Appendix O

Assessing The Susceptibility of Transient Noncommunity Water Supply Wells to Pathogens

ASSESSING THE SUSCEPTIBILITY OF TRANSIENT NONCOMMUNITY WATER SUPPLY WELLS TO PATHOGENS

Introduction

This paper presents a conceptual methodology for determining the susceptibility of transient noncommunity water supply wells to pathogen contamination. It is needed to support 1) source water assessments required under Section 1453 of the 1996 amendments to the federal Safe Drinking Water Act (SDWA) and 2) susceptibility determinations for pathogen contamination which will be required under the upcoming Ground Water Disinfection Rule (GWDR). The six states which comprise EPA Region 5 and EPA regional staff have agreed to develop a uniform approach to preparing pathogen susceptibility determinations for transient noncommunity water supply wells.

It would be a waste of time and money to use a susceptibility methodology addressing pathogen risk to transient noncommunity wells which does not address both SDWA and GWDR requirements. The owners of a transient noncommunity water supply wells and the public which use them must be assured that susceptibility determinations for both SDWA requirements will be consistent and identify transient noncommunity wells which are at risk to contamination from pathogens. Otherwise, they will have no confidence in either state or federal efforts to implement SWP and GWDR requirements.

Once consensus between the Region 5states is reached on the conceptual design, it will be used to develop procedures for assigning the susceptibility of transient noncommunity water supply wells to contamination. The Minnesota Department of Health (MDH) has selected two counties in which it will test these procedures so the other states and EPA Region 5 staff can evaluate their applicability to meeting needs throughout the region. The time line that the MDH proposes is to 1) reach consensus on the conceptual design by September 30, 1998 and 2) have the procedures tested in the two counties in time for a review of findings at the semi-annual Region 5 drinking water program protection managers conference in December, 1998.

Background

The 1996 amendments to the federal Safe Drinking Water Act (SDWA) require states to prepare source water assessments for public water supplies which must 1) delineate a source water area and 2) identify contaminants of concern which may impact the source water. Contaminants of concern must include those which are regulated under the SDWA, although a state may elect to address others. Currently, the regulated contaminants for transient noncommunity wells are coliform bacteria and nitrate nitrogen. The GWDR will likely require that viruses be included as regulated contaminants. For the purposes of this paper, pathogens are defined as all microbial organisms which may have an adverse impact on human health and include viruses..

The six states which comprise U.S. EPA Region 5 have approximately 40% of the noncommunity water supply systems in the country. Transient noncommunity water supply wells comprise a large percentage of the noncommunity wells in these states. For example, over 80% of the 9000 noncommunity water wells in Minnesota are transient types of wells. There is currently no methodology available to assess the susceptibility of transient noncommunity wells to regulated contaminants, particularly pathogens. This presents a major concern to the U.S. EPA Region 5 states which must complete source water assessments no later than the year 2003 and also address upcoming GWDR susceptibility requirements. The basic attributes of any methodology for assigning susceptibility to pathogens to transient wells are 1) it must be efficient to use and 2) technically valid or it will be of limited use in meeting this deadline.

The methodology presented in this paper only addresses pathogen contamination because there does not appear to be a direct correlation between nitrate contamination and the presence of pathogens in ground water. A separate, although parallel effort needs to be undertaken to identify groundwater supplies or transient noncommunity wells which are at risk of reaching or exceeding the drinking water standard for nitrate.

Basic elements of the conceptual design -

Several fundamental concepts have been used for decades by state public water supply programs and state water well construction regulatory programs to protect water supply wells from pathogens. These concepts form the basic elements of a pathogen susceptibility assessment methodology and identify -

> the presence of one or more geological barriers which prevent pathogens from leaving a source and entering a public water supply well during the time period in which pathogens are viable in groundwater; or
>
> hydraulic conditions within the aquifer related to pumping, well construction, and aquifer composition which prevent pathogens from entering the well in sufficient numbers to cause a human health concern; or
>
> the absence of potential pathogen sources in the recharge area of the well which is defined using a time of travel in groundwater over which pathogens will remain in viable numbers.

Identifying one or more of these elements or barriers should be sufficient to determine that a transient noncommunity well is not susceptible to pathogen contamination of the groundwater source. Inherent in this conceptual design is knowing that the well is properly constructed so that it does not offset these barriers by serving as a pathway for pathogens to directly enter the water supply system. It cannot be over emphasized that knowledge of well construction and maintenance must be known or an inaccurate determination of pathogen susceptibility may result. In cases where well construction records are not available, a process must be in place for estimating construction details which is integrated with increased microbial monitoring to obtain an meaningful assessment of pathogen vulnerability. Well construction must be determined before any methodology should be used. A discussion of well construction considerations is presented in Appendix I for reference.

Suggested priority for using conceptual elements -

The three elements identified above are listed by the increasing amount of time estimated to implement them. Therefore, the most efficient means of using these elements is to begin with determining whether a geological barrier is present followed by evaluating well hydraulics for wells where a geological barrier cannot be identified. The third method focuses on determining the absence of pathogen sources in the recharge area to the well and requires the greatest amount of time to implement. It is likely to be the least attractive method or option to use because it will likely require that greatest amount of staff resources and data management capabilities to implement. However, the availability of qualified staff needed to implement each element; the resource limitations of the agency identified to conduct a pathogen susceptibility assessment; and staff preferences toward a method will affect how priorities be established. The following discussion of how each element could be used is intended to help the reader understand the degree of difficulty related to implementation as well as related staffing and resource requirements.

Defining a geological barrier

Fine-grained geologic materials such as clay or shale serve to hydraulically separate aquifers and possibly prevent the vertical movement of pathogens into an aquifer during the time in which they are viable in groundwater. Therefore, if the aquifer used by the public water supply well is covered by an effective confining layer, the well should not be at risk to pathogen sources. Confining layers may already be identified for many areas by state and federal water resource agencies. If so, efforts can be directed to identifying whether a transient noncommunity well 1) pumps from an underlying aquifer and 2) is adequately constructed so it does not serve as conduit for pathogens to enter the source aquifer. However, many potential confining layers have not been formally identified and additional effort is required to confirm their presence. A methodology for doing this is presented in Appendix II. There is a large amount of possible information available to help states identify whether confining layers are present. Maps and reports identifying the presence of a confining layer are often available through state agency contaminant source control programs or groundwater research agencies such as state geological surveys or the Water Resources Division of the U.S. Geological Survey.

