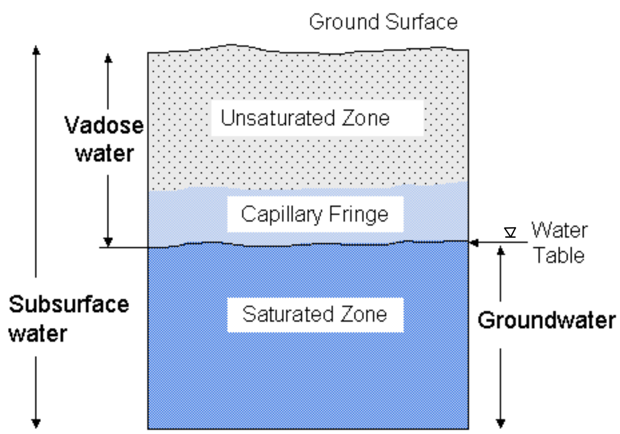
Groundwater

Groundwater is both a precious resource lying beneath much of the state's land surface and a great engineering challenge to those who encounter it during planning and construction of the state's infrastructure. As a resource, it is worthy of the extreme care that must be taken to protect it. As an engineering challenge, it can humble even the most experienced designer or contractor, particularly if it catches them by surprise.

"Hydrology is the study of water. In the broadest sense, hydrology addresses the occurrence, distribution, movement, and chemistry of all waters of the earth" (Fetter, 1988). This section will deal with the interaction of water and geologic materials, referred to as **hydrogeology.**

Water that reaches the earth's surface will either drain across the land via some type of surface drainage regime, or will infiltrate into the subsurface. Infiltrated water is given the name **subsurface water** (figure 1), and it includes water in the zone of aeration (unsaturated zone), where it is called **vadose water**, and water in the zone of saturation, known as **groundwater**. The **capillary fringe** consists of vadose water held immediately above the saturated zone by capillary forces, the height of which depends on the diameter of the pore spaces in the material.

Figure 1: Subsurface water diagram



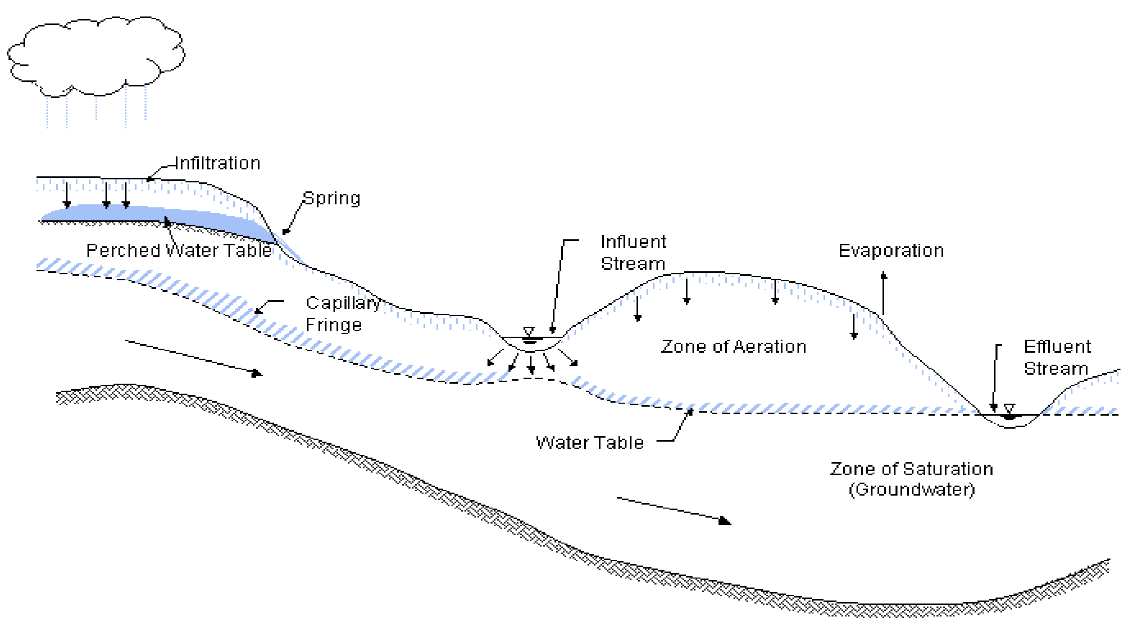
An **aquifer** is typically defined as a saturated rock or soil unit that is sufficient in both permeability and extent to transmit economic quantities of water to wells or springs. The term is relative to other available sources of water and to the quantity of water required. Thus, a formation that is an aquifer in one situation may not be so in another. Unconsolidated sands and gravels, sandstones, carbonates, basalt flows, and fractured igneous and metamorphic rocks are examples of geologic units known to be aquifers.

