HYDROGEOLOGY, GROUND-WATER FLOW, AND TRITIUM MOVEMENT AT A LOW-LEVEL RADIOACTIVE-WASTE DISPOSAL SITE NEAR SHEFFIELD, ILLINOIS

By George Garklavs and R. W. Healy

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who prefer metric (International System) units rather than the inch-pound units used in this report, the following conversion factors may be used:

Multiply inch-pound unit	by	To obtain metric unit
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
	Flow	
inch per year (in/yr)	25.40	millimeter per year (mm/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
	Radiometry	
nanocurie per liter (nCi/L)	37.0	Becquerel per liter (Bq/L)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level." All altitudes in this report are referenced to NGVD of 1929.

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ABSTRACT

Ground-water flow and tritium movement are described in an area at and near a low-level radioactive-waste disposal site near Sheffield, Bureau County, Illinois. Ground-water flow in the shallow aquifer is confined to three basins, all of which ultimately drain into a strip-mine lake. Two principal ground-water flow paths were identified. A pebbly sand unit conveys ground water and tritium eastward from the site to the strip-mine lake in the largest basin, which drains about 70 percent of the site. Ground water in the other two basins is directed toward a stream before flowing toward the strip-mine lake. Lithologic and hydraulic characteristics of the geologic materials making up the shallow aquifer are described and used to develop a conceptual model of ground-water flow for each basin. Results of digital modeling refined the conceptual models for two basins and provided estimates of ground-water velocities, directions of ground-water flow, and recharge rates for the basins.

In the largest basin, ground-water flow through the pebbly sand was measured at about 2,500 feet per year in a buried channel-like depression filled with the pebbly sand. Virtually all ground water in the largest basin flows through this channel-like depression. Ground water in the other two basins flows through outwash and till deposits at an estimated average velocity of about 25 feet per year.

Tritium, moving as water, was the only radionuclide found on or off site. The most extensive migration of tritium off site was coincident with the buried channel-like depression. Tritium was found along the entire channel-like structure, as well as in seeps along the bank of the strip-mine lake. With the exception of one well, there is no extensive off-site migration of tritium in the other two basins. The flow path from the site to the one well containing tritium is not defined. Tritium concentrations in ground water ranged from detection level (about 0.20 nanocurie per liter) to more than 300 nanocuries per liter.

INTRODUCTION

Background

A low-level radioactive-waste disposal site was operated from 1967 through 1978 about 3 miles west of the town of Sheffield, Bureau County, Illinois (fig. 1). In 1976, the U.S. Geological Survey began a series of investigations to

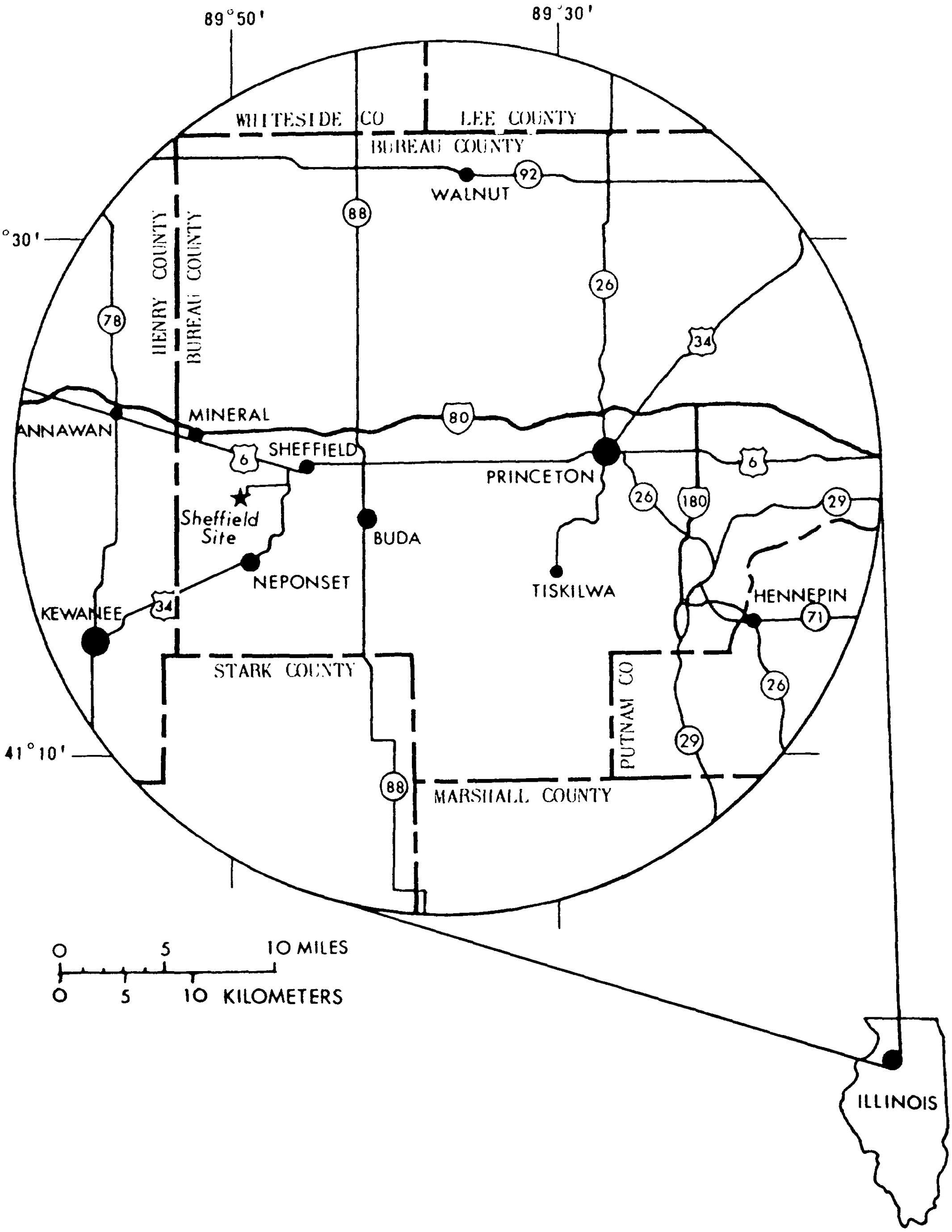


Figure 1.--Location of Sheffield low-level radioactive-waste disposal site.

characterize quantitatively the hydrogeologic environment at and near the site. Hydrogeologic information obtained at the Sheffield site will be used to (1) add to the understanding of those factors affecting the containment and movement of radionuclides at low-level radioactive-waste disposal sites, and (2) provide types of information that regulatory agencies and site managers can use to formulate and optimize site-management plans.

