## Chapter 3

# Contamination of the Hydrogeological System: A Primer

### CHAPTER HIGHLIGHTS

- Movement of chemicals is directly linked to water movement, over and through the soil.
- Natural factors affecting potential for agrichemical contamination of groundwater are complex, interactive, and not enough is known about them to specify solutions for most locations.
- Diffuse sites and diverse modes of entry, and multiple agrichemical transport mechanisms render agrichemical contamination of groundwater true nonpoint source pollution.
- Natural factors associated with suspected groundwater vulnerability are widespread and support national concern. Federal and State data collection and information management activities to identify and understand these natural factors are underway, but national-level efforts to synthesize this information to assist decisionmaking are still evolving.
- Long periods of time elapse between changes in surface activities and impacts on groundwater contamination, and contamination is extremely costly to reverse, such that prevention is preferable to redemption.
- Reduction of agrichemical contamination of groundwater requires that the entire agroecosystem be managed to minimize waste and leaching*

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## Chapter 3

# Contamination of the Hydrogeological System: A Primer

## INTRODUCTION

Groundwater has represented a vast and seemingly inexhaustible resource for years, and has become an indispensable source of freshwater. Even until the 1970s, the soil was believed to be a' 'living filter' preventing groundwater contamination from chemicals applied to the land (74). Today, however, a growing body of information tells us that agrichemicals (pesticides and nitrate) have moved through the soil cover to contaminate groundwater. Contaminated well-water in many U.S. agricultural areas is evidence that groundwater is ultimately affected by man's aboveground activities. Clearly, environmental contamination from agrichemicals requires a three-dimensional view of agriculture and its impacts rather than the two-dimensional view held by many in the past,

Three categories of factors largely determine the potential for agrichemical leaching to groundwater:

1. natural characteristics of the site of agrichemical use that affect leaching of water and thus transport of agrichemicals,
2. nature and extent of human modification to those natural characteristics that may affect leaching patterns, and
3. characteristics of the agrichemicals used that determine their environmental fate.

To understand how the problem originated and how it might be solved requires a basic understanding of how water moves through the atmosphere, over the land surface, and below the ground-the hydrologic cycle.

### *Groundwater and the Hydrologic Cycle*

***The*** hydrologic cycle begins with the evaporation of water from oceans and other open bodies of water, vegetation, and land surfaces (figure 3-l). The moisture from evaporation forms clouds, and falls back onto the Earth's *surface* as rain or snow. When it rains, some of the rainfall is taken up by vegetation, some returns to the atmosphere by evaporation and through transpiration by plants, and some water runs off the land to lakes and rivers and on to the sea.

Part of the rainfall falling directly on the land or collected in surface water bodies seeps downward through the Earth's surface. Water moves through the interconnected spaces among individual particles of soils and geologic materials, along cracks and fissures in these materials, or through openings where worms have burrowed or roots have decayed. These spaces may become temporarily saturated with water after a heavy rain, but near the surface, in the ''vadose zone,''[2] open spaces normally contain air as well as water. With increased depth, water fills all available pore space in the Earth's sediments and rock formations. This fully saturated zone is where groundwater is stored; the upper surface of this saturated zone defines the water table (figure 3-2).

Although groundwater is ubiquitous, only certain geologic formations (aquifers) have an extractable quantity of water sufficient for human use. Aquifers may reach hundreds of feet in thickness and may extend laterally for hundreds of miles. The Ogallala aquifer, for example, underlies parts of eight Great Plains States (6,18) and is vital to agriculture over a large region. *Other* groundwater aquifers are thin and of small areal extent and, thus, only a few wells can draw from them. The smallest aquifers—perched water tables—sit on small impermeable layers of geologic material above the region's general water table (figure 3-3).

Water moves continuously below the Earth's surface, much as surface water flows from higher regions towards the sea. Many aquifers contribute to surface water bodies, such as springs, wetlands, rivers, and lakes, and others flow directly into the ocean. Some deep aquifers, however, contain 'fossil water' sequestered under the soil thousands of years ago.

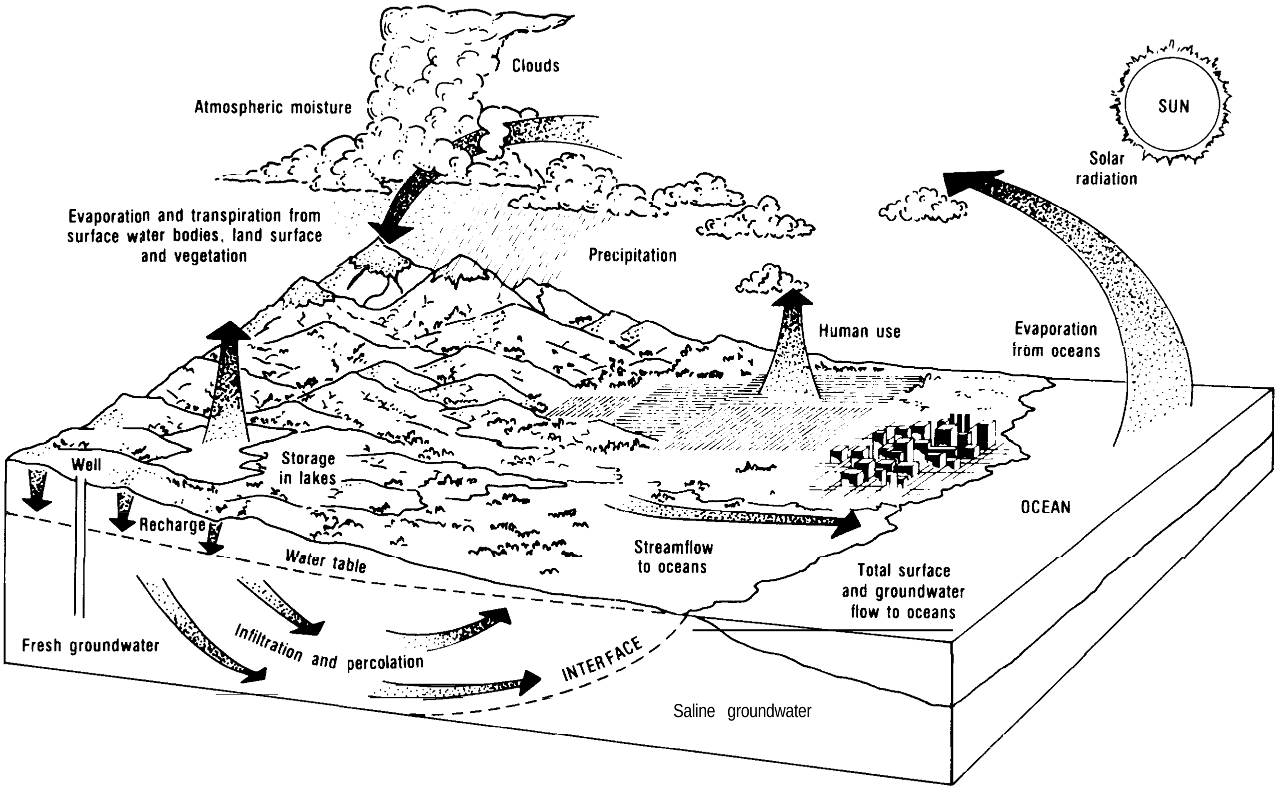
### *Contamination of the Hydrogeologic System*

Water reaches the groundwater table through two primary natural pathways in the course of the

[1]Contamination here refers t. the measurable presence of an agrichemical or its breakdown products, and does not necessarily imply the existence or absence of a threat to human health or the environment.

[2]This zone also may be referred to as the unsaturated zone or the zone of aeration.

**Figure 3-1—Hydrologic Cycle**




SOURCE: Adapted from B.J. Skinner and S.C. Porter, *The Dynamic Earth (New York, NY:* John Wiley& Sons, 1989).

hydrologic cycle: direct leaching through soils and rock formations, and via recharge from surface waters. Although the waters leaching through farmlands to groundwater may pickup agrichemical and natural contaminants as they move through the system, contaminants also may derive from atmospheric deposition or contaminated surface waters.

### Atmospheric Deposition

Agrichemicals can be transported and dispersed in the atmosphere, eventually returning to lands and surface waters. With spraying from airplanes, in particular, pesticides aimed at a specific field are likely to drift beyond its boundaries and settle on distant land areas, lakes, and streams.

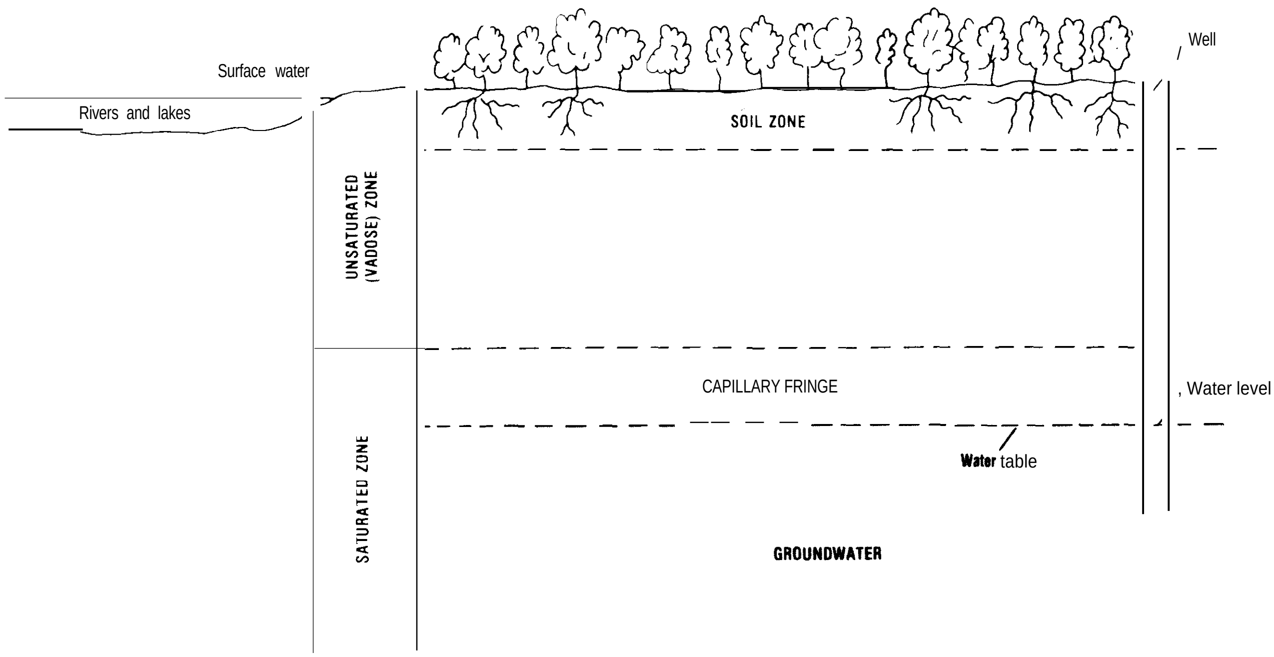
Contamin ation of rainfall has been documented for certain organochlorinated pesticides. Studies show that the pesticide toxaphene (now banned by the Environmental Protection Agency (EPA)) was carried long distances from its use site and deposited through rainfall in concentrations high enough to damage fisheries (1 1). Similarly, in a pilot study of atmospheric dispersal of pesticides in the Northeastern United States, rainwater samples were analyzed for 19 commonly used pesticides and 11 were found in detectable levels (62).

The detected compounds showed strong seasonal variation consistent with application times and chemical stability and, thus, are thought to have originated mostly from local sources (62). However, wind also can transport agrichemical particles and vapors hundreds or thousands of miles before they fall back to Earth. In 1980, an insecticide used to control boll weevils in cotton fields in the Southern United States was discovered in fish in the waters of Lake Superior. The global scope of atmospheric transport became apparent when insecticides used in Asia and southern Europe appeared in Arctic and Antarctic waters.

### Recharge by Contaminated Surface Waters

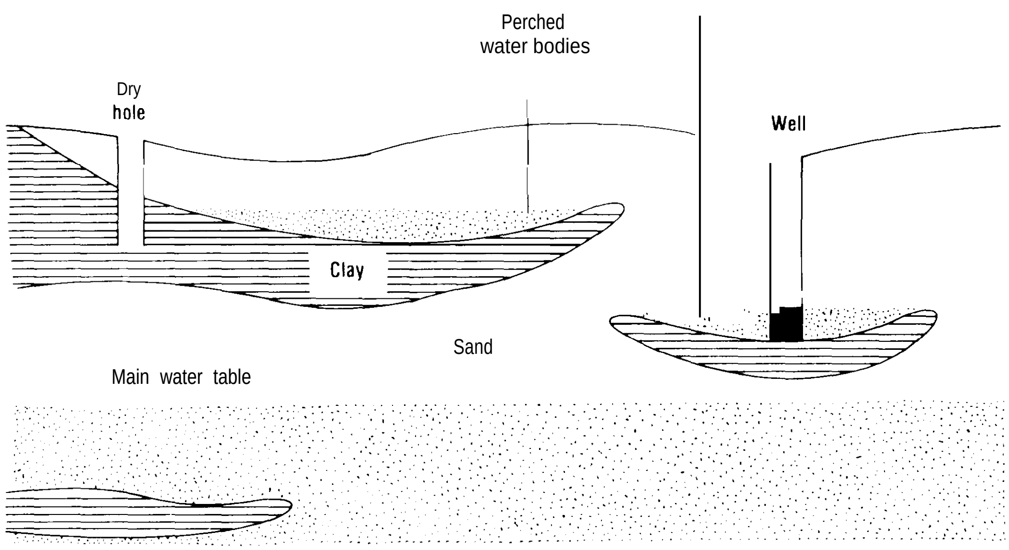
Readily soluble agrichemicals maybe carried off fields with runoff. Some agrichemicals have a tendency to attach themselves to certain soil parti-

**Figure 3-2—Zones of Subsurface Water**



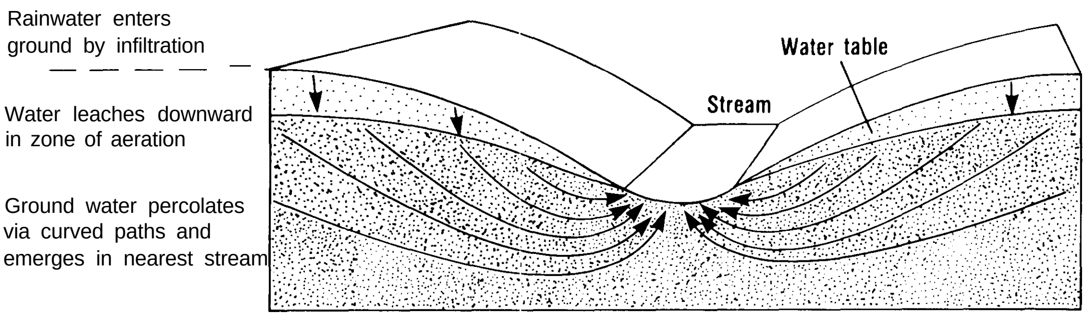

SOURCE: Adapted from R. C. Heath, ***Ground- Wafer Regions of the United States,*** Geological Survey Water-Supply Paper No. 2242 (Washington, DC: U.S. Government Printing Office, 1984).

