Potential Effects of Subsurface Drainage on Water Appropriation and the Beneficial Use of Water in North Dakota

RESPONSE to SENATE BILL No. 2020, Section 11
of the 60th LEGISLATIVE ASSEMBLY of NORTH DAKOTA

By
W. M. Schuh
(Cartography by Rod Bassler)

Water Resources Investigation No. 45
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EXECUTIVE SUMMARY

During the Sixtieth Legislative Assembly of North Dakota, the Assembly directed that the North Dakota State Water Commission:

" study, develop, and recommend policies for assessing the impact of tile drainage on the beneficial use of water by prior water appropriators."

A summary of the findings are as follows:

1. There are no provisions in North Dakota Century Code or Administrative Rule requiring consideration of waters drained through surface or tile drainage in evaluation of water appropriation and the beneficial use of water. In neighboring states (Minnesota, Montana and South Dakota) effects of tile drainage on the beneficial use of water are not considered in the water appropriation process. In Minnesota tile drainage is specifically exempted and protected from consideration for water permits.

2. In North Dakota there is nothing (at the time of report publication) in state law or administrative rule specifically authorizing the regulation of subsurface or tile drainage. The language of North Dakota Century Code (Section 61-32-03) refers only to the draining of a *"pond, slough, lake, or sheetwater or any series thereof."* The State Engineer, however, currently requires a drainage permit for tile drainage, since potential problems from increasing water flow to drainageways are identical to those of surface drains.

3. Median annual drainage amounts measured at Lamberton, MN, Waseca, MN, and Oakes, ND in the 1990s and early 2000s were: 5.6 inches for Lamberton (1994-2000), 5.2 inches at Waseca (1990-1993), and 5.8 inches at Oakes (1987-2005). A simulation of drainage based on drainage vs. precipitation data from Lamberton, MN, Oakes, ND, and Waseca, MN, and the 20th century precipitation record at Oakes, ND, indicated that over the last (20th) century normally constructed drains would have been expected to flow between 15% and 35% of the years, depending on tile depth and local crop, soil and management conditions. The simulated median drainage for years in which drainage was indicated to occur was between 2.4 and 3.2 inches per year.

4. The economic benefits of tile drainage for agriculture are large and well proven.

5. The SWC currently has on record a total of 131 permitted tile-drained fields, all distributed within 11 counties, and all except one near or within the Red River Valley. Of these only 20% (28 permits) overlie major aquifers. Reports of drained acreage are unclear because of confusion by applicants concerning the proper identification of drained acreage. Forms have been revised to clarify the reporting requirements. An approximation of permitted acreage (June 2008) is about 22,963 acres of drained land. Because of the possibility of non-permitted acreage, this number may be low. An additional 34 tile-drainage permit applications are pending approval.

6. Potential drainable acreage overlying aquifers was estimated for an 18-county study area in the Red River Valley and Devils Lake basin [including Barnes, Benson, Cass, Cavalier, Dickey, Grand Forks, Griggs, LaMoure, Nelson, Pembina, Ramsey, Ransom, Richland, Sargent, Steele, Towner, Traill and Walsh Counties] using two methods: (1) *aquic* soil great group taxa, and (2) USDA-NRCS drainage classifications (very poorly drained, poorly drained and somewhat poorly drained). Results indicated that:

- The estimate that 20% of potentially drainable acreage would overlie major aquifers in the 18-county study area agrees with findings that about 20% of 135 currently permitted tile drain installations overlie major aquifers.

- About 35% of the aquifer acreage is classified as having an *aquic* soil moisture regime. About 40% is classified within the three drainage classes including: very poorly drained, poorly drained, and somewhat poorly drained.

- Only 7% of the total land in the 18-county area (0.2 x 0.35 x 100) need be considered for potential conflict between tile drainage and the beneficial use of water.

- Using a 20th century drainage scenario, **if all of the *aquic* soils overlying aquifers were tile drained**, the median 20th century drainage would have been between 650,000 and 850,000 acre-feet when the drains were flowing. But drains would have been expected to flow in only 15% to 35% of the years, depending on tile depth, and crop, soil and management characteristics. Also, some of the water removed through tile may have been previously drained through natural or artificial surface drainage.

7. While the estimated total annual drainage seems large, tile-drained waters are removed from an upper zone of "active" storage which is not sustainable for long-term storage. Almost all tile-drained waters would be removed through natural discharge within a year or two at most, if not drained, by seepage to surface waters or through evapotranspiration. In the hydrologic cycle common to North Dakota's glacial aquifers, recharge occurs through precipitation and runoff (and sometimes losing streams), and discharge occurs through evaporation, transpiration, runoff, and seepage to rivers and streams. Sustainable withdrawal of water for human purposes (drainage or pumpage) must be recovered from existing natural discharge.

- Tile drainage is economically feasible on water-logged soil. Soil with high water tables is subject to evapotranspiration. Water tables commonly fluctuate as much as four or five feet due to evapotranspiration alone. Almost all tile-drained waters in North Dakota's glacial aquifers will eventually be captured from evaporation or transpiration in the hydrologically active zone, or from intercepted runoff. This is accomplished by lowering the water table, thus preventing surface evaporation or shallow transpiration of drained water through plant roots, and by enhancing infiltration of waters that may have run off from saturated surfaces.

- Under management based on "sustainable yield," ground water pumped for beneficial use must be captured from evapotranspiration in shallow water-table areas, from seepage, or from waters that would be naturally surface drained. Most waters pumped from glacial aquifers in eastern North Dakota are captured mainly from evapotranspiration. This is accomplished by lowering the water table through pumpage, which serves as an alterative form of discharge. As waters are pumped, water tables drop, causing evaporation and root extraction of water from the aquifer to decrease and eventually decouple (cease). For most crops, root extraction decouples when the water table is between 6 and 10 feet below the land surface. Some plant communities may draw deeper.

- Where tile drainage and well fields compete to capture the same evapotranspiration, the well fields are almost always situated for most efficient capture because well screens are placed deeper than the drains. Under optimal design and management, well fields can simply dewater the drains.

- For confined aquifers (aquifers separated from the land surface by a slow permeability material called an aquitard), tile drainage may, in some rare cases, substantially change the local recharge regime. The vulnerable condition exists where the water table in the aquitard is near land surface (as would be expected in a drainable area), and where the piezometric head of the confined aquifer is also near land surface and very close to that of the aquitard. In such cases small changes in the water table caused by tile drainage may have a significant relative effect on local recharge to the aquifer, and may even cause a change from a recharge area to a discharge area. The greater the thickness of the aquitard, the less the potential relative effect of drainage on recharge and discharge. Circumstances of vulnerability would be expected to be relatively rare, and even when they occur they would be limited to the area of local drainage and would not likely have a large impact on the entire aquifer.

- For a confined aquifer, even if drainage were to cause a change in the recharge-discharge balance, a local well field would have the capability to offset the effects of the drains. Pumping the underlying aquifer will decrease the piezometric head, increase the gradient from the water table to the aquifer, and increase the rate of recharge, thus compensating for any losses caused by the hydraulic effects of drainage. Eventually the enhanced recharge caused by pumpage would be able to dewater the drains. As with an unconfined aquifer, the well field in a confined aquifer is almost always best positioned for first capture.

8. Tile drainage in soil overlying an unconfined aquifer will decrease the saturated thickness, and will proportionally decrease pumpage. The time and degree of change will depend on the initial saturated thickness of the aquifer and the distance of the drain field from the well field.

- The time of effect (the lag time in response to pumping) will vary directly with the square of the distance between the well field and drain field, directly with aquifer specific yield and inversely with aquifer transmissivity. The time of effect may vary from days locally on a coarse thick aquifer to many years at several miles distance within a fine textured thin aquifer.

- The effect of tile drainage on saturated thickness at the well will decrease with the acreage of evaporative *(aquic)* soils intervening between the well field and the drain field.

- The degree of drainage interference with the well field will be very small, with the possible exception of well fields placed in very thin areas of the aquifer.

- Where aquifer thinness causes vulnerability of a well field to tile drainage, it will also be vulnerable to natural changes in water tables due to climatic variation. Such a well field would be, arguably, poorly designed and/or inefficiently located.

- Where aquifer thinness causes vulnerability of a well field to tile drainage, effects of drainage could almost always be offset by the addition of wells.

9. One area of specific concern is the Traill Rural Water Association well field in the north Page-Galesburg aquifer in Traill County, ND. We estimate the maximum potential effect of interference of a drainage field with the well field to be less than 2%. Because of intervening poorly drained soils between the proposed drainage fields and well fields, actual effect would likely be much less. Additional local wells could offset any losses that did occur. The Traill Rural Water Association is currently seeking an additional well field where the aquifer is thicker. Drainage effects where saturated thickness is greater would be expected to be negligible.

10. Water quality impact of tile drainage would usually be:

- Less soil erosion and soil particles delivered to surface water;

- Less phosphate and possibly a proportionally greater amount of organic phosphate delivered to surface waters through tile drains than through overland flow;

- More nitrate delivered to surface water through tile drains than through overland flow, but likely less nitrate would be delivered to ground water; and

- Relatively less pesticides delivered to surface waters through tile drainage than through overland flow.

11. Water-quality of tile effluent can be managed by passing waters through:

- Grass buffer strips,
- Wetlands, or
- Various design filters, such as wood-chip filled filter channels.

12. Beneficial use of water can be enhanced through use of subsurface drainage with water conservation and water-table management practices.

- Water-table controls can be incorporated into tile-drainage design, which will minimize drainage and allow crop roots to maximize root-zone water.

- Water from exterior (surface or ground-water sources) can, in some places, be applied as sub-irrigation through tile drains.

- Artificial recharge and recovery can be used to capture and store drained waters for beneficial use. Drained waters can be used by withdrawing them from surface-water bodies and storing them in surface reservoirs or in aquifers. Recovered drain water can be stored in aquifers through surface spreading, infiltration through open basins, or through injection wells. Artificial recharge and recovery has been used successfully in several instances in North Dakota.

Because a very large portion of tile drainage in North Dakota will occur in fine textured soils, and most (about 80%) will occur in soils not overlying aquifers, by far most of the water will be drained from lands not accessible for pumping and beneficial use. In these areas, tile drains can be viewed as low-head horizontal wells, mobilizing large amounts of water from low-permeability materials over large acreage. If properly managed conjunctively with surface-water management, and if properly stored, tile drainage may actually provide a large supply of water for beneficial use that would not, before drainage, have been available.

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1. INTRODUCTION

During the Sixtieth Legislative Assembly of North Dakota, inquiries were raised concerning the effects of tile drainage on water use and appropriation. In response, the Assembly mandated that:

> *"The State Water Commission shall study, develop, and recommend policies for assessing the impact of tile drainage on the beneficial use of water by prior water appropriators. The State Water Commission shall report its findings and recommendations to the legislative council by July 1, 2008. " (Senate Bill 2020, § 11, 2007 North Dakota Legislature)*

The purpose of this report is to provide the results of the study, findings and recommendations mandated by the legislature.

This report will examine the issue of tile drainage effects on water appropriation by examining: (1) The current relationship between water appropriation and drainage laws in the state of North Dakota; (2) the approach of neighboring states to regulating the relationship of tile drainage to the beneficial use of water; (3) the benefits of drainage; (4) an evaluation of waters removed during drainage using existing drainage measurements; (5) a review of the locations of current permitted drainage in relation to pumpable waters, estimated drained acreage, and estimated water drained, (6) an analysis of maximum potential tile-drained acreage and waters drained; and (7) an analysis of drainage effects on the availability of pumpable waters based on hydrologic factors. The report will also briefly discuss potential drainage-related management technologies that could affect the beneficial use of water, including water-level control and artificial recharge and recovery.

1.1 The Water Problem: Scarcity vs. Excess

From the standpoint of human needs and objectives, natural water supplies are seldom optimal, and fluctuate between scarcity and excess. Fluctuations occur not only geographically, where certain areas are characteristically classified as dry (arid, semi-arid) or wet (subhumid, humid, hyperhumid, ultrahyperhumid), but seasonally and, it is increasingly recognized, periodically over varying spans of years (Wright 1996, Vance 1984, Wiche et al. 1996, Murphy and others 1997, Milly and other 2008). Drought and flooding may occur as isolated events. But the probability of their occurrence may increase or decrease greatly within periodic climate changes that are roughly repeatable, and to some degree qualitatively predictable (Gosnold 1999, Hartman and Kuehn 1999, Solc 2005, Vecchia 2008). Retrospective analyses (Schuh 1998) following the catastrophic flood of the Red River in Grand Forks in 1997 and potentially catastrophic flooding of Devils Lake since exceptionally wet conditions began in 1993, observed that current wet climatic tendencies lie within larger trends of increasing floods and rising waters that began at the end of the "dirty thirties," in 1940. Conversely, the severe prolonged drought of the 1930s was, in itself, merely the tail end and the bottom extreme of a drying climatic trend that had been in progress since at least the 1820s. Indeed, flooding events similar to, or exceeding those in the 1990s, have been documented for the early 1800s. Long-term studies (Gosnold 1999, Hartman and Kuehn 1999, Solc 2005) have indicated that drying and wetting cycles recur at (very rough) intervals between 100 and 200 years, and that both floods and droughts in excess of those experienced in this century have occurred over the last several thousand years (Hartman and Kuehn 1999, Murphy and others 1997, Solc 2005).

It is important to understand that both floods and droughts can occur any time within the fluctuating climate regime, but that the probability of occurrence and magnitude is likely to be affected by the timing of the event within the overall climatic trend. It is also important to understand that the extremes of drought and flood trends are defined not only by events, but by predisposing conditions wrought by the trends themselves. Thus, part of the extremity of the effect of the 1930's drought was not only the period dryness, but the trends of receding water tables which ultimately decreased access to needed water for livestock, farms, and municipalities. Similarly, beyond the highly visible catastrophic effects of Devils Lake and Grand Forks, merely the tips of the iceberg, are large-scale chronic problems of flooded farmsteads, towns, basements, agricultural fields, and overflowing septic fields caused by rising soil water tables throughout eastern North Dakota during the 1990s (Schuh 1999). These, while less visible, were caused by the same succession of events and trends that affected the river and lake floods. But all of these, in turn, have been partially preconditioned by effects of a large-scale wetting trend that has been in process since the early 1940s. Like the 1930's drought, their final and most drastic effect may seem to have "appeared" abruptly, but they did not "occur" abruptly. They were predisposed by decades of a more predominant wetting trend (or in the case of the 1930's drought, a drying trend).

The greatest challenge of water management lies in protecting human habitability and prosperity within this highly variable envelope. It is a formidable challenge. Ideally, we would store water during wet periods for use in dry periods; but we can only store a limited amount and for a limited period of time. Ideally we would allow maximum use of waters during wet periods and curtail them during dry, but the economic commitments required by infrastructure for municipal, industrial and agricultural enterprises do not abide well such curtailment, particularly if it occurs too soon after the investment.

Moreover, transitory effects for ground-water supplies - the amount of time it takes for extracted water to replenish when recharge sources may be distant - cause large uncertainties when combined with climatic fluctuations and our inability to ascertain how long a "wet" or "dry" period may be sustained.

The limited problem of this report, assessing potential effects of tile drainage on water use and appropriation, must be viewed within this framework of "too much" vs. "too little." But this report cannot resolve the complex issue of where the lines should be drawn. The issues of individual rights and social needs involved in such a value assessment are beyond the scope of a hydrologic report. It must suffice to establish, in the extreme case, that at some point control of excess water through drainage is essential for human prosperity and habitability. Certainly proper drainage for our streets, and tile drainage of our homes is recognized. Protection from, and removal of flood waters is essential for our farms, homes and municipalities. Properly drained fields are also essential for agricultural production. Simultaneously, there can be no denying the critical need for adequate and sustained water supplies. Both drainage and supply needs are affected by planning and management - where and how one chooses to build with respect to flood risk or supply, or where one proposes to place a well field. Where necessary, these are regulated by laws and zoning ordinances governing floodplain management, or laws and administrative rules requiring "efficient capture" designs for well fields. But in the final analysis it is not generally the "extreme" cases that cause the most difficulty in regulatory policies. It is the tight calls. Few dispute the need to expedite excess water removal during a flood, and few dispute the need to conserve water during a drought. For the most part, the interests of all will concur in these extremes. Conflicts will most likely occur in the transition periods between climate extremes and during intermediate and special cases.

1.2 Scope and Methods

The limitations of a study such as this, must be clearly understood at the outset. First, scientific and technical literature related to drainage and its requirements is vast, broad and extremely complicated. Drainage concerns include issues of wetland drainage and adverse effects on wildlife, water quality impacts on surface waters and estuaries from leached salts and nutrients in surface waters, flood-peak impacts, and many others. All of these are extremely complex issues. A comprehensive report on the potential effects of subsurface drainage on surface hydrology and ecosystem impact in the Red River Valley, based on an extensive review of available scientific literature, has been prepared in two papers by Blann, Anderson, Sands and Vondracek (1988 In Press) and

Blann, G. Sands, B. Vondracek, and J. Anderson (in review). Pending publication, an overview of their work has been prepared as a white paper (*Implications of Subsurface Drainage for the RRB:Aquatic Ecosystems;* by K. Blann, G. Sands, B. Vondracek, and J. Anderson) and was recently presented at the MN-ND Subsurface Drainage Forum, Fargo, ND, 2/14/08). We refer those interested in the broader issues of tile drainage to the authors of these reviews.

This report will focus on the specific issue of water appropriation and beneficial use impacts, as presented in the legislative mandate. Second; this study is, as they say, "starting from scratch." A review of the literature has indicated almost no work addressing the relationship between drainage and water appropriation. It has not previously been on the "radar screen" as a major issue in water management. Third; a one-year study resolution does not allow for fieldwork or extended research, and is very limited even with respect to time for data analysis. The reviewers must rely on existing data; but very little data directly related to tile-drained water is available for North Dakota. Spatial estimates thus depend on extended interpretations of sparse localized data, or data obtained elsewhere, with the implied differences in climate and soil conditions. Some of the available data, such as drained acreage listed on drain permits, is of uncertain reliability, and must be used with skepticism and judgment. Much reliance must be made on fundamental hydrologic processes of aquifer recharge, storage, discharge, and well function and design. These, in turn, are applied using hydrologic data only indirectly related to drainage itself. In short, it is what is commonly referred to as a "data-mining" exercise - attempting to glean every plausible source of information from limited existing data sources.

The imprecision of such work is seldom pleasing for the analyst. It relies on defining broad "envelopes" of plausible outcomes. But it can, in many cases, provide an adequate answer to the question at hand. In this report, we attempt to use limited existing data to provide a semi-quantitative "sense" of how much and where drainage of ground-water may occur, and how it may affect the beneficial use of ground water. Despite data limitations, we believe that the question, from a practical standpoint, can be answered with reasonable confidence.

2. LAWS AND REGULATIONS CONCERNING TILE DRAINAGE EFFECTS ON BENEFICIAL USE OF WATER

Consideration of recommendations for protection of the beneficial use of water requires a review of the adequacy of current laws and administrative rules for solving potential conflicts between tile-drainage and beneficial use. It is also useful to examine the regulatory approaches of neighboring states with respect to tile drainage and the water permitting process.

2.1 North Dakota Water Law, Administrative Rule and Policy

There are currently no provisions in North Dakota Century Code or Administrative Rule requiring consideration of waters drained through surface or tile drainage in evaluation of water appropriation and the beneficial use of water. Drainage in North Dakota Century Code, is regulated under Section 61-32. A summary of North Dakota Drainage Law was provided by Craig Odenbach and Julie Prescott, then of the North Dakota State Water Commission, and is provided in Appendix A. Section 61-32-03 states:

> *"Any person, before draining a pond, slough, lake, or sheetwater or any series thereof, which has a watershed area comprising eighty acres or more, shall first secure a permit to do so..."*

It further states:

> *"If the investigation shows that the proposed drainage will flood or adversely affect lands of downstream landowners, the water resource board may not issue a permit until flowage easements are obtained."*

And finally:

> "*The state engineer may adopt rules for temporary permits for emergency drainage..."*

For authorization to drain, a party must file an application with the State Engineer. The State Engineer then determines whether the project as proposed is of statewide or inter-district significance. State administrative rules explain that the State Engineer may determine any project to be of statewide significance. Consideration is given to: whether drainage which would affect property owned by the state or its political subdivisions; whether it is drainage of sloughs, ponds, or lakes having recognized fish and wildlife values; whether it is drainage or partial drainage of a meandered lake; whether the drainage would have a substantial effect on another district; or if it would convert previously noncontributing areas into permanently contributing areas.

Factors to be considered by a Water Resource District in evaluating an application not determined to be of inter-district or state-wide significance include:

1. The volume of water proposed to be drained and the impact of the flow or quantity of this water upon the watercourse into which the water will be drained.

2. Adverse effects that may occur to the lands of lower proprietors. This factor is limited to the project's hydrologic effects such as erosion, duration of floods, impact of sustained flows, and the impact on the operation of downstream water control devices.

3. The engineering design and other physical aspects of the drain.

4. The project's impact on flooding problems in the project watershed.

5. The project's impact on ponds, sloughs, streams, or lakes having recognized fish and wildlife values.

6. The project's impact on agricultural lands.

7. Whether easements are required.

8. Other factors unique to the project.

If the application is considered to be of state-wide or inter-district significance, the State Engineer must also consider these factors:

After determination of "statewide or inter-district significance" the application is sent to the appropriate Water Resource District Board. For applications of "statewide or inter-district significance," the Board must set a time and place for a hearing, and notice must be given by mail at the applicant's expense. The list of those who must be notified is provided by rule and includes potentially impacted landowners downstream and several government agencies that might be impacted. Notice must also be published in a newspaper of general circulation once a week for two consecutive weeks, with the final publication being not more than 15 days nor less than 5 days from the date of the hearing. The notice must give the essential facts of the project including the time and place for the hearing. Additionally, the applicant must provide to the Board all of the documentary information to be submitted during the hearing at least 14 days prior to the hearing, and the Board must make this information available to the public. The information can be made available in the office of the Board if they have an office that is open to the public at least 20 hours a week, or if not, then the information is to be on file with the County Auditor. The hearing must be recorded, either stenographically or electronically. The State Engineer may request a transcript, in which case the cost is borne by the applicant. If the Board approves the application, it must forward the application along with the hearing record and their determination to the State Engineer, who makes the final decision.

NDCC 61-32-03 also provides the State Engineer with the statutory authority to develop rules for the issuance of emergency drain permits. These rules are published in Chapter 89-02-05.1 of the North Dakota Administrative Code, and they provide that a license may be issued for up to six months for an emergency. An emergency is defined as:

> *"...a situation which if not addressed immediately will cause significant damage to persons or property which would not occur under normal circumstances. An emergency may exist as a result of an extremely wet cycle. However, damages caused by deliberate acts of any individual do not constitute an emergency under this chapter unless the damage can be alleviated without harm to other persons or property."*

Further details of the permit process are provided in Appendix A.

Impact on beneficial use is not currently considered in the list of factors to consider in granting a drainage permit. **If tile drainage effects on the beneficial use of water by prior appropriators were to be considered in the future, it could be added as item 9 of the "factors to be considered" specified by administrative rule as described above. However, unless the issue were to become a frequent and serious issue, it could likely be accommodated under item 8 of the current rules. If the potential impact were to be considered immediate and critical, the emergency authority of the State Engineer could be employed.**

2.2 Minnesota, Montana and South Dakota Policies for Potential Conflicts between Tile Drainage and Water Permits

In states neighboring North Dakota, the issue of potential effects of tile drainage on the beneficial use of water has never been considered, nor has it been limited on the basis of water appropriation.

Ms. Terri McLaughlin, director of water appropriations for the state of Montana, stated in a phone conversation (9/20/07) that tile drainage was not considered as a part of the water permit process. The only related specification was that drained waters within an irrigation district could be captured, stored and reused by the district.

Mr. Eric Gronlund, assistant to the South Dakota State Engineer, informed in a phone inquiry (9/18/07) that the issue of tile drainage effects on the beneficial use of water had never been raised, and that all regulation of tile drainage in South Dakota was through county water boards. There is no connection between drainage and water appropriation in South Dakota regulatory structure.

An inquiry through the Minnesota Department of Natural Resources, referred us to Ms. Laurel Reeves, Water Appropriations Program Manager for DNR Waters. Ms. Reeves informed us that the DNR water appropriation division does not regulate tile drainage in any way and that it is not a consideration in water appropriation. Minnesota water appropriation procedures allow open use to 1,000 gallons-per-day, or alternately one million gallons-per-year, above which a state permit is required. The water permit is evaluated on the basis of a long-term (7-to-30 day) pumping test at the proposed use rate. In the case of Minnesota, however, tile drainage is specifically exempted and protected from consideration for water permits. Under Minnesota Rule 6115.0620 (SCOPE):

> *Permits shall be required for, and these parts shall apply to, any appropriation of waters of the state, except for the following:*
>
> *D. Agricultural field tile or open ditch drainage systems, including pumping, to remove water from croplands. This shall not preclude the need for compliance with Minnesota Statutes, chapter 103E and for permits for changes in course, current, or cross section of public waters in the event that the agricultural drainage system adversely affects public waters. Adverse effects on public waters may include partial or complete drainage of public waters, high water or flooding conditions on surrounding lands, and accelerated erosion and sedimentation.*
>
> *E. Reuse and discharge of waters resulting from an appropriation of waters of the state for which a permit has been granted, subject to applicable laws, and rules of other state and federal governmental agencies.*

Thus, the only consideration of tile drainage with respect to the beneficial use of waters in neighboring states is the specific legal protection of tile drainage from consideration in the State of Minnesota.

