Wells and Ponds: Water Quality and Supply

E.C. DICKEY AND W.D. LEMBKE

Bulletin 758
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This bulletin is one of six publications growing out of a four-and-a-half-year study of nitrogen as an environmental quality factor. Although the study, including publication costs, was supported principally by a grant from the Rockefeller Foundation, the effort was initiated through a grant from the Illinois Agricultural Association. This phase of the study was supported through staff assistance provided by a number of state agencies but in particular by the Illinois Agricultural Experiment Station and the Illinois State Water Survey.

Three other bulletins in the series have been published: "Nitrates, Nitrites, and Health," Bulletin 750; "Environmental Decision Making: The Role of Community Leaders," Bulletin 756; and "Economic Effects of Controls on Nitrogen Fertilizer," Bulletin 757. One final bulletin will deal with the management of nitrogen in crop production. A book on nitrogen in relation to food, environment, and energy is also being prepared as part of the series.

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The authors wish to thank the following people: C. D. Baker, research associate, M. D. Stone, research assistant, and E. C. Doyle, consultant, for their research contributions; L. E. Arnold, associate forester at the Dixon Springs Agricultural Center, and W. H. Walker, formerly with the Illinois State Water Survey; T. R. Peck, professor of soil chemistry, for his help with data analysis; B. Commoner, G. Shearer, and D. Kohl, with the Center for the Biology of Natural Systems, Washington University, St. Louis, Missouri, for conducting the delta ^{15}N tests and for offering valuable suggestions; W. D. Smith, Extension adviser in Washington County; and O. Pannier, L. Groennert, and several other farmers who, with their families, encouraged us and allowed us to conduct research on their property.

Urbana, Illinois July, 1978

Publications in the bulletin series report the results of investigations made or sponsored by the Experiment Station. The Illinois Agricultural Experiment Station provides equal opportunities in programs and employment. 4M—7-78—41022—SW

In a broad geographic band immediately south of the central Corn Belt, water supplies for domestic use and livestock are beset with problems. The flow of groundwater into shallow dug wells tends to be unreliable during dry seasons, and the flow rate through compact soils is at best only moderate to low at all times. In addition, the nitrate-nitrogen content in nearly three-fourths of the shallow wells in a representative county exceeded the U.S. Public Health Service standard, in some cases by tenfold. In contrast, seventy-two farm ponds sampled for nitrate-nitrogen were well below the standard of 10 milligrams per liter.

Preliminary findings in Washington County, Illinois, in 1970 led to the research reported here, which is part of a larger study of nitrogen in the environment. The first section of this bulletin advances a theory to explain excessive nitrate concentrations in some farmstead wells. The second section focuses on nitrogen regimes in fifteen farm ponds and one lake. We assumed at the outset that little can be done in the short run to reduce the amount of nitrates in farm wells. For this reason we studied ponds as possible alternative sources for drinking water.

An economic analysis shows that well-water systems in use in Washington County are the least costly available, but that water quality and quantity are for the most part undependable (Moore, 1972). Alternatives include farm ponds, municipal water supplies, transported water, and various combinations of these sources. Moore concluded that farm ponds with a purification system could be one of the more satisfactory alternative sources provided that water storage facilities are available for prolonged droughts.

FARM WELLS IN WASHINGTON COUNTY

Most of the wells in Washington County are dug rather than drilled. The typical dug well, which is about 20 feet deep and 4 feet in diameter (6 and 1.2 m), is lined with brick that allows water to seep from the surrounding soil into the well cavity (Figure 1). Drilled wells, sometimes reaching a depth of 200 feet or more (60 m), directly tap deep aquifers, which are water-bearing beds of permeable rock, sand, or gravel. Unlike dug wells, those that are drilled are lined with an iron casing, which prevents shallow groundwater seepage into the well.

Because of the geology of the area, groundwater supplies in most of Washington County are inadequate (Pryor, 1956). The geologic situation also makes it extremely difficult to drill deep wells successfully.

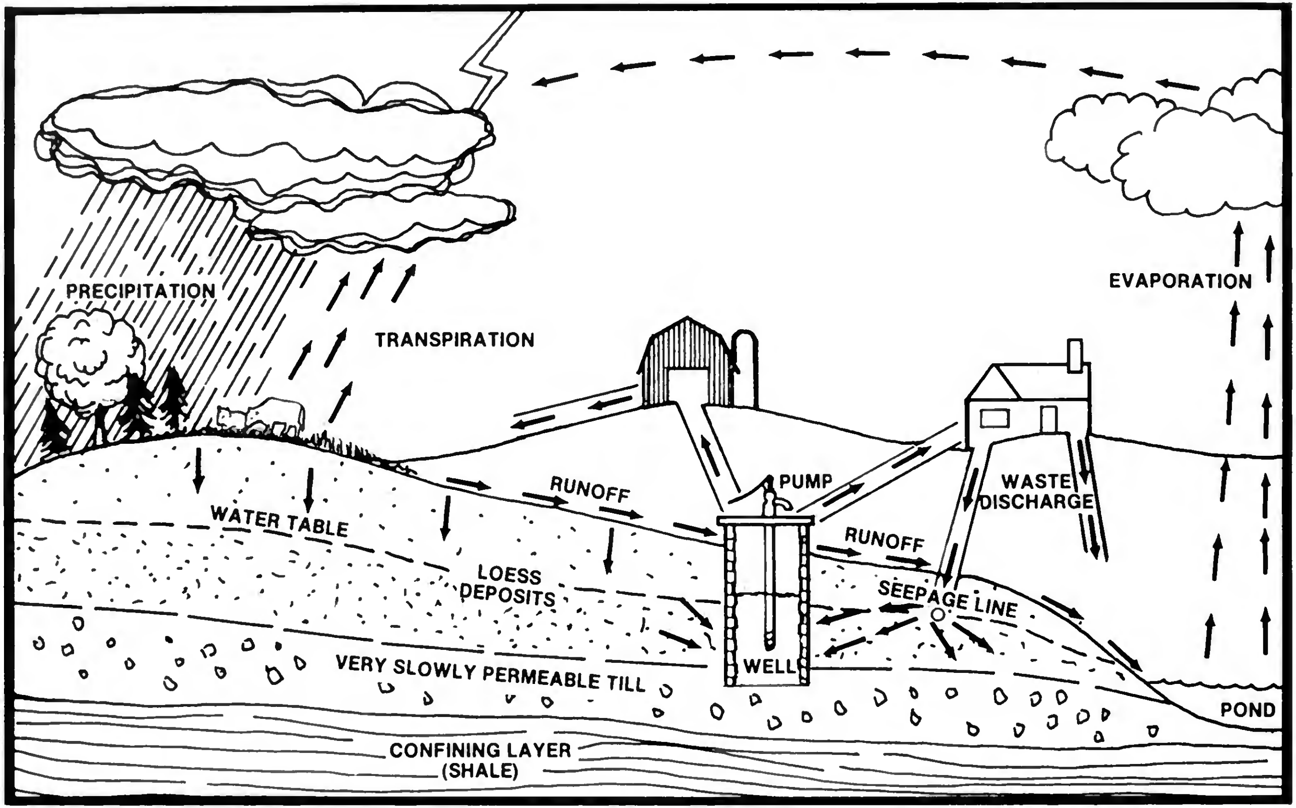

Figure 1. The hydrologic cycle from a farmstead viewpoint; a shallow dug well and a farm pond.

Table 1.* — *Percentage of 213 Dug and 31 Drilled Wells in Washington County, Illinois, With Various Nitrate-Nitrogen Concentrations, 1970

Type of well	Nitrate-nitrogen, mg/l					
	0-10	11-22	23-45	46-67	68-90	over 90
			percent			
Dug	27	10	29	20	7	7
Drilled	82	3	3	3	6	3

Even with an annual rainfall of more than 40 inches (1,000 mm), the groundwater supply in the claypan region of south central Illinois and adjoining states is sporadic, shallow, and often polluted. In a preliminary study Smith *et al.* (1970) found that 73 percent of the 213 dug wells sampled in Washington County and 18 percent of the 31 drilled wells exceeded the public health standard for nitrate-nitrogen (Table 1). Water supplies from low-quality and low-yielding wells are supplemented by cisterns, transported water, and some ponds. Larson and Henley (1966) had previously reported that nitrate levels in farm wells in several other sections of Illinois are also high.

The pollution problems are both chemical and bacterial. Older wells are usually the most dangerous. Open brick linings near the surface, cracked casings and covers, and nearby privies, septic tanks, and barnyards accentuate the problems in shallow groundwater aquifers. The high levels of nitrate-nitrogen (NO_3-N) frequently present in domestic well water of Illinois were recognized as a potential health hazard as early as 1948 (Weart, 1948). The significance of nitrates in relation to human and livestock health is discussed in a companion publication in this series, "Nitrates, Nitrites, and Health" (Deeb and Sloan, 1975).

Research shows that areas with intensive livestock operations, such as farmsteads, corrals, and feedlots, are more apt to have nitrate-contaminated groundwater than unfertilized grassland and even heavily fertilized fields. Gentzsch *et al.* (1974) found this to be true in southwestern Illinois. Keller and Smith (1967) had noted a related situation in Missouri, where over 3,000 pounds per acre of NO_3-N (3,300 kg/ha) had accumulated beneath feedlots on which cattle had been fed for more than fifty years. Keller and Smith concluded that in rural areas of Missouri infiltrates from feedlots were the main source of nitrates in groundwater.