Water well contractors can provide valuable information about the effectiveness of potential confining layers and should not be overlooked as a source of geological expertise. Drillers can provide great insight into the composition of subsurface materials and local groundwater levels. Often, their written logs are very brief because they are not trained in describing subsurface geologic materials or they do not have the space to write on the forms provided to them by a state well program. However, their drilling experience and years of observing groundwater levels are invaluable for determining the effectiveness of local confining materials. For example, in many areas of Minnesota drillers report that they have to ream out boreholes left open over night in some till units. This indicates either these tills contain clay minerals which expand on contact with water or the tills are tightly compressed and expand when unloading occurs. Either explanation supports the assumption that they will effectively seal around the well casing after it is installed. Wells cased through these till units should be adequately sealed into the borehole and protected from the vertical movement of pathogens along the well column. Another example is drillers report that they complete wells below surface water to ensure potability. Here, they have identified the presence of a confining layer which separates the water table aquifer from a deeper aquifer.

Recognized confining layers - If a confining layer has already been identified by a state or federal water resources agency to exist throughout an area, than an area-wide assessment of transient wells can be used.   That is, all transient wells within the geographical extent of a confining layer can be designated not vulnerable to pathogens once it can be shown that they are properly constructed into an underlying aquifer.   For example, geological maps show that a bedrock confining layer exists throughout an area covering several townships. The geologic logs from well construction records or geologic test drilling confirm the presence and thickness distribution of the confining layer. Within this area, transient noncommunity wells for which it can be documented are properly constructed into the underlying aquifer can be unilaterally assigned a low vulnerability potential to pathogen contamination.

Confirming that transient noncommunity wells are properly constructed through a confining layer can be accomplished several ways. Wells for which a geologic log and construction record exist can be designated non-vulnerable to pathogens using this information. However, if a geologic log and a construction record are not available, more research is required. If the well depth is known, it can be used to confirm that the well is drilled to the underlying aquifer. The best source for this information is the well repair business which services the well or building permit information. These sources may also have information describing the depth cased, the pump setting, and the static water level in the well. Also, a sanitary survey of the well will collect useful information about its age, diameter, casing type, pumping equipment, and physical condition. This information should be compared to the records of nearby wells to determine 1) the presence of the confining layer and 2) the most likely construction of the transient noncommunity well. Transient noncommunity wells for which only depth information is known should be further evaluated to ensure that their construction does not present a problem. It would be prudent to sample these wells for coliphage organisms or other microbial indicators to ensure that the assumptions regarding well construction are correct. Also, age dating analyses using enriched tritium analyses should be used to determine the relative rate of recharge to the aquifer. If the microbial tests are negative and the tritium data suggest water older that a decade, the well can be designated non-vulnerable to pathogens.

Identifying the presence of a confining layer - There are many areas where confining layers have not been officially mapped but still exist. This is particularly true for unconsolidated materials where only reconnaissance level geologic mapping has occurred and where well records provide the only description of subsurface geological materials and hydraulic conditions. A minimum thickness of geologic material needed to serve as a confining layer can be calculated using the methodology presented in Appendix II. For example, well records indicate that a rocky clay layer exists in an area. This material is interpreted to be a clay-rich till. Data collected from research programs and from contamination control programs have been compiled by the source water protection agency to give a general vertical hydraulic conductivity value for this type of material. The static water levels from wells completed in stratigraphically lower geologic units can be compared to surface water elevations and define the difference in hydraulic head across the rocky clay layer. Using these values for vertical hydraulic conductivity and hydraulic head in the equation presented in Appendix II defines the minimum thickness of rocky clay needed to protect a transient noncommunity well from pathogens. Well record data can then be used to document where the rocky clay is at least this thickness and where transient noncommunity wells pumping from deeper aquifers should be protected from pathogens.

Evaluating the effects of well hydraulics

Well hydraulics is defined for the purposes of this paper to mean the effects that the pumping of a transient noncommunity well has on the movement of pathogens from their entry point in the aquifer to the well intake. An analytical tool needs to be developed which determines whether the pumping of a transient noncommunity well will cause the vertical movement of pathogens from the water table surface to the well. Once prepared, this tool can be used by states to determine the susceptibility of transient wells which pump from porous media aquifers which are not protected by a confining layer.

Basic assumptions related to evaluating well hydraulics - There are several assumptions inherent with using this approach to evaluating pathogen susceptibility which restrict its use to certain types of aquifer materials and hydraulic settings. First, the methodology is limited to addressing aquifers where groundwater movement is controlled by intergranular flow. It is very difficult to predict the movement of water toward a well which is pumping from an aquifer in which groundwater movement is controlled by fracture flow or conduit flow. Therefore, this methodology cannot address the pumping influences of transient noncommunity wells which pump from fractured or solution weathered bedrock. Aquifer materials that will be addressed are composed of sand and gravel-sized particles in which vertical movement of water molecules is not reduced by the presence of finer grained particles. This assumption will likely represent a worst case scenario for porous media aquifers and will present the most conservative assessment of possible pathogen migration into a well intake. Therefore, if the analytical results are negative, pathogen susceptibility should be minimal.

The second assumption is that the vertical and hydraulic conductivity of the aquifer materials are the same and there is no retardation to vertical flow. This assumption provides a worst case scenario in terms of pathogen movement because the vertical component of water movement of water in a porous media aquifer is often restricted compared to horizontal flow by differences in aquifer composition, the arrangement of rock particles due to compaction, and the viscosity of water. Therefore, if the analytical results are negative, pathogen susceptibility should be minimal.

The third assumption is that the methodology will address aquifers which exhibit unconfined hydraulic conditions. This no need to use this methodology on wells which are protected by a confining layer. Implicit in this assumption is the idea that the aquifer does not exhibit any degree of leaky confined conditions and any retardation of pathogen movement related to this effect is not considered. Therefore, if the analytical results are negative, pathogen susceptibility should be minimal.

