Potential Effects of Subsurface Drains on the Beneficial Use of Water in North Dakota. Addendum: Special Cases

By
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Water Resources Investigation No. 45A
North Dakota State Water Commission

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EXECUTIVE SUMMARY

Special cases of potential tile drainage impairment of the beneficial use of groundwater are examined.

1. Perforated pipe is sometimes placed below the water table between the collector/lift station for a drainage project and the final discharge point to offset buoyancy problems during construction. When an uncontrolled perforated pipe is placed below the water table of an aquifer, it functions as a horizontal well and will drain continuously, even when the design drain field is not flowing. For a drain field overlying an aquifer discharging to a river, the perforated pipe, in penetrating the alluvium bordering the river, will create an artificial spring, constantly draining the aquifer. Losses will be proportional to the length of the pipe, and can be substantial, depending on local circumstances. Perforated pipe should not be used, or when its use is necessary a final control structure should be placed near the final discharge point to prevent non-beneficial diversion of water when tile drains are not active.

2. Subsurface drains placed in fields overlying shallow artesian aquifers may increase the non-beneficial loss of water. Factors affecting losses are complex, and include the hydraulic conductivity of the aquitard overlying the aquifer, the thickness of the aquitard, the amount of pressure head at the lower boundary, climate, and the size of the drainage project in relation to the extent of the aquifer. Potential impact varies considerably with these factors. For example, drainage of small localized seeps would usually be of negligible impact. Drainage of land affected by slow advective seepage from deep confined aquifers having high pressure, like the Dakota Fm. in eastern ND, which can cause widespread salinization in some areas, would be recovered from evapotranspiration and seepage, and would be negligible as well as beneficial from the standpoint of land reclamation. Similar effects would be expected from deep confined glacial aquifers affected by bedrock pressure. Drain losses could also be pre-empted for beneficial use by pumpage.

   Most impact would occur where the artesian aquifer is of small extent and has little saturated thickness, such as shallow confined coarse lenses encased within till, or underlying local lacustrine deposits in lowlands overlying aquifers with upslope recharge. For locally recharged small aquifers, artesian head is usually small, and decreases in head caused by drainage will be mitigated by local substitution of drain water for previous seepage and in some cases, evapotranspiration. In addition, decreases in aquifer pressure cannot exceed the difference between the elevation of the artesian pressure head in the recharge area and the elevation of the drains, usually not more than a few feet. Where artesian head in the area of the drain does not exceed a few feet above land surface, design inclusion of a lift station having a top elevation above the elevation of the local artesian head would enable curtailment of drainage, should unreasonable adverse impact be determined to occur. A final control structure which can control drainage is a valuable management tool.

An additional potential drawback, depending on design, of drainage under artesian flux conditions would be that areas affected by substantial artesian upflux would not be effectively drained using designs based on climate and watershed-based drainage coefficients, and would remain wet.

3. In some cases, shallow wells placed in confined sand and gravel deposits near and upgradient (usually upslope) of a large drainage project, may lose some pumping capacity through loss of available drawdown. This would be expected only where the well-screen placement is so shallow that the loss of a few feet of head would be critical. In most cases this can be remedied deeper pump settings, or by constructing a deeper well.

Drainage itself is a beneficial use with respect to land management, and drainage benefits must be weighed against potential loss of other beneficial uses. Drain and outlet designs should minimize unnecessary (non-beneficial) losses, such as demonstrated aquifer drainage caused by submerged perforated discharge pipes without final control structures. Appropriate control structures at drain outlets can usually be used to prevent, manage and mitigate unnecessary or excessive losses. North Dakota water appropriation law does not protect inefficient capture systems, such as sand point wells, placed near land surface from loss of available drawdown caused by other uses. Isolated cases of potential impact on shallow domestic wells have been reported, but no evidence of widespread occurrence has been brought forward. In cases of shallow well impairment, separation of drain effects from those caused by climatic variation and pumpage for irrigation and other uses is difficult. Inconvenience of lost available drawdown for domestic wells in isolated cases can occur, but has not been established as but must be weighed against all factors affecting local water availability options and drainage benefits.

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INTRODUCTION

The 60th Legislative Assembly of the State of North Dakota directed the North Dakota State Water Commission to:

"study, develop, and recommend policies for assessing the impact of tile drainage on the beneficial use of water by prior water appropriators."[1]

The results of that study (Schuh, 2008) were presented to the Interim Natural Resources Subcommittee in August of 2008.

The general conclusions, summarized in the Executive Summary, were that tile drainage does not pose a substantial threat to the beneficial use of groundwater in either of confined or unconfined aquifers. I will not review here the analysis or reasons leading to those conclusions, leaving them to the report itself, except to state that after further examination I still hold those conclusions to be fundamentally sound.

As in all general conclusions, however, the problems are usually in the details, and there are circumstantial cases of risk that can occur. The purpose of this addendum is to further examine three risk cases that have been brought forward. These include: 1. Situational creation of artificial springs through certain tile project outlet designs; 2. depletion effects of tile drainage in a shallow confining cap overlying an artesian aquifer; and 3. possible impairment of local shallow wells.

[1] Senate Bill 2020, Section 11 of the 60th (2007) Legislative Assembly of the State of North Dakota.

PERFORATED DRAIN PIPE AND CREATION OF ARTIFICIAL SPRINGS

One issue of concern is the use of perforated drain pipe for discharge from a drained field overlying an aquifer to a river or stream. The problem occurs when an extended length of perforated pipe is placed below the water table in a shallow aquifer at the discharge end of the drainage field, after a control structure (ex. lift station) and through the fine materials bordering the stream. Contractors may use perforated pipe because of flotation problems that make it difficult to place the non-perforated pipe below the water table.

The maintenance of head in a shallow unconfined aquifer intersected by a stream depends on impeding fine materials between the river and the aquifer, limiting seepage. In many cases, impeding materials consist of river alluvium deposited on river banks and terraces during floods as the river incises into the substratum. Gaining streams receive aquifer water through bank and bed seepage, or through springs that occur at breaches in the border materials. Placement of the perforated pipe through the alluvium creates a breach, hence an artificial spring. In addition, depending on the length of the drain pipe within the aquifer in the uncontrolled discharge segment, the perforated pipe can act as a horizontal well, gathering water and feeding that artificial spring. Waters drained from an aquifer in this manner are incidental to the goals of upslope drainage, provide no direct drainage benefit, and represent non-beneficial losses of usable water. A general schematic of the problem is shown on Fig. 1.

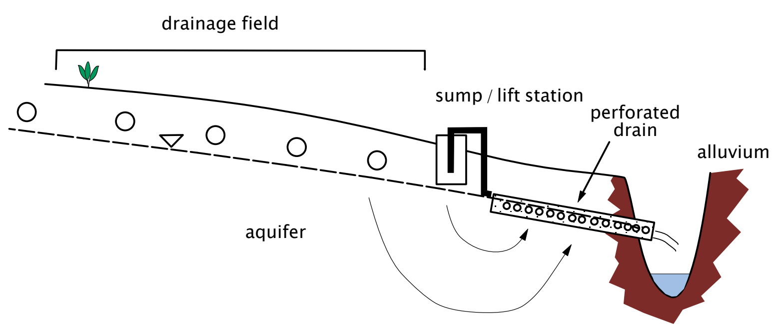

Figure 1. Schematic illustration of uncontrolled drain field discharge through a perforated pipe.

Creation of an Artificial Spring: The Venlo Drain

A tile drainage project consisting of six quarter sections was constructed in T135N R54W, east of the Sheyenne River 8 miles east of Lisbon, ND (Fig. 2). The site is referred to as the Venlo site, from the abandoned Venlo town site, just east of the east border of the drain field.