The usage of the term aquifer in regards to water supply requirements makes it difficult and misleading to use in discussions of general subsurface water occurrence. A more appropriate term for use in highway construction would be **water-bearing zone** (or layer), which may be defined in a broader sense as being any geologic formation or stratum, consolidated or unconsolidated, or geologic structure (such as a fracture or fault zone) that is capable of transmitting water in sufficient quantity to be either of use or of concern.

A **confining layer** is a geologic unit having low permeability in comparison to a stratigraphically adjacent water-bearing zone. There are very few, if any, geologic formations that are absolutely impermeable. Weathering, fracturing, solution, and biological disturbance have affected most rock and soil units to some degree. However, the rate of groundwater movement in these units can be exceedingly slow. Typical geologic materials that make up confining beds are clays, tills, shales, and igneous and metamorphic rock units that are not extensively fractured.

Water-bearing zones (aquifers) can be classified on the basis of the presence or absence of an overlying confining bed, and the resultant **potentiometric surface** - which is defined as the level to which water will rise in a tightly cased well. A water-bearing zone with no overlying confining layer will have a potentiometric surface that is equal to the atmospheric pressure. This type of system is known as an **unconfined** or **water table aquifer** (figure 2), and the potentiometric surface is often called the **water table**. Recharge to this type of aquifer can be from downward seepage through the unsaturated zone, through lateral groundwater flow, or by seepage from underlying strata.

Figure 2: Schematic Illustration of the Occurrence of Groundwater in an Unconfined (Water Table) System (Adapted from FHWA, "Highway Subdrainage Design")[1]



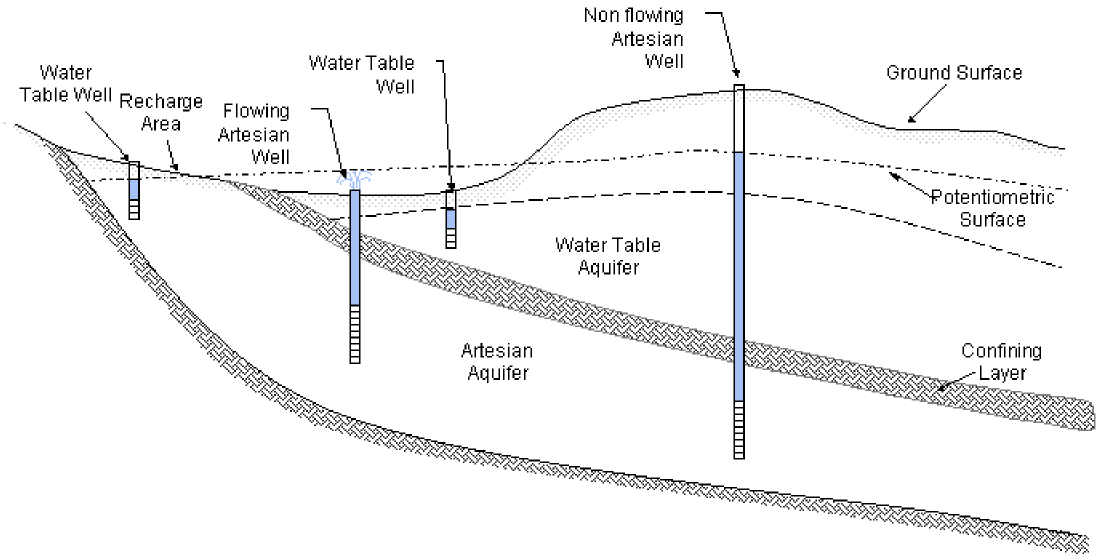
[1] Moulton, Lyle K., 1980, “Highway Subdrainage Design”, Report No. FHWA-TS-80-224