The fourth assumption is that the pumping of the well is not constant and represents the cyclic stress on the aquifer caused by the pump turning on and off. Transient noncommunity wells typically do not operate for hours or days at a time and steady state pumping conditions do not apply to them. The duration of each pumping cycle is determined by dividing the daily volume of water needed by the amount of water pumped into the water reservoir per pump cycle. The frequency of pumping is determined by dividing the duration by the number of hours per day the facility is open to the public. This assumption reflects the cyclic (transient) pumping conditions exhibited by transient noncommunity wells and will provide more accurate estimates of pathogen movement within the aquifer than using steady state pumping conditions.

The fifth assumption is that the concentration of pathogens entering the top of the aquifer remains constant and any projection of their arrival at the well intake signifies they are at levels that present a human health concern. In other words, the methodology cannot estimate seasonal variations in pathogen concentration or the rates at which different organisms die off in the groundwater environment. It only determines if a pathway is possible based on the projected time period for overall viability established under the GWDR.

Pumping effects - The principle reason for evaluating the pumping effects of a nontransient noncommunity well is because the aquifer it uses is not protected by a confining layer. The conceptual hydrogeologic setting reflecting this condition represents a porous media aquifer which occurs at or near the land surface which contains the water table. Pathogens enter the aquifer by moving from their source to the upper surface of the water table. Under non-pumping conditions, pathogen movement would most likely have a much greater horizontal than vertical component because discharge to rivers, streams, and lakes controls the hydraulic gradient.

Pumping stress on the aquifer is likely to increase the vertical component of flow significantly in the area immediately around the well by creating a lower hydraulic head deeper in the aquifer and causing drawdown to occur. However, drawdown effects will quickly decrease away from the well because 1) of the short time period it is actually pumping, 2) gravity drainage response mechanisms of unconfined aquifers probably will not occur because the well does not pump long enough to overcome the initial horizontal flow response to pumping within the aquifer, and 3) horizontal recharge due to pumping is much greater than vertical recharge in a transmissive porous media aquifer. This means there is a very small area of pumping influence (cone of depression) established around the well during each pumping cycle but pathogens located at the water table surface may be pulled deeper into the aquifer by drawdown effects.

Assessment methodology - The likelihood that pathogens move vertically into the aquifer and enter a transient noncommunity well can be estimated by evaluating whether the drawdown effects at the water table surface are part of the vertical capture zone or only in the vertical zone of influence. The probably of pathogen entry should be directly proportional to aquifer porosity, the pumping rate of the well, the duration and frequency of pumping, the areal extent of the cone of depression, the amount of drawdown, and the survival time of pathogens in groundwater. Probability should be inversely proportional to the density difference between groundwater and pathogens (pathogen buoyancy), the vertical distance between the water table surface and the well screen, the hydraulic conductivity of the aquifer, and the ambient vertical hydraulic gradient within the aquifer,

An analytical solution which includes the variables described above needs to be prepared so a tool for conducting a probability analysis of pathogen contamination for transient noncommunity wells is available. Wells which are considered vulnerable because a confining layer is not identified would be assessed using this tool. If such analysis indicates that a well is not vulnerable due to well hydraulics, a state may wish to develop a monitoring strategy to ensure that the analysis is correct.

Evaluating the presence of pathogen sources

This option for determining whether a transient noncommunity water supply well is vulnerable to pathogens 1) assumes that no geological barrier exists and 2) well hydraulics indicates that pumping may draw pathogens into the well. This option focuses on identifying potential pathogen sources in the wells capture zone. The fundamental premise of this assessment method is the well is not vulnerable to pathogen contamination if there are no sources of viable pathogens in the area which supplies water to the well. It can be applied to all hydrogeological settings although the practicality of its use is directly related to the difficulty of determining the capture zone.

Identifying the capture zone - There are many approaches to designating the recharge area to a well which range from very simple to complex. However, the principle factor relating to pathogen susceptibility should be the extent of the capture zone defined by the time over which pathogens are viable in groundwater. Pathogen sources which are located in this area should make the well vulnerable to contamination and the source water should be disinfected to prevent exposure to people.

It is not likely that states will have the time and resources to prepare in-depth analysis of capture zones for transient noncommunity wells. A simple, yet effective method is to 1) set an arbitrary radius for the well to account for pumping effects near it (zone 1) and 2) project the circular area defined by this radius a specified distance in the upgradient direction of groundwater flow to address pathogen sources which may contaminate the well over the time period pathogens are viable in groundwater (zone 2). An estimate of an appropriate radius and upgradient distance for porous media aquifers is presented in Appendix III. A simple method for defining the upgradient distance is to prepare a table using the WHPA Code which specifies a distance relative to ranges in the volume of water required each day.

The approach to designating a capture zone for transient noncommunity wells completed in crystalline bedrock or solution weathered bedrock is left to the discretion of the individual state.

Sanitary surveys conducted on the transient well provide a good starting point to identify potential pathogen sources but likely will have to be expanded to address pathogen sources in the upgradient direction of groundwater flow. This extended capture zone area can be defined by estimating the compass direction of ambient groundwater flow and then projecting the circular area defining zone 1 the appropriate distance along this compass direction. It may be prudent to define a larger area than this by projecting areas using compass directions which are 10 degrees greater and less than the angle of groundwater flow selected. This reduces the error in determining the local angle of groundwater flow and provides a more conservative estimate of the capture zone for the well.

Assessing vulnerability using the source inventory - The inventory of potential contaminant sources should include plotting the distance and compass direction of each pathogen source in relationship to the transient noncommunity water supply well This may already have been completed for zone 1 through a sanitary survey. The well would be considered vulnerable if pathogen sources are present. If not, the source inventory needs to be completed for zone 2 where the same logic applies. If there are no sources, than the well is designated nonvulnerable to pathogens. However, the source inventory must be updated annually to ensure that no new potential source for pathogens is introduced. Once this occurs, the well is designated vulnerable to pathogens.

APPENDIX I

WELL CONSTRUCTION ISSUES RELATING TO ASSESSING PATHOGEN CONTAMINATION RISK TO TRANSIENT NONCOMMUNITY WATER SUPPLY WELLS

Introduction

The drilling method, construction materials used, physical condition, and maintenance of a transient noncommunity water supply well must be evaluated to determine whether any of these factors contributes to pathogen contamination. Therefore, a source water assessment is not complete until these factors are included. The following discussion identifies attributes of well construction and maintenance which may offset natural barriers to pathogen movement in groundwater afforded by hydrogeologic conditions.