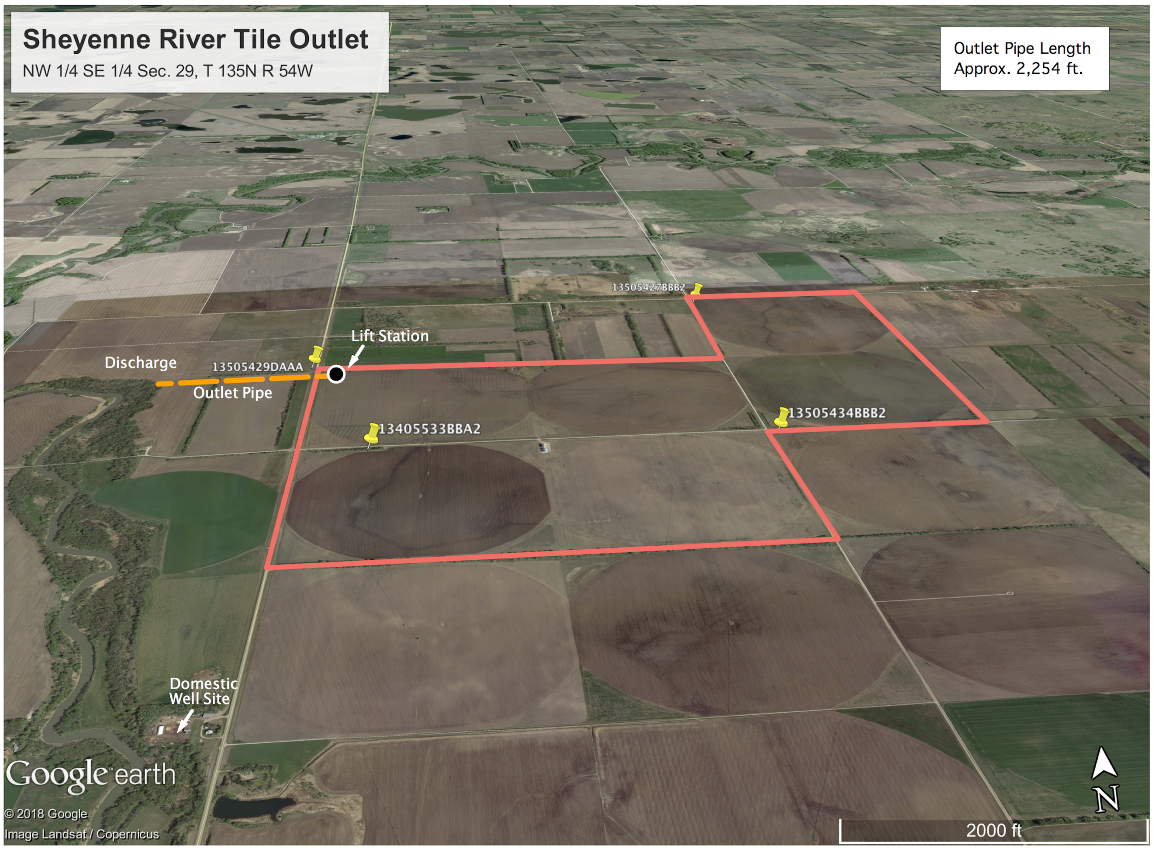

Figure 2. Location of Venlo drain field and discharge.

All subsurface drainage at the Venlo site is directed to a lift station (Fig. 3) in the northwest corner of the SW ¼ of Section 24, from which it is (pumped) through a perforated 16-inch diameter pipe 2,254 feet to the Sheyenne River valley, where it is discharged to the river.

Figure. 3. Sump and lift station for the Venlo drainage project.

The outlet to the river has been flowing steadily since construction of the well field (Fig. 4). For most of that time, the lift station has not been pumping, so that the observed outflow is entirely through the perforated pipe. Outflow on July 22nd, 2015 is shown on Figure 4.

Figure 4. Outflow from the Venlo discharge to the Sheyenne River, July 22, 2015.

To determine the amount and variability of discharge and hydraulic factors affecting discharge rates, the U.S. Geological Survey, under contract with the North Dakota State Water Commission, placed an H-flume[2] at the outlet (Fig. 5) in late April of 2017 and measured continuous outflow through October of 2017.

Figure 5. Outflow from the Venlo discharge site through the U.S.G.S. Gage, October 30, 2017.

Discharge (Q) measurements for a reading frequency of 15 minutes are shown on Fig. 6, with water-level elevations measured in four area monitoring wells shown on Fig. 1. Discharge was about 0.17 cfs (about 75 gallons per minute) on April 20, increased until early May, and thereafter fluctuated between a minimum of 0.23 to a maximum of 0.28 through May and early June, usually 0.25 and 0.26 cfs. Outflow then gradually decreased to a steady 0.1 cfs in September through October. Discharge trends corresponded closely with water levels in four area wells at varying distances from the outlet pipe. Of these the well location 13505429DAAA is closest to the perforated outlet pipe. Discharge and aquifer water-level elevations were all closely approximated using third-order polynomial regression functions shown on Fig. 6.

[2] USGS 462841097295101 Tile Drain 1 near Venlo, ND, https://waterdata.usgs.gov/nd/nwis/uv?cb_00045=on&cb_00060=on&cb_00065=on&format=gif_default&site_no=462841097295101&period=&begin_date=2017-04-14&end_date=2017-04-21 ; accessed Oct. 17, 2017

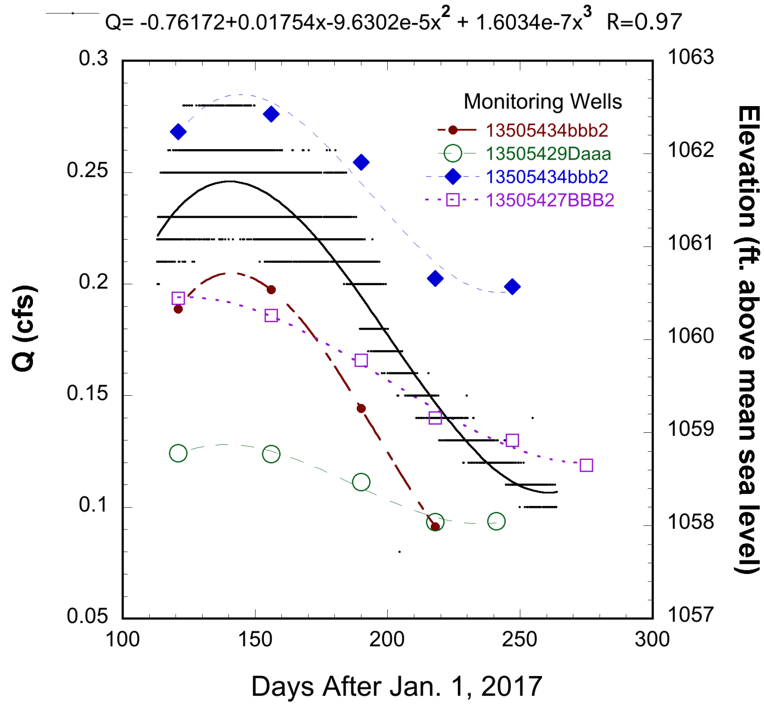

Figure 6. Discharge from the Venlo drain discharge outlet, and elevations for water levels at four local observation wells, April through October, 2017.

The third order polynomial equation shown on Fig. 6 was used to calculate simulated Q for each of the days corresponding to each of the monitoring well measurements. Simulated Q was then plotted vs. water level elevations for each of the wells. Results were the linear relationships shown on Fig. 7. The relationship between discharge from a single drain and the water-level elevations driving that discharge is normally approximated, using Dupuit-Forchheimer assumptions, by an elliptical $(h_1^2 - h_0^2)/L$ function of the difference between the square of the elevation (h_1) above an impermeable layer of the water at distance, L, and the square of the drain elevation (h_o) (Bear 1972, p. 367). However, the monitoring wells cited cannot be interpreted directly using a drain function, because local depths to the impermeable layer at the drain and nearby monitoring wells are unknown.

