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# Fundamentals of Groundwater Contamination

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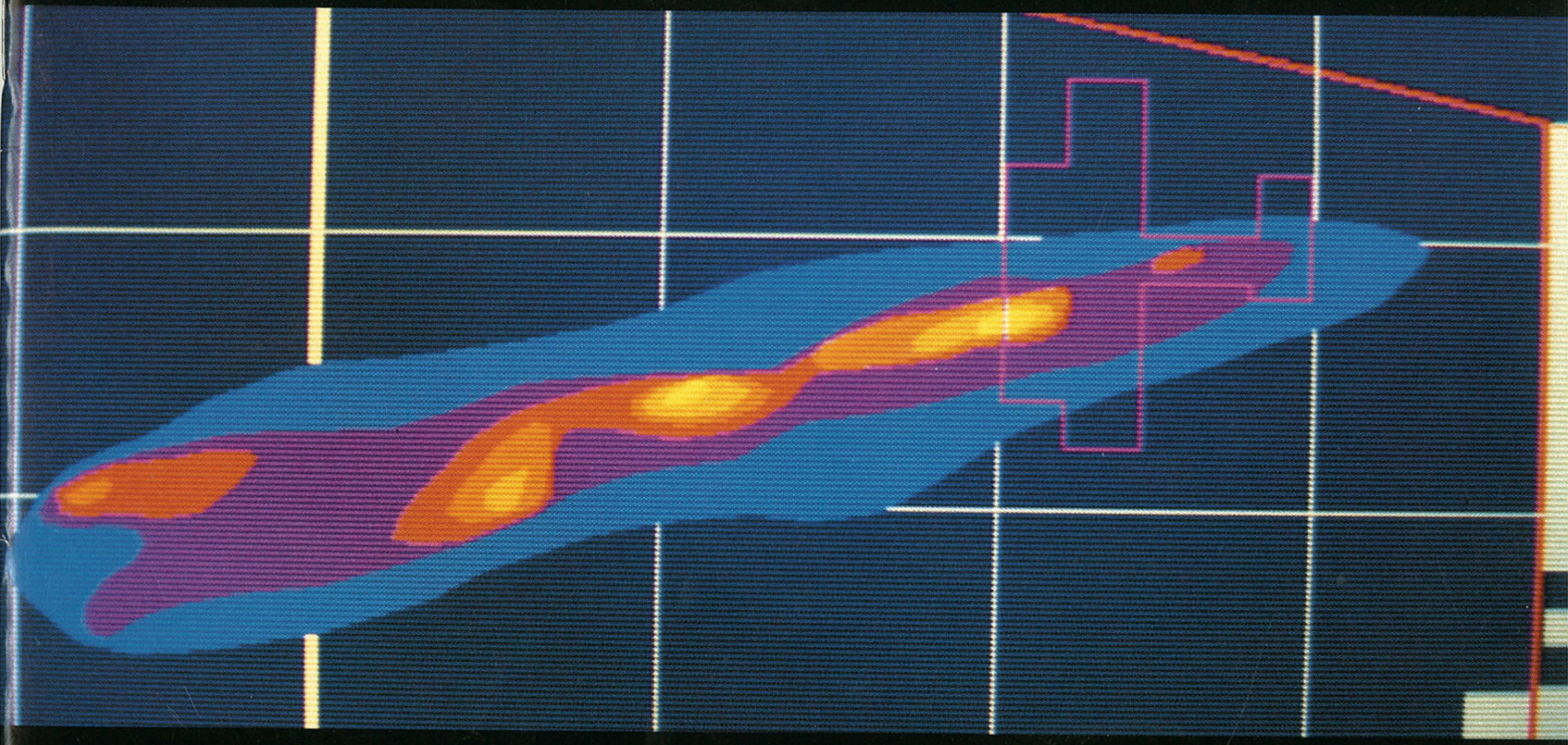

by
Darryll T. Pederson

Educational Circular No. 11

Conservation and Survey Division
Institute of Agriculture and Natural Resources
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# University of Nebraska

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On the front cover: *Areal distribution of U.S. Army Research Department Explosive (RDX) plume in groundwater as of November-December 1984, an example of point-source contamination. Eastern end of plume is under the Capital Heights area (outlined in pink) near Grand Island (white area to the right). Blue is a concentration of .1-10 parts per billion RDX: violet: 10-40 ppb; red: 40-50 ppb; orange: 50-70 ppb; yellow-orange: 70-100 ppb; yellow: >100 ppb. White lines are section roads; bold white line is eastern boundary of Cornhusker Army Ammunition Plant.* Graphics by Donn Rodekohr, CALMIT, CSD.

February 1994

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# Illustrations

## Factors for Converting English System to the International System of Units (SI)

| Multiply English Units | By | To Obtain SI Units |
|---|---|---|
| | **Length** | |
| inches (in) | 25.4 | millimeters (mm) |
| feet or foot (ft) | 0.3048 | meters (m) |
| miles (mi) | 1.609 | kilometers (km) |
| | **Area** | |
| acres | 4047 | square meters (m) |
| square miles (mi) | 2.590 | square kilometers (km) |
| | **Volume** | |
| gallons (gal) | 3.785 | liters (L) |
| acre-feet | 1233 | cubic meters (m) |
| | **Flow** | |
| gallons per minute (gpm) | .00006309 | cubic meters per second ($m^3/s$) |

## Introduction

Groundwater contamination is a common item in today's news. Huge sums of money are being spent to clean up contamination once it has occurred. Experience gained in these cleanup attempts has taught us some valuable lessons. Remediation (cleanup) of a contaminated aquifer is costly and often difficult, if not impossible, to achieve.

Our aquifers will need protection if they are to be sources of water for our future. To provide that protection we need to know how aquifers can become contaminated and how contaminants interact with and travel through aquifer systems if we hope to restore them to a usable condition.

There are two main things to consider in groundwater-contamination investigations. One is the nature of the contaminant. Is it soluble in water? Does it interact with the rock or sediment matrix through which it is moving? Does the contaminant attach itself to other particles or molecules that move with the groundwater flow? Does it degrade to other chemicals? Is it denser than water? These are but a few of the possibilities that must be considered when looking at a given contaminant. Of equal importance is the matrix of earth material that determines the path of the water and contaminant.

Without a detailed knowledge of the geology of an area, any contaminant-movement study would be fruitless. The best one could do would be to see where the contaminant enters and wait to see where it comes out. Low permeability layers of clay and silt have a significant constraining effect on contaminant movement. (*Permeability* is a measure of how readily aquifer material transmits water.) Sands and gravels create high-speed paths for contaminant movement, as do fractures and joints in glacial tills and rock. The continuity of individual beds of earth material is extremely important. These are but a few of the factors that must be considered when studying the paths of contaminant movement.

Hydrogeology is the science of geology that studies the solid part (rocks and sediment) of the earth with emphasis on how fluids such as water occur within this geologic medium. In this publication the principles of groundwater occurrence and movement will be discussed in terms of the different types of geologic settings found in Nebraska and how various kinds of contaminants are likely to move.

## Hydrologic Cycle

Groundwater is part of a hydrologic (water) cycle that is in a dynamic equilibrium. Recharge in the form of infiltrating rainwater and snowmelt is continually replenishing groundwater supplies (fig. 1). The amount of recharge in a given area is determined by the permeability of the soils and the amount, duration and intensity of rainfall. Where soils are finer grained, infiltration rates through the earth's surface are less; more of the total precipitation runs off to nearby streams and rivers. This is especially

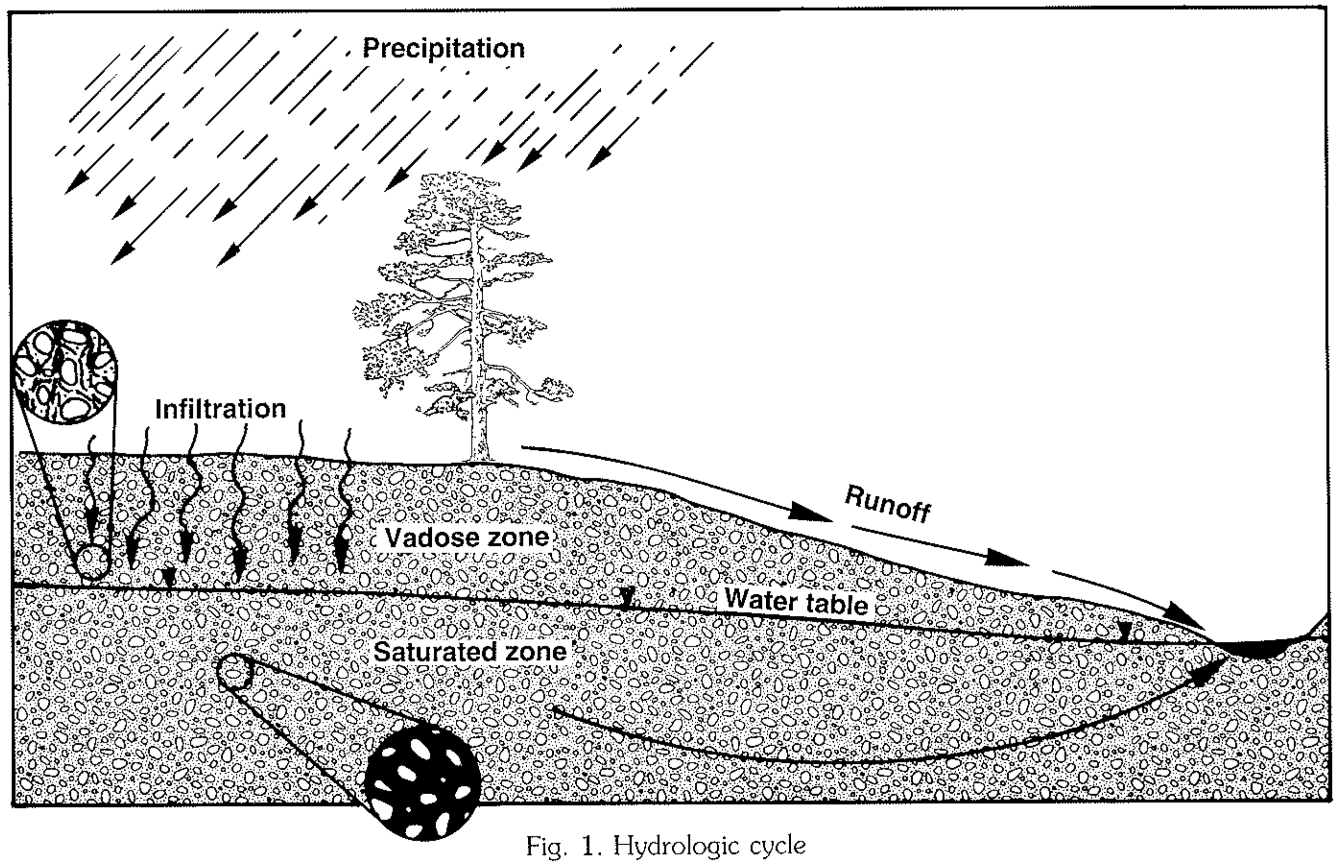


Fig. 1. Hydrologic cycle

true in southeastern Nebraska, where rainfall is higher but the soils have a high clay content, which decreases permeability. If there is less rainfall, as is the case in the western part of Nebraska, infiltration amounts will be less. An exception is in the Nebraska Sand Hills, where the permeability of the soils is so high that a high percentage of the often limited precipitation infiltrates. In the soil zone and underlying unsaturated zone (vadose zone), water movement is vertical in response to the pull of gravity. Water in this zone would be called vadose water.