Stewart *et al.* (1967) found in Colorado that the amount of soil NO_3-N varied widely, but that as much as 4,000 pounds per acre (4,500 kg/ha) had accumulated in a 20-foot profile (6 m) under a feedlot. Some researchers have attributed the variation to differences in denitrification, a bacterial process by which NO_3-N and NO_2-N are converted to nitrous oxide and nitrogen gas. This process will not occur if oxygen is readily available to the bacteria. Redox potential in soil is a measure of oxygen availability; above 300 to 400 millivolts, the bacteria can get enough free oxygen so that NO_3-N is unnecessary for respiration. Several other environmental factors such as temperature, pH, and food also affect the needs of bacteria for NO_3-N (Bartholomew and Clark, 1965). When the bacteria use available oxygen, NO_3-N remains unchanged in the soil.

In Kansas Murphy and Gosch (1970) found that in a 13-foot profile (4 m) nitrates ranged from essentially zero to as much as 4,500 pounds per acre (5,000 kg/ha). Older feedlots had greater accumulations than newer lots. Ellis *et al.* (1975) found that abandoned feedlots contained higher nitrate concentrations in the soil and in the associated groundwater than active feedlots. Apparently in active lots the continuous compacting of the soil by livestock aids denitrification and hinders nitrification.

The studies discussed above indicate the probable relationship between animal wastes and nitrate contamination in shallow wells. To prove this relationship, however, additional techniques for measurement and study are needed. The objectives of our investigation were therefore to develop the necessary methods, to describe soil and water measurements made in the vicinity of some high nitrate wells, and to advance a theory of how the high concentrations were generated.

Study Area Description

First settled in 1813, the area used for this study is near the western edge of Washington County, Illinois, 37 miles (60 km) southeast of East St. Louis (Figure 2). The Kaskaskia River forms the northern border of the county. Until about 1955 grain farming with some dairy herds and hogs was common. Since then, some farmers have intensified their dairy and hog operations, while others have shifted to corn, wheat, and soybean cash-grain farming, often raising two crops in one year. We selected three study sites, designated in this report as farmsteads A, B, and C.

FARMSTEAD A

Farmstead A, described in greater detail elsewhere (Dickey *et al.*, 1972; Walker *et al.*, 1972), is on a slight rise on a loessial plain. Only

Figure 2. Location of three farmsteads in Washington County and the Dixon Springs study sites in Pope County.

the house and a few outbuildings are used by a tenant family. During the period of this study from 1971 to 1973, tenant turnover was frequent, with an average family size of three. In 1967 a septic tank and seepage line were installed (Figure 3). Water is obtained from an old brick-lined well, which is 28 feet deep and 4 feet in diameter (8.5 and 1.2 m). This well, located on the lowest part of the farmstead, is at an elevation that is about 6 feet (1.8 m) lower than the farmhouse foundation (Figure 3). In 1970 the nitrate-nitrogen concentration in the well was 85 milligrams per liter (mg/l). There have been no livestock since 1956, and there is no record of any fertilizer use on the farmstead, but the surrounding fields have been heavily fertilized by the owner, with 150 pounds per acre of nitrogen (170 kg/ha) applied each year that corn is grown.

FARMSTEAD B

Farmstead B is about 500 feet (150 m) across the road from farmstead A and has the same general topography (Figure 4). At the time of this study an abandoned well was the only visible indication of the farmstead location. The brick-lined well, about 4 feet in diameter, is now filled in with trash. After the owner razed the house and outbuildings in

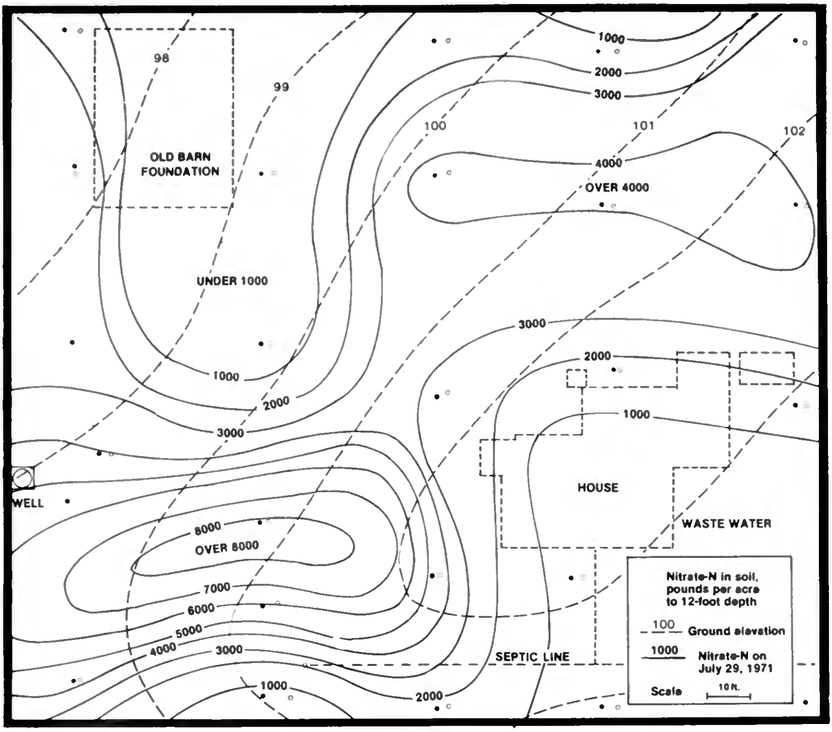

Figure 3. Farmstead A, showing isonitrate contour lines, ground elevation (feet), septic line, well, and piezometer test holes.

1953, the farmstead was incorporated into fields that are now farmed under a rotation of corn, soybeans, wheat, and meadow. The fertilization rate is similar to that used on fields around farmstead A.

FARMSTEAD C

Farmstead C, which is in a low area near a waterway, was an active farm with an intensive swine operation and some beef cattle at the time of this study. Figure 4 shows the location of the septic line and a brick-lined well, 22 feet deep and 4 feet in diameter (6.7 and 1.2 m). Land immediately around the farmstead is used for pasture. Cultivated fields, beginning about 500 feet from the well, are heavily fertilized. In 1970, as a result of some unexplained baby pig deaths, the well water was tested and was found to contain 88 mg/l of nitrate-nitrogen.

Farmstead A is typical of many farms in Washington County with respect to soil type, land use, shallow well construction, and location on a ridge; farmstead B is much like A in these features. Farmstead C

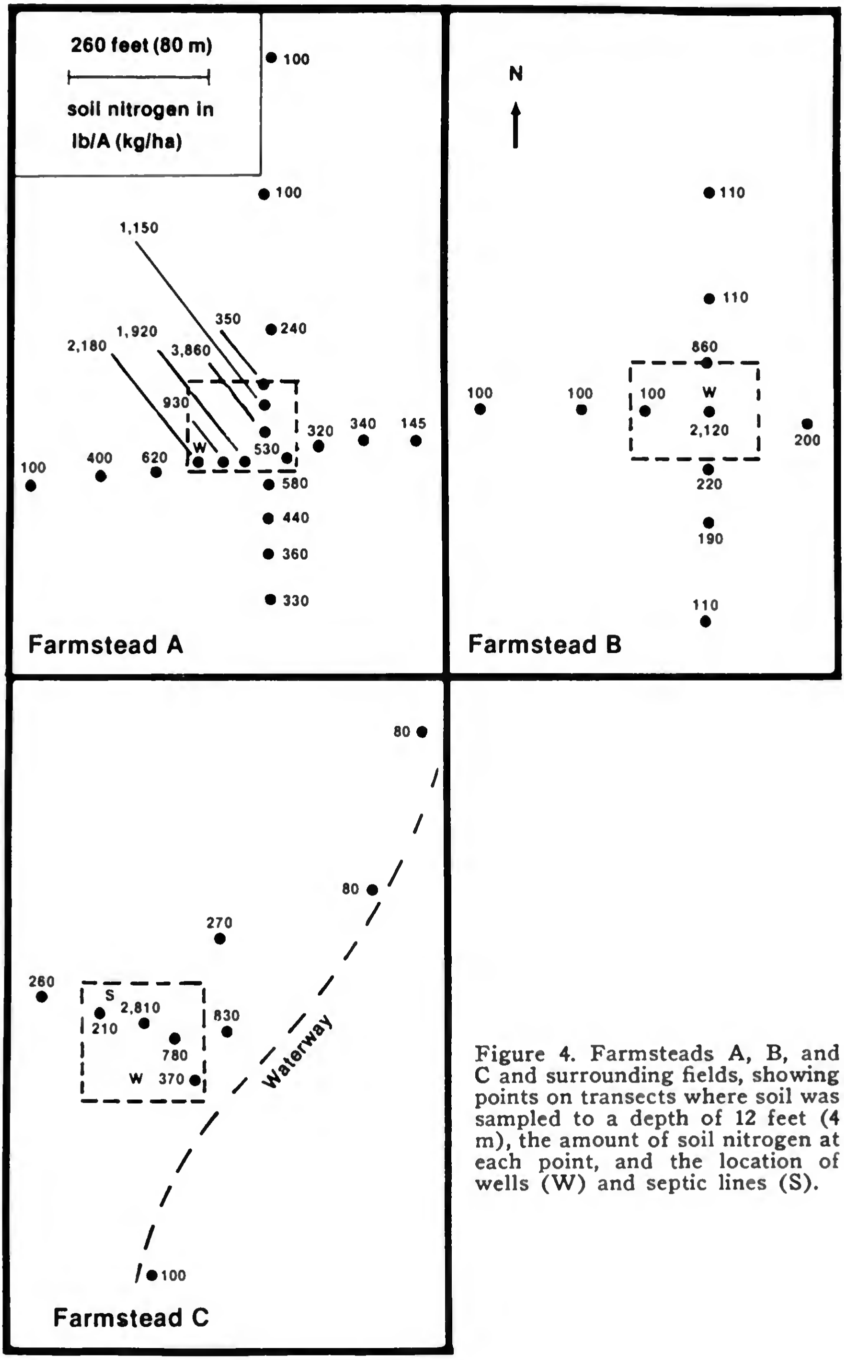

Figure 4. Farmsteads A, B, and C and surrounding fields, showing points on transects where soil was sampled to a depth of 12 feet (4 m), the amount of soil nitrogen at each point, and the location of wells (W) and septic lines (S).

differs somewhat because of its location in a low area along a waterway. Data were collected from all three farmsteads, but because of personnel and time limitations only farmstead A was studied intensively.

