible pumping may be on a daily, weekly, monthly, or yearly interval, or some combination thereof. The rotation may be instituted over the entire area of interest or only in localized areas of overdevelopment. This approach may be effective in maintaining artesian pressures. Depending on the interval, there may be an indirect control on the amount of water withdrawn. If the timing of permissible pumping does not coincide with crop and soil needs, water will be inefficiently used. Administration of rotation schedules is problematic and compliance is difficult to monitor (Aiken and Supalla, 1979).

Pumping rotations could be used in Minnesota to resolve water use conflicts. Under Minnesota's Rules (6115.0810), local water use management plans may be formulated. Such a plan could make administration of pumping rotations possible and could increase compliance because of local input to the plan.

Well Drilling Moratoria

Temporary well drilling moratoria may be useful as a means of gaining time to develop more equitable and feasible methods of control. It is inequitable to individuals who have not developed systems prior to the moratorium and does nothing to control current withdrawals. Well drilling moratoria are very unpopular because they give water to the current users who caused the problem to begin with.

Well drilling restrictions have been imposed by Minnesota counties in the past. In an emergency it is possible that the Governor or Legislature could impose statewide restrictions.

Water Allocation and Rationing

Limits on the total annual withdrawal from a ground water system may be imposed. These limits may be temporary, may be limited in scope (new wells only, for example), and may be allocated in a number of ways. Possible allocation schemes include (after Aiken and Supalla, 1979):

1. limit withdrawals from each well in the area to a given amount of water. This amount would be fairly simple to determine via metering, but administration of meter reading could become complex. Differences in aquifer yield, soils, crop needs or the number of wells owned by one person or corporation would not be considered.

2. determine total allocation for an individual based on previously irrigated acreage. The assumption is that soils, geology and crop needs had previously determined the extent of irrigation. This would allow an individual to determine where and when irrigation would be most productive. It may be difficult to determine what was previously irrigated. This technique may not eliminate any interference conflicts and would give an advantage to current users.

3. determine total allocation for an individual based on the total potentially irrigable acreage owned. This method would treat current and potential developers alike, and with no other restriction would allow the efficient use of water for the individual's crop needs. Again, there may be problems in defining the term irrigable acre and interference conflicts may not be eliminated.

4. limit the sum of all current allocations within a given area plus the proposed allocation to a predetermined quantity of water. The area may be determined by a circle with its center at the proposed well location and with a radius of a given distance. The quantity of water slated for withdrawal may be based upon the amount of estimated recharge to the aquifer, on the saturated thickness of the aquifer, or on the amount of natural discharge from the aquifer which can be captured by pumping. Many unknowns are involved in the typical case: aquifers will probably vary from one circle to another and a circle of influence may not reflect the actual conditions in the aquifer.

5. ration water by allocating an equal amount to each user to be used as desired. The total amount of water to be rationed may be derived from basin yield or through ground water mining in accordance with local policy. This plan does not allow owners of large parcels to supply all their land, it leaves some users with excess water (which they may be allowed to sell).

Such management schemes may also be used to reduce the amount of ground water withdrawals during periods of drought. The reductions could be enforced for a set period of time or until the stress on the ground water resource is relieved.

Water allocation/rationing is feasible in Minnesota; allocation has been used to resolve a surface water use conflict on the Clearwater River. The success of allocation and rationing plans will be enhanced by the establishment of local administration bodies which could be created under Rules 6115.0810. Local administration can remove some logistical barriers to the implementation of allocation or rationing plans.

Mining

Ground water mining depletes ground water in storage in excess of ground water recharge. Ground water mining has occurred in the Twin Cities artesian basin, although it has stabilized since approximately 1970. Mining without explicit limitations is in direct opposition to conservation of the resource or *safe yield* concept and cannot be considered for ground water management in Minnesota. In other states it is used to support economic development over a defined period of years.

Renewable Resource Concept - Basin Yield

Under the renewable resource concept, that portion of the ground water resource which can be renewed on an annual basis (on the average) is available for use. This management principle falters unless the capture of natural discharge is considered. It is not possible to maintain the natural system unaltered while withdrawing water for use because the stable natural system required a balance between natural discharge and natural recharge.