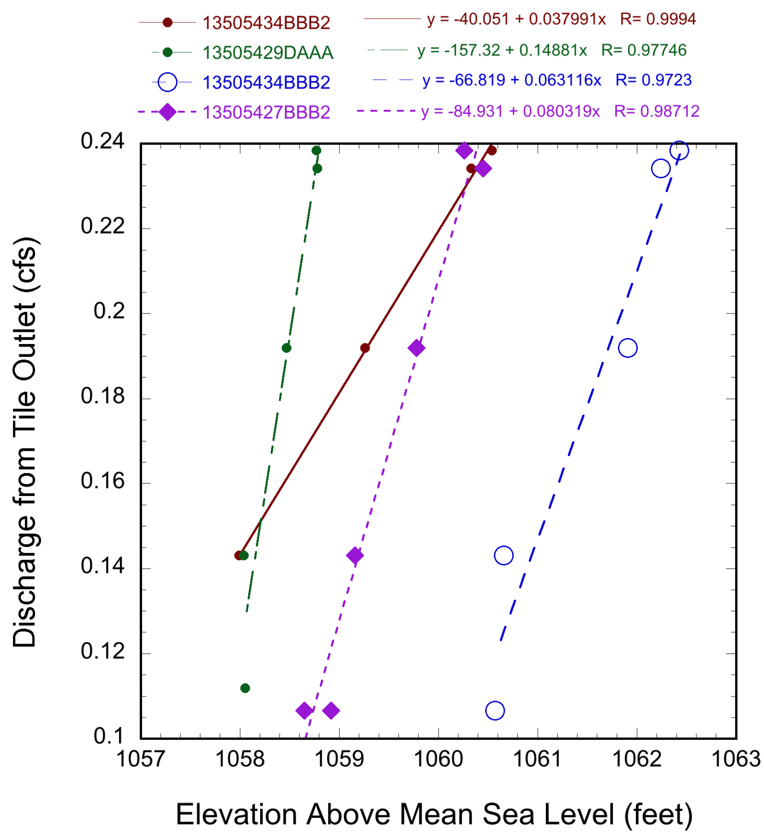

Figure 7. Relationships between drain outlet discharge and local observation well elevations.

All of the monitoring wells analyzed were installed in 2005. A historical record of their water levels is shown on Fig. 8. Water levels in all wells exhibited a downward trend following 2015. Flow lines to a drain are tightly arrayed, with most of the inflow from the surface occurring within a few feet of the drain (Schwab et al. 1966, p. 419). There is insufficient local lithologic information (aquitard depths) to support more detailed analysis of drain flux. However, there does appear to be an initial direct impact of the drains on water levels near the perforated drain pipe. The well closest to, in fact in the immediate area of the perforated drain (13505429DAAA, see Fig. 1) exhibited the greatest decrease of 6 ft. elevation beginning in November of 2014 and continuing through 2015, indicating probable direct impact of the drain. The second greatest decrease in water level elevation in 2015 was measured in the well next closest to, but about a half mile from the drain (13505429DAAA, see Fig. 1).

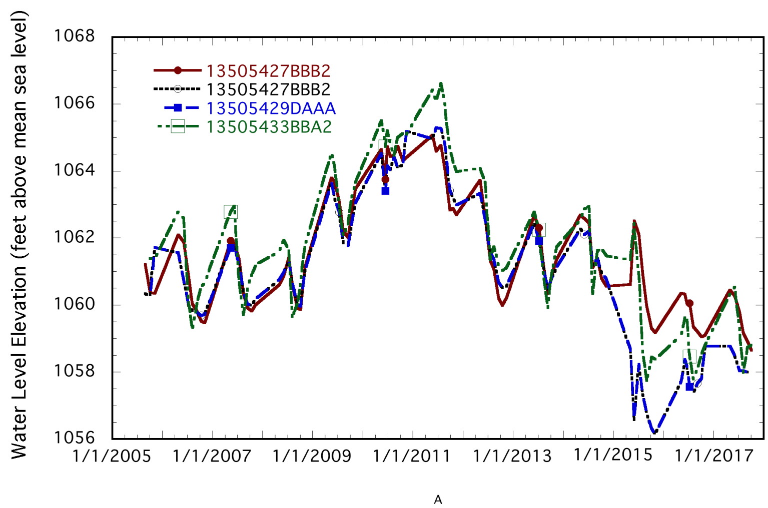

Figure 8. Water level elevations for local observations wells from 2005 through summer, 2017

Because of many factors influencing local water levels, including climate, pumping, evaporative discharge from depressional areas, natural springs, and river-bed seepage, the drain-outlet pipe cannot reliably be considered the primary cause of changes in water table elevations. There is, however, sufficient evidence to approximate drainage losses using the relationships indicated for drain-outlet discharge vs. aquifer water elevations at all of the observation wells. An appropriately conservative interpretation is to treat the discharge and well observations as a surrogate correlation of the overall head condition of the aquifer, represented by monitoring wells of varying distance from the drain, with drain discharge. Drain discharge follows the general conditions of the aquifer itself, as clearly shown on Fig. 7.

Assessment of Water Loss

The mean measured discharge for 2017 (April 21 through Sept. 24th) was 0.186 cfs. Assuming the relatively constant low-end value of 0.1 cfs through the remainder of the winter, an annual mean Q estimate for April 21, 2017 through April 21, 2018 would be [$Q_{2017-2018}$ ~ (150 days x .186 cfs + 215 days x 0.1 cfs) x 86,400 sec/day) / 365 days = 0.135 cfs. This would yield 98 acre feet of annual total discharge through the drain.

However, water level elevations during 2016 and 2017 were the lowest water levels recorded, dating back to 2005 (Fig. 8). Using the linear relationships (Fig. 7) maximum estimated Q values are shown on Table 1. They would range from 1.21 cfs for the well nearest the drain to common values of about 0.5 cfs for the other three wells. If the maximum value were sustained for an entire year (an unlikely scenario) a scaled median annualized loss of about 400 acre feet would be predicted. Using the median of all monthly water level values for each well (collected April through October), a median loss of about 200 acre-feet per year would be estimated for the time period 2005 through 2017 using the three concurring estimates. Again, the closest well would predict about double that. In general, based on 2005 through 2017 data, a minimum annual loss of about 100 acre-feet, and an overall annual loss of about 200 acre-feet per year, or about 2,500 acre feet total for the 11-year time period is estimated. This would be enough water to irrigate about 300 acres annually based on an average use of 8 inches per year. These long-term estimates are based on extrapolation of the linear functions. All of these estimated losses are predicted for the perforated drain between the final lift station and the outlet during conditions of no-flow from the tile drains, and are therefore perennial. They do not count water from drainage fields.

Table 1. Estimated annual outflow from the discharge pipe calculated from the maximum, and long-term mean annual Q values.

Well Location	$El._{max.}$ ft.	Q_{max} cfs	$El._{med.}$ ft.	$Q_{med.}$ cfs	An. $Q_{max.}$ acre-ft.	An. $Q_{med.}$ acre-ft.
13505429DAAA	1065.3	1.21	1060.96	0.56	875	407
13505433BBA2	1066.62	0.47	1061.4	0.27	341	198
13505434BBB2	1067.97	0.59	1063.175	0.28	425	206
13505427BBB2	1065.07	0.61	1061.1	0.30	445	214

Potential Drought Losses: Limits of Loss

A second issue of interest concerns potential limits of loss. This is of special concern, as it relates to extended periods of drought and aquifer depletion in which non-beneficial drainage losses from the aquifer would be particularly harmful. First, for non-beneficial loss to occur, the water must be above the bottom of the perforated pipe. Local water levels in relation to the drain are unknown, and future predictions of decoupling the drain pipe would be difficult to predict based on elevation knowledge alone.