SOIL TYPES

Nitrate-nitrogen is soluble in water and is transported by water moving through the soil. Therefore, a familiarity with soil types and their permeability (hydraulic conductivity) is important in describing the history of NO_3-N at a particular location. The soils of our study area are predominantly in the Cisne-Hoyleton and Bluford-Wynoose soil association areas, and are mainly silt loams characterized by an almost impervious clay subsoil (Smith and Smith, 1937). The bedrock is shale at a depth of about 20 feet (6 m). The shale grades upward into a thin Illinoian till, in most cases at a depth of 12 to 15 feet (3.5 to 4.5 m). Above 15 feet two post-glacial loessial deposits, Roxanna and Peoria, are usually evident. In most cases the Peoria loess is somewhat more permeable than the Roxanna. Loess is a wind-blown material, while glacial till is material moved in by glaciation during the Ice Age.

Nitrate-nitrogen, as well as any other chemical in solution, moves through the soil primarily in two ways: by convection, that is, through the mass flow of groundwater; and by diffusion, which occurs because of a difference in chemical concentration. The movement of NO_3-N by convection is limited by the groundwater flow rate. Attraction or repulsion between the charge of the chemical ion and the charge of the surface of the soil particles affects the flow rate. The NO_3-N ion, unlike the ammonia form of nitrogen, has the same charge as the soil particles; consequently NO_3-N movement is not restricted by this interaction. When, however, a soil such as the claypan soil of our study area is almost impermeable, then even without this restriction nitrate movement is very slow.

Precipitation, which is part of the hydrologic cycle (Figure 1), is necessary to recharge groundwater. But evaporation, also part of this cycle, reduces the amount of water that eventually gets into shallow wells. Therefore, both precipitation and evaporation are important factors in studying nitrate movement. Based on the period 1931 to 1960, the average annual precipitation in this section of Washington County was 40 inches (1,000 mm). Using Thornthwaite's methods as described by Chang (1968) to calculate potential evaporation, we found that the annual potential evaporation within the study area averaged 28 inches (710 mm). This means that almost three-fourths of the annual precipitation may be lost through evaporation.

Field and Laboratory Procedures

Two different field techniques were used to collect soil samples. During the first phase of the investigation a heavy-duty drilling machine was used to auger holes 3 inches in diameter (7.6 cm) to a depth of between 16 and 30 feet (5 and 9 m) to or into the shale bedrock. In the second phase all soil samples were collected with a Giddings hydraulic sampler with a split tube coring device mounted on a pickup truck. Compared at points close together, the two techniques gave similar results, except that the heavy-duty drilling machine made it possible to penetrate the shale.

Piezometers installed in the holes were used as access tubes for several purposes: (1) to sample groundwater at certain points in the soil profile, (2) to measure the water table level when the soil was saturated, and (3) to measure the hydraulic conductivity of the soil, using the method described by Luthin and Kirkham (1949). The piezometers were made of PVC plastic pipe having an inside diameter of ¾ inch (19 mm). Several slits were made through the pipe on the bottom 6 inches (15 cm) to allow groundwater to seep into the pipe. This end was covered with 50-mesh window screen, and the pipe then installed in the hole. Coarse sand was packed around the pipe from the base to a point 6 inches above the screen. Bentonite clay mixed with soil was packed into the next 12 inches (30 cm) to seal the sample tip against seepage from higher strata.

Groundwater samples were removed from the piezometers through a plastic tube, with an inside diameter of ⅛ inch (3.2 mm), attached to a vacuum carry tank. To prevent contamination from the previous test, 3 tablespoons of water (50 ml) were discarded before the sample was collected. Water level was measured by lowering a metal tape covered with dry chalk into the piezometer tube. Hydraulic conductivity was measured by initially suctioning all water out of the piezometer through the carry tank tube and then making successive observations of the rate at which the water level rose.

Well-water quality and quantity were tested occasionally over a three-year period on farmstead A. With the cooperation of the tenant, a water stage recorder was installed on the well for one year in order to record the water level, and a water meter was installed in the house to measure the amount of water used.

Soil nitrates were determined by the phenoldisulfonic acid method (Jackson, 1958); analyses were based on an air-dry weight of soil. Water nitrates were measured with an Orion nitrate ion-selecting electrode. Nitrates were checked frequently with the chromotropic acid method (APHA Standard Methods, 1971). Soil and water chlorides were determined by using techniques described in the USDA Salinity Handbook (1954) and in APHA Standard Methods. Soil potassium measurements were determined with a Coleman model 21 flame photometer, using a 1:10 ratio (soil to ammonium acetate, pH 7) equilibrium extraction (Jackson, 1958).

Soil and Groundwater Measurements

A farmstead is the site of manure piles, feed and exercise lots, privies, and septic tanks, but there is seldom any fertilizer used. Compared with surrounding fields, all three farmsteads in this study had high levels of nitrates. We concluded that the nitrate accumulation came primarily from the decomposition of animal and human wastes rather than from fertilizer. Data leading to this conclusion were derived from soil and groundwater measurements of nitrates, chlorides, potassium, and delta ^{15}N.

NITRATES

Soil samples from each of the three farmsteads and the adjacent fields enabled us to characterize the distribution of nitrate in the groundwater flow system. Using the field techniques described on page 9, we drilled a series of test holes along two transects intersecting on the farmstead (Figure 4). Piezometers were installed at depths of 6, 8, 10, and 12 feet (1.8, 2.4, 3.0, and 3.7 m). On farmstead C the loess was about 6.5 feet deep with an underlayer of glacial till. On farmsteads A and B the loess was 7 to 12 feet deep with a slightly thinner layer of till. Shale bedrock was struck at 20 feet on each farmstead.

By averaging the NO_3-N in the soil profile to a depth of 12 feet, we determined the amount of NO_3-N for each sample hole (Figure 4). The nitrate-nitrogen in the soil varied from 100 pounds per acre in the fields to more than 2,600 pounds in some places on the farmsteads (112 to 3,000 kg/ha). Soil samples analyzed from additional holes drilled on farmstead A were used to construct isonitrate lines, which indicate equal nitrate levels (Figure 3). These measurements show that some areas of farmstead A contained more than 8,000 pounds per acre of NO_3-N (9,000 kg/ha). Figure 3 also shows that, although soil nitrates were generally high, the amount varied considerably from one location to another. We then measured NO_3-N in soil samples taken from an area in the fields corresponding in size to the half-acre (quarter-ha) farmstead, and found that the amount of nitrate on farmstead A exceeded that in the field by 400 pounds per acre (450 kg/ha).

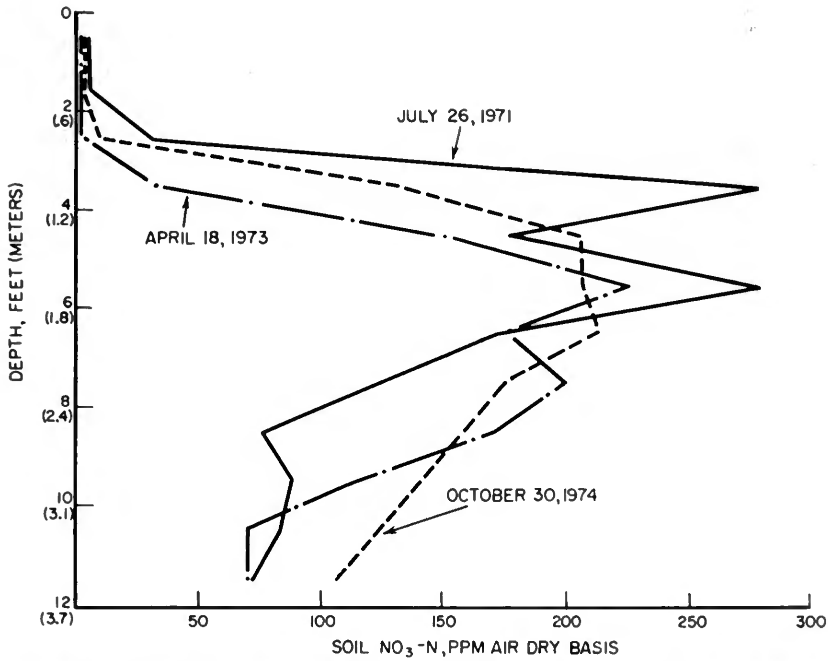

Figure 5. Nitrate-nitrogen concentrations in the soil profile at three sites on farmstead A, measured over a thirty-nine-month period.

Interestingly, soil nitrate concentrations changed very little over time. In July, 1971, we drilled fifty-eight test holes on farmstead A, some additional holes in April, 1973, in most cases near the piezometers originally installed, and one final hole in October, 1974 (Figure 5). During this thirty-nine-month period soil samples showed no major increase or decrease in nitrate concentration at any of the sites. We noted some downward movement at one site, but this finding was inconclusive.