Well construction -

The importance of knowing how well construction practices contribute to pathogen contamination cannot be overemphasized for preparing meaningful source water assessments for transient noncommunity water supply wells. Many states have developed water well construction codes to protect well water potability by establishing 1) minimum standards for construction materials and construction practices and 2) minimum setback distances for pathogen soureces. However, some state well codes focus on the quality of the materials used to construct the well but do not consider the effect that hydrogeologic conditions have on contaminant movement. For example, few state well codes prohibit well construction practices which interconnect aquifers and offset the presence of confining layers to protect the well. Therefore, even if a well meets state construction standards, it may still present a pathway for pathogens to enter an otherwise geologically protected aquifer. All of the following practices must have been used to construct the well or it should be considered vulnerable to pathogen contamination because a geological barrier has been offset by well construction practices-

> **Watertight casing is used throughout the entire cased interval of the well.** The term watertight is defined as meeting the following conditions: 1) the material used for casing does not permit the entry of water through it, and 2) the joints between lengths of casing do not permit the entry of water into the well. Wood, masonry, or concrete casing materials are not watertight and may even support the growth of pathogens. .
>
> **The well casing extends at least to the stratigraphic top of the confining layer overlying the aquifer used by the transient noncommunity well.** The well casing should be installed to this confining layer to prevent the introduction of pathogens from overlying aquifers. Ideally, the casing should extend through the confining layer and be sealed into the borehole.

The well casing is sealed into the borehole to prevent the vertical movement of groundwater in the annular space between the casing and the borehole. The seal must extend from the bottom of the casing to 1) the land surface or 2) where the water discharge line is located. An open annulus provides a direct pathway for pathogens to enter the well. There should be sufficient information about the grouting technique used or how the annulus was backfilled to determine that the casing was effectively sealed into the borehole.

For flowing artesian wells, the casing must be installed to a depth sufficient to prevent the entry of near-surface water into the well. Flowing wells may not be vulnerable to pathogen sources because groundwater is discharging upward and a pathway for pathogens does not occur. However, a minimum depth of casing is needed to prevent near-surface water containing pathogens from entering the well. States will likely differ on the definition of a well. For example, a few feet of steel casing placed in a spring may be viewed as a well. Whatever the definition, there must be enough casing so that water pumped by the well is solely derived from the aquifer underlying the confining layer. The actual depth of casing is left to the individual state to define.

Well maintenance and condition -

Well maintenance refers to how the integrity of the well has been continued since it was constructed. The condition of the well reflects whether the materials used to construct it have deteriorated or have been damaged to allow pathogen entry. These factors cannot usually be identified using well construction records and must be assessed by actually visiting the well site. Information regarding well maintenance and condition is best coordinated with the sanitary survey conducted under the Public Water Supply Supervision program. This will help ensure that information needed to address these condition are collected in a standardized and uniform manner. Any of the following conditions should be viewed as making the well susceptible to pathogen contamination regardless of whether a geologic confining unit is present -

Surface drainage around the site is towards the well - This permits the overland flow of surface water toward the well and increases the likelihood that contaminants may enter the well either because of defects in well construction or its state of repair.

The well is subject to flooding - Wells which are covered by flood waters typically are contaminated by bacteria and other microbes. These wells must be monitored closely to ensure that disinfection methods eliminate all pathogens. Contaminants may enter the well immediately through the well cap or over time as infiltrating water moves vertically along the well column.

The top of the well does not have a water -tight cap or there is no water-tight seal around

the pump - Contaminants can enter through the top of a well if the casing or pitless adaptor is open to the air. Wells which do not have a cap securely attached to the casing or pitless adaptor are vulnerable to entry by insects or other vermin as well as to people dropping debris down the well. Also, it may be difficult to install a water-tight seal on a hand pump or other pumps which seat on the top of the casing. This may permit surface water and precipitation to enter the well where the pump is attached to the casing.

The well is located in a pit - Wells located in pits may be subjected to flooding or condensation and precipitation may collect on the floor of the pit and enter the well. Well pits are difficult to maintain in a sanitary condition and often serve as breeding grounds for vermin.

The casing is cracked, bent, twisted, or shows other signs of physical damage - Defects in the casing may serve as points for pathogens to enter the well.

Water can be heard running inside of the well - This may reflect a leak in the water discharge line and the well is in need of servicing. More often, this is caused by infiltrating surface water cascading into the borehole in wells which do not have casing installed below the static water level. Such wells are highly vulnerable to surface water containing pathogens.

Air can be heard entering or escaping from the well with changes in barometric pressure - Wells which respond to changes in atmospheric pressure by permitting the rapid movement of air likely do not have the casing installed below the static water level. This method of construction is often used where bedrock is at or near the land surface and only a surface casing is installed to keep unconsolidated materials from collapsing into the borehole. Infiltrating surface water carrying pathogens can readily seep into the well along fractures or joints.

APPENDIX II

METHODOLOGY FOR PREDICTING GROUNDWATER TRAVEL TIME IN FINE-GRAINED CONFINING UNITS

Predicting Groundwater Travel Time through Fine-Grained Confining Units

This paper presents a methodology for estimating the thickness of a confining layer needed to prevent the vertical movement of pathogens into an aquifer. Fine-grained confining units exist in many stratigraphic sequences in Minnesota, and often retard the vertical movement of water because of their low hydraulic conductivity. Estimating the thickness of confining material needed is best done for specific geological materials because the analysis requires information on the vertical hydraulic conductivity and porosity of the confining unit, as well as the hydraulic gradient across it. This paper does not address other factors that may attenuate disease organisms such as 1) adsorption of microbes to rock particles, 2) temperature and groundwater chemistry, or 3) parasitic microbes. Therefore, a thickness calculation represents a conservative approach to estimating pathogen risk to a well.

Background

Confined aquifers often are protected from activities at the ground surface mainly because it can take years for groundwater to traverse confining units. Accordingly, pathogens introduced into groundwater above a confining unit may not pose a risk to underlying aquifers if they die off naturally over time, as is the case with disease organisms such as bacteria or viruses. The U.S. Environmental Protection Agency (EPA) is considering that water supplies be separated from potential sources of pathogens by distances corresponding to groundwater travel times of two years. Flow through fine-grained units is usually very slow due to their low hydraulic conductivity. Confined aquifers, therefore, may be protected from sources of pathogens where the travel times through overlying confining materials exceed the viability period for pathogens in groundwater.