In 1980, the U.S. Geological Survey began an investigation to determine the direction and rate of ground-water flow at the site. The objectives of this investigation were to describe the shallow aquifer, develop a conceptual model of ground-water flow, compare the conceptual model to results of digital modeling, and to describe the migration of tritium at and near the site.

Purpose and Scope

This report describes the hydrogeology at and near the low-level radioactive-waste disposal site. It presents a conceptual model of the shallow aquifer and a description of a digital model of the same aquifer. It also describes tritium movement at and near the site.

The geology was described from core samples and drill cuttings obtained during well construction and during construction of a tunnel underneath four disposal trenches near the southeastern corner of the site. Water levels and water samples were obtained from the wells shown in figure 2. A conceptual model of ground-water flow was developed for the shallow aquifer based on the description of the hydraulic properties of geologic materials, records of water levels, and the configuration of saturated and unsaturated zones. A finite-element digital model was used to test the conceptual model in the study area. Historical records of tritium concentrations from wells at and near the site were used to define tritium migration.

Description of Study Area

The 20-acre disposal site is in a region of hilly terrain (fig. 3). Landforms in the vicinity of the site are primarily of glacial origin, though surface-mining operations during the 1950's have produced some areas of pronounced ridges and valleys. Many of these valleys, as well as the final cuts of mining operations, are now occupied by lakes. One such lake is located approximately one-fourth mile east and northeast of the site. The site is in a sparsely populated, rural area. Grazing is the primary use of land near the site. A hazardous-waste disposal site is located to the west and northwest of the low-level radioactive-waste disposal site. The two sites are separated by a 200-foot-wide buffer zone. The local geography, climate, trench construction, and composition of buried wastes is described by Foster, Erickson, and Healy (1984).

The study area includes the 20-acre site and the area east of the site to the strip-mine lake. The study area has been subdivided into three ground-water basins (fig. 4).

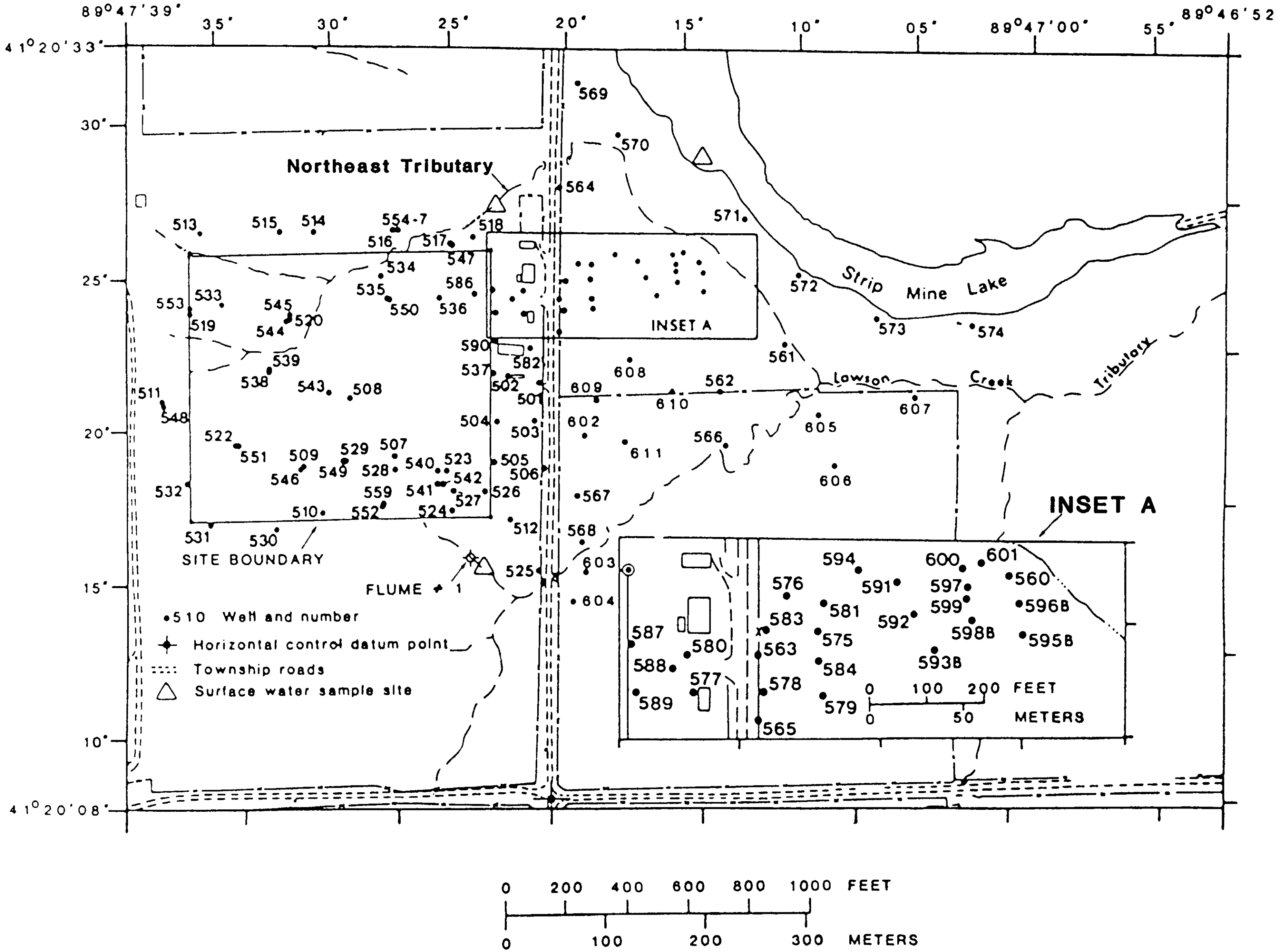


Figure 2.--Location of U.S. Geological Survey wells and borings, and lines of geologic sections.