**Figure 3-3-Perched Water Tables in Relation to the Main Water Table**

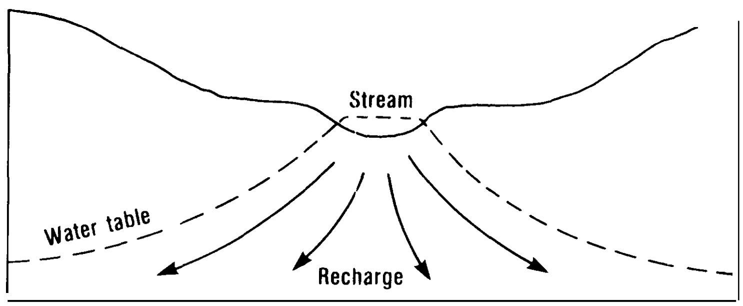



SOURCE: B.J. Skinner and S.C. Porter, ***The Dynamic Earth (New*** York, NY: John Wiley& Sons, 1989).

**Figure 3-4-Surface Water and Groundwater Relationships**




A. Generalized movement of groundwater in uniformly permeable **rock** in a humid region, or during high precipitation conditions in an arid/semiarid region




B. Generalized movement of groundwater in uniformly permeable rock in arid/semiarid regions-or during long-lasting drought in humid regions

SOURCE: **B.J.** Skinner and **S.C.** Porter, ***The Dynamic Earth (New York, NY:*** John Wiley& Sons, 1989).

cles; the impact of raindrops can erode soils and associated agrichemicals from the field. In such cases, agrichemicals may end up in surface water bodies. From there, agrichemicals or their breakdown products may leach into groundwater.

Groundwater and surface waters are closely linked, with the flow of one to the other depending on the relative altitudes of the surface water and the groundwater table (figures 3-4a and b). For example, in humid regions, the flow of groundwater generally is toward surface water bodies because the groundwater table in the surrounding land is higher than the surface water body. In arid/semiarid regions, however, the flow direction is reversed because the altitude of streams tends to be higher than the groundwater table (75,18,66). Under conditions of abnormally high rainfall in arid/semiarid regions or abnormally low rainfall in humid regions, the predominant direction of water flow may change accordingly. Thus, in any region of the country, potential exists for climatic factors to promote recharge of groundwater by surface waters. In addition, pumping of high-capacity municipal wells can draw surface water into the aquifer.

The absence of oxygen below the water table precludes most reactions that degrade contaminants in the vadose zone (40). Contaminants that reach and move with groundwater are therefore likely to remain chemically intact for long periods.

Once contaminants reach groundwater they may spread laterally to a greater extent than they may have in the vadose zone. In certain instances, a large aquifer may be encountered through which contaminants can disperse regionally (e.g., Ogallala aquifer) (25). While it might be years before contaminants reach the deeper parts of a very thick aquifer, deep groundwater may act as a long-term reservoir for contaminants. Thus, contaminants in groundwater

Photo credit: U.S. Fish and Wildlife Service-L. Childers

Groundwater and surface water, such as the wetlands shown here, are intimately connected. Contamination of groundwater can therefore result in contamination of surface-water bodies, and vice versa

may be discharged to a stream decades, or centuries, after percolating rainwater introduced pollutants in the first place (86).

### *Natural Factors Affecting Leaching of Agrichemicals to Groundwater*

***The*** potential for agrichemicals to leach directly through soils and rock to groundwater depends on numerous factors. Natural site characteristics can enhance or reduce the potential for a given agrichemical to leach and to contaminate groundwater. Local topography and landforms can favor surface runoff over downward soil seepage or vice versa. Vegetation and climatic parameters (temperature, precipitation, air movement, and solar radiation levels) affect the environmental fate of contaminants as well (14). Roots and sunlight can interact directly with the contaminant (e.g., photochemical degradation of chemicals exposed to sunlight, root uptake of nutrients and pesticides); vegetation and climate also have impacts on soil properties. Other variables such as the depth to the water table, characteristics of the unsaturated zone, and the presence and distribution of low-permeability layers also can affect contaminated water flow. Pesticide degradation may occur via one or a combination of several biological and chemical pathways, and the operative pathways may vary from site to site (58).

Certain soils may have direct physical or chemical interactions with agrichemicals. Some chemical reactions, relating to the presence or absence of oxygen or to the hydrolysis of a chemical, may serve to detoxify contaminants in the soil. Sometimes, though, the pesticide breakdown products may be more toxic than the parent compound (14).

#### Topography and the Soil Surface

Topography of the land and the roughness of the soil surface can affect the movement and fate of agrichemicals applied to agricultural lands. Sloping agricultural lands tend to be more prone to water erosion than are flat lands. On flatter agricultural lands, water erosion is less of a problem and the likelihood for infiltration of the agrichemical-bearing water into the soil and into groundwater may be enhanced. On flat land, wind is likely to be the agent that erodes soil and carries agrichemicals from agricultural lands. Strong winds can remove fine soil particles and lightweight organic matter from dry soils. These airborne materials may end up in distant water bodies; any attached agrichernicals may ultimately move into the groundwater. Rougher soil surfaces, such as those produced by leaving crop stubble on the field, tend to reduce runoff and thus hold agrichemicals and soil particles on site, affording time for agrichemical degradation.

Some pesticides will break down when exposed to direct sunlight, a process called photochemical degradation. The longer pesticides are exposed to sunlight, the more likely it is that photosensitive chemicals will break down. Topography obviously affects length of exposure to sunlight (e.g., north-v. south-facing slopes); it also affects soil temperature and microbiota, which in turn affect pesticide degradation.

### Vegetation

The presence and type of vegetation-forests, grasslands, or agricultural crops—strongly affect the movement of water and water-borne solutes within the vadose zone. Crops such as alfalfa with roots up to 20 feet deep and high water demand, and sunflowers and safflowers with roots penetrating to at least 6 feet, have impacts far different from those of shallow-rooted crops with lower water demand. Agrichemicals are less likely to pass beyond deep-rooted crops to contaminate groundwater than to travel beyond the much shallower root zone of crops like corn (17,64). Once agrichemicals pass the root zone there is little to stop them from moving downward to the groundwater.

The closer the spacing between individual plants the less potential there is for soil erosion and the inadvertent movement of agrichemicals to off-site locations and potential groundwater contamination. Close-grown crops such as grasses or small grains, are more likely to intercept raindrops and shield the soil from wind than widely spaced crops such as corn, soybeans, or cotton. Moreover, the denser the root system the less likely it is that soluble nutrients will pass the root zone and move into groundwater. This is particularly true when the nutrients are applied at that time during the growth period when the plants have the most demand for them. Those areas having the longest growing seasons provide for the maximum nutrient uptake.

*Photo credit: U.S. Department of Agriculture, Agricultural Research Service*

USDA researchers take groundwater samples from a test site next to a cornfield in Beltsville, Maryland. Groundwater will be tested for pesticides in a study on the effects of different tillage methods on pesticide movement.

When annual crop plants die, nutrient and water uptake by the plants ceases, thus providing a period when water, agrichemicals remaining in the soil, and nutrients from decomposition of crop residue can move downward. Some nutrients may be sequestered by soil organic matter; others are subject to leaching and may contaminate groundwater. Consequently, the removal or harvest of annual crops and its timing plays an important role in the fate of agrichemicals (64).

### Water Table

The movement of water into and through the soil is very complex, and there are seasonal and regional variations in the amount of water that enters the soil and eventually recharges groundwater (25,57). The amount of recharge, depth to the water table, and fluctuations in depth to water table vary with climate, soils, topography, and geology.

The water table tends to be shallower and more readily recharged in the Eastern United States where precipitation normally exceeds evaporation, than in the arid/semi-arid regions of the Western United States, where the reverse is true. Streams supplied by water sources originating in distant mountains are for the most part the only significant source of groundwater recharge in some arid regions of the Western United States (75). With little rainfall over long periods of time, the groundwater table in arid/semiarid regions may be as much as 1,500 feet below the land's surface (6).

In humid regions, the likelihood of contaminating groundwater with agrichemicals is higher than in dry regions where water is scarce, because of the shorter distance between the land surface and the groundwater table. Longer transit time in dry regions than in humid areas may afford greater opportunity for the natural breakdown of pesticides. However, for those pesticides requiring moisture for degradation, this condition may lead to a persistence in the soil.

The water table fluctuates seasonally, typically rising during the winter and early spring rains, and falling during drier months. Under drought conditions, the water table will continue to fall. Streams and ponds that once served as outlets for groundwater may begin to dry up as their waters follow the falling water table. In normal times, the water table may rise to the plant root zone during the "spring flush' '-when snows melt and rains are more frequent or intense-minimizing potentially mediating soil effects, Spring also tends to be the period of heaviest plant nutrient application.

## Soil Characteristics

Soil characteristics are determined by the interaction of soil-forming factors such as the soil's geologic parent material, the climate under which the soil formed, its topographic position, the nature of the vegetative cover, the kinds and abundance of soil organisms, and the amount of time the soil has been forming. The resulting soil properties in turn have a direct influence on how rapidly or slowly agrichemicals move through the soil into groundwater. Therefore, in a country as large as the United States where significant variation exists in soil, geology, climate, and topography, it is natural to expect large variations in soil properties vertically and horizontally in different areas. It would be necessary to have site-specific data on the soil type to indicate soil structure, mineralogy, chemistry, and texture before making detailed predictions on the potential for contaminating groundwater with agrichemicals.

Soils exist in a water-saturated or unsaturated state. Plants growing in ponds and marshes have their roots in water-saturated soils. Most agricultural crops, however, grow on unsaturated soils comprising the top few feet of the vadose zone. The soil factors that affect leaching and degradation processes through unsaturated soils include organic carbon, clay and moisture content, pH, temperature, texture and structure, nutrient status, and microbial activity (14).

***Physical and Chemical Soil Characteristics—The*** *texture* of soil relates to the size and shape of its constituents, and extent of particle aggregation (56), all of which affect the volume of air or water a soil can hold or transmit. Soil texture exerts substantial control over the movement of water and associated agrichemicals.

Soils have many open spaces between constituent particles that can hold and transmit water. This open space in a soil is called *porosity.* However, if the open spaces or pores are not interconnected, water cannot flow through the soil rapidly. Such soils are said to lack *permeability* even though they are porous. Clean sand (sands containing little silt or clay or other fine-grained materials) and gravel soils are porous and permeable but as the content of fine silt and clay particles increases, the pores become plugged and the rate at which water moves through such soils decreases. Therefore, it is important to know how porous a soil is, how large the pores are, and to what degree the pores are interconnected before predicting the fate of agrichemicals applied to that soil.

Some of the best agricultural soils are called loams, i.e., those containing about 5 to 25 percent clay with approximately equal parts of silt and sand constituting the remainder. Such soils commonly remain well-aerated throughout the year and drain effectively. Loam soils are better than either coarse-grained soils or fine-grained, poorly drained soils in faltering out and arresting downward percolating contaminants (45).

Pore size is an important characteristic to consider when evaluating the likely movement of contaminated water. A thin film of water is held tightly on the mineral particles making up soil by forces of molecular attraction. This film of water (adsorbed water) does not behave like the water in the center of large pores. The adsorbed water will not flow out of a soil's pores as will the water in the center of a large pore (absorbed water). Consequently, a soil composed of fine-grained materials may have a high porosity and the pores may be interconnected, but because the pores are so small most of the water is adsorbed and little will be able to flow through the soil (66). Such soils give farmers problems bemuse they are slow to dry out, waterlog easily, are difficult to cultivate, and do not crumble but form clods (53). The oxygen content of the soil can be reduced in such situations to the point where plants are adversely affected.

Soil particles tend to be spherical in the large grain sizes (e.g., sand) but more plate-like in the freer fractions (e.g., clay). Fine clay particles can be arranged in two general forms, one like a deck of cards and the other like a house-of-cards. The adsorbed water is continuous between parallel clay particles and, therefore, essentially is immobile. Little pore space exists in the "deck-of-cards" arrangement. The house-of-cards clay arrangement has a high porosity and may have interconnected pores, but because the clay sheets are so small, the layer of adsorbed water on each sheet overlaps with that of adjacent sheets, also restricting water flow. Clay-rich soils and rocks thus transmit water poorly and, therefore, retard agrichemical movement into groundwater.

Clay *minerals* have other important properties for retarding the movement of certain agrichemicals, heavy metals (toxic constituents of sewage sludge containing industrial wastes), and bacteria into groundwater. Many U.S. soils contain several common types of clay minerals that can trap fertilizer nutrients on their outer surfaces as well as between mineral layers. The clays can incorporate nutrients important to plants such as potassium, calcium, or magnesium, hold them in an exchangeable form, and release them later to plant roots or the soil solution. The movement of nutrients to and from clay surfaces is called ''ion exchange. '

Some pesticides and heavy metals also can be trapped by appropriate kinds of clay minerals. In addition, some bacteria that might originate in sewage sludge, manure, or even dead farm animals can be filtered out of soil water or groundwater and trapped by clays and even fine-grained sands (66). Viruses, being much smaller than bacteria, are not easily faltered out but their properties are such that they are likely to adhere to clay mineral surfaces.

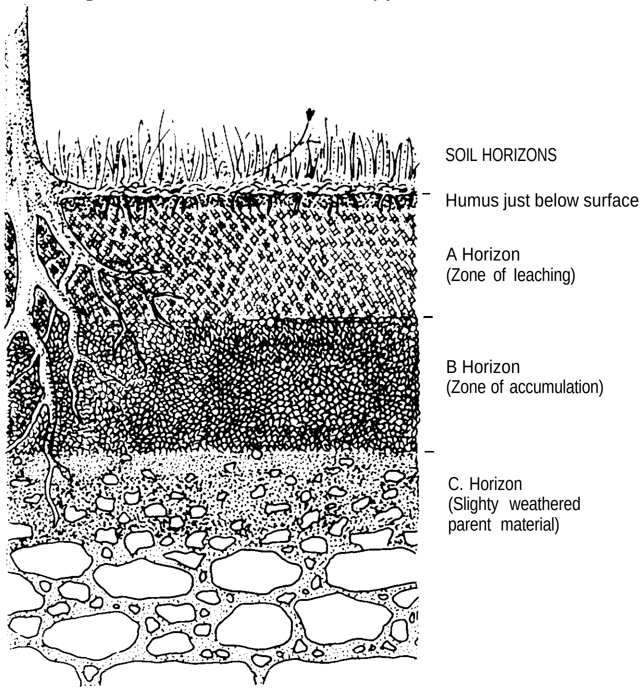
Another important component of soils is the humus that gives the uppermost part of soils their dark color (figure 3-5). Humus is a breakdown product of plant and animal *organic matter* and, like clays, has the ability to filter out and capture bacteria and many chemical contaminants. Organic matter can hold water, heavy metals, and some organic chemicals and it promotes the retention of soluble plant nutrients that otherwise would tend to leach downward with percolating waters. Pesticide adsorption in soils in many studies has been found to correlate with the soil organic-matter content (14).