Once the impact and extent of natural discharge capture is quantified through basic studies which link ground water withdrawals to the surface water resource, management through use of this concept would be feasible. The principle behind the determination of a basin yield is the water budget. The amount of water entering the basin must equal the amount of water leaving the basin, plus or minus the change in storage. The assumption must be made that surface and ground watersheds are coincident. This is directly applicable to the establishment of *safe yields* under water table conditions because the long term annual recharge, discharge to or recharge from surface waters, and net changes in storage (water levels) are considered. This approach requires good climatological data and knowledge of subsurface geology so that the hydrological modeling will be representative of actual processes. Information at this level of detail is rarely available.

A potential drawback to this approach is the lack of any site specific determination of predicted conditions; there is no direct field measurement which can be used as a flag for potential problems.

Water Quality Thresholds

The intrusion of low quality water into an aquifer is usually slow; the speed with which the contaminant or undesirable substance travels is at most as fast as the speed of the water itself. Travel of the low quality water is in response to gradients and will not stop immediately when pumping is stopped, but will continue until the new equilibrium is established. Monitoring of water quality must be done in close proximity to potential sources of contaminants, be based on local hydrogeologic conditions, and detect low levels of contaminant to allow discovery before substantial contamination has occurred. In principle the monitoring of water quality is straight forward, yet administration of such a program will require the continued funding and cooperation of several state agencies, in particular the Departments of Natural Resources and Health, and the Pollution Control Agency. Minnesota has groundwater quality problems associated with many types of land use. The problems are most severe near landfills, hazardous waste sites, under some agricultural lands, and in urban areas. Some hydrogeological situations are more susceptible to contamination than others (e.g. the karst area in the southeastern part of Minnesota).

Protected Levels

Minnesota's statutory definitions of *safe yield* imply that a "protected level" may be determined for an aquifer that will act as an indicator for the *safe yield*. The goal under confined conditions must be to keep the water levels above the bottom of the confining layer. A warning level may be determined to allow leeway before the water level reaches the protected level. The established level would then act as a warning flag, equivalent to the cutoff level used in surface water management. When it is approached, closer scrutiny of the aquifer system could be initiated, the public could be notified to begin executing voluntary conservation plans, while there is still time to avoid problems.

The current Rules ignore that fact that aquifers exist under unconfined, confined and intermediate (leaky) conditions, all of which may occur in a small area. The protected level under water table conditions is not defined in the Rules and would currently have to be determined after an analysis of the areal recharge to the system. A change in the Rules to include a rational, measureable criteria for protected levels under water table conditions should be considered.

Management based on protected levels determined for individual observation wells in each aquifer or aquifer system allows consideration of regional differences. The flexibility inherent in this approach is advantageous due to differences in hydrogeology, climate, water requirements, economic structure, and social factors between regions. It will not be practical to set protected levels where relatively little information is available and where the aquifer system is poorly understood.

The administration of a ground water management program based on protected levels requires the monitoring of water levels in a well-designed network of observation wells at regular intervals. The observation well network must be upgraded and maintained continually. The more critical (in terms of either quality, quantity, or both) the aquifer system, the more closely spaced the monitored water levels must be, in both space and time. A drawback of the protected levels approach is that critical conditions could develop on a local basis before the protected level in the nearest observation well is reached.

If water levels approach the protected or warning levels, it must be determined if the decline in water levels is due to overdevelopment of the aquifer, i.e. withdrawals exceed recharge, or if the decline is due to a discrete climatological condition. If water levels are not expected to recover, appropriate measures will then be taken to protect the resource.

OPERATIONAL POLICY FOR GROUND WATER MANAGEMENT IN MINNESOTA

Because Minnesota's rules specify *safe yield* as the management criteria to be employed in this state, we are devising a program to implement management based on *safe yield*. Indicators must be selected for the determination of whether the *safe yield* of an aquifer has been or will soon be exceeded. The rules assume that all aquifers can be placed in two distinct categories of confined and water table aquifers. Protected levels for confined aquifers can be determined in a straight forward fashion because there is a physical definition of the water level at which statutory *safe yield* is exceeded.