Movement continues downward until reaching the water table, below which all pores are saturated. Below the water table, the water is now called *groundwater,* and movement can be in any direction depending on energy gradients. The water level in a well is a measure (referenced to sea level) of the total energy of the groundwater flow system at the point where the screen contacts the aquifer. Flow would be from higher energy to lower energy.

Flowlines shown on figure 2 show typical paths that a molecule of water might follow depending on where it first entered the groundwater flow system. Water entering at the left of the diagram becomes part of the regional groundwater flow system and travels a long distance, as well as being in the ground for a long period of time.

In contrast, recharge water in the immediate area of the lake (by well B) would travel only a short distance before being discharged. Because travel time and distances are short, contaminants entering the groundwater flow system from a source such as a sewage disposal system for a vacation cabin would have a high probability of discharging into the lake. Contaminant movement in local flow systems can be troublesome because geological, chemical and biological processes that could attenuate (break down, capture and/or alter) contaminants do not have time to operate.

Groundwater in intermediate flow systems would be in the ground longer than in local systems. It should be noted that the deeper the groundwater, the longer it has likely been in the ground and the farther it has traveled. If three wells were drilled at the location shown (fig. 2), the shallow well (A) would intersect a local groundwater flow system, a somewhat deeper well (B) would intersect an intermediate groundwater flow system and the deepest well (C) would intersect a regional groundwater flow system.

Discharge areas are represented by local topographic low features such as the lake and by regional features such as major river systems like the Platte River. Note the vertical flow shown in the discharge area. Wells constructed in discharge areas may flow at the surface if the vertical energy gradient is large enough. (D) The wells are essentially short circuits in the flow system because of their low resistance to water movement.

The water table in figure 2 is a subdued reflection of the surface topography. Overall, the regional water-table slope is to the right with a local reversal of slope to the left in the area of the lake. This slope or energy gradient is commonly called either the *hydraulic gradient* or *water-table gradient* in groundwater literature.

Groundwater flow systems are in a dynamic equilibrium. Water is continually being added to the system in the form of recharge, moving through the system along the flowlines or paths shown and out of the system in discharge areas. If more recharge were added, as during wet years, water tables would rise until the hydraulic gradient becomes steep enough and the thickness of the saturated zone great enough to convey the groundwater to the discharge areas. Over time, the discharge would increase until it matched recharge and the flow system would reach a new equilibrium with a higher water table.

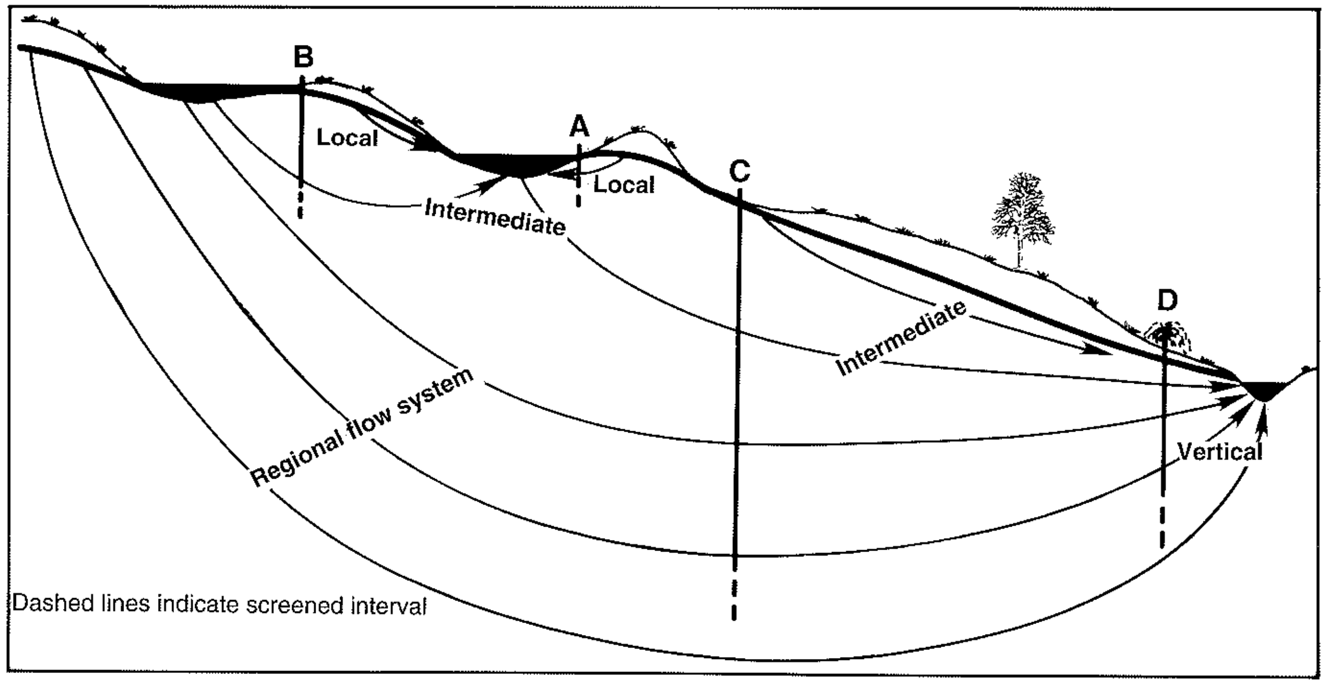


Fig. 2. Local, intermediate and regional groundwater flow systems

During drought years there would be less recharge, but discharge would continue (although declining), resulting in a lowering of the water table. The water table would continue to decline until a new stable balance was reached where discharge would be equal to recharge.

The equilibrium can be and has been changed by human activity. Withdrawals for irrigation have caused water tables to drop. Increased recharge because of irrigation with surface water has caused water levels to rise in some areas of Nebraska. In both cases, the existing equilibrium has been changed with less or greater discharge from the system being a consequence with time.

## Groundwater Movement

Heterogeneities (fine-grained and coarse-grained sediment in a single area, such as alternating layers of shales and sandstones) have significant impacts on groundwater flow systems and movement of contaminants. Flow of groundwater is much faster through highly permeable sediments, such as sand and gravel, compared to silts and clays. The essential difference is in particle size and consequently the size of the pore spaces between particles (fig. 3). There is much greater resistance to groundwater flow where pore spaces are very small, as in silts and clays. As mentioned earlier, permeability is a measure of the resistance to flow. The permeability that is formed as sediments are deposited is referred to as *primary permeability.*

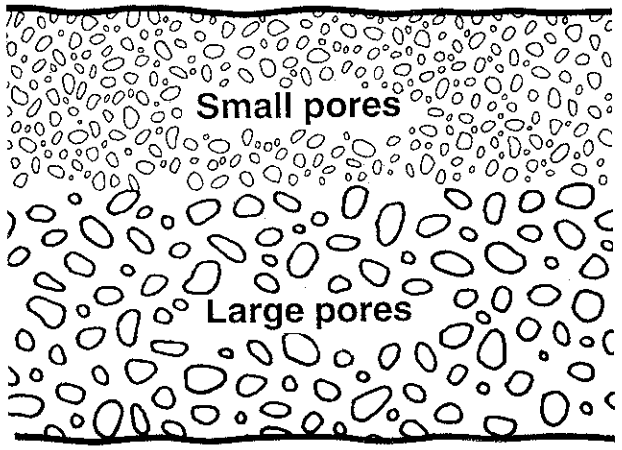


Fig. 3. Pore size as related to particle size

*Secondary permeability*, when developed, can be extremely important in the movement of groundwater and contaminants. Where fractures or joints occur in mudstones, shales, limestones, etc., secondary permeability can be the path for very rapid movement of groundwater and contaminants. There is little resistance to flow along fractures or joints because of the large openings.

Included in the definition of an aquifer is a high enough permeability to convey water to a well in the amounts required. Suitable permeability for most purposes is found in saturated, unconsolidated sediment of sand and gravel size. Many Nebraska aquifers are the results of deposition of sand and gravel by rivers (alluvial) and sand by wind (eolian). Some lake deposits (lacustrine) are also used for water supplies. Bedrock (consolidated sediment) with higher permeabilities includes the Ogallala Group and Dakota Group sandstones. Secondary permeabilities due to fractures, joints and rocks dissolved by solution have enabled some limestones in eastern Nebraska to serve as aquifers. Similarly, secondary permeability in the form of joints and fractures allows the Brule Formation to be used as an aquifer in western Nebraska.

*Aquitards* are sediments or rock layers with low permeabilities. Unconsolidated silts and clays, well-cemented sandstones, limestones and shales all have low primary permeabilities. Groundwater will flow slowly through these sediments and rocks but not fast enough to yield economic amounts of water to a well. Similarly, contaminants can move through these geologic materials but at a slow rate. There is also the possibility for increased interaction between the geologic and contaminant material because of the greater contact time.

By definition no groundwater movement can occur through *aquicludes* because they have a permeability of zero. In Nebraska, no near-surface geologic materials are absolutely impermeable. Rates of groundwater flow may be very slow, but flow will still occur. The essential difference is how long will it take for water and/or a contaminant to flow through a given unit.

Where alternating layers of high and low permeability exist, groundwater flow paths and rates can be highly variable. In general, groundwater movement would be more horizontal in high permeability layers and more vertical in low permeability layers (fig. 4). Flow rates can be ten times faster through gravel compared to a fine-grained sand. This presents a problem in monitoring the movement of a contaminant since rates of movement are not the same over a vertical section where particle size varies.

## Types of Contaminants

There are many types of contaminants that can affect aquifers. Two major kinds would be organic and inorganic. Organic contaminants have chains of carbon atoms as their basic building blocks. These carbon chains can be straight, branched, in rings or some combination of the above. The carbon chains may have additional atoms or groups of atoms such as sulfur or chloride attached at specific points. Pesticides, herbicides, solvents, petroleum products, plastics and many household and industrial compounds are all examples of organic compounds.

How the organic molecule interacts with the groundwater flow system is determined by its unique structure. For example, large-chain molecules would move slower than small-chain molecules in a groundwater flow system and have different solubilities in water. Their densities would be different, with the result that one molecule might float at the water table while another would sink through the saturated zone to the bottom of the aquifer. A molecule may vaporize readily, as is the case with some components of gasoline. Every organic compound was formulated for some specific purpose and as a result has different properties and behaves differently in groundwater flow systems.

Inorganic compounds are far fewer in number compared to organic compounds. They are still important sources of contamination, as shown by the nitrate problem in Nebraska groundwater supplies. Metals from industrial processes are another source of groundwater contamination. Salt used to de-ice roads has made its way into the groundwater system. Movement of inorganic compounds is easier to predict than that of organic compounds but is still difficult because each compound is unique and reacts differently with water and geologic material.

Some contaminants are distinct from the two types previously discussed because of a special property. Radioactive material would be one example. The chemical properties of a radioactive element may cause no problem, but the fact that it is radioactively decaying and giving off radiation causes it to be a groundwater contaminant. With time, as decay continues, the radioactive contaminant becomes less of a problem unless the daughter products formed are also radioactive or have chemical properties that are undesirable. Depending on the half-life (time required for half of the original amount to decay) and the time of travel to and in the groundwater flow system, there may or may not be a problem.

One further note on a naturally occurring radioactive element is needed. Radioactive radon gas is a product of the decay of naturally occurring uranium in the earth's crust. Radon gas can be dissolved in groundwater and enter a house through a home water-supply system where it bubbles out of water leaving the faucet. Radon can also enter a house as a gas through fractures in basement floors and other openings. The radon problem is totally separate from the issues addressed in this article, although the hydrogeology of an area determines in part the degree of the problem for a given homeowner.