Formula for Calculating Thickness

Flow through confining units can be predicted using Darcy's equation as presented in the EPA document titled *Wellhead Protection Strategies for Confined Aquifer Settings* (1991):

$$q_v = \frac{K_v (h_o - h)}{b'} \qquad (1)$$

where q_v = Vertical leakage (unit of length/unit of time);
K_v = Vertical hydraulic conductivity (unit of length/unit of time);
$(h_0\text{-}h)$ = Hydraulic head difference across the confining unit (unit of length); and
b'= Thickness of confining unit (unit of length).

This equation shows that the amount of leakage through a confining unit is proportional to K_v and h_0-h. The higher either of these values is, the higher the leakage. In contrast, as the unit thickens (e.g. as b increases), the leakage decreases. The primary assumption for evaluating the effectiveness of a confining unit is that the smaller the leakage, the better protected is the underlying aquifer.

Equation (1) can be modified by including the porosity of the confining material to obtain the average linear velocity, which is the rate at which groundwater moves through the material (Freeze and Cherry, 1979):

$$v = \frac{K_v(h_o - h)}{n_e b'} \qquad (2)$$

where n_e = effective porosity and v = average linear velocity(unit of length/unit of time). Because this equation is based on the Darcy equation, the average linear velocity varies with changes in K_v, h_0-h, and b in the same way that q_v does and it is inversely proportional to the effective porosity, n_e. Therefore, the average linear velocity increases with decreasing porosity.

Once this velocity is computed, it is straightforward to determine the amount of time it takes for groundwater to travel through a confining unit. Using equation (2), the travel time through a confining unit of thickness b is :

$$t = \frac{b'}{v} \qquad (3)$$

where t = travel time (units of time). We can re-arrange terms in order to obtain the confining unit thickness as a function of K_v, h_o-h and n, for a fixed groundwater travel time, t. This is accomplished by first substituting equation (2) for v in equation (3), which yields the following expression:

$$t = \frac{b'}{\left(\frac{K_v(h_o - h)}{n_e b'}\right)} \qquad (4)$$

Re-arranging terms in order to solve for b results in:

$$b' \sqrt{\frac{K_v(h_o - h)t}{n_e}} \qquad (5)$$

This relationship puts the confining unit thickness as a function of K_v, h_0-h, n_e and t, and is a convenient form for evaluating the thickness of confining unit for various input values.

Methodology

Hydraulic parameters Calculations of the thickness of a confining layer were conducted using different values of vertical hydraulic conductivity, K_v. The values used in calculations presented in this paper are representative of values observed in hydrogeologic environments in Minnesota. Generally, confining units are composed of either 1) unconsolidated materials such as glacial till or lake clays or 2) shale, siltstone, or mudstone. Table 1 contains K_v measurements for unconsolidated materials in Minnesota which were obtained from pumping tests, field tests, and laboratory tests. Table 2 contains a similar set of values for some of the bedrock confining units.

The values for effective porosity, n_e, and the hydraulic head difference across the unit (h_0-h) were held constant, for the purposes of this study. The effective porosity is the amount of interconnected pore space through which fluids can pass, expressed as a percent of bulk volume. Effective porosity is always less than total porosity (EPA, 1987). The value selected for porosity, 0.20, is based on ranges for unconsolidated materials (Freeze and Cherry, 1979), specific yield compilations (Johnson, 1967), and direct measurements (Miller, 1989). These results indicate that, generally, while the total porosity of fine-grained unconsolidated materials is as high as 60 to 70 percent, the effective porosity, which in some circumstances is the same as specific yield, can be as low as 5 or 10 percent. Johnson (1967) indicates that specific yield measurements based on field tests (with results on the order of 5 to 10 percent) likely underestimate effective porosity in fine-grained materials. This observation is substantiated by actual effective porosity measurements which range from 0.268 to 0.312 (Miller, 1989). Therefore, the value of 0.20 used for the effective porosity throughout this paper provides conservative (i.e., faster) estimates of groundwater flow velocities. Higher porosities than the value selected will yield slower groundwater flow velocities.

Hydraulic head differences are the driving force for groundwater movement, and values of 10 and 25 feet were used in the analysis presented in this paper. A 10 foot head difference is used in Minnesota at a reconnaissance level to identify confining layers using static water levels reported by well drilling contractors. Clearly, greater and lesser head differences across effective confining layers are documented for some areas. However, the values used here will likely be used for many areas where detailed characterization of hydraulic relationships have not been conducted. The main objective of the analysis presented here is to provide a conceptual basis for approaching travel time through confining units. The 25 foot head difference is used to demonstrate the effects increasing hydraulic separation have on thickness estimates.

Time of Travel (TOT) The presence of fine-grained confining units in many areas of Minnesota likely protects wells from pathogen sources. The viability of bacteria and viruses in groundwater must be factored into determining a TOT for porous media aquifers. However, no definitive studies are available to provide a reference for this. Most studies are directed toward evaluating pathogen viability in 1) soils where sewage sludge is applied or 2) soil columns constructed in laboratory settings. Very limited field research is available for porous media aquifers (MDH, 1995). A two-year TOT was used as a conservative value and is based on discussions with EPA staff.

Example Calculation

To compute the thickness of confining material required to ensure a TOT of 2 years, it is necessary to use equation (5). Assuming the vertical hydraulic conductivity, K_v, of the confining material is 0.005 ft/day, the effective porosity, n_e, is 0.2, and the head difference is 10 ft. The calculated thickness is then given by equation (5):

Thus, the minimum thickness of this confining material to provide for a two-year TOT is 13.5 ft.

Results

Hydraulic conductivity values ranging from 0.000001 to 1 ft/day were used to calculate confining layer thicknesses using equation (5). The confining unit thickness reflecting a two year TOT are presented in Table 3 and in Figure 1. Results show that as the vertical hydraulic conductivity decreases, so does the confining unit thickness required. For very low values of K_v (i.e., less than $5x10^{-5}$ feet/day), the thickness is less than 1 foot, whereas for values in excess of 0.01 and 0.03 feet/day (for h_0-h values of 25 and 10 feet, respectively), the required thickness is over 30 feet.