An approximation can be attempted using the extrapolated linear head relationships which are interpreted as indirect covariance between discharge and aquifer water levels, rather than direct causal relationships. Water level elevations at which drain loss would cease (Q = 0 cfs) are estimated by dividing the regression intercepts of each monitoring well by the coefficients (Table 2). Somewhat surprisingly, given the variations in slopes, they all concur at about 1059 ft. amsl +/- one foot. This would correspond to a maximum water level elevation drop of 2 to 6 feet before decoupling, based on the May 2017 water level elevation reference point. Based on a median long-term (since 2005) water elevation for all four wells it would range from about 4 to 7 feet from the median elevation to the decoupling elevation. Thus, based on extrapolation of the linear estimates, as water levels decline during an extended drought, loss through the perforated drain would likely become negligible. This, however, is the determination for the Venlo drain, and the extended effects may be larger or smaller for other situations.

Table 2. Estimated elevations for observation wells corresponding to the extinction of discharge (Q = 0).

Well Location	Initial El.	Initial Date	Final El.	Final Date	Δ El. i-f		Int.	Coeff.	Q=0 El.	Δ El. Q=0
	ft.		ft.		ft.	ft.	ft.	cfs/ft.	ft.	ft.
13505429DAAA	1058.78	5/2/17	1057.92	10/3/17	-0.86	2094	-157.32	0.1489	1057.19	1.59
13505433BBA2	1060.33	5/2/17	1058.82	10/3/17	-1.51	3221	-40.051	0.03799	1054.22	6.11
13505434BBB2	1062.24	5/2/17	1060.39	10/3/17	-1.85	7887	-66.819	0.06312	1058.67	3.57
13505427BBB2	1060.45	5/2/17	1058.65	10/3/17	-1.8	8060	-84.931	0.08032	1057.42	3.03

Summary

The Venlo drainage field, in using perforated pipe from the sump to the outlet, has effectively created an artificial spring to the Sheyenne River. In addition, the perforated pipe has created an extended drain which acts as a horizontal well, gathering water and feeding that artificial spring at a rate of about 100 to 200 acre-feet per year. Water losses, while not large, are significant and non-beneficial. Losses would likely become negligible under extended drought conditions. A remedy for the losses, and awareness of the potential problem for avoiding aquifer losses under similar situations at other locations is desirable.

Potential Solutions

One potential solution to avoid artificial spring formation is avoiding using perforated pipe as a conduit from the last control structure to the outlet.

A second potential solution would be the placement of a final control structure (ex. gate valve with a sump having sufficient elevation to equalize upstream pressure head when the upstream lift station is not operating, etc.) near the outlet point, near the upstream boundary of the fine alluvium.

Some considerations for placement of a final control structure, illustrated on Fig. 9, would be as follows:

1. The ideal location of the control would be exactly at the boundary of the alluvium [Fig. 9(c)]. This location would stop all drainage loss. However, in a natural system exact boundaries are difficult to define.
2. Placement on the downstream end of the pipe within the alluvium would possibly cause seepage and erosion around the pipe within the alluvium [Fig. 9(e)]. This would be caused by transfer of pressure head from the aquifer through the perforated pipe into the surrounding materials, inducing outflow through the perforations. This could be avoided by using non-perforated pipe within the alluvium for an appropriate distance (to the boundary of the alluvium) upstream of the control structure.
3. At any location between the sump and the alluvium [Fig. 9(d)], if the aquifer materials are similar, the decrease in drainage loss through the perforated pipe should be decreased approximately linearly with the decrease in the uncontrolled length. Drainage to a single drain would be approximately represented by the Dupuit-Forchheimer relation:

$$Q = \frac{K}{2}\frac{(h_1^2 - h_o^2)}{L} \qquad (1)$$

where K is the hydraulic conductivity and h_1, h_o, and L are as defined above (Bear, 1972)[3]. Units for Eq. 1 are in discharge per foot of drain. Thus, a control at any intervening distance

[3] Bear, Ibid

between the sump and the outlet should be beneficial. Because of difficulties in locating the exact contact with the alluvium, placement of the control as near to the alluvium boundary as possible without placing within it, or placing the control within the alluvium but using only non-perforated pipe immediately upstream of the control structure between the control and the aquifer would likely be the best options. While some seepage may occur, it could reasonably be limited to an inconsequential amount. Any shortening of the uncontrolled perforated pipe length (submerged length of discharge pipe after the lift station) would be beneficial in minimizing the non-beneficial discharge. Other solutions may be offered by those having expertise in tile-drainage design.

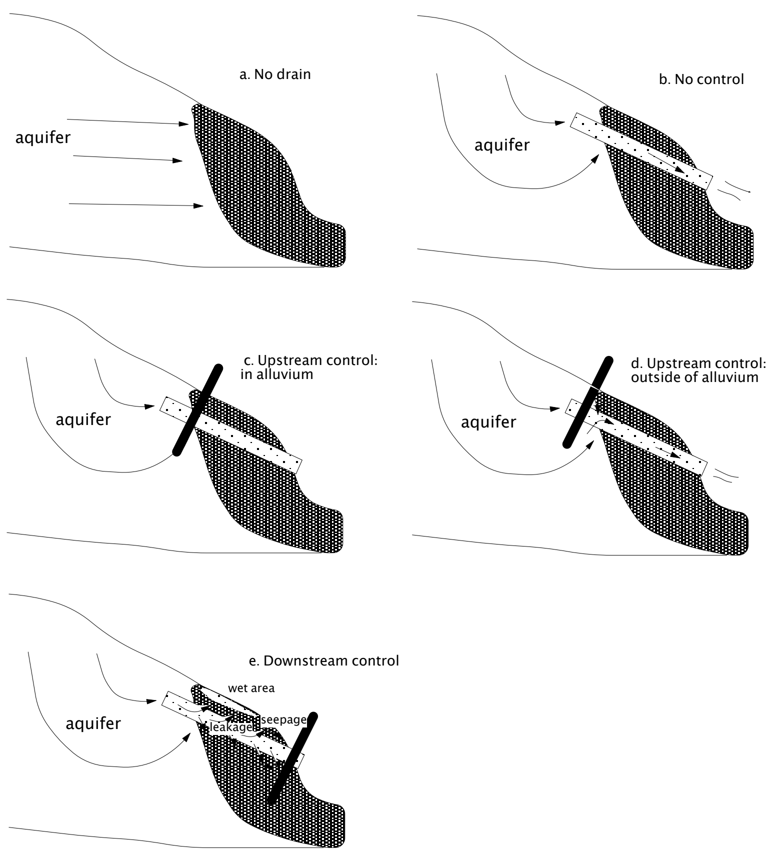

Figure 9. Illustration of possible terminal control scenarios for minimizing aquifer water losses when perforated pipe between the drainage field, through confining materials to a stream.

POTENTIAL EFFECTS OF TILE DRAINS IN CONFINING CAPS OVERLYING ARTESIAN AQUIFERS ON THE BENEFICIAL USE OF WATER

Different from unconfined aquifers, wherein water removal through shallow drains is limited by the drain elevations, drains in confined aquifers will flow continuously if the local artesian pressure of the aquifer is above the elevation of the drains. Drains under these conditions are functioning as horizontal wells driven by the pressure head of the underlying aquifer.