3. SOIL DRAINAGE: PURPOSE, BENEFITS AND PRACTICE

A reasonable comparison of two potentially antagonistic practices should consider benefits as well as impairments. In this analysis we will consider the value of beneficial use of water to be axiomatic. The need for water in all phases of society for human consumption, livestock, industry, mining, irrigation, and wildlife and recreation are addressed as a fundamental need in article XI, § 3 of the State Constitution; and requirements and procedures for its allocation and conservation are addressed under chapter 61-04 of ND Century Code and article 89-03 of ND Administrative Code. The final question of drainage impact will be "how much adverse impact will tile drainage have on water supplies?" But we can only properly weigh the cost and benefit of the effect against the benefits of drainage.

3.1 Purpose and Benefits of Tile Drainage

Agricultural drainage is one of the primary tools for enhancing and protecting crop yields. It is used primarily to offset water-logging through sustained high water tables. The most direct effects of water-logging are suppression of root-zone aeration and consequent impairment of root proliferation, function, and metabolism. Indirect effects on crop growth include soil temperature suppression, salinization, impaired field access, and changes in the root-zone chemical environment that can adversely impact crop growth. According to Dr. Hans Kandel, there are few agricultural practices that provide more practical and economic benefits for the Red River Valley than tile drainage (*Why Producers in the Red River Basin are interested in subsurface drainage;* by Dr. Hans Kandel, MN-ND Subsurface Drainage Forum, Fargo, ND, 2/14/08). The following brief summary of benefits is derived mainly from monographs by Evans and Fausey (1999), Ayars and Tanji (1999), and Cannell and Jackson (1981), with respect to soil aeration and its effects; and Maas and Grattan (1999), Hoffman (1999), and USDA Handbook 60 (1954) with respect to soil salinization.

Water-logging has been shown to quickly decrease root-zone oxygen through displacement of soil air by water, and through the slow oxygen-diffusion rate of water which prevents atmospheric oxygen from reaching crop roots. Crop roots have been shown to cease growing once inundated, and fail to penetrate a static water table. Under high-water table conditions this can strongly restrict the root zone and plant growth capabilities. Optimal water-table depths for many crops on mineral soils have been shown to be between 50 and 100 cm (approximately two and three feet), varying with individual crops and conditions. On most crops, yields gradually decline with increasingly lower water tables, mainly due to less capillary water available for plant use. Yields decline quickly with incrementally higher than optimal water tables and consequent restricted root zones (Benz and others 1981). Oxygen depletion occurs quickly in the root-zone following inundation (within 2-3 days on fallow soils and more quickly with plants present). The rate of depletion increases with higher temperatures. Oxygen is required by roots for respiration, metabolism and energy transfer. These in turn are needed for water and nutrient uptake. Thus, waterlogged conditions cause nutrient starvation and wilting. Yield suppression on corn can occur within one to two days of the onset of waterlogged conditions. Generally winter wheat is more tolerant of water-logging than barley and rye, corn is more tolerant than grain legumes and grass forage species are more tolerant than forage legumes.

Indirect adverse effects of water-logging include the concentration of toxic byproducts of anaerobic respiration (examples are: acetic and butyric acid, acetylaldehyde, hydrogen sulfide, ethylene, and excessive reduced iron and manganese). Their crop symptoms include wilting, epinasty, chlorosis, desiccation, leaf abscission, slow growth and dry matter accumulation, and swelling at the base of the plant stem (Cannell and Jackson 1981). Other indirect adverse effects include impaired crop germination and seed viability through excessive moisture and lower soil temperatures, moisture effects on cool-soil nutrient availability, reduced field access and workability, nitrogen loss through denitrification, and inhibited root nodulation on soybeans. Water-logged conditions also increase pathogenic activity for many crops.

Finally, in many environments soil salinization is an important result of high water tables. According to Maas and Grattan (1999), "A long-term salt balance can only be achieved at the farm scale or regional scale if there is adequate drainage. Crops grown in regions with saline water tables near the soil surface are subjected to soil salination if the water table rises. Crop production in these situations cannot be sustained indefinitely since a long-term salt balance cannot be achieved." Salinization is particularly damaging where irrigation with saline waters is practiced. Additional waters required for leaching salts added in irrigation waters can, without adequate drainage, cause the water table to rise, increasing water-logging and exacerbating salinization of the root zone. But it can also occur where natural salts are brought to the soil surface by evaporation from shallow water tables and concentrated within the root zone. From Ayars and Tanji (1999), "It has been given over the centuries that in order to sustain production, drainage was required along with irrigation in arid areas to control the buildup of salts in the soil profile;" and Van Schilfgaarde (1999), "It is axiomatic that irrigated agriculture cannot be maintained unless there is adequate drainage." According to Hillel (2006) and Maas and Grattan

(1999) salinization caused by high water tables and inadequate drainage have caused the decline and fall of many advanced agricultural civilizations. Damage from salt accumulation includes osmotic inhibition of plant water uptake and, in some cases, direct toxicity from excessive concentrations of sodium, chloride, boron, or other dissolved ions (USDA 1954). Crops vary in their susceptibility to ground-water salinity and toxicity from specific ions (Hoffman 1999, Cannell and Jackson 1981). Presence of sodium ions also causes slaking and destruction of soil structure (USDA 1954, Cannell and Jackson 1981). Adequate drainage is required for both the prevention and reclamation of soils salinized by shallow water tables and the presence of natural or exogenous salts.

Soil salinization has recently been recognized as a significant problem in North Dakota and South Dakota, due to rising water tables following wet climatic shifts that began in 1993. During a 2005 USDA-NRCS soil problem assessment meeting in Bismarck, ND, Jim Millar, USDA-NRCS soil scientist from Huron SD, reported that as much as 10% of soils in the Lake Dakota area near Aberdeen, SD, were undergoing salinization. In addition, salinization has been raised as a potentially serious problem in relation to a proposed irrigation project in the Devils Lake region. Surface salinization has been observed and measured for fields with shallow water tables near the Devils Lake Outlet (WPC 2006, Schuh 2006). The USDA-NRCS has recognized that soil degradation through salinization caused by high water tables is occurring in North Dakota, and Mike Ulmer (USDA-NRCS), Bismarck, and his colleagues are currently assessing the problem. The importance of drainage as one tool to prevent and remedy salinization under such conditions has long been understood (USDA 1954).

3.2 Review of Subsurface Drainage Practice

Tile-drain systems are designed to lower the water table following a specified major precipitation event to a specified depth below the land surface, at the mid-point between the drains, within a specified period of time. All of the discussion and specifications for tile-drainage equations in the next four paragraphs are from (Madramooto 1981), except where otherwise specified. The specified depth (a) in North America is commonly between one to two-and-a-half feet below land surface (30 and 70 cm). The drainage coefficient (q), the water removal rate in a 24-hour period, is based on evaluation of "tolerable risk." One common standard used for risk assessment is based on a 1-in-5 year storm. 'q' is commonly between 0.4 and 0.5 inches/day (10 and 12 mm/day) in North America. Max Fuxa of Ellingson Companies, Inc. has stated (personal communication 12/12/07) that a common drainage coefficient used in North Dakota is about 0.375 inch (10 mm)/day. The minimum grade for 4-inch (75-mm) pipe is 0.1%, but may be as flat as 0.05. According to Max Fuxa (Ellingson Companies Inc.) tile grades of one-foot-per-thousand (0.1%) are commonly used in North Dakota. Grades on mainlines should not exceed 3%. Drainage-field design on level fields tends toward whole-field drainage, while fields with larger relief and isolated "wet-spots" are commonly drained using what is called a "random design," which targets the wet areas of the field.

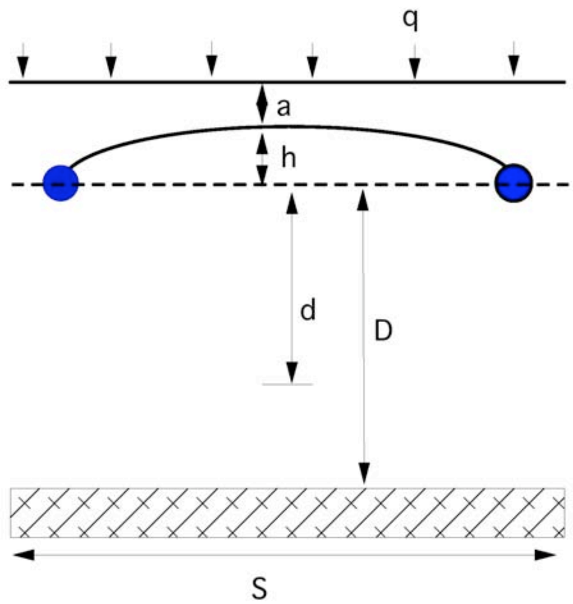

Figure 1. Diagram of drainage-design parameters for Equations 1 and 2.

Tile drainage-field designs employ various tools, including personal local experience, drainage simulation models, like DRAINMOD (Skaggs 1999), and steady-state and transient equations based on an elliptical water-table configuration (Fig. 1). Steady-state equations, like that of Hooghoudt (Eq. 1), are commonly used for design of drain-size, depth and spacing where climatic conditions favor long-duration low-intensity rainfall.

$$q = \frac{4\left(dhK_b + h^2K_a\right)}{S^2} \qquad (1)$$

where d is the thickness of the 'equivalent layer,' which is a function of drain spacing (S) and pipe radius, and the depth of the impermeable layer below the drain bottom (D); h is the height of the water table above the drain level; K_a is the hydraulic conductivity of the soil above the drain, and K_b is the hydraulic conductivity of the soil below the drain.

Non-steady-state equations, like that of van Schilfgaarde (Eq. 2), are commonly used in irrigated areas, or for areas where rainfall is commonly intense and of short duration.

$$S = \left[\frac{9Ktd}{f\left[\ln h_o\left(2d + h\right) - \ln h\left(2d + h_o\right)\right]} \right]^{0.5} \quad (2)$$

where S is the drain spacing width, K is hydraulic conductivity; t is the time for the water table to drop from h_o to depth h_1 (a on Fig. 1); f is the drainable porosity of the water-conducting soil; h_o is the initial water table height at drain mid-spacing; d is the "equivalent depth" to the impermeable layer [calculated using an additional equation; see Rodrigue (1998)] and h_1 is the water-table height at mid-spacing after time t. In addition, tile-drain designs are frequently supplemented locally by the experience of design engineers and contractors.

Generally, tile spacings can be wider with deeper drains. According to Max Fuxa, of Ellingson Companies, Inc., a major tiling contractor in North Dakota, they seldom use a drain spacing more than 100 feet. Practices may vary with individual contractors. Drains are commonly installed between three and four feet in depth below land surface, but may be as shallow as 2.5 feet beneath the bottom of a surface-drainage ditch to maintain grade.

From the standpoint of water storage for beneficial use, tile drains placed in coarse soils over aquifers, are "skimming" the surface of the aquifer. For practical purposes, the water will be desaturated and in quasi-equilibrium with the water table at the level of the tile. However, during the growing season, not all of the water removed during the drainage period need enter tile drains. For example, using the van Schilfgaarde equation for a tile-drain in a sand having a horizontal K of 20 feet-per-day, a storage coefficient of 0.16, a tile-drain of 4-inch diameter placed at four feet below land surface, and specifying drainage from full saturation (surface) to two feet below land surface within one day at mid spacing, d is estimated at 5.4 feet, and the design tile spacing is 106 feet. Computations are made using the USDA-NRCS web-based tools documented provided by Rodrigue (1998). Using the same equation, the estimated time to fully drain the soil profile to the level of the tile would be 10 to 11 days. For well-developed roots within the top two feet, an approximate storage coefficient of 0.16, and a potential evapotranspiration between 0.2 and 0.4 inches per day, transpiration could remove sufficient water to account for one to two feet of water-table depth during that time. Thus, not all waters above tile drains need be removed through the drains themselves. The K value used would be for a fine sand. A loamy sand or loam soils would have a smaller K, causing a longer period for root extraction before equilibration with the drains.

The critical issue is: What effect will drained waters have on pumpable waters? To evaluate this we must examine: (1) The amount of water drained or potentially drained from aquifers; (2) the effect of those drained waters on water supplies, i.e. effects on the recharge/discharge balance and water storage available for beneficial use; and (3) the effect of drained waters on the availability of stored waters for pumping.

4. POTENTIAL WATER LOSS FROM DRAINAGE

A first step in evaluating tile-drainage impact on the beneficial use of water is to estimate how much water is being drained, or may be drained, at some future time. This is difficult to estimate because of limited data on drained acreage, limited knowledge of quantitative drainage from that acreage, no information on how much land may be drained in the future, and the difficulties of assessing what portion of those drained lands may affect the beneficial use of water. Using the available data we will attempt to provide a very broad quantitative sense of current and potential drainage losses and effects in four steps. First, we will use limited available data for measured drainage to examine the distribution of potential drainage over a rainfall distribution common to eastern North Dakota. Second, we will examine a minimum drainage-loss case by applying the simulated drainage vs. precipitation relationship to current permitted tile-drained acreage. Third, we will examine a maximum case by estimating how much acreage "could be" tile drained in eastern North Dakota, and applying the simulated drainage vs. precipitation distribution. Fourth, and last, we will examine the potential effects of tile-drainage on beneficial use by analyzing the hydrologic processes related to tile-drained waters and their potential interactions with well field supplies and pumping capabilities.

To evaluate the potential effects of tile drainage on the beneficial use of water, it is useful to develop a framework of estimated total water loss through drainage. It is cautioned that such estimates must be very general in nature. There are many factors affecting drainage from a given field, and locations where drainage is measured over a period of years are limited. We will use published tile-drainage measurements for southwestern Minnesota at Lamberton and south-central Minnesota at Waseca, and for the Garrison Conservancy "five-thousand-acre test plot" area at Oakes, ND. We will employ, in addition, an indirect approximation using calculations of drainage for a single annual soil-profile saturation based on the effects of a receding water table, and the field-measured soil-water-retention curve for common soils over aquifers in eastern ND. These data will be used to establish a broad sense of the amount of drainage that may be occurring and how it varies with climate trends. They must be interpreted, however, with a sense of caution, recognizing that local factors may vary widely. Climate for southern Minnesota, for example, differs somewhat from eastern ND, and the Oakes test area drain design is deeper and more broadly spaced than most current drainage-field designs. Water tables near Oakes have also been affected by irrigation development. Despite these limitations and cautions it is still useful to develop a rough quantitative envelope of drainage-induced water losses. The greater challenge will be to evaluate the meaning of these numerical estimates in terms of waters that could be available for beneficial use.

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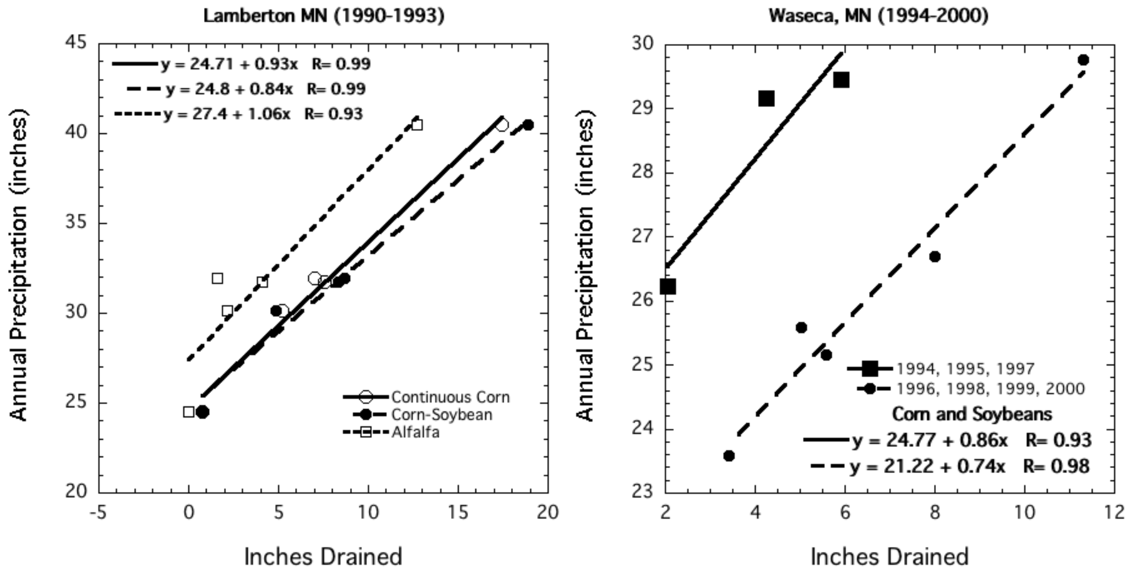

Figure 2. Annual drainage vs. precipitation (P) summary for published data from Lamberton, MN and Waseca, MN (From Chung and others 2001, and Randall and others 2005).

4.1 Lamberton, MN and Waseca, MN Drainage

The amount of drainage for any given year will depend on many factors, including the design of the drainage field, the amount and timing of precipitation and evapotranspiration, predisposition of the water table from the previous year's climate, and the rooting depth and water withdrawal characteristics of the crop. Short-term data published for Lamberton MN (Chung and others, 2001) and Waseca MN (Randall and others 2005) illustrate some of these general relationships. These data are from experimental plots having drains set at *approx.* six-feet (1.8-m) below land surface. Soils drained are fine in texture and have *aquic* moisture regimes. The Waseca experiment soil is a Canisteo clay loam (Endoaquoll) and the Lamberton soil is of the Nicollet series (*Aquic* Haplustoll). In general, all of the drainage vs. precipitation relationships exhibited a "threshold" behavior, requiring a minimum annual precipitation (between 21 and 27 inches) for drainage to occur, after which almost all residual precipitation was removed through the tile drainage, as indicated by a regression coefficient near one (line slopes on Fig. 2). It should be stressed that this a general descriptive relationship between climatic moisture regimes and drainage, and not an annual minimal prerequisite precipitation for flow. The thresholds were about 25 inches (10 cm) for corn and soybeans at both Lamberton and Waseca. They were more for alfalfa at Lamberton, and they differed by years, which exhibited a bimodal grouping at Waseca, MN.

4.2 Oakes Test Area Drainage, Dickey County, ND

Tile drains in the Garrison Diversion Oakes Test Area were constructed during the 1980s as a part of a project to test various irrigation practices proposed for the Garrison Diversion project (Frietag and Esser 1986). The total area of the test plot was about 7,143 acres; an average of about 3,500 acres has been irrigated since 1993. All 7,143 of the project acres were tile-drained, with the exception of a couple of excluded interior quarter sections, and a couple of exterior quarter sections that were included. Total drainage, and average drainage in inches-per-acre for the entire operational period, beginning in 1987, are shown on Fig. 3. All drainage data were provided by Dale Esser, area manager for the Garrison Diversion Project at Oakes, ND. The large difference in drainage from early to later times can be attributed to the combined influence of irrigation and climate. The year 1988 was a drought year and conditions were generally dry through 1992 (causing low initial water-table conditions). Relatively small recharge during this time was combined with increased water use during the dry period for extensive irrigated acreage. Beginning with large rains in 1993 generally wet conditions followed for several years. Large recharge combined with curtailed pumping for irrigation during this period combined to increase drainage.

Management and design factors also complicate assessment of causes. Oakes test-plot area drainage design, based on an optimizing model of the U.S. Bureau of Reclamation, was deeper and more widely spaced than most current drainage project designs. Drain depths were usually six to eight feet (1.9 to 2.5 m) and as deep as 13 feet (4 m) on some of the mains, and average tile spacing of 1,200 feet (366 m) (Arden Frietag, personal communication 12/12/07). This compares with common depths of three to four feet (1 to 1.2 m) and spacings of about 40 to 100 feet (12 to 30 m) for most current drainage projects (personal communication, Max Fuxa, Ellingson Companies, Inc., 12/12/07). Water table elevations above tile drains may not differ from common drainage depths as much land surface elevations because of initially lower water tables affected by extensive pumping for irrigation in the Oakes area.

Water tables were also affected by aquifer recharge and recovery practices in the test-plot area, and by standpipes which were used to maintain high water tables and retain recharged waters. In the springs of 1989 through 1993 the Bureau added recharge water pumped from the James River through water-spreading. Rates varied annually from one to four inches, averaged over the entire test area. Some local quarter sections, however, received as much as 17 inches (43 cm) of spring recharge water within a given year. To prevent water loss through the drains the Bureau installed stand-pipes in several drains to increase aquifer storage by one to six feet (0.3 to 1.8 m) above the natural drains (Frietag and Esser 1986).

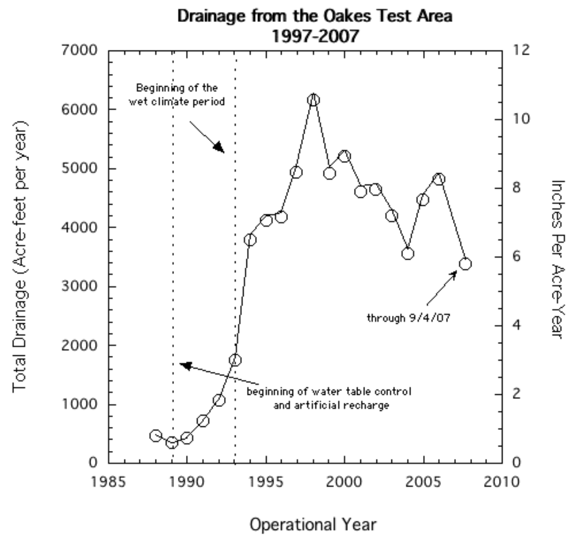

Figure 3. Annual Drainage for the Oakes Test Area, Dickey County, ND (Data provided by Dale Esser, Garrison Conservancy District, Oakes, ND).

The 20th century mean precipitation at Oakes was about 21 inches per year (+/- 1 inch at $p \leq 0.05$). The drainage data on Fig. 3 represent four time periods. These are: (1) An initial dry period in 1987 and 1988 having precipitation in the bottom 15% (15.4 inches) and 8% (13.8 inches) of the century record, respectively; (2) a period of near normal precipitation (average of 20 inches per year) from 1989 through 1992, but with added water spreading of one to four inches; (3) a period of large average precipitation (*approx.* 26 inches per year) from 1993 through 1999; and (4) a period of about average precipitation (21 inches) from 2000 through 2005. The maximum precipitation for the 1993 through 1999 period was *approx.* 34 inches in 1998 (the century maximum), and the mean for the entire period exceeded the top 20th percentile for the century. Drainage was negligible (*approx.* 0.5 inches per year) for the dry period [(1) above]; increased slightly to *approx.* two inches during water spreading and with water control at the standpipes (2); increased to a maximum of about 11 inches per year during the wet period (3); and decreased to about seven inches per year in the final period (4). The mean drainage from 1993 through 2007 was 7.7 inches per year (+/-0.6 inches).

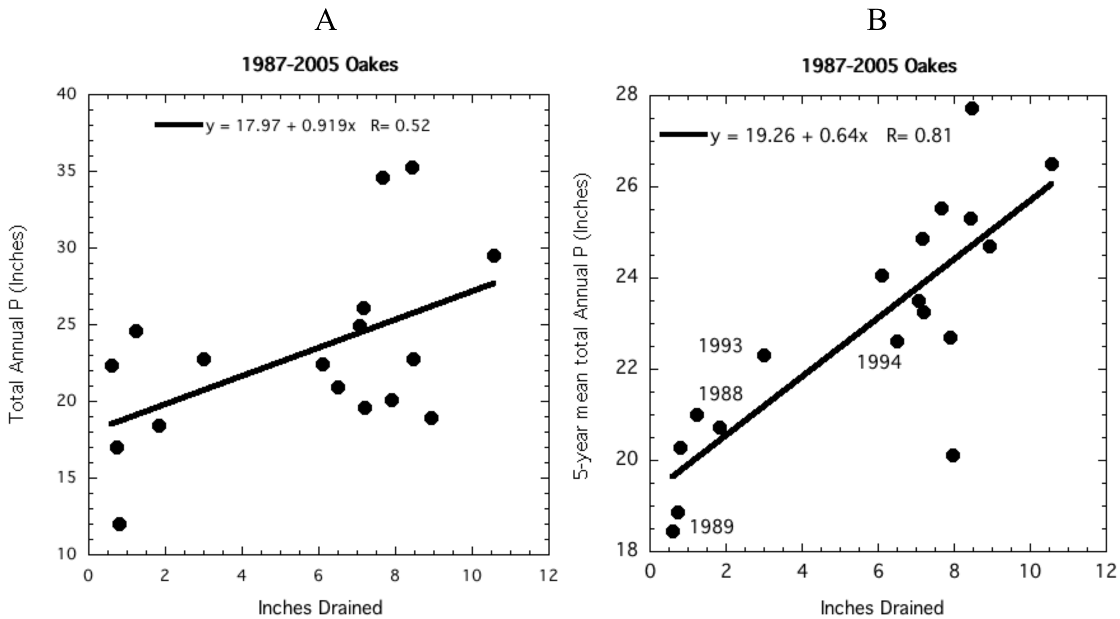

Figure 4. Annual drainage, and five-year mean annual drainage vs. precipitation (P) summary for 1987 through 2005 for the Oakes Test Area of the Garrison Diversion, Dickey County, ND.

Unlike the Lamberton and Waseca data, the Oakes data did not correlate well with annual precipitation data. This, however, is not surprising because the Oakes drainage data was longer-term, covering 19 years, and two distinct climate regimes, one initially very dry (1987 through 1992) and the other initially very wet (1993 through 2005). Initial water levels were thus different for the two periods. Moreover, water-table management varied from aquifer recharge and recovery to water-table control between the wet and dry periods. Indeed, the data (Fig. 4) separates into two time periods. Adjusting the precipitation data for five-year means smooths the climatic effects, providing an approximately linear relationship with a threshold of about 18 inches.

The precipitation record for Oakes during the 20th century is shown on Fig. 5. The period from 1920 to 1925 was the highest sustained precipitation, the period from 1925 through 1940 was the driest, with another dry period bottoming near 1950. The highest precipitation was in the mid 1990s, and the largest projected drainage of the century would have occurred in 1998.