Comparison of the data in Tables 1 and 2 with the results in Figure 1 indicates that many confining units in Minnesota have sufficiently low hydraulic properties that groundwater TOTs of two years or more result from thicknesses of as little as 0.5 feet. Generally, a thickness of 10 feet or less is required for clay-rich sediments. Two or three times that thickness may be required for silty or sandy till.

The methodology presented can be used to estimate the minimum thickness of confining material required to protect a drinking water supply well from disease organisms. For illustrative purposes, only the values of K_v were changed while n_e, (h_0-h), and time were held constant. These parameters can be applied to reflect local hydrogeologic conditions and provide greater flexibility in using this methodology. Methods of measuring vertical hydraulic conductivity vary and some may be more representative of actual field conditions than others. Because the TOT estimates are so closely tied to vertical hydraulic conductivity, care should be taken to ensure values used in TOT calculations are representative of the geologic material being evaluated.

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APPENDIX III

PUMPING EFFECTS OF TRANSIENT NONCOMMUNITY WELLS ON A FIXED RADIUS APPROACH TO DELINEATING WELLHEAD PROTECTION AREAS

Pumping Effects of Transient Noncommunity Wells on a Fixed Radius Approach to Delineating Wellhead Protection Areas

Introduction

The purpose for this paper is to 1) assess the area of contribution for small diameter, public water supply wells and 2) determine whether isolation distances specified in the Minnesota well code (MR 4725) can be used to define a wellhead protection area that will protect users from acute health effects related to disease organisms.

Background

The Minnesota Department of Health (MDH) is the lead agency for developing and implementing Minnesota's wellhead protection (WHP) program. The goal of WHP is to prevent contaminants which may adversely affect human health from entering public water supply wells. WHP must address short- and long-term health effects of potential contaminant sources. MDH has determined that the users of public water supply wells must be protected from acute health effects related to disease organisms and direct entry of contaminants into the well. The isolation distances from contaminant sources which are specified in the Minnesota well code have been identified as the means of providing this basic level of WHP. MDH proposes that an inner WHP zone be defined using 1) a 150 foot radius for all public wells with watertight casing or 2) a 200 feet for wells without watertight casing. These are the maximum isolation distances used for new well construction. Owners of all types of public wells will have to ensure that isolation distances for contaminant sources specified in the Minnesota well code be maintained or that non-complying sources be adequately monitored. The owners of community and nontransient noncommunity wells will have to delineate an outer WHP area and implement a contaminant source management plan in addition to maintaining the isolation distances in the inner zone. Because of this requirement, these types of wells will not be addressed in this paper and the focus will be on transient noncommunity wells.

The principal health concerns of the users of transient water supply wells are the acute health effects of 1) pathogens or 2) high levels of chemical contaminants. Both of these concerns, particularly high levels of chemical contaminants may result from physical damage to the well or to nearby spills or leaking storage tanks. MDH or local agencies with delegated authority regularly inspect transient water supply wells to ensure that they are protected from physical damage. The emergency response programs of the Minnesota Pollution Control Agency and the Minnesota Department of Agriculture that deal with contaminant releases from accidental spills or leaking storage tanks are implemented on a statewide basis. These efforts should protect the users of transient wells from high levels of contamination resulting from these types of contaminant releases. Therefore, delineation of WHP areas for transient wells can focus on protecting these wells from pathogens. MDH proposes that 1) the 150 foot radius for transient wells with watertight casings and the 200 foot radius for wells without watertight casings is sufficient to protect them from pathogens and 2) these distances are most effective for unconfined porous media (sand, gravel, or sandstone) aquifers.

The applicability of assigning a fixed radius to delineate a WHP area for transient noncommunity wells must reflect the hydrogeologic setting of the aquifer being used. Typically, transient noncommunity wells are small diameter (six inches or less) and pump less than a million gallons annually. Minnesota has approximately 10,000 transient water supply wells located throughout the state which pump from aquifers representing a wide variety of hydrogeologic settings. Groundwater movement in near-surface karst or near-surface fractured rock aquifers cannot be accurately determined without local hydrogeologic studies. For the purposes of this paper, near-surface is defined as where the bedrock surface occurs within 50 feet of the land surface. Assigning a fixed radius, no matter what practically applied distance, to wells in these hydrogeological settings is not likely to be successful in identifying and properly managing all potential pathogen sources. More frequent microbiological monitoring is the most appropriate and practical approach to public health protection for transient noncommunity wells which pump from near-surface karst and near-surface fractured rock aquifers. However, the 150 foot and 200 foot radii proposed to delineate WHP areas will still be used to identify nearby potential sources of pathogens or chemical contaminants.

Transient noncommunity wells which pump from confined aquifers are likely to be protected from pathogen sources by the presence of one or more confining layers. Maintaining the isolation distances from pathogen sources for these wells is likely to be more than sufficient to accomplish wellhead protection goals. Here, identifying and properly managing other wells within the WHP area should have priority over managing potential pathogen sources.

Recognizing that a fixed radius approach to delineating WHP areas 1) is not appropriate for near-surface karst or near-surface fractured rock aquifers and 2) has limited applicability for confined aquifers narrows its effective use to unconfined porous media aquifers. The following discussion reflects this application for using a fixed radius to delineate WHP areas for transient noncommunity wells which pump from these types of aquifers.

Methodology

The WHPA Code (Version 2.0) developed by the U.S. EPA was used to 1) calculate hypothetical capture zones for several types of transient noncommunity wells pumping from an unconfined porous media aquifer and 2) reflect the maximum amount of pumping anticipated for this type of public water supply well. The wells are assumed to fully penetrate the aquifer. Daily water use was calculated using the <u>On-site Sewage Treatment Handbook</u> published by the Minnesota Extension Service. This is the principal water use reference used by MDH for review of plumbing plans for public buildings and facilities. It was assumed that by combining the maximum anticipated daily pumping with minimal aquifer performance a worst case scenario for radial flow toward the well will be achieved. The calculated zone of contribution was then compared to the 150 foot and 200 foot isolation distances proposed by MDH to delineate WHP areas for transient noncommunity water supply wells.

Aquifer parameters - An unconfined, fine-grained sand aquifer was selected having a thirty foot saturated thickness, a transmissivity of 1350 feet squared per day, no recharge to the aquifer, and a hydraulic gradient of .001 feet per feet. The minimum aquifer thickness calculated to keep draw down to less than ten percent of the saturated thickness for this aquifer setting is thirty feet. This was determined using the Single Layer Analytical Element Model developed by the University of Minnesota. This aquifer setting will likely produce the widest possible capture zone relative to the direction of groundwater flow and still be realistic in terms of 1) the draw down requirements of the WHPA Code and 2) the estimated yield requirements for large- sized transient noncommunity systems.