The regulatory goal of a protected level under water table conditions is to avoid withdrawing more water than is annually recharged to the aquifer over the long term. Long term must be defined as a number of years sufficiently long to encompass the typical climatic cycle of the region. The *safe yield* for water table conditions cannot be determined based on simple measurements at one site. Because water table aquifers are more susceptible to water quality degradation, because they frequently affect surface water levels, and because recharge is a function of discharge, the establishment of protected levels in water table aquifers is complex and may be linked to protected levels or flows in surface water bodies.

Possibilities for action, once it is determined that more than the *safe yield* is being withdrawn, include limitations imposed on total withdrawals and the timing of withdrawals. As it becomes apparent that *safe yield* may be exceeded, it must be established whether the problem appears to be due to a long-term trend or to a short-term climatic effect; identify the area, the permittees and other water resources affected; determine if further study is necessary before permit limitations are imposed; and educate the public about the situation and the available options.

An outline of the procedure for the establishment of protected levels in selected Minnesota aquifers or aquifer systems is given in Table 3. Each of the steps in the procedure is discussed below.

Ranking

It will be necessary to create a formal ranking and categorization of all aquifers in which appropriation permits have been issued and aquifers in which development is projected. The potential problems in each category must be listed and the appropriate analysis methods decided upon. For example, if there are areas where water quality rather than quantity is projected to limit the use of water; water quality should be the focus of the analysis. In areas where irrigation has increased substantially, the analysis would concentrate on the seasonal and cumulative effects of withdrawals from many high capacity wells during times of inadequate precipitation. Because the extent of many aquifers is not known, this ranking will be changed as more is learned about Minnesota's ground water resource.

Table 3: Procedure for the establishment of protected levels for confined and unconfined aquifer systems

Ranking of aquifers

Based on susceptibility to water use conflicts, potential increase in development, and past water use history.

Categorization of aquifers

Determine where the aquifer or aquifer system in question is to be considered confined, where unconfined.Determine if water quality or quantity is expected to be the primary limiting factor.

Assessment of available data

Collect existing hydrogeologic data. Review the literature.

Development of a conceptual model

A simple system model incorporating assumptions and available information allows preliminary study and analytical modeling.

Preliminary analysis

Warning levels are set for specific observation wells. Time and data constraints may dictate that most analysis will stop at this point. Site required new observation wells and begin monitoring levels.

Detailed aquifer studies

Warning levels have been exceeded or the area has been ranked as critical.
Devise work plan to keep study on track.
Field data acquisition.
Data analysis.
Create numerical model.
Calibrate.
Simulate future development and climatic conditions.
Predict best monitoring sites and parameters.
Predict effectiveness of potential solutions to the impending problems.

Act to restrict or change withdrawals if warranted

Monitor effectiveness of program, change if necessary

<u>Categorization</u>

The categories to which aquifers are assigned must remain flexible and there must be a provision for aquifers which do not fit the strict definition of either water table or confined aquifers. These special cases are interconnected (mutually leaky) aquifer systems. The protected level for such a complex system should be set as the more restrictive of the determinations for the system if it were actually confined or under water table conditions.

<u>Assessment of Available Data</u>

The type of hydrologic system information necessary to make sound hydrologic decisions on appropriation issues includes the following:

-surficial and subsurface geology
-hydraulic parameters of aquifers and confining beds
-aquifer and/or basin boundaries
-land use within the basin
-statistical characteristics of precipitation
-estimate of potential evapotranspiration
-areas of natural recharge or discharge
-lake levels and stream discharge
-distribution of pumping wells
-timing of withdrawals
-direction and velocity of regional ground water flow
-estimate of total ground water storage
-current water quality
-pollutant sources and amounts

In recognition of the fact that personnel, time and money are limiting factors, the initial step in the collection of information about a specific aquifer must involve gathering and evaluating available information from many sources, including:

1. Permit files for all permittees in the area directly affected and permit files for those pumping from what is considered to be the same aquifer.