Water nitrates measured in groundwater samples taken from the piezometers likewise showed little change during a twelve-month sampling period. This relatively static condition indicates that the high nitrate problem on farmstead A was essentially a local phenomenon due to very little groundwater movement through the impermeable subsoils.

Water tables at two piezometer sites on farmstead A dropped 8 feet from May through November (Figure 6). Since this is the growing season, we concluded that the drop probably occurred because of evapotranspiration, which is the loss of water from the soil both by evaporation from the surface and by transpiration from the plants. The well

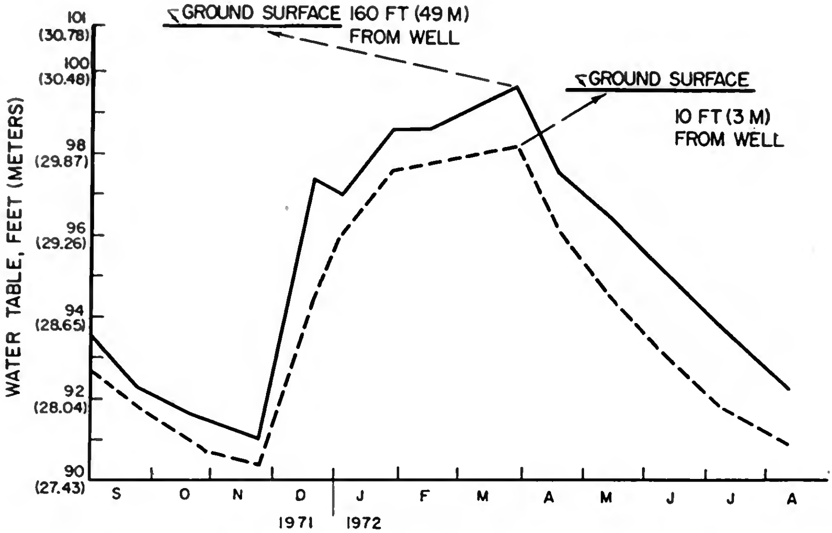

Figure 6. Water tables from September, 1971, through August, 1972, at two test holes 10 and 160 feet (3, 49 m) from the well on farmstead A.

removes some water, but most of it is returned to the soil through the septic tank system. With very little downward or lateral movement of water through the soil, salts not removed by harvesting plants become concentrated in the soil in much the same way that salts build up when plants are watered in nonporous flower pots. The only major removal mechanisms for nitrogen in such a system are denitrification of NO_3-N or volatilization of ammonia nitrogen, a process by which ammonia gas goes directly into the atmosphere. We did not measure either of these processes in this study.

CHLORIDES

Chlorides as well as nitrates are residual products of the decomposition of animal wastes. Like nitrates, chlorides move through the soil by convection, but unlike nitrates, they are not lost by gasification. Chloride ions are therefore often used as tracers to determine if nitrates have been lost by gasification following denitrification. Reddell *et al.* (1971) found that both chlorides and nitrates were high in samples of beef feedlot manure, the total nitrogen varying from 2.3 to 3.5 percent and chlorides from 1.1 to 1.5 percent of the manure weight on a dry weight basis.

When we tested soil samples for chlorides, we found that in the upper 12 feet of soil on farmstead A the chloride content was four times

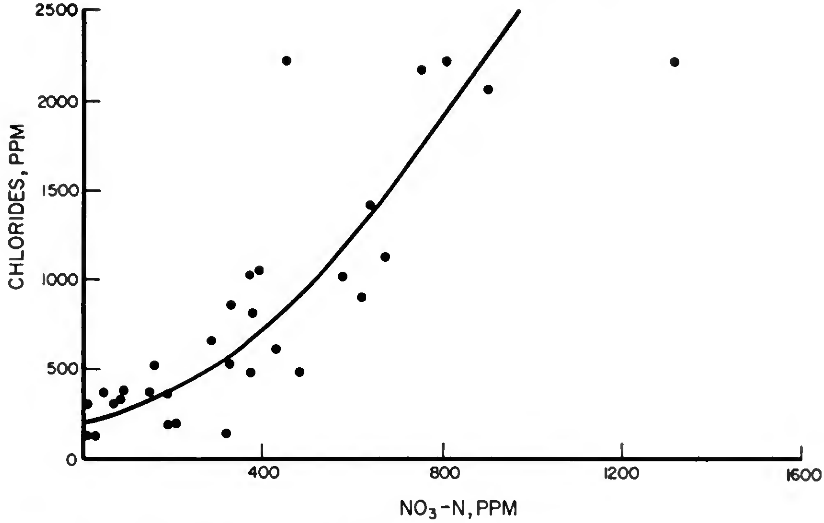

Figure 7. Chloride and nitrate levels in water samples taken from piezometers on farmstead A on September 2, 1972.

greater than that in the nearby fields. Figure 7 shows the relation between nitrates and chlorides in groundwater samples taken from different piezometers on farmstead A. Each circle represents a sample taken from a different piezometer. A curve was drawn freehand to show the relationship between chlorides and nitrates. The high chlorides associated with high nitrates in soil and groundwater samples are further evidence that excessive nitrates resulted primarily from animal and human wastes.

POTASSIUM

Beef manure from outdoor, unpaved feedlots has been found to contain from 1,200 to 8,000 parts per million (ppm) of potassium on a wet weight basis (Gilbertson *et al.,* 1971). Analyses for potassium in soil samples from farmstead A and neighboring fields showed that potassium in the upper 4 feet of soil on the farmstead was about double the levels in the fields, 957 versus 460 ppm at 1 foot (0.3 m) and 507 versus 382 ppm at 4 feet (1.2 m). The high potassium levels in the soil of farmstead A provided additional evidence that large amounts of animal and human wastes were incorporated into the soils of the farmstead during its history of operation. It should be kept in mind that, even though no livestock had been kept on the farmstead since 1956, residues from the decomposition of animal wastes remain in the soil.

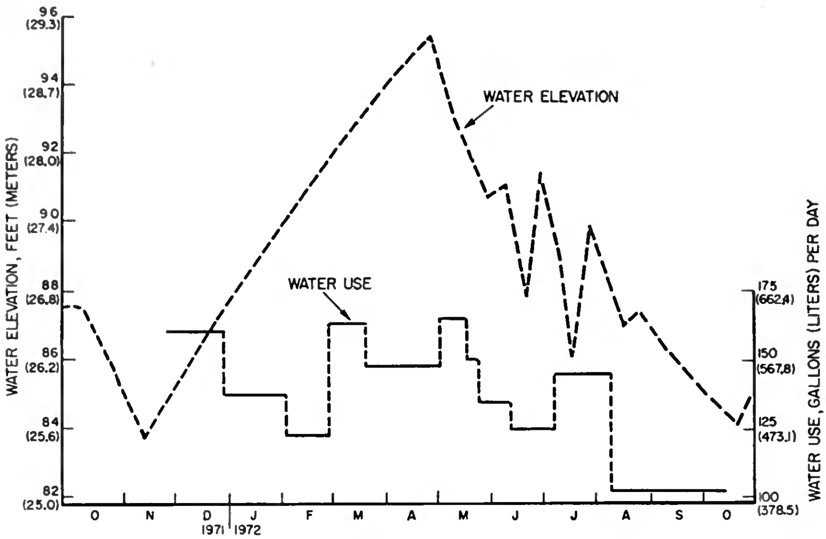

Figure 8. Water elevations in well on farmstead A for 13 months and water use for 11 months. Ground elevation at well is 99 feet (30.2 m).

DELTA ^{15}N

In the environment there are two stable isotopes of nitrogen, one with an atomic mass of 14 and the other of 15. These two forms are often referred to as ^{14}N and ^{15}N. In the atmosphere the more commonly found isotope is ^{14}N. After biologic cycling in the soil, ^{15}N may increase very slightly; this increase is usually designated $\delta^{15}N$ (δ = delta or change).

The Center for the Biology of Natural Systems in St. Louis, Missouri, measured the $\delta^{15}N$ in groundwater samples taken from piezometers on farmstead A. The average $\delta^{15}N$ for twenty-one samples was +17.7, with a range of +13.9 to +29.1. These values are high compared with the near-zero values for various types of fertilizer nitrogen used in many parts of Illinois (Shearer *et al.,* 1974). According to the theory of Kohl *et al.* (1971), high $\delta^{15}N$ values are characteristic of nitrogen in biologic cycling rather than of nitrogen in recently applied fertilizer. Moreover, the $\delta^{15}N$ values found in samples from farmstead A are higher than values ordinarily found in soils not associated with farmsteads (Hauck, 1973). Results of the $\delta^{15}N$ test are yet another indication that animal wastes are the source of nitrate problems on these farmsteads.

Well Water Measurements

Several interrelated factors can be linked with well water problems in our study area: (1) height of the groundwater table, (2) hydraulic conductivity of the subsoils, and (3) nitrate levels in the farmstead soils. In order to clarify these relationships, we made a series of observations and measurements of the water moving through the soil of farmstead A.

GROUNDWATER TABLE AND HYDRAULIC CONDUCTIVITY

The well on farmstead A was monitored for water elevation and water use from September, 1971, through August, 1972 (Figure 8; for ground elevation near the well see Figure 3). In Figure 8 water use is represented by plateaus because the water meter was read only periodically. Water level, on the other hand, was monitored by a continuous recorder. The maximum amount of water used was 164 gallons (620 l) per day from March through May and the minimum used was 100 gallons (380 l) per day during September. The small quantity of water available during September was insufficient for a three-member family with no livestock. Even if the quality of the water were improved, an alternative supply would still be needed. In this case, the family hauled water from a municipal source.