Perched groundwater is unconfined groundwater separated from an underlying body of groundwater by an unsaturated zone. It occurs when subsurface water percolating downward is held by a bed or lens of low-permeability material. Perched groundwater may be either **permanent**, where recharge is frequent enough to maintain a saturated zone above the perching bed, or **temporary**, where intermittent recharge is not great or frequent enough to prevent the perched water from disappearing with time as a result of drainage over the edge or through the perching bed.

A water-bearing zone with an overlying confining layer and a potentiometric surface that rises above the base of the confining layer is known as a **confined** or **artesian aquifer** (figure 3).

When the potentiometric pressure is sufficient to raise the water level above the ground surface, it is referred to as a **flowing artesian** condition. Recharge to confined aquifers generally occurs some lateral distance away, where the aquifer is not confined.

Figure 3: Confined Aquifer (artesian flow conditions) Adapted from FHWA, "Highway Subdrainage Design"



Groundwater Occurrence

Differing geologic features and land forms of Minnesota cause significant differences in groundwater conditions. Minnesota is situated on the southern margin of the Canadian Shield, which is a region of Precambrian crystalline and metamorphic rocks. In Paleozoic times, nearly 2,000 feet of clastic and carbonate sediment were deposited in a shallow depositional basin known as the Hollandale embayment. During the Cretaceous period, shallow seas again deposited a layer of sediment, mainly in the southwestern and extreme western portions of the state. During the Pleistocene Epoch, four continental glaciations advanced and retreated across Minnesota, blanketing the bedrock with drift as thick as 600 feet. Sand and gravel deposits in the drift constitute important aquifers, particularly in western Minnesota where the drift is thickest and where bedrock aquifers have small yields.

Quaternary Hydrogeology

Surficial drift aquifers are exposed at or near the land surface and cover a large portion of the central part of the state. These aquifers consist of alluvial outwash, beach-ridge, and ice-contact deposits. Extensive outwash deposits are a significant source of water and are potential problems for construction excavation and dewatering.

Buried drift aquifers are present in nearly all areas of the state, except in the northeast and southeast where the drift is thin or absent. The aquifers consist of discontinuous layers of fine to coarse sand and gravel that are isolated from one another by till. Where they have sufficient aerial extent, these aquifers are a good source of moderate to high volumes of water. Occasionally, these aquifers are confined and produce flowing artesian conditions when encountered during pile driving or structure excavations.

Alluvial aquifers consist of sand and gravel locally interbedded with silt and clay. They are found in present-day river valleys and buried river channels, and include river terrace deposits. These aquifers are often very prolific producers, and can be difficult to dewater for construction of bridge piers and abutments. The layered nature of the deposits along with the typical river valley topography often yields significant artesian conditions that must be addressed during the subsurface exploration program.

Bedrock Hydrogeology

Only in the southeastern portion of the state are the bedrock aquifers prolific water producers. These Paleozoic sedimentary formations (such as the St. Peter sandstone, Prairie du Chien dolostone, Jordan sandstone, etc.) can be a potential source of problems for construction dewatering because of their proximity to the surface in many locations. Also, because these formations are used extensively for water supply, care should be taken to limit their exposure to contamination from construction activities or from removing overlying confining beds.

Elsewhere in the state, bedrock aquifers are typically low yielding and are used only because of the absence of Quaternary aquifers. These aquifers generally have little impact on construction projects, but care must be taken to limit impact to wells completed in these aquifers.

More detailed information on the hydrogeology of specific areas within Minnesota can be obtained from the Minnesota Geological Survey (link below).