## Interaction of Contaminant, Groundwater and Geologic Material

The simplest case of contaminant interacting with either groundwater or geologic material would be where the contaminant is soluble in water and does not react with the geologic matrix comprising the solid part of the groundwater system. The contaminant would be said to be *conservative* (moving with the same velocity as groundwater). If the contaminant enters the groundwater flow system at a specific place, movement from that point on would be advective (moving with the groundwater flow). Diffusion rates (movement of molecules in response to chemical concentration gradients) are usually much lower than advective rates of groundwater flow and are considered negligible. As the contaminant moves along the irregular flow paths of the pore spaces in the geologic matrix, *transverse dispersion*, or spreading of contaminant molecules perpendicular to the direction of flow, would occur (fig. 5). *Longitudinal dispersion*, which is dispersion in the direction of flow, would also occur because of the different rates of flow through pore spaces due to frictional drag on mineral grains (fig. 6) and through pore voids because of different flow path lengths. Determining the actual amount of dispersion in a groundwater flow system for a given contaminant is difficult.

The contaminant can react with the geologic matrix in a number of ways. Contaminants with unbalanced electrical charges may bond to mineral grains such as clays, which have unbalanced charges. Exchange of ions such as sodium and calcium between contaminants and mineral grains will also occur when there are unbalanced electrical charges. The contaminant can move into small pore spaces within the mineral grains or migrate into fine-grained material such as soil peds (soil clumps) from secondary permeability paths represented by cracks or joints. With changing conditions, the contaminant may rejoin the main groundwater flow paths. The net effect of this type of interaction is to slow (retard) the overall movement of the contaminant. Once again it is difficult to determine how much retardation has or will occur.

If the contaminant is not soluble or only slightly soluble in water, factors such as density become important. When a contaminant (such as gasoline) is less dense than water, it will migrate to the top of the saturated zone and float. This location is in the capillary or tension-saturated zone immediately above the water table. It is difficult to remove floating contaminants because they will not readily flow to wells from this location. If the contaminant is more dense than water, it will sink through the saturated zone and pond on top of low-permeability layers. Contaminant movement is then determined by the slope of the top of the low-permeability layer.

A contaminant will likely have other fluid properties that are different than water, such as being more or less viscous. A low-viscosity contaminant may move through a clay liner faster than the groundwater. The contaminant may also react with the clay liner, changing its permeability values. Permeabilities of earth materials are commonly indexed to water. A mistake often made is assuming that a contaminant moving through earth materials will behave like water. Movement of contaminants must be considered in light of their unique fluid properties.

The contaminant may chemically react with groundwater, forming new compounds. Hydrolysis of organic molecules or metal ions results in new chemical molecules, which may have entirely different characteristics such as toxicity. These and other types of reactions make it harder to determine the path of contaminant movement in some situations because testing is required for the daughter product, as well as for the original contaminant. There is