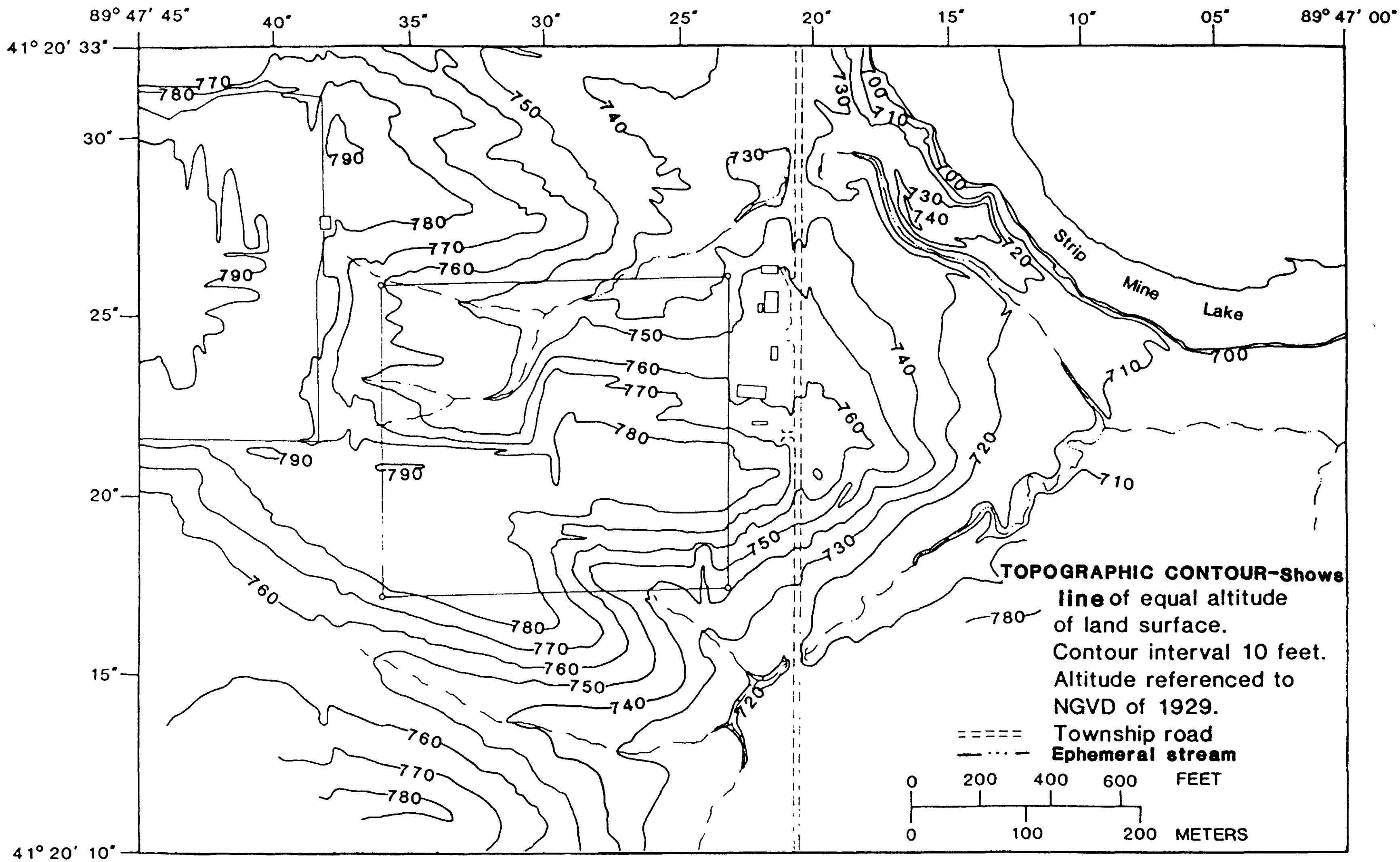


Figure 3.--Topography at the Sheffield site.