Artesian pressure conditions occur when an aquifer recharged upslope is locally confined beneath a low-permeability cap. Local water pressure, driven by upslope pressure and overburden pressure, is higher than the upper boundary of the aquifer (Fig. 10). The local pressure head pressing on the bottom of the confining layer, if measured by a piezometer placed in the aquifer, may be at any depth within the cap, or above land surface. In some cases of confined bedrock units, such as the Dakota Formation in eastern North Dakota, and in deep overlying glacial aquifers connected to the Dakota aquifer, the pressure head tapped by a well can be tens of feet above land surface. This case is not applicable for evaluation of tile drainage impact because of the thickness of the confining layer. In agricultural areas of eastern North Dakota the piezometric head is usually below land surface, and seldom more than a few feet, often less than five feet, above land surface, fluctuating with climatic effects on upslope recharge areas and pumpage.

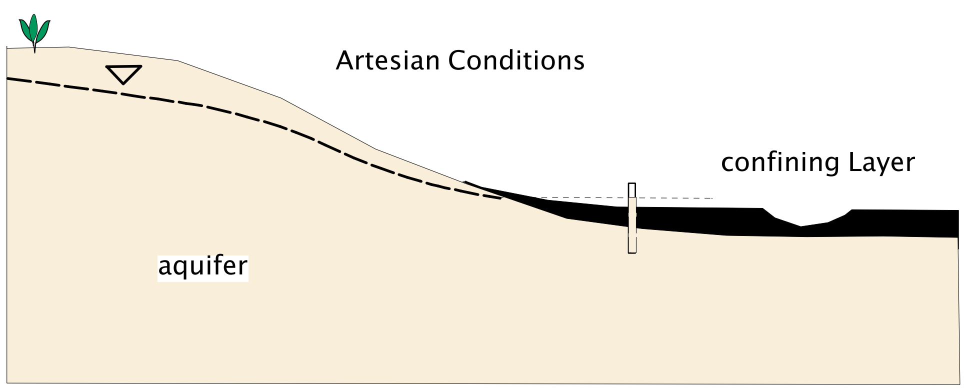

Figure 10. Illustration of a locally confined aquifer with artesian pressure head.

In a confined aquifer at quasi-steady state (quasi because transitional states of some degree are almost always operating due to climatic flux) recharge (R) and discharge (D*) are approximately balanced (R~D*). Using a simplified illustration, for a flow path at steady state with constant recharge (R) along the flow path, piezometric head (h) above an impermeable layer at any distance, x, from a constant head boundary (the discharge point at x_o) to a groundwater divide (upper recharge length boundary) at distance L from x_o, can be represented as:

$$h(x) = \frac{R}{T}\left(Lx - \frac{x^2}{2}\right) \qquad (2)[4]$$

The relative head difference from the maximum recharge head elevation at x=L to the discharge elevation at x=0 depends on the recharge rate (R) and the transmissivity (T). As would be intuitively expected, this means that the piezometric head magnitude in the discharge zone for a given upslope head will be less with a larger transmissivity, with a decrease in the overall recharge rate, or a longer distance from an upslope recharge position.

Drainage Effects on Water Balance and Confined Aquifer Storage

Natural discharge under artesian conditions occurs as seepage (Se) or evapotranspiration (ET), (Fig. 11a) according to the water budget:

$$\Delta S = R - ET - Se$$

Where R is recharge and aquifer storage is S. Under steady state conditions ($\Delta S = 0$) recharge and discharge must balance ($R = ET + Se$). When perturbed the system undergoes transitional

[4] Derivation of Eq. (2) is provided by A Nygren.

Assume that the discharge point (x_o=0), h=0; at the upslope divide (x=L), the gradient is 0 ($\frac{dh}{dx} = 0$).

$$\frac{d^2h}{dx^2} = -\frac{R}{T} \qquad (2a)$$

Integrating on x gives:

$$\frac{dh}{dx} = -\frac{R}{T}x + C_1 \qquad (2b)$$

Applying the x=L gradient assumption, $-\frac{RL}{T} + C_1 = 0$ (2c)

Further integrating (2b) gives

$$h = -\frac{R}{2T}x^2 + C_1 x \qquad (2d)$$

Substituting (2c) in (2d) gives

$$h = -\frac{R}{2T}x^2 + \frac{RL}{T}x \qquad (2e)$$

or,

$$h = \frac{R}{T}\left(Lx - \frac{x^2}{2}\right) \qquad (2)$$

adjustments to restore that balance. The addition of a drain (D) modifies the water-balance equation to:

$$\Delta S = R - ET - Se - \mathrm{D}$$

$$\text{At steady state, } R = ET + Se + \mathrm{D}$$

A drain placed in the discharge zone in or overlying a shallow confined aquifer will function as a horizontal well. It will no longer be limited by the falling head induced by the drainage itself, but rather be continuously driven by the underlying piezometric head in the aquifer as long as the water level in the confining cap induced by the underlying piezometric pressure is above the drain.

The transitional state following addition of the drain can be accommodated by lowering ET and Se in the discharge zone, or by upslope gradient adjustments.

If drainage is less than combined Se and recoverable ET, the new steady-state head distribution will compensate by capturing Se and ET through the drain, and upslope head adjustment will be minimal.

If the pressure head in the discharge zone is above land surface, first compensation will occur as a decrease in Se with less pressure head above the drain. If the reduced pressure head above the drain is at an elevation below land surface, Se will be terminated.

If pressure head in the discharge zone is initially below land surface, a lower water level in the confining cap will result, potentially capturing ET. However, for a normal drain at 3 to 4 feet depth, little decrease in ET will usually occur because soil capillarity in a fine soil above the drain will still maintain the near surface soil at a wetness optimal for using potential ET (Benz and others, 1978; Benz and others, 1981).

If the post-drainage water loss is fully compensated by captured Se (springs and seeps) and ET, there will be no net loss from the aquifer through the drains, only a change in discharge sinks. The result would be minimal upslope pressure loss.

For a tile drain system designed using drainage coefficients based on removing precipitation and runoff, the drained area will remain wet as maintained by continued subsurface flows or a continued high-water table.

If drainage is larger than combined original Se and ET and cannot be fully compensated by pressure drop in the confining layer above the drain, so that downslope discharge exceeds upslope R, ($R < ET + Se$ + D) the transition to a new steady-state condition will affected by an upslope adjustment in hydraulic gradient. This will consist of lowering the upslope pressure head, which will decrease the downslope delivery of water to the drain until drainage is balanced by upslope recharge ($R = ET + Se$ + D) (Fig. 11b and 11c). The transition will occur as lower water pressure upslope, which will also include a change in elastic storage if the recharge zone is confined, or a change in porewater storage if the upslope aquifer is, or transitions to unconfined conditions.

Capture of ET and Se will not be limited to the drain location, as interception of pressure head downgradient from the drains, and lower heads upgradient caused by gradient adjustment from the drains will serve to decrease Se and ET and limit gradient adjustments further upslope.

The result of lower water pressure upslope can be a decrease in water pressure in shallow wells within the aquifer, upslope of the drains.

If, for an extended period of time, recharge would cease, water pressure upslope will decline until the upslope water level or pressure elevation is equal to that of the downslope drains. For example, if the upslope water level elevation in the recharge zone is three feet above the land surface in the downslope confined discharge zone, and the tile elevation is three feet below the land surface in the discharge zone at t=0, a combined drop of 6 feet in the upslope pressure head or water level will occur at final equilibrium.

The difference in elevation between the pressure head in the upslope recharge zone and the elevation of the drains is the maximum water-level drop that will occur in the aquifer (the no recharge case). In a dynamic system, recharge and discharge occurring, the pressure drop (and storage drop) will be less, limited by the aquifer T.