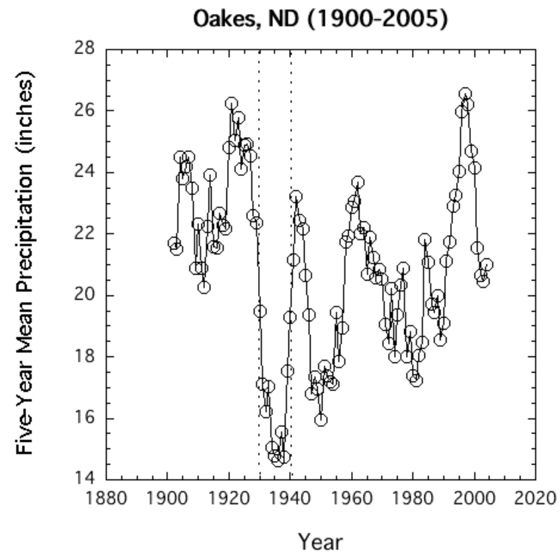

Figure 5. Five-year moving-average precipitation for Oakes, ND from 1900 through 2005, from the National Oceanic and Atmospheric Administration cooperative observer network (compiled by Royce Cline, SWC).

If we use the five-year mean precipitation function from Fig. 4B as a transfer function for a rough approximation of drainage, results (Fig. 6B) indicate that the century median drainage for the Oakes Test Area (had it been constructed) would have been about 4 inches per year, with no drain flow about 20% of the time, and six inches-per-year or more about 20 percent of the years.

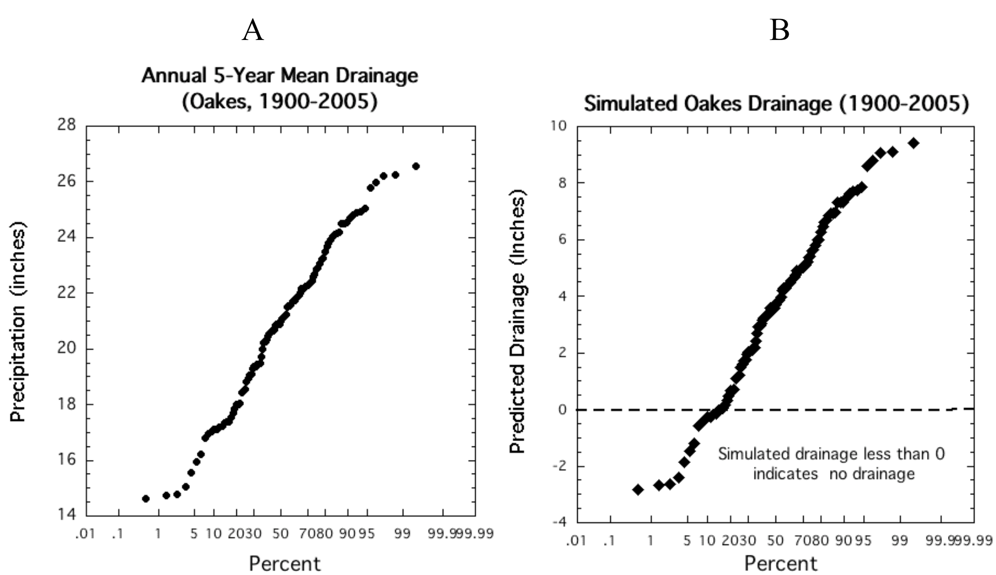

Figure 6. Percent distributions for: (A) 20th century five-year mean annual precipitation at Oakes, ND; and (B) simulated drainage from the Oakes Test Area calculated using the data distribution on (A).

4.3 Water-Retention Drainage Estimates

An indirect method for estimating drainage is to examine incremental losses of water from a receding water table based on steady-state downward translation of the soil water-retention curve (Gillham 1984). This method was employed using field measured water retention for six common soil series in southeastern ND. The method and computations are reviewed in Appendix B. Results (Table 1 below) indicate that for a single annual recharge event causing the water table to rise to land surface, and with tile drains placed at *approx.* 3.3 feet (100 cm) below land surface, an annual mean of about two inches would be drained. This would provide an estimate for shallow drains (three to four feet) deep.

Table 1. Calculated incremental drainage for varying initial and final water tables on six ND soil series that commonly overlie glacial aquifers (Appendix B).

Soil Series	Drainage inches (cm)								
Drainage increment --------->	Surface to 1 ft. (30 cm)	Surface to 1.5 ft. (46 cm)	Surface to 2 ft. (61 cm)	Surface to 3.3 ft. (100 cm)		0.5 ft. (15 cm) to 2 ft. (61 cm)	0.5 ft. (15 cm) to 3.3 ft. (100 cm)	1 ft. (30 cm) to 2 ft. (61 cm)	1 ft. (30 cm) to 3.3 ft. (100 cm)
Hamar loamy sand (1)	0.1 (0.26)	0.39 (1.0)	1 (2.6)	4.3 (11)		0.94 (2.4)	4.3 (11)	0.63 (1.6)	3.9 (10)
Hamar loamy sand (2)	0.008 (0.02)	0.1 (0.26)	0.39 (1.0)	3 (7.5)		0.39 (1)	3 (7.5)	0.31 (0.79)	2.9 (7.3)
Ulen sandy loam (1)	0.02 (0.05)	0.09 (0.24)	0.27 (0.69)	1.8 (4.5)		0.25 (0.64)	1.7 (4.4)	0.18 (0.45)	1.7 (4.2)
Ulen sandy loam (2)	0.06 (0.15)	0.26 (0.6)	1 (2.6)	2.2 (5.5)		0.98 (2.5)	2.1 (5.4)	0.79 (2.0)	1.9 (4.9)
Arveson sandy loam (1)	0.14 (0.35)	0.35 (0.89)	0.55 (1.4)	1.3 (3.4)		0.39 (1.0)	1.2 (3.1)	0.19 (0.49)	0.98 (2.5)
Arveson sandy loam (2)	0.14 (0.35)	0.35 (0.89)	0.63 (1.6)	1.6 (4.1)		0.47 (1.2)	2.1 (3.7)	0.27 (0.68)	1.3 (3.2)
Stirum sandy loam (1)	0.09 (0.23)	0.23 (0.59)	0.43 (1.1)	1.3 (3.2)		0.33 (0.84)	1.2 (3.0)	0.19 (0.48)	1 (2.6)
Stirum sandy loam (2)	0.15 (0.37)	0.38 (0.97)	0.63 (1.6)	1.3 (3.4)		0.47 (1.2)	1.2 (3.1)	0.25 (0.63)	0.98 (2.5)
Eckman loam (1)	0.04 (0.09)	0.11 (0.29)	0.27 (0.68)	0.91 (2.3)		0.23 (0.59)	0.87 (2.2)	0.15 (0.39)	0.79 (2.0)
Eckman loam (2)	0.01 (0.03)	0.05 (0.12)	0.19 (0.47)	0.43 (1.1)		0.17 (0.44)	0.43 (1. 1)	(0.34) 0.13	0.39 (1)
Gardena loam (1)	0.13 (0.34)	0.32 (0.81)	0.55 (1.4)	1.5 (3.9)		0.43 (1.1)	1.4 (3.5)	0.24 (0.61)	1.2 (3.1)
Gardena loam (2)	0.04 (0.10)	0.14 (0.34)	0.31 (0.7)	1.1 (2.7)		0.27 (0.68)	1 (2.6)	0.17 (0.43)	0.91 (2.3)
Mean (all)	0.08 (0.19)	0.23 (0.59)	0.51 (1.3)	**1.7 (4.4)**		0.43 (1.1)	1.7 (4.2)	0.29 (0.74)	**1.5 (3.8)**
Mean (sands)	0.09 (0.22)	0.27 (0.69)	(1.6) 0.63	**2.1 (5.4)**		0.55 (1.4)	2 (5.1)	0.35 (0.89)	**1.9 (4.7)**

To compare these numbers with the Lamberton and Waseca measurements, deep incremental increases in drainage per unit soil drainage are *approx.* 0.16 for the sands, and *approx.* 0.06 for the finer soils. Thus, for comparable tile depths (6 feet or 1.8 m) an additional 5 inches (12 cm) of drainage, or a total of about seven inches drainage would be expected on the sands. An additional 2 inches (5 cm), or a total of four inches drainage would occur on the fine soils. These estimated values (four to seven inches) compare reasonably well with the median values for Lamberton (2, 7, and 8.3 inches on three treatment plots) and Waseca (4.9 and 5.6 inches). Thus, under similar precipitation about two-to-five inches-per-year less drainage would likely have occurred during the 1990s at normal depths of drains currently being constructed in North Dakota, compared with those at Lamberton and Waseca, MN.

4.4 Estimating the Twentieth-Century Distribution of Drainage

For estimating the amount of water drained through current permitted tile drains, and for estimating the potential drainage that could occur through maximum tile-drainage development, a transfer function relating the long-term precipitation record to drainage is useful. The only complementary 100-year precipitation, and long-term (20-year) drainage data available in North Dakota is the Oakes Test Area data. Use of a relationship based on Oakes drainage data is problematic, however, because of design and management characteristics that are non representative of most new tile-drainage fields.

The Oakes data share two common useful characteristics with the Lamberton and Waseca data. All exhibit an approximate "threshold" precipitation above which all waters drain (Figs. 2 and 4). For Oakes the threshold during the 1990s was about 17 inches (43 cm), while for five treatments at Lamberton and Waseca the threshold varied from 22 to 26.7 inches (56 to 68 cm), with a mean of 24 inches (61 cm). In addition, all share an incremental drainage coefficient close to one above the threshold. We will use the range of Lamberton and Waseca precipitation thresholds of 22, 24 and 26 inches and a coefficient of one with the Oakes long-term precipitation record to estimate the **maximum potential** drainage.

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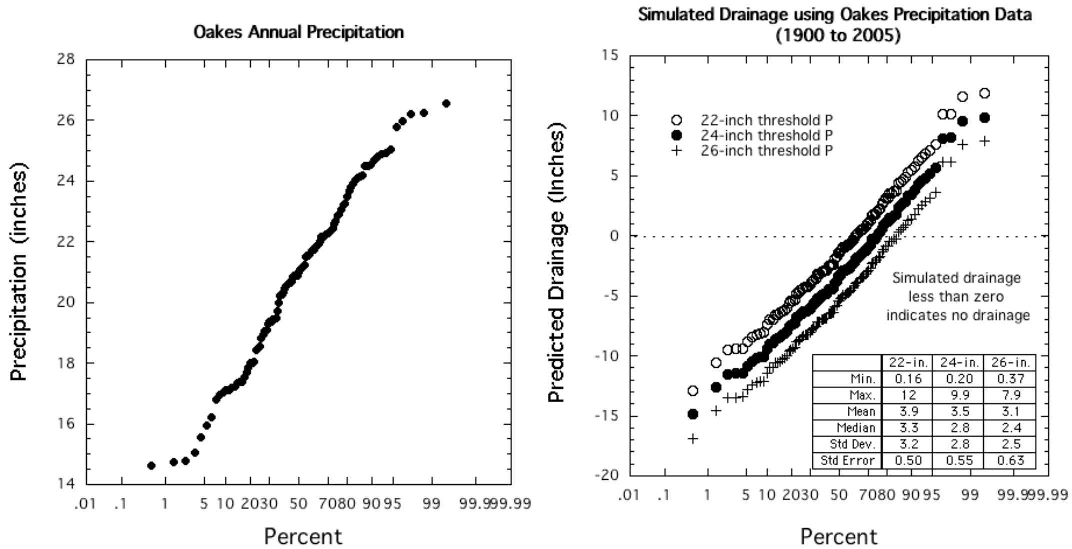

Figure 7. Annual precipitation distribution for 1900 through 2005 at Oakes (A), and the estimated drainage distribution for precipitation thresholds of 22, 24 and 26 inches.

Normal precipitation in eastern North Dakota varies from 21 inches in the southeast (including Oakes) to 19 inches in the northeast. However, evapotranspiration decreases northward, which would offset differences in the net water balance. The Oakes precipitation data should thus be adequate for a general comparison.

Simulated drainage for 20th century precipitation scenarios at Oakes, ND, using 22-, 24-, and 26-inch (56-, 61- and 66-cm) thresholds (Fig. 7-B) indicate that there would have been no drainage during 65%, 75%, and 85% of the years, respectively, at Lamberton and Waseca under the 20th-century Oakes climate scenario. The median drainage on years when drainage did occur would have been about 3.2, 2.8, and 2.4 inches (8, 7, and 6 cm) respectively.

There are many factors that may affect the threshold, including precipitation in immediately preceding years, and characteristics of the crop rotation and associated management practices. While drain placement and spacing at Lamberton and Waseca are closer to current practice in North Dakota than the Oakes design, current design usually places drains shallower (3 to 4 feet, or 0.8 to 1.2 m) below land surface then the drains at Lamberton and Waseca (6 feet, or 1.8 m). Because a shallower water table allows for more profile storage, this would tend to cause a higher threshold of precipitation before drainage would occur. Conversely, small grain commonly grown in eastern North Dakota would use less water than a corn and soybean rotation. This would tend to lower the threshold. Nonetheless, the range of threshold values provided by the transfer function should provide a reasonable "ballpark" estimate of potential drainage. It is my view that the higher threshold value (26 inches) may provide the better estimate of potential drainage.

4.5 Summary

Drainage amounts are dependent on several factors, including drainage-field design, crop water-use characteristics, potential evapotranspiration, annual rainfall, and prior climatic conditions which define the initial water table in relation to the drains. Tile drainage seems to follow an apparent "threshold" behavior that requires a short-term climatic mean (annual to five-year, depending on the time period and location) minimum annual precipitation of 18 to 26 inches for drains to flow. The median value for drainage on three sites during the wet conditions of the late 1990s and early 2000s was *approx.* six to eight inches per year. This, however, included a time of generally wet climate, and at Oakes the wettest climate of the century. Soil-moisture estimates for the drainage of a single saturated profile would be similar. Variation was high, however, ranging from negligible to as much as 18 inches drained on one site (Lamberton), and from negligible to about 12 inches on the other two (Waseca and Oakes). For Oakes, drainage was negligible during the dry period (1988 through 1992).

Estimated median drainage for the 20th-century precipitation distribution at Oakes would be about four inches, with negligible drainage 20% of the years, and exceeding six inches per year only 20% of the years. Because of deep drains and exceptional management practices that affect local hydrology, including irrigation, aquifer recharge and recovery using surface waters, and periodic use of water-table control practices, the Oakes drainage data are unsuitable for comparison with contemporary drainage designs. Instead, a range of threshold precipitation values for incipient drainage, derived from the Lamberton MN and Waseca MN drainage experiments are used with a drainage coefficient of one above the threshold, to estimate annual tile-drainage from precipitation. The range of threshold values used is 22, 24, and 26 inches per year. Results indicated that for a 20th century precipitation scenario, significant drainage would be expected in only 35%, 25% and 15% of the years, corresponding to the respective precipitation thresholds. Median drainage for years where significant drainage occurs was estimated to be 3.2, 2.8, and 2.4 inches (8, 7, and 6 cm) for the respective precipitation thresholds. These amounts are similar to the magnitude of drainage estimated using the soil-water retention method.

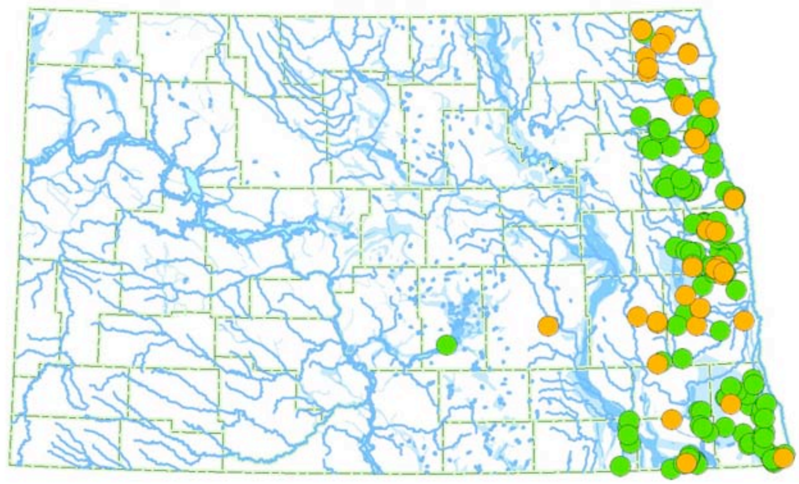

Figure 8. State-wide distribution of approved (green) and pending (orange) tile-drainage permits (SWC database, June, 2008).

4.6 Estimated Waters Drained through Current Permitted Tile Drainage

A summary of current drainage permits (Table 2) filed with the SWC indicates that as of June, 2008, there were a total of 131 approved permitted tile-drained fields, all were distributed within eleven counties, and all except one were near or within the Red River Valley (Fig. 8). Of these only 20% (28 permits) were for lands overlying aquifers. The reporting of drained acreage has been inconsistent, likely because of confusion over the definition of "drained area" and "contributing area" fields on the report forms. The forms have been recently revised to provide a better information base. For the purpose of this report, two database entries in Cass County with a non-listed "action" status were excluded. In addition, there are currently (June, 2008) 34 permit applications pending approval.

Applying the drainage distribution scenarios on Fig. 7-B to the 22,963 estimated state-wide drained acreage, we derive the distribution shown on Fig. 9. During years in which drains flow, median total drainage would be 6,085, 5,339, and 4,650 acre-feet for 22-, 24-, and 26-inch precipitation thresholds. Based on 540 irrigated acres per section (excluding corners) and water permit allocations of 1.5 acre-feet per acre, this would allow for an equivalent of irrigation permits for 5.7 to 7.5 sections. However, the expected frequency of drainage is only 35, 25, and 15% of the years, respectively. The average amount of water drained over the entire 20th century precipitation scenario would be 698 to 2,129 acre-feet per year. If one were to further adjust drainage estimates for the percent (20%) of the land area that would coincide with pumpable waters, average drained waters would be in the range of 140 to 426 acre-feet per year. Potential competition of current permitted drainage for pumpable waters is thus very small.

Table 2. Distribution of current (SWC database, June, 2008) approved tile-drained acreage.

County	No. Drainage Permits	Estimated Drained Acres
Cass	9	1928
Dickey	4	575
Grand Forks	27	5515
Kidder	1	55
Pembina	2	194
Ransom	2	1087
Richland	30	4890
Sargent	14	1405
Steele	1	115
Traill	28	5048
Walsh	13	2151
Total	132	22,963
Mean	12	2,088

While water loss estimated from drainage response to precipitation is approximate at best, a more serious problem is the unreliability of the SWC data on tile-drained acreage. First, there is the issue of possible unpermitted drainage. We currently lack the ability to assess the reliability of the data. In addition, some contractors stated that they had difficulty understanding the tile-drain forms. The SWC recently developed a new form for tile drains for improved clarity.

For this discussion, if we assume that the permits on file represent an approximate random sample of the distribution of drainage throughout the state, the area placement (eastern counties), the percent of drainage fields over aquifers, and the estimated percent of time for which no drainage would have been occurring under the 20th century precipitation regime are likely reasonable. However, estimates of the actual acreage of tile drainage in the Red River Valley vary widely. Some estimates, using assumed similarity with comparable lands in Minnesota, have been above fifty thousand acres. Mr. Fuxa, of Ellingson Companies, Inc., believes that past tile drainage in North Dakota has not been comparable to Minnesota, and that, while underestimation of acreage in state records is likely, it is not large. The accuracy of state records of absolute drain locations, acreage, and drained water is currently unknown.

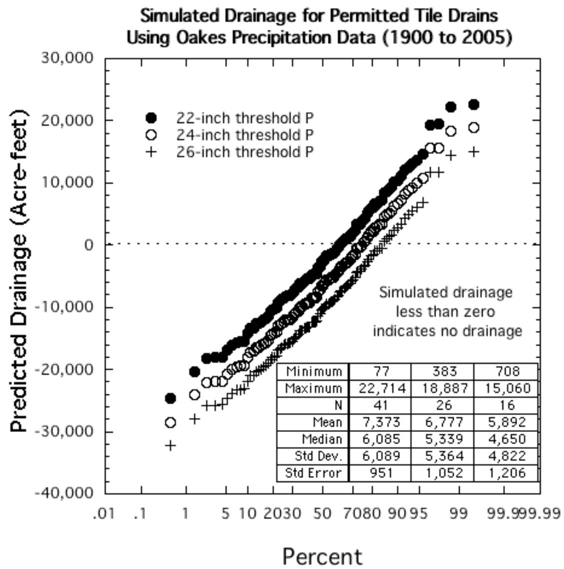

Figure 9. Simulated total state annual drainage distribution based on current (2007) estimated permitted drained acreage, measured 20th century precipitation at Oakes, and drainage thresholds derived from Lamberton, MN (Chung and others 2001) and Waseca, MN (Randall and others 2005) experimental data.

4.7 Estimated Total Maximum Potential Drainage Loss

It is useful to provide an estimate of potential drainable acreage and the maximum amount of water that might feasibly be drained. To limit time in analysis we will focus our estimates on the portion of the state most likely to be drained. The State Water Commission database indicates that about 99% of all permitted tile drainage is in the eastern fifth of the state, and particularly in the Red River valley. For this reason, we will focus our analysis on 18 counties in the eastern part of the state. These are shown on Figure 10.

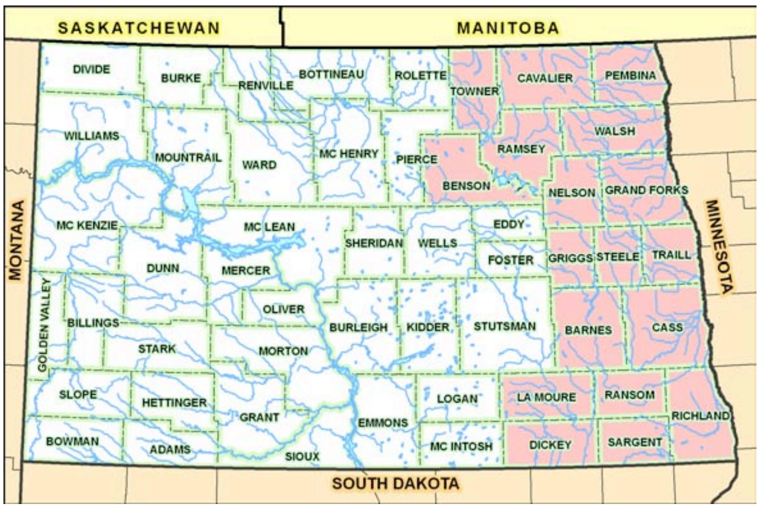

Figure 10. Location of counties used for estimates of potential drained acreage and water.

4.7.1 Estimated Drainable Acreage using the Aquic Soils Criterion

There are many methods or criteria, including professional judgment and local experience, that contribute to tile drainage design. Madramootoo (1981) has stated that one design criterion is a drainage coefficient that is commonly based on the one-in-five year storm, with the objective of dropping the water table below one to two and a half feet (30 to 75 cm) below land surface within 24 hours. For purpose of general analysis we will assume that tile drainage in North Dakota will be confined to soils having intermittent, or seasonal high water tables during the growing season. These soils are described as having *aquic* moisture regimes. According to the USDA:

> *The aquic (L. aqua, water) moisture regime is a reducing regime in a soil that is virtually free of dissolved oxygen because it is saturated by water... the duration must be at least a few days...Because dissolved oxygen is removed from ground water by respiration of microorganisms, roots, and soil fauna, it*

is also implicit in the concept that the soil temperature is above biologic zero for some time while the soil is saturated. (USDA; Soil Taxonomy, p 96)

In short, the soil must be waterlogged for some period during the growing season. This seems to provide a reasonable description for a soil that may economically benefit from drainage. Soils may be classified as *aquic* either at the suborder level, or the subgroup level. For our analysis we will use soils classified as *aquic* at the suborder level. Some of the great groups and series selected for the Red River Basin are shown on Table 3. Mapping units include combined series. These are summarized for each county with acreage in Appendix Table A.

Table 3. Summary of soil great-group taxa and soil series used to screen soil-survey mapping units for estimation of potential drained acreage.

Suborder	Great Group	Series			
Aquolls	Calciaquolls	Antler Arveson Barnes Beardon Borup	Colvin Divide Easby Elmville Fram Gilby	Glyndon Grimstad Hamerly Lowe Marysland Ojata	Rockville Ulen Vallers Wheatville Wyndmere Wyrene
	Endoaquolls	Delamere Flom Fossum Gaborg	Hamar Kindred Kratka Lamoure	Perella Playmoor Rauville Southam	Tifany Venlo
	Argiaquolls	Lindaas	Parnell		
	Natraquols	Heriet Manfred	Stirum Tonka	Totten	
	Epiaquolls	Dovray	Espelie		
Aquerts	Epiaquerts	Clearrwater	Fargo		
	Calciaquert	Hegne			
	Natraquert	Ryan			
	Endoaquert	Grano	Ludden		
Aquents	Fluvaquent	Lallie			
	Endoaquent	Mauvais			
	Psammaquent	Bantry	Minnewaukan		

For each county, *aquic* soils were selected only within the boundaries of aquifers, as defined within the SWC database. Soil mapping units were selected from the SSURGO database (USDA-NRCS 2007). Soil mapping units were included if their predominant soil was of an *aquic* suborder. Acreage for all included mapping units within aquifers was then summarized for each county. Results are summarized on Table 4.

For the 18 counties analyzed, percent of acreage overlying aquifers ranges from negligible (Cavalier, Pembina and Walsh Counties) to a maximum of 52% for Griggs County, with a composite average of 20%. This means that overall, 80% of the land in the 18 counties could be drained with no negligible impact on pumpable ground water.