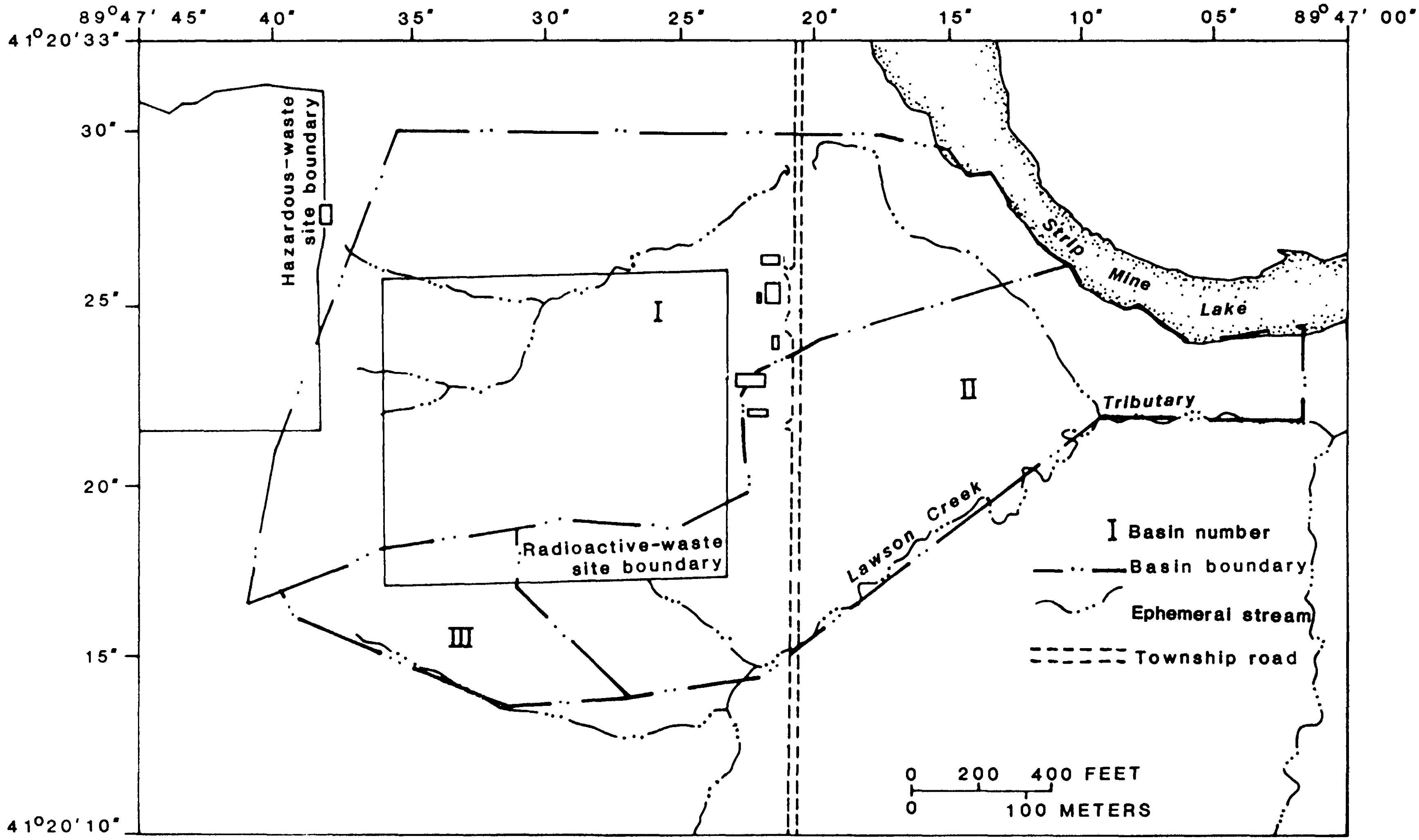


Figure 4.--Ground-water basins in study area.

Previous Work

Foster, Erickson, and Healy (1984) examined and described the shallow aquifer at the low-level radioactive-waste disposal site. The extent of the investigation was limited to the site and land immediately adjacent to the site, bordered on the east by a township road. The shallow aquifer was defined as being composed of Quaternary sediments and marked by complex stratigraphy. The Quaternary sediments are underlain by Pennsylvanian bedrock. A continuous pebbly sand unit was found to underlie about two-thirds of the site.

Three ground-water basins and two principal ground-water flow paths were defined within the shallow aquifer. The boundaries of the shallow aquifer were defined at the northern, western, and southern limits of the study area. To the north, the contact between undisturbed Quaternary materials and strip-mine spoils defines a ground-water divide. To the west, a bedrock high forms a ground-water divide. To the south, a tributary to Lawson Creek forms a ground-water sink. This directs ground-water flow from about the southern one-third of the study area southward and eastward toward the strip-mine lake. The shallow aquifer was assumed to extend eastward to the strip-mine lake.

The first principal flow path conveys ground water from the northern three-fourths of the site. It is in the pebbly sand unit and trends eastward. Ground-water velocities in this flow path were estimated to attain a maximum velocity of about 1.6×10^3 feet per year near the eastern limit of the study area. The second flow path conveys ground water from the southern one-fourth of the site. It generally is coincident with the channel of the tributary to Lawson Creek and also trends eastward. Ground-water velocity in this flow path was estimated to be 25 feet per year.

The hydrogeologic setting east of the site was described by Foster and others (1984a). The shallow-aquifer boundaries were defined by Foster, Erickson, and Healy (1984) and were extended to the strip-mine lake. The strip-mine lake was confirmed as being the eastern limit of the shallow aquifer. The pebbly sand was found to extend continuously from the site to the strip-mine lake.

Altitudes of water surface in wells and the strip-mined lake; ground-water chemical analyses; mineralogy; grain-size distributions; stratigraphy and hydrologic properties of the glacial sediments; and locations and descriptions of wells at and near the site were presented by Foster and others (1984b).

Ground-water velocity in a small area to the east of the site was measured using Rhodamine WT as a tracer. The results of that investigation were presented by Garklavs and Toler (1985).

Acknowledgments

The authors are grateful for the assistance of the U.S. Nuclear Regulatory Commission, in particular to Messrs. Dave Siefkin and Dan Goode, and to Ms. Maxine Dunkleman, for their support and technical assistance. The staff of the Illinois Department of Nuclear Safety also provided assistance, and we wish to thank Messrs. David Ed and Terry Lash. A Tritium Migration Steering Committee, with members representing the Illinois Department of Nuclear Safety, U.S. Nuclear Regulatory Commission, Illinois Attorney General's Office, Illinois State Geological Survey, US Ecology, Inc., and the U.S. Geological Survey, provided much valuable information. This report is prepared in cooperation with the U.S. Nuclear Regulatory Commission and the Illinois Department of Nuclear Safety.

HYDROGEOLOGY

The Quaternary materials that comprise the shallow aquifer range in thickness from about 10 to 80 feet. These materials are thinnest near bedrock highs and thicken in bedrock valleys. The Pennsylvanian bedrock is about 450 feet thick. It is thought to be a relatively impermeable barrier between the shallow aquifer and deeper bedrock aquifers in the area. The Quaternary materials are diverse in lithologic character and have complex spatial and stratigraphic configurations. This makes it difficult to precisely define the direction and velocity of ground-water flow.

Ground water from all three basins in the shallow aquifer ultimately flows eastward to the strip-mine lake. Within each basin, different hydrogeologic factors control the direction and velocity of ground-water flow. The shallow aquifer is described in terms of the geology, hydrology, and hydraulic properties of the geologic units. The geologic units are described in ascending stratigraphic order, beginning with the bedrock. The stratigraphic nomenclature used in this report is that adopted by the Illinois State Geological Survey and does not necessarily follow the usage of the U.S. Geological Survey. The geology at and near the site is described in more detail by Foster, Erickson, and Healy (1984) and Foster and others (1984a). The hydrology and hydraulic properties of the geologic units are discussed in the order of importance of the units in controlling ground-water flow. Time-stratigraphic and lithostratigraphic units found at the site are shown in figure 5.

Geology

Pennsylvanian System

The Carbondale Formation of the Desmoinesian Series of the Pennsylvanian System underlies Quaternary deposits throughout the study area. Core samples available from borings indicate that from 1 to 4 feet of weathered shale is at the contact between the Carbondale Formation and overlying Quaternary units. Coal fragments were observed in some samples of the weathered shale. Beneath the weathered zone the lithologic units are shales, coal seams, and mudstones (Willman and others, 1975, p. 187). Bedrock highs with altitudes just over 740 feet are present at the southeastern corner of the site and just outside the southern boundary of the site. The area to the northwest of the site also has bedrock at altitudes of about 740 to 750 feet. These bedrock highs form the head of a buried valley which trends northeast, from about the center of the site, toward the strip-mine lake. Near the lake, the shale is at or below an altitude of about 650 feet.