Soil organic matter plays a key role in successful agriculture, imparting benefits to soils that, for the most part, cannot be obtained by merely adding chemicals. Soil organic matter promotes soil particle aggregation, which in turn improves soil tilth and soil percolation (74). Thus, soil organic matter relates directly to the capacity of the soil to hold air and moisture, and promote more extensive, deeper crop root systems. The latter is important in the overall water use efficiency of the crop.

Further, organic matter ultimately is biologically degraded to release the ''macronutrients' (nitrogen, potassium, and phosphorus) most essential to plant growth. The main natural source of nitrogen for plant growth is soil organic matter, however, most of the nitrogen is unavailable to plants until it is converted to ammonia and nitrate by microorganisms. Soil organic matter also helps control potassium supply for plant growth. As soil reservoirs of available potassium are depleted, they are replenished by potassium released from organic residues, fertilizer, living organisms, and soil minerals (47).

The *mineral part of soils* ordinarily contains about 400 to 6,000 lb. per acre foot of nitrogen in the plow layer. Somewhat lesser amounts are found in subsoils (3). Nitrate levels in range and wheat fallow soils of central and south central Nebraska were estimated up to 150 pounds per acre foot at depths of 30 to 40 feet. These high natural volumes of nitrate exceed the amount applied as fertilizer in the State,

**Figure 3-5—Horizons of a Typical Soil Profile**




SOURCE: B.J. Skinner and S.C. Porter, *The Dynamic Earth (New York, NY:* John Wiley & Sons, 1989).

and constitute a considerable threat to groundwater should they leach (13).

Soil inorganic matter may contain from 15 to 80 percent of the total soil phosphorus, an important plant nutrient (3). Mycorrhizal fungi are active in collecting phosphorus for plant use. As the phosphorus is slowly released during weathering of certain soil minerals, it is moved to plant roots by the fungi (76).

Characterizing the amounts and types of clay minerals, organic matter, and other soil components is complex, yet such information is fundamental to assessing the fate of commercial fertilizers, pesticides, and the heavy metals in sewage sludge that might be applied to agricultural land. Increased regional and soil series data are needed.

**Biological Characteristics**

Biological agents also affect the movement of water and water-borne substances within the vadose zone. Organic compounds break down most readily within the uppermost ''bioactive" soil layers, although microbial populations are present and can be significant in deeper unsaturated zones (58). The soils most reactive with agrichemicals possess substantial water-holding and ion-exchange capacities, an open physical structure, and thriving populations of beneficial bacteria, fungi, and invertebrates (figure 3-6).

However, burrowing animals and decaying plant roots may create vertical ''macropores' that permit the rapid passage of water (41,55). Rapid, channeled flow, as opposed to dispersed, slow seepage leaves less room for soil reactions to cleanse water physically or chemically, and increases the potential for the movement of soil nutrients and other contaminants into groundwater.

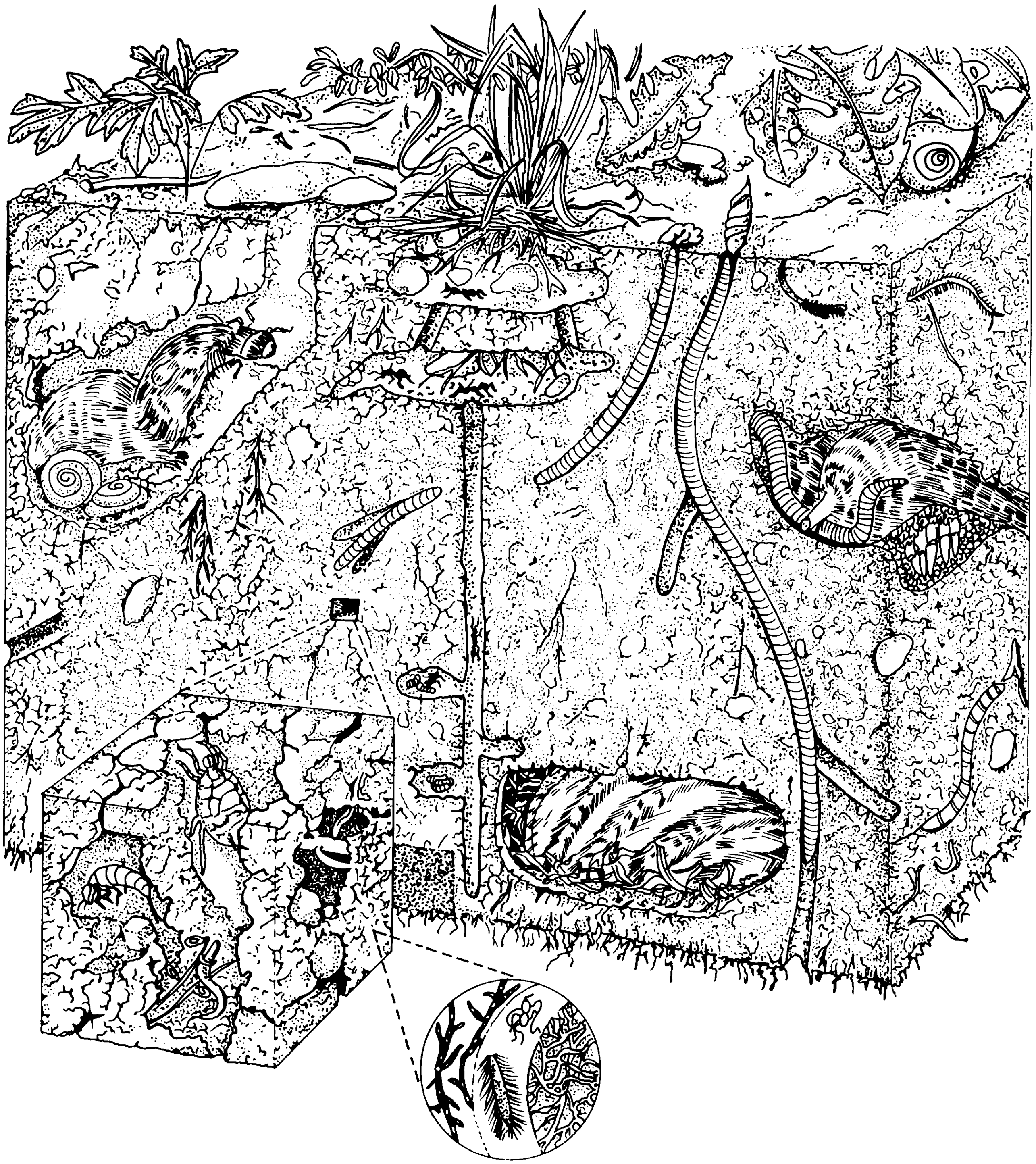
***Microorganisms-Most soil*** microorganisms are microscopic or barely visible to the naked eye. Soil microorganisms (bacteria, fungi, actinomycetes, and protozoa) serve a critical function in that they metabolize extant organic matter to release the nutrients essential for plant growth. Microbial decomposition of organic matter also releases elements not used directly as plant nutrients. Some of these elements may be converted to gaseous form (e.g., carbon dioxide and nitrous oxides). By such conversions, microorganisms in part regulate the chemistry of the Earth's surface and atmosphere.

Microorganisms comprise the sole or chief natural means for converting organic forms of nitrogen, sulfur, phosphorus, and other elements to plant-available forms. In the final stages of biochemical decomposition of organic matter, nutrients are recycled, humus forms, and soil particle aggregation is fostered (21). Any actions or agrichemicals deleterious to these microbial processes ultimately would have adverse consequences on crops.

Potential groundwater pollutants can be degraded (converted to a non-toxic form) or created by biological agents. Certain "nitrifying" soil microbes convert organic compounds of nitrogen into nitrate useful to plants and potentially available for leaching to groundwater. In the absence of high levels of commercial nitrogen fertilizers, the rate at which microorganisms convert nitrogen to products useful to plants largely determines the rate of plant growth. Leaching of microbially produced nitrate-not of fertilizer nitrate-is thought by some British scientists to be the primary source of nitrate detected in some of their water supplies (l).

Further, soil microorganisms are responsible for decomposing a wide array of synthetic organic chemicals in agricultural soils and water, including

**Figure 3-6—Microfauna and Macrofauna Open Conduits and Create Pore Spaces in Soils**



SOURCE: P.H. Raven, R.F. Evert, and S.E. Eichhorn, *Biology of Plants* (New York, NY: Worth Publishers, Inc., 1986).

pesticides, industrial wastes, and precipitated air pollutants, converting them to inorganic products. The breakdown process may lead to detoxification of toxic chemicals, the formation of short- or long-lived toxicants, or the synthesis of nontoxic products. Scientists have investigated only a few of the multitude of chemicals to determine what breakdown products are formed when microorganisms encounter chemicals in natural systems (2).

***Soil Invertebrates and Vertebrates*-Most soils *are*** inhabited by a diversity of life forms. The soil biota includes, in addition to numerous microbes, a wide variety of invertebrate animals and a few vertebrates. Some of these larger soil invertebrates such as earthworms, ants, other soil insects, and land snails and slugs are important to agrichemical leaching or degradation processes. Small mammals are the dominant vertebrate animals found below ground, but some amphibians, reptiles, and even a few birds live at least a part of their lives within soils.

Soil "macro-organisms" often modify and enhance the soil by their activities, carrying out the early stages of the physical and chemical decomposition of all types of organic debris in or on the soil. They are vital to the formation and maintenance of the natural soil system and perform functions essential for plant growth. Annually, earthworms in one hectare of land can produce as much as 500 metric tons of castings, the soil material passing through their gut. The castings are enriched in nutrients compared to the adjacent soil: 5 times as much nitrogen, 7 times as much phosphorus, 11 times as much potassium, 3 times as much magnesium, and 2 times as much calcium (61). Before the widespread availability of commercial fertilizers, nutrients recycled by the biota were recognized as a major component of soil fertility and so soil biology ranked high among the agricultural sciences. In recent decades, however, there has been much less emphasis on soil biology as increased soil fertility has been achieved through use of commercial fertilizers.

Despite the lack of quantitative data on the impact of farming practices on invertebrates in most U.S. soils, some qualitative information does exist. The situation is not the same for soil vertebrates, which include such animals as moles, gophers, mice, other burrowing mammals, and some reptiles and amphibians. Even though some people worry that agrichemicals may harm beneficial soil invertebrates, the activities of soil vertebrates are commonly and narrowly viewed as negative: for example, making burrows in which farm machinery can become entrapped, consuming valuable grain or forage, or providing pathways for agrichemicals to reach the groundwater table. Some studies of soil vertebrates suggest that they may also have beneficial impacts, such as breaking up hardpan a foot or more below the surface, thus improving drainage and increasing rooting depth. Unfortunately, such ecological studies typically are conducted on virgin land and are difficult to relate to agricultural lands (63).

No economically feasible substitutes exist for the significant functions of organic matter and soil biota, so their maintenance in croplands and rangelands is critical. Soil invertebrates and microorganisms assist in breaking down plant remains, producing new organic compounds that promote good soil structure, and convert soil nutrients to forms usable by plants. Microbes also break down pesticides and other toxic chemicals. Without the soil biota, the organic matter from plant residues and manure would be of little use. Consequently, care is needed to assure that agrichemicals moving through the soil and groundwater do not adversely affect the soil biota.

## *Characteristics of Underlying Geological Materials*

***In*** situations where soils lie directly over bedrock it is generally easier to predict the likelihood for agrichemical leaching to underlying aquifers than in instances where unconsolidated sediments separate the soil from the bedrock. In this latter situation, the characteristics of the intervening materials play an important role in determiningg the fate of agrichemicals.

### Bedrock Characteristics

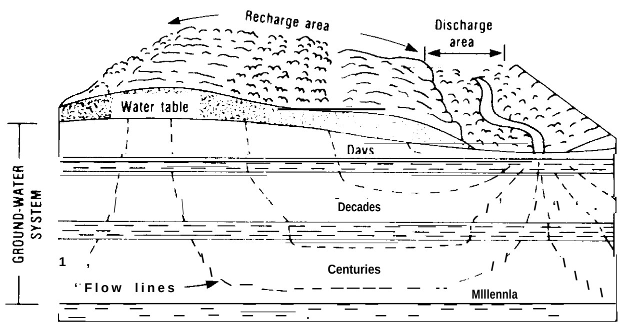
Accumulations of unconsolidated materials and various kinds of bedrock may lie beneath the soil surface. Whatever its name and origin, it is largely the chemical and physical nature of bedrock that governs water flow and pollutant dispersal. Even though the permeability of some types of bedrock is very low (table 3-1; figure 3-7), most types of bedrock are criss-crossed with hairline cracks and fractures, and larger cracks or "joints" provide pathways through which water can flow. *Some* rocks like sandstones and conglomerates may be highly permeable even where joints are scarce.

**Table 3-l—Estimated Permeability of Typical Geologic Materials in Illinois**

| Geologic material | Flow rate | Comments |
|---|---|---|
| Clean sand and gravel | 100 ft/yr | May be highly permeable |
| Fine sand and silty sand | 1 ft/yr -100 ft/yr | — |
| Silt (Ioess, colluvium, etc.) | 10 ft/yr -1 ft/10 yr | . |
| Gravelly till, less than 10% clay | 1 ft/yr -1 ft/100 yr | Often contains gravel/sand lenses or zones |
| Till, less than 25% clay | 1 ft/10 yr -1 ft/1 ,000 yr | |
| Clayey tills, greater than 25% day | 1 ft/100 yr -1 ft/10,000 yr | Often contains gravel/sand lenses or zones |
| Sandstone | 10 ft/yr | — |
| Cemented fine sandstone | 10 ft/yr -1 ft/100 yr | Frequently fractured |
| Fractured rock | 10 ft/yr | May be extremely permeable |
| Shale | 1ft/100 yr -1 ft/1,000,000 yr | Often fractured |
| Dense limestone/dolomite (unfractured) | 1ft/1000 yr -1ft/1,000,000 yr | — |

SOURCE: Adapted from R.C. Berg, J.P. Kempton, and K. CartWright, "Potential for Contamination of Shallow Aquifers in Illinois," Illinois State Geological Survey, 1984.

**Figure 3-7-General Direction and Rate of Groundwater Movement**




SOURCE: R.M. Wailer, "Groundwater and the Rural Homeowner, " (Reston, VA: U.S. Geological Survey, 1988),

Generally, fractures and joints in bedrock become less common with increasing depth and groundwater movement and storage volume decreases. At least one-half of all groundwater, including most of the usable groundwater, occurs within the upper 2,500 feet of the land's surface (66).