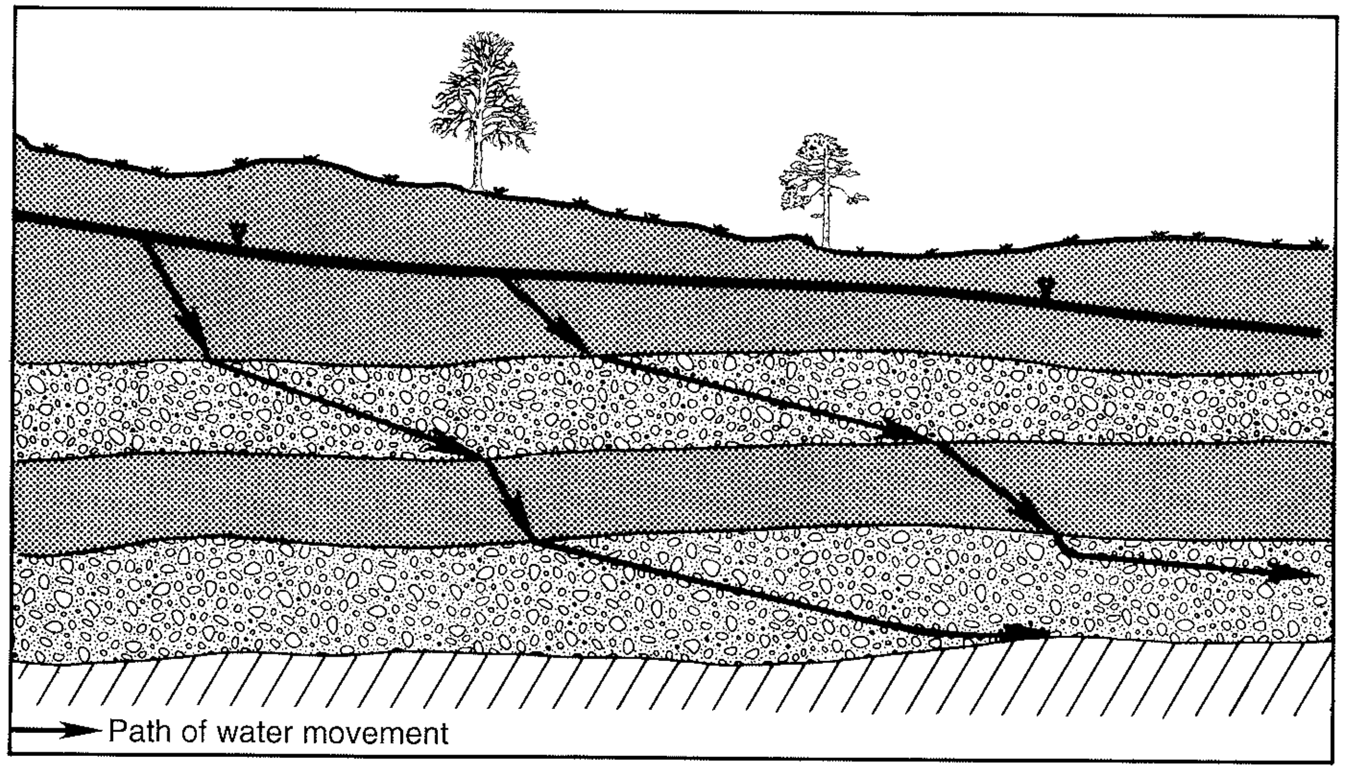


Fig. 4. Groundwater flow paths in low and high permeability layers

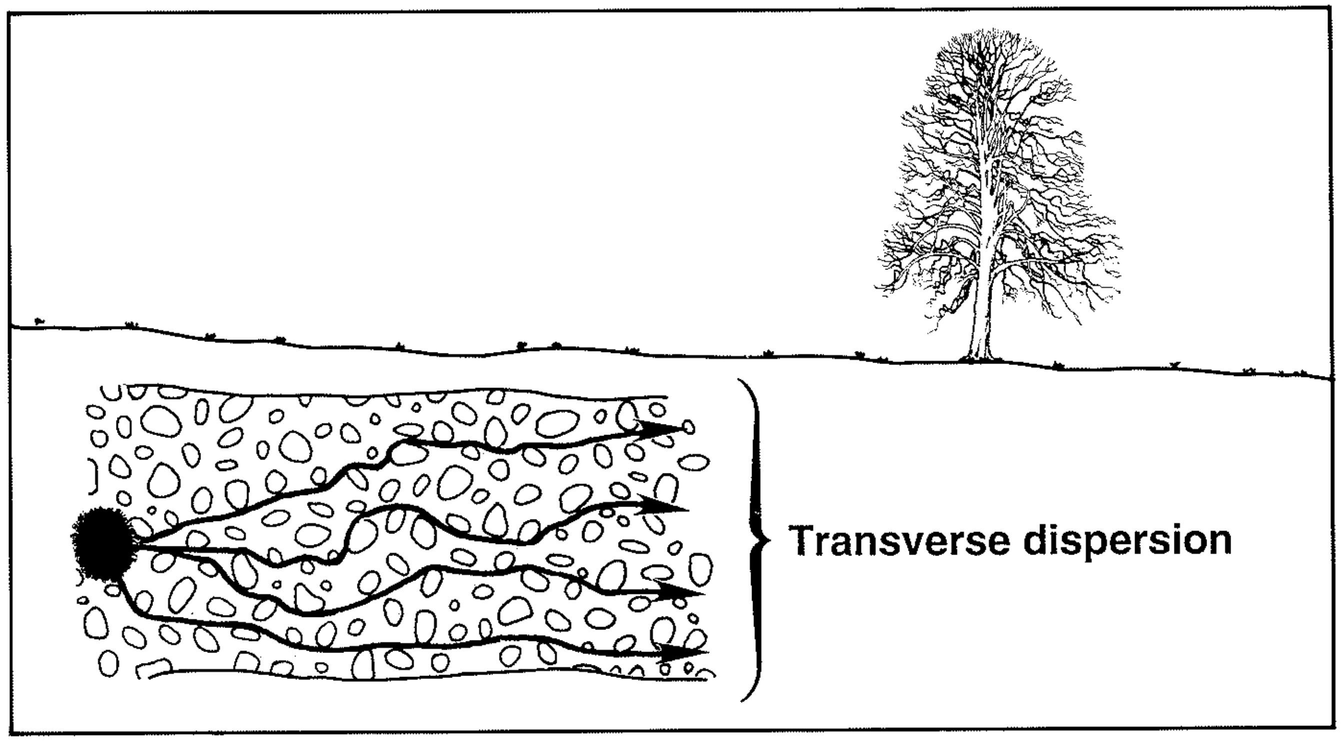


Fig. 5. Transverse dispersion of a contaminant as a result of varying flow paths

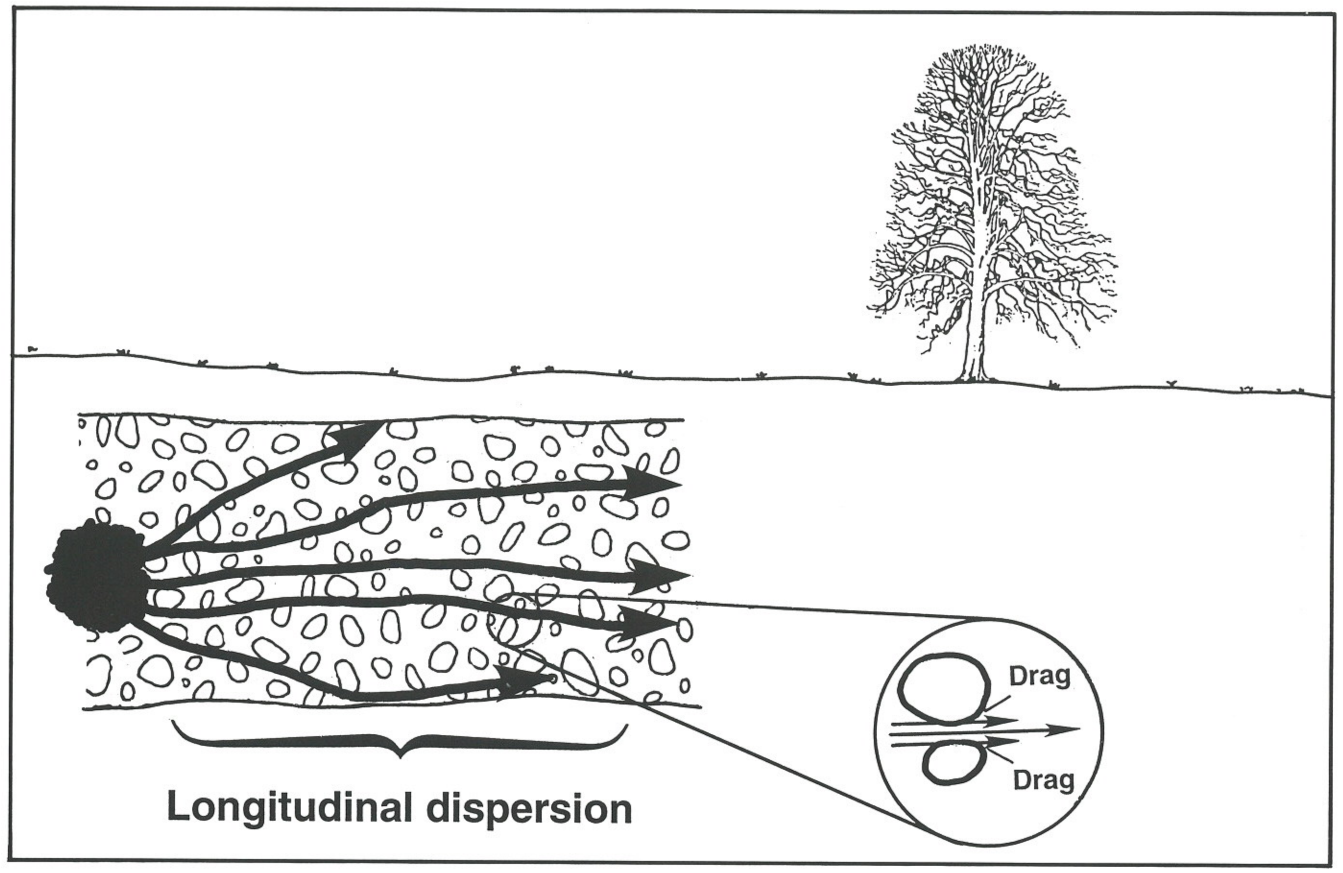


Fig. 6. Longitudinal dispersion of a contaminant as a result of varying flow paths and different rates of groundwater movement

always the possibility the new molecule will be more threatening to the environment than the original contaminant.

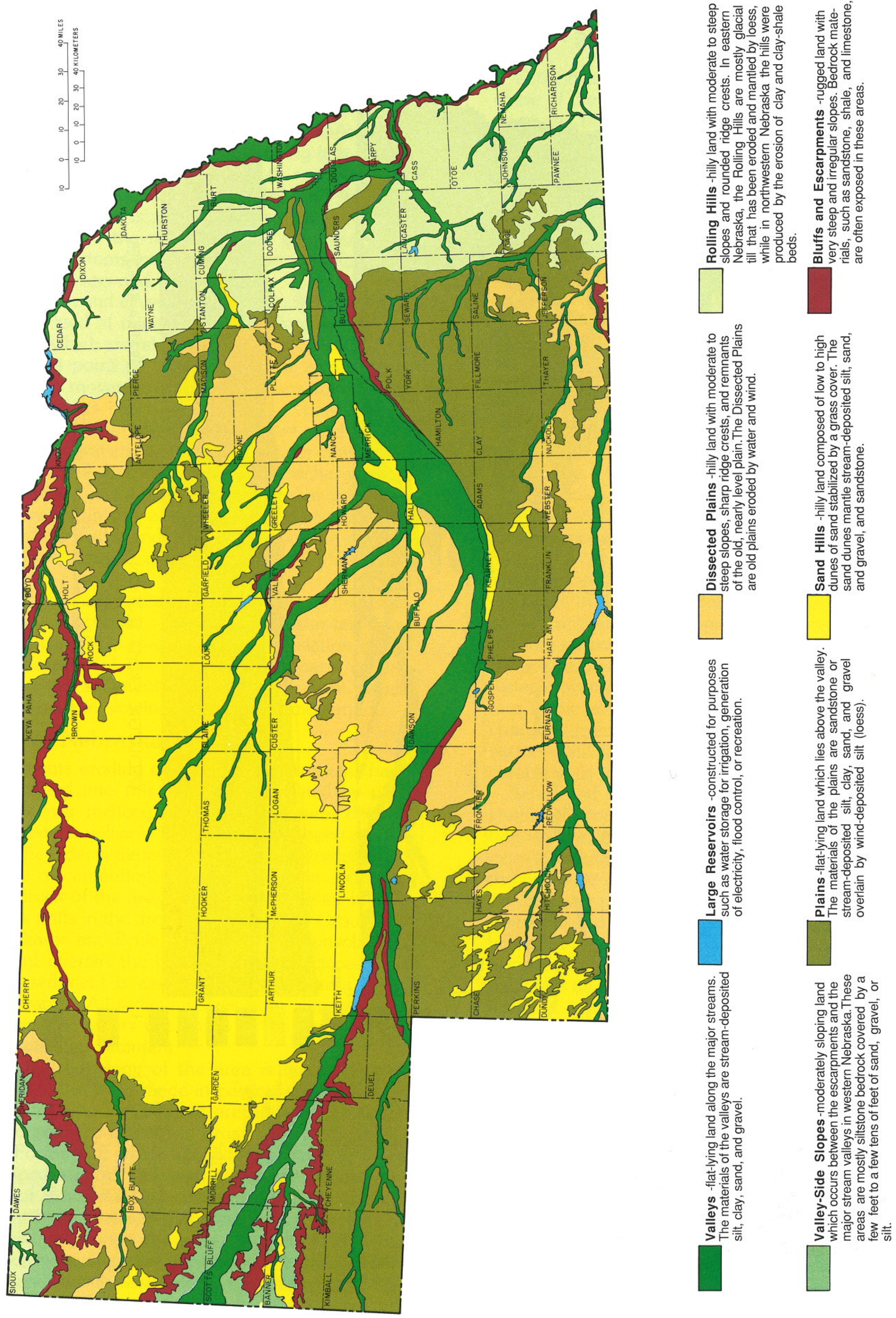
Contaminant movement and occurrence can be affected in the unsaturated zone. The contaminant could be oxidized. Movement may be periodic because of intermittent recharge with the contaminant being held by capillary forces between individual mineral grains. Fractures or joints in the unsaturated zone may provide high-speed routes for contaminant movement. Considerable research is needed to determine the nature of contaminant movement and occurrence in the unsaturated zone.

When a large quantity or slug of contaminant enters the ground, it may move as a single mass even if it is soluble in water. When denser than water, such contaminants are referred to as Dense *Non-Aqueous Phase Liquids* or DNAPLs for short. Rates of movement of contaminant slugs are commonly much slower than groundwater flow rates. Over time the slug will slowly dissolve in the groundwater flowing past if the contaminant is soluble. DNAPLs are extremely hard to clean up if there is complicated hydrogeology at the site. Similarly, *Light Non-Aqueous Phase Liquids* (LNAPLs) will float on top of the saturated zone.

Biological degradation because of microorganisms can have a significant impact on contaminants. Microorganisms are found throughout the groundwater flow system. Microorganisms may digest organic molecules, breaking up the original carbon chains. In some cases they have been cultured to attack specific organic contaminants. Their potential impact in a specific setting is difficult to determine.

## Generalized Hydrogeologic Settings in Nebraska

A series of generalized descriptions of the hydrogeology of different areas of Nebraska follow. After these are concrete examples of contaminant movement. While the processes that will be described exist at known locations of groundwater contamination, these descriptions are not site specific. Any interpretation of a specific site should include a detailed assessment of the local hydrogeologic setting to determine the nature of each geological unit and the impact of the suggested processes described in this paper. Two maps may help identify these settings, some of which correspond roughly to identifiable landscape or bedrock features. Included are the Topographic Regions Map of Nebraska (fig. 7) and the Geologic Bedrock Map of Nebraska (fig. 8) to aid in locating some of these hydrogeologic settings.



🟩 **Valleys** -flat-lying land along the major streams. The materials of the valleys are stream-deposited silt, clay, sand, and gravel.

🟦 **Large Reservoirs** -constructed for purposes such as water storage for irrigation, generation of electricity, flood control, or recreation.

🟧 **Dissected Plains** -hilly land with moderate to steep slopes, sharp ridge crests, and remnants of the old, nearly level plain. The Dissected Plains are old plains eroded by water and wind.

🟩 **Rolling Hills** -hilly land with moderate to steep slopes and rounded ridge crests. In eastern Nebraska, the Rolling Hills are mostly glacial till that has been eroded and mantled by loess, while in northwestern Nebraska the hills were produced by the erosion of clay and clay-shale beds.

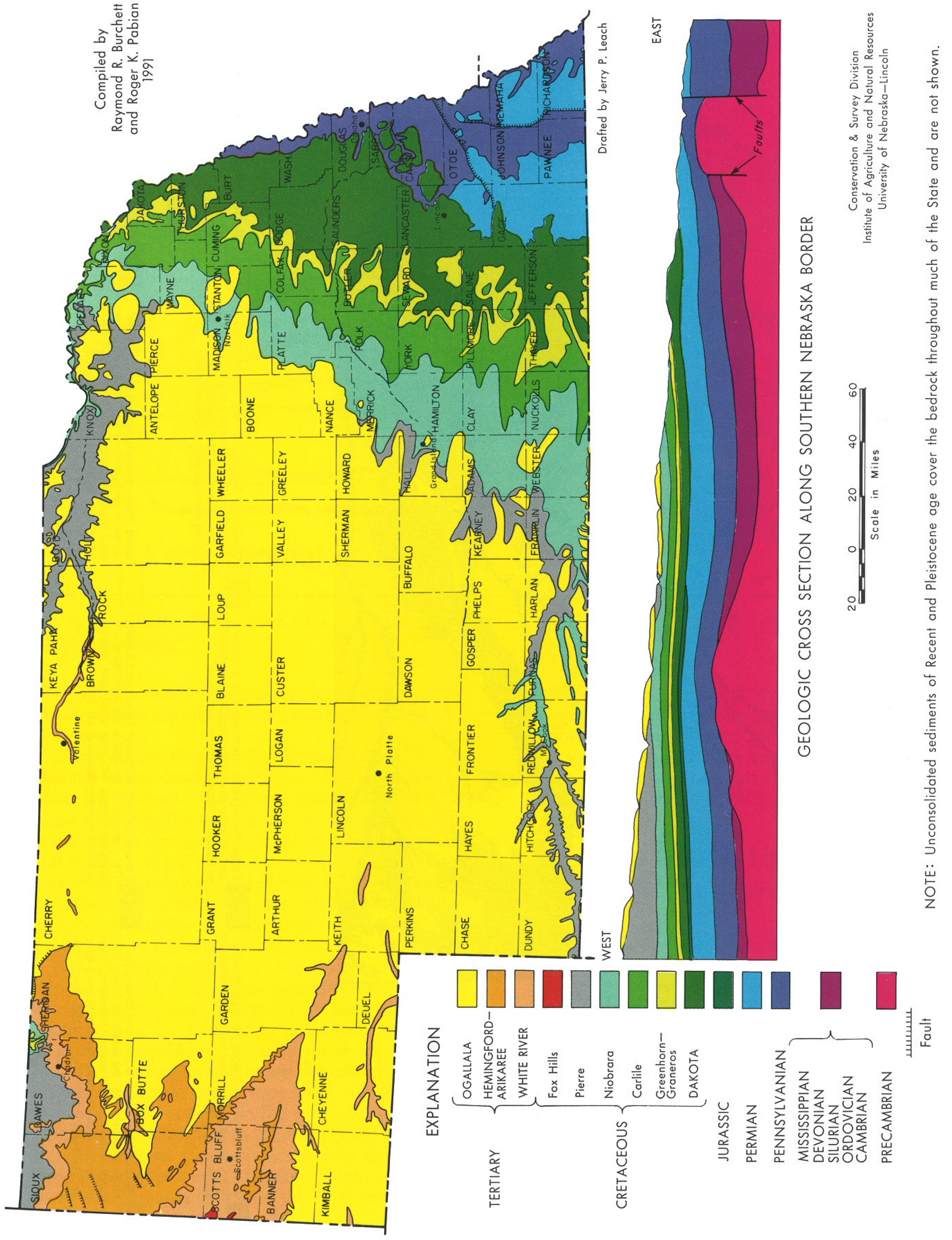
🟩 **Valley-Side Slopes** -moderately sloping land which occurs between the escarpments and the major stream valleys in western Nebraska. These areas are mostly siltstone bedrock covered by a few feet to a few tens of feet of sand, gravel, or silt.