Of the aquifer acreage for the 18 counties analyzed, *aquic* soils (soils likely to be profitably drained) vary from negligible (LaMoure County) to a maximum of 54 percent (Richland and Traill Counties), with a composite mean of about 35% [Table 4, col. (8)]. This means that about 35 % of the aquifer land itself could be profitably drained.

If 20% of the land (aquifer land) could potentially affect well capture [Table 4, col. (7)], and 35% of that land (*aquic* soils) could be profitably drained, then a composite average of about 7% [Table 4, col. (9)] of all the land in the 18 counties evaluated would potentially have a conflict between tile drainage and water pumpage.

Table 4. Summary of estimated potential drainable soils overlying aquifers in an 18-county study area of eastern North Dakota.

(1) County	(2) County (Acres)	(3) Aquifer (Acres)	(4) *Aquic* soils* (Acres)	(5) Sandy *aquic* soils* (Acres)	(6) Fine *aquic* soils* (Acres)	(7) % County soils over aquifers	(8) % Aquifer soils that are *aquic*	(9) % County soils that are *aquic* and over aquifers (7)x(8)	(10) % *Aquic* soils that are sandy*	(11) % Aquifer soils that are *aquic* and sandy (9)x(10)
Barnes	968,403	129,349	63,495	0	63,495	13	49	6	0	0
Benson	921,414	209,720	72,750	3,977	68,773	22	35	8	5	2
Cass	1,131,209	185,415	93,669	6,131	87,538	16	51	8	6	3
Cavalier	967,269	9,717	7,134	0	7,134	1	73	1	0	0
Dickey	731,032	178,210	81,658	15,687	65,971	24	46	11	19	9
Grand Forks	921,450	105,400	49,166	10,135	39,031	11	47	5	20	10
Griggs	458,557	241,339	4,846.35	4,846	0	52	2	1	99	2
Lamoure	736,670	205,952	478	477.7	0	27	0	0	99	0
Nelson	645,919	59,029	1,631	1,631	0	9	3	0	100	3
Pembina	718,353	6,928	293.44	0.01	293	0	4	0	0	0
Ramsey	832,999	130,118	51,048	871	50,177	15	39	6	1	0
Ransom	552,786	181,840	53,026	25,870	27,156	32	29	10	48	14
Richland	925,096	438,444	235,608	73,461	162,147	47	54	25	31	17
Sargent	555,215	288,389	63,034	21,952	41,082	51	22	11	34	8
Steele	457,888	110,731	40,206	27,888	12,318	24	36	9	1	25
Towner	667,230	249,665	124,929	1,419	123,510	37	50	19	1	0
Traill	551,964	40,680	21,975	1,676	20,299	7	54	4	7	4
Walsh	828,685	8,900	675.57	0	675	1	8	0	0	0
Total (acres)	13,572,139	2,779,826	2,552,500	196,021	2,356,479					
Average (%)						20	35	7	20	7

* Overlying aquifers

4.7.2 Estimated Drainable Acres using the USDA-NRCS Drainage Class Criterion

An alternate approach to estimating potentially drainable soils would be to use the USDA-NRCS drainage classes. Classes, as defined by the USDA-NRCS (http://soils.usda.gov/technical/manual/contents/chapter3c.html#27, 3/9/08), are:

- Excessively drained. Water is removed very rapidly. The occurrence of internal free water commonly is very rare or very deep. The soils are commonly coarse-textured and have very high hydraulic conductivity or are very shallow.

- Somewhat excessively drained. Internal free water occurrence commonly is very rare (1 to 5 times in 100 years) or very deep.

- Well drained. Internal free water occurrence commonly is deep or very deep; annual duration is not specified.

- Moderately well drained. Water is removed from the soil somewhat slowly during some periods of the year. Internal free water occurrence commonly is moderately deep and transitory through permanent.

- Somewhat poorly drained. Water is removed slowly so that the soil is wet at a shallow depth for significant periods during the growing season. The occurrence of internal free water commonly is shallow to moderately deep and transitory to permanent.

- Poorly drained. Water is removed so slowly that the soil is wet at shallow depths periodically during the growing season or remains wet for long periods. The occurrence of internal free water is shallow or very shallow and common or persistent.

- Very poorly drained. Water is removed from the soil so slowly that free water remains at or very near the ground surface during much of the growing season. The occurrence of internal free water is very shallow and persistent or permanent.

We select the very poorly drained, poorly drained, and somewhat poorly drained soils as plausible "drainable" candidates for subsurface drainage. A summary of drainable soil acreage overlying aquifers for the 18-county survey area is on Table 5. The overall percent drainable area overlying aquifers for the USDA-NRCS drainage classes was 40%, very close to the estimate of 35% using the *aquic* soil criterion. On a county basis results were nearly identical for 15 counties, and differed significantly only for Griggs, LaMoure and Nelson counties. The difference may have been due to the "very poorly drained" class, which may have included wetlands and standing surface waters in some cases.

Table 5. Estimated soil area overlying aquifers in 18 North Dakota counties for which subsurface drainage may be an economically viable option, based on the USDA-NRCS drainage class criterion.

County	**VP** very poorly drained (acres)	**P** Poorly Drained (acres)	**SP** Somewhat Poorly Drained (acres)	**TD** Total (VP+P+SP) Drainable Acreage (acres)	**AA** Total County Aquifer Area (acres)	% Drainable Area (TD/AA x 100)
Barnes	7,225	15,131	41,426	63,782	129,356	49
Benson	20,935	25,127	27,387	73,449	209,722	35
Cass	1,747	51,914	41,113	94,775	185,420	51
Cavalier	123	1,010	6,001	7,134	9,721	73
Dickey	7,537	19,375	57,752	84,663	178,253	47
Grand Forks	1,437	9,212	38,978	49,627	105,401	47
Griggs	8,649	18,768	74,709	102,127	241,393	42
Lamoure	6,995	12,429	3,667	23,090	205,919	11
Nelson	1,571	6,696	5,872	14,139	59,021	24
Pembina	73	192	40	304	6,928	4
Ramsey	4,620	20,486	26,672	51,778	130,141	40
Ransom	3,467	23,772	27,034	54,274	181,709	30
Richland	10,430	100,131	141,739	252,300	438,473	58
Sargent	17,269	22,624	25,371	65,265	288,370	23
Steele	1,748	7,369	31,089	40,206	110,680	36
Towner	4,648	25,917	94,365	124,929	249,701	50
Traill	585	6,530	15,912	23,026	40,713	57
Walsh	12	12	652	676	8,900	8
Total (acres)	99,070	366,692	659,779	1,125,541	2,779,820	
% Total						40

4.7.3 Simulated Potential Total Drainage

As with permitted drainage estimates (section 4.6), it is useful, from the standpoint of beneficial use, to attempt an approximation of how much water might be removed through drainage from areas overlying aquifers in the entire 18-county study area. We will do so by using the Oakes precipitation record for the 20th century (National Oceanic and Atmospheric Administration), and applying it to the maximum drainable soils overlying aquifers in the study area (based on *aquic* soil great group taxa). Climate distributions and cropping practices vary somewhat over the study area. But for the objective of general placement, and given overall error involved in each of the procedures, there would be little to gain from a more detailed county-by-county climatic analysis. All the more so since there are no other long-term tile drainage studies within the study area to provide for more localized calibration of drainage estimates.

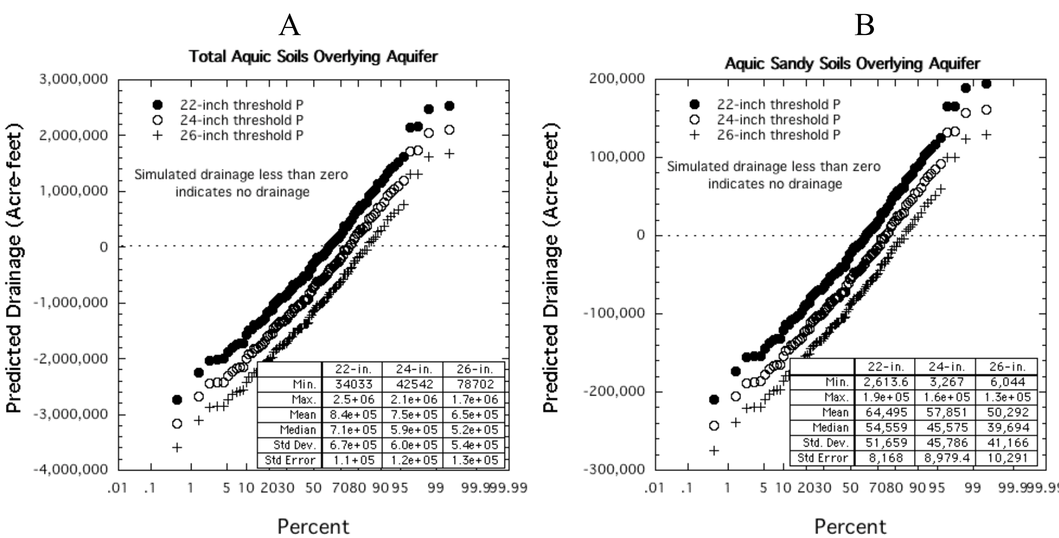

Figure 11. Simulated 20th century distribution of drainage for estimated maximum potential drainage on: (A) all *aquic* soils, and (B) all *aquic* sandy soils overlying aquifers in the 18-county area analyzed.

Using the Oakes precipitation distribution for the 20th century (Figure 6A) and threshold precipitation values of 22, 24, and 26 inches, drains would be expected to flow in 35%, 25%, and 15% of the years, respectively (Fig. 11A). During years in which drainage occurs, simulated median 20th century drainage for all *aquic* soils, regardless of texture, overlying aquifers (confined or unconfined) in the 18-county study area would be about 840,000, 750,000, and 650,000 acre-feet per year, respectively. This would be the equivalent of 800 to 1,000 permitted sections of irrigation (540 acres per section minus corners, and 1.5 acre-feet of water permitted per acre). However, most (80%) of the water would be drained from fine matrix materials that would be unavailable for pumping; and the drainage losses would be occurring on the wettest 15% to 35% (depending on the simulated precipitation threshold) of years when water is most plentiful, and likely in excess. In addition, waters mobilized by tile drains may be accessible for reuse. This will be treated later in this report. Simulated mean annual drainage amounts, adjusted for the percentage of dry years over the century, would be 294,000, 187,000, and 97,500 acre-feet per year, respectively, for the 22-, 24-, and 26-inch precipitation threshold scenarios.

Only a relatively small portion (about 20%) of this drainage would occur on sandy soils. Simulated total drainage on all *aquic* sandy soils overlying aquifers in the 18-county area analyzed, using the same methods described in the previous paragraph, indicates that in years when tile drains are expected to flow (35%, 25%, and 15% of the years for 22-inch, 24-inch, and 26-inch precipitation threshold scenarios, respectively) median drainage values of 54,559, 45,575, and 39,364 acre-feet per year would be expected (Fig. 11B). These would be the equivalent of 50 to 67 sections permitted for irrigation. However, while these waters would possibly be pumpable if they were not lost through runoff, the water supply would be undependable and available only in the wettest years when it is least needed and may be present in excess. The 20th century mean drainage values, adjusted for non-draining years, would be between 5,900 and 19,000 acre-feet per year.

In using these numbers, the following caveats must be understood: (1) The estimates constitute a **potential maximum**, if ALL *aquic* soils (about 2.5 million acres based on great group taxa) overlying aquifers in the entire Red River valley were to be drained. (2) They are calculated using drainage distribution estimates for Minnesota installations, which are slightly deeper than those common for North Dakota. (3) Drained waters are not necessarily available for alternative pumping and beneficial use. (4) Drained waters are in an active hydrologic zone and are not retained for long periods if they are not drained. They are already discharging, either through seepage, runoff from overfilling of the aquifer, or evapotranspiration. In order to understand the potential impact of extensive tile drainage on beneficial use, we must understand the hydrologic interaction of the varying discharge mechanisms and the competing processes of pumpage, drainage, seepage, evapotranspiration, and runoff. This will be further discussed in section 5 of this report. (5) Some tile-drained waters would have been drained through natural or artificial surface drainage without drain-field construction. This is discussed further in Section 5.1. (6) In some cases, the drained waters may be captured and retained for use elsewhere. This will be discussed in section 8.1 of this report. (7) In many cases pumping for beneficial use may capture waters before they are drained. This will be discussed in section 5 of this report.

5. TILE DRAINAGE EFFECTS ON GROUND WATER AVAILABLE FOR BENEFICIAL USE

In considering tile-drainage effects on the supply of water available for beneficial use, we are considering effects of drainage on the balance of recharge to and discharge from the aquifer. First, we need only consider drainage of soils overlying aquifers. Effects of all other areas will be too remote or too slow to have a substantial effect on ground-water recharge. Second, we need only consider glacial aquifers. Modern recharge areas of most bedrock aquifers in North Dakota are sufficiently distant, located in western North Dakota, South Dakota, or Montana, that effects of tile drainage will be inconsequential. An exception would be the Fox Hills aquifer in the central part of North Dakota. Glacial aquifers in the 18-county study area selected comprise only about 20% of the surface area (Table 4). All other aquifers are eliminated as inconsequential. Third, we assume that we need only consider areas underlying *aquic* soils as candidates for drainage. The recharge-discharge hydrology of *aquic* soils will be important in evaluating the effect of tile drainage on well supplies. Fourth, because of differences in hydrologic function, we will consider confined and unconfined glacial aquifers separately.

5.1 Recharge and Discharge Hydrology of Surficial Glacial Aquifers

The removal of water from an aquifer through pumping for beneficial use or through drainage introduces alternative discharge mechanisms. For an aquifer to be in hydrologic balance, within a given recharge regime, waters discharged through pumping or draining must be balanced by a decrease in runoff, evaporation, transpiration, or seepage. This can be expressed as:

$$\Delta D = \Delta P_u + \Delta E + \Delta T + \Delta S + \Delta R$$

where D is drainage, P_u is pumpage, E is evaporation, T is transpiration, S is seepage, and R is runoff. Drained waters, specifically, must be balanced by a reduction of evaporation, transpiration, runoff, seepage, or pumping for beneficial use. In shallow water-table areas of North Dakota's glacial aquifers, much of the ground water cycled through the natural processes E, T, S and R is in flux and is not retained for long-term storage and pumpage for beneficial use. Most water recharged within a shallow closed depression or micro-depression focused hydrologic system is discharged within a year or two, and is not retained within the aquifer as long-term storage.

The critical question for this study is whether the tile-drained waters will be captured predominantly from pumping for beneficial use, or from the natural discharge mechanisms. In order to understand this, we will briefly examine some of the similarities and differences between tile drainage and pumpage with respect to the type and order natural discharge captured.

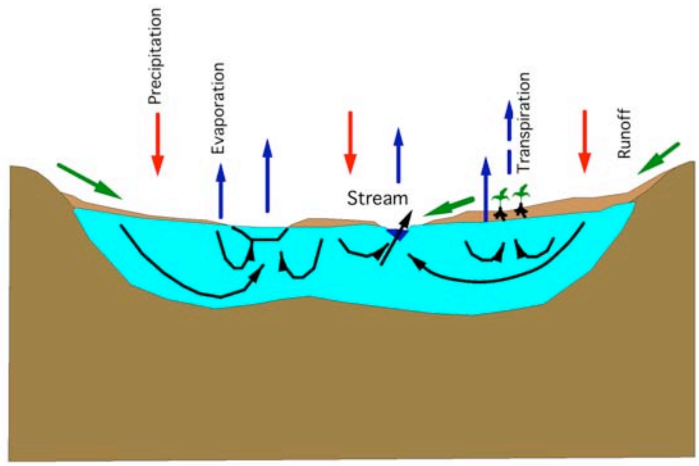

Figure 12. Natural recharge and discharge from an unconfined surficial glacial aquifer.

For glacial aquifers in eastern North Dakota, tile drainage is practiced on soils having high water tables. Where shallow unconfined glacial aquifers are intersected by gaining streams in North Dakota, soils above the flood plain near the stream are usually well drained because of discharge to the stream. Thus, flow systems on soils having high water tables consist primarily of local depression and micro-depression focused recharge and discharge regimes having recharge and evaporative flow paths of a few tens to a few hundred feet (Knuteson and others 1989, Seelig and others 1991, Schuh and others 2006). For most crops grown in eastern North Dakota optimal yields and transpiration occur when the water table is between three and five feet below land surface (Benz and others 1981). At shallower depths impaired root growth and function decrease transpiration, and water is discharged primarily through direct evaporation. When the water table breeches land surface, ponding occurs and evaporative discharge is maximized. If surface storage is exceeded discharge occurs through runoff. The partition between runoff and evaporation is related to local drainage characteristics and precipitation events. A well-integrated drainage system with external outlets or a land leveled field will tend to have a relatively larger runoff component compared with a poorly integrated drainage system, such as a closed-depression pothole setting where rejected waters will tend to stand and evaporate. Moreover, larger precipitation events will cause more runoff when topographic storage is filled. These processes are illustrated on Fig. 12.

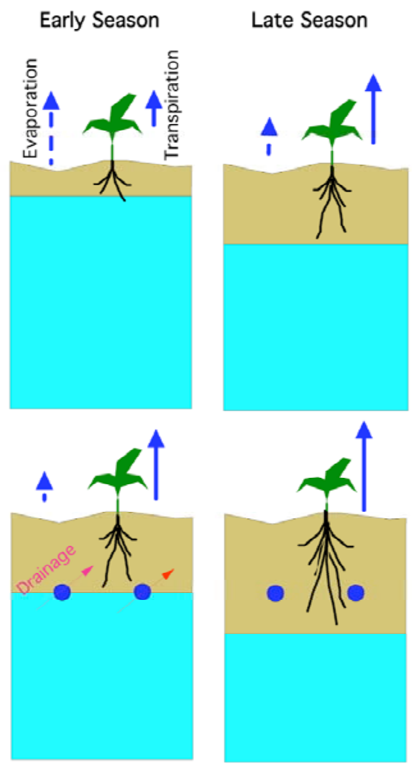

Figure 13. Effects of tile drainage on root extension, evaporation and transpiration.

Soils above the flood plain near gaining streams are usually well drained because of discharge to the stream and usually will not require drainage. For this reason, the discussion will focus on poorly integrated depression or micro-depression focused recharge and discharge regimes discussed above. In such a hydrologic landscape, the first discharge water captured by pumpage or drainage will be evaporation and surface runoff, partitioned according to the hydrologic landscape and events. If drainage or pumpage require deeper capture to offset removal, such as through deeper drains or larger pumpage, the next level of extraction will be captured from transpiration. However, capture from transpiration has some limiting characteristics. Because pumpage and tile drainage cause a saturation deficit in the soil profile, and because crop roots extract capillary waters below field capacity, the ability of the soil to intercept and hold capillary water is enhanced, and plant roots are able to extract waters before they reach the water table. For this reason, once a new lower water-table regime is established through pumpage or drainage, the plant roots exercise the capability of first capture during the active growing season, and can indirectly affect the storage of water in the non-growing season to some degree, through establishing a moisture deficit. Earlier and deeper plant-root proliferation will also decrease annual evaporation, and may increase annual transpiration (Fig. 13). This phenomenon is reflected in the "threshold" precipitation values required for drainage in the established experimental drainage fields discussed previously (section 4) of this report. In a natural plant community, waters captured from transpiration by deep drainage or pumpage may be temporary, as deeper rooted plants may eventually become established that are capable of extracting waters at greater depths. A hydrologic system modified by shallow drainage is illustrated on Fig. 14. Note the decrease in runoff and evaporation near the drain compared with Fig. 12.

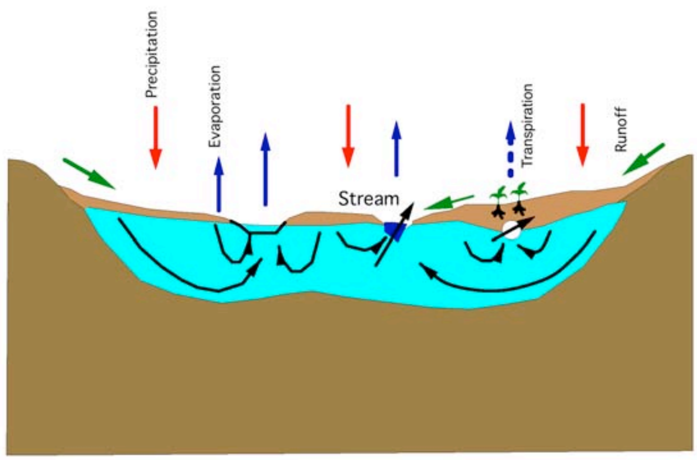

Figure 14. Recharge and discharge modified by a shallow drain.

After drainage or pumpage, then, hydrologic balance is maintained by the capture of natural discharge in the following general order: (1) local runoff and evaporation (short-term storage); (2) local transpiration (short-term storage); (3) long-term storage components, such distant discharge through stream-bank seepage or major evaporative wetlands. If and where drainage or pumpage maintains the water-table within the optimal yield and transpiration depth range (*approx.* 3 to 5 feet for many crops, Benz and others 1981), transpiration may be enhanced and cause a decrease is drained water as well as runoff and evaporation waters in the overall discharge budget (Fig. 13). If the water table is drawn below the zone of optimal yield and transpiration, then drained or pumped waters will also capture water from transpiration.

A hydrologic system modified by deep drainage or extensive pumpage is shown on Fig. 15. Note that well discharge is captured from runoff, evaporation, transpiration, the shallow drain, and from stream flow as well. In this illustration, the decoupling of the drain discharge by the deeper well is an important point for our analysis. If water is pumped from a well field and shallow subsurface drainage is present in the proximity of the well field, the well field is usually positioned for first capture of drained waters because of deeper placement of the well screen(s) (Fig. 15). An efficiently designed well field should be able to dewater a shallow drain during times of limited water supply. Hydrologic relationships between well fields and drainage fields will be discussed in greater detail in the following sections.

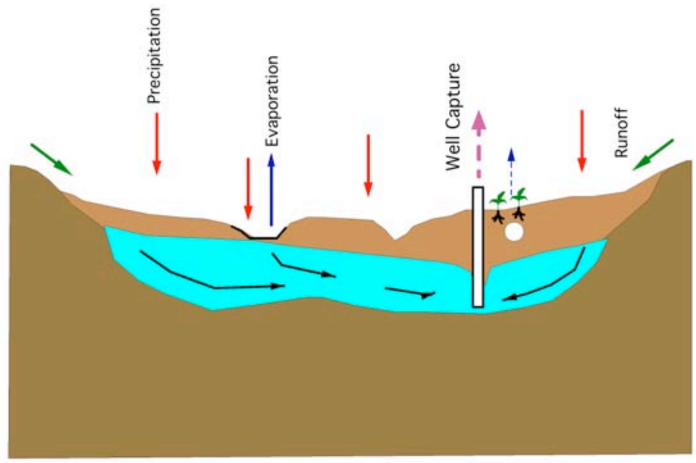

Figure 15. Potential effect of a well field on subsurface drainage and natural discharge.

The simplest and most direct answer to the question of drainage effects on hydrologic balance, which we will explore in greater detail below, is that in the absence of pumping, subsurface drainage will be captured from waters previously discharged through runoff, seepage to streams, evaporation and transpiration. Tile drainage is practiced where there are high water tables. High water tables cause enhanced evaporation and runoff. Drainage, by lowering the water table, decreases evaporation and runoff. For conditions of most glacial aquifers in eastern North Dakota, tile-drain waters will be captured primarily from combined evaporation and runoff. Efficiently designed well fields, because of their deeper capture zones, are usually positioned to dewater local drains.

5.2 Hydrologic Effect of Drainage on Well Fields

The fundamental hydrologic principle governing the beneficial use of ground water is that all extraction of water must come from storage or from discharge elsewhere in the system. Shallow glacial aquifers having high water tables, when first developed, usually undergo a "developmental decline" in which the water table lowers, and then approximately stabilizes, with some fluctuations from climatic variation. With incremental development, the water table eventually declines to a point of optimal sustainable development where no further stabilization is possible. At this point of development, mining begins.[1]

While pumping for beneficial use from an aquifer can be sustained within the range of developmental decline, water discharged through pumpage is inevitably diverted from another local or more distant point of discharge. All pumped waters were formerly discharged through evaporation or transpiration in wetlands, subirrigation from shallow water tables on cropped lands, or from deeper water tables with more deeply rooted plants; through discharge to flowing surface waters; or in deep confined aquifers through the intermediate loss of piezometric pressure (Fig. 16). Maximum sustainable development, from the standpoint of optimized pumping alone, occurs when all of these discharge sinks are inoperative, and all discharge is through the well-field. All discharge sinks, pumpage, surface-water discharge, evaporation, and transpiration compete for the same water. To this we may add drainage.

Tile drainage represents an augmentation of the evaporation and runoff discharge components. Somewhat analogous to springs and seeps, tile drainage adds some previously evaporated ground water to surface water outlets, but delays the delivery of some runoff water to surface water outlets. Because its purpose is the prevention of water logging, it is practiced on soils that periodically have high water tables. The soil taxonomic descriptor for this condition is *aquic*, which was defined in a previous section (4.5.1). To understand effects of tile drainage on beneficial use, it is necessary to understand the natural recharge and discharge characteristics of *aquic* soils and their effect on underlying aquifers.