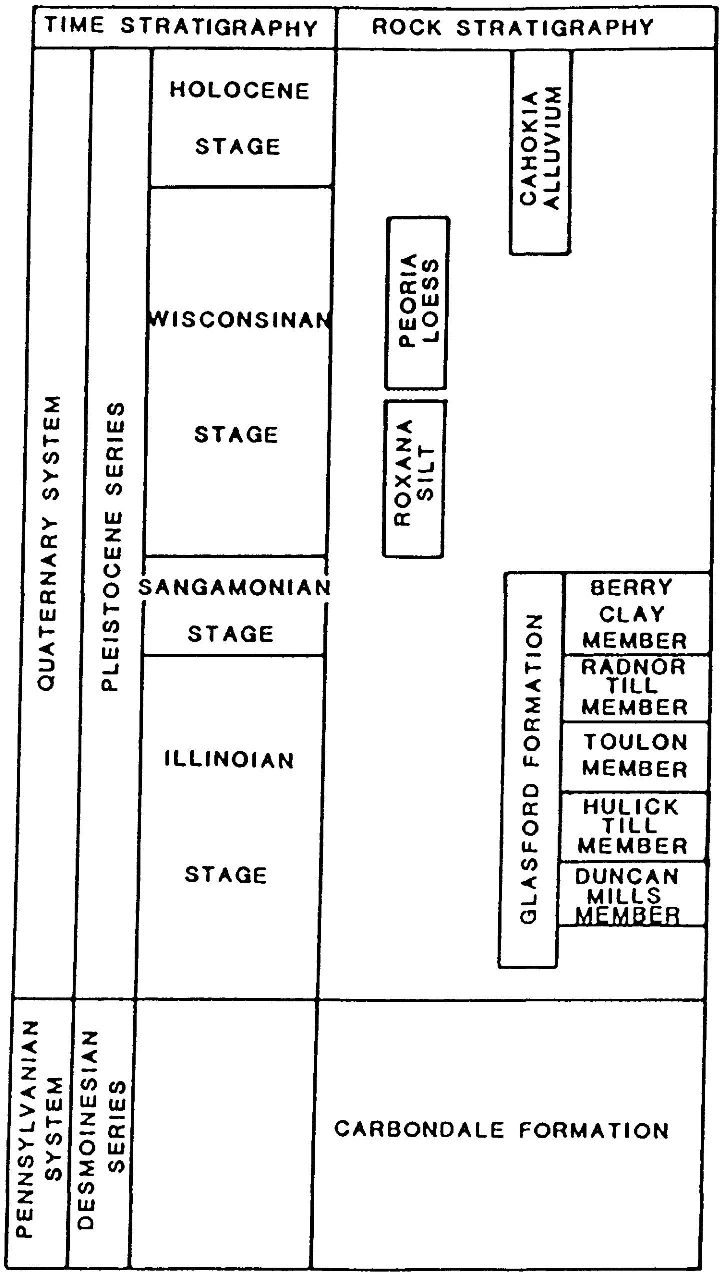


Figure 5.--Illinois State Geological Survey geologic-time classification system in relation to rock-stratigraphic classification system (modified from Willman and Frye, 1970).

Quaternary System

The Quaternary deposits consist of unconsolidated tills and outwash, lacustrine, and backwater deposits blanketed by loess. The stratigraphic relations of these units are shown in figures 6, 7, and 8. Section locations are shown in figure 2.

The principal units of Quaternary age are the members of the Glasford Formation of the Illinoian Stage (Willman and Frye, 1970). The oldest of these units is the Duncan Mills Member, which consists of lacustrine and outwash deposits (Willman and Frye, 1970). The Duncan Mills Member is limited to the bedrock valley within the confines of the site. This unit reaches a thickness of about 55 feet near the northeastern part of the site where the bedrock valley deepens.

The Hulick Till Member of the Glasford Formation is found throughout much of the study area (Willman and Frye, 1970). It overlies the Duncan Mills Member, where present, and elsewhere overlies bedrock. The Hulick Till Member has been eroded and replaced by alluvial deposits in parts of the valley of the tributary to Lawson Creek. East of the site, the upper surface of the Hulick Till Member is irregular. A channel-like depression and an adjoining ridge-like structure extend eastward from the site towards the strip-mine lake. These features are most prominent near the site and become difficult to identify at a distance about 500 feet east of the north-south township road. The depression and ridge are shown near the middle of the geologic section in figure 8. Near the eastern border of the site, the channel-like depression begins to trend south. The depression extends southward along the eastern border of the site for about 400 feet. This depression is filled with sand and pebbly sand of the Toulon Member of the Glasford Formation.

The Toulon Member of the Glasford Formation overlies the Hulick Till Member under about 67 percent of the site and virtually all of the area east of the site (Willman and Frye, 1970). In the southwestern part of the site, the Toulon Member is composed of lacustrine silt and clay with some sand and gravel lenses, and near its upper surface is composed of silty sand and sand. From the center of site to the east, the Toulon Member is composed of sand, pebbly sand, and sand and gravel, and can be characterized as a pebbly sand. The pebbly sand of the Toulon Member fills the channel-like depression in the Hulick Till Member to the east of the site. The ridge-like structure in the Hulick Till, just to the south of the channel-like depression, also is overlain by the Toulon Member. The ridge-like structure has sufficient relief to act as a local ground-water divide. The altitudes of the bottom of the pebbly sand east of the site are shown in figure 9.

The Radnor Till Member overlies the Toulon and Hulick Till Members of the Glasford Formation (Willman and Frye, 1970). It is distinguished from the Hulick Till Member by differences in clay mineralogy and sand content. The greatest areal extent of the Radnor Till Member is in the southern half of the site, although it was observed in a small area in the northwestern part of the site and near the final-cut lake.