🟫 **Plains** -flat-lying land which lies above the valley. The materials of the plains are sandstone or stream-deposited silt, clay, sand, and gravel overlain by wind-deposited silt (loess).

🟨 **Sand Hills** -hilly land composed of low to high dunes of sand stabilized by a grass cover. The sand dunes mantle stream-deposited silt, sand, and gravel, and sandstone.

🟥 **Bluffs and Escarpments** -rugged land with very steep and irregular slopes. Bedrock materials, such as sandstone, shale, and limestone, are often exposed in these areas.

Fig. 7. Topographic regions map of Nebraska



NOTE: Unconsolidated sediments of Recent and Pleistocene age cover the bedrock throughout much of the State and are not shown.

Fig. 8. Geologic bedrock map of Nebraska

## Sand Hills

The Sand Hills of Nebraska are characterized by soils of high permeability underlain by a thick layer of sand and gravel. The water table is very close to or at the surface in many interdunal valleys. Little surface runoff occurs, with most precipitation infiltrating where it falls or evapotranspiring (the combination of evaporation from surfaces and transpiration by plants) back into the atmosphere. Regional groundwater flow is to the east with intermediate flow systems to the rivers rising in the Sand Hills. Local flow systems are developed from the dunes to the nearby rivers and lakes.

The eolian and alluvial sediments in the Sand Hills are composed of mineral grains such as quartz and feldspars, which are relatively inert (non-reactive) from a chemical point of view. They are also coarser grained, so movement through the unsaturated and saturated zones can be quite rapid. There are deposits of very coarse-grained sediment, such as the Broadwater gravels, where groundwater flow could be very rapid. Because of the high recharge rates (due to the high infiltration rates of what precipitation does fall in this area of semi-arid climate), the shorter flow paths and the inertness of the mineral grains, groundwater quality in the Sand Hills is excellent.

A contaminant spilled on the surface in the Sand Hills would move very rapidly to the water table, especially where it is shallow. Little retardation would occur because of the inertness of mineral grains. Finer grained sediment layers, where present, would be important in slowing contaminant movement.

## Western Nebraska

Sediments eroding off the Rocky Mountains have been carried into this area and deposited by river systems over millions of years. Sediment derived from western volcanic activity has also been deposited. The older sediments have become consolidated because of cementing or other processes and form the bedrock of the area. Some of the better known bedrock units in the area are the Ogallala Group and the Arikaree and Brule formations. Unconsolidated sediment overlies the bedrock in some places, and alluvial sediment is associated with the area rivers and streams. All sediment sizes from clay to gravel in alternating layers are found in the bedrock and unconsolidated sediment.

The hydrogeology of the area is quite complex because of the large range in particle sizes and mineral composition. Aquifers are limited to coarser grained geologic layers and situations such as in the Brule Formation, where secondary permeability has developed in fracture zones. Coarser grained deposits of limited extent are found filling paleovalleys (ancient buried valleys) that were cut by ancient rivers flowing through the area. Equally limited but productive aquifers are represented by the alluvial sands and gravels associated with present river systems. The Brule Formation has low primary permeability, but in places it has large interconnected openings that permit rapid movement of groundwater to wells.

Groundwater flow is primarily to the east, but because of the low rates of recharge, the water table is deep and movement slow. Long contact with mineral grains and the wide range of mineral composition have resulted in groundwater being higher in total dissolved solids, as is typical in a semi-arid region.

The thick unsaturated zone, low recharge rates, alternate layers of fine- and coarse-grained material and availability of a wide range of minerals for interaction would reduce the impact on the groundwater system of a contaminant spill on the surface. A special problem exists where the interconnected openings in the Brule Formation would permit the rapid movement of a contaminant with little attenuation.

## Republican River

The Republican River, roughly paralleling the southern border of southwestern and central Nebraska, has eroded a valley into the underlying Niobrara Formation chalk and the Pierre Shale. Alluvial sediments, deposited by the Republican River, fill the bottom of the eroded valley. The alluvial sediments are composed of clay- to gravel-sized particles with a full range of mineral content. The Pierre Shale and Niobrara chalk are fine-grained deposits with low primary permeabilities. In places the Niobrara chalk is fractured and can serve as a path for rapid groundwater movement. The major groundwater flow system in the area is within the alluvial deposits. Recharge is from precipitation falling on the overlying surface with fairly rapid infiltration through the permeable soils to the shallow water table.

Sands and gravels of the alluvial deposits are the source of groundwater for domestic, city and irrigation wells in the area. There is movement of water from the alluvium to the Republican River and, where the hydraulic gradient has been reversed because of groundwater pumping, from the river to the alluvium. There is also some irrigation using surface water brought in by canals. Increased recharge rates have occurred in the fields where this water has been applied and where there is leakage from the canal distribution system. Groundwater quality is generally good because of the short flow paths and permeable soils permitting recharge of precipitation.

A contaminant spill on the surface can move rapidly to the shallow water table. Contamination of the aquifer in this area could be a problem because of the limited areal extent of the alluvial sediment. Attenuation rates would be low because of the limited lengths of groundwater flow paths.

## Big Blue River Basin

During the last glacial period, the eastward movement of rivers in this area was interrupted by glaciers causing thick layers of sand and gravel to be deposited, alternating with layers of silt and clay. Bedrock permeability is generally low except where there are joints and fractures, such as in some parts of the Niobrara chalk. More water is available for recharge because of the greater amounts of precipitation in southeastern Nebraska, although the higher content of fine-grained particles in the soils reduces infiltration rates. Some of the deeper sand and gravel layers are isolated from the surface by several layers of silt and clay alternating with layers of sand and gravel. The groundwater flow system is complex because of the multiple layers with different permeabilities.

Regional groundwater flow is to the east. The water table is at an intermediate depth except where rivers have cut valleys. There is evidence for good hydraulic connections between sand and gravel layers through macropores in the intervening fine-grained layers. (Macropores are features such as fractures and joints or zones within fine-grained layers through which water moves more easily than through the fine-grained material.) Vertical movement of groundwater is also possible through wells screened in multiple geologic units and along gravel packs around the well (see fig. 9). In some situations, fine-grained layers have been mined, providing additional high-speed paths for water movement between the surface and deeper sand and gravel layers. Dense irrigation-well development in the area has caused groundwater-level declines and the development of vertical hydraulic gradients within the groundwater flow system. Water quality is generally good, reflecting higher recharge rates and intermediate flow path lengths.

There is potential for a contaminant to move from the surface into the groundwater system. Because of the limited thickness of the unsaturated zones, attenuation rates are lower. The groundwater flow system has been interrupted locally by the development of vertical, high-permeability paths through fine-grained layers, allowing contaminants to move more readily to deeper sands and gravels.

## Eastern Nebraska

The eastern section of Nebraska was covered by continental glaciers during the last ice age. This area is called "Rollng Hills" on the Topographic Regions Map (fig. 7). A complex assortment of unconsolidated sediment mantles the bedrock. This sediment was derived from erosion of the land surface both in Nebraska and to the east and north in adjacent states. The bulldozing action of the glacier mixed sediment of all sizes. As a result, the pore spaces of the larger particles are occupied by the smaller particles in the mixed sediment. Primary permeabilities are commonly quite low in this type of poorly sorted sediment. Where deposited directly by the glacier, the sediment is called till. In some cases, the mixed sediment carried by the glaciers was reworked and sorted by meltwater. The coarser grained sediment was deposited along rivers and streams draining the glacier while the finer grained sediment was transported out of the area in suspension. The glaciers advanced and retreated a number of times, burying sediments deposited during previous advances. A complex of thin isolated sand and gravel layers, till and clay and silt layers makes up the unconsolidated sediment mantling the bedrock. Additional sand and gravel deposits are found in association with present river systems, as well as in buried paleovalleys of river systems developed before and during the ice age.

Bedrock in the area consists of limestones, shales and sandstones. In places where the limestones have been exposed to the surface at some time in the geologic past, joints and fractures have formed because of weathering processes. Where this secondary permeability has developed, the water quality is good because of flushing by active groundwater flow systems, and flow to wells is significant. It is difficult to locate this secondary permeability without site-specific investigation.

The primary sandstone would be associated with the Dakota Group. The Dakota Group is a shoreline deposit in an ancient sea. The sandstone layers are interbedded with fine-grained shale deposits. Groundwater is saline in some parts of the Dakota Group. Upper sandstone units and those farther to the east are more likely to contain freshwater because of flushing by groundwater flow systems. Bedrock is near to or exposed at the surface in some places in eastern Nebraska. A Dakota sandstone unit is exposed in road cuts along Interstate 80 in the area of the Platte River.

Jointing and fracturing of till deposits have provided paths for rapid movement of recharge water and for potential contaminants in many areas. Improper well construction has also provided paths for movement of contaminants to shallow sands and gravels within the glacial deposits. As a result, many domestic wells have been contaminated. Rural water districts have been formed because of the limited extent of groundwater supplies and the poorer water quality in many parts of the area.

## Platte River

Saturated alluvial deposits of the Platte River are an important source of groundwater in Nebraska. Large thicknesses of sand and gravel are common, and there is a good hydraulic connection of groundwater flow systems with the Platte River. Water tables are shallow, so recharge moves quickly to the water table. Soils have high infiltration rates, so recharge amounts are higher, especially in the more subhumid climate of the east.

Considerable water development has occurred in the Platte River valley. Diversion of Platte River flow into surface-water irrigation systems has caused large amounts of recharge in the area of the irrigation-distribution systems. Numerous high-capacity wells have been constructed for irrigation and municipal use. Induced recharge from the Platte River has occurred where the local hydraulic gradient (water-table slope) has been reversed because of heavy pumping. The Platte River is an important source of recharge to aquifer systems supplying municipal water for a number of major cities. Evapotranspiration rates are high because of the shallow water table.