5.3 Soil Effects on Aquifer Recharge and Discharge

Except where redistributed by wind and dune formation, glacial aquifers in North Dakota are usually of early Holocene or Pleistocene glacial-fluvial or -deltaic origin. These land forms are usually quite level, often having relief of a few inches to a few feet. Regional recharge-discharge systems (several hundred feet to a few miles) associated with *aquic* soils have, in some cases, been identified as successions of recharge,

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[1] The concept of "developmental decline" describes the optimal well capture of ground water in a hydrologic landscape where natural discharge zones and wells are well distributed, or where wells are placed in close proximity to natural discharge zones. It applies reasonably well to the natural state of shallow water table areas (which would be candidates for tile drainage) in many shallow glacial aquifers in eastern North Dakota. It does not consider potential problems of water availability for pumpage in areas where large well extraction is practiced at large distances from natural discharge areas. In such cases extended aquifer drawdown between the point of well extraction and the natural discharge zone may seriously decrease the saturated thickness of the aquifer and impair well development. This problem has been described by Theis (1957), Bredehoeft (1997) and Sophocleous and Sawin (1997). It is particularly problematic where thin aquifer areas intervene between the natural discharge zone and the point of well extraction. This problem will be considered with respect to tile-drainage fields later in this report.

discharge and flowthrough wetlands (Winter and Rosenberry 1995). In eastern North Dakota *aquic* soils are most commonly found within predominantly closed-depression, or in some cases (such as the Elk Valley aquifer in Grand Forks County) closed-micro-depression focused recharge and discharge regimes of a few feet to a few hundred feet.

In low-relief landscapes the flow regime is mainly local. An example would be a toposequence having Endoaquoll soils in depressional areas, and Calciaquolls in slightly more elevated positions. Both soils have seasonal high water tables. Both have substantial local recharge during precipitation and snowmelt events, but the Endoaquolls receive an additional portion of runoff water from associated Calciaquolls. The net hydrologic effect is that both Endoaquolls and Calciaquolls undergo both recharge and evaporation, but for Endoaquolls recharge predominates while for the Calciaquolls evaporative discharge predominates (Knuteson and others 1989). Similar and related hydrologic regimes have been described by Fulton and others (1986), Seelig and others (1991), Arndt and Richardson (1993) and other researchers.

During early high water-table phase, evaporation may occur directly as capillary draw from the shallow water table at a bare, or sparsely covered land surface. As the water table recedes, and as a plant community develops, plant roots draw water as "subirrigation" from the moist capillary zone above the water table. As plant roots draw water, the water table recedes, and plant roots successively follow the water table as it deepens. Benz and others (1981) have shown that optimal crop production and yield occurs generally when water tables are between three and five feet below land surface. Shallower water tables tend to restrict the root zone impairing crop growth, encourage phreatophytic weed growth, and direct evaporative moisture loss. Deeper water tables gradually become "uncoupled;" that is, the water table eventually recedes beyond the reach of plant-root extraction. Effective subirrigation depths vary with plants and soil types. Usually, in agricultural areas we consider minimum uncoupled depth to be between six and eight feet in crop areas; but it can be considerably deeper in areas of deep rooted plants, such as alfalfa or some forest species.

Conversely, soils in uplands or near discharge to surface waters commonly have deeper water tables, often of the Hapludoll (formerly Haploboroll) soil great group. These are particularly well defined near gaining streams that are incised within the area of the aquifer and serve as drains. Some examples are the Arvilla, Hecla and Maddock series. Hapludoll soils are also commonly found in the uplands of depression-focused recharge areas where the landscape is more humocky and has greater relief (a few feet or more). Some have an intermediate character, with *aquic* characteristics on the sub-order level, such as the Hecla series (an *aquic* Hapludoll). These soils would not normally be a target for tile-drainage, but may be incidentally drained with *aquic* soils on a shared landscape. Most importantly, when they are formed through natural seepage to rivers and streams, they would seldom be tile drained. This means that tile-drained waters would not, in most cases, be compensated through loss of stream-bank seepage. In a closed-depression hydrologic landscape with poorly integrated drainage, tile-drained waters would most often be captured from reduced evaporation on local *aquic* soils for which the drainage was intended.

Five important conclusions are drawn from this discussion. First, in glacial aquifers, pumping of waters for beneficial use is compensated by capture from evapotranspiration and runoff in areas of shallow water tables and from seepage to surface waters. Second, tile drainage is seldom practiced in deeper soils draining to deep-cut gaining streams. While, in some cases, drained waters may be recovered from surface seeps (when aquifers are overfilled and rejecting waters), there should be no net loss, and a possible net gain for surface waters caused by tile drainage. Third, tile drainage will be beneficial primarily on shallow water-table soils and, except for rejected waters, will be primarily compensated by decreased evaporation and runoff caused by lowering the water table. Fourth, in closed-depression recharge-discharge systems, drained waters would normally be discharged through evaporation within the same year and would thus not cause a change in water supplies available for distant wells. Fifth, because waters removed by both drainage fields and well fields are captured from evaporation and runoff, and sometimes transpiration within their zone of influence, they do compete for the same water. However, well-fields also serve as drainage fields. Because the well-screen is invariably more deeply placed than the tile drain, a properly designed well-field should almost always be able to capture potentially drained waters (Figure 15). Optimal pumping of waters captured from runoff, evaporation and transpiration, with a transpiration decoupling depth of about eight feet, would also serve to lower the water table below the tile drains, assuring well capture.

5.4 Drainage in Soils Overlying Confined Aquifers

An aquifer is *confined* when pore-water pressure exceeds atmospheric pressure. This occurs when it is overlain by a layer of low-permeability material (called an aquitard), and the piezometric-pressure head of the aquifer is of higher elevation than the aquitard-aquifer boundary. In the 18-county survey discussed above, 80% of all *aquic* soils overlying aquifers were of fine texture and therefore possibly confining under natural conditions. About 35% of soils overlying aquifers were *aquic*. Combined, about

28% of soils overlying aquifers would be in this category. We will consider the following confined cases: (1) an impermeable aquitard, (2) artesian systems with aquifer piezometric elevation above the tile drain, and (3) confined aquifers with piezometric elevation below the tile drain and recharge occurring locally through slowly permeable aquitard materials.

(1) In some cases, as in with the West Fargo aquifer, aquitard permeability is so low (*approx.* 0.0003 ft./d to 0.000003 ft./d, or 10^{-9} to 10^{-11} m/s) that negligible recharge is occurring. In such cases, pumping of ground-water is non-sustainable, and small changes in overlying head caused by tile drainage can have no substantial effect on the aquifer.

(2) Where aquitard K is non negligible (*approx.* > 0.03 ft./d, or 10^{-8} m/s), and where confined aquifer pressure is greater than the water level in the tile drains in the aquitard, the tile drains will flow continuously. Drained waters do not, however, represent an additional loss from beneficial use. First, local recharge occurs only sporadically if at all, since this condition is, by definition, a discharge area. Second, because the piezometric elevation is above the tile, it is shallow and is already discharging, either through surface seepage (piezometric elevation above land surface) or evapotranspiration through capillary upflux to the soil surface or the plant roots. Relatively more loss will be partitioned to surface-water flow than evapotranspiration before drainage; but the net loss of water for beneficial use will be negligible. This case would cause problems for tile designs based on precipitation-based drainage coefficients, and would require design considerations for drainage of seeps (Doering and others 1999).

(3) Very commonly, recharge to confined aquifers occurs under the force of small hydraulic gradients, which are caused by small differences between the piezometric pressure-head elevation of the underlying aquifer and the elevation of the water table in the overlying confining unit. Common gradients for confined aquifers underlying till have been summarized from the literature by Shaver (1994) as ranging from -0.12 (artesian) to 0.2, having a mean of about 0.09 for non-weathered till; and -0.36 to 2.06, having a mean of 0.68 for non-weathered till in east-central South Dakota (from Cravens and Ruedisili 1987). Hendry and others (1986) presented a range of gradients from 0.1 to 0.2 on weathered till and 0.02 to 0.7 for non-weathered till in southern Alberta.

First, aquitards overlying glacial confined aquifers commonly have low hydraulic conductivities. For fractured oxidized till, K values are commonly within an order of magnitude of 0.03 ft./d (10^{-7} m/s). For unoxidized till (usually deeper) K values are commonly within an order of magnitude of 0.003 ft./d (10^{-8} m/s), but have been measured below 0.0003 ft./d (10^{-9} m/d) (Shaver 1994, Schuh and others 2006). While gradients and K are small, recharge need not be negligible. For a sustained hydraulic gradient of 0.1, for example, annual recharge would be 1 ft./year for 0.03 ft./d. and 1.2 inches/year for 0.003 ft./d. For 0.0003 ft./d recharge or less (a fraction of an inch) we may consider recharge negligible and likely in the category of an isolated confined unit, (1) above.

Second, recharge in confined aquifers having small hydraulic gradients can be highly sensitive to small changes in the water table (Schuh and Klinkebiel 2003). A relatively small change in the water table can, in fact, cause a reversal of local vertical flow system from one of aquifer recharge to aquifer discharge. The initial hydraulic gradient (i_o) is defined as:

$$\frac{h_o - h_a}{h_o} = i_o \qquad (3)$$

where h_a is the piezometric head elevation above the upper aquifer boundary, and h_o is the initial saturated head elevation above the upper aquifer boundary in the till aquitard (Fig. 16). Then if the water table is lowered by an amount, h, the new hydraulic gradient will be:

$$\frac{h_o - h - h_a}{h_o - h} = i_1 \qquad (4)$$

If $h<h_o-h_a$ $\quad$ $i_o>0$ and the aquifer is being recharged
If $h=h_o-h_a$ $\quad$ $i_o=0$ and no recharge or discharge is occurring
If $h>h_o-h_a$ $\quad$ $i_o<0$ the aquifer is discharging

Thus, a small change in the water table overlying a confined aquifer may, in some cases cause a substantial relative decrease in aquifer recharge, or even a change to a discharge-dominated flow system. This is illustrated on Figure 16.

Third, the degree of recharge attenuation, or the change from a recharge to a discharge-dominated flow system will depend on the thickness of the aquitard in relation to the change in the water table. The greater the saturated thickness ($L=h_o$) overlying the aquifer, the larger the change in water table required to affect a flow reversal, and the less effect a small change in the water table will cause.

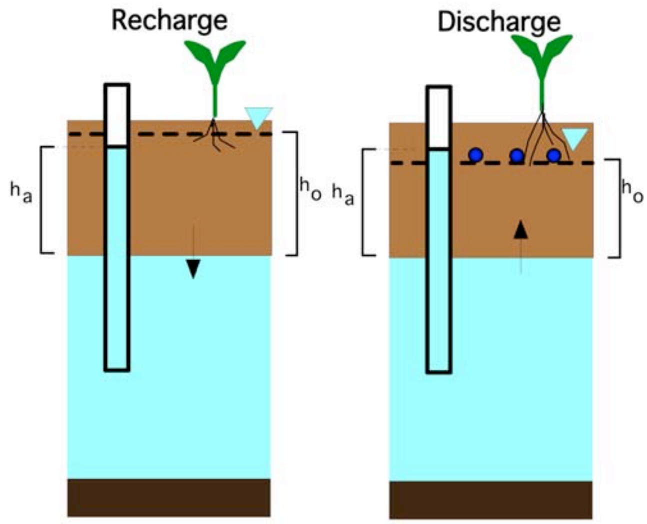

Figure 16. The potential effect of subsurface drainage on local recharge to, or discharge from, a confined aquifer having a piezometric head with elevation close to that of the water table and near land surface. *h* is the change in water table (from left to right in the illustration).

For example, Fig. 17 illustrates a theoretical confined aquifer having an initial hydraulic gradient of 0.1 (from the above citations). Then for any saturated thickness of the confining layer (greater saturated thickness means greater depth to the aquifer) the initial relationship between aquifer and till water level will be:

$$\frac{h_o - h_a}{h_o} = 0.1 \qquad (5)$$

or $h_a = 0.9\ h_o$. If the water table is lowered three feet through drainage, then the new hydraulic gradient is:

$$\frac{h_o - 3 - h_a}{h_o - 3} = i_1 \qquad (6)$$

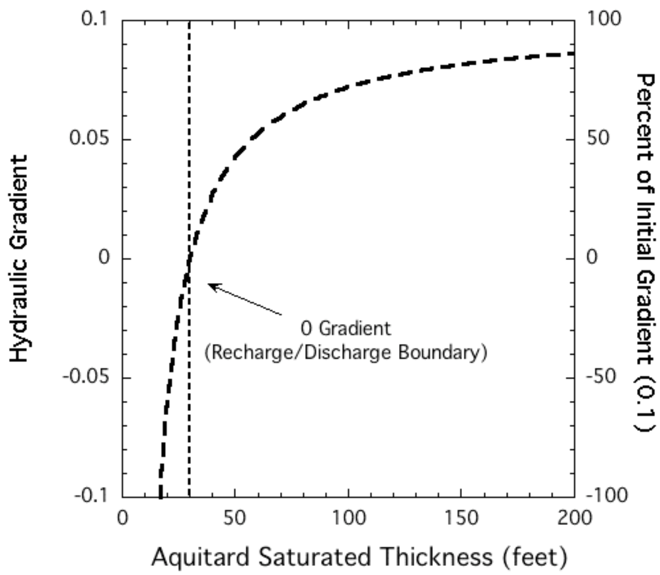

Figure 17. Hydraulic gradient (left vertical axis) and relative gradient (right vertical axis) caused by three feet of drainage drawdown for varying aquitard saturated thicknesses above the aquifer, where the initial hydraulic gradient (i) is 0.1.

The calculated i_1 are shown on the left vertical axis of Figure 17 for different initial saturated depths to the aquifer. For anything less than 30 feet of saturated aquitard thickness, in our example, i_1 is negative, indicating that flow is now upward from the aquifer (the aquifer is discharging). For a saturated aquitard thickness of 30 feet, the aquifer has zero recharge or discharge and is in hydrostatic equilibrium with the water table. For all saturated thickness greater than 30 feet, the hydraulic gradient is positive and recharge is occurring. The greater the thickness, the closer the gradient approaches the initial value of 0.1. ***Thus, the deeper the aquifer is buried, the less the effect of drainage on the recharge rate.*** The right vertical axis presents the percent of the initial gradient caused by three feet of drainage for different saturated aquitard thicknesses. Because recharge is directly proportional to gradients, the percent recharge rate will be identical to that of the gradient.

The example (Figure 17) illustrates that recharge and discharge to confined aquifers can, in some cases, be affected by water-table changes within the range commonly caused by tile drainage, including decreased local recharge and even flow reversals. For deep confined aquifers (> 100 feet of saturated aquitard) effects would be negligible. For intermediate thickness (~ 50 to 100 feet of saturated aquitard) recharge would be reduced by a factor of about half. For a thin aquitard, recharge could be nullified, or the flow system could be modified to a discharge system at the drain field. For the worst case scenario, a very thin aquitard, the tile drain could be drawing constantly from the aquifer, as discussed for case (2) above.

5.4.1 Case Example: the Spiritwood Aquifer

A case study has been provided by Shaver's (1994) report on the Spiritwood aquifer in southeastern North Dakota. The Spiritwood aquifer system extends from the southern border of North Dakota in Dickey and Sargent counties to the northern border in Towner County, and possibly into Canada, and is the largest glacial aquifer in North Dakota. While unconfined and connected with surficial aquifers in some areas, much of the Spiritwood aquifer is confined. Data derived from figures in Shaver (1994) for piezometer nests (134-061-13DAD and 133-062-02CDD in Lamoure County) are compared on Table 5. The characteristic gradients (1983-1987 and 1991-1992) are between 0.27 and 0.4, but saturated thicknesses above the Spiritwood aquifer are sufficient that a decrease of three feet in the upper water level from drainage would have only a small effect (% diff, Table 5) on the gradient after drainage (i_1). Moreover, the hypothetical three-foot drainage case is within the normal range of fluctuation of the unconfined water table in shallow wells (+/- 2-to-4 feet) and piezometric elevations in the confined aquifer (+/- 3 feet). Potential effects of drainage on aquifer recharge were much less than the effects of maximum shallow water-level declines (*approx.* 7-to-8 feet) during the drought period of 1988-1989.

Table 6. Water-level elevations (WL El.) for observation wells placed in the Spiritwood aquifer and shallower formations at specified screened intervals (SI); consequent initial vertical hydraulic gradients (i_o), hypothetical new hydraulic gradients caused by draining the shallow water table three feet (i_1), and the hypothetical percent difference in gradients (% diff.*) caused by the drainage. *amsl* is "above mean sea level." *bls* is below land surface.

Location	Shallow SI ft. *bls*	Shallow WL El. ft. *amsl*	Spiritwood SI ft. *bls*	Spiritwood WL El. ft. *amsl*	Δz* ft.	i_o	i_1	% diff. *
13306002CDD	26-31	1388 +/- 4	117-122	1363 +/3	92	0.27	0.24	13
13406113DAD	68-73	1375 +/- 2	132-137	1349 +/3	64	0.4	0.36	11

5.4.2 Mitigating Factors

There are several mitigating factors that may affect the actual hydrologic impact of drainage over a confined aquifer. First, relative (drained vs. natural) changes in recharge and discharge are subject to natural variations and controls. The relative changes caused by drainage are only effective for the period of actual change from natural conditions. Ground-water systems sufficiently shallow to require drainage are usually subject to local evaporative discharge so that water tables fluctuate seasonally in their natural cycles (see Spiritwood example, Table 5 above). In our assessment we used published hydraulic gradients that were, essentially, snapshots and assumed them constant. But the intra-annual variation of gradients has not been well documented, and they may vary considerably at a given location or between locations. Natural variability would affect the same gradient changes as drainage, only more slowly. Thus, the main effect of drainage will be to attenuate recharge or augment aquifer discharge more quickly and for a longer annual period. Fluctuations in gradients caused by climatic cycles or drainage will be dampened with depth in the aquitard, and will act, hydraulically, as *mean* gradients. The probable effect of tile drainage would be to cause a small downward shift in the *mean* gradient. The relative effect of drainage, then, would only be appropriately assigned to the period of augmentation. For the case of gradient reversal and persistent discharge, this could occur as well due to evaporative discharge. In this case, waters equivalent to those drained would likely be captured by transpiration.

Second, drainage impact on recharge is limited by the spatial variability of the hydrologic landscape. Potential recharge-discharge reversals can only occur under very specific conditions (both water-table and aquifer piezometric surface near land surface). These conditions would be highly localized and would occupy a relatively small portion of the landscape, even within aquifer boundaries.

Last, and most important, the relative changes in recharge and discharge caused by drainage are subject to controls from well-field design and management. If the aquifer is pumped, the piezometric gradient will increase as the aquifer pore-water pressure decreases from pumpage. The increased gradient will increase recharge. Increased recharge will, in turn, lower the water table. Fig. 18 illustrates the change in piezometric gradient with increasing drawdown of piezometric pressure head (h_a) for different initial saturated thickness of the aquitard 30, 40, 50, 60 and 80 feet for the same theoretical case discussed above ($h_o = h_a/0.9$ or $i_o = 0.1$). If pressure-head drawdown caused by pumpage is sufficient to decrease piezometric elevation to less than the elevation of the top of the aquifer, all gradients converge at 1, or ten times the initial gradient of 0.1. The increase in pumpage will thus increase recharge, causing a drop in the water table, eventually to the point where the tiles will be disengaged. The main point is that, ***for a confined aquifer that is being pumped for a water supply, the compensating effects of pressure drawdown accomplished by the wells will ultimately have far more influence on aquifer recharge than shallow tile drainage. For confined***

aquifers, regardless of depth, the ultimate rate of recharge will eventually be governed by the hydraulic conductivity of the materials and hydraulic gradient affected by the rate of pumpage, rather than tile drainage.

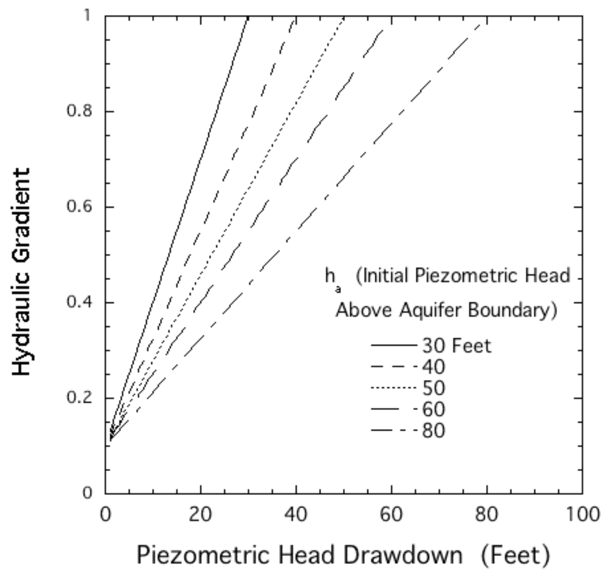

Figure 18. The effect of aquifer pressure drawdown through pumpage on hydraulic gradients governing aquifer recharge through a saturated aquitard of varying thickness, and having an initial gradient (i_o) of 0.1.

5.5 Drainage in Soils Overlying Unconfined Aquifers

Unconfined aquifers are those in which the water-level in a monitoring well is the same as that of the water-table outside of the well. Unconfined conditions occur when the aquifer is continuous to land surface, or is otherwise overlain by a highly permeable layer. Aquifers overlain by thin moderately permeable layers of silt or loam commonly have unconfined characteristics. From discussion above (Table 4) about 20% of all *aquic* soils overlying aquifers in the 18-county study area were coarse, and about 35% of soils overlying aquifers were *aquic*. Combined, about 7% of the soils overlying the aquifer area would be coarse to land surface. However, a portion of the fine soils overlying aquifers, particularly relatively thin caps of silty or loamy soils, would act as unconfined aquifers with respect to long-term recharge and discharge.

The potential effects of water discharge through tile drains on well fields in an unconfined aquifer are of two types: (1) Recharge-discharge balance effects on water availability, and (2) operational effects on the well field. Recharge-discharge balance effects would require that in the overall long-term hydrologic system, drained waters would detract specifically and predominantly from waters available for well capture, and not from another discharge sink. Operational effects are those that would alter the ability of the well-field to extract water, without necessarily having a large effect on long-term supply available to the well field. They comprise hydrologic alterations of the well environment that affect pumping capacity of the well field, such as local head loss and available drawdown. Another term for this is "interference." Operational effects can often be offset through augmentation of the well-field design.

5.5.1 Effects of Soil Hydrology and Recharge and Discharge in an Unconfined Glacial Aquifer

In the discussion of soil recharge and discharge (Section 5.3 above), it was explained that the natural recharge-discharge balance in glacial aquifers in North Dakota is maintained by the discharge of recharge waters through seepage and evapotranspiration from wetlands or soils having shallow water tables. ***Within the constraints of sustainable development, waters pumped for beneficial use must be captured from these alternative discharge areas.*** It was also explained that, because drainage occurs on wet soils, it will seldom be used near discharge zones at stream banks or coulees because ground water is already draining to the streams. For this reason, tile drainage on unconfined aquifers will usually occur on soils more distant from receiving streams and will usually be compensated through capturing waters normally discharged through evaporation or runoff. This compensation is affected by lowering the water table, a natural outcome of pumping, and consequent reduction, and possibly eventual decoupling of the water table as a direct source of local evapotranspiration. A case example is the Elk Valley aquifer in Grand Forks County.

5.5.2 Case Example: The Elk Valley Aquifer

The Elk Valley aquifer is a "losing stream" that drains to tributaries of the Forest, Turtle and Goose rivers. Areas draining to surface waters have relatively deep water tables because of drawdown from seepage. Soils in areas having relatively deep water tables are classifed in the Haploboroll (now Hapludoll) great group. They are shown in pink on Fig. 19. Local precipitation and snowmelt, not intercepted by crop roots, drain to the water table and then move regionally toward discharge in local rivers and streams. Developmental decline from pumping in these areas would be compensated mainly by loss of discharge to the surface waters. Well-integrated drainage is indicated near surface discharge areas by closely-space equipotential lines on Fig. 19.

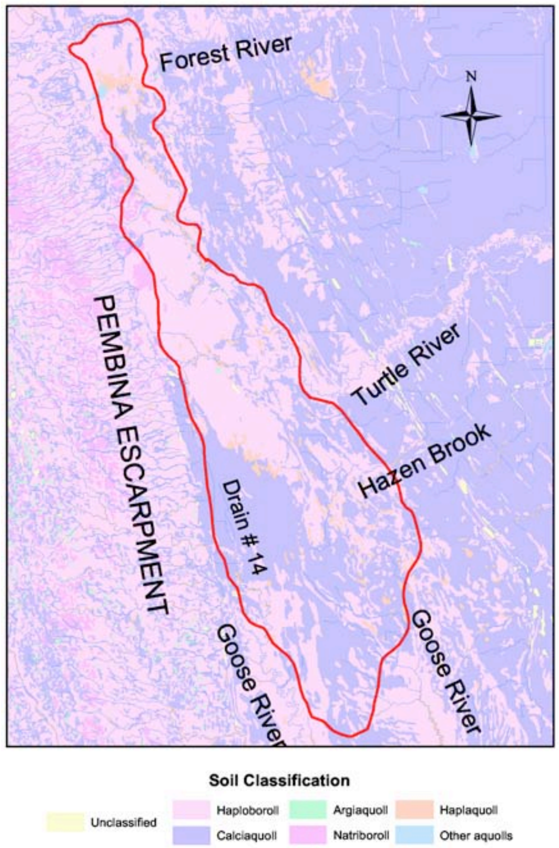

Figure 19. Generic taxonomic soil map (USDA great group taxa) for soils overlying the Elk Valley aquifer and the neighboring landscape.

The southwestern portion of the Elk Valley aquifer which, in addition to local precipitation, receives runoff waters from the Pembina Escarpment generally has high water tables. These have caused a long-term *aquic* moisture regime, which has caused the development of Calciaquoll and Endoaquoll soils. Calciaquolls serve as predominant evaporative discharge areas for Endoaquolls in a closed-depression local hydrologic system (Section 5.3 above). The local Bearden (Calciaquoll) and Perella (Endoaquoll) landscape composition has been described by the USDA-SCS (1980) as about 65% Bearden and 30% Perella, and "appear in associations so closely intermingled or so small that mapping them separately is not practical." Recharge-discharge cells commonly consist of a few tens of meters (Knuteson and others 1989). The Calciaquoll-dominated areas are indicated by the purple color on Fig. 19. The predominance of the closed-depression recharge and discharge regime is indicated by the broadly spaced equipotential lines for the southwest Elk Valley aquifer on Fig. 20. These indicate that in shallow water-table areas ground-water discharge is occurring primarily as evapotranspiration, and it is occurring locally. These are the hydrologic regimes most likely to be drained. Locally drained waters will therefore be recovered primarily through a decrease in local evapotranspiration.