Bedrock commonly shows evidence of distortion and folding and faulting. The variation of bedrock types and properties, and the different geologic structures present beneath the land's surface, all affect the flow of water and, hence, complicate predictions of contaminant movement in surface and groundwater. Groundwater follows an erratic path rather than a straight, vertical line and contaminants may be carried considerable horizontal distances away from the original site of surface application. Where water encounters solution cavities and channels in an area of carbonate bedrock, it may move rapidly downward as if through an open well. Without detailed subsurface geological data, it is nearly impossible to predict precisely where groundwater and its pollutants are likely to move or accumulate in the subsurface.

### Solution Cavities in Carbonate **Rocks**

Limestone, dolomite, and marble are common rocks that can dissolve slowly as water comes in contact with them. Over centuries, rainwater and groundwater can dissolve a considerable volume of these rocks leaving behind a variety of solution features (cf: 66). Regions where limestone is common at, or very near, the land surface and where solution of this rock is at an advanced stage, are characterized by sinkholes, caves, and streams that seem to disappear into the ground. These features typfiy what geologists call karst topography.

If agrichemicals are used in karst regions there is high probability that groundwater will be contaminated. Once such chemicals move into the groundwater in such a setting, they can move rapidly over large distances diluting to lower concentrations or causing contamination in unexpected places. Wells in karst regions, therefore, are highly susceptible to contamination from agricultural activities.

In certain cases, limestone karst topography is buried far below the land surface. Overlying sediments may have low permeabilities and consequently downward moving agrichemicals may not reach the water-filled limestone cavities. In such cases, well-water pumped from the limestone aquifer may be uncontaminated, However, in cases where the limestone beds are tilted and crop out at the land surface, the entire aquifer may become contaminated as agrichemical-laden groundwater flows laterally from its shallow to its deepest parts. Wells miles from the source of contamination can be adversely affected. Thus, groundwater contamination that begins as a local problem can, under certain conditions, become regional in nature.

### Unconsolidated Materials

Unconsolidated materials commonly underlie soils in many parts of the United States. For example, extensive unconsolidated glacial deposits separate the soil from bedrock across much of the farmlands of the northern part of the United States from Montana to Maine. These and other unconsolidated materials affect how slowly or quickly contaminated water will reach groundwater in confined and unconfined aquifers. Geologists can assist with assessing the subsurface character of these sediments where concerns exist about agrichemical contamination of subsurface waters.

Unconsolidated sediments deposited along streams and rivers (alluvium) can cover bedrock and can vary greatly in thickness. Similarly, sediments that move downhill and accumulate at the foot of slopes (colluvium) also can cover bedrock to varying depths. Other unconsolidated material form in place from weathering of underlying bedrock. These types of sediments can vary in composition vertically and laterally over short distances, thus directly affecting the downward flow of water.

The porosity and permeability of the unconsolidated materials relate to the sediment's source material, the degree of weathering, whether or not the unconsolidated material has been transported, and the mode of transportation. Where unconsolidated materials are thick, porous and permeable, they commonly are filled with water in their lower parts if rainfall is sufficient, and they are used as unconfined aquifers by farmers and others. Of course, where they have a high degree of porosity and permeability and underlie agricultural sites, they are likely to be contaminated easily where agrichemicals are applied to the land surface.

### Glacial Geology and US. Midwest Agriculture

Glaciers moving south from what today is Canada once covered large parts of the United States from Montana to Maine and as far south as southern Illinois (figure 3-8). The last glaciers melted or retreated about 10,000 years ago leaving behind a variety of sediments of varying thicknesses, filling in old river valleys and giving the land a much smoother topography than before. Today, rivers have cut through these glacial sediments in some places but much of the flat land of this region still has a glacial sediment cover.

This glaciated region—nearly one-quarter the area of the lower 48 States--contains 40 percent of the U.S. population and some of the best agricultural land in the world, including the "Corn Belt. " This also is the region of the United States where the application of agrichemicals is highest.

The geology of the glacial deposits is complicated because the sediments had different origins; the composition of this sedimentary veneer varies laterally and vertically. Some of the sediments were deposited directly by moving ice and are clay rich and relatively impermeable (glacial tills). These till deposits are likely to contain intermixed sand, cobbles, and boulders. Trapped beneath tills in some localities are the compressed remains of forests and other vegetation that may assist in agrichemical breakdown. Some sediments were derived from glacial melt-water and consist of permeable, clean sands and gravels. Still other deposits are composed of the fine silts from stream valleys blown across the land during dry periods (loess).

Each of these sediment types transmits water at a different rate. Wind-blown loess deposits, for example, drain more slowly than gravels and sands but much more rapidly than clay-rich tills. Consequently, knowledge of the origin, distribution, and composition of these glacial sediments vertically and horizontally is key to understanding where agrichemical-bearing water from agricultural operations may have potential to reach groundwater.

## *Aquifer Configuration*

Below the groundwater table, pores of the rocks and sediments are filled with water. However, this does not imply necessarily that the water is available to a well in sufficient amounts to satisfy human needs (an aquifer). For example, a completely saturated fine-grained sediment or rock would yield water to a well too slowly to be considered an aquifer. (Many mines exist below the groundwater table but because the tunnels are in rock having little permeability, the mines stay quite dry and have few water problems.) Therefore, downward-moving water containing agrichemical contaminants could in fact contaminate groundwater but not necessarily an aquifer.

**Figure 3-8-Extent of Pleistocene Continental Glaciation in the United States**


SOURCE: Adapted from R.E. Snead, *World Atlas of Geomorphic Features* (Huntingdon, NY: R.E. Kreiger Publishing Co., Inc., 1980).

Aquifers are classified as being "unconfined' or ''confined. ' Unconfined aquifers are those in which the water table is the top of the aquifer. A confined aquifer (or artesian aquifer) is separated from the groundwater table above by a layer of relatively impermeable sediment or rock and is sealed at its base by another layer of materials having low permeability. The water in the aquifer is under pressure and, therefore, rises above the top of the aquifer in a well. A greater potential for agrichemical contamination of well-water exists in unconfined aquifers than in confined aquifers that may have relatively small recharge areas.

### *Putting It All Back Together*

***The*** hydrogeologic cycle is a complex system of interactive components and processes, driven by the Sun and modified by local variations in climate, topography, vegetation, soils and bedrock, and human activity. Groundwater problems and solutions, therefore, cannot be addressed without reference to the atmosphere, surface waters, the soils and bedrock that overlie and contain groundwater, and human activity at the Earth's surface.

Changes affecting any one component of the hydrological cycle are likely to be felt by other components, or throughout the system. Over the long term, changes in regional climates affect how rocks weather and, hence, influence soil development and soil thickness. Soils, in turn, help determine what kinds of agriculture are possible in a region, and the extent to which agricultural activities and different cropping and tillage systems might affect groundwater.

Because water on and below the ground's surface is part of the same integrated system, what happens to groundwater, through human use, ultimately affects water resources on the land's surface and vice versa. Due to changes in rainfall patterns and agricultural activities, infiltration rates may vary over time in a given area, leading to fluctuations in aquifer levels (groundwater storage), and affecting the dynamics of surface and groundwater exchange, and sometimes water quality.

Because of the many different factors that affect groundwater storage and quality, groundwater management poses complex challenges. In assessing known or potential groundwater quality problems, all components of the hydrologic cycle as well as man's ability to modify them should be taken into account.

## HUMAN MODIFICATIONS OF THE HYDROGEOLOGIC SYSTEM

Agriculture, by definition, continually modifies the landscape and its vegetative cover throughout the year and over the years. Application of chemicals to agricultural fields is but one possible source of groundwater and surface water contamination problems related to agriculture. Two additional pathways exist for agrichemicals to reach groundwater, both related to changing the nature of the hydrogeological system itself. The first way is through openings in the soil or exposed bedrock that circumvent soil filtration processes (preferred pathways), and the second way is through land-use practices that change the groundwater/surface water relationships.

Humans have dug and drilled holes in the ground for many purposes over time, inadvertently providing pathways for agrichemicals to reach groundwater. These include, for instance, water-wells, drill holes for mineral exploration, seismic shot-holes, test drilling for foundations, injection wells, tile-drainage wells, missile silos, and mines. On a much smaller scale, plant roots and burrowing animals may create vertical charnels allowing for rapid infiltration of water.

Similarly, land-use changes also can affect the flow of surface water and groundwater thereby moving agrichemicals to unwanted sites. For example, changing dry-land agriculture to irrigated (and perhaps chemigated) agriculture, construction of ponds for groundwater recharge, construction of dams and reservoirs, and channeling and diking streams can cause such changes. The following section describes a few of these land-use examples and relates them to possible movement of agrichemicals beneath the land surface.

*Photo credit: U.S. Department of Agriculture, Agricultural Research Service*

Since climate affects pest outbreaks, weather balloons are released near the Mexico-U.S. border to study migratory behavior of can and cotton pests. Better information on pest populations can help farmers be more selective on when and where to apply pesticides.

### *Preferred Pathways*

Water will flow along the path of least resistance. Even though a soil maybe fine-grained and have low permeability, if it is pierced by small, natural channels (macropores) or larger manmade conduits (megamacropores), water contaminated with agrichemicals can move rapidly through these toward the groundwater table rather than slowly through the soil matrix where most contaminants are trapped or broken down. Although the amount of agrichemicals moving downward through such openings may be small for any single opening, the total that can be moved during a growing season could significantly and adversely affect water quality.

The most common natural macropores derive from earthworm channels, decayed plant roots, or cracks from soil drying. Freezing and thawing will collapse some of these conduits. Nevertheless, during the warm spring and summer months, agrichemical contaminated water can move easily downward. Similarly, the burrows of larger vertebrate animals provide pathways deep into the soil. Such conduits will not extend below the groundwater table unless the water table rises.

Megamacropores can be natural, such as sinkholes where the land's surface has collapsed into underground caves eroded from carbonate rocks ("solution cavities"), or manmade conduits like abandoned wells and drill holes. The latter may be several inches to several feet in diameter, while sinkholes may be hundreds of feet across.

Poorly constructed water-wells can lead to groundwater contamination problems. Water-wells having continuous steel casing from the land surface down into the aquifer can eliminate the possibility of degrading the drinking-water source with contaminated water from shallower aquifers. Completion of such wells so that contaminated surface runoff cannot enter the well head is essential to keep agrichemicals from contaminating the well-water. If active or abandoned wells are only partly cased or if casings corrode or crack, a potential will exist for contaminants to reach the well's aquifer.

### Abandoned Drill Holes and Wells

Drilling holes in the ground for oil, water, mineral exploration, foundation testing, and other uses has been a common practice in the United States for many years. The first productive oil well was completed in Titusville, Pennsylvania in 1859 (66), but water-wells predated oil exploration by many years. Only recently have States developed regulations about the proper sealing of abandoned wells and other such holes. Quantitative data on the number of wells and drill holes is sparse and the number of improperly sealed abandoned holes in each State probably will never be known.

Minnesota is one State where some quantitative information exists, although estimates are based on extrapolation of certain field sites. The Minnesota Department of Health (MDH) estimates that some 700,000 to 1.2 million abandoned water-wells in Minnesota have a potential to endanger groundwater quality (88). Today, Minnesota has roughly 500,000 producing water-wells, and some 10,000 new water-wells are drilled annually. By a conservative estimate, about 10 percent of these are replacement wells. Therefore, at least 1,000 additional water-wells are abandoned each year. At the present rate of sealing (2,500 in 1988 at an average cost of $500 each), the MDH estimates that it will take 480 years to seal already abandoned wells. If 1,000 additional water-wells are abandoned each year, sealing the combined backlog of abandoned wells will take 800 years.

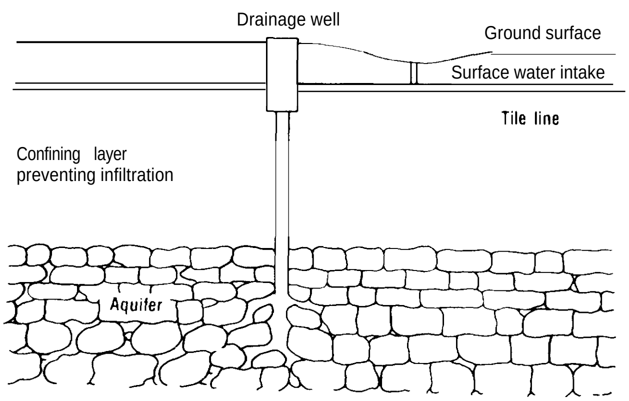
Minnesota is not an oil- or gas-producing State, so the number of abandoned wells there probably is far below the total number of wells and exploratory drill holes and seismic shot-holes scattered over States such as Texas and Oklahoma. Some abandoned wells and holes may have collapsed so that they no longer present avenues through which agrichemicals might move to contaminate groundwater. Further, water flowing down the walls of an open hole through the unsaturated zone are subject to strong withdrawal into the unsaturated zone. Contaminants, therefore, may not reach the water table if the contaminated supply of water is small (5). Yet other abandoned holes and wells probably are still open and may present a serious threat to States' groundwater resources.

### Agricultural Drainage Wells

Agricultural drainage wells are structures designed expressly to provide access to underground strata for disposal of water drained from saturated soils or from irrigation systems. Farmland drainage, the primary agricultural water management and farm reclamation activity in this country, occurred throughout the last century, peaking in the 1930s (74). Nearly 75 percent (77 million acres) of the cropland on which wetness is a dominant constraint on production (105 million acres; (77)) have manmade surface or subsurface drainage systems (79). There are indications that many of the drainage systems constructed in the early 1900s, particularly in the Midwest, are now obsolete and in need of repair; in their current state, they promote leaching (74).

Drainage outflows can be directed through drainage wells and sinkholes into subsurface strata (figure 3-9). If outflow waters are directed into sinkholes for disposal, the relatively rapid movement of groundwater through karst may provide relatively rapid dilution of the soluble chemicals carried, However, in areas with fractured bedrock or slow-moving groundwater, chemicals may remain concentrated in the subsurface.

**Figure 3-9-Schematic Diagram of Agricultural Drainage Well**




SOURCE: Adapted from Iowa Department of Natural Resources, Environmental Protection Commission, *Iowa Groundwater Protection Strategy, 1987*

Drainage outflows and irrigation tailwaters commonly carry agrichemicals and naturally occurring soluble soil minerals, such as nitrate and selenium into surface- and groundwaters (see box 3-A). Unless properly processed or diluted, concentrations of natural and introduced chemicals can contaminate groundwater or aquifers posing environmental and health hazards.