2. Well logs and well locations from the files of the Minnesota Geological Survey.

3. Reports of aquifer studies completed by the U.S. Geological Survey; preliminary results of unfinished studies.

4. Regional and local climatic data from local observers and the office of the State Climatologist.

5. Records of water levels in existing observation wells.

6. Generalized geologic and hydrologic information from Minnesota Geological Survey maps and publications.

7. Construction details for affected wells.

8. Records of past water use in the area.

9. Past development history of the region.

10. Records of historical stream discharge and lake levels.

11. Water quality data from the Department of Health, Minnesota Pollution Control Agency, United States Geological Survey and local communities.

Development of a Conceptual Model

The study of an aquifer or aquifer system must include the design of a model for a specific set of hydrologic conditions that can be used as a tool in analyzing conditions. The model designed initially may be a hydrologic budget (mass balance) or a simplified conceptual model which incorporates what is known and assumed about the aquifer system. At this point the model can serve as the framework for initial analysis. If it is determined that the aquifer system is complex or that water use conflicts are probable, this initial model will guide the gathering of data for a detailed system model.

Preliminary Analysis

In areas where information is readily available due to previous studies and aquifer tests, analytical calculations may be adequate to predict the impact of potential stresses on the system without the need to conduct physical tests or construct a complex three-dimensional numerical model.

A major conclusion of the preliminary evaluation will be categorization of the aquifer. If an aquifer is deemed to be truly confined, the confining bed must be delineated and characterized. If the aquifer is semi-confined (leaky) or under water table conditions, the degree of connection to surface water supplies must be investigated. At this point the *safe yield* of the aquifer may be linked to protected flows or levels in surface waters.

In areas where low potential for water use conflict exists, analytical methods may prove adequate to guide the selection of wells for which protected levels are to be assigned. During the analytical modeling process, the aquifer will be subjected to pumping and climatic stresses until the model predicts that withdrawals would exceed *safe yield*. We suggest that a safety factor of a minimum of 20 percent of *safe yield* should be incorporated both to allow time for reaction and because of the potential for errors of at least 20%. Wells for monitoring will then be selected or sited based on whether the impending exceedance of *safe yield* is expressed at that site. The chosen safety factor will be translated into a specific warning flag water level for each well.

The calculation of long term annual recharge used in the establishment of *safe yield* under water table conditions may be a result of water budget calculations, hydrograph analysis or induced infiltration and evaporation calculations from an analytical model. The effect on water levels or flows of withdrawing an amount of water equal to the long term average recharge is then predicted.

Detailed Aquifer Studies

Further analysis may be necessary in areas ranked as high priority and in areas where the warning levels are triggered. A detailed model of the local aquifer system allows areal differ ences in the aquifer to be accounted for and allows great flexibility in modeling aquifer boundaries. However, the data requirements for a numerical model, the time required to create, calibrate and run it, and the expense of computer time will only allow this method to be used for a few aquifer systems. The time period alloted by the USGS for regional studies of individual aquifer systems and the development of extensive numerical models is typically four years. Where a regional model exists, it may serve as a data base for the local aquifer study.

Aquifer tests may be required as may mass measurements of water levels in lakes, wetlands and area wells. It may be necessary to field locate and survey in the elevations of many wells. Observation wells and test holes may be drilled, their siting guided by the results of the preliminary study and by surficial geophysical studies. Water quality studies in both surface and groundwater will be completed whenever warranted. The inclusion of water quality into the model of the system is possible; it can be efficiently handled by superimposing analytical contaminant tracking modeling onto the results of the hydrologic model.

Once the model is calibrated it can be used to simulate the conditions of future development and climatic stress. If it is feasible that *safe yield* by either definition will be exceeded, the model can be used to decide where monitoring wells are needed and what water levels in those wells are indicative of impending trouble.

It is not enough to be aware that a problem is possible, potential solutions for the problem must be decided upon so that they are available if the problems arise. The numerical model can allow the simulation of the effects of pumping rotations, limited withdrawals, and many of the other possible restrictions which could be imposed upon users. The potential effectiveness of those restrictions could then be evaluated.

Act on Results

The implementation of voluntary or regulated limitations on water use is one possible action. If it is determined that the current water use conflict is due to a transient climatic event, it may be decided that temporary overdrafts should be allowed. Many of the decisions can be made in advance with the help of local advisory panels and local government. The goal is to reduce the impact of the water use conflict on all users.