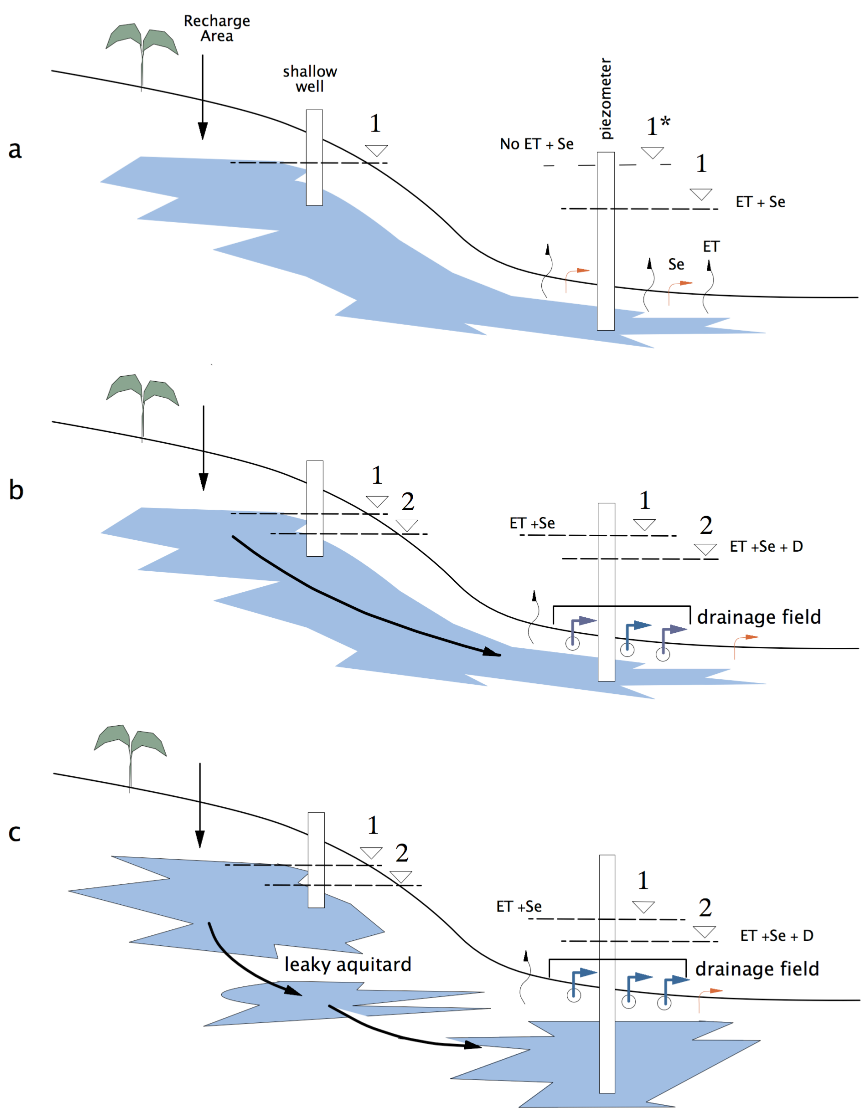

Figure 11. Illustration of potential effects of tile drainage in the discharge area of a confined aquifer having locally artesian pressure head: (a) artesian head without drainage; (b) artesian head with subsurface drains; (c) artesian head with drains in a low transmissivity aquifer.

The greater the depth of the confining layer, the less the effect on upslope water pressure.

The greater the aquifer area relative to the drainage area, the less change in pressure-head will result.

The greatest drain loss scenario would occur when the drain placement breaches the shallow confining layer and the drain is placed in the aquifer itself.

Drain losses are proportional to the hydraulic conductivity of the confining cap. In very low K materials, such a sodic silt-loam cap, additional water losses from drainage would likely be minimal.

Where Would Shallow Artesian Conditions Be Encountered?

Thin shallow confined aquifers or small sand and gravel deposits are most common in glaciated areas where multiple glacial advances and melts caused deposition of outwash deposits during periods of melt, followed by periods of repeated glacial advances and till deposition; or, in downslope positions where lower landscape positions overlying aquifers were ponded, resulting in deposition of fine lacustrine sediments. These conditions are common in southeastern North Dakota.

What Problems Might Result?

Shallow wells, for example sand point wells upgradient of the drainage, that rely on suction lift or otherwise have little available drawdown and are affected by relatively small amounts of head loss, would be the main potential impairment of beneficial use.

Drainage benefits in the downslope position of a fine soil overlying a shallow artesian coarse unit will be minimal because a drain field designed to remove storm drainage and runoff will be insufficient to remove artesian water added to the storm drainage, and because the zone of capillary rise on very fine soils, such as a sodic silty clay loam, can approach land surface.

Potential Mitigating Circumstances

Greatest impact coincides with least need: Wetter conditions augmenting artesian water elevations coincide with conditions of least water shortage and demands. They tend to subside as drier conditions and lower recharge rates prevail.

Head and storage drop caused by drains is limited: In areas of flatter topography artesian head elevations in potential drained areas are usually limited to no more than a few feet above land surface. The maximum aquifer head and storage loss upslope from drainage would be limited by the sum of the head above land surface and the depth of the drain. For example, if the drain is at 3 ft. and the head is 1 ft. above land surface, the maximum upslope head loss through drainage would be 4 ft. Decreases in local water levels in the confining cap induced by changes in Se and ET caused by the drains would be subtracted from this.

Drains cannot compete with properly constructed high-capacity wells: If the aquifer source of piezometric head in the drained area is of substantial thickness and extent, a high capacity well screened below the elevation of the drain will always have the first capture of the water, and will eventually decouple the drains. Put differently, upslope head loss caused by the drain is converted to developmental head decline for the well.

Drains affected by low artesian pressure can be controlled: Drains capturing water under piezometric head that is below, or within a few feet of land surface can be controlled, if necessary, through appropriate discharge structure design. If drain collectors are sumps with top elevations above the drainage field head elevation, so that pumping is necessary for discharge, drainage can be curtailed by simply turning off the pumps.

Small area results in small impact: Drainage of small seeps fed by large artesian aquifers, is unlikely to be excessive.

Drain capacity may limit impact: Limits of drainage imposed by drain design (size and spacing) may restrict losses caused by artesian pressure.

Additional Considerations

Unfortunately, from a practical standpoint it is often difficult to pre-assess the presence, extent, and thickness of shallow confined aquifers, particularly when they consist of small limited deposits that are unmapped, or are mapped only as intermittent inclusions within the larger surficial deposits.

Drilling to test is ill advised, because it can result in "blowouts" (artesian surface flows) that require plugging if the local head is above land surface.

Concerns presented here pertain only to effects of large-scale drainage over small shallow confined aquifers. They do not pertain to small localized seeps. In addition, an important exception would be local seepage and salinization that is caused by advective transport of saline bedrock water through a deep aquitard under high artesian pressure. One such situation has been studied by Strobel (1996) and Gerla (1992) who identified an area of extensive soil salinization and surface seepage in northeastern North Dakota caused, at least to a substantial extent, by upward advective transport of Dakota Fm. water through overlying till and lacustrine sediments, where they directly overlie the Dakota bedrock. Drainage in this case would be capturing water currently flowing, seeping, evaporating or transpiring; and it would be capturing salty water sourced in a deep underlying aquifer of very large extent. In addition, drained water could be otherwise captured by high capacity wells placed within the formation, or overlying confined aquifers affected by the Dakota water. Tile drains for land reclamation under these conditions may require more intensive design than those based on drainage coefficients. They would not, however, be considered an impairment of beneficial use of water. The Dakota Fm. in North Dakota directly underlies glacial materials along a relatively narrow, and likely intermittent, band (a few miles wide) in the Red River Valley from Canada to South Dakota, and advective salinization may possibly be identified anywhere within that band. Recent measurements of eight Dakota Fm. wells in Cass County near Buffalo, ND, have indicated Dakota pressure heads of tens of feet above land surface in the Dakota Fm. and in some of the deep buried glacial aquifers within the overlying Pleistocene materials.[5] However, Dakota Fm. subcrops, or areas of potential effect have not been extensively identified.