### *Changing Groundwater/Surface-Water Relationships*

Certain human activities can alter the natural relationship of surface waters and groundwater and, hence, how easily and in which directions contaminants are likely to move. Some common examples include darn construction, stream diversion, drainage and irrigation, and over-pumping of water-wells. These can either promote contamination, or dilute groundwater contaminated from *other sources.*

#### Dam Construction and Stream Diversion

Construction of a dam can greatly reduce the natural rate and volume of groundwater recharge downstream of the dam. Consequently, the groundwater table may drop to such an extent that contaminated surface- water bodies disappear as they drain into the falling groundwater table. Conversely, the water reservoir that forms behind the dam can raise the area's water table bringing the groundwater table close to or above the land surface. In such cases, the near-surface and surface water can pick up agrichemicals as contaminants. Previously contaminated groundwater may also be diluted.

Streams sometimes are diverted from their natural channels to new charnels to irrigate farmland, to divert water around developments, or to redirect water to water-poor areas. The groundwater impacts along the old charnel are similar to those that occur downstream of a new dam, and those along the diversion channel will parallel those occurring behind the dam.

#### Irrigation

Used on some 55 million acres of U.S. crops (75), irrigation is essential for crop production in arid areas, will increase crop yield or quality every year in semiarid areas, and ensures consistent crop yield and quality in subhumid and humid areas. However, irrigation has the potential to hasten leaching of applied and natural chemicals if excessive deep percolation occurs.

Irrigation systems commonly are established on agricultural lands with excessive soil drainage where they provide water for leaching. Irrigation water may release naturally occurring water contaminants including nitrate from certain mineral-bearing formations, Leaching of naturally occurring nitrate has been documented in several areas in the Great Plains and the Southwest (73).

In arid parts of Western States rainfall may not be sufficient to leach excessive soil salts below the root zone, requiring periodic ''soil flushing' with large amounts of water to allow continued agricultural production. This will also transport chemicals other than salts into the deeper soil profiles and potentially to groundwater. In arid areas where the contaminated ''outflow'' waters from soil flushing are directed into surface waters, they can seep directly below the water table to recharge groundwater (box 3-A).

#### Over-pumping Water-wells

When water is pumped from a well the water table is drawn down in the area adjacent to the well forming what is called a "cone of depression.' The size of the cone of depression and how quickly the depression disappears after pumping ceases depends on the rate of water withdrawal from the well and the permeability of the surrounding rocks or sediments. If the cone of depression becomes large enough it can change the slope of the groundwater table. In

***Box 3-A-Groundwater Contamination From Natural Sources: Kesterson National Wildlife Refuge***

Kesterson National Wildlife Refuge was established from ponds built in 1971 for disposal of agricultural drainage water and also to provide wildlife habitat. Agricultural drainage water became the only source of inflow to the ponds by 1981, and by 1982 problems were first observed. Large-mouth bass and striped bass and carp disappeared from the ponds. In 1983, investigations of declining waterbird births showed deformities in embryos that were blamed on selenium (22,23,49).

Irrigated agriculture depends on the flushing of salts that accumulate in the rooting zone in order to maintain productivity; tailgaters thus have high salt content. Normally, the oceans are the ultimate sink for dissolved salts, however, depending on the drainage system these waters may or may not reach the ocean and drainage into contained basins may create a highly saline water body (e.g., Salton Sea, Dead Sea, Great Salt Lake).

Generally, trace elements (e.g., arsenic, selenium, molybdenum) are not contained in tailwaters, however, the soils in the San Joaquin contain naturally elevated levels of selenium and the hydrologic conditions promoted the movement of soluble selenium into irrigation tailwaters. The damage has been attributed to a combination of factors, including: 1) the high soluble-selenium content of soils, 2) increased irrigation development and installation of subsurface drains, and 3) lack of understanding of the potential adverse impacts from the method of disposal (49). Irrigated agriculture can clearly create adverse offsite effects over time. Irrigation management then must include adequate treatment and disposal plans for tailwaters.

A survey of 20 sites conducted by the Department of the Interior in Western States shows that at least four (Stillwater Wildlife Management Area, NV; Salton Sea, CA; Kendrick Reclamation Project, WY; Middle Green River Basin, UT) show potential trace-metal levels (boron, arsenic, molybdenum, and selenium) similar to those at Kesterson (22,49).

Technical options for remediation of the Kesterson refuge have been examined, including:

- transport and disposal of drainage water (ocean disposal, and deep-well injection);
- source control (retirement of land from irrigation, irrigation management, evaporation ponds); and
- water treatment (desalinization, chemical and biological removal of contaminants) (49).

The Bureau of Reclamation, the Fish and Wildlife Service, and the California Department of Fish and Game have developed a plan to offset the loss of the nearly 1,283 acres of wetlands destroyed. The plan calls for acquisition and management of 23,000 acres in the San Joaquin Drainage Basin to replenish the wetland acreage. Water needed to maintain the wetland will come from the Bureau's Central Valley Project (27).

some cases contaminated water from another well can flow downslope along the cone of depression of the uncontaminated well, degrading its water supply (figure 3-10). Each water-well produces its own cone of depression and where many wells exist, their intersecting cones of depression create complicated patterns in the surface of the groundwater table and affect normal flow patterns. In such cases, a properly maintained and constructed farm well still may become contaminated with agrichemicals even if none percolate downward directly from farm operations.

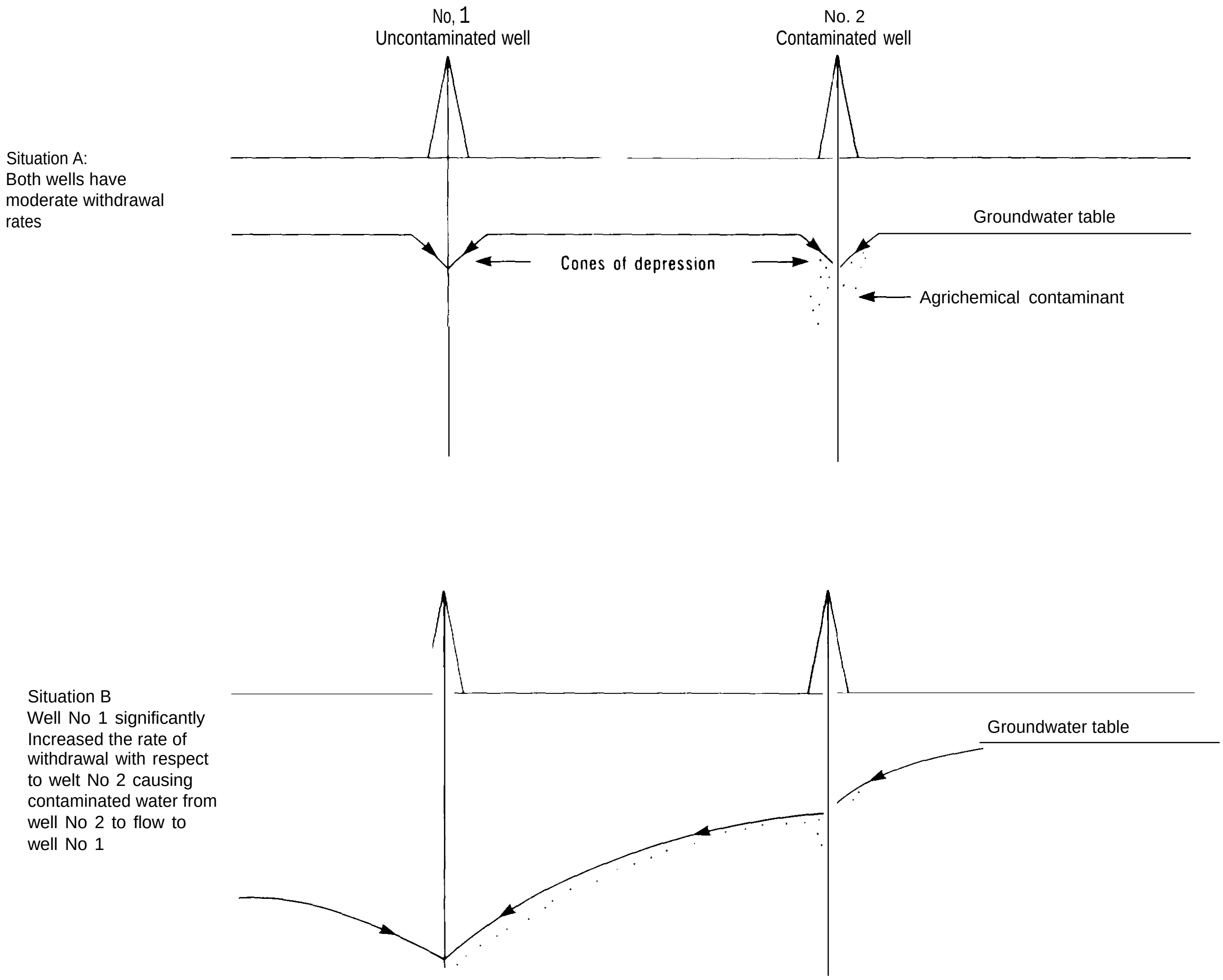
## AGRICHEMICAL CHARACTERISTICS RELATED TO LEACHING

Characteristics of agrichemicals may be as important as site hydrogeological characteristics in predicting groundwater contamination potential. Agrichemicals vary in chemical structure, behavior and stability and, hence, in the extent to which they volatize into the air, are taken up by plants, disperse through the soil, degrade through chemical, biochemical, or photochemical action, or remain available for leaching through the soil (28).

Determining the probable fate of an agrichemical (it's "partitioning" among a variety of sequestration and degradation processes) is a complex process, but determination of certain key chemical characteristics helps scientists make such analyses (see table 3-2). In general, however, agrichemicals that are mobile and persistent, if used in hydrogeologically sensitive areas in sufficient quantities, have the highest probability of leaching to groundwater (16). Nitrate and certain pesticides have these characteristics (table 3-3).

Some studies suggest that nitrate might be used as a ''mwker' for potential vulnerability to pesticide

**Figure 3-10-Cones of Depression Resulting From Water Withdrawal May Result in Contamination of Water Supplies Near Non-contaminated, Well-constructed Wells**




SOURCE: Office of Technology Assessment, 1990.

contamination, although no study has shown a clear one-to-one link between the presence of nitrate contamination and pesticide contamination. In areas of Nebraska, at least, occurrence of high nitrate concentrations has been shown to be correlated with triazine-herbicide concentrations (71 ,84). Likewise, LeMasters and Doyle (38) found a significant association between wells in Wisconsin containing greater than 10 ppm nitrate and detectable levels of pesticides. However, the same researchers did not find a quantitative relationship between pesticide concentrations and nitrate concentrations. Similarly, the correlation was very weak in one two-county area of Iowa (39). Thus, in areas where herbicides are known to be used, nitrate might serve as an inexpensive test to identify areas potentially contaminated by herbicides (84), but more extensive data are needed for a broader correlation analysis.

**Table 3-2—Some Chemical and Mineralogical Factors Commonly Considered When Assessing a Pesticide's Behavior and Ability To Leach[a] From Agricultural Lands**

***Volubility in water*** The amount of pesticide that will dissolve in water in part will relate to the pH of the water (pH is a measure of acidity).

***Half-life/persistence:*** The time needed in the field for 50 percent of the pesticide molecules to degrade.

***Stability in wafer*** The degree to which a pesticide resists hydrolysis (breakdown in water).

***Volatility from the soil:*** A measure of how easily a liquid pesticide applied to the soil is able to change to a gas.

**Octanol-water partition coefficient** A laboratory test to determine the preference a pesticide has for fats versus water.

***Photolysis*** The breakdown process of a pesticide when exposed to sunlight.

***Ability to ionize:*** Whether the pesticide behaves as a cation (+), anion (-), zwitter ion (+ and -), or is neutral at various pH values in water.

***Nature and amount of soil organic matter*** *The biological* breakdown products in a soil's A horizon (uppermost layer of a soil).

***Clay mineralogy of the soil and underlying geological materials:*** The nature of the fine-grained minerals, some of which can bind pesticides tightly.

[a]Ability to leach (leachability) refers to the following pesticide property: when used in a normal agricultural manner under conditions conducive to movement, the pesticide moves down through the soil in quantities sufficient to be detected in nearby wells of proper construction.

SOURCES: D. Gustafson, "1989 Ground Water Ubiquity Score: A Simple Method for Assessing Pesticide Leachability," Journal *of Environmental Toxicological Chemistry,* pp. 339-357, unpublished paper; A. Moye, pesticide chemist, personal communication, December 1989.

**Table 3-3-Pesticides With High Potential for Leaching to Groundwater**

| | |
|---|---|
| Acifluorfen | Disulfoton |
| Alachlor | Diuron |
| Aldicarb | EDB |
| Aldicarb sulfone | Endrin |
| Aldicarb sulfoxide | ETU |
| Ametryn | Fenamiphos |
| Atrazine | Fluometuron |
| Baygon | Heptachlor |
| Bentazon | Heptachlor epoxide |
| Bromacil | Hexachlorobenzene |
| Butylate | Hexazinone |
| Carbaryl | Methomyl |
| Carbofuran | Methoxychlor |
| Carboxin | Metolachlor |
| Chloramben | Metribuzin |
| Chlordane-alpha | Nitrate/nitrite |
| Chlordane-gamma | Oxamyl |
| Chlorothalonil | Picloram |
| Cyanazine | Prometon |
| 2,4-D | Pronamide |
| Dalapon | Propachlor |
| DBCP | Propazine |
| Diazinon | Propham |
| Dicamba | Simazine |
| 1,2-Dichloropropane | 2,4,5-T |
| cis-1 ,3-Dichloropropene | Tebuthiuron |
| tram-l ,3- Dichloropropene | Terbacil |
| Dieldrin | Terbufos |
| Dinoseb | 2,4,5-TP |
| Diphenamid | Trifluralin |

[a]Priority pesticides included in the EPA National Pesticide Survey of Drinking Water Wells, which includes testing for over 100 pesticides (general use, restricted use, or banned) or their breakdown products.

SOURCE: U.S. Environmental Protection Agency, "Pesticide Included in the EPA National Pesticide Survey," Apr. 14, 1988.

A mobile agrichemical tends to move in the water phase without tightly adhering to soil. A pesticide would be considered mobile if its soil/water partition coefficient is 1 in a soil with 1 percent organic carbon (15). Pesticides vary widely in mobility. The pesticide paraquat, for example, is attracted to clay surfaces where it is held tightly whereas pesticides like picloram are repelled by the clay surfaces and can move freely through the soil (53). Atrazine, one of the most widely used agricultural pesticides, is only weakly held by the soil (30), and has appeared in the groundwater of at least 13 States (82).

Volubility can also affect a pesticide's mobility and fate. Highly soluble pesticides are more likely to be mobile and can move long distances with the natural flow of surface or groundwater. Plants can capture water-soluble pesticides along with soil moisture, potentially sequestering them in plant tissues. Pesticides that are not degraded by the plants may be re-released to the environment through crop residues remaining after harvest (14).

A persistent pesticide tends to degrade very slowly in the soil-water matrix. A pesticide with a soil-degradation half-life of 100 days would be considered persistent. Certain pesticides, such as DDT, can persist unchanged for long periods of time in the soil, and will accumulate over time if used regularly.