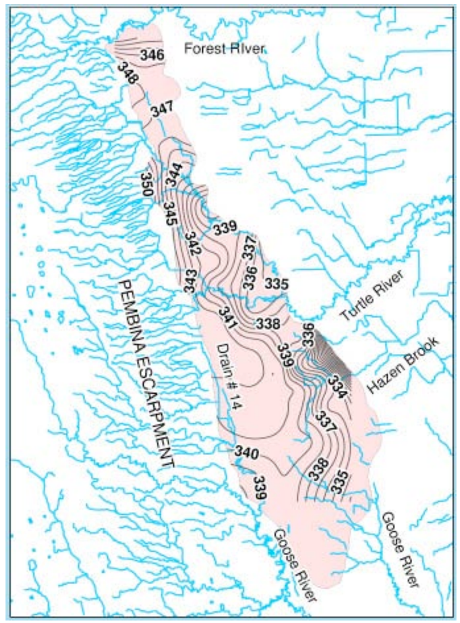

Figure 20. Map of water-level elevations (meters amsl) in the Elk Valley aquifer.

5.5.3 Potential Effects of Tile Drainage on Well-Field Water Supplies

In a sense, because discharge through both well extraction and tile drainage are recovered from evaporation (and in some cases transpiration), they are competing for the same water. But there are several reasons why limitations on beneficial use from drainage will be negligible. First, during dry periods, when water is most scarce, water-tables will decline beneath the elevations of the tile drains, curtailing drainage. This can be seen in the drainage vs. precipitation relationships described in Section 4 above, and particularly in the record of drainage from the deep drains in the Oakes Test Area (Fig. 3). In this case there is no drainage competition with the well field for capture of waters normally discharged through evapotranspiration. Second, under normal water-table conditions, where the zone of well capture of evapotranspiration does not interact with the drainage field, there can be no effect. Because most recharge water in areas of *aquic* soils is recovered through local evaporation, usually within a given annual cycle, and because local shallow drainage would reduce evaporative loss within that local flow cell, shallow drainage should have little effect on water supplies available for well fields.

Third, where drainage fields and drawdown from well fields do overlap, there will be competition for the same evaporation. In this case, the well field and the drainage field are both serving as competing sinks. Because the well screens are more deeply placed than the drains, however, under optimized well-field management (where developmental decline is fully exploited by the wells) the well-field capture must prevail over the drains (Fig. 15). As well drawdown first contacts the drained field, the well will be less able to capture evapotranspiration than it would without the drain field, and well drawdown will thus extend further to capture evapotranspiration from a larger area than it would without the drainage field. But when the advance of the cone of depression from pumping causes drawdown to a depth greater than the depth of the drains, all drained waters will be captured by the wells and the drains will become inoperable.

In summary, ***because wells serve as alternate drains and their points of diversion are more deeply placed in the aquifer, supplies of waters for well fields should not be impaired by drainage fields. Where drainage fields compete for recovery of the same local evapotranspiration as well fields, they may affect the extent and depth of the cone of depression exploited by the well field. But under optimal design and development, where well fields fully capture evapotranspiration and optimize the capture of sustainable yield, developmental decline will decouple the drains and available waters will be fully captured by the well field.***

5.5.4 Potential Effects of Tile-Drainage on Well-Field Function and Water Recovery

The potential effects of water discharge through tile drains on well fields include operational effects on the wells. *Operational effects are those that would alter the ability of the well-field to extract water, without necessarily having a large effect on the long-term water supply available to the well field.* They comprise hydrologic alterations of the well environment that affect the pumping capacity of the well field, such as loss of saturated thickness. Operational effects can often be offset by drilling more wells.

The relationship between the pumping rate (Q) from a well and aquifer drawdown (s) for a confined aquifer at distance, r, from a pumping well at time t can be represented by the Theis equation as:

$$s = \frac{QW(u)}{4\pi T} \qquad (7)$$

where W(u) is the well function, and where u is:

$$u = \frac{r^2 S}{4Tt} \tag{7a}$$

For an unconfined (water-table) aquifer, drawdown (s_{wt}) is further adjusted using the Dupuit-Forchheimer correction (from Walton 1970, p 224):

$$s = s_{wt} - \frac{s_{wt}^2}{2m} \tag{7b}$$

for initial saturated thickness (m).

The relationship of s_{wt} vs. Q is nonlinear, decreasing at an increasing rate approaching the upper limit of Q (Fig. 21). This occurs because transmitting aquifer thickness at the well decreases with s_{wt}, limiting flow to the pump. To maintain increasing Q as flow constricts, the aquifer must compensate with a steeper hydraulic gradient near the well. The steepening gradient, in turn, causes an increasingly rapid drawdown at the well which further constricts flow. Eventually it can cause the pump to break suction. Because of negligible gains in pumping rates per unit drawdown near the upper limit of Q, and consequent problems with pump operation, a properly designed well is constructed so that Q during operation is below the range of steep s_{wt} vs. Q, as shown by the dashed box on Fig. 21. Because water is flowing to the well only from the interval between the design drawdown, cost-effective well design usually limits the screened interval to the aquifer interval below the design drawdown at the well.

The example in Fig. 21, is for an aquifer having a saturated thickness of 40 feet, an hydraulic conductivity (K) of 100 feet per day, and a storativity of 0.2. The "near-vertical" Q vs. s_{wt} at the well is shown to occur at approximately 2/3 the aquifer thickness, so a reasonable screened interval would be the bottom third of the aquifer. Potential effects of tile drainage on well operation are limited to their effects on the water-table elevation within the environment of the well field. We will examine two hypothetical cases: (1) the potential effect of tile-drainage within the well field, and (2) potential effects of tile drainage more distant from the well field.

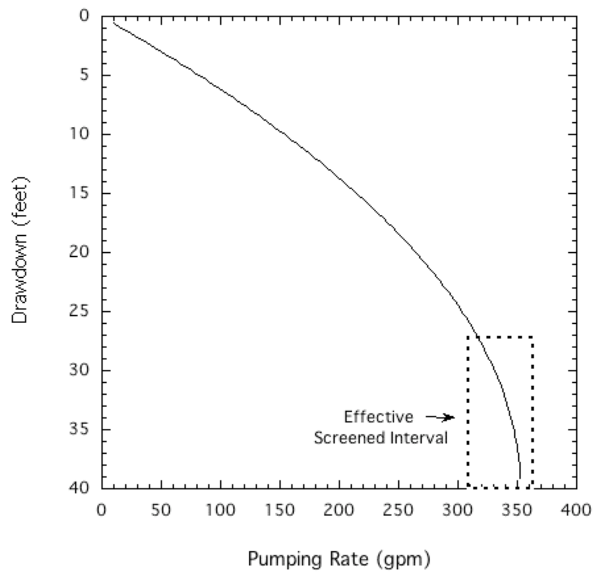

Figure 21. Effect of pumping rate on water-table drawdown at a well.

5.5.5 Interactions Between a Well Field, Evapotranspiration, and Drainage Fields

In discussion of "developmental decline" we explained that waters pumped from shallow water-table aquifers in North Dakota are usually captured from evapotranspiration and seepage by lowering the water table. An illustration of effects of an evapotranspiration natural discharge sink on well drawdown and pumping capacity is shown schematically on Fig. 22. After initiation of pumping, the transient "cone of depression" in the aquifer, as described by the Theis equation above, will continue to deepen and advance approximately concentrically (for an homogeneous aquifer) until the pumping rate equals the decreases in evapotranspiration caused by the lower water table. The change in evapotranspiration is caused by the interception of evaporative shallow water-table areas, characterized by *aquic* soils, by the advancing cone of depression. The example in Fig. 22, below, shows the relative position of several hypothetical evaporative discharge areas in relation to an advancing cone of depression from a pumping well. At the earliest time (t=1) well withdrawal is partially captured by recovery of evapotranspiration from drainage-area one. If not fully compensated, then by t=2 well withdrawal is more fully compensated by all of drainage-areas 1, 2 and 3, and part of area 4 and 5, with discharge areas closest to the well possibly fully decoupled[2]. If not fully captured within these areas, then by t=3, further capture of evaporative discharge is achieved through partial decoupling of discharge areas 6 and 7. This continues,

[2] The term "decoupled," with reference to the water table, indicates that the water table is deep enough that direct capillary draw of aquifer by transpiring plant roots is negligible.

increasingly decoupling evaporative areas, until Q is fully compensated by decreased evapotranspiration caused by lowering the water table in all of the affected discharge areas. When this has occurred, the cone of depression approximately stabilizes, subject to changes in the natural water table with climate.

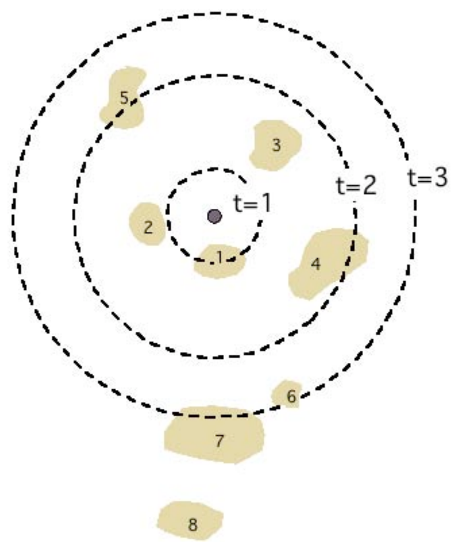

Figure 22. Illustration of time effects on well-operation interactions with evaporative fields.

5.5.6 Potential Effects of Tile-Drainage Within the Well Field

Tile drainage within a well field defines the most immediate case for potential effects on well-field operation. Because of close proximity of drains to the wells, changes in the cone of depression caused by drainage would be immediate and would not be buffered by intervening evaporative soils.

Lowering a water table through drainage affects a well field primarily through decreasing transmissivity (T), which is proportional to the change in saturated thickness. Drainage effect on T will depend on the texture of the overlying soil. Unconfined glacial aquifers often consist of coarse materials to land surface. In this case, the effect of a lower water table caused by tile drainage will be to cause the "cone of depression" of the pumping well to translate downward, as shown on Figure 23. This causes a decrease in the saturated thickness, b. This may cause a relative decrease in pumping capacity for the period of time in which T has changed. The degree of effect, however, will depend on well field design and operation, and also on the normal seasonal and climatic water table elevations.

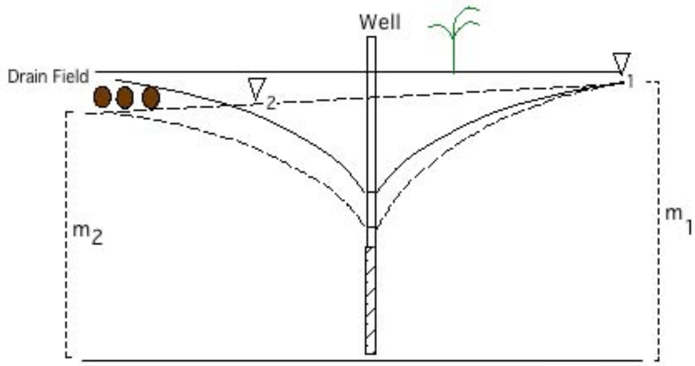

Figure 23. Potential effects of tile drainage in an unconfined aquifer having coarse materials to land surface on drawdown and consequent saturated thickness during pumping.

The effect of a plausible head loss through drainage can be illustrated by a hypothetical well in an unconfined aquifer having a moderate (40-foot) saturated thickness, and one having a thin (20-foot) saturated thickness, both having a storage coefficient of 0.2, and a screened interval of one-third the saturated thickness (discussed above). In our simplified example we will allow maximum pumping drawdown only to the top of the well screen (wells are actually designed to allow for a margin above the screen), or pumpage of two-thirds the saturated thickness. The effect of removing two feet and four feet of water through drainage is approximated by decreasing the saturated thickness by two and four feet, but maintaining the initial screened interval at one-third of the saturated thickness (See Figs. 21 and 23). Computations were made for a 60-day continuous pumping run using the "macTheis" program written by Royce Cline, using the "Dupuit-Forchheimer" adjustment (Equation 7b) for an unconfined aquifer. Results are shown on Table 7. For a 40-foot saturated thickness, reductions for two- and four-foot drainage are 10% and 20% respectively. For the 20-foot saturated thickness, they are 20% and 40%. Potential maximum effects vary from small effect for large saturated thicknesses, to large effects for thin saturated thicknesses. If the drawdown on the well is not constrained by the top of the screen and allowed to drop proportionally with the saturated thickness, then well-capacity loss would be about 3% less for the 40-foot saturated thickness, and about 7-9% less for the 20-foot saturated thickness.

Table 7. Comparison of approximate pumping capacities (PC) for a well in an aquifer having saturated thicknesses of 40 feet and 20 feet, and with reductions of two feet (b=38 feet) and four feet (b = 20 feet), with K values of 10, 100 and 300 feet per day.

K Ft./d	b=40' PC (gpm)	b=38' PC (gpm)	b=38' PC38' / PC40'	b=36' PC (gpm)	b=36' PC36' / PC40'	b=20' PC	b=18' PC (gpm)	b=18' PC18' / PC30'	b=16' PC (gpm)	b=16' PC16' / PC40'
10	37	33	0.9	29.5	0.8	9.8	7.8	0.8	6	0.6
100	312	280	0.9	259	0.8	82	65	0.8	50	0.6
300	875	784	0.9	725	0.8	228	181	0.8	142	0.6

These simulated effects, however, are maximum, and would be relatively effective only during the time when the tiles are flowing. Once the water-table is below the tile, the final depth of the water table will be determined by the decoupling depth for evapotranspiration, which is determined by the local plant community (or crop). The effect of shallow drainage is thus limited and transitory. This can be illustrated using a hydrograph (Fig. 24) for a well (151-055-23BBB) located within an area mapped to Calciaquoll soils in the western Elk Valley aquifer (Grand Forks County). We use the time period from 1994 through 2007 (From 1988 through 1992 was an exceptionally dry period). Potential tile-drainage effects are simulated by truncating the water-table peaks at four feet (four-foot tile drainage), and five feet (five-feet of tile drainage). These depths are chosen to be conservative, as common current drainage practice in North Dakota would set tile depths between three and four feet. The approximate annual peak water-table is between one and two feet, conforming to common annual maxima for Calciaquolls in Grand Forks County (USDA-SCS 1981).

Out of 13.9 years, water tables were above four feet 5.3 years, or 38% of the total time. The relative attenuation of pumping rates caused by tile drainage would only be effective for that time. During that time, the mean water-table height above the tile drain (at four feet) would be 1.1 feet (between 0.53 and 1.67 feet at 95% confidence), with a median of 0.65 feet, so the actual effect on pumping would be maximum about 1 foot 38% of the time, or about 0.38 feet net attenuation of available drawdown. For an initial 40-foot saturated thickness, less than one percent attenuation of annual pumping capacity would result. For a tile drain at 5 feet, the water table would be above the tile about half (51%) of the time, and the mean height above the drain would be 1.39 feet (between 1.11 and 1.75 feet and 95% confidence) with a median of 1.1 feet. The mean net result would thus be about 0.71 feet less of available drawdown - about 2% for a 40-foot saturated thickness, or 5 % for a 20-foot saturated thickness.

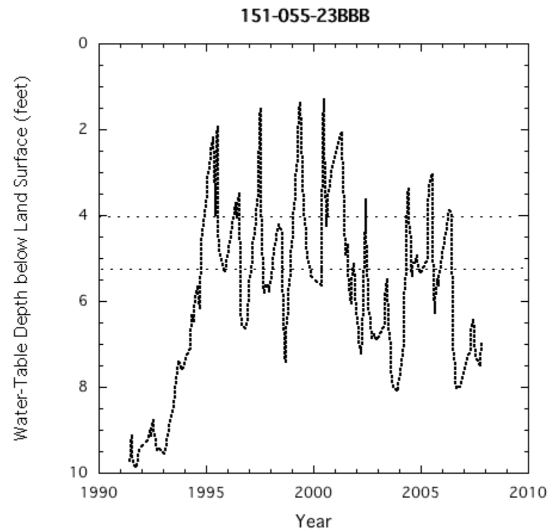

Figure 24. Hydrograph for an observation well in the Elk Valley aquifer, located in an area mapped predominantly to Calciaquoll and Endoaquoll soils.

This example assumes that the final water level is governed by the local "decoupling" depth of the plant community and is not affected appreciably by the tile drain. The actual peak water level elevations and times for relative elevation above the tile will vary with location and local hydrology. This example, however, serves to illustrate the manner in which local hydrology of an *aquic* soil would interact with tile drainage to affect well-field pumping capacity.

In many cases, however, the aquifer is overlain by a relatively thin loamy cap up to a dozen or more feet thick. In this case, illustrated on Fig. 25, the tile drain will have no effect on saturated thickness and T. The fine-soil cap does not contribute to T and therefore is not diminished by the lower water table. The pumping well causes the aquifer to desaturate beneath the loam cap, so that local aquifer recharge occurs under an hydraulic gradient of one. Tile drainage, as explained previously for confined aquifers, will not affect this gradient. Where a thin loamy cap overlies an unconfined glacial aquifer, no effects of tile drainage on a well-field operation may be expected.

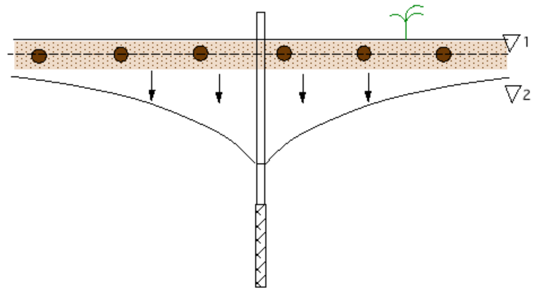

Figure 25. Potential effects of tile drainage in a thin, fine soil layer overlying an unconfined aquifer drawdown and consequent saturated thickness during pumping.

5.5.7 Potential Effects of Tile-Drainage Distant from the Well Field

The effect of a more distant drain field on the operational capacity of the well field will be similar to, but slightly augmented from, the local effect. The main augmentations will be: (1) The time before effective interaction between the well field and the drainage field will occur; and (2) the damping effect of recharge and discharge regimes intervening between the well-field and the drainage field. If the distant drainage field is the main evaporative discharge area from which a well recovers discharge, and if there are no substantial intervening evaporative or seepage discharge areas, then the hypothetical maximum final effect of a drainage field can be approximated by translating the cone of depression downward by the difference in the water table in the drained field (Fig. 25). The drainage effect on available drawdown at distance is thus approximately similar to that of the local drainage field within the well field described above. The difference is that the intra-annual variations in the water table will be dampened, and the effect will be more uniform, approximating a uniformly lower water table. A slightly different computational approach for the dampened effect, using the hydrograph in Fig. 24, can be expressed as:

$$\Delta h = \frac{\int_{1994.0}^{2007.9} \ell dt - \int_{1994.0}^{2007.9} \ell^* dt}{t} \qquad (8)$$

where ℓ is the water-table depth below land surface at given time t, and ℓ^* is same data set modified by truncating all ℓ shallower than the tile depth at the tile depth. Results are Δh = 0.48 feet for the four-foot tile depth, and 0.89 feet for the five-foot tile depth. Slight differences between the distant and local drainage effects are due to differences in computational methods. The main difference in effect on well operation will be the time required for a newly constructed drainage field to affect the well field.

The time for first influence (lag time) of drainage stress on pumping capacity can be described using:

$$t = \frac{Sd^2}{2.25T} \qquad (8)$$

where d is the distance of the drain from the well, S is aquifer specific yield and T is transmissivity (hydraulic conductivity x saturated thickness). Theoretical lag times with distance for different T values on an unconfined aquifer having a storativity of 0.2 are shown on Table 8. For a low T aquifer, for example, a homogeneous fine sand having a hydraulic conductivity of 10 feet per day, and a saturated thickness of only 20 feet, the effects of a drainage field a mile distant would take about 34 years to influence the well, while a thick sand and gravel would take less than a year to influence the well.

Table 8. Theoretical lag times for well-drawdown effects on a drainage field located at varying distances from the well. Group A values for T are derived from a K of 10 feet per day, and varying saturated thicknesses (b) of 20 (A1), 40 (A2), and 60 (A3) feet. The b sequence is repeated for K=100 feet per day (B1, B2, B3) and K-300 feet per day (C1,C2,C3).

T =	(A1) 200 ft^2/d	(A2) 400 ft^2/d	(A3) 600 ft^2/d	(B1) 2,000 ft^2/d	(B2) 4,000 ft^2/d	(B3, C1) 6,000 ft^2/d	(C2) 12,000 ft^2/d	(C3) 18,000 ft^2/d
Distance Feet	t (years)	t (years)	t (years)	t (years)	t (years)	t (years)	t (years)	t (years)
2,500	7.61	3.81	2.54	0.761	0.381	0.254	0.127	0.0846
5,280	33.9	17	11.3	3.39	1.7	1.13	0.566	0.377
10,600	137	68.4	45.6	13.7	6.84	4.56	2.28	1.52

5.5.8 Other Mitigating Effects

The above described operational effects of distant drainage are potential maximum effects. They assume that no alternate discharge sinks intervene between the well field and the drainage field. The existence of alternative discharge zones, such as evaporative soils or seeps to local surface waters between the well field and the drainage field (Fig. 22) will modify, and even potentially nullify effects of the drainage field. If a drainage field is sufficiently distant from the well field that all pumped water is captured from evapotranspiration and runoff before effects of pumpage reach the drainage field, then there will be no effect on well field operation. If, for example, on Fig. 22 Q is fully captured from evapotranspiration and runoff in areas one through seven, the effect of tile drainage located in area eight will have no effect on the saturated thickness, and therefore the operational capacity at the well field.

6. EFFECTS OF WELL-FIELD MANAGEMENT AND DESIGN

Because well screens are always more deeply placed than tile drains, well fields can almost always be designed or managed to offset tile drainage losses. A well field that fully captures local evapotranspiration will eliminate local tile drainage. For example, pumping losses from reduced saturated thickness caused by drainage might be compensated by additional wells. In fact, it is suggested that because local tile drainage within a well field implies a seasonal high water-table which must decrease with evaporation within any given year, proper design of a well field having a local aquifer thin enough to be substantially affected by tile drainage, should be based on a common annual low water table. This is important because periodic water-table decline will occur with or without the drainage field, and may adversely affect the operation of the well when saturated thickness is critical. Thus, the well field should be designed to provide efficient capture when the "live storage" component of the aquifer is depleted. The relative effect of the drainage field is, in most cases, only to prolong the period of lower pumping capacity.

6.1 The Traill Rural Water District (TRWD) Well Field: A Case Study

Tile drainage is becoming more common along the beach ridges of the Lake Agassiz plain. Traill Rural Water District (TRWD), which operates a well field in the northeast portion of the Page-Galesburg aquifer in Traill County, ND, has expressed concern that the expansion of tile drainage may impact the local recharge upstream from their existing well field. Tile drainage is planned or has already been developed both upgradient and downgradient of the TRWD well field. TRWD has expressed concern only for the drainage occurring upgradient. TRWD does not believe the well field has been impacted to this point, but is more concerned about the future implications tile drainage will have on the local aquifer.

6.1.1 Characteristics and Properties of the TRWD Well Field

Traill Rural Water District's existing well field is located in the SE 1/4 Section 29 and NE1/4 Section 32, all in T146N, R053W. TRWD currently has 18 wells in operation. Fig. 26 shows the location of proposed and developed tile drainage upgradient of TRWD well field. In a conversation with Rex Honeyman (SWC, 12/27/2007) the TRWD manager, Jerome Olson, has indicated that the well field was initially designed for seven wells. One well failed to operate effectively immediately, leaving only six wells. TRWD added four more wells on three different occasions over the years for the current total of 18.

Because of slow well recovery TRWD had difficulty meeting its users' demands. Acquisition of new water users required that TRWD increase its capacity. Seven of the current wells have an average pumping rate of 30 to 40 gpm, while the remaining 11 wells have an average pumping rate of 10 to 20 gpm. Their cumulative rate with all the wells in operation is 550 gpm. TRWD has replaced wells, only to find that the rates are very similar.

Olson indicated that the main well-field capacity problem is the "tightness" of the formation. In 2004, as part of a water supply expansion project for TRWD, the SWC installed test holes and observation wells in the area of the well field.