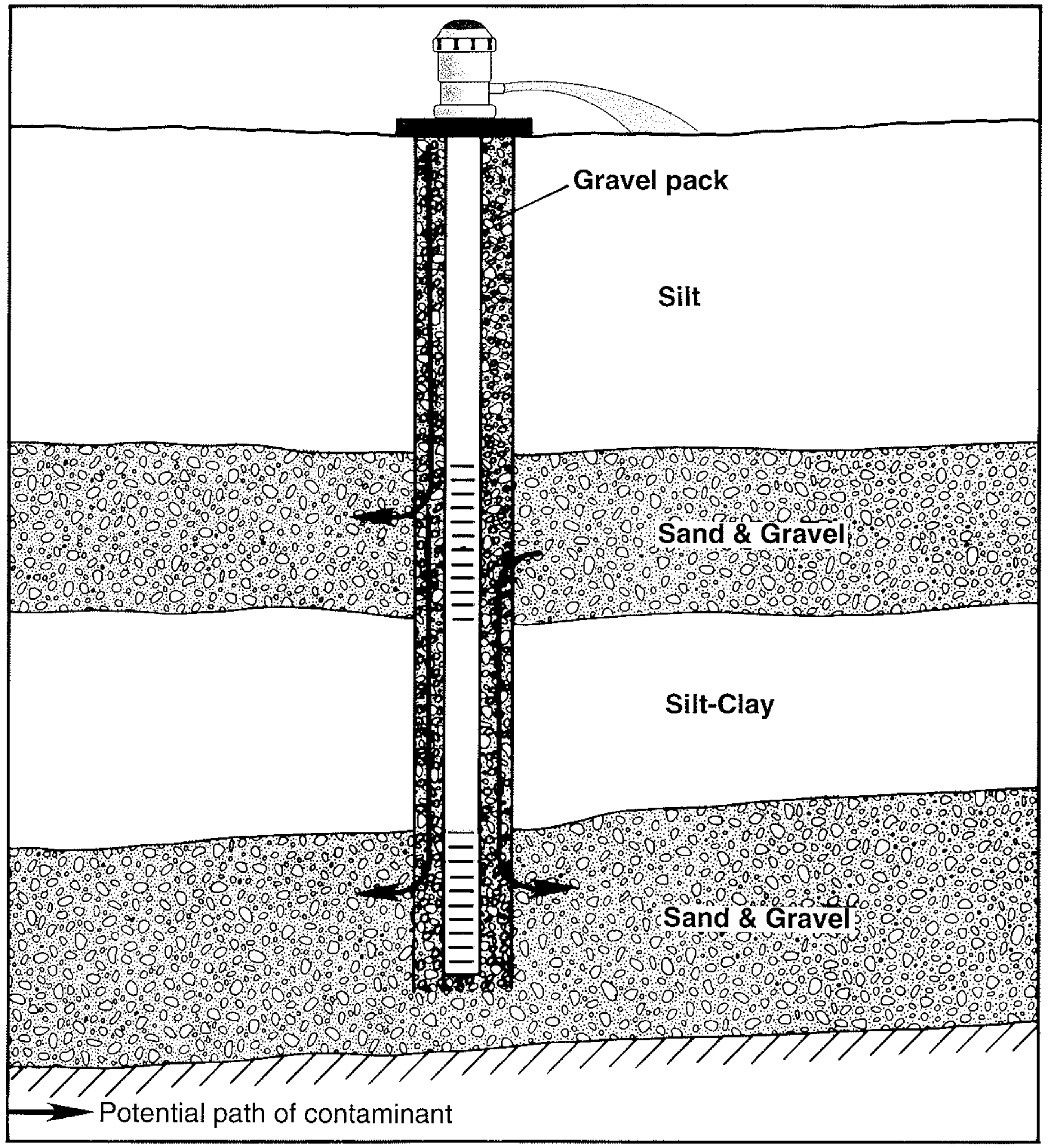


Fig. 9. Potential paths of vertical contaminant movement along gravel packs around wells

The potential for groundwater contamination is high because of the shallow water table, permeable soils and intense development. The potential for contamination of well fields also exists from induced recharge of contaminated river water. An example of this is agricultural chemicals borne by runoff, especially after heavy rains in the spring and early summer, shortly after these chemicals are applied.

## Common Examples

Several common ways that groundwater has been contaminated in Nebraska follow. The focus will be on the role of hydrogeology and the specific behavior of the contaminant. The discussion will not detail any specific contamination site in Nebraska and should not be so interpreted.

### Spill from an Industrial Site

Industrial contamination is commonly the result of two types of events. One type would be a sudden spill from a ruptured tank, tearing of a liner in a lagoon or an error in opening valves, allowing the contaminant to escape into the environment. A second type of event could occur over time with successive spills, such as in loading of trucks or in slow leakage of contaminants from storage facilities. The contaminant may or may not be soluble in water and could be more or less dense than or as dense as water.

A denser-than-water, slightly soluble contaminant released as a result of a ruptured tank will be used for this example. It will be assumed that a dike was previously built around the tank to prevent contaminant spills from draining off the immediate site area.

The hydrogeologic setting is an alluvial deposit of a nearby river underlain by an unfractured shale whose surface dips slightly away from the river (see fig. 10). Soils in this setting will likely have high infiltration rates. The sand and gravel deposits commonly have interbedded silt and clay lenses. Precipitation readily infiltrates the permeable soils and moves rapidly to the shallow water table. Groundwater flow direction is towards the river with a path length of several hundred feet from the tank to the bank of the river.

When the tank ruptured, a pond of the contaminant formed within the dike area. Infiltration of the contaminant occurred as a slug, which rapidly reached the water table; then, sinking through the saturated zone, it ponded on top of the underlying shale (see fig. 10), forming a DNAPL (or Dense Non-Aqueous Phase Liquid). The DNAPL will slowly move away from the river down the sloping surface of the shale. Groundwater flowing toward the river will slowly dissolve the DNAPL, carrying some of the contaminant back toward the river. Groundwater will also slowly dissolve the contaminant where it was captured by capillary forces between mineral grains in the path of the DNAPL as it descended through the saturated zone.

Cleanup (remediation) at this site will be very difficult. The DNAPL will have entirely different fluid characteristics than water, so recovery wells will have to be carefully designed and located to remove the contaminant. Even then it will be very difficult to control pumping as the DNAPL is removed because of the surrounding groundwater with its potential for flow. The removal of the contaminant where it is immobilized by capillary forces in pore spaces may be impossible over a shorter period of time (it may take years) because of its low solubility. In short the aquifer may be contaminated for a very long time regardless of the effort put into remediation.

### Leak from an Underground Storage Tank

While excavating for the foundation of a new building on a downtown lot, workers noticed a strong

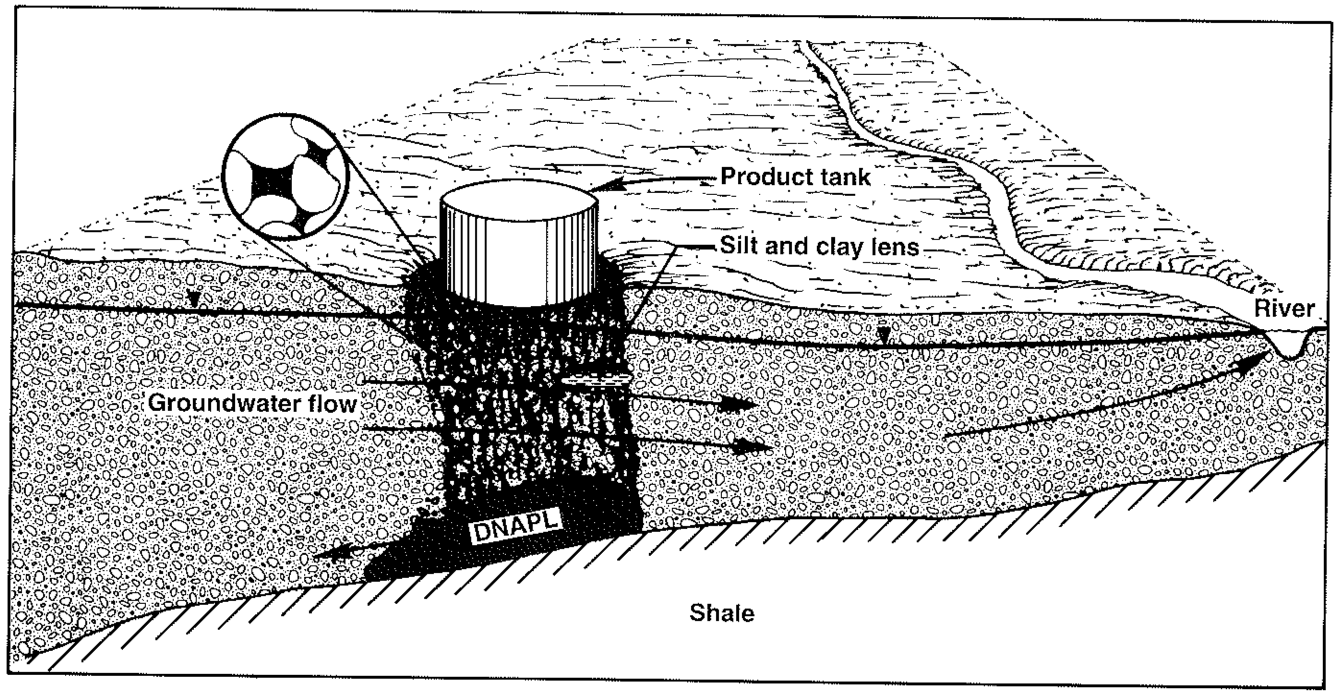


Fig. 10. Movement of a denser-than-water contaminant from a ruptured tank

smell of gasoline. Further excavation uncovered a corroded gasoline tank that remained from when a long-forgotten gas station occupied the corner lot. Investigators drilled several monitoring holes and found that up to 6 inches of petroleum product could be measured in the test holes. It was also called to their attention that there had been complaints of a gasoline smell in the elevator shaft of a hospital located across the street from the site. In checking through the area, no other complaints of gasoline odor arose.

Gasoline is composed of a number of organic compounds to better control combustion and to provide for ease of vaporization in internal combustion engines. Less dense than water, it will initially float on the water table but will undergo some mixing. Vapors of the gasoline will move through the unsaturated zone.

Test-hole logs in the area showed a clay till approximately 15 feet thick, mantling a poorly consolidated sandstone (see fig. 11). The water table was at 20 feet, so there is an unsaturated zone in the upper 5 feet of the sandstone. Water levels in test wells showed a slope of the water table away from the hospital and into the interior of the city block containing the site.

Gasoline leaking from the tank over an unknown period seeped down to and formed a layer floating on the water table. At the time one could not rule out other petroleum products such as motor oils. The likely movement of the petroleum liquid is in the direction of the slope of the water table into the interior of the city block or perhaps further.

Movement of the vapor of the petroleum product is primarily confined to the unsaturated sandstone with the clay till forming an effective cap for rapid movement of vapors to the surface. Movement of gaseous contaminants in the unsaturated zone depends on vapor pressure. Vapors probably moved through the unsaturated zone to the elevator shaft, which penetrates the clay till. Any fractures or joints in the foundation or floor of the elevator shaft would provide entry for the vapors.

Unfortunately, life is not always this simple; it is also possible that a second source, such as another forgotten gasoline tank, is the cause of the vapors in the elevator shaft. The potential exists for movement of vapors into other buildings in the city block where the clay till has been penetrated and fractures, cracks or other openings have developed. Explosions have occurred in Nebraska because of subsurface gasoline vapors.

This could be a very costly situation to remediate because of the location in a downtown business district and the unknown duration of leakage and unknown quantities involved. The product would be removed by pumping the upper levels of the saturated zone and separating the water from the petroleum product. In addition, vapors would have to be pumped from the unsaturated zone.