All else being equal, if agrichemicals resistant to degradation and only weakly interactive with soil particles are applied to widely-spaced, shallow-rooted row crops, where the water table is near the surface, there is great potential for groundwater contamination. If the same chemical is used on close-grown crops with deeply penetrating roots, the underlying aquifer may not be affected, particularly if it is confined. Chemicals that are more easily degraded in, or retained by soil materials, have less potential to reach groundwater than persistent chemicals that interact poorly with the soil.

## SUMMARY AND POLICY IMPLICATIONS

Groundwater is one of the key components of the global hydrogeological cycle, as well as being an important resource. Whether pure or contaminated, groundwater can reside in some aquifers for thousands of years. Still, groundwater discharge (e.g., at surface springs, or into lakes, rivers, or the ocean) and recharge through rainfall eventually cycles water, and any contaminants it may hold, through most aquifers (14), Because groundwater recycles so slowly, over decades, centuries, or even millennia, and because the aquifers in which groundwater is contained lack the cleansing mechanisms of surface watersheds, a degraded aquifer may not recover at all in human time frame, The surest way of protecting groundwater is to prevent contamination at the source.

In areas characterized by many different soils and rocks it is extremely difficult to predict where, or how fast water-soluble pollutants will spread once they are underground and out of sight (40). Predicting the patterns of contaminant dispersal below the water table can be nearly impossible, particularly in geologically complex regions. Understanding the hydrogeology of a site is integral to determining the potential for leaching agrichemicals to groundwater (box 3-B), and therefore is imperative in identifying technologies that may reduce potential contamination.

Because of its close link to surface conditions and activities, groundwater must be considered a part of any agroecosystem. Agrichemical contaminants can invade groundwater as a result of a farmer's agrichemical handling or agricultural management practices, changes in land uses, or through poorly constructed or abandoned manmade holes or wells. Whether agrichemical contamination actually occurs depends on a large number of interactive physical, chemical, and biological factors. A systems approach to mitigate or eliminate such problems today is essential.

Different agricultural chemicals move through the environment at different rates. In some cases, low levels of detection may simply represent the forward edge of a contamination pulse that is working its way through the soil profile (35). Without expanded research efforts on the fate and transport of these chemicals, we will not know if these low levels indicate that there is nothing to worry about, or that the worst is just now coming (54). Clearly, repeated sampling of each aquifer, and testing for every agrichemical, would be impractical. Systematic procedures for monitoring, sampling, testing, and for data collection and management are necessary to identify critical site/agrichemical combinations (33).

### *Improving Data Collection and Management for Groundwater Protection*

Numerous Federal agencies collect natural resource and land-use information relevant to prediction of potential agrichemical contamination of groundwater. An evaluation of the data collection, management, and coordination systems within Federal agencies is beyond the scope of this assessment. However, prediction of potential vulnerability, design of site-specific agricultural practices to mitigate that potential, and implementation of programs to reduce adverse impacts of agricultural practices will require extensive, detailed data and comprehensive, readily accessible information derived from that data.

It would clearly be advantageous for agricultural and groundwater scientists and policymakers to have access to relevant databases, including:

- climate data (National Oceanic and Atmospheric Administration and Agricultural Experiment Stations);
- topographical, hydrological, and aquifer mapping data (USGS);
- surface water quality and associated data (EPA; USGS);
- soil data (USDA/SCS);
- cropping patterns data (USDA/ASCS);
- nitrogen use data (TVA/NFERC);
- pesticide use data (USDA/NASS, USDA/ERS, EPA, and Resources for the Future);
- groundwater quality monitoring data (EPA, USGS); and
- data on hydrogeological vulnerability (USDA/ERS).

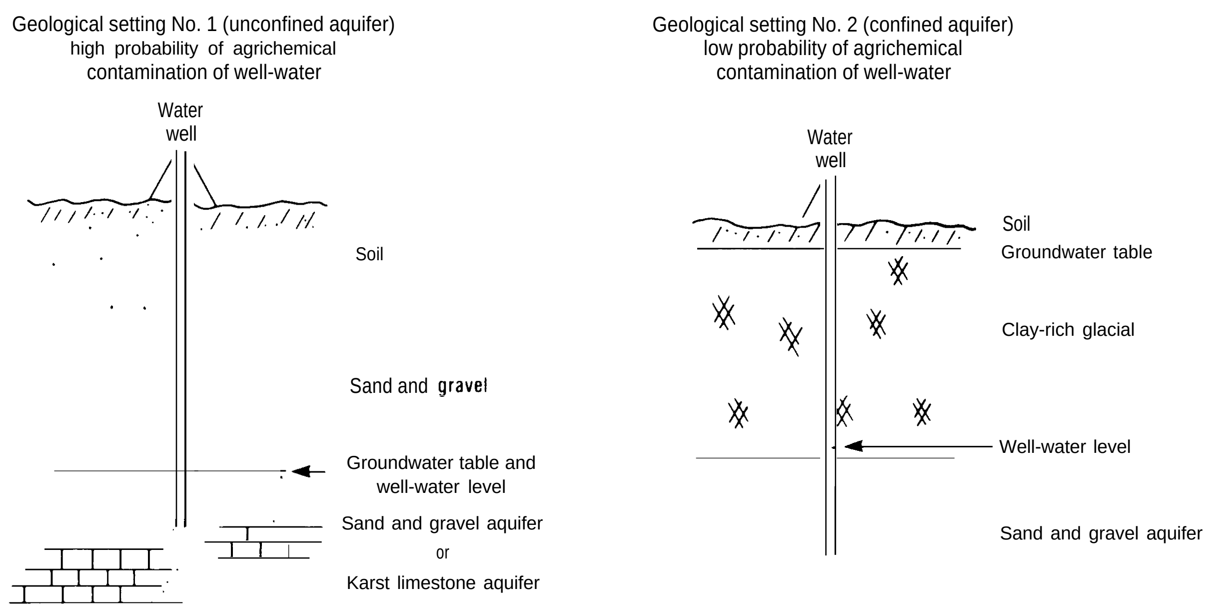
Other data not currently available in national-level databases, such as extent of tillage patterns or distribution of and waste production from livestock confinement facilities, would also improve decision-making.

### *Box 3-B—Using Hydrogeologic Information To Predict Sites Vulnerable to Groundwater Contamination: Minnesota's Groundwater Contamination Experience*

Recent baseline field and laboratory research by Minnesota's Departments of Health and Agriculture (36,37) illustrates how hydrogeological information can be put to use in making a first approximation of the nature and magnitude of agrichemical contamination of groundwater resources. Researchers tested well water in two different settings: 1) where coarse-grained soils overlie either sands and gravels or limestone bedrock having well-developed solution channels and cavities, conditions thought to promote movement of contaminants to groundwater; and 2) where clay-rich glacial tills overlie sand/gravel aquifers, conditions thought to retard movement of contaminants to groundwater. Depth to bedrock generally was 25 feet or less in most wells but in some it was 50 feet. Most samples were taken intentionally from wells in geological setting number one, therefore the percentage of wells found contaminated with agrichemicals probably is higher than if samples had been taken randomly from both settings.

The assumption that "confined aquifers" underlying the clay-rich tills would be less likely to show contamination from agrichemicals than the groundwater in shallow, karst limestone environments and/or overlain only by coarse-grained soils and glacial sands and gravels (''unconfined aquifers") seems borne out by the field and laboratory work. The researchers found that, in general, pesticide contamination was higher in private wells than in public wells. The former normally are shallower and nearer to fields where pesticides are applied than wells used for public water supplies.

Pesticide contamination was common in the karst limestone region of southeastern Minnesota; most contaminated wells were not associated with obvious point sources of pollution. The fewest detections of aquifer contamination occurred where a thick layer of clay-rich till or other fine-grained materials separate surface contaminants fkom the aquifer.




SOURCE: Office of Technology Assessment, 1990.

Also playing important roles in whether a particular well showed contamination were the contamination source, the properties of the agrichemicals, local agrichemical practices, and well construction. These factors varied from well to well. However, the local hydrogeology seems to have played a lead role. Such determinations are likely to be repeated as further data on other sites become available.

## Data Adequacy for Prediction of Agrichemical Contamination of Groundwater

Producing maps and developing three-dimensional displays to show where agrichemical contamination of aquifers is likely to occur in the absence of detailed data on soils, unconsolidated sediments, bedrock geology, and subsurface waters can lead to incorrect interpretations. It seems clear that the synthesis of such information is critical for assessment of where and when possible adverse impacts from agrichemicals might affect groundwater resources. Increased State and Federal activities in producing and presenting information depicting the Earth in three dimensions is highly important to understanding the nature of agriculture's impact on groundwater quality.

***Status of Major Hydrogeologic Data Collection Efforts-The*** natural earth materials-soils, unconsolidated sediments, and bedrock-that contain groundwater are sometimes referred to as the "container" for groundwater. Characteristics of this container will determine the groundwater's direction of flow, its chemical purity, its residence time in the Earth, and a host of other variables. Therefore, it is important to know the status of the information base that currently exists to describe the "container." Data on topography, soils, and bedrock geology are fairly comprehensive, but detailed knowledge of the intervening unconsolidated sediments is less certain. Additional data continuously are being gathered at the State and Federal level to add to this knowledge base, but as yet may not exist in a published form. Synthesis of the major databases described below is starting to occur, but certain gaps still need to be filled.

***Soils—The Soil*** Conservation Service has long striven to develop detailed maps of soils, topography, other site characteristics, especially as they relate to capability to support conventional agriculture. Today, soil maps for most States have been compiled. Soil data for some States have been digitized to allow for computer manipulation, and the other States are moving in that direction (figure 3-1 1). Digitized soil databases include SOILS-5 and SOILS-6 that describe soil characteristics and suitability for uses such as cropping, woodlot management, and certain types of development. SCS databases also include the progressively freer-scale Soil Geographic Data Bases, including National Soil Geography database (NATSGO) of soils data related **to the** major land resource areas (1 :7,500,000 scale), State Soil Geographic database (STATSGO) for ''general' soils mapping (1:250,000 scale), and Soil Survey Geographic database (SSURGO) presenting detailed soils data (1:15,840 to 1:31,680 scale) (8).

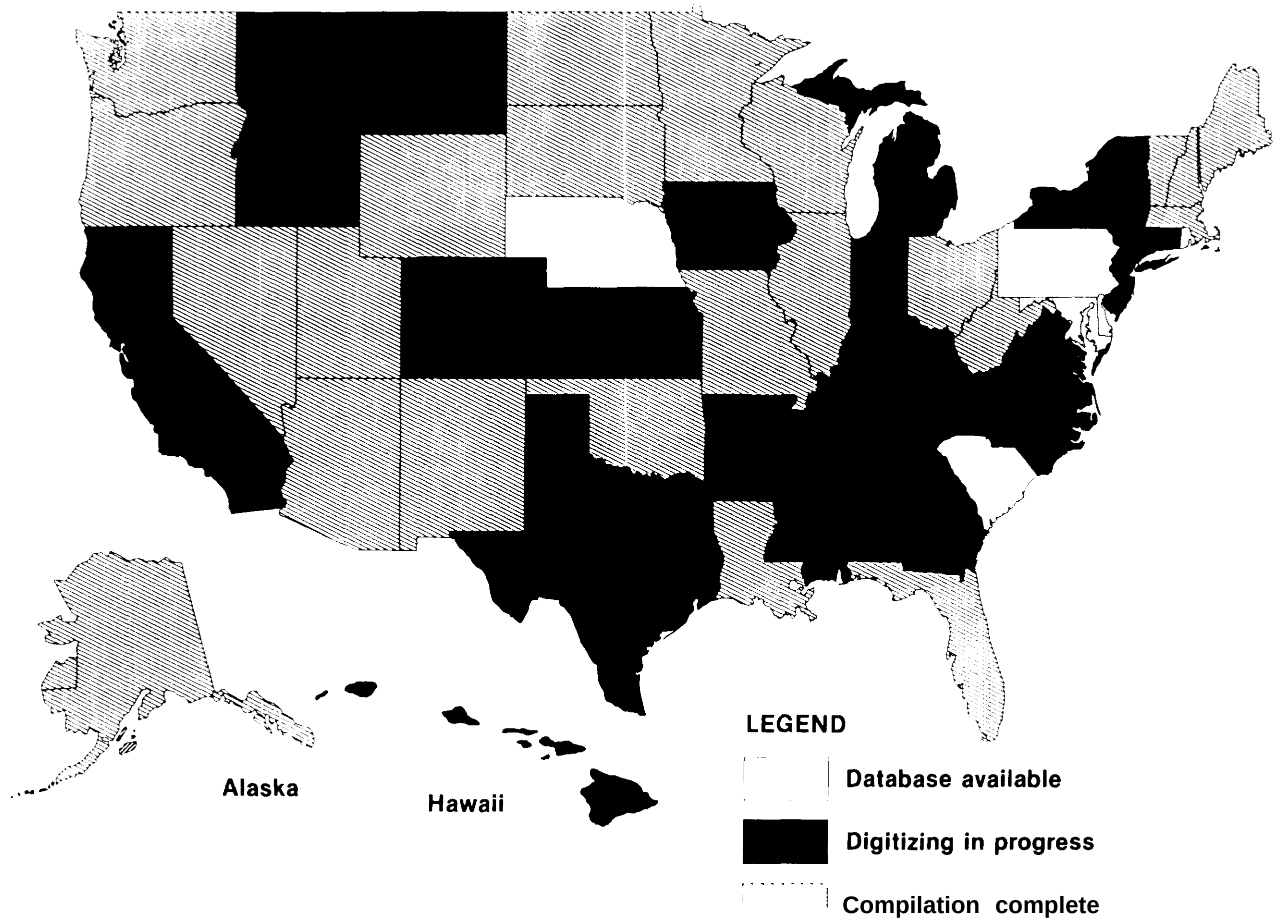
Geology ***and Topography-Each*** of the 50 States has produced a map showing the bedrock geology. The oldest State map is Ohio's, published in 1920; most other States have published maps produced between 1970 and 1980. A provisional bedrock geological map was prepared for Puerto Rico in 1964; few other U.S.-afffiated islands have been mapped. Most of these maps were published at a scale of 1:500,000; some at 1:100,000; Wisconsin and Nebraska at 1: 1,000,000; and Alaska at 1 :2,500,000. Even though some of these maps are old, detailed related information is continually collected and evaluated by each of the State geological surveys as well as the USGS (85).

Topographic maps are important to geological mapping and all aspects of land-use evaluation or planning. The Defense Mapping Agency will, in 1990, complete and publish the last 7½ minute scale topographic maps for all States except Alaska. Alaska is completely mapped in 15-minute quadrangles and, at this time, no plans to map at the 7½ minute scale have been made (85).