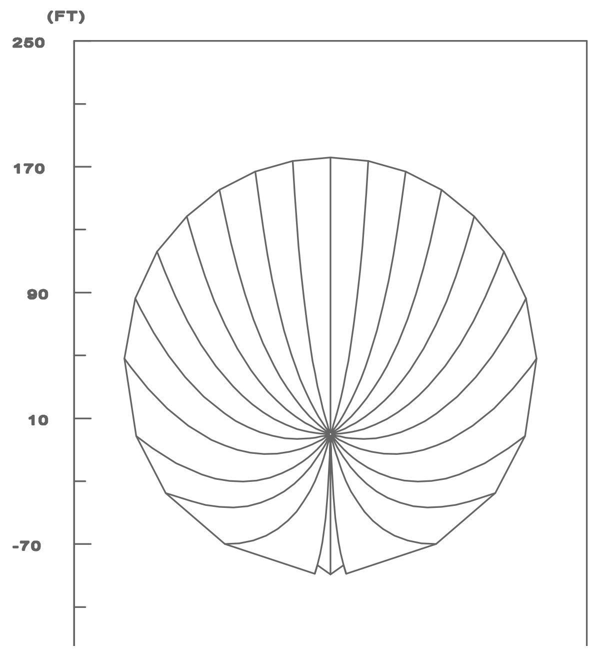
Time of travel - A principal function of the inner WHP zone is to protect wells from pathogen sources. The viability of bacteria and viruses in groundwater must be factored into determining a time of travel for porous media aquifers. However, no definitive studies are available to provide reference for this. Most studies are directed toward evaluating pathogen viability in 1) soils where sewage sludge is applied or 2) soil columns constructed in laboratory settings. Very limited study is available for porous media aquifers, especially those which exhibit low hydraulic gradients. A one year time of travel was selected for this exercise to reflect the maximum time period recommended by U.S. EPA to protect wellheads from virus and pathogenic bacteria contamination. (U.S. EPA, Office of Groundwater Protection, "Guidelines for Delineation of Wellhead Protection Areas", June 1987).

Types of transient wells modeled - MDH determined that restaurants and hotels/resorts will most likely have the greatest daily water use among transient noncommunity water supply wells. Hypothetical restaurant and hotel wells were modeled which 1) use more water than anticipated and 2) pump from a low yield aquifer setting. It is assumed that if the proposed radii are an equal or greater distance than the one year zone of contribution for these wells, than they should apply to all transient wells which pump less water and have smaller zones of contribution. Therefore, the radii proposed by MDH to define an inner WHP zone should apply to transient wells which pump from unconfined sand, gravel, and sandstone aquifers. The limitation is the proposed radii often will not be as great as the upgradient distance of the zone of contribution but this can only be determined by delineating an outer WHP area. This will not be required for transient non-community wells.

Restaurant Wells

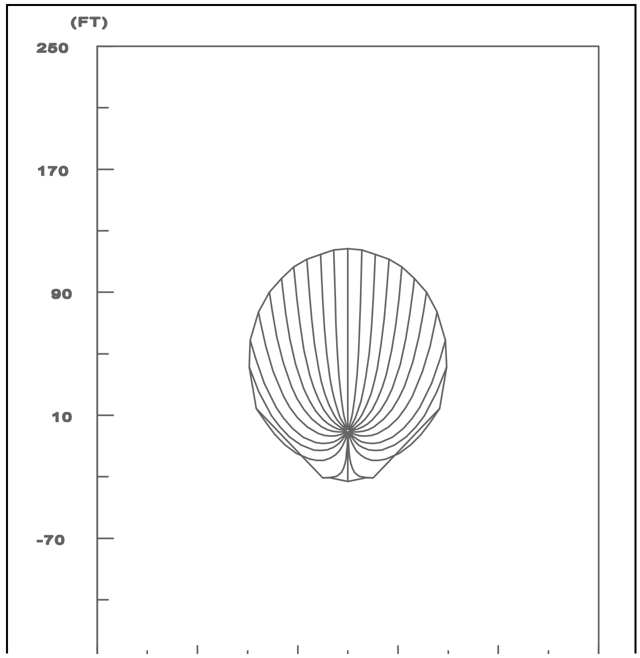
The maximum daily water use for restaurants is 40 gallons per seat per day according to the On-site Sewage Treatment Handbook. A restaurant with 200 seats was used which would reflect a large truck stop or the restaurant at a large country club. The daily water use for this hypothetical restaurant is 8,000 gallons or 1,070 cubic feet per day. The MWCAP module in the WHPA Code was used to delineate a capture zone using a one year time of travel. One year is considered the minimum time that should be considered for bacteria to die off or be present in non-viable numbers. The following input parameters were used to produce the modeling results shown in figure 1:

daily water use	1070 $feet^3$/day
aquifer thickness	30 feet saturated
transmissivity	1350 ft^2/day
porosity	.25
hydraulic gradient	.001
time of travel	1 year



The capture zone for the well is shown by the lines which originate at the well and go the top of the page. The direction of groundwater movement is from the top of the page to the bottom. The well is located at X and Y coordinates of 0 feet. This well probably represents the maximum amount of water that would be pumped by a restaurant well and would require an appropriations permit from the Minnesota Department of Natural Resources because it would pump more than one million gallons of water annually. The capture zone for this well does not extend beyond 150 feet except in the upgradient direction which can only be adequately determined by delineating an outer WHP area. Note that the down gradient portion of the capture zone is less than 100 feet which is significantly less than the 1) 150 feet proposed by MDH to define a WHP area for a transient noncommunity water supply well which has a watertight casing and 2) 200 feet for wells without watertight casing.