An additional note worth mentioning in connection with storage of petroleum products is that, if not properly maintained and monitored, above-ground storage tanks of petroleum can rust and leak, or faulty valves can leak. Both can eventually cause contamination of groundwater as the petroleum product in-

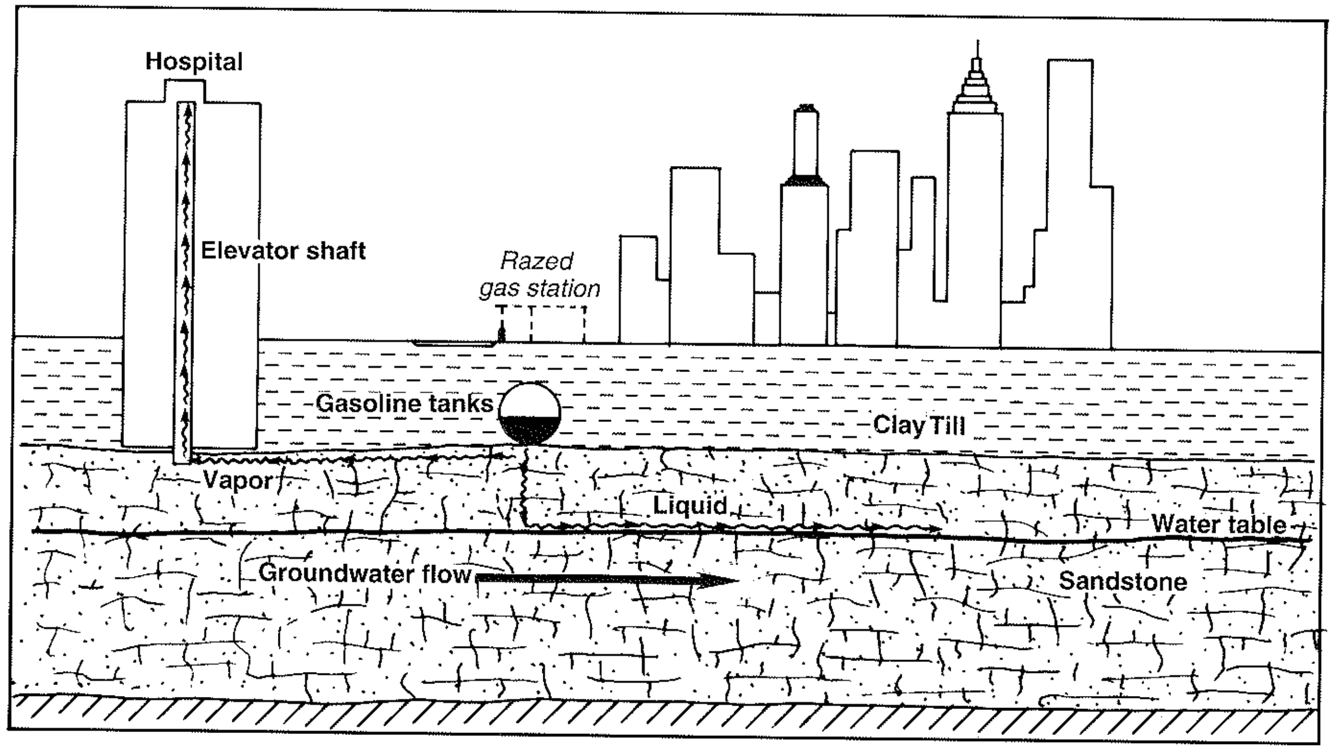


Fig. 11. Potential paths of movement of vapors and liquids leaking from an underground gas tank

filtrates and comes in contact with the water table (fig. 12).

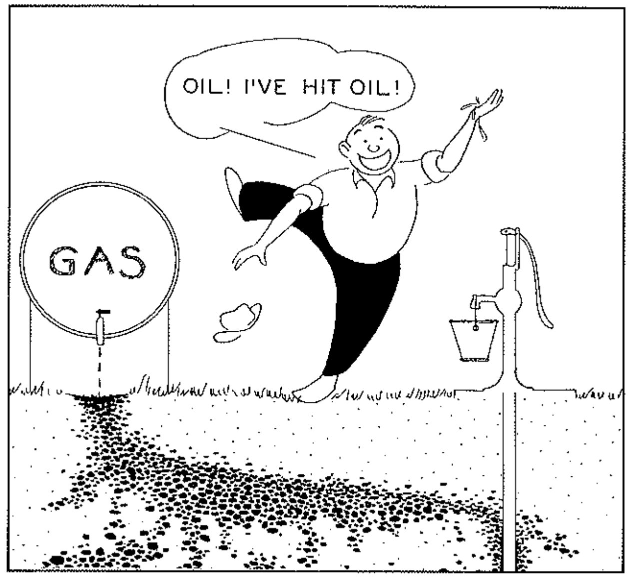


Fig. 12. Possible effect of leakage from surface storage tank

## Landfills

The evolving names (*dump, landfill, sanitary landfill*) of landfills suggest a potential for problems. Evolving management and changes in refuse content introduce even more complexities in determining the impact of a landfill on groundwater in the vicinity.

The initial reason for the location of many landfills also points out the potential for problems. If there was a hole in the ground (fig. 13) because of gravel mining, clay mining for bricks or any other reason, the odds were high in the past that it would be used for a dump. In many situations, such an excavation represents a short circuit (very high secondary permeability) to the water table. In addition, the bottom of the excavation is closer to the water table. The other location commonly selected is a ravine, where there is a high potential for surface runoff to flow through the dump.

During closure of landfills, fine-grained material is used to cover the site to keep the refuse in place and to reduce infiltration rates. Studies have shown, however, that infiltration rates through landfill covers are usually much higher than surrounding soils. This is due to the development of secondary permeability because of cracks from drying and settling and problems developing a homogeneous cover without clumps. The net effect is that more recharge will move through a landfill cover compared to native soils. Refuse will react with infiltrating water, forming leachate. The greater the recharge rate, the more leachate is formed.

Increased recharge at a point in the groundwater flow system will alter that flow system. Some change in groundwater flow patterns may be expected around a landfill, and a site-specific investigation would be needed to determine local flow directions. In addition, the leachate may have different properties than groundwater, such as density, temperature, viscosity, etc., and flow more rapidly through clay liners and the various geologic layers in the vicinity.

Some landfills are located in discharge areas. Leachate would then migrate toward a discharge point such as a stream or river in conjunction with the flow of the groundwater system. The focus then would be on what impact the leachate has on the stream or river rather than on the groundwater reservoir.

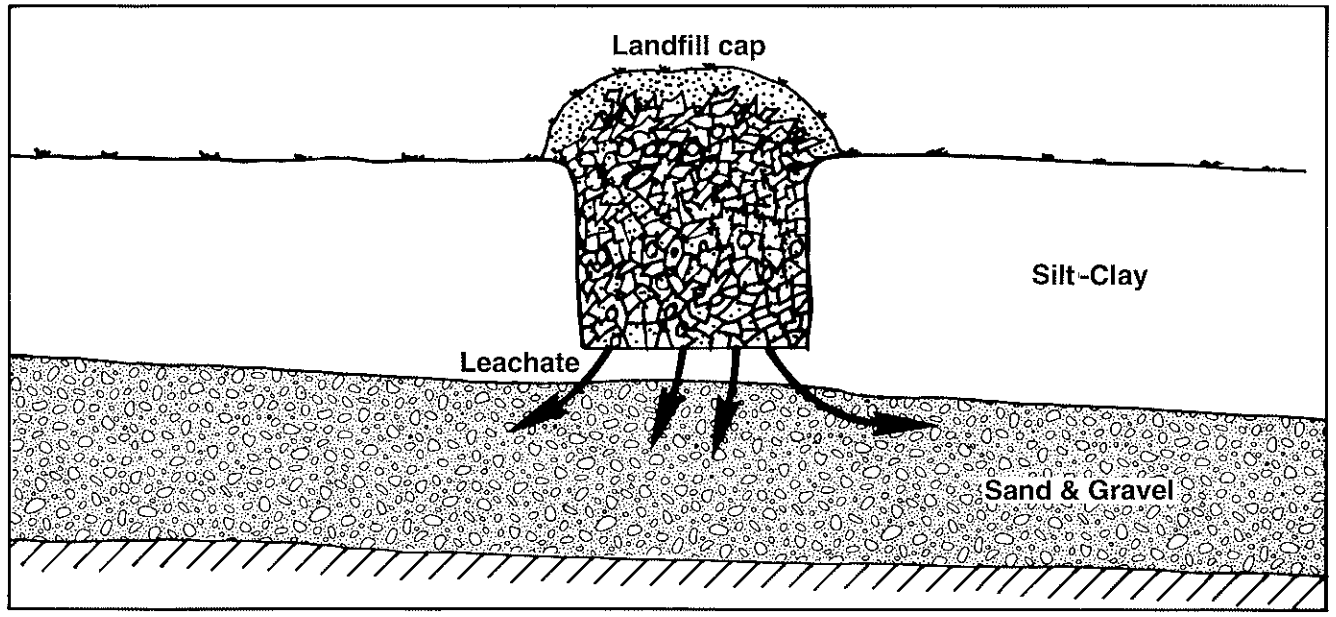


Fig. 13. Movement of contaminant from a landfill

## Nitrates in Rural Water Wells

Nitrate levels exceeding 10 parts per million (ppm) are frequently reported in rural domestic wells. Some domestic wells may have very high concentrations of nitrate. High concentrations of nitrate are also reported in some irrigation wells. It is not unusual for nitrate concentrations to change with time as these wells are pumped. Often recently drilled irrigation wells, screened only in a lower sand and gravel, have minimal concentrations of nitrate.

Clay-loam soils in our hypothetical region are intensively irrigated for corn production. These soils have moderate permeability, allowing for leaching and transport of fertilizers by applied irrigation water and infiltrating precipitation throughout the region. Nitrates reaching the groundwater table by this type of process are described as being from a *nonpoint source.*

A second pathway exists for movement of nitrates to the water table. Poorly constructed domestic and irrigation wells permit movement of water through the gravel pack around the well casing or through openings in the well casing into the well itself. This situation is often made worse by surface conditions around the wells. Local surface runoff from cattle pens (nitrates), storage sheds (fertilizers, pesticides and herbicides), spills during loading of application equipment, refuse piles, etc. may reach the well and move down one of the possible paths. Most of the cases of high nitrate contamination of rural domestic wells can be attributed to these types of situations. Contamination in this situation would be described as being from a *point source.*

The water table in our hypothetical area is at a depth of 30 feet. There are three distinct sediment layers (fig. 14) in this example. The uppermost layer on which the soil developed is a coarse sand 80 feet thick. Twenty feet of clay make up the middle layer. The bottom layer is composed of 50 feet of sand and gravel overlying a shale bedrock. Most domestic wells and early irrigation wells were developed in the upper sand layer. More recently, irrigation wells have been screened in both the upper coarse sand and in the lower sand and gravel.

The first thought on finding contamination in domestic wells in this region should be directed toward well construction and point sources of contaminants. Contamination potential would be highest in the upper coarse-sand layer because of the relatively shallow water table, the high permeability and the often inadequate well construction.

Groundwater flow rates through the 20-foot clay layer would be very low, and contaminant transport would be significantly retarded because of interaction with the clay minerals. The clay layer would help protect the lower sand and gravel layer from contamination.

Because of economics, remediation is impractical. Construction of a well, screened only in the lower sand and gravel, with a bentonite (swelling clay) and/or cement mixture instead of a gravel pack opposite the 20-foot clay layer is the best way to assure higher quality water (fig. 15). This action may not be successful if a nearby well has breached the clay layer and poor design allows groundwater to flow from the upper coarse sand to the lower sand and gravel.