The water level in the well of course fluctuates with daily use, but there is also an annual cycle, peaking in April at 3.8 feet (1.2 m) below the ground surface and then dropping in October and November to 15 feet (4.6 m) below the surface. Typical of the area, this cycle results from seasonal changes in precipitation and evapotranspiration. The rise and fall of the cycle can be seen in Figure 6, which shows the water table at two test holes, one 10 feet and the other 160 feet (3 and 49 m) from the well. Note the similarity of the water-table elevations at the two test holes. This similarity shows that the well does not exert a broad cone of influence on the surrounding water table. Ideally, water is drawn with relative ease through an aquifer and down into the well when water is pumped out. In this well, however, there was no such cone of influence, an indication that the hydraulic conductivity (permeability) of the soil was low.

To verify this observation we measured the hydraulic conductivity, which is an index of the rate at which water moves through a substance. Using the technique devised by Luthin and Kirkham (1949), we made calculations for fourteen piezometers terminating at a depth of 8 feet (2.4 m). (See Appendix for the two equations used.) The average hydraulic conductivity was 0.018 inches (0.046 cm) per hour at a soil temperature of 68°F (20°C); the maximum was 0.036 and the minimum 0.008 inches (0.091 and 0.021 cm). These are recognized as extremely low rates in an aquifer.

The low permeability of the aquifer under farmstead A is not unusual in Washington County. The maximum output of other shallow wells seldom exceeds 200 gallons (755 l) per day. Farmers commonly haul water for their families to use during the late summer and fall and often develop farm ponds to provide water for livestock.

NITRATE LEVELS

Nitrate concentrations in most Washington County wells are high. But we were surprised to discover that the levels on farmstead A more than tripled, from 83 to 255 milligrams per liter, during a three-year period when twenty-three well-water samples were tested. Because livestock, a suspected major source of nitrates, were no longer kept on the farmstead, we tried to determine the cause of this increase.

One possible reason for the rising nitrate content of the well water is that the nitrates in the system were being recycled and added to by human wastes. Some of the water was used for flushing human waste through a septic tank and seepage line. The remainder of the water was discharged on the soil surface from a waste-water outlet. With an average of 0.025 pounds of NO_3-N (0.011 kg) discharged per day by each of three family members during a two-year period, we calculated that almost 55 pounds (24 kg) of NO_3-N were added to the soil. However, the waste-water outlet on farmstead A is 160 feet and the seepage line 75 feet (48 and 23 m) from the well, distances that would seem to be adequate for dilution.

Another, more probable explanation is that the high soil nitrates in the vicinity of the well were moving through the groundwater towards the small cone of depression formed by the well (Figure 3). Walker *et al.* (1972) showed that during periods of rainfall there is a hydraulic gradient downslope in the region.

Although farmsteads B and C were not studied as intensively as A, they provide evidence that excessive soil nitrates are not unusual in this part of Washington County. Data from farmstead B show that once the high nitrate problem develops, it is long lasting in these almost impermeable soils. Even after twenty-four years of incorporation into the surrounding fields, farmstead B still had markedly higher soil nitrates than the heavily fertilized fields. Data from farmstead C, which is in a low area, indicate that the nitrate problem is not confined to upland soils.

Summary

The prevalence of nitrate-contaminated farm wells in Washington County, Illinois, led to a study of nitrate in these wells. We found that the primary sources of nitrates in the study area were livestock and human wastes. Our findings, however, do not eliminate nitrogen fertilizer as a major cause of high nitrate levels in groundwater elsewhere. Nitrate-nitrogen in well water from one farmstead increased threefold over a three-year period, probably because of soil nitrates moving slowly toward the well. We attributed the high local concentrations to the low permeability of the soil, minimum runoff, and low gasification following denitrification. When evapotranspiration is the only major way that water is removed from the aquifer, nitrate ions remain behind and become concentrated in the soil solution.

PONDS IN WASHINGTON AND POPE COUNTIES

Considerable information on the water quality and limnology of Illinois lakes and streams is available, but seasonal information on farm ponds is lacking. Developing this information has become extremely important with the increasing use of ponds for human and animal drinking water supplies, irrigation, sport and commercial fisheries, recreation, and animal waste treatment lagoons.

Our study objectives were to determine the seasonal water quality of small ponds and to evaluate the potential of ponds as an alternative source of drinking water in areas with high groundwater nitrate levels. We conducted two separate but related investigations: (1) ten farm ponds in Washington County from November, 1970, through November, 1972; and (2) five ponds and one lake in Pope County (Figure 2) from February, 1972, to May, 1973.

Farm ponds are developed by impounding runoff from a watershed, as illustrated in Figure 1. If one side of the naturally depressed area is low, a dam is constructed, sometimes with a spillway to allow excess water to be diverted to a waterway or other drainage system. These ponds range from 0.1 to 10 acres (0.04 to 4 ha) and may be 3 to 30 feet deep (1 to 9 m). A body of water of more than 10 acres is, for our purposes here, considered a lake.

Ponds in Washington County

Fourteen ponds in an Ohio study showed an average maximum nitrate-nitrogen level of 3.1 mg/l with a mean of 0.17 (Hill *et al.,* 1962).

We suspected, however, that pond water in Washington County might exceed the public health limit of 10 mg/l for much the same reason that groundwater is contaminated. We also thought that differences in watershed types might influence pond-water quality. A study was therefore initiated in November, 1970, to determine seasonal and monthly fluctuations of several variables related to water quality in farm ponds that have different covers and management of the watershed. Consideration was also given to the advisability of substituting water from Washington County farm ponds for low-quality well water.

STUDY AREA DESCRIPTION

Although the ten ponds studied are scattered throughout Washington County, the soils are similar. The Cisne-Hoylton and Bluford-Wynoose clay-bearing soils drain very slowly and often remain wet and cold in the spring. Sheet and rill erosion on the more rolling slopes in cultivated fields is a serious problem. Slick spots (sodic soils) frequently occur in conjunction with the major soil groups.

A little more than half the average annual precipitation of 40 inches (1,000 mm) occurs between April 1 and September 30. Rainfall in Nashville, the centrally located county seat, was 34.7 and 40.8 inches (881 and 1,036 mm) for calendar years 1971 and 1972, respectively. The mean temperature is 58°F (14°C), with average January and July temperatures at the extremes of 35° and 80°F (1.5° and 26°C).

In November, 1970, a field inspection was made of Washington County ponds having three basic types of watersheds: ungrazed pasture or trees, cultivated land, and a livestock exercise area. The ten watersheds and ponds selected for this study are described in Table 2.

FIELD AND LABORATORY PROCEDURES

During the two-year study period, water samples from each pond were measured for the following: nitrogen (ammonia and nitrate), coliform bacteria, biochemical oxygen demand (BOD), soluble orthophosphate, dissolved oxygen, hardness, and water temperature. All measurements were taken at approximately monthly intervals throughout the study period, with the exception of coliform bacteria and BOD measurements, which were discontinued in March, 1971. Water was sampled at a single location on each pond at 8 inches (20 cm) below the water surface and 8 inches above the pond bottom. Using a telescoping rod and reel principle, Mitchell and Dickey (1973) devised a sampler that allows the operator to stand on the shore while collecting water samples.

Table 2. — Description of Ten Washington County, Illinois, Ponds Studied From 1970 to 1972

Pond	Watershed management	Watershed area, acres (hectares)	Average slope, percent	Pond surface area, acres (hectares)	Maximum depth, feet (meters)
A1	Woodlot	24.0 (9.9)	3.5	1.4 (0.6)	12.0 (3.7)
A2	Grassed	3.2 (1.3)	6.7	0.8 (0.3)	12.0 (3.7)
A3	Grassed	71.0 (28.6)	4.9	9.1 (3.7)	15.0 (4.6)
B1	Cultivated	8.6 (3.5)	1.0	0.6 (0.2)	7.0 (2.1)
B2	Cultivated	20.0 (8.1)	4.0	2.1 (0.9)	10.0 (3.0)
B3	Cultivated	11.0 (4.5)	2.0	0.2 (0.1)	12.0 (3.7)
B4	Cultivated	12.0 (4.9)	2.6	0.3 (0.1)	20.0 (6.1)
C1	Livestock (dairy)	7.9 (3.2)	1.8	0.2 (0.1)	5.0 (1.5)
C2	Livestock (sheep)	4.2 (1.7)	1.0	1.3 (0.5)	10.0 (3.0)
C3	Livestock (hogs)	1.0 (0.4)	1.5	0.2 (0.1)	8.0 (2.4)

Water nitrate-nitrogen concentrations were measured with an Orion nitrate ion-selecting electrode, according to the procedure described by Dickey (1974). Nitrate concentrations were checked frequently with the chromotropic acid method, described in APHA Standard Methods (1971). Soil nitrates were analyzed by using a Bray (1945) color test without a quantitative determination. BOD and coliform bacteria were measured using procedures described in APHA Standard Methods. Soluble orthophosphate, hardness, nitrate-nitrogen, and ammonia nitrogen were determined by the Illinois Natural History Survey, using a Technicon Auto-Analyzer, Model CSM-6. Dissolved oxygen was measured at the time of collection with a Yellow Springs Instrument, model 54.