[5] Well sample data provided and interpreted by Rex Honeyman, SWC, documentation in recommended decision for Water Permit #6884, in preparation (Feb. 13, 2018).

The North Dakota Geological Survey would be the best reference for information on Dakota Fm. subcrops. Dakota water has a distinctive sodium-sulfate and sodium-chloride signature which can be identified in water samples.

Pattern drains in areas of widespread springs and seeps, as opposed to drainage of a local wet spot caused by a local artesian seep, may be problematic, both from the standpoint of effective drainage and from the standpoint of upslope water storage. Areas of widespread springs and seeps are indicative of artesian conditions. Local landowners are often aware of these areas and can be helpful in identifying their location.

If there are no shallow wells within, near or upgradient[6] of the area to be drained using pattern drainage in a shallow confined aquifer, adverse impact on a domestic well is unlikely.

Fine soils formed from lacustrine deposits in low areas of upslope coarse deposits, are frequently under artesian pressure, particularly if they are persistently wet near land surface throughout the year.

Recommendations

No simple clear recommendation is possible. In general, drainage of land overlying shallow aquifers under artesian pressure approaching land surface will be problematic and should be avoided, or otherwise given special consideration of local design requirements and impact. If possible, pre-assess local conditions for signs of artesian conditions. Unfortunately, in a complex glacial environment, determining the presence of small localized shallow artesian aquifers is no easy or sure task and is often impractical. Some clues of artesian conditions would be abundant springs and seeps, year-round wetness, even during dry seasons, widespread salt deposits on land surface not limited to lowlands and lowland margins, etc. However, even these may be indicative of deeper bedrock influence or slow seepage through thick aquitard materials which would not be problematic. Landowners are often aware of shallow artesian conditions affecting their wells and their land. Water chemistry can be an indicator of a deeper bedrock advective source.

[6] A well placed downgradient of a drain placed at 3 ft. below land surface would have to be screened so shallow to be impaired from potential drain impact as to be an unrealistic attempt at capture.

The best practice is to construct drain collectors to have sufficient top elevation above land surface to prevent overflow so that artesian drainage can always be controlled. A controlled system can always be managed as necessity requires.

Further Work: Detailed quantitative modeling work is beyond the scope of this discussion, which has been based on general hydrologic principles. Modeling work would be beneficial for further exploration of potential quantitative effect. In particular, I would suggest the following:

1. Exploration of aquifer area to drainage area effects on head distribution, incorporating realistic R, ET and Se dynamics using varying soil K values, would be useful to assess quantitative impact of drains on local head changes above the drains, and potential Se and ET recovery.

2. Effects of actual drain designs on drainage losses under artesian pressure, with different cap thicknesses. Specifically, drain projects (size, depth, spacing) are normally designed using drainage coefficients based on climatic events and falling soil water levels following those events. Effects of constant heads above the drains affected by underlying piezometric pressure under realistic size, depth and spacing scenarios would be useful for exploration of both field benefit and drainage losses.

Summary

Drainage of soils overlying shallow confined aquifers under local artesian conditions with pressure head above the elevation of the drain is not a good idea, for several reasons. First, the drains will likely be ineffective because water levels will be maintained at or above the elevation of the drains, which will often cause continued wet conditions. Second, continued artesian discharge can, under some conditions, deplete pressure head upslope beyond the drainage area if drained water exceeds quantities that were previously discharged through evapotranspiration and drainage in the discharge zone, and the additional water drained cannot be fully compensated by changes in Se and ET within, and beyond the area of the drains. Where drainage exceeds recoverable natural discharge, shallow wells upslope, which are sensitive to minor head loss for available drawdown, may lose some utility.

Factors affecting artesian aquifer, including the depth and size of the artesian aquifer in relation to the drain project, and the potential recoverable seepage and ET, are usually difficult to predict in areas of extensive buried isolated sand and gravel layers. They can be negligible, or substantial, depending on conditions. Because drains, in these cases, are functioning as horizontal wells, there may be cases or conditions wherein the drains should be closed to prevent adverse impact. Under prevailing wet conditions impacts are likely minor in most cases, but under prolonged dry conditions when water shortage is critical it may be necessary to curtail drainage in some of these confined systems. There has been no clear case of impairment of water supply for beneficial use through aquifer depletion caused by drainage. There have been a few cases in which shallow wells with limited available drawdown in confined sand and gravel deposits may have been impacted. In such cases, contribution of climate and drain effects can be difficult to separate. The best approach for minimizing potential problems, based on limited predictive capability, is risk management, through design inclusion of drain outlets that can be closed if necessary.

POTENTIAL TILE DRAINAGE EFFECTS ON LOCAL DOMESTIC WELLS

A question has been raised whether subsurface drainage could, in some cases, affect the performance of nearby domestic wells. The conclusion of the drainage report (WRI No. 45) pertained to impairment of the beneficial use of water through aquifer depletion, which was determined to be unlikely in most cases. However, the caveats for individual wells, as summarized in the Executive Summary, were:

- 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 could almost always be offset by the addition of wells.

The last of these would likely not apply to the most problematic conditions of domestic wells. In most cases, dropping a water table three feet should not affect an efficiently constructed domestic well. Conditions most likely to cause impairment of a local domestic well would be a shallow water table well in which the available drawdown for the desired use is critically small and a two to four-foot change can make a substantial difference in the sustainable pumping rate for the well, and conditions where pumping depends on suction lift, or artesian pressure head in the well.

Unconfined Conditions

Based on above criteria, impairment of domestic wells from tile drainage should not be a common occurrence. One example of potential impairment occurred in the Venlo case. About 1/5 mile south of the perforated drain outlet pipe, next to the river valley, a homestead has a shallow domestic well. The homestead is located on a terrace adjacent to, and in near proximity to, the Sheyenne River valley cut. The owner claimed that his well lost half of its pumping capacity after construction of the drainage project in 2015, and was wondering if the drains could have caused the problem. A domestic well log was not available, but the owner stated that the well was relatively recently constructed (after 2000), and had a bottom depth of about 22 ft. (the local depth of the underlying aquitard as the aquifer pinched out near the river). Lithologies of boreholes at

13505433BBB and 13405404BBB indicate that the local coarse sediment depth is about 20 to 26 ft. The owner was using a positive displacement pump, and was not reliant on suction lift, although the depth of the pump placement in the casing is not known. The owner stated that normally the water level in the well had been 12 ft. (water table 10 ft. below land surface). Following 2015 the water level in the well dropped to about 18 ft. a drop of about 6 ft.

Hydrographs for local wells (Fig. 8) indicate general drying trends since 2011. Observation wells distant from the drain outlet and the domestic well all indicate a water-level decline of about two to three feet when comparing the peak water level elevation in 2015 to the peak elevation in 2016. For example, observation well 13405401DDD, about three miles from the domestic well declined about 3.5 ft. from an annual peak of 1071 ft. to a peak of 1067.5 between 2015 and 2016. Observation well 13405402DDDD, about 4 miles from the drain outlet and domestic well declined from a peak of 1069.5 ft. to 1067.5 ft., a difference of two feet. Observation well 13505328BBB4, about 6 miles from the drain outlet and the domestic well, decreased from a peak of 1058.8 to a peak of 1056 ft., or two feet. These are attributed strictly to climate and pumping, rather than the drains. Peak water-level elevations in the observation well (13505429DAAA) closest to the uncontrolled perforated drain outlet pipe, decreased about four to six feet over the same period (Fig. 8). Peak annual elevations in the well second nearest the drain and nearest the domestic well, 13505433BBA2 (Fig. 8), decreased about three to four feet.

Slightly greater drops in water level elevations nearest the perforated drain outlet pipe by about two to three feet compared wells distant from the drain outlet and not within the drainage project, indicate a possible slight influence of the perforated drain outlet pipe on the pumping capacity of the well. But a broader analysis indicates that a substantial component of the decrease in domestic well capacity is attributable to climate and pumping upgradient of the domestic well.