Groundwater Analysis

The level of analysis will depend on the extent of the project and the potential impact of the groundwater (or in some cases, the potential impact to the groundwater). All projects will require some knowledge about groundwater levels and soil types in order to identify potential impacts. This initial data can found from a variety of sources, including geologic and hydrologic publications from the Minnesota Geological Survey (MGS); drilling records from the MnDOT Foundations Unit; and well construction records from the Minnesota Department of Health. Online links to these sources are:

Minnesota Geological Survey:
http://www.mngs.umn.edu/index.html

MnDOT Geotechnical borings:
http://www.mrr.dot.state.mn.us/geotechnical/foundations/Gis/gi5_splash.html

Department of Health well records:
http://www.health.state.mn.us/divs/eh/cwi/index.html

For constructions projects, Initial studies are typically carried out by District level Materials/Soils personnel, and normally include their own shallow drilling exploration program. This level of investigation will often reveal only that there is a need for groundwater control. Depending on the extent or complexity of the anticipated control, additional exploration and analysis may be warranted. Exploration assistance and groundwater control designs are available through the MnDOT Geotechnical Section. Additional exploration is often necessary to provide information for the design of a groundwater control system, such as **hydraulic conductivity**, **aquifer thickness**, **hydraulic gradient**, and gradation of aquifer materials.

Aquifer Characterization

The property of a water-bearing formation that relates to the flow of groundwater is called **hydraulic conductivity (*K*)** and indicates the quantity of water that will flow through a unit cross-sectional area of a porous medium per time under a hydraulic gradient of 1 at a specified temperature. A **hydraulic gradient** of 1 means that the head falls 1 foot for every 1 foot of horizontal flow distance. For convenience, *K* is expressed as the flow in gallons per day (or cubic feet per day) through a cross-sectional area of one square foot of water –bearing medium under a hydraulic gradient of 1 at a temperature of 60^0F. This results in units of gpd/ft^2 (Equation 1) or feet/day (Equation 2)

$$1\ K\ \text{Unit} = \frac{\text{1 gallon of water at } 60^0\text{F/day}}{\text{1ft}^2\text{ of aquifer (-1ft/ft gradient)}} = \text{gpd/ft}^2 \quad \text{(Equation 1)}$$

$$\text{Or, } 1\ K\ \text{Unit} = \frac{\text{1 ft}\cancel{^3}\text{ of water at } 60^0\text{F/day}}{\cancel{\text{1ft}^2}\text{ of aquifer (-1ft/ft gradient)}} = \text{feet/day} \quad \text{(Equation 2)}$$

Hydraulic conductivity can be estimated from a table that shows typical ranges of values for common soil types (Table 1) or it can be calculated from the “Moulton” formula (Equation 3) if certain parameters of the porous media are known. It should be noted that many publications use the term **Coefficient of Permeability,** or often just **permeability** when discussing the same aquifer parameter as hydraulic conductivity. When dealing in the realm of groundwater, these parameters are essentially the same, but that does not hold true when other fluids (such as petroleum) are involved.

Table 1 Typical Soil Permeability Values

MnDOT Triangular Textural Classification	Hydraulic Conductivity (ft/day)	Degree of "Permeability"
Gravel	100-10,000	High Permeability
Sand	1-100	Permeable
Loamy Sand	.001-1	Low Permeability
Sandy Loam	.001-.1	Low Permeability
Loam	.0001-.001	Impermeable to Low Permeability
Silt Loam	0001-.001	Impermeable to Low Permeability
Sandy Clay Loam	0001-.001	Impermeable to Low Permeability
Clay Loam	10^{-5}-10^{-3}	Impermeable
Silty Clay Loam	10^{-5}-10^{-3}	Impermeable
Sandy Clay	10^{-5}-10^{-2}	Impermeable
Silty Clay	10^{-6}-10^{-3}	Very Impermeable to Impermeable
Clay	10^{-7}-10^{-5}	Very Impermeable

The following formula was adapted from the formula developed by Moulton (FHWA-TS-80-224) for permeability (hydraulic conductivity) analysis on granular bases and sub base material:

$$K(feet/day) = \frac{6.214*10^5(\frac{D_{10}}{25.4})^{1.478}*n^{6.654}}{(P_{200})^{0.597}} \qquad \text{(Equation 3)}$$

Where:

$$n = porosity = (1 - \frac{\gamma_d}{62.4*G})$$

G=Specific Gravity (assumed 2.7)