NITRATE AND AMMONIA NITROGEN

As expected, the average nitrate values were highest in ponds with livestock on the watershed and lowest in ponds with grassed or wooded watersheds (Figure 9). The maximum for any specific pond sampled during the study was as follows: 1.38 mg/l for a grassed watershed,

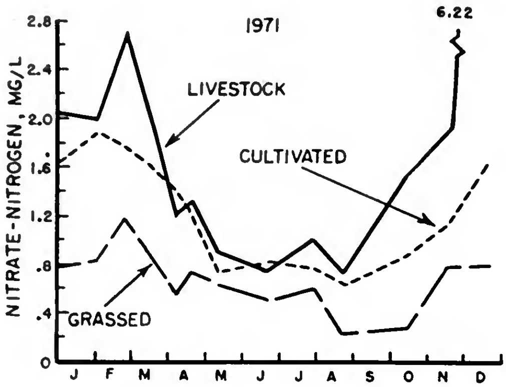

Figure 9. Average nitrate-nitrogen concentrations in ponds with three watershed types, 1971.

2.22 for a cultivated watershed, 2.84 for a cultivated watershed with some hogs in the vicinity, and 22.0 for a livestock watershed. Nitrate and ammonia levels from a typical pond in each watershed type are shown in Figure 10. The pond with a grassed watershed had a maximum of 1.06 mg/l; the pond with a cultivated watershed, 1.88 mg/l; and the pond with a livestock watershed, 2.22 mg/l.

In general, nitrate levels were highest during the cooler months and peaked in early spring (Figure 10). Levels were lower during the warmer months and reached the lowest level during August. Subsequent data, however, have shown that peaks can sometimes occur during the summer months for short periods of time.

As NO_3-N decreased in the spring, ammonia tended to increase. Again, the watersheds with a large quantity of nutrients had relatively high ammonia levels in the ponds. The maximum ammonia levels occurred near the bottom of the ponds, where anaerobic conditions often exist during portions of the year. Extremely high levels of ammonia (more than 15 mg/l) were observed in ponds having either dense livestock populations on the watershed or cultivated watersheds manured on an annual basis.

In the anaerobic parts of the pond, lack of oxygen and the decomposition of organic matter can cause the ammonia concentration to increase during the warmer months. Without oxygen, ammonia released during decomposition will remain in the ammonia or ammonium form until oxidation can occur (Sawyer and McCarty, 1967). Reduction in nitrate levels during the summer may be explained by either algal growth or denitrification. The farm ponds studied have enough nutrients to sustain abundant algal growth. As algae grow, they may remove nitrates

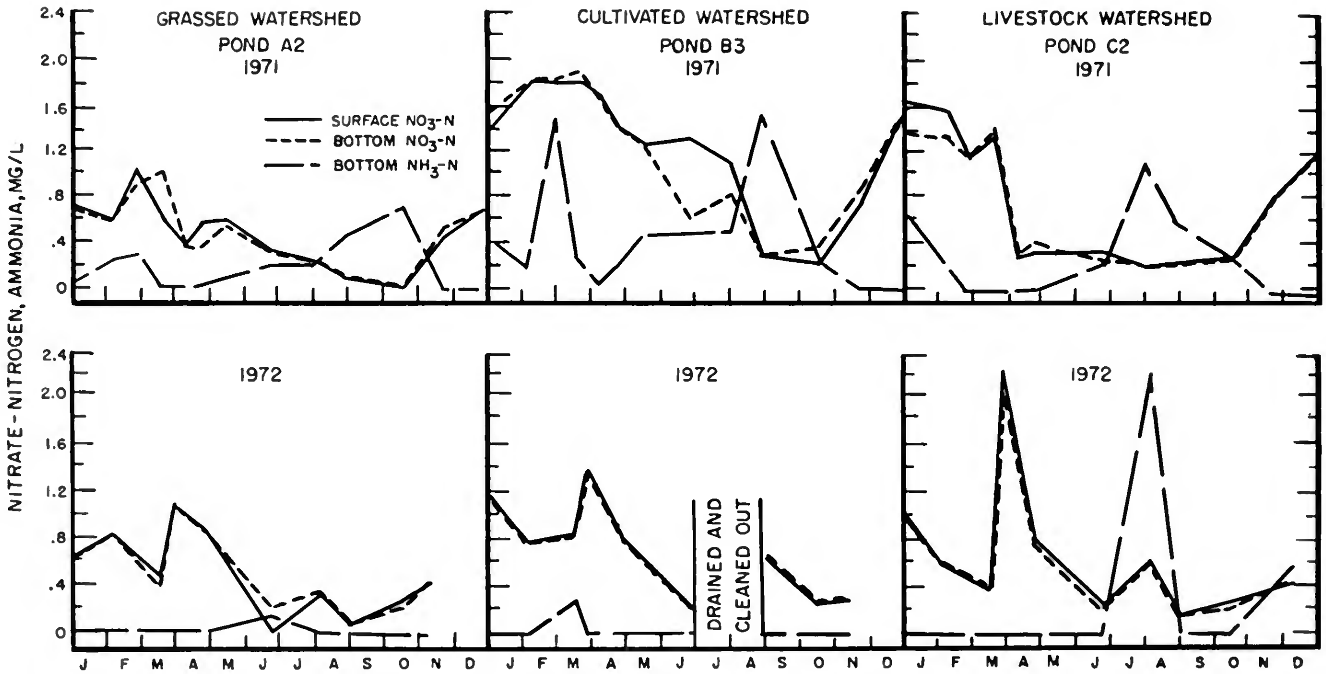

Figure 10. Nitrate and ammonia nitrogen concentrations measured during a two-year period in typical farm ponds having three different types of watersheds. Nitrate-nitrogen was measured in water taken from the pond surface and bottom, and ammonia in water from the bottom only.

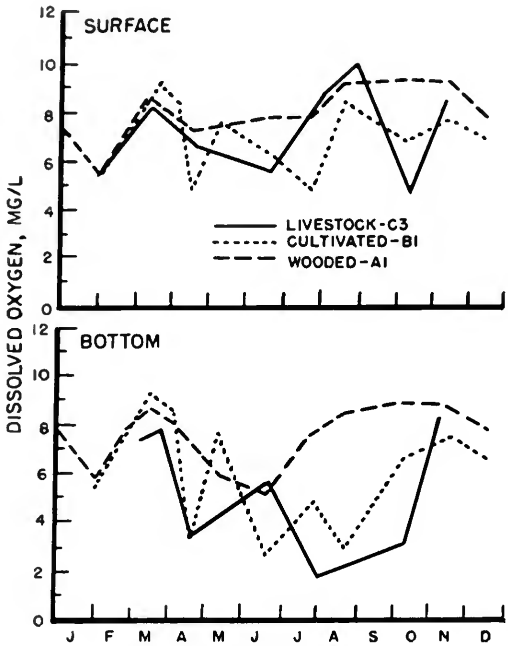

Figure 11. Dissolved oxygen in surface and bottom layers of ponds with different types of watersheds. Ponds A1 and B1 were sampled during 1971, and C3 during 1972.

directly. Under favorable conditions, nitrate-nitrogen may also be lost to the atmosphere through denitrification.

During the first year of the study, nitrate measurements were below the public health limit of 10 mg/l. In December, 1971, however, NO_3-N rose sharply in pond C1, with a dense livestock concentration on the watershed. The level reached 14 mg/l, but by February, 1972, it had returned to 3 mg/l. It again rose, to 18 mg/l, in August and peaked at 22 mg/l in October. Nitrate concentrations in ponds are more likely to increase when combinations of the following occur: the initial water volume in the pond is low; the nitrate concentration of the runoff is high; the amount of runoff is large; and samples are taken shortly after the runoff event.

All of these conditions were met when nitrate levels rose dramatically in the pond in question. Soil analyses show that warm, dry, unpaved cattle lots have high nitrate concentrations on or near the surface, while cool, wet lots are low in NO_3-N. Miner *et al.* (1966) had also found high levels in the runoff from previously dry beef feedlots. Each of the high concentrations in pond C1 came after a heavy rainfall and runoff from the dairy cattle watershed. Also, sampling was conducted each time within two days after the runoff event so that very little of the incoming nitrate had time to denitrify.

BACTERIAL QUALITY

Although all ten ponds tested positive, coliform bacteria counts were highest in those ponds having livestock on the watershed. Mean fecal coliform counts per 100 milliliters were 14.7 on grassed watersheds, 145 on cultivated watersheds, and 982 on livestock watersheds. However, after manure was applied to a cultivated watershed, counts reached 7,200 per 100 milliliters. During an intense runoff period, a count of 16,000 was recorded for a pond having a livestock concentration of approximately 23 milk cows per acre (50 per ha) on the watershed. Fecal streptococci counts paralleled the fecal coliform counts.

Unless water is properly treated, these high counts constitute a potential health hazard for humans but not necessarily for livestock. The pond having the highest coliform count in this study was used to supplement a water supply for dairy cows. Although fecal coliform counts frequently exceeded 1,000 per 100 milliliters, the farmer detected no problems after the animals adjusted to the water.

DISSOLVED OXYGEN AND WATER TEMPERATURE

The lush growth of vegetation in ponds rich in nutrients often results in poor water quality. Photosynthesis during daylight hours and respiration at night often cause a wide diurnal fluctuation in the dissolved oxygen content. Near the surface the water may become supersaturated with dissolved oxygen, while the bottom may be nearly anaerobic (Figure 11).