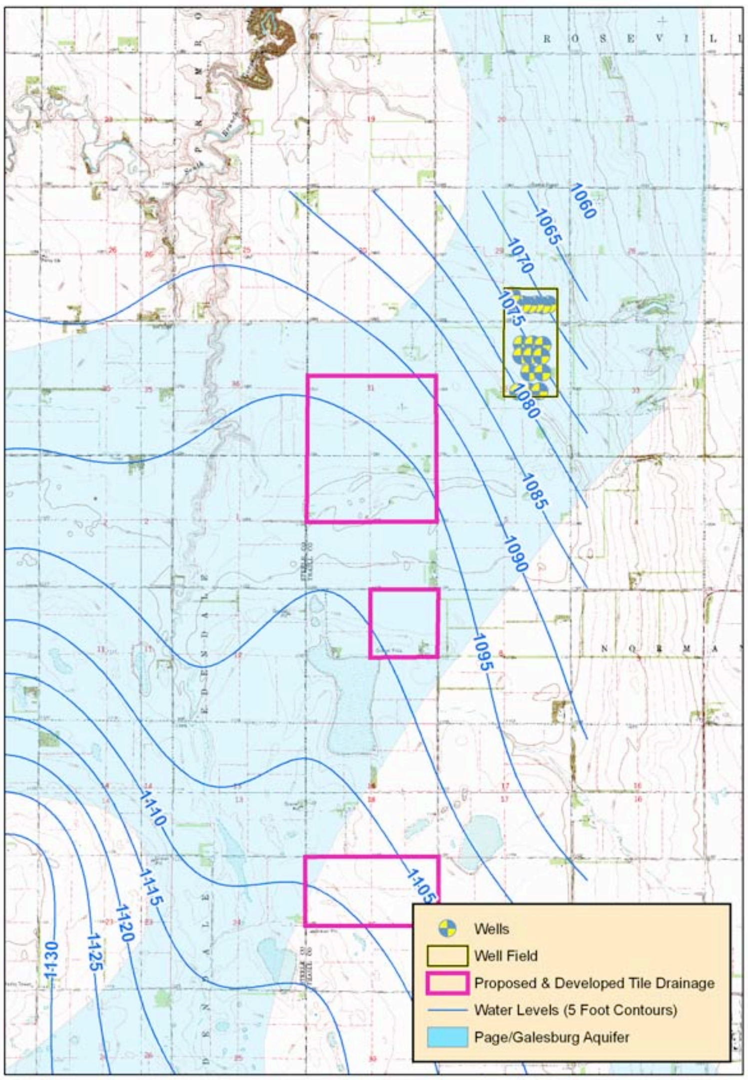

Figure 26. Location of proposed tile drainage in relation to the Traill Rural Water District Well field in the Page-Galesburg aquifer, Traill County, ND.

In a review memorandum dated December 27, 2007, Rex Honeyman (managing SWC hydrologist for the Page-Galesburg aquifer) stated that limited well capacities for the TRWD well field are likely caused by slow conducting properties of the aquifer, rather than by the well construction and design. He explained that initial well-field designs were based partially on short-term pumping tests conducted in December 1973 and 1974, and on driller's logs that indicated a predominant texture of fine to medium sand and a saturated thickness of about 41 feet. Actual well pumping capacities have demonstrated that initial designs were overly optimistic. Underestimates of design well yields were likely caused by deficiencies of short-term pumping tests, which do not account for delayed yield and casing storage, and a misinterpretation of grain size. Most recent drilling in the area has indicated the presence of a substantial amount of silt within the sand matrix. In the professional judgment of Honeyman, "The hydraulic conductivity of a very fine to fine sand with moderate silt content is about 20 feet per day. Based on an average saturated thickness of 41 feet near TRWD well field, a more accurate estimate of transmissivity would be 800 to 900 ft^2/day. A typical storativity for an unconfined aquifer composed of unconsolidated very fine to fine sand would be in the range of 0.1 to 0.15."

6.1.2 Potential Tile Drainage Effects on TRWD Well Field

Based on the well-field characteristics discussed above and the recharge-discharge hydrology indicated by soil drainage classification units (Fig. 27); the following qualitative assessment of likely effect of tile drainage on the TRWD well field can be made:

1. All of the areas proposed for tile drainage are mapped, predominantly, to evaporative discharge soils, as would be expected. This means that drainage losses will be compensated primarily through lower local evaporative discharge and not from waters discharged through pumpage. Because wells are more deeply placed than tile drains, they are positioned for first capture of ground water, and under optimal design and operation could utilize waters so as to minimize both evapotranspiration and drainage losses. There should be very little net loss in water supply for pumpage.

2. Potential decreases in pumping capacity caused by decreased saturated thickness from tile drainage would be mostly independent of the well-field or drainage field placement within the flow regime (upgradient or downgradient). Pumping effects will dominate the hydraulic relationship between the tiled field and the well field.

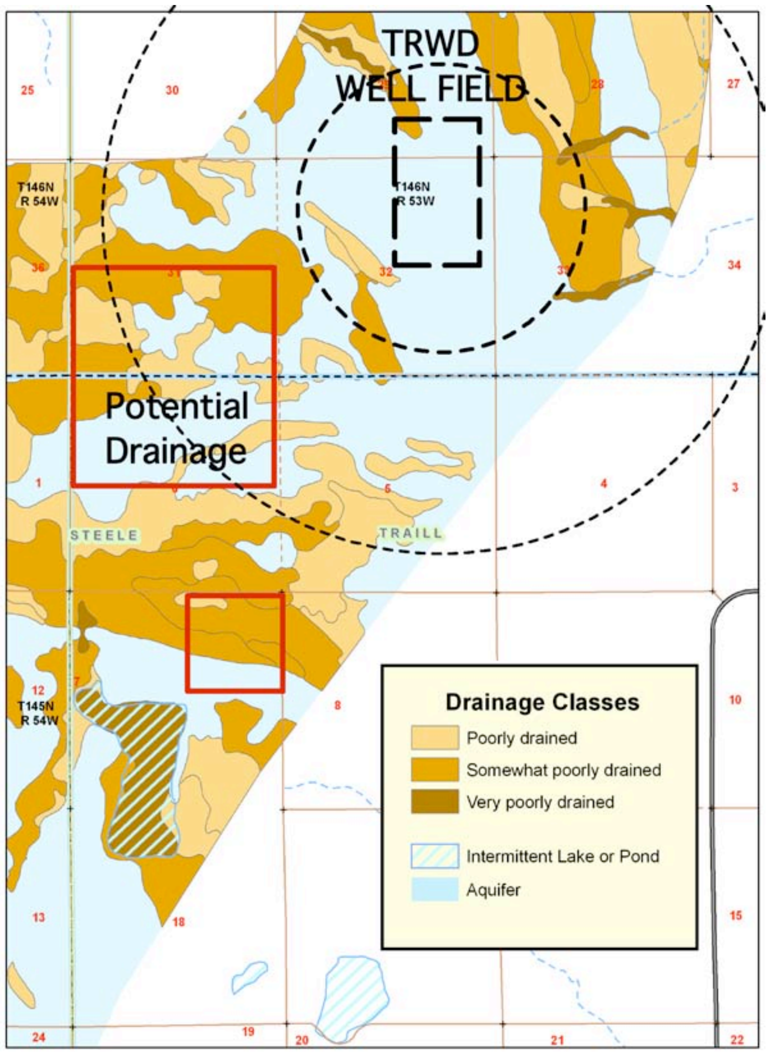

Figure 27. Proposed tile drainage locations and Traill Rural Water District (TRWD) well field in relation to area soil drainage classes. Concentric circles are: inner- half mile radius from well-field center, and outer-mile radius from well-field center. Poorly drained and somewhat poorly drained soils correspond to Calciaquoll and Endoaquoll soils.

3. The well field is located within well drained soils mapped predominantly to the Hapludoll great group. Deeper local water table soils, combined with drawdown from pumping make local tile drainage unlikely. This eliminates any immediate likely effect on well pumping capacity through decreased saturated thickness.

4. Low T for the aquifer near the wells is primarily caused by low K, and not aquifer thickness. Moderate thickness of about 40 feet means that any effect on T due to tile

drainage near or distant from the wells would be minimal. The potential decrease in well-field capacity caused by a 4-foot deep tile drain, based on discussion above (Table 6) would likely be less than 2%.

5. There are substantial areas mapped to evaporative soils, predominantly Calciaquolls, between the well field and the proposed tile drainage areas. Other evaporative areas are mapped northeast and northwest of the well field. These will partially or fully compensate for possible decreases in saturated thickness caused by distant tile drainage.

6. The nearest point of a tile-drained field has a radial distance of about a half mile from the nearest corner of the mapped well field. Using Equation (3) with T of 900 $ft.^2$ per day and S of 0.15, the nearest **potential** drainage point would affect the well field no sooner than 1.4 years. Drainage fields at 1, 2 and 3 miles from the well field would be predicted to affect the wells no sooner than 6, 23 and 50 years respectively.

Based on: (1) Primary compensation of drainage losses from waters that would normally be evaporated or transpired from poorly drained soils, (2) the distance of the well field from drained fields which limits the time of effect, (3) the presence of compensating evaporative soils between proposed drainage fields and the well fields, (4) the moderate saturated thickness of the aquifer near the well field, and (5) the likely placement of the tile drains within a fine soil cap rather than in the sandy matrix of the aquifer itself, potential effects of tile drainage on long-term sustainability of the aquifer and effects on pumping capacity of the TRWD well field would be expected to be negligible.

6.2 Summary: Well-Field Design Effects on Water Capture by Tile Drainage

Because tile drainage is primarily used to remove water from soils having a shallow water table, drained waters are primarily captured from waters that are normally evaporated or transpired within a closed or semi-closed depression or micro-depression focused flow system. This is commonly accomplished by lowering the water table through pumping, which decreases plant-root extraction of water. Within the overall recharge-discharge balance of an unconfined glacial aquifer, tile-drained waters do not, therefore, greatly decrease water pumped from a well field. Where wells, through developmental decline, might compete for capture of the same natural evaporation and runoff as the drainage field, wells are positioned, by virtue of their deeper placement, for first capture and use of waters normally discharged through evaporation, runoff and transpiration and can, if optimized, affect the water table sufficiently to minimize or prevent drainage through the tiles.

Tile drainage may affect the operational pumping capacity of nearby wells through decreasing saturated thickness. The importance of small changes in saturated thickness varies with the initial saturated thickness, and is most significant for well fields in very thin areas of an aquifer. The relative change in pumping capacity caused by tile drains would be affected by the depth of the drains, the proportion of operational time that the drains flow, the proximity of the drainage field to the well field, the percent of Q captured from the area of the drain field prior to drainage, the time of effect as determined by aquifer diffusivity, and effects of alternative discharge sinks (evaporative soils, seeps, etc.). Time and distance interactions also increase the likelihood of intervening mitigating hydrologic processes, such as large recharge events.

With respect to pumping capacity, as with water availability, well fields are positioned for first capture and have the capability to mitigate, limit and even eliminate effects of tile drainage through optimal design. Specifically, slight differences in saturated thickness can be offset by more wells with slightly lower design pumping rates. While the greatest operational limitations and difficulties in design compensation would be incurred for well fields in thin aquifer areas, water tables fluctuate naturally and without tile drainage their depths are frequently governed by local depths of plant-root extraction. Tile drainage under such conditions causes an earlier and more frequently lower water-table. Where seasonally high water tables are tile-drained, a well field properly designed for operation under conditions of a late-season (low) natural water table should have little difficulty with operational impairment caused tile drainage.

7. SUBSURFACE DRAIN EFFECT ON WATER QUALITY FOR BENEFICIAL USE

The focus of this report is mainly an assessment of potential subsurface drainage impact on the quantity of water available for beneficial use. Detailed treatment of water quality issues, effects of subsurface drainage on agricultural nutrients and pesticides in ground water and surface water, are issues beyond the scope of our objectives, and constitute in themselves major issues. However, because changes in water quality can affect its beneficial use, we will briefly summarize some of the major issues that may be involved with increased subsurface drainage in North Dakota. A more comprehensive review of potential ecological impact of tile drainage in the Red River Valley has been prepared by Blann and others (in review) and Blann and others (in review), and should be referred to for more detailed consideration of these issues.

The issues of primary concern with agricultural drainage are pesticides and nutrients. The two principal nutrients of concern are nitrate and phosphorus.

7.1 Pesticides

According to Gilliam (1999) "pesticide concentrations [in runoff] are usually much greater than those in leaching water." In addition, greater infiltration early in a storm (caused by a drier drained soil) places pesticides deeper in the soil profile and decreases vulnerability to erosive transport later in the storm. Gilliam cites research in which pesticide losses in surface-drained fields are substantially larger than combined surface- and subsurface-drained fields, and tile-drain pesticide concentrations are usually one or more orders of magnitude below those of the surface drains. In addition, he cites research indicating that the total mass of pesticides removed by subsurface drains was less with wider drain spacings - a conclusion likely caused by pesticide degradation for a longer residence time, and increasing cumulative sorption along the flow path. The net effect of subsurface drainage on pesticide contamination, then, would be expected to have no adverse impact on ground water, and beneficial impact on the quality of surface water through filtration.

7.2 Phosphorus

Phosphorus is normally applied to agricultural fields as orthophosphate or manure phosphate. Orthophosphate immobilizes quickly in the high-calcium and relatively high-pH environment of eastern North Dakota soils. Phosphorus losses are usually associated with erosion rather than sub-surface drainage, and are therefore strongly influenced by the hydrologic impact of subsurface drainage (Gilliam 1999, Ayars and Tanji 1999). Gilliam (1999) has cited research in which subsurface drainage decreased runoff by 34% in the lower Mississippi Valley, and soil loss in northern Ohio and Indiana by 40% and 84% respectively. Median total phosphorus in Grand Forks County was *approx.* five times as high in surface-runoff as in subsurface drain effluent (Stepan, in press). Randall and others (2000) reported that total phosphorus exceeded the minimum detection limit on 40 to 52% of drainage samples, and losses of total phosphorus and organic phosphorus through subsurface drains averaged only 0.012 and 0.005 lb./acre/year (13 and 4 g/ha/year) respectively. Subsurface drainage would be expected to have no adverse impact on ground water quality, and to have a beneficial impact on surface water with respect to phosphorus. In addition, reduction of suspended sediment would be expected from reduced erosion following subsurface drainage.

7.3 Nitrate

Substantial nitrate losses through subsurface drainage have been documented by many researchers (Randall and Mulla, 2001, Mitch and others 2001, Gilliam 1999, Ayars and Tanji 1999). Gilliam (1999) cited work in North Carolina indicating that the average total loss of N from fields nearly doubled with subsurface drainage from 12.3 to 27.8 pounds per acre (13.8 to 31.1 kg/ha), and cited similar results for Georgia, Michigan and Great Britain. Tile-drainage effluent studies in Grand Forks County conducted by Dan Stepan of the University of North Dakota Energy and Environmental Research Center, indicated, similarly, that the average concentrations of nitrate-N in effluent water were about double those of overland flow. Lower crop season precipitation and lower nitrogen applications on common dryland crops in North Dakota (such as small grains and sunflowers) would likely result in lower nitrogen losses through drains than in the Corn Belt states.

In North Dakota nitrate is commonly stratified in ground water, with highest nitrate near the land surface, and decreases approximately logarithmically at depth (Mayer 1992, Schuh and others 1997, Casey and others 2002). The expected result of tile drainage, then, would be that nitrate would be skimmed from the surface of the aquifer and released to surface waters. This, however, would be affected by the depth of the drains and by other chemical and biological processes in the environment of the drains. Ayars and Tanji (1999) have cited research indicating that deeper drains change the characteristics of drained waters, with 30% contribution from deep groundwater in 6-feet (1.8-m) deep drains and 60% contribution from groundwater in 9-feet (2.8-m) drains. Casey and others (2002) have reported that in the Oakes aquifer, Dickey County, ND, nitrate-N concentrations in subsurface drains were less than (77% of) concentrations in monitoring wells at comparable depths. They speculate that the lower nitrate-N may have been caused by denitrification in the environment of the drains. They cite work by Knighton (1997) identifying the presence denitrifying bacteria near the drains. Korom and others (2005) have identified the contribution of reduced iron and sulfide to denitrification in ND ground water. In summary, subsurface drainage generally increases nitrate delivery to surface water, but would likely decrease nitrate loading of ground water.

It has been shown that careful nitrate management practices can minimize nitrate losses through subsurface drains (Mitsch and others 2001). In addition, nutrient delivery to surface waters can be minimized by riparian zones. Gilliam (1999) cite research indicating that up to 90% of nitrate can be removed from waters passing over a 50-m (165 feet) wide grass buffer strip. Nutrients can also be removed by passing drained waters through wetlands (Mitsch and others 2001). Moraghan (1993) demonstrated the utility of a marsh in removing nitrate from tile effluent from the Oakes Test Area in Dickey County, ND. Current research is being conducted on the use of biofilters to remove nutrients from drain discharge waters (Dr. Craig Schrader, ND-MN Subsurface Drainage Forum, Fargo, ND 2/14/08). Water-table management of subsurface drains can also be used to minimize nitrate losses. By maintaining a shallower water table, drainage of nitrate is reduced, nitrate is retained within the reach of crop root recovery, and more reducing conditions above the tile drains will contribute to denitrification before drainage (Gilliam 1999, Ayars and Tanji 1999).

8. DRAIN-WATER MANAGEMENT FOR BENEFICIAL USE

The hydrologic impact of subsurface drainage in glacial aquifers of North Dakota has been described in this report as the augmentation of surface waters through the removal of waters that are normally evaporated and transpired. While subsurface drainage often increases total water entering off-field drainageways on an annual basis, potential flood impacts depend on many factors, including tile effects on soil water holding capacity, the timing of outflows and effects on overland sheet flow. These issues are highly complex and beyond the scope of this report.

With respect to beneficial use, however, we have estimated that in an 18-county study area only about 20% of the area overlies aquifers. While almost all of eastern North Dakota has ground-water, about 80 percent of the area has ground water that cannot be pumped because the water is held in porewater of slow-permeability soils. Subsurface drains in fine-textured soils can, with proper management, provide a means for extracting waters from slow-permeability materials for beneficial use. They can serve as low-head horizontal well fields, capable of removing substantial amounts of water because of their extensive area and consistent drainage over long periods of time. While normally non-pumpable in the ground, these waters can, once they enter surface waters, be recovered, stored and later pumped from storage and be applied for beneficial use. In this sense, tile drainage may, in some cases, actually increase the amount of water available for beneficial use.

There are three related technologies that can facilitate the use of tile-drained waters. These are: (1) artificial recharge and recovery (ARR), (2) surface retention of tile-drained waters, and (3) water-table control.

8.1 Aquifer Recharge and Recovery and Surface Storage

Aquifer recharge and recovery (ARR) is a water management practice by which surplus surface waters are diverted and stored in an aquifer for later recovery. Excess tile-drained waters could be pumped from surface-water bodies and stored for future use. The main limitation of this technology is the requirement for a suitable aquifer, with surplus storage capacity, near the point of diversion from the surface-water body. ARR can be accomplished either by surface spreading or infiltration basins for unconfined aquifers, or by pumping surface water into confined aquifers.

ARR technology is well developed, and has been applied in several instances in North Dakota. Valley City used ARR to store water from the Sheyenne River and augment its well fields during the 1930s. The city of Minot used ARR to store water from the Souris River to augment its wells during the 1950s and 1960s. In the late 1980s ARR through an infiltration basin was investigated for the purpose of storing James River water for irrigation in the Oakes Test Area as a part of the Garrison Project (Schuh and Shaver 1988, Shaver and Schuh 1989). It was found to be feasible with proper management. The U.S. Bureau of Reclamation successfully implemented a surface-spreading ARR project in the Oakes Test Area from 1989 through 1993 (Frietag and Esser 1986). Water was pumped from the James River at high flows during spring to agricultural fields, where it was applied through various means, including spreading through center-pivot irrigation equipment and direct discharge into lowland storage areas for infiltration. Storage for the Oakes irrigation project was enhanced by water-table control using standpipes (Frietag and Esser 1986). ARR was also investigated as a potential method for enhancing irrigation water supplies in the Englevale aquifer using Sheyenne River water (Cline and others 1993). The Energy and Environmental Research Center of the University of North Dakota has investigated the use of ARR for Moorhead, MN (Solc 2001). An ARR facility has been successfully employed by the Forest River Hutterite Community, in Grand Forks County, since 1993, and has stored annually as much as 900 acre-feet of water pumped from the Forest River during periods of high flow in spring.

Subsurface storage of waters mobilized through drainage would require transport to aquifer areas. This could be accomplished where conveyance ditches transverse or pass near aquifers. More commonly, however, transport would be accomplished by drainage to rivers and subsequent transport to areas of active ARR. For example, increased flows from subsurface drainage in the James River basin could be recovered for recharge to the Oakes aquifer; or waters from the Sheyenne River basin could be recovered near Englevale or near West Fargo. Such uses would require detailed understanding of the effects tile drainage on hydrographs and the impact on prior appropriators using surface waters. They would likely, however, be feasible.

8.2 Surface Retention of Subsurface-Drained Waters

Another more limited option is that of surface storage of subsurface drained waters for irrigation use. An advantage of local surface storage is that long-range transport is not required. A disadvantage is that it is land-intensive and losses of water to evaporation are increased. Experiments of storing subsurface-drained waters in basins and reusing them for irrigation were conducted at the Lamberton Research Station in southwestern Minnesota during the 1970s, and current consideration is being given to storage in drainage ditches (personal communication, Dr. Jeff Strock 2/25/08). Other experimental work with surface storage has been conducted in southern Manitoba. The Forest River Hutterite community is currently proposing an experimental surface impoundment for tile-drained waters on their lands in Grand Forks County.

8.3 Water-Table Management (WTM)

Conservation of soil water through "water-table management" is an increasingly important technology where subsurface drainage is practiced. In practicing WTM, head control structures are placed within the drainage system to control water release. Water tables are maintained at high levels following the crop year (fall and winter) to prevent drainage and maximize soil water retention for the following year. In the spring, before tillage and planting, the water-table is then allowed to drain to an appropriate depth to facilitate field operations. A summary discussion of results from work in Illinois, Indiana, Minnesota, Iowa, and Missouri has been provided by Frankenberger and others (August 2006). In addition, in level landscapes Benz and others (1981) have shown that crop yields can be enhanced by maintaining the water table at depths optimal for subirrigation of crop roots. Issues related to water-table management for subirrigation have been discussed by Skaggs (1999). The design and operation of controlled drainage facilities has been summarized by Fouss and others (1999a, 1999b). Water-table control was practiced in conjunction with the Oakes irrigation test area, to retain ARR applied waters in the Oakes aquifer (Frietag and Esser 1986). Controls were affected using standpipes. Following large rains in 1993 and during the wet 1990s the standpipes were removed. However, in some areas large rains overwhelmed the drains and caused flooding. Slow response to standpipe removal was likely exacerbated by design characteristics of the drainage field that included deeper and more-widely spaced drains than commonly practiced. This indicates a need for consideration of adequate drainage rates in designing subsurface drain systems to be used with water-table control systems. A field demonstration experiment for water-table control using tile-drained, and subirrigation using ground water reversed through tile drains is currently being planned for Richland County by the departments of Agricultural and Biosystems Engineering and Soil Science of North Dakota State University (Dr. Xinghua Jia, Dr. Tom DeSutter, Dr. Tom Scherer, Dr. Dean Steele and Dr. David Hopkins).

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APPENDIX A

Summary of North Dakota Drainage Law

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North Dakota State Water Commission

Chapter 61-32 of the North Dakota Century Code regulates drainage in North Dakota. Section 61-32-03 states:

> "Any person, before draining a pond, slough, lake, or sheetwater or any series thereof, which has a watershed area comprising eighty acres or more, shall first secure a permit to do so..."

It further states:

> "If the investigation shows that the proposed drainage will flood or adversely affect lands of downstream landowners, the water resource board may not issue a permit until flowage easements are obtained."

And finally:

> "The state engineer may adopt rules for temporary permits for emergency drainage..."

Rules adopted by the state engineer and included in the North Dakota Administrative Code provide additional insight. In addition to the language presented in the statute, the rules also state that a permit is required before any person may drain by pumping a pond, slough, lake, or sheetwater or any series thereof, having a watershed of eighty acres or more. A permit is required before any person may drain, cause to be drained, or attempt to drain any meandered lake. A permit is required for an assessment drain. A permit is required for the construction of any lateral drain. A permit is also required before any person may modify the drainage authorized in the original permit. Modification of drainage includes deepening and widening of a drain or the extension of any drain, and finally, a permit is required before any person may fill a pond, slough, lake, or sheetwater which has a watershed of eighty acres or more, for the purpose of causing the pond, slough, lake, or sheetwater to be drained by elimination of all or a portion of the existing storage.

The rules also provide insight into when a permit is not required. A drainage permit is not required for maintenance of a drain. Also, the permit requirements listed above do not apply (except for subsection 3 which covers the draining of meandered lakes) to any drain constructed under the direct and comprehensive supervision of certain federal or state agencies. Agencies deemed capable of providing supervision and analyzing downstream impacts include: the State Water Commission, the Army Corps of Engineers, the NRCS (for projects constructed pursuant to the Watershed Protection and Flood Prevention Act), the

APPENDIX A (Cont.)

Bureau of Reclamation (for projects that are part of the originally authorized Garrison Diversion Unit authorized in 1965), and the State Department of Transportation (for federal aid projects.)

The laws requiring drainage permits have changed through the years. If a drain was constructed prior to 1957, no permit was required. If a drain was constructed between 1957 and 1975, a permit was required unless a county drain board existed when the drain was constructed, or the construction was supervised by a state or federal agency, or the project was constructed as an assessment drain pursuant to NDCC 61-21. From 1975 to 1981, a permit was required unless the project was constructed under the supervision of a state or federal agency. Since 1981, a permits has been required unless the drain was constructed under the supervision of the agencies listed above.

The chapter of the century code that regulates drainage in North Dakota is chapter 61-32. However, Chapter 61-15, which deals with water conservation, also mentions drainage. Section 8 of that chapter states:

> "Any person who, without written consent of the state engineer, shall drain or cause to be drained, or who shall attempt to drain any lake or pond which has been meandered by the government of the United States in the survey of public lands, shall be guilty of a class B misdemeanor."

Thus, the State Engineer has a separate authority and responsibility to manage the drainage of any meandered lake. This responsibility is included in the drain permit process; the written consent mentioned here is actually a drain permit approved by the State Engineer.