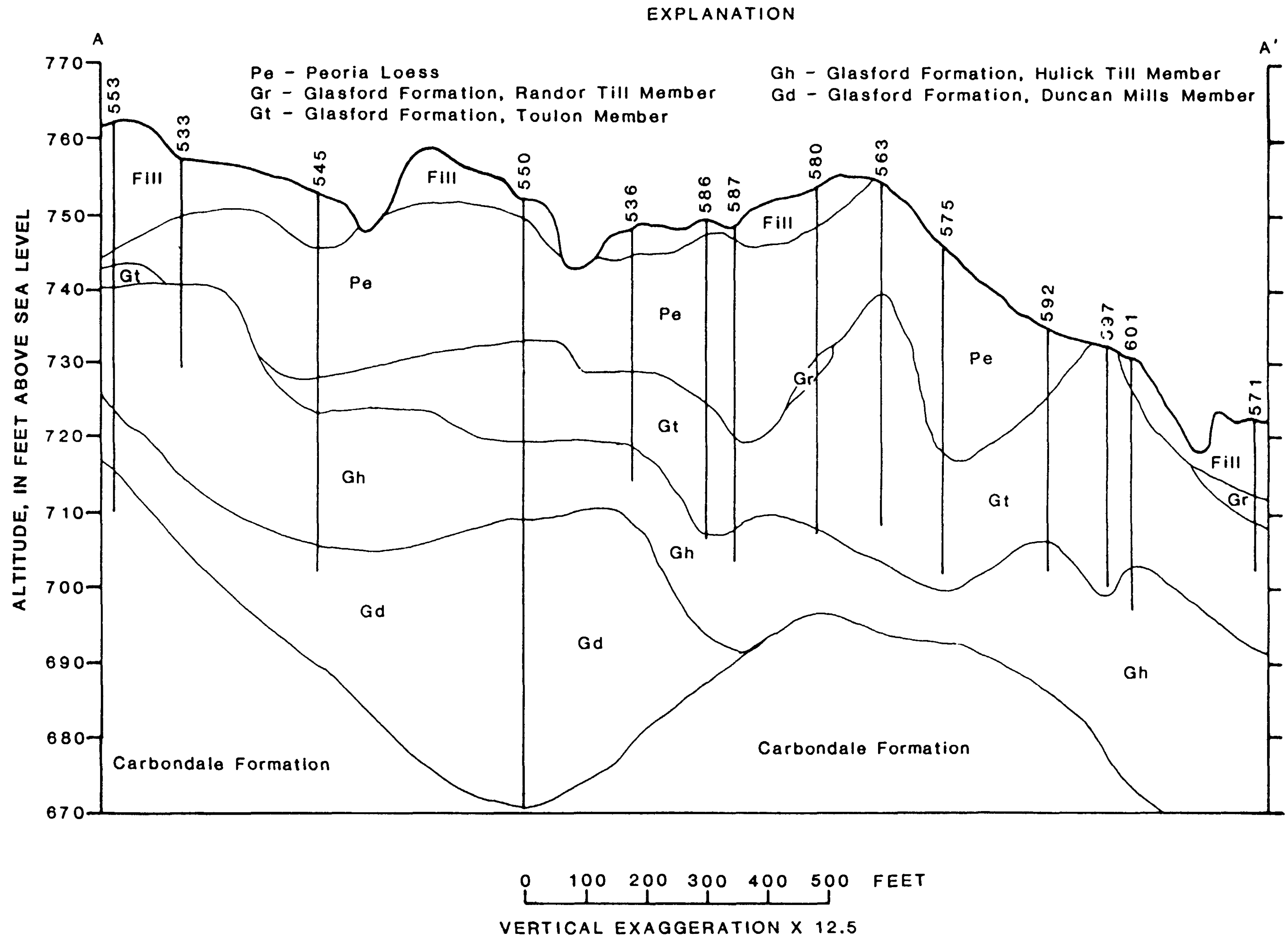


Figure 6.--Geologic section A-A'. Line of section shown in figure 1.