The well shown in figure 1 represents the maximum daily pumping anticipated for a restaurant that would have its own water supply. A lower daily water consumption was used to represent the size of restaurant that is more representative of those in rural Minnesota. This scenario is a restaurant with six booths, six tables, and a lunch counter that seats eight. The maximum of 40 gallons per seat was used to determine the following daily water consumption:



(6 booths X 4 seats/booth) + (6 tables X 4 seats/table) + 8 counter = 56 seats

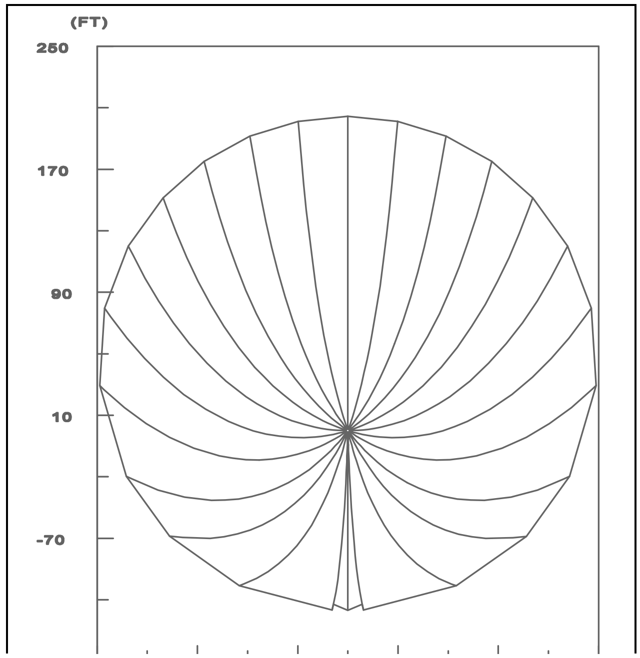
56 seats X 40 gallons/seat/day = 2,240 gallons/day = 300 $feet^3$/day

With the exception of the lower daily water use, the same model input parameters were used as for the large restaurant. The capture zone for this well is shown in figure 2. Note how much smaller the capture zone for this well is compared to the well shown in figure 1. The capture zone does not extend beyond the 150 foot isolation distance even in the upgradient direction of groundwater flow.

Hotel and resort wells

The maximum daily water use for hotels and resorts is 60 gallons per guest according to the On-site Sewage Treatment Handbook. A hypothetical resort was used which serves 200 guests and therefore, pumps 12,000 gallons of water per day (1,604 ft^3). A facility larger than this will likely have enough employees to be classified as a nontransient noncommunity supply.

The same model input parameters as in the large restaurant scenario (figure 1) were used except for the greater daily volume of water pumped. The capture zone for this well is shown in figure 3. Note that it has a larger sized area of contribution than the well shown in figure 1. This is due to the increased pumpage because all other input parameters remained the same. This well probably represents the maximum amount of water that would be pumped by a transient noncommunity facility that has its own water supply. It would require an appropriations permit from the Minnesota Department of Natural Resources because it pumps more than a million gallons of water annually.



Note that the zone of contribution extends about 1) 210 feet in the up gradient direction of groundwater flow, 2) 100 feet down gradient, and 3) 155 feet at right angles to the direction of groundwater flow. The later distance is about five feet greater than the 150 isolation distance for wells with watertight casing.

Discussion of Results

The WHPA Code used for this exercise assumes that the well pumps continuously which is not likely for actual operation. Rather, nontransient noncommunity wells would pump for a total time period of about six to eight hours a day. This would require the aquifer to have a much greater saturated thickness or a greater hydraulic conductivity to provide the desired yield over this time period. Increasing either of these aquifer properties would result in a higher aquifer transmissivity and would produce a more narrow zone of contribution around the well, except that it would be extended in the upgradient direction of groundwater flow. Also, the model assumed that there was no recharge to the unconfined aquifer which is unlikely. Therefore, the aquifer conditions used in this exercise should be viewed as a worst case scenario in which to produce the daily yield anticipated for a transient noncommunity water supply well. This is particularly true for the large restaurant and large resort well scenarios.

Model results demonstrate that a 150 foot isolation distance coincides or exceeds a one year time of travel for the three scenarios, except in the upgradient direction of flow. Defining the upgradient extent of the capture zone can only be accurately accomplished by delineating an outer WHP area. This will not be required for transient noncommunity wells. Also, the calculated distance at right angles to groundwater flow for the large resort well (figure 3) was about 155 feet. However, because the aquifer setting used for this exercise is a worst case scenario, the five foot difference should be viewed as not significant. Existing transient wells are usually completed in more transmissive materials and/or pump much less water than the wells used for this exercise.

The 150 foot radius for wells with watertight casings and a 200 foot radius for wells without watertight casings can be used to delineate an inner WHP for wells pumping from unconfined porous media aquifers. These radii should meet or exceed a one year travel time estimated to reflect the time required to reduce the viability of pathogens in groundwater. Implicit with this assumption is these isolation distances are most appropriately applied to transient wells completed in unconfined porous media aquifers.

Conclusions

Using a fixed radius to delineate an inner WHP areas is most practical for unconfined aquifer settings where porous media flow predominates. Capture zone analysis for near-surface karst and near-surface fractured aquifers requires detailed hydrogeologic investigations around a specific well. Here a fixed radius, no matter what practically applied distance, is not likely to identify all potential pathogen sources which may impact the well. However, it is currently not practical to do this and the 150 and 200 foot radii proposed by MDH would still be used to identify nearby potential pathogen sources. More frequent monitoring of microbiological contamination is probably the most appropriate approach to protecting well users.

A fixed radius should provide more than adequate protection to confined aquifers which are already protected by one or more confining layers. An inner WHP area for wells which are properly constructed into confined aquifers is still needed. However, protecting the well from damage and focusing source management on other wells which reach or penetrate the confined aquifer should receive highest priority.

MDH proposes to use a 150 foot radius to define the inner WHP zone for all types of public water supply wells which pump from unconfined porous media aquifers and which have water tight casings. This distance would be increased to 200 feet for wells which do not have watertight casings. The inner WHP zone will be the only one required for transient noncommunity wells. The proposed radii are intended to define a WHP area to protect nontransient noncommunity wells from pathogens, damage, and direct entry of chemical contaminants. The modeling results described in this paper demonstrate that, except in the upgradient direction of groundwater flow, a 150 foot radius should approximate and likely exceed the one year zone of contribution for small diameter wells which pump from unconfined, porous media aquifers. A one year travel time is recommended by U.S. EPA to protect wellheads from bacteria and viruses. Therefore, the radii proposed by MDH are appropriate for defining the WHP area for transient wells which pump from these types of aquifers.