The first step in obtaining authorization to drain is to file an application with the State Engineer on a form provided by the State Engineer. The application is reviewed for completeness by the State Engineer's staff, the application receives a number, and the information is entered into a data base. The next step is for the State Engineer to make a determination as to whether or not the project as proposed is of statewide or interdistrict significance. The rules provide some guidance as to how that determination is to be made. Consideration is given as to whether is drainage which would affect property owned by the state or its political subdivisions; whether it is drainage of sloughs, ponds, or lakes having recognized fish and wildlife values; whether it is drainage or partial drainage of a meandered lake; whether the drainage which would have a substantial effect on another district; or if it would convert previously noncontributing areas into permanently contributing areas.

The rules also explain that the State Engineer may determine any project to be of statewide significance. As an example, the State Engineer has declared that all drainage in the Devils Lake Basin is currently of statewide significance. The question of whether or not a project is of statewide significance is important because it determines the course of the permit process to be followed. However, the factors to be considered in evaluating an application are the same for all drainage projects. These factors are:

APPENDIX A (Cont.)

1. The volume of water proposed to be drained and the impact of the flow or quantity of this water upon the watercourse into which the water will be drained.

2. Adverse effects that may occur to the lands of lower proprietors. This factor is limited to the project's hydrologic effects such as erosion, duration of floods, impact of sustained flows, and the impact on the operation of downstream water control devices.

3. The engineering design and other physical aspects of the drain.

4. The project's impact on flooding problems in the project watershed.

5. The project's impact on ponds, sloughs, streams, or lakes having recognized fish and wildlife values.

6. The project's impact on agricultural lands.

7. Whether easements are required.

8. Other factors unique to the project.

When projects are determined not to be of statewide or interdistrict significance, the application is forwarded to the appropriate Board. The Board then determines if a public meeting is required and holds one if necessary. The Board shall deny or grant the application with or without modifications or conditions pursuant to the criteria described above. The Board must make their decision within 60 days of receipt of the application from the State Engineer. The Board must provide written notice to all parties of record and to the State Engineer.

The process for applications that are of statewide or interdistrict significance is a bit more involved. The Board must set a time and place for a hearing, and notice must be given by mail at the applicant's expense. The list of those who must be notified is provided by rule and includes potentially impacted landowners downstream and several government agencies that might be impacted. Notice must also be published in a newspaper of general circulation once a week for two consecutive weeks with the final publication being not more than 15 days nor less than 5 days from the date of the hearing. The notice must give the essential facts of the project including the time and place for the hearing.

Additionally, the applicant must provide to the Board all of the documentary information to be submitted during the hearing at least 14 days prior to the hearing, and the Board must make this information available to the public. The information can be made available in the office of the Board if they have an office that is open to the public at least 20 hours a week, or if not, then the information is to be on file with the County Auditor. The hearing must be recorded, either stenographically or electronically. The State Engineer may request a transcript, in which case the cost is borne by the applicant.

APPENDIX A (Cont.)

If the Board votes to deny the application; it is denied. If the Board approves the application it must forward the application along with the hearing record and their determination to the State Engineer, who makes the final decision.

As explained above, NDCC 61-32-03 provides the State Engineer with the statutory authority to develop rules for the issuance of emergency drain permits. These rules are published in Chapter 89-02-05.1 of the North Dakota Administrative Code, and they provide that a license may be issued for up to six months for an emergency. An emergency is defined as:

> "...a situation which if not addressed immediately will cause significant damage to persons or property which would not occur under normal circumstances. An emergency may exist as a result of an extremely wet cycle. However, damages caused by deliberate acts of any individual do not constitute an emergency under this chapter unless the damage can be alleviated without harm to other persons or property."

An application for an emergency drain permit must be written and must include the landowners name and address, a legal description of the land on which the emergency drain will be located, a map showing the location of the drain, an estimate of the surface acreage of the pond, slough, lake, or sheetwater or any series thereof, and the volume of water to be drained by the emergency drain, a list of landowners whose land is adjacent to the course the water drained will take for a distance of one mile downstream, along with the addresses and telephone numbers of these landowners, copies of any written permission received from downstream landowners, a compilation of any written or oral refusals from downstream landowners to give permission, a description of the emergency, and written permission allowing the state engineer and board to inspect the drain.

An application for an emergency drain must be filed simultaneously with the Board and the State Engineer. Both will review the application for completeness and make a preliminary determination as to the existence of an emergency. As soon as possible, a conference call or an onsite meeting among the Board, the State Engineer, and other affected parties must be held and must be electronically recorded. During the call, after all parties have been given an opportunity to present their views, the Board shall make a recommendation to the State Engineer whether or not the license should be granted.

Based on this information, the State Engineer shall decide whether the emergency license should be granted. The license must contain a condition limiting the duration of the license to a time frame of not greater than six months. The receipt of a license for emergency drainage does not relieve an applicant from liability for damages resulting from any activity conducted pursuant to the license.

APPENDIX A (Cont.)

Who can file a complaint depends on whether the drain was constructed before or after January 1, 1975. Only a landowner experiencing flooding or adverse effects from an unauthorized drain constructed prior to 1975 may file a complaint with the local water resource board. Any person can file a drainage complaint about a drain constructed after 1975. All complaints are initially filed with the local board in the county in which the drainage is located. Complaints filed with the State Engineer are forwarded to the board unless the complaint is filed because of board inaction on a complaint.

Upon receipt of a drainage complaint, the board must investigate and make a determination of the facts with respect to the complaint within a reasonable time but not to exceed 120 days. If the board determines that a drain has been opened or established by a landowner or tenant contrary to state law or any rules adopted by the board, the board shall notify the landowner by registered mail and send a copy of the notice to the tenant, if known. This notice must specify the nature and extent of the noncompliance and also state that if the drain is not closed or filled within a reasonable time but not less than 15 days, the board will procure the closing or filling of the drain. The landowner does have the right to demand in writing a hearing on the matter within 15 days of the date the notice is mailed. If after the first complaint, in the opinion of the board, the complaint is frivolous, the board may assess the costs of the frivolous complaint against the complainant.

If the board fails to investigate and make a determination concerning the complaint within the 120-day time limit, the complainant may file a board inaction complaint with the State Engineer if the drain complained of was constructed after january 1, 1987. The State Engineer will then either take action against the board or conduct an investigation and make a determination himself.

Any person aggrieved by an action of the board may appeal that decision to the district court of the county in which the land is located. District courts also have the authority to assess damages and to determine prescriptive rights to drain. Only appeals about unauthorized drains constructed after January 1, 1987, may be filed with the State Engineer. All appeals to the State Engineer must be in writing and must include: the identity of all parties involved; a statement identifying the errors in the board's decision; the petitioner's interest in the board's decision, including a statement of the impact the decision will have upon the petitioner; the relief sought; all facts presented to the board which support the petitioner's position; and a legal description and map of the drain and drainage area involved. Such an appeal must be made within 30 days from the date notice of the board's decision has been received.

Upon receipt of an appeal, the State Engineer reviews the board's decision, ownership of the land on which the drain is located, topographic maps and aerial photographs of the area, any existing surveys of the area, all documentation and testimony given to the board for its consideration, and any pertinent board rules. Once this review is completed, the State Engineer determines whether the information reviewed is sufficient to make a sound decision. If the information is not deemed sufficient, the State Engineer will either return the record to the board for its further investigation or will conduct an investigation himself. If the information is deemed sufficient to make a sound decision, the State Engineer will determine whether the drain has been opened contrary to state law or to any rules adopted by the State Engineer or the board. If it has not, the complaint will be dismissed.

If it is determined that an unauthorized drain is present, the State Engineer will take one of the following actions: he may notify the landowner regarding the noncompliance and require that the drain be closed within a reasonable time but no less than 30 days, giving the affected landowner 15 days from the date the notice is mailed to file a written demand for a hearing on the matter, and if the drain is not closed within the reasonable time limit the State Engineer can procure the closing or filling of the drain and assess the cost against the landowner responsible; the State Engineer may also choose to return the matter to the board to carry out his decision; or the State Engineer may choose to forward the complaint to the State's Attorney for prosecution.

There have been some administrative rules changes from 1998 to the current 2000 version:

1) Factor number 6 in the list of factors to be considered for drain permit applications has changed in that the portion of the sentence referring to the impact on ponds, sloughs or lakes has been deleted to just say the project's impact on agricultural land.

2) The condition which applies to all drainage permits has changed from stating "construction must: Commence within 2 years from the date of final approval" to stating "construction must be completed within 2 years from the date of final approval."

3) A provision for extending the completion date of permits is also new, it states that a permit may be extended beyond 2 years for good cause shown. If the permit was not of statewide or interdistrict significance when it was originally approved, an extension request must be approved by the local board. If it was of statewide or interdistrict significance when it was originally approved, then the extension request must be approved by the State Engineer. No extension may exceed 2 years.

4) A new section was also added, dealing with landowner assessment appeals to the State Engineer. It states that any landowner appeal to the State Engineer claiming no benefit from the construction of a new drain must be made within 10 days after the assessment hearing, must be in writing and must specifically state the facts upon which the claim is based.

5) Title 89-09 of the ND Administrative Code, dealing with wetland restorations, has been repealed.

CO/JSP:1053

APPENDIX B

Estimates of Soil Drainage Using Water-Retention Data

The amount of water drained through a tiled field varies with local hydrology and with changing drainage status over time. If the water table is deep, usually greater than six feet on sands, the fraction of drainage for each increment of drawdown will be approximately constant and equal to the storativity, S, of the aquifer. These are commonly in the range of 0.1 to 0.15 for fine sands, and between 0.15 and 0.3 for medium sand through gravel. For loamy soils they are more commonly between 0.05 and 0.1. If the water table is shallow (between the surface and about six feet on sands) the fraction of drainage per unit of water table-table recession will be determined by the water retention curve corresponding to the capillary relationship between the water table and land surface. These vary between zero at land surface and S at about six feet below land surface. If the water table is above land surface (ponded), the fraction of water drained for each increment of water-table recession above land surface will be one. It will revert instantaneously to the capillary relationship when the water table drops to land surface. These relationships are described schematically for a water-table before drainage on Fig. B-1.

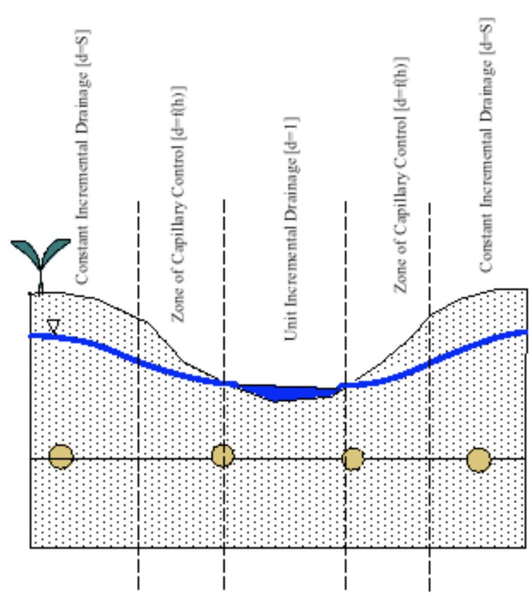

Figure B-1. Soil and landscape controls on incremental drainage.

APPENDIX B (Cont.)

Capillary Controls on Soil Drainage

When a soil is desaturated, as during drainage, the retained water is held under negative pressure, or matric potential. The scalar of the pressure head is often expressed in positive numbers as a "suction" head (h). For any soil, the amount of water retained (volume of water/volume soil, or θ), can be identified by a corresponding h. The closer h is to 0, the wetter the soil, and conversely as the soil dries, higher suctions correspond to lower water retention. This is normally characterized using a "moisture-retention" curve, θ(h). Moisture-retention curves for the sandy topsoil of the Hamar soil series, and the loamy topsoil of the Gardena series are shown on Fig. B-2A. Sands have more large pores, and thus release water quickly in the low suction range, while finer soils have less large and more smaller pores and release water more gradually.

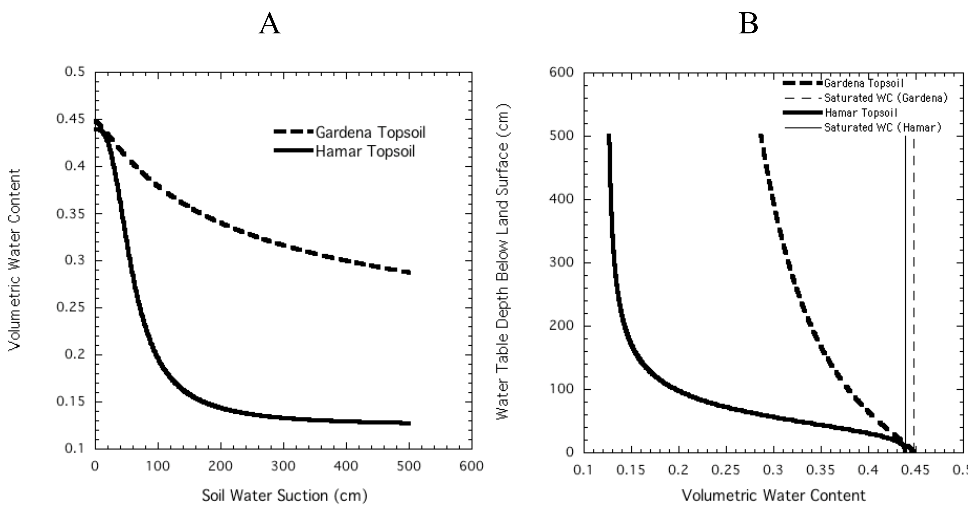

Figure B-2. Comparison of the soil-volumetric moisture-retention vs. pressure-head curve (A) with a homogeneous soil moisture profile above a water table (B).

The soil-moisture retention curve can be used to characterize the soil moisture profile when it is in equilibrium with the water table. Soil water flux, q (cm/h) is expressed as:

$$q = K\left[\frac{(h_i - h_w) - (z_i - z_w)}{(z_i - z_w)}\right] \qquad \text{(A-1)}$$

APPENDIX B (Cont.)

where h_i is the soil water suction at depth z_i, h_w is the soil water suction at the water table (depth z_w), K is the hydraulic conductivity (cm/h), $\frac{(h_i - h_w)}{(z_i - z_w)}$ is the suction gradient and $\frac{(z_i - z_w)}{(z_i - z_w)}$ is the gravitational gradient. This can be manipulated to:

$$\frac{q}{(z_i - z_w)K} = (h_i - h_w) - (z_i - z_w) \qquad \text{(A-2).}$$

When the soil moisture is in equilibrium with the water table, q=0. If we choose our reference datum as the water table, $z_w = 0$, and since soil is saturated at the water table $h_w = 0$. Then, $0 = h_i - z_i$ and $h_i = z_i$. Because suction equals the distance above the water table at equilibrium, the soil moisture profile can be represented by simply inverting the soil moisture curve with saturated moisture content θ_s at the water table, and plotting θ_i for each distance z_i above the water table where $h_i = z_i$. This inversion is shown on Fig. B-2B.

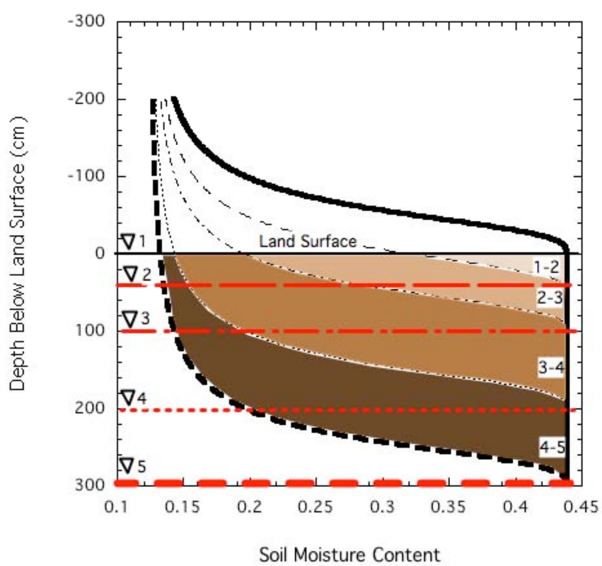

Figure B-3. Illustration of incremental drainage with receding water table from land surface to 50, 100, 200 and 300 cm depths.

APPENDIX B (Cont.)

Because the soil-moisture retention curve is non linear near saturation, drainage (D) resulting from lowering the water table varies greatly with initial water-table depth below land surface. This relationship has been described by Gillham (1984). Incremental drainage for each incremental change in water-table depth can be calcutated as:

$$D = \int_o^t \int_{h_i}^{h_{i+1}} \frac{\partial \theta}{\partial t} dhdt = \int_o^t \int_{Z_i}^{Z_{i+1}} \frac{\partial \theta}{\partial t} dzdt \qquad \text{(A-3)}$$

This is illustrated on Fig. B-3 for a Hamar sandy loam using topsoil moisture-retention curves. Drainage intervals are: (1) Water table (WT) at land surface then drained to 50 cm below land surface (bls); (2) WT drained from 50 to 100 cm bls; (3) WT drained from 100 to 200 cm bls; (4) WT drained from 200 to 300 cm bls. The total amount of water drained in each case is shown by the corresponding colored area. It can be seen that the incremental drainage near land surface is initially small, and that as the water table lowers there is an incremental increase in drainage volume. This difference occurs because of the truncation of the water retention curve near land surface. As the water table lowers, the dry ranges of the water retention curves eventually converge (left side of Fig. B-3). At and below the convergence depths incremental drainage will be approximately constant. For sands this constant increment is defined as the storage coefficient. Convergence is illustrated by drainage step 4-5 on Fig. B-3. Increasing incremental drainage with each incremental drop in a water table beginning at land surface is shown on Fig. B-4 for the Hamar and Ulen soils. For the first foot (30 cm) of declining water table, there is almost no drainage. Only when the water table is dropped beyond two feet (about 60 cm) does drainage become substantial. Incremental drainage corresponding to relatively constant storage coefficients are definable for drainage beyond three feet (61 cm). They are quantified as the linear coefficients (0.25 for the Hamar and 0.19 for the Ulen) in the regression equations.

The simplified cases shown in Figs. B-2 and B-3 assume a single representative water-retention relationship for the entire soil profile. In reality, most soils are stratified with different moisture-retention properties between layers. Thus, one layer may retain more water at a higher suction than another at lower suctions. Saturated and equilibrium soil-moisture profiles for six stratified soils having an initial water table at land surface (saturation moisture) and a final water table at 100 cm below land surface (equilibrium moisture) are shown on Fig. B-5. They include the Arveson sandy loam (Coarse-loamy, mixed, superactive, frigid Typic Calciaquolls), Ulen sandy loam (Sandy, mixed, frigid Aeric Calciaquolls), Hamar loamy sand (Sandy, mixed, frigid Typic Endoaquolls), Stirum sandy loam (Coarse-loamy, mixed, superactive, frigid Typic Natraquolls), soils commonly overlie unconfined glacial aquifers in areas having seasonally high water tables. The Eckman silt loam (Coarse-silty, mixed, superactive, frigid Calcic Hapludolls), and Gardena loam (Coarse-silty, mixed, superactive, frigid Pachic Hapludolls) do not have seasonal high water tables, but are used to represent some of the finer soils, like the Wyndemere or Bearden series, that may overlie some unconfined glacial aquifers. Field measured soil-moisture retention curves were measured by Schuh, Cline and Sweeney (1991).

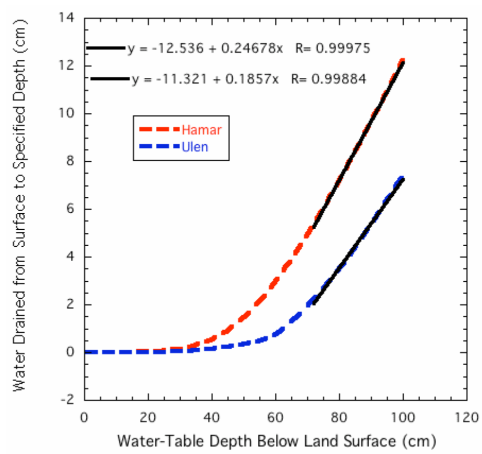

Figure B-4. Cumulative drainage for incremental declines in a water table below land surface.

APPENDIX B (Cont.)

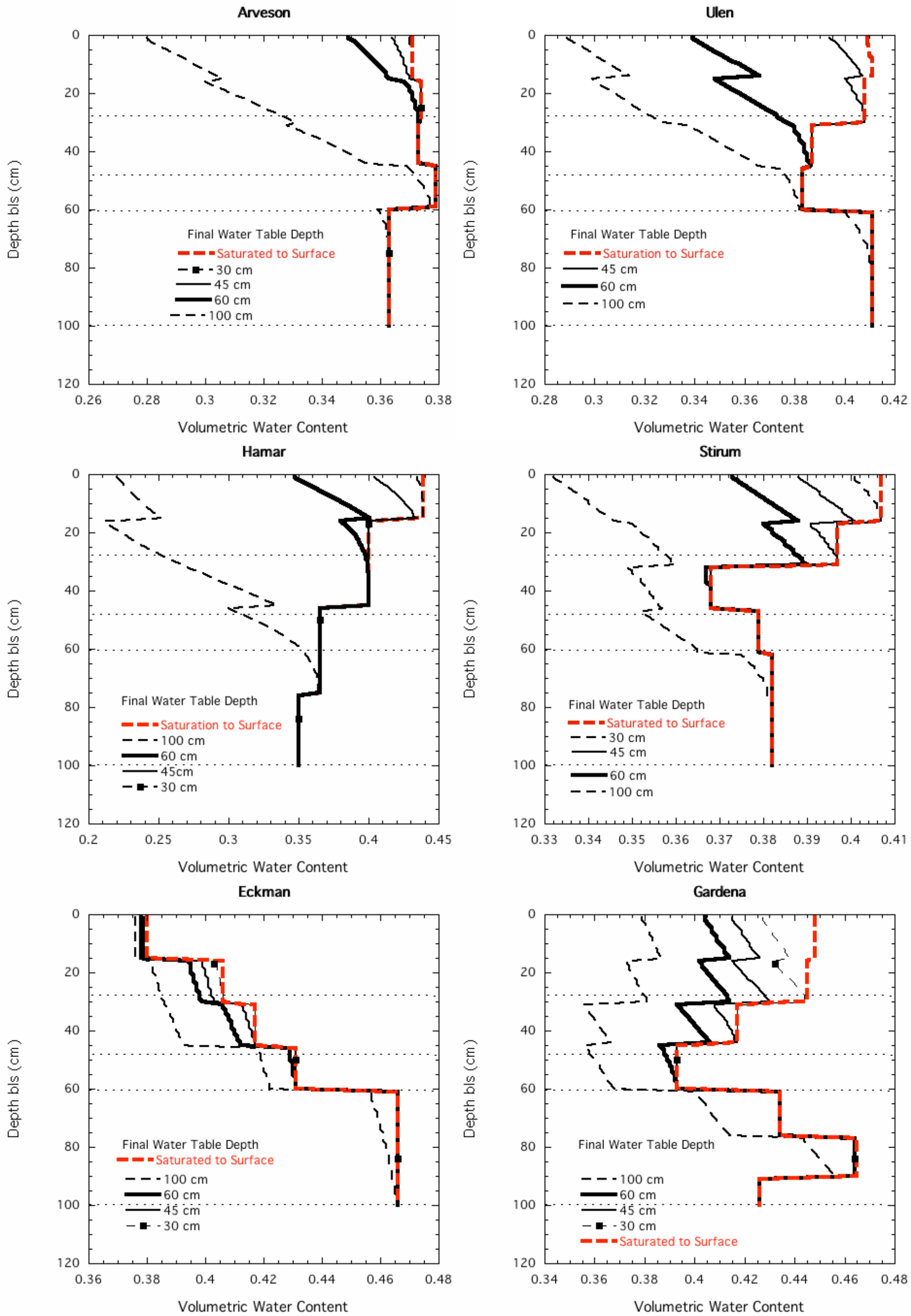

Figure B-5. Equilibrium soil volumetric water content distribution for soil profiles saturated to the land surface, and with water tables at 30, 45, 60 and 100 cm below land surface. Soils illustrated include the Arveson sandy loam, Ulen sandy loam, Hamar loamy sand, Stirum sandy loam, Eckman silt loam , and Gardena loam.

APPENDIX B (Cont.)

Total drainage consists of the areas between the full saturation profile and the equilibrium soil-moisture profile with the water table at 100 cm below land surface. It can be seen that the incremental drainage from dropping the water table one foot (30 cm) is very small, but increases with each successive deeper drainage step. Incremental changes in drainage are shown on Fig. B-6.

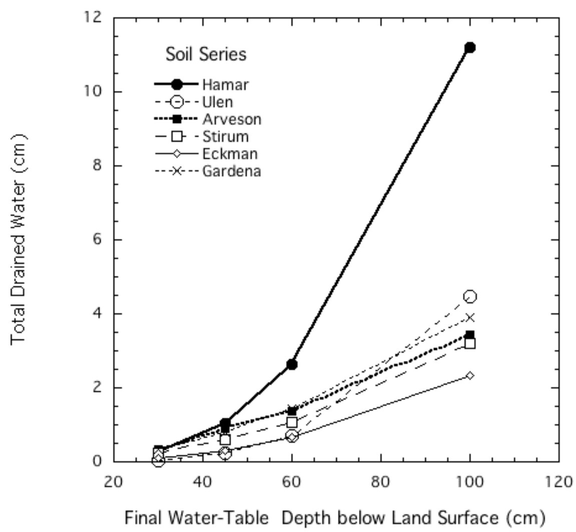

Figure B-6. Incremental drainage to varying depths, from a soil initially saturated to land surface, on six representative soil profiles.

Calculated incremental drainage for varying initial and final water table depths on six soil series examples are provided on Table 1 (in the main report). Total drainage from land surface to 100 cm (about 39 inches) is, on the average, between four and six cm (about two inches). The average fractional drainage for the top three feet is about 0.05. These would be the expected drainage losses. The contribution of short-term ponded waters in some landscape positions would add slightly to the overall average. Drainage from neighboring well-drained soils may vary depending on landscape and local hydrologic conditions.