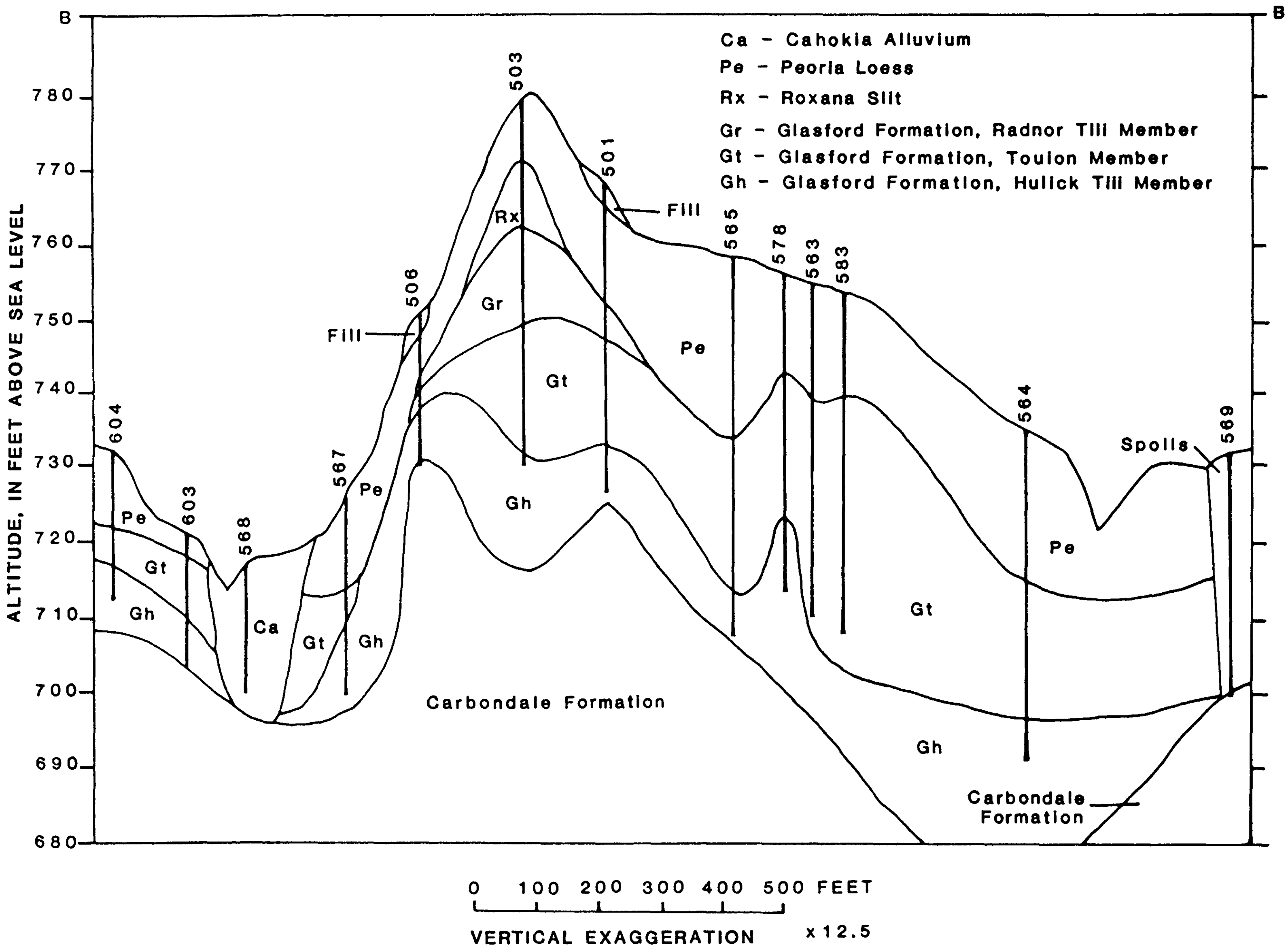
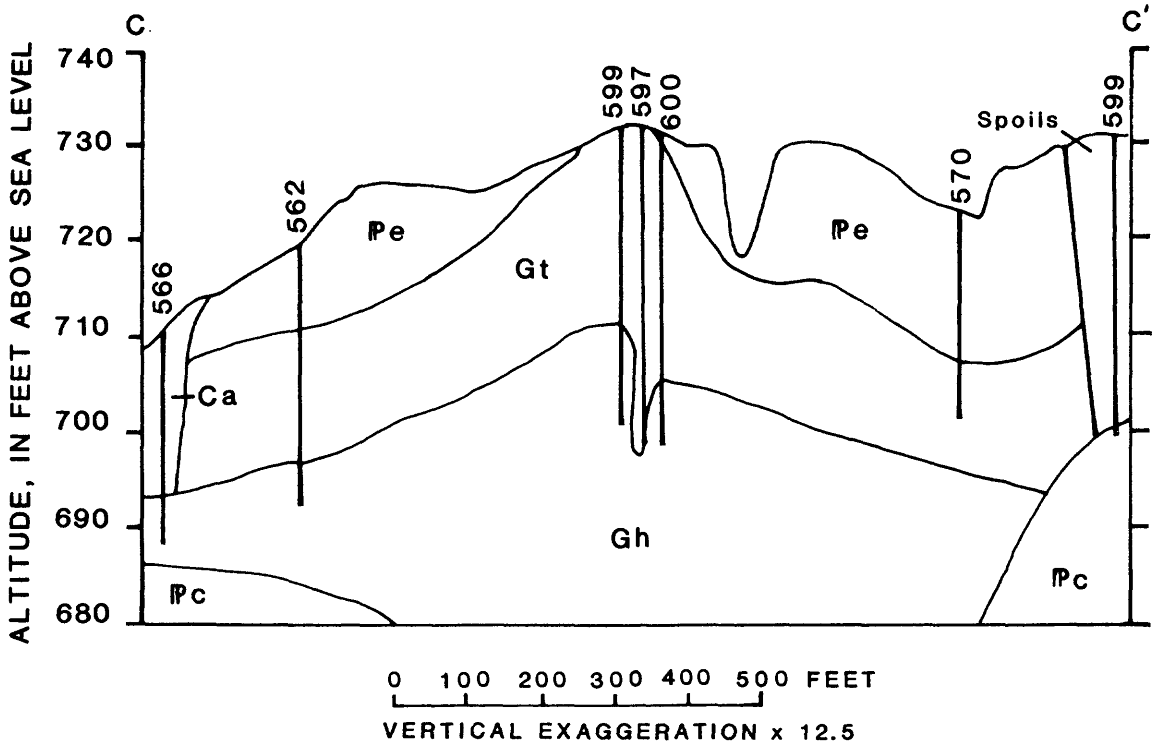