In summary, the decrease in domestic well pumping capacity by about a half was caused by a water level drop of about 6 to 8 feet in a shallow well that had only 12 feet of available head. The cause of the drop in available drawdown involved drying climate, pumping, and a plausible small contribution from the perforated drain outlet pipe. The relative contribution of the drain outlet pipe was only one component of the decrease, and apparently a small one. It does illustrate, however, the sort of local well effects that can occur in some cases. This does not indicate a problem of aquifer water supply depletion.

Confined Conditions

The above discussion of hydraulic effects of tile drains in thin confining caps overlying confined aquifers, illustrated on Fig. 10, has indicated that tile drains overlying artesian aquifers function as horizontal wells and can flow continuously in many cases. If drain discharge cannot be compensated by decreased evapotranspiration and seepage, a decrease in upslope water pressure and storage can occur. In a low relief landscape, the changes should not exceed a few feet at most. However, for shallow wells, such as sand-point wells, wells screened in the upper aquifer, wells dependent on artesian pressure for available drawdown, or wells dependent on suction lift, a small amount of pressure-head change can constitute an impairment. In most cases, if the aquifer is thick enough, the induced deficiency can be remedied by drilling a deeper well within the aquifer, or into a deeper aquifer unit. Where both the well and the downslope pressure source are within a very thin sediment, and where no other deeper water source can be locally tapped, local impairment can be inconvenient and sometimes expensive to remediate.

Summary

Local impairment of domestic wells can be caused or aggravated by tile drainage projects. The two cases discussed both involve very vulnerable wells screened at shallow depths, and highly susceptible to impairment from very minor changes in pressure head.

The unconfined case, the Venlo case, involved the potential combined effect of a dry climatic cycle, location in close proximity to other discharge sinks (springs) near a river bank and within the zone of large marginal head change over small differences, and the possible additional impact of a perforated discharge pipe located about 1/5 mile away, which functioned as a horizontal well and created an artificial spring at the discharge point. The relative impact of the perforated drain cannot be clearly separated from the other causes. This case was exacerbated by thinness of the aquifer which was pinching out near its boundary at the well site. This represents an extreme case of vulnerability. Impairment of wells by drainage in unconfined aquifers should be rare.

The confined scenario is also limited to highly vulnerable wells screened shallow in a confined aquifer upslope of a drainage project in which drains were placed in a thin confined cap overlying an aquifer having artesian pressure caused by upslope recharge. If drainage extent is large in relation to the size of the aquifer (as in a thin local sand and gravel layer), and if the amount of water drained cannot be compensated by decreasing seepage and evapotranspiration through drainage, some upslope loss of pressure head can result. In a relatively flat landscape, as in eastern North Dakota, head change should be relatively small, within a few feet. However even a relatively small head loss can limit the pumping capacity of a well having little available drawdown. This condition would most commonly occur in a glaciated environment in which cycles of glacial advance and meltwater deposition resulting in fine materials overlying outwash; or in low formerly ponded areas overlying sand and gravel outwash where fine materials have deposited over extended periods of time.

In any aquifer having sufficient thickness to construct a deeper well, or place a pump deeper within the well, minor head changes caused by drainage can be offset.

CONCLUSIONS

1. Perforated pipe placed below the water table for use as a discharge conduit after the final collector and control structure for a drain field will function as a continuously flowing horizontal well as long as the pipe remains in the saturated zone, and will cause the formation of an artificial spring. This discharge can be substantial, provides no useful function insofar as drainage is concerned, and represents a non-beneficial loss of water. The following results are expected:

- Non-beneficial discharge will vary with the length of the pipe, and the head above the pipe.

- Non-beneficial discharge will occur only as long as the water table is above the discharge pipe.

- Non-beneficial discharge will decrease with drier climate and with irrigation pumping, and will therefore be minimized during prolonged droughts.

Use of perforated pipe after the drain collector should be avoided. When perforated pipe is used for a final outlet conduit, an appropriate control structure should be placed as close as possible to the final discharge point to minimize non-beneficial loss.

2. Tile drainage within a thin confining layer overlying an aquifer or minor coarse sediment layer under artesian pressure from upslope recharge, will function as a horizontal well, and will discharge continuously as long as the local piezometric head is above the elevation of the drains.

- Tile drains designed using event-based drainage coefficients will fail to adequately drain the intended lands, and wet conditions will persist due to pressure-induced head above the drains and capillary extension to land surface. Drainage under these conditions is non-beneficial.

- If the drainage area is large in relation to the extent of the aquifer, and if the drain discharge is not sufficiently recovered from decreases in local seepage and evapotranspiration affected by the drains, pressure loss and aquifer storage loss upslope may occur. Discharge losses from storage are non-beneficial. Adjusting the drainage design to fully dewater the drained area will increase the non-beneficial loss of stored water.

- Drain discharge is directly proportional to the hydraulic conductivity and thickness of the layer underlying the drain. Drain impairment and aquifer losses should be minimal for very thick and low conductivity materials overlying aquifers (deep confined aquifers).

- In a low-relief landscape artesian head is normally limited, and upslope head and storage adjustments should be limited to a few feet.

- Pressure head and discharge through drains overlying a shallow confined aquifer should decrease with drier climate, thereby minimizing losses under most critical conditions for water availability.

- Under low-pressure artesian conditions (head within a few feet above land surface), final discharge can usually be controlled by the final control structure if properly constructed.

- If the underlying aquifer is thick enough to allow for construction of production wells, drainage discharge can always be recovered by the production wells, decoupling the drains and diverting the water for beneficial use.

Tile drainage in thin fine confining layers overlying shallow confined aquifers having artesian pressure elevations above the drains should be avoided, where possible. These areas are generally located in areas where glacial advances and retreats occurred frequently and cyclically, as in southeastern North Dakota. The problematic areas here referenced are not localized seeps, which can be effectively locally drained with little broader hydrologic impact. Rather they are characterized by extensive areas of year-round spring seepage, or widely distributed year-round wet areas and salinity, not limited to topographic low areas which are normally ponded by runoff. Drainage results will generally be unsatisfactory and water discharge losses, therefore, non-beneficial. Unfortunately, these areas are not always easily identified. However, outflow can usually be controlled in low-head areas with properly design collectors. As long as the final outlet structure requires pumping to affect drain discharge, which implies that the sump top elevation is above the elevation of local piezometric pressure head, drains can be controlled, if necessary, minimizing risk.

3. In some cases tile drainage may result in impaired utility of local domestic wells. Wells affected would be shallow or otherwise inefficiently constructed wells having shallow well screens, shallow sand points, shallow pump placement or reliance on suction lift, in which very small changes in available drawdown can impair well capacity. Such highly vulnerable wells would also be affected by climatic cycles, and differentiating drainage effects can be difficult.

   Impairment of wells in unconfined aquifers should be uncommon, unless their placement is very shallow.

   Under confined conditions, loss of pressure head in shallow wells depending on artesian pressure can occur upgradient (usually upslope) of a drains placed in thin confining caps overlying shallow confined aquifers. Pressure head loss would be expected to be small, a few feet, but could have an impact on well yield in some cases of highly vulnerable shallow wells.

   In most cases loss of capacity in shallow wells can be remedied by drilling deeper or otherwise more efficient wells. Where depth is insufficient, other alternative remedies, such as rural water may be applied.

   Loss of capacity in a local shallow well, does not constitute a serious general impairment of the beneficial use of groundwater, as long as the groundwater supplies themselves are not overly depleted. Rather it is a case of isolated effect which should be evaluated on a case-by-case basis. Local domestic well impairment would be confined to shallow wells, and can often be remedied by construction of more deeply placed and efficiently constructed wells.

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