*Unconsolidated Materials—Even* though local soil and geologic maps showing the hard, subsurface bedrock may exist, little is known in detail of the makeup of the unconsolidated sediments lying between soil and bedrock in many States. This hinders efforts to collate information and predict vulnerable sites. Illinois is a notable exception. The Illinois State Geological Survey has developed maps showing the thickness of unconsolidated glacial sediments throughout the State (figure 3-12), and detailed lithological and mineralogical data exist for many glacial deposits there. Data are sufficient over much of this area to permit detailed, three-dimensional analyses of variations of the glacial lithologies. With this information at hand, Illinois is in the position to make reasonably sound estimates of where its groundwater and its aquifers might be vulnerable to agrichemical contamination.

The U.S. Geological Survey (USGS) is preparing a map based on data assembled from 850 sources that will show the extent, thickness, and gross lithology of glacial deposits in 28 glaciated States east of the Rockies (70). The map combines soil

**Figure 3-n-Status of State Soil Geographic Databases**

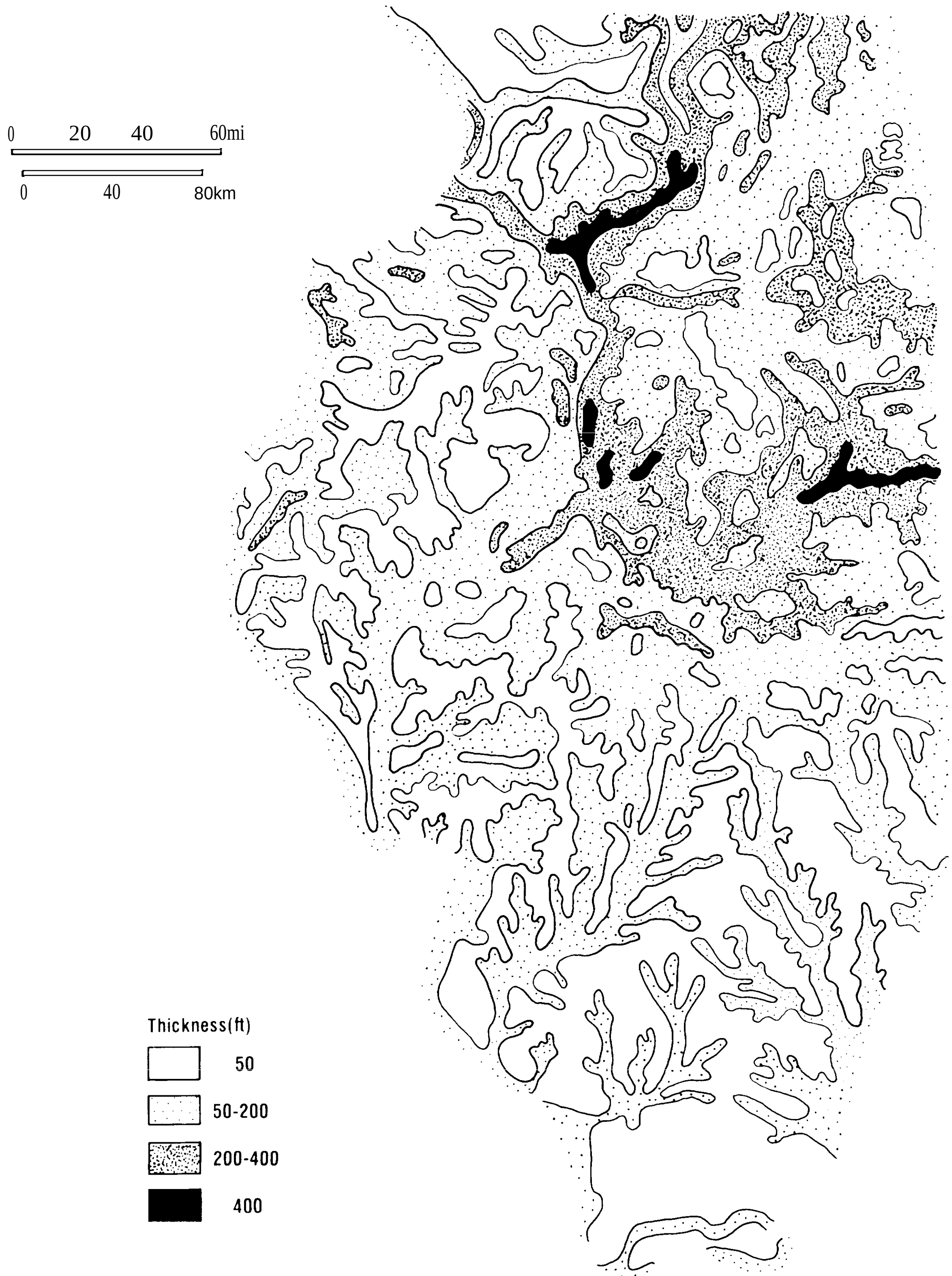



SOURCES: Adapted from U.S. Department of Agriculture, Soil Conservation Service, "Status of State Soil Geographic Databases (STATSGO)," map compiled using automated map construction with the FOCAS equipment, National Cartographic Center, Fort Worth, TX, revised November 1989; D. Goss, soil scientist, National Water Quality Technology Development Staff, South National Technical Center, Soil Conservation Sergvice, U.S. Department of Agriculture, personal communication, February, 1990.

data, glacial sediment data, and subsurface bedrock geological data into a three-dimensional geological picture, but published in a two-dimensional map called a ''stacked map. '' Such three-dimensional depictions are useful for analysis of where potential agrichemical groundwater problems might exist. This new map will show for the first time the general nature of the glacial sediments covering this large region (69). The map shows that the thickness of the glacial deposits is 50 feet or less over much of the region but that broad areas exist that have at least 200 feet of sediment; in some cases, thicknesses may reach 1,000 feet or more. The thickest section of glacial sediments (1,200 feet) occurs in the lower peninsular of Michigan (68). Acceleration and expansion of efforts to produce maps showing information on unconsolidated sediments in greater detail is integral to predicting the fate of agrichemicals applied to the land, and to assuring that groundwater contamination is minimized.

*Water Quality*-EPA and USGS maintain water quality databases. EPA's REACH file is a digitized, graphical database of surface water attributes covering three-quarters of a million miles of the Nation's rivers, streams, lakes, bays, and estuaries. It was designed primarily to analyze pollutant movement in surface water bodies, and would require considerable expansion to include movement in groundwater. Associated with the REACH files are the EPA and USGS Water Quality Databases, which include

**Figure 3-12—Thickness of Pleistocene Deposits in Illinois**




SOURCE: R.C. Berg, J.P. Kempton, and K. Cartwright, "Potential for Contamination of Shallow Aquifers in Illinois," Illinois State Geological Survey, Circular No. 532, 1984.

Photo credit: U.S. Geological Survey

U.S. Geological Survey personnel have routinely collected groundwater data on water levels, total dissolved solids, and many inorganic chemicals in monitoring wells throughout the country. However, information has not been **collected** routinely on organic substances and other key chemical parameters.

approximately 40 million observations of chemical and natural attributes.

The USGS has a recently developed National Water Quality Assessment Program designed to assess water quality on a regional watershed/aquifer basis through joint monitoring of surface- and groundwater. The information collected includes: 1) source of agrichemicals, 2) rate of loading, and 3) where and how they are moving. Seven 2-year pilot studies based on the initial program proposal are nearing completion, and followup monitoring is planned to occur in 5 years. Further, the data collection program is based on drainage systems, not political boundaries. A pilot study just completed in Kansas and Nebraska provides a common data set for both States, and indicates that some agrichemicals are moving from Nebraska into Kansas surface waters (31). Full implementation of the Program would involve work at about 120 aquifer systems and river basins nationwide, covering about 80 percent of the water currently used in the United States.

*Aquifers-The* USGS also had a Regional Aquifer-System Analysis (RASA) Program, in operation since 1978, to study the 28 major regional U.S. aquifer systems USGS has identified. To date, 14 studies have been completed (42). Objectives of the RASA programs are to ''define the regional hydrology and geology, and to establish a framework for background information-geologic, hydrologic, and geochemical-that can be used for assessment of local and regional groundwater resources" (83,42). The RASA studies use computer simulation to assist in the understanding of groundwater flow patterns, recharge and discharge characteristics, and effects of development on aquifer systems. The Program already has helped improve the matching of geologic and hydrologic data at State boundaries, and has developed numerous groundwater flow-models for regional use (83).

*Integrated Natural Resource Information Databases—By* congressional mandate, the SCS maintains a comprehensive survey of agricultural and related natural resources on 1.5 billion acres of non-Federal rural lands. Surveys have been conducted six times in the past 30 years, including the extensively detailed 1982 National Resources Inventory (NRI). The 1982 NRI consists of data collected from roughly 1 million individually inspected locations. Attributes evaluated included nearly 200 variables, such as land use and cover, conservation needs and practices, and irrigation water source. The NRI sample points (inspected locations) also are directly linked to the SOILS-5 databases described above (44). Because the data on multiple attributes were collected simultaneously for each sample point, this database allows analysis of associations between specific land use and resource conditions, whereas combined use of non-integrated databases using data generalized to an area (e.g., county) cannot.

***Status of Agrichemical Use Data-Collection*** Efforts-Groundwater contamination potential is based on the combination of natural factors and type and intensity of agrichemical use or livestock waste application. While NRI data is collected to evaluate soil conservation efforts, no comparable information gathering process currently exists related to other resource conservation concerns (e.g., agrichemical losses to the atmosphere and groundwater) (19).

As a result of special appropriations in 1964, ERS provided a great deal of information on pesticide and fertilizer use from the mid-1960s up until the early 1970s, in order to provide a basis for determining costs and benefits of pesticides and to determine trends in pesticide use. However, the U.S. Government has drastically reduced its surveys of pesticide-use patterns in the last nine years: published information for the early 1980s is sparse and published pesticide-use data for the mid-1980s is almost nonexistent. Resources for the Future, a nongovernmental organization, has developed a national pesticide use database by compiling State- and county-level use data, but these data are based on average use estimates (26). Hence, we now have less specific knowledge of how farmers and other pesticide users are actually using materials than in the 1960s and 1970s (87).

USDA's Water Quality Program Plan developed in response to the President's Water Quality Initiative identifies the need for comprehensive national data on agricultural chemical use, related farming practices, and the links with the agroecosystem to assist Federal and State governments to "assess the benefits, costs, and other effects of current agricultural practices and to evaluate consequences of alternative policies and practices for reducing any adverse effects of agricultural production on water quality" (78).

The Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS) are charged with the design of a continuous cycle of national surveys. The NASS plans to collect data on farm use of pesticides and certain other chemicals, and type of production practices. Farm survey efforts will cover field crops in major producing States as well as a range of vegetables in five large producing States (9). Statistical analyses are to be conducted by NASS and results summarized and disseminated by ERS. The first pilot test of this survey process is planned for a single crop in 1990 and will be expanded over a 3- to 4-year period to cover the other major commodities (78).

### Rationalization of Data Collection and Management

Although many pertinent databases exist, in most cases they were created autonomously to address different fundamental questions. This hinders their use in predicting potential groundwater or aquifer vulnerability to agrichemical contamination. Myriad natural resource, land-use, and agrichemical-use factors combine to determine vulnerability to groundwater contamination, however, preliminary identification of regions exhibiting high association with agrichemical contamination of groundwater can be made.

Congress could direct USDA to correlate agrichemical-use data contained in the planned NASS Agrichemical-Use **Survey and the National Agricultural Census with EPA and USGS data on identified groundwater contamination problems to identify areas or regions with high apparent vulnerability to groundwater contamination.** Regions showing a high correlation between incidence of agrichemical contamination and intensity or type of agrichemical use could be designated target areas for intensified monitoring, and hydrogeologic research efforts. As data and data integration procedures improve, definition of highly vulnerable region can be refined.

Baseline information on current nutrient and pest management practices and continued information on changing agricultural practices will help policymakers assess the impacts of policy changes on groundwater quality, agricultural productivity, and the farm economy. Understanding of how and where the chemicals with greatest contamination potential are being used could assist in identifying pest control or nutrient problems that are in the greatest need of research and extension of alternate products or practices. Without such a clear link, research and extension may remain focused on issues unrelated to groundwater protection and associated environmental issues,

Although established, many extant natural resource databases are not readily accessible for users outside each agency, and may be of unusable format for integrated or geographically specific analyses. Moreover, no clearly defined Federal commitment has been made for provision of multi-use, national-scale maps and related geographic information for public and private users (50). Provision of information derived from these data probably would be of more use to agriculture and water quality decisionmakers than the raw data.

Most legislation has dealt with parts of the total hydrogeologic system; only in the last several years have studies of how agrichemicals move through the larger environment been initiated. EPA is organized to address different components rather than the total ecosystem; its offices address air or water or groundwater rather than attempting to follow movement of particular contaminants through the entire environment. USDA and TVA have historically focused on the effect of agrichemicals on crop growth. Thus, they have studied the movement of these chemicals from site of application through the plant root zone, which usually is considered to be 6 feet deep (20). USGS traditionally has focused on movement of contaminants within the saturated zone, from the groundwater table down (60). Little research by these agencies has focused on the movement of contaminants between the root zone and the saturated zone. A Memorandum of Understanding between USGS and USDA has defined relative responsibilities of these agencies regarding such research, but few cooperative efforts have been initiated (54). Were this separation of research and data collection focus to continue, it would impede development of agricultural practices to reduce agrichemical contamination of groundwater in vulnerable areas, and would likely result in duplication of effort.

For example, a group of hydrologists might create a database that includes information on the movement of herbicides through the soil profile. They might measure parameters relevant to the chemistry and physics of chemical transport through the soil, but as hydrologists they may need to consult with soil scientists, and cropping system specialists to include measurements describing influences of tillage practice or crop types, information that would be critical to an agronomist trying to develop new cultural practices to minimize the movement of an herbicide out of the root zone (54). Preliminary consultation with potential database users could save substantial money and effort by adding measurements of a few extra attributes to the database.

Further, only some of the databases have been automated (entered into a computerized data management system), or "digitized" (entered into a spatial or geographically registered database in generic format) to allow ready transmission to users, easy manipulation of data for different decisionmaking efforts, or integration of different data sets to allow for more comprehensive analysis. In addition, the systems of information search and retrieval (manual or computerized) commonly are unique to each database system. Consequently, many data have been collected relevant to groundwater protection, but much is inaccessible or of unusable format for scientists from other agencies. Efforts are underway to define data-entry protocols and standard formats such that future databases might be more integrable (cf: 82,48).

**Congress could undertake a number of mutually beneficial options to rationalize natural resource data collection and management efforts.** Such efforts might include:

- accelerating extant hydrogeologic and agricultural land-use data collection efforts (e.g., SCS soils surveys, USGS RASA analyses);
- initiating additional data collection efforts to ensure comprehensive provision of information (e.g., used and abandoned well locations, State-level groundwater monitoring);
- accelerating digitization of data already collected by Federal agencies;
- mandating digital storage of all new, relevant land-use and natural resource attribute data collected by the Federal agencies; and
- requiring regular data updating, maintenance of databases, and cost-effective provision of data to users.