Ruttner (1963) reported that oxygen is usually at the minimum in the early morning and at the maximum in late afternoon. Table 3 gives the maximum and minimum oxygen levels in the ponds we studied. Because our samples were collected in late morning and early afternoon, the range for dissolved oxygen concentrations was probably greater than recorded. This variation indirectly indicates differences in the amount of nutrients in different types of ponds. Ponds having livestock on the watershed had an average range of 13 mg/l, while the cultivated and the grassed watersheds averaged 9 mg/l and 6 mg/l, respectively. For pond water from livestock watersheds, the wide range between maximum and minimum dissolved oxygen was primarily a function of algal growth stimulated by an abundance of nutrients.

The maximums and minimums listed in Table 3 occurred almost entirely between June and September. Although algal blooms and intense

Table 3. — Average Maximum and Minimum Dissolved Oxygen Levels in Ten Ponds Sampled Between Late Morning and Early Afternoon, November, 1970, through November, 1972

	Maximum DO	Minimum DO	Range
		mg/l	
Grassed watershed			
A1	9.5	4.4	5.1
A2	10.0	2.0	8.0
A3	10.5	5.6	4.9
Cultivated watershed			
B1	11.0	3.0	8.0
B2	9.5	2.5	7.0
B3	10.5	1.5	9.0
B4	13.5	1.5	12.0
Livestock watershed			
C1	20.5	2.0	18.5
C2	12.5	2.4	10.1
C3	11.5	1.0	10.5

runoff followed by low oxygen levels were noted during other times of the year, the extremes occurred during the summer months, when water temperatures reached 86°F (30°C). The type of watershed had little influence on water temperature.

If there is ice on a pond for an extended period of time, low oxygen levels can occur during winter. Weather records for southern Illinois show, however, that average temperatures during any month rarely drop below freezing. Thus ice cover will not be a significant factor affecting oxygen levels. These levels will usually be at the lowest during the summer. Because January, 1972, was the only month we sampled water through the ice, we did not have an extended period to determine the effect of ice cover.

BIOCHEMICAL OXYGEN DEMAND

Only the ponds with grassed watersheds met a water quality standard of less than 7 mg/l BOD at all times. On occasion, two of the livestock watersheds exceeded 20 mg/l. One of the ponds with a cultivated watershed had a BOD level of 18 mg/l after runoff carried recently spread manure into the pond. Average BOD measured in ponds with grassed watersheds was 0.77 mg/l, and in ponds with cultivated watersheds, 4.85. These data are inconclusive, however, because the period of record lasted only four months and because BOD varied widely in ponds with a livestock watershed.

PHOSPHORUS

Phosphorus measurements for soluble orthophosphate fluctuated more than the other measurements. Some of the maximum levels of phosphorus, especially for watersheds having high nutrients, occurred after a runoff event. The average soluble orthophosphate in water samples from ponds with grassed watersheds was 0.18 mg/l; the maximum was 1.35. Ponds with cultivated watersheds had an average of 1.71 mg/l, with a maximum of 10.20. However, this maximum level occurred on a cultivated watershed that had received some manure.

Phosphorus in pond water from livestock watersheds appears to be largely influenced by the runoff. A maximum of 36.0 mg/l occurred in one pond after a 2-inch (50 mm) rainfall. Another peak of 26.2 mg/l was also observed after a heavy rainfall. The average level for ponds with livestock watersheds was 5.82 mg/l, which was thirty-two times the average occurring in grassed watersheds. Soluble orthophosphate levels in all three types of ponds far exceeded 0.07 mg/l, believed to be the upper limit to avoid excessive algal growth in lakes and ponds.

HARDNESS

Pond water in Washington County is relatively soft because it is primarily surface water. Hardness, expressed as $CaCO_3$ (calcium carbonate), averaged 37.0 mg/l for grassed watersheds, 58.8 for cultivated watersheds, and 80.0 for livestock watersheds. Soft water is normally defined as less than 70.0 mg/l $CaCO_3$, according to Sawyer and McCarty (1967).

Ponds and a Lake in Pope County

STUDY AREA DESCRIPTION

The five ponds and one lake studied in this phase of our research are in the western part of Pope County, on or near the Dixon Springs Agricultural Center, which is a University of Illinois experiment station (Figure 2). This area was unglaciated, present soils having developed in wind-blown material (loess) from barren outwash areas during glacial periods. The natural forest cover resulted in a relatively shallow surface layer organically enriched. Where the land was cropped, erosion was extensive.

Dense silt, fine sand, or a combination of both severely limits downward movement of water in upland soils. Unlike claypan soils, these fragipan soils contain no clay-enriched layer, but even so they are almost impermeable. Their naturally low pH and low fertility favorably influence water quality.

Table 4. — Description of Five Pope County, Illinois, Ponds and One Lake Studied During 1972 and 1973

	Pond					Lake Glendale
	Robbs	Forestry	Boaz	Lauderdale	Wells	
Year impounded	1955	1965	1937	1938	1937	1938
Surface,[a] acres (ha)	2.7 (1.1)	0.9 (0.4)	1.0 (0.4)	0.9 (0.4)	1.0 (0.4)	82.0 (33.0)
Depth						
maximum, feet (m)	13.4 (4.1)	12.6 (3.8)	10.5 (3.2)	11.5 (3.5)	15.0 (4.6)	22.0 (6.7)
mean, feet (m)	5.0 (1.5)	6.1 (1.9)	7.3 (2.2)	4.4 (1.3)	7.5 (2.3)	10.9 (3.3)
Watershed, acres (ha)	5.6 (2.3)	4.1 (1.7)	13.1 (5.3)	5.8 (2.4)	8.0 (3.2)	1,350 (547)
Watershed management[b]	FL-TF	PF-OF	DSR-2	DSR-3	DSR-6	PF-OF
Fertilizer, manure applied[c]	None	None	Heavy	Moderate	Light	None
Water use	Livestock	Irrigation	Irrigation, livestock	Irrigation, livestock	Irrigation, livestock	Recreation

[a] Area at spillway crest.
[b] FL-TF = feedlot-tall fescue; PF-OF = pine forest-old field; DSR-2, 3, 6 = Dixon Springs rotation, second, third, and sixth years (see text).
[c] Heavy = 1,700 to 2,800 lb/A in 1971-72; 3,800 to 8,300 lb/A in preceding 15 years. Moderate = none in 1971-72; 1,100 to 2,300 lb/A in preceding 15 years. Light = none in 1971-72; 540 to 770 lb/A in preceding 15 years.

Descriptive data for the ponds and the lake are summarized in Table 4. Note that the variables used for Lake Glendale were similar to those used for the ponds, despite the considerable differences in pond and lake size. The watershed management system associated with each pond and the lake is as follows:

Robbs Pond — large cattle barn and sales feedlot complex

Forestry Pond — loblolly pine and an abandoned field

Lake Glendale — loblolly pine and an abandoned field

Boaz Pond — second-year Dixon Springs rotation of wheat, legume, and grasses

Lauderdale Pond — third-year rotation of hay or pasture

Wells Pond — sixth-year rotation of hay or pasture

The Dixon Springs rotation is a six-year cycle beginning with zero-till corn the first year; wheat, legumes, and grasses the second; and hay or pasture through the sixth year.

FIELD AND LABORATORY PROCEDURES

Water samples were collected at least monthly from February, 1972, to May, 1973. When weather conditions and work schedules permitted, Robbs and Forestry Ponds were sampled every two weeks. Using a Van Dorn horizontal sampler operated from a boat, we collected samples at the deepest part of the pond or lake at vertical intervals of 1 and 2 feet (0.3 to 0.6 m). Samples were transferred to plastic bottles, placed in a cooler to maintain temperatures, returned to the laboratory, and analyzed immediately for pH, conductivity, oxidation-reduction potential, biochemical oxygen demand (BOD), turbidity, and chlorides. Other samples were preserved and analyzed later according to procedures in APHA Standard Methods (1971), Golterman (1969), or EPA Methods (1971).

Oxygen profiles, determined with a dissolved-oxygen meter, and water temperature were measured *in situ*. When testing indicated vertical differences, measurements were taken at intervals of 0.5 to 1 foot. Continuous recording thermographs were placed in Robbs and Forestry Ponds at three locations to obtain water temperatures from the surface, middle, and lower depths.

POND FINDINGS

The Dixon Springs ponds are soft water ponds, with low values for alkalinity, hardness, specific conductance, BOD, chemical oxygen demand, and total organic carbons, chlorides, and surface nutrients. Physical and chemical variables were similar from the surface of the pond to its bottom during periods of mixing from October to May. In four of the five ponds, temperature gradients developed in the late spring and early summer, but were eliminated in July or August as the water column gradually heated.

Vertical changes in the physical and chemical conditions took place during periods of temperature stratification. These changes were most striking in Robbs Pond with its intense production of blue-green algae. Some of the more interesting findings are as follows:

— Nitrate-nitrogen levels were low in the surface waters, never exceeding the public health limit of 10 mg/l. The high ammonia levels in Robbs Pond and in Boaz, Lauderdale, and Wells Ponds, which were impounded during the 1930's, indicate that periodic maintenance and cleaning of organic sediment from the bottom may be necessary to maintain a high-quality water supply.

— In the four ponds with either a cultivated or a livestock watershed, oxygen levels often exceeded saturation in the surface waters, but declined to near zero in the bottom. In Forestry Pond, which has a forested watershed, oxygen was sometimes higher near the bottom because of benthonic algae activity.

— Significant increases in alkalinity, hardness, and specific conductance were associated with the oxygen deficit in the deeper layers. Lowered oxygen-reduction potentials and elevated ammonia readings indicate that active denitrification was occurring. Apparently these ammonia increases were in part a result of bacterial conversion when the physical-chemical environment was favorable.