$\gamma_d = DryDensity(lbs/ft^3)$

P_{200} = *Percent passing No. 200 sieve (use percentage value such as 2 for 2%)*

D_{10} = *Effective Grain Size (in inches)*

Additional aquifer parameters such as aquifer thickness and water levels are essential for determining the potential impact that groundwater may have on the project. This information may be generally estimated from existing publications or historic subsurface drilling information, but for detailed analysis, there is no substitute for the direct measurement of groundwater levels. Groundwater levels are typically measured by drilling into the subsurface and constructing some type of structure that will allow the groundwater to be measured or sampled, depending on the information required. In Minnesota, subsurface drilling is regulated by the Minnesota Department of Health (MDH) under Chapter 4725, "Rules Relating to Wells and Borings."

A solid stem **auger boring** can be used for a quick look at the subsurface materials and the instantaneous groundwater level. These types of borings are quick but are usually limited in depth, produce a disturbed soil sample, and yield information about the groundwater only while the hole is open. A **piezometer** can be constructed in a drilled hole which usually has a section of the pipe open to the aquifer. Piezometers are typically small diameter (2-inch) plastic pipe with a well screen on the bottom that is placed in a borehole that has been sampled while drilling. This type of construction allows for the long term monitoring of water levels and some aquifer testing such as a **slug test**. According to MDH rules, piezometers cannot be used for pumping water or taking water quality samples. A **monitoring well** can be constructed in a similar fashion to piezometers, but requires a MDH permit and more stringent surface protection. Monitoring wells are usually used to <u>sample</u> groundwater to determine contamination, but can be used to measure overall groundwater quality for the design of permanent groundwater control systems.

On projects where construction dewatering will have a large-scale effect on the project, project costs, the aquifer, or surrounding buildings, **pump tests** may be employed. **Pump tests** are conducted by pumping a **well** for a period of time and noting the change in hydraulic head. They are much more costly to run than slug tests but can provide more accurate information. Contact the Geology Unit with questions on the types of testing appropriate for a project.

Engineering Hydrogeology

Hydrogeological data are applicable to a variety of problems both directly and indirectly affecting the success of any construction project. Groundwater can affect the stability of structures or highways, the costs of construction, the costs of maintenance, and the effects of construction on adjacent properties, wetlands, and wells. It is important to predict adverse conditions so they can be mitigated in the design stages, and not come as a surprise during or after construction. Such predictions can be made only on the basis of adequate hydrogeological information, and can be only as accurate as the data on which they are based. It is, therefore, essential to gather groundwater data as carefully, accurately, and thoroughly as possible.

The determination of groundwater conditions and the general hydrogeological regime of a project site should be addressed during the initial investigative portions of the project. The location of the water table, including the presence of artesian conditions, or a perched water table are important items that must be determined by an exploration program; and careful consideration must be given to its potential impact on construction and long-term life of the project. Current Department design standards require that groundwater be kept at least five feet below the finished grade on roadway projects. Consideration must also be given to groundwater conditions (whether true groundwater or perched water) behind retaining walls and bridge abutments, in backslopes, and springs from rock outcrop/cuts.

Care must be taken to prevent contamination of near-surface aquifers, especially when removing overlying confining layers or when penetrating the aquifers by soil borings or during construction. Construction in areas where groundwater may be encountered has the potential for impacting water wells, particularly down gradient from the project. In areas of the state where wells are particularly sensitive (such as the bedrock aquifers along the North Shore) or where wells are located within 200 feet of major construction, preconstruction inventories are often taken to document the existing condition of the wells. This data can then be used for comparison to post-construction conditions should claims occur.

Control

Groundwater control may be necessary when the water table exists within the frost zone of the roadway. To insure that groundwater does not adversely affect long-term performance of the roadway, the finished grade should be separated from the water table by a depth roughly similar to the depth of frost penetration. This depth is generally considered to range from four to seven feet across the state, and is generally considered to be 5 feet on average.

Every effort should be made to satisfy the grade-water criteria. If grades cannot be kept at least five feet above the water table, then special **groundwater control** designs will be required. Water levels will need to be lowered both temporarily during construction, and permanently for the life span of the pavement.