Monitor Effectiveness of Program

Once an impending problem has been observed and dealt with, the system must be monitored intensively to observe any changes. If the actions initially taken are not sufficient to avert increasing water use conflict, then more vigorous methods must be applied. If it becomes evident that what was considered to be a shortterm shortage is not alleviated; it will be necessary to impose restrictions on water use or provide equitable allocations to users.

CONCLUSIONS

We recommend a change in the Rules to allow the use of more objective and more readily determined criteria in addition to *safe yield* analyses. Such criteria could provide guidance to well drillers and homeowners without requiring extensive preliminary study. If, for example, an initial protected level under water table conditions were set as a certain percentage of the predevelopment saturated thickness, new wells would be constructed to adequate depths. Current policy requires a well to be in existance before the permit is obtained; the installation proceeds without guidance even though changes in the construction of installed wells are expensive. Basin yield studies would then be carried out in critical areas with the goal of protecting the resource for the future.

Under the current Rules, it is possible to include *safe yield* analysis of individual aquifer systems as part of Minnesota's ground water management program. Due to budgetary, staff and time constraints, it is recommended that initial aquifer studies be limited in scope. These preliminary studies will serve to guide the siting of observation wells in high priority areas and to set estimated protected levels in those wells. Once sufficiently expanded, the observation well network will provide part of the information necessary to perform detailed aquifer studies in critical areas, if funds for such studies are available.

Safe yield analyses cannot be carried out in a time frame short enough to respond to management crises. This work must be completed as part of the ongoing program in the Division of Waters; it will not be possible to set protected levels on an emergency basis except where a *safe yield* study had previously been completed. Other ground water control measures, specifically conservation, pumping rotations, and water allocation are available to deal with crises. These measures are more likely to be successful if local ground water management organizations can administer them and if a major public education effort is part of the process.

GLOSSARY

Aquifer. — Aquifers are rock strata or sediments which contain sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquiclude, aquitard, aquifuge. Rock strata or sediments, which although porous and capable of absorbing water slowly, will not transmit it fast enough to furnish an appreciable supply for a well or spring. (Replaced by the term confining bed.)

Artesian. — Artesian is synonymous with confined.

Buried aquifer. — Buried aquifer is synonymous with confined aquifer.

Confined aquifer. — An aquifer bounded above and below by confining beds. Ground water in a confined aquifer is under pressure and will rise in a well to a level above the bottom of the confining bed.

Confining bed. — A layer of relatively impermeable material stratigraphically adjacent to one or more aquifers.

Drift. — Drift is used to refer to all kinds of glacial deposits.

Evapotranspiration. — The sum of all water evaporated from soil and water surfaces plus any water transpired by plants.

Gradient. — Water moves in response to the force of gravity; rate of movement is proportional to the slope (gradient) of the water table (under confined conditions the gradient is determined by measureing water levels in wells which penetrate the confined zone, the difference is the potential gradient).

Hydraulic conductivity. — Permeable rock transmits water under pressure. The hydraulic conductivity is a measure of the rate at which water is transmitted.

Hydrograph. — Graphical representation of water levels over time.

Outwash. — Glacial drift which has been stratified and sorted by the action of meltwater streams beyond the front of the glacier.

Permeability. — The relative ease with which a porous medium can transmit a liquid under a potential gradient.

Porosity. — Porosity expresses the volume of pore space in a substance. The pores contain water when the substance is saturated.

Saturated thickness.	That part of the aquifer where the pore spaces are full of water.
Storage coefficient.	The volume of water released from or taken into storage when the head in that aquifer changes. Values of the storage coefficient range from 0.30 to 0.00001.
Surficial aquifer.	The saturated layer between the water table and the first lower confining bed. The surficial aquifer is an unconfined aquifer.
Till.	Unstratified and unsorted glacial drift.
Transmissivity.	The rate at which water is transmitted through a width of aquifer under a gradient. The transmissivity is equal to the hydraulic conductivity of the aquifer times the saturated thickness of the aquifer.
Unconfined aquifer.	An aquifer that has a water table; this aquifer is between the water table and the first lower confining bed.
Water table.	The water table is the top of the saturated part of the soil or rock strata. Wells that penetrate the saturated zone just far enough to hold standing water are water table wells.

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