Furthermore, in order to ensure that the necessary information is collected for accurate Federal, State, and local decisionmaking to reduce agrichemical contamination of groundwater, Congress could encourage establishment of an interagency Technical Information Integration Group[3] that will determine what data is necessary, what data is available, who might collect data not presently available, and how data might be integrated to support non-technical decisionmakers and how data might be shared among public user groups.

Although the efforts listed above could be undertaken simultaneously and immediately, the costs of data collection and digitization can be enormous. Many data collected thus far are available only "manually," on maps or in tables, and thus must be transferred into computerized databases. Digitizing data is an expensive process. For example, the SCS estimates the cost of updating and digitizing soils data for the Nation at $200 million (72). Therefore, Congress might initially require the General Ac-

[3] A Technical Integration Group (TIG) is an interagency organizational structure designed to promote coordination and standardization at a technical level. At present, the only extant TIG is a three-tiered structure sponsored by the USGS including technical and administrative representatives of several Federal agencies, States, and academic research organizations. The tiers include four Strategy Teams comprised of researchers in certain topical areas, the Technical Integration Group of technical program managers, and a Headquarters Team of research administrators with authority to allocate research resources (59) [Ragone, personal communication Mar. 1990].

counting Office or a Federal interagency group (e.g., the Technical Information Integration Group) to evaluate the status and needs of data collection and management efforts specifically related to agrichemical contamination of groundwater, and to recommend specific steps to achieve a comprehensive, integrated system in the most cost-effective manner.

***Coordination of Data Collection and Storage***—Most Federal agencies have means to internally coordinate the information collected by that organization. Other systems have been developed to coordinate data acquisition and sharing of certain types of information. For example, the U.S. Geological Survey coordinates water resources data acquisition and data sharing activities among Federal organizations through its Office of Water Data Coordination (42). Coordination is accomplished among Federal agencies through a Federal Interagency Advisory Committee on Water Data and between Federal agencies and the States and private sector through a non-Federal Advisory Committee on Water Data for Public Use. While of immense use to those seeking specific information, such systems do little to improve integration of different types of data (e.g., integrating water data with soils and vegetation data) without specifications describing data detail, content, and accuracy.

Congress could require the creation of a coordinated database network, to ensure that the relevant agencies develop rational interfaces between extant databases and follow standardized data entry, format, and search protocols. Alternatively, Congress could aggregate all of the relevant databases into a single national database clearinghouse.[4] The Federal Interagency Coordinating Committee on Digital Cartography (FICCDC), was established in 1983 by the Office of Management and Budget (OMB) to facilitate coordination of 30 participating Federal agencies' digital information system activities and geographic information system activities and to establish standards for production of digital cartographic data (24). However, FICCDC has no authority to require that Federal agencies follow data protocols.

Further, the FICCDC has focused on thematic data collection, for example by recommending that the Soil Conservation Service be the lead agency on collection and management of digital soils information. It was not structured to assist in development of integrated databases, nor to coordinate data collection and management among Federal agencies and State and local information management systems or users (43). Any data management system also will need to be designed to accept data 'uploaded' from regions and States that likely will be collecting more detailed data related to crops, cropping systems, and hydrogeologic vulnerability than national efforts. Such a system would have capacity to aggregate information "upwards" to evaluate national trends and needs, providing a more accurate national picture than a random sample of a few points, as well as allowing resolution "down" to the local decisionmaking scale.

If all national-level natural resource and relevant land-use databases were transferable to a centralized organization, standardization of protocols and coordination among Federal, State, local, and private users might be simplified. Each Federal agency could maintain its own system, following formats for specific sets of environmental information set by the clearinghouse, but would periodically move their data to the clearinghouse.

However, some agencies may resist changing their own systems to accommodate outside users. Further, agencies may be reluctant to house all of their information within a separate organization, especially if it is part of an established agency.

If Congress wishes to focus solely on groundwater and agricultural production, the central database clearinghouse might be located within the Soil Conservation Service or at the National Agricultural Library. But if Congress prefers to address database integration for a broader array of agricultural/environmental issues, it may be preferable to create a separate office for environmental data acquisition, integration, and management (54). Such an office could be established with a ''neutral' data collection agency (e.g., USGS), within a central governmental unit such as the Council on Environmental Quality, or as a new part of the Department of Environmental Protection. Wherever located, the agency components of the system could remain

[4]A variation on this concept would be the creation of a ''universal computer search program.'' Rather than learning the computer language or search protocol of each database, or wait until the information is transferred to a national clearinghouse, individual inquirers could access an interactive search program that would ask them a series of questions. On the basis of the answers, the program would ''dial-out' to the appropriate databases and retrieve the relevant information (54).

housed within the agencies, but the central office would provide the integrating structure and mandate.

### *Coordinating Agroecosystem Simulation Modeling*

Data are collected and managed to help make decisions. A working model of the world—whether a formal computer paradigm or an informal set of assumptions—is used when decisions are made.

In the case of groundwater management, as well as other environmental issues, the number of variables and parameters of concern are so numerous and the interactions between these factors so complex that there is an increasing reliance on computer models[5] (cf: 52). Computer modelers, in turn, are discovering that environmental modeling has become a large and complex undertaking. Consequently, discussions are underway regarding the development of "modular modeling. ' Individual researchers and teams develop the particular models for which they have interest and expertise, but build the "input" and "output" components of their models according to agreed upon standards so that other scientists can incorporate models without having to repeat work that has already been done by others.

For example, one scientist could develop a model of nitrogen movement through the soil, another could develop a model of how plants absorb nitrogen from the soil, another could develop a model on nitrogen volatilization, and yet another could develop a model of how nitrogen leaches through the soil profile to groundwater. Left as individual projects, these models would not be able to help answer questions on how to balance nitrogen fertilizer applications so as to ensure healthy plant growth while protecting groundwater resources. However, if the models are developed according to agreed on standards, an integration team could concentrate on the interactions of the models and put them together into a comprehensive nitrogen management model.

**Congress could require that the U.S. Department** of **Agriculture, perhaps jointly with other agencies, evaluate current simulation modeling efforts related to the environmental fate of agrichemicals.** Based upon this analysis, a Technical Agroecosystem Modeling Integration Group (TAMIG) could be established to coordinate research and development of computer simulation models related to the environmental fate of agrichemicals in farming systems. Such a TAMIG should include the technical program managers from relevant Federal agencies undertaking such modeling efforts (e.g., USDA, EPA), State government and academic specialists, and might include members of the environmental and agricultural research community.

One goal of such a group might be to ensure development of simulation models that can be generalized, through agreed upon means, to allow prediction of environmental fate on sites with different hydrogeology or agricultural systems. Another goal might be to coordinate development of detailed simulation models of certain parts of hydrogeologic systems (e.g., the Pesticide Root Zone Model developed by EPA or the Groundwater Loading Effects of Agricultural Management Systems model developed by USDA/ARS) so that they may be "hooked" to simulation models of other parts of hydrogeologic systems to allow more comprehensive analysis. USDA/ARS has used this approach in developing NTRM, a Soil-Crop Simulation Model for Nitrogen, Tillage, and Crop-Residue Management (65).

### *Developing Geographic Information Systems*

Geographic Information Systems (GISs) are computer-based technologies including hardware, software, and graphics capabilities. More than automated mapping systems, GIS can encode, analyze, and display the natural and built environment in multiple ''layers' that are geographically registered to unique locations on the Earth's surface. Results of GIS analyses can be described in reports, tables, and most importantly, in maps at any scale.

Relationships between data can be used to depict complex variables such as hydrogeologic vulnerability to agrichemical contamination as well as spatial displays of component simple variables such as average depth to water table. Further, GISs are capable of displaying "option" variables, such as the percentage of lands eligible for the Conservation Reserve land-retirement program that coincide with areas containing hydrogeologically vulnerable cropland. By using GIS, the decisionmaker can alter

[5]For detailed discussion of groundwater models, see National Research Council, Water Science and Technology Bored, Committee on Ground Water Modeling Assessment, *Ground Water Models: Scientific and Regulatory placations* (Washington DC: National Academy Press, 1990).

variable components and test the impacts of decision alternatives before enacting new provisions. Given adequate and reliable data, and a sufficient understanding of the pertinent variables and their interactions, GISs provide a rapid means to assess where efforts might be allocated to have the greatest beneficial impact, or whether proposed policy options have potential to solve problems.

### Databases and Systems

**The** first requirement for a GIS is spatially coordinated, geographically registered, digitized data: data transferred **into a** computer so that it is electronically associated with known geographic coordinates (unique locations on the Earth's surface). Then, using those coordinated layers, other geographic information can be added and attributes or characteristics of those geographically referenced locations can be described by the computer in graphic colors, textures, and shapes as well as numbers. For example, a county might have attributes including 1990 population, amount of agrichemicals used in a year, or wheat production in bushels per acre. A well shown as a point on the map may have attributes including depth to bedrock, nitrate concentration, or yield of water in gallons per minute. A stream shown as a curved line at a particular location may have a known flow rate, sediment loading at certain times, or average numbers of bass.

Some of the most important databases for assessing potential groundwater vulnerability to agrichemical contamination are digitized soil and geologic data at National, State, and local levels. SCS is in the process of digitizing soil surveys; however, digitizing all soils data, collected at the county level, for the Nation will cost nearly $200 million. This estimate includes $100 million for updating, recompiling, and establishing the geographic referencing system for soil survey data, and $100 million for digitizing (72).

Dearth of Federal funding has led a number of States to proceed with digitization on their own; however, some are not using the protocols proposed by SCS or USGS so that State-level 'pieces' are not likely to be easily assembled into a national system (54). On the other hand, EPA has moved to provide digital surface-water networks—another important data layer—based on USGS hydrography data at a relatively detailed, but still national scope. How and whether this database, known as the ''Reach File, ' together with associated Water Quality Assessment data and systems will be freely available for GIS users outside the agency is not yet clear (43).

Approaches to using GIS to describe vulnerability of surface- and groundwater should:

- Integrate gee-referenced overlays of natural resource information such as geology, subsurface hydrology, and terrain from USGS; soils from SCS; and surface hydrography from USGS and EPA.
- Incorporate agricultural land use variables for agricultural vulnerability assessments, including cropland and individual crops and cropping systems, vegetative cover, climate, pesticide and chemical use, and irrigation practices.
- Incorporate derived variables such as: 1) meaningful hydrogeological units, *2)* watershed units based on elevation and terrain data, and 3) surface stream and river networks that route water-borne contaminants through watersheds (this information should include associated water quality information including well and water samples, and the location of water intake sites for community water supplies).
- Develop or use existing GIS capabilities to manage and display the information, including maps of hydrogeologic parameters of particular concern to groundwater management.
- Identify needed information and databases that do not yet exist (54,43).

### GIS Users

GIS for surface- and groundwater assessments have been developed and used for some time by certain Federal agencies, such as USGS, private organizations concerned with natural resources such as the newly established National Center for Resource Innovations, many State agencies, and some Agricultural Experiment Stations and Land Grant Universities such as Minnesota (7).

USDA, EPA, and others are showing increasing interest in these systems and have included proposed uses of such systems in their planning documents (cf: 78). A survey of Federal organizations using or intending to use GISs found at least 37 used GIS in 1988, 20 plan to have an operational GIS by 1990, and 10 others have developed policies related to GIS (24). For example, the NASS is planning to develop a GIS to support USDA's water quality program plan. The proposed system will link nationwide data and statistical information on agricultural productivity, cropping practices, land use, agrichemical use, physical attributes of the land and surrounding watersheds, climate and water quality (9).

Perhaps the greatest need for GIS development, however, lies at the local level where detailed information is most extensive. A 1985 survey conducted by the American Farmland Trust found that approximately 22,000 non-metropolitan rural governments have authority to allocate 1.5 billion acres of non-Federal rural lands and resources in 3,041 counties, 16,000 townships, 6,000 natural resources special district governments. Only 25 of these governments had operating GISs (4). That number is rapidly increasing; today it is estimated that approximately 1,000 urban and rural local governments use GISs.

### Current Programs for GIS Support and Delivery

To assist with GIS research and development, the National Science Foundation recently established the National Center for Geographic Information and Analysis to: 1) serve as a clearinghouse on GIS research, teaching, and application; 2) promote use of GIS analysis and train users; and 3) study the legal, social, and institutional aspects of GIS (12). To assist with GIS technology delivery to primarily non-technical local, regional, and national decision-makers, Congress has funded the National Center for Resource Innovations (NCRI). NCRI is a consortium of regionally distributed GIS technology transfer centers whose objectives include: 1) encouraging the use of established specifications and standards for data development, quality, and applications; 2) coordinating technical assistance from public resource specialists in interpretation and use of information in GIS systems; 3) developing training programs; 4) delivering GIS technology research; 5) supporting and identifying needed GIS development in the applications and decisionmaking environments; and 6) developing GIS into education tools for public decisionmakers and the public.

## Approaches to GIS Assessment of Groundwater Vulnerability to Agricultural Land Uses

Two key impediments exist to GIS development for non-technical decisionmakers concerned with water quality protection at all levels of government. These are: 1) lack of needed data; and 2) difficulty integrating information from many sources at scales suitable for local, regional, and national assessments.

**Congress could mandate development of interagency GISs for management of groundwater protection.**[6] A first focus could be on completing and digitizing soil survey maps developed by the Soil Conservation Service. This should be extended to all data sets identified as important for water quality assessment and protection. To assist with this, data sets developed outside Federal agencies might be encouraged to meet specifications and standards established by agencies with lead responsibility for collecting and interpreting the data. Such an effort could be coordinated through current OMB/FICCDC efforts to ensure orderly GIS development within Federal agencies, or could be assigned to a concomitantly expanded Council on Environmental Quality. Development of such a system also could be handled through a centralized Office of Environmental Data Acquisition, Integration, and Management mentioned earlier.

A comprehensive and carefully developed approach to provide an "open architecture" GIS—allowing users to combine databases with new data and add models as well as interpret interrelationships-could eventually lead to integration of national-level databases into geographic information of specified accuracy and scientifically supportable applications (43). By being "open," such a "core" GIS could allow incorporation of decision support, and expert systems to provide a powerful and accessible information management system. Such a system could also be developed to allow regional and local levels of detail to be added together with regionally appropriate factors including local climate, cropping systems, chemical use, location of livestock confinement facilities, watershed characteristics, and other regionally specific factors. A core GIS might provide a model for local systems and could assist in integrating national-level databases, Geographic Information Systems, and expert systems into powerful information management and decision-aid systems. These, in turn, could foster development and integration of voluntary, incentives-based, and regulatory systems to protect groundwater (54).

[6] Digitized databases also can support development of computerized farm decisionmaking aids, such as ''expert systems' (see ch. 5).

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