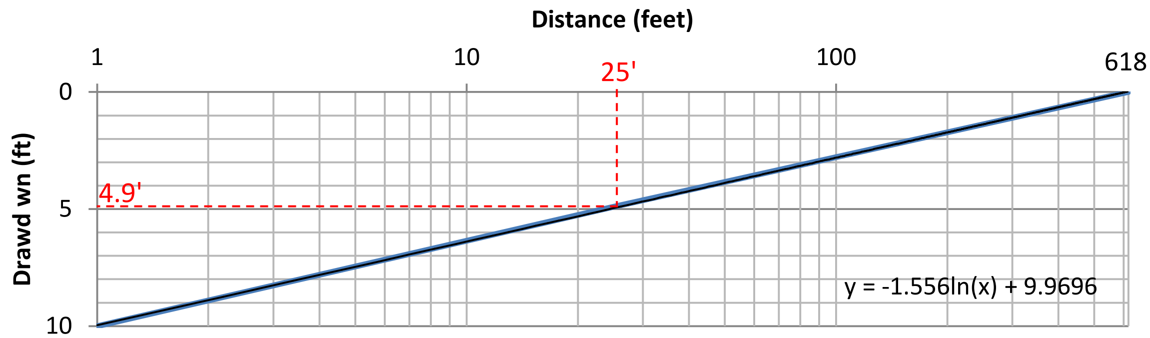
Temporary construction dewatering is normally the responsibility of the contractor. It is important to provide a general assessment of the aquifer characteristics to potential contractors prior to the bidding process. The necessary elements that are important to a contractor, such as hydraulic conductivity, aquifer thickness, and gradation of aquifer materials, are generally necessary for design of the permanent groundwater control system.

Permanent groundwater control is accomplished through the use of gravity drainage methods including longitudinal drains, blanket drains, or cut-off drains. In most cases such drains require project specific designs that relate to aquifer parameters such as soil type, hydraulic conductivity, depth of lowering required, thickness of the aquifer, and most importantly, a place to drain the captured water to. Permanent lowering of the water table should not be undertaken without consideration of possible **adverse impacts**, such as settlement of adjacent structures built on organic soils of loose sands, influence on nearby wells, increased construction expense, and longevity of design (and consequence of failure). The distance from the dewatering site where **drawdown** becomes insignificant is known as the **radius of influence** (L_i). The drawdown at any location between the dewatering location and the radius of influence can be estimated by a simple semi-log plot of drawdown versus distance (Figure 4) by knowing the maximum drawdown at the dewatering element and the radius of influence. The radius of influence (L_i) can be estimated from a formula (Equation 4) derived from Moulton (1980) where the hydraulic conductivity (K) and the maximum drawdown (D) are known.

$$L_i\ (feet) = 5.64 * D\ (feet) * \sqrt{K}\ (ft/day) \qquad \text{(Equation 4)}$$

For example, if the drawdown at the dewatering element is 10 feet, and the estimated hydraulic conductivity of the saturated soil is 120 feet/day, the radius of influence would be: $L_i\ (feet) = 5.64 * 10 * \sqrt{120} = 618\ feet.$ Figure 4 is a semi-log plot of this example problem; the drawdown at 25 feet would be 4.9 feet. [Equation 4 assumes a homogeneous, isotropic media that falls into the "granular" end of the soil spectrum.]