Nitrate contamination in irrigation wells, because of the more remote location, is more likely to be the result of nonpoint sources (for example, leaching of fertilizers). Lower nitrate concentrations in recently completed irrigation wells, developed only in the lower

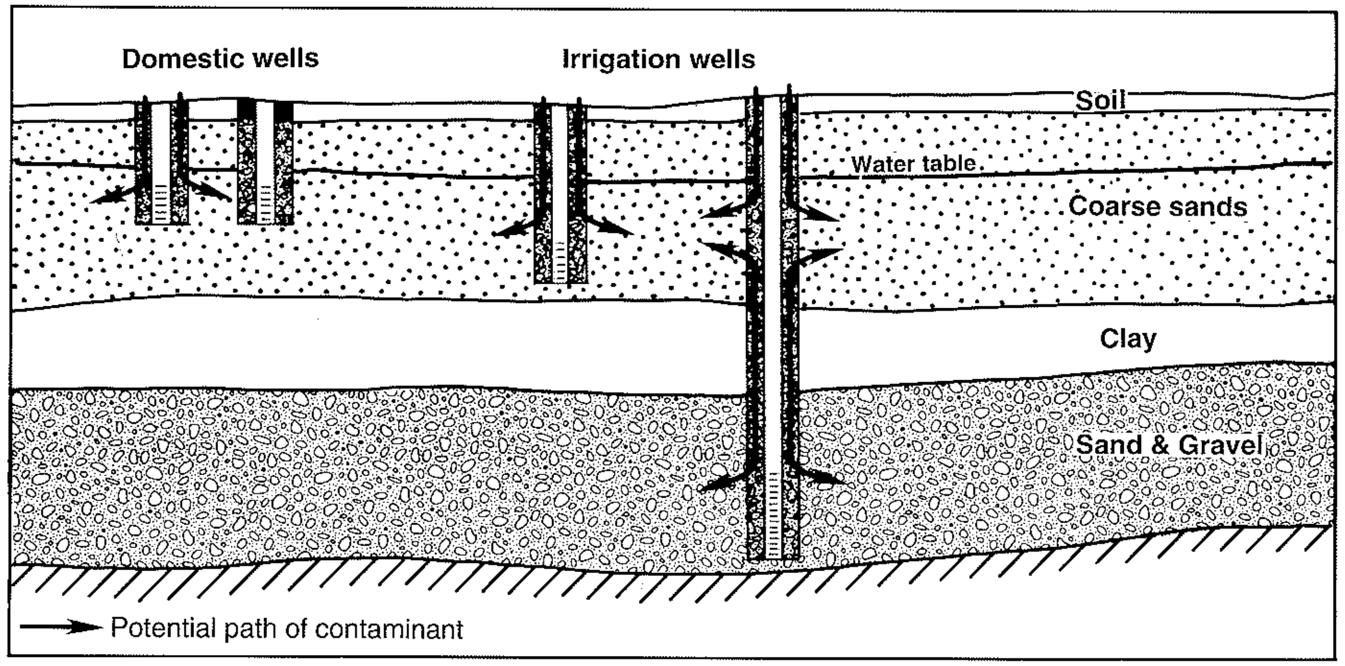


Fig. 14. Potential paths of nitrate movement around wells

sand and gravel, would suggest that the clay layer is intact and no paths for nitrate movement are available.

With time there could be flow from the upper coarse sand to the lower sand and gravel along the gravel pack in the annular space (gravel pack around the well) of the irrigation wells and through joints in the casing. If the wells are screened in both the coarse-sand layer and the sand and gravel layer, flow could be very rapid through the well itself.

During non-pumping periods, groundwater flow from the upper coarse sand through the well could "recharge" the lower sand and gravel layer. If nitrates are carried with the flow, a zone of contamination would develop in the sand and gravel around the well screen. When the irrigation pump is turned on, this "recharged" water would be withdrawn in addition to water from the upper coarse sand. After a long enough period of pumping, most "recharged" water would be withdrawn and higher quality water would enter the well from the lower sand and gravel. This higher quality water would dilute water coming from the upper coarse sand, resulting in lower nitrate concentrations in the mixed water produced by the well. This situation is one possible explanation when it is found that nitrate concentration in a producing well changes during a pumping period.

## Floodplains

The floods of the summer of 1993 have provided us with vivid testimony of the potential for groundwater contamination by flooding rivers. Cemeteries, landfills, petroleum-storage facilities, hazardous-waste disposal sites and industrial facilities are but a few of the human structures that were overwhelmed by floodwaters. In addition there was massive erosion and deposition of soils. Many agrichemicals tied to soil particles were transported to new locations.

The complexities of floods prevent an easy interpretation of possible impacts. One can conceive of many possibilities of what might happen to contaminants eroded from a hazardous-waste site and being deposited at some distance downstream. A key point would be the tremendous quantities of water available for massive recharge, dissolving of contaminants and interaction with the contaminants.

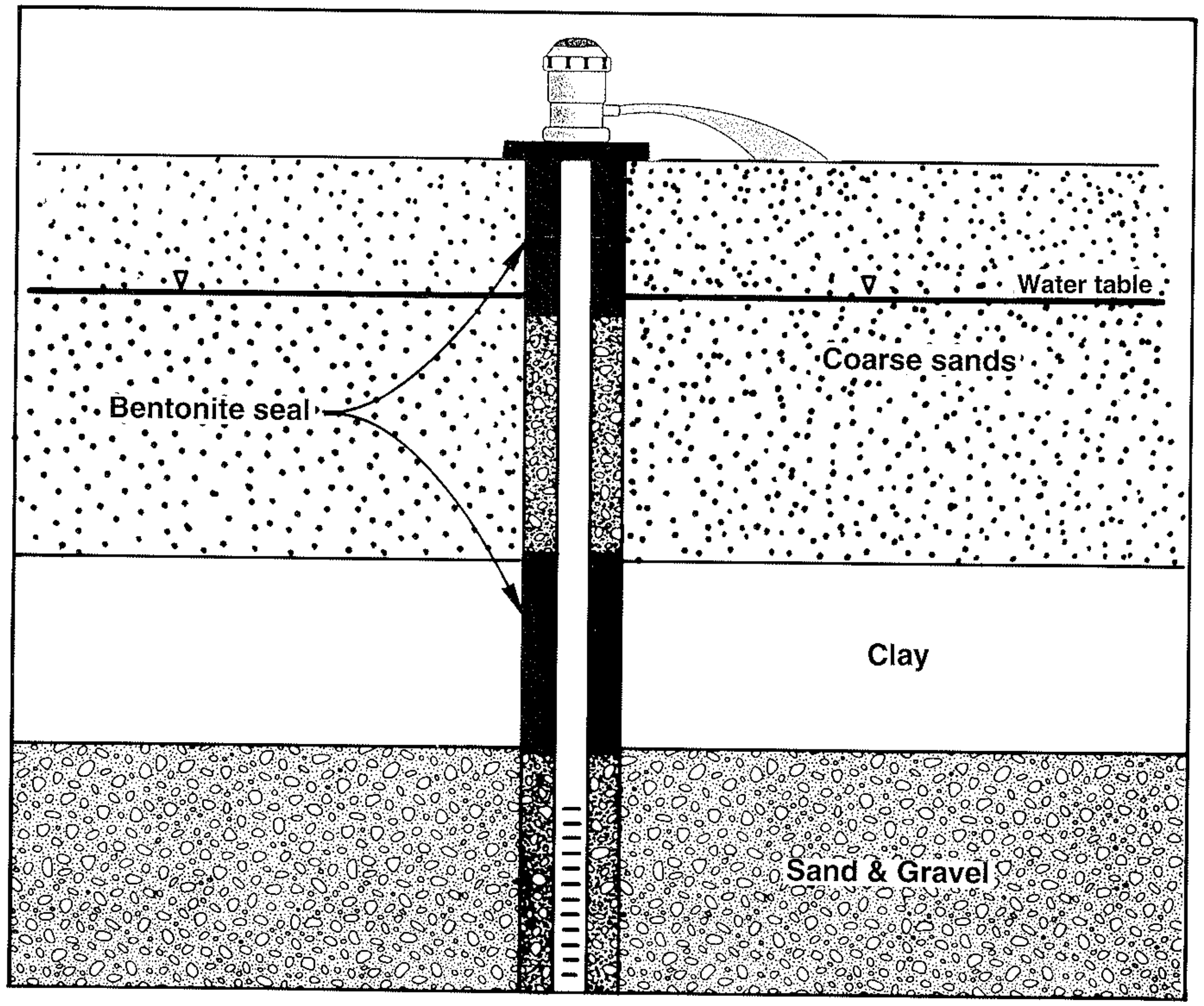


Fig. 15. Properly designed well to prevent vertical movement of contaminant around well

## Summary

Hydrogeologic principles and processes are critical to understanding the movement of contaminants in the environment. It is also clear that the contamination of an aquifer is not easily reversible from a scientific and an economic point of view.

Because Nebraska is so heavily dependant on its groundwater resource, any contamination is serious. Technical, scientific and economic problems in remediation of groundwater point out the need for contaminant control at the source. Once contaminants have started their journey, it is very difficult and expensive to stop them or remove them.

## Glossary

**Alluvium**--a general term for clay, silt, sand, gravel or other unconsolidated material deposited by a stream or other body of running water.

**Aquifer**--a water-bearing layer of rock or sediment capable of yielding supplies of water.

**Aquifer, confined (or artesian)**--an aquifer overlain by a low-permeability layer or layers, in which pressure head will force water to rise above the aquifer.

**Aquifer, principal**--the aquifer or combination of related aquifers in a given area that is the important economic source of water to wells--not necessarily synonymous with groundwater reservoir.

**Aquifer, unconfined (or water table)**--an aquifer in which the upper surface is the water table.

**Aquiclude**--a geologic formation or stratum that confines water in an adjacent aquifer. It has a permeability of zero.

**Aquitard**--a geologic formation or stratum that retards water movement significantly. It has low permeability.

**Bedrock**--a general term for any consolidated rock, commonly applied in Nebraska to pre-Miocene-age rocks.

**Conservative**--(adjective) a contaminant that moves with the same velocity as water.

**Dense non-aqueous phase liquid**--a contaminant that is denser than water and exists as an isolated "plug."

**Discharge**--the flow of surface water in a stream or canal or the outflow of groundwater from a well, ditch or spring.

**Evapotranspiration**--the process by which water is transmitted as a vapor to the atmosphere as the result of the evaporation from any surface and transpiration from plants.

**Groundwater**--water occupying voids within the saturated zone of the earth.

**Hydraulic gradient**--the change in energy along a flow line in an unconfined or confined aquifer.

**Hydrologic cycle**--the continuous movement of water among the oceans, air and the earth in the form of precipitation, percolation, evapotranspiration and stream discharge.

**Light non-aqueous phase liquid**--a contaminant that floats on the top of the saturated zone as an insolated layer.

**Leaching**--the downward transport by percolating water of minerals or chemicals in a soil, often with reference to contamination.

**Loess**--a wind-blown deposit of silt having little or no stratification.

**Longitudinal dispersion**--dispersion of a contaminant in the direction of flow.

**Nonpoint-source contaminant**--a contaminant stemming from a diffuse source or sources; dispersed contamination, such as runoff or percolation from agricultural or urban areas.

**Paleovalley**--a valley of the geologic past, frequently buried under younger sediments.

**Permeability**--the capacity of a porous rock, sediment or soil to transmit fluid.

**Point-source contaminant**--a contaminant stemming from a single, isolated source, such as a drainpipe or an underground storage tank.

**Runoff**--water that flows over the land surface after rainfall, snowmelt or irrigation that eventually reaches streams, lakes, wetlands, etc.

**Transverse dispersion**--dispersion of a contaminant perpendicular to the direction of flow.

**Water table**--the level at which the pore pressure equals atmospheric pressure and below which the pore spaces generally are saturated. This term is generally associated with unconfined aquifers.

**Zone of Saturation**--porous earth materials in which all pore spaces are filled with water.

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