— Surface pH values rose in the ponds because of low alkalinity combined with large surface phytoplankton populations that removed carbon dioxide; pH measurements above 10.5 were recorded in the surface waters of Robbs and Wells Ponds.

— Forestry Pond with its watershed of pine forest and abandoned fields was somewhat different from the other ponds. Situated in an area providing few plant nutrients, the pond had unusually low and basically unmeasurable levels of most variables. An oxygen deficit occurred in only a few samples taken near the bottom.

— Populations of phytoplankton and zooplankton, which are minute aquatic plants and animals, varied from pond to pond. Several species of phytoplankton were found, while rotifers were usually the dominant zooplankton. As expected, Robbs Pond with a large cattle operation on the watershed had the highest recorded levels of phytoplankton and zooplankton. Lauderdale Pond had low populations, but a relatively dense growth of water smartweed along the water's edge. In general, blue-green algae were the dominant phytoplankton in Robbs and Wells Ponds, while euglenophytes predominated in Boaz, and pyrrophytes in Lauderdale. Chlorophyll measurements correlated well with phytoplankton populations.

We also analyzed the dynamics of ponds for fish production, an aspect of the study that was carried out in greater detail for Pope than for Washington County. Alkalinity and hardness for the five ponds and Lake Glendale were low. The limiting factors for fish production are therefore free carbon dioxide and bicarbonates as well as nitrate-nitrogen and phosphorus levels. Another significant finding of the Pope County study was that excessive blue-green algae may have a harmful effect on zooplankton production. To a fisherman this means that rough fish such as carp may eventually predominate unless a better watershed and pond management program is developed.

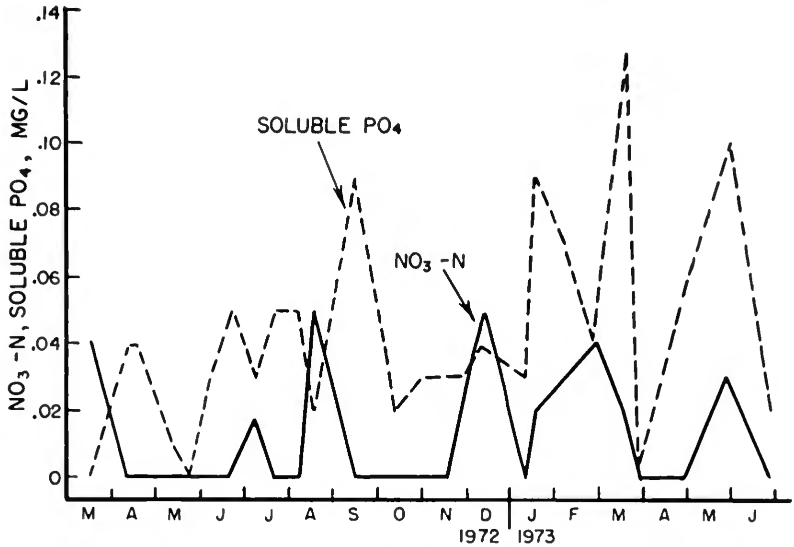

Figure 12. Seasonal variation of surface nitrate-nitrogen and soluble phosphate concentrations in Lake Glendale.

LAKE GLENDALE FINDINGS

Nitrate-nitrogen concentrations in Lake Glendale surface water were low throughout the study, never exceeding 0.05 mg/l (Figure 12). Concentrations of more than twenty times this level are common in the surface water of well-nourished lakes. There was no NO_3-N in several Lake Glendale samples, in part because of nitrate uptake by phytoplankton. Depletion of nitrate by rather small phytoplankton populations indicates that the lake received very few nutrients from its pine forest watershed.

Although soluble orthophosphate concentrations in surface water samples were not as high as those typically found in well-nourished lakes, concentrations were high enough to prevent depletion by phytoplankton uptake. The effects of uptake were at times noticeable, dropping, for example, from 0.09 to 0.02 mg/l during late September and early October, 1972 (Figure 12).

Dissolved oxygen concentrations, also measured in surface water, exceeded 7.9 mg/l throughout the study. The highest recorded level was 13.3 mg/l in September, 1972. During both years of the study, dissolved oxygen decreased with spring warming conditions (Figure 13).

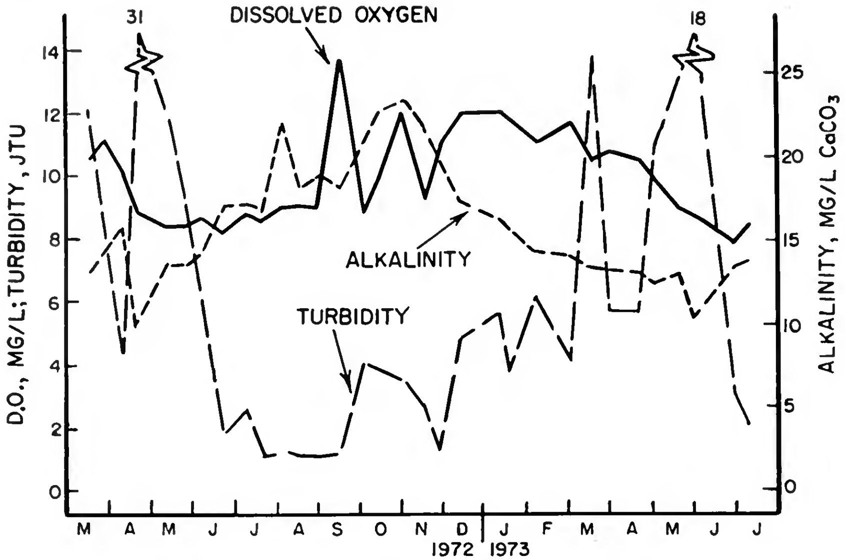

Figure 13. Seasonal variation of surface dissolved oxygen, turbidity, and alkalinity in Lake Glendale.

Although the surface layer remained well oxygenated throughout the summer, depletion occurred in the deep layers because of the nearly complete decomposition of organic matter caused by high temperatures on the bottom of the lake, rather than because of increased production of oxidizable substances (Stone, 1974).

Turbidity was generally low except for brief periods after heavy rainstorms. The highest turbidity measurement was 31 JTU in April, 1972. Turbidity decreased soon after the rainfall ended, indicating that relatively large particles of foreign materials, rather than phytoplankton production, were responsible for the high turbidity. A similar trend occurred in the spring of 1973 (Figure 13). During the summer months turbidity was extremely low, approaching 1 JTU.

Surface alkalinity varied throughout the study period from less than 10 to 23 mg/l. Lake Glendale has the lowest alkalinity reported for an Illinois lake. Alkalinity generally decreased during periods of heavy rainfall and increased during summer months (Figure 13).

Summary

The ten Washington County farm ponds studied were characterized by watershed type, namely grassed, cultivated, or livestock. Ponds with a cultivated watershed were, for the most part, less polluted than those with livestock. But even within one type, pond characteristics and hence performance were quite different. For example, one pond with a cultivated watershed was more polluted than one with a livestock watershed. The owner of the livestock watershed pond had a successful fish business, but the owner of the other pond could not raise fish. Because ponds differ within each type, averages can only suggest trends.

Nitrate-nitrogen concentrations in farm pond water varied greatly with the type of watershed. Pond water from grassed and cultivated watersheds reached a maximum NO_3-N level of 2.84 mg/l during the early spring. All three ponds having dense livestock populations on the watershed exceeded the public health limit of 10 mg/l, in one case by twofold for a brief period, and reached maximum levels in late fall after heavy runoff events. Nevertheless, pond water nitrate levels were considerably lower than nitrate levels in shallow dug wells. Pond water for human consumption would need some type of treatment for bacteria. At present, ponds having grassed or cultivated watersheds are the most reliable source of drinking water for livestock.

All five ponds and the one lake in the Pope County study never exceeded the public health limit for nitrate-nitrogen, unlike some of the best-managed ponds in Washington County. The nitrate difference among ponds in the two counties is due largely to the presence of grassy areas on all six of the watersheds in Pope County. Even Robbs Pond with its livestock sales lot had a wide grass border between the lot and the pond. In contrast, each of the livestock watersheds in Washington County was heavily grazed and in some cases had no grass at all on much of the land. Except for high levels of ammonia near the pond bottoms during the summer months, the water from the Pope County ponds is suitable for a livestock water supply and, with treatment, could be used for household drinking water.

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APPENDIX

The two equations given below were used to measure aquifer hydraulic conductivity, discussed on page 15.

Equation using the piezometer technique devised by Luthin and Kirkham (1949):

$$K = \pi R^2 [\ln ((d - y_1)/(d - y_2))]/A(t_2 - t_1) \quad (1)$$

where:
K = hydraulic conductivity
R = inside radius of pipe
ln = natural logarithm
d = depth of pipe below water table
y_1 = depth below water table of water in pipe at time t_1
y_2 = depth below water table of water in pipe at time t_2
$t_2 - t_1$ = time required for water to rise from y_1 to y_2
A = a function of the geometry of the flow system having the dimension of length

Steady state well equation based on well capacity:

$$K = (4.39\ Q \log (r_2/r_1))/y_2^2 - y_1^2) \quad (2)$$

where:
Q = well capacity in liters per minute
r_2 = the distance to an observation well at the edge of the cone of influence in meters
r_1 = the distance to the nearest observation well in meters
y_2 = depth of water table above shale at r_2 in meters
y_1 = depth of water table above shale at r_1 in meters
K = hydraulic conductivity in centimeters per hour