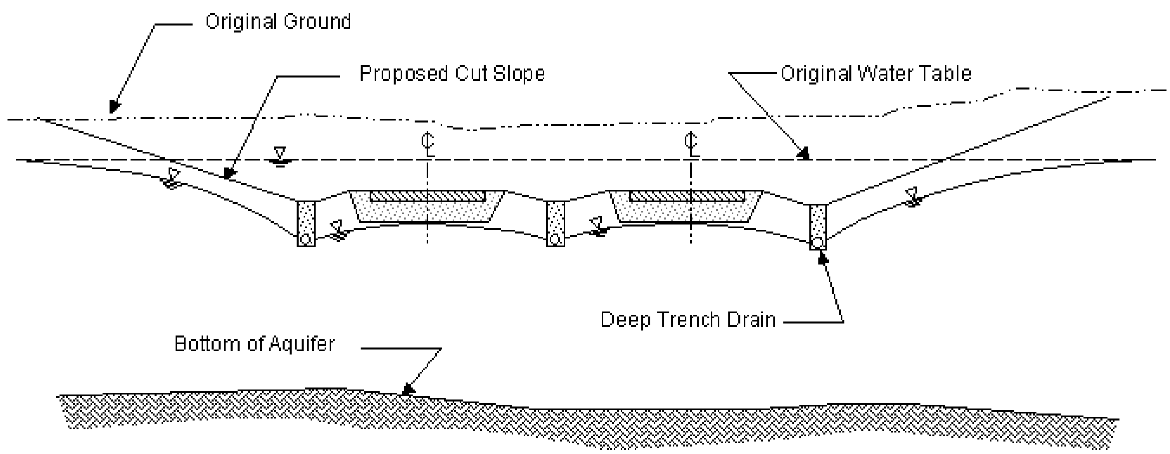
Figure 4: Semi-log Plot of Drawdown vs. Distance



By request, the Geotechnical Section will analyze the hydrogeology of the project area in relation to the roadway design, and provide recommendations for controlling groundwater on the project. The Geotechnical Section currently recommends the use of passive drainage systems to lower the water table. Typically, project requirements and soil properties dictate the use of a specific system, or combination thereof. The two most common systems include the **Deep Drain System** and the **Blanket Drain System.**

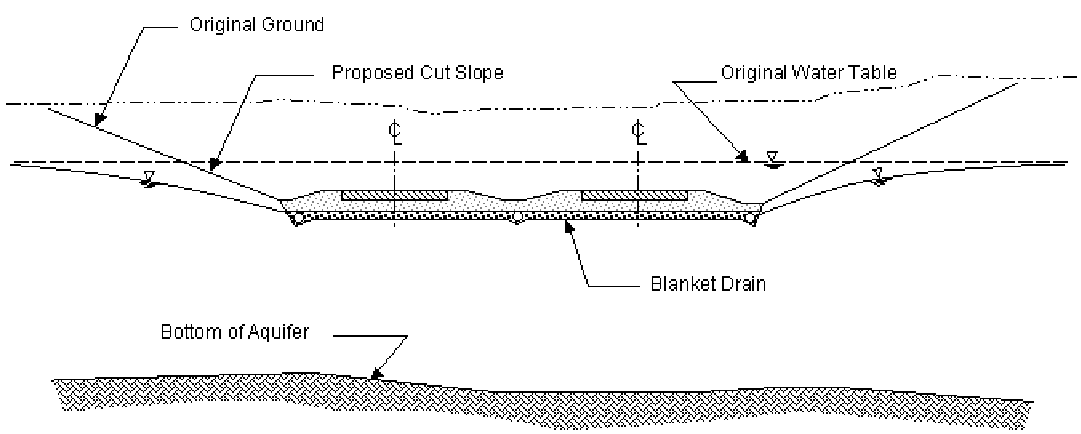
The Deep Drain System consists of deep perforated drainage pipes spaced at distances to keep the groundwater at the appropriate level. These pipes usually parallel the roadway (Figure 5). This system is recommended for moderate to high permeability soils only, since drawdown of the water table between drains would not be adequate in lower permeability soils unless they were very close together.

Figure 5: Deep Drain System, Adapted from FHWA, "Highway Subdrainage Design"



A second drainage system is the **Blanket Drain System**. Blanket drainage systems use an aggregate drainage layer between two geotextile layers. These layers act as filters keeping the fines from plugging the aggregate layer. The blanket is placed in the bottom of the subcut and parallels the finished grade. Water flows into the drainage pipes from the blanket and is then carried to a storm water system. Figure 6 shows the standard blanket drainage system and the assumed groundwater flow. The pipes for the drainage blanket design should be properly sized to carry the amount of water desired for the entire length of the blanket.

Figure 6: Drainage Blanket System Adapted from FHWA, "Highway Subdrainage Design"



These two drainage systems may also be used together on a particular project. This is common on high profile projects where failure of one system could cause closure of a multilane highway and effect many people. The redundancy of two systems would lessen the chance of that occurring.