Figure 7.--Geologic section B-B'. Line of section shown in figure 1.



EXPLANATION

Ca - Cahokia Alluvium

Pe - Peoria Loess

Gt - Glasford Formation, Toulon Member

Gh - Glasford Formation, Hulick Till Member

Pc - Carbondale Formation

Figure 8.--Geologic section C-C'. Line of section shown in figure 1.

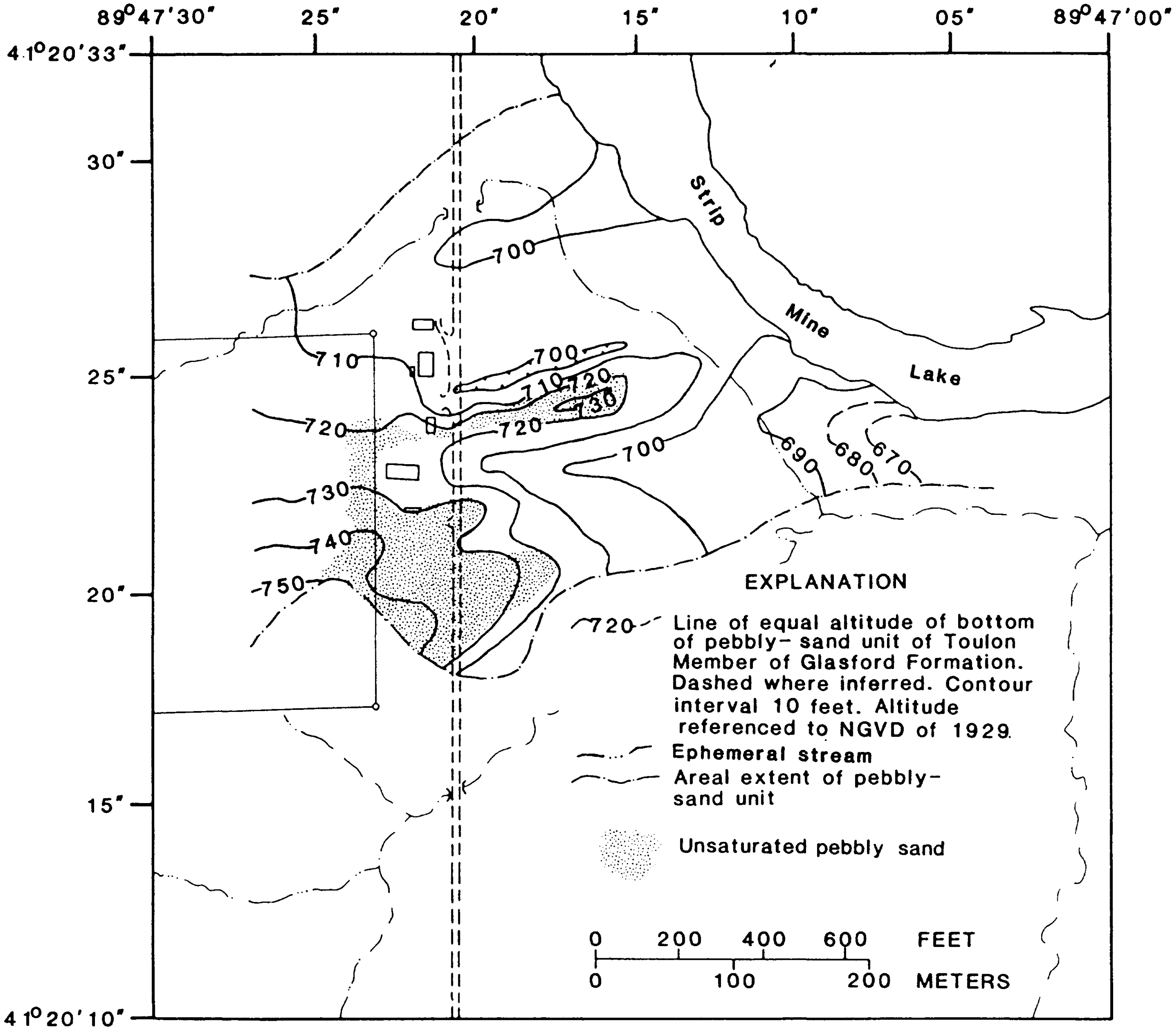


Figure 9.--Altitudes of bottom of pebbly sand unit east of site.

The Berry Clay Member of the Glasford Formation is an accretion-gley deposit developed in the upper portion of the Radnor Till Member. It is typical of the intrazonal soil profile of the Sangamon Soil (Willman and Frye, 1970, p. 85-86). The Sangamon Soil developed during an extended erosional period after the retreat of Illinoian glaciers. The Sangamon Soil is present as two distinct pedologic soil types in two upland areas of the site.

During the Wisconsinan Stage, aeolian silts were transported to the area of the Sheffield site from along the Mississippi River (Willman and Frye, 1970, p. 36). Aeolian sands were transported from nearby outwash deposits. Lower Wisconsinan aeolian deposits are assigned to the Roxana Silt. Middle to upper Wisconsinan aeolian deposits are assigned to the Peoria Loess. Peoria Loess covers the entire site and study area except for present stream valleys. Roxana Silt is found near the eastern boundary of the site.

The Cahokia Alluvium was deposited during late Wisconsinan and Holocene Stages. It consists of clayey, silty-sand and is found in the valley of the tributary to Lawson Creek. It is derived from reworked glacial deposits found in the study area.

A soil cover was developed in the upper part of the Peoria Loess and is assigned to the Modern Soil (Willman and Frye, 1970, p. 89). The soil is mostly clayey silt and, where present, ranges in thickness from 2 to 9 feet. Most of the soil has been removed by ground clearing and erosion in the area east of the site.

To the north of the site, Quaternary deposits have been disturbed by mining. Coal-mine spoils extend from land surface to the top of the shale bedrock. The spoils were emplaced when the area was stripped for coal in the early 1950's.

Hydrology and Hydraulic Properties

The shallow aquifer in the study area is composed of lithologic units having varying degrees of saturation and water-transmitting properties. The only significant inflow to the shallow aquifer occurs as recharge derived from precipitation falling directly on the basins. Average annual precipitation at the site is 35 inches (Foster, Erickson, and Healy, 1984, p. 5). Recharge is seasonal (mostly during spring months) and is estimated to be from 1 to 2 inches per year (Foster, Erickson, and Healy, 1984, p. 20; Healy and others, 1984, p. 820). Vertical collapse holes in the vicinity of trenches occur on site during spring months. Although filled with earth material by the site contractor on a routine basis, these collapse holes provide a pathway for rapid movement of surface water into the shallow aquifer through waste-disposal trenches.

Depth from land surface to the saturated zone of the shallow aquifer averages about 25 feet and ranges from about 5 feet in valleys to 45 feet at topographic and bedrock highs and in the bedrock valley within the site. Water-table fluctuations are related to periods of recharge to the shallow aquifer. Water-table altitudes are generally highest during spring months.

Water-table fluctuations are least in wells screened in the sand of the Toulon Member, seldom exceeding 1 foot during a 12-month period. Water-table fluctuations in wells screened in other materials are as great as 5 feet during a 12-month period (Foster and others, 1984b). The water surface in the saturated zone measured in June 1982 is shown in figure 10. This water surface generally follows surficial topography. General directions of ground-water flow can be estimated by constructing flow lines perpendicular to lines of equal altitude of the water surface. These flow lines can only be considered approximate because many lithologies with various hydraulic properties are represented in figure 10. Nevertheless, ground-water flow is ultimately eastward toward the strip-mine lake, even though flow paths in the study area may trend in any direction.

Most of the site is drained by the pebbly sand in basin I. The pebbly sand is the dominant controlling factor in defining ground-water movement at the site. Glacial tills, outwash, and possibly bedrock control ground-water flow in basins II and III.

The Toulon Member and, in particular, the pebbly sand within the Toulon Member, is partially to completely saturated through about 80 percent of its extent. The pebbly sand is unsaturated over the ridge-like structure in the Hulick Till Member east of the site. Areas where the pebbly sand is unsaturated are shaded in figure 9. The pebbly sand is not found at the bedrock high near the southeastern corner of the site. The bedrock high and unsaturated parts of the pebbly sand over the ridge-like structure in the Hulick Till Member are coincident with the ground-water divide between basins I and II. The channel-like depression in the Hulick Till Member, filled with pebbly sand, acts as a conduit that controls the direction of ground-water flow to the east of the site in basin I. Thus, the configuration of the surface of the contact between the pebbly sand and Hulick Till Member defines both a ground-water divide and a structural control of ground-water flow.

Field and laboratory determinations of hydraulic conductivities for the Toulon Member range from 1.2×10^{-3} feet per second in pebbly sand and gravel to 7.0×10^{-7} feet per second in silty sand (Foster and others, 1984b). Additional values of, and methods for determining, hydraulic conductivity at the site are presented in Foster, Erickson, and Healy (1984) and Foster and others (1984b). Because the Toulon Member is saturated only in part of its extent, it may act as a drain for ground water within the shallow aquifer. Virtually all of the flow through basin I converges on the channel-like structure in the Hulick Till Member to the east of the site.

Rhodamine WT was used as a tracer to determine ground-water velocity in the pebbly sand filled channel-like depression near well 601 (Garklavs and Toler, 1985). The leading edge of the tracer traveled 110 feet in 16 days, whereas the peak concentration of the tracer took 19 days to travel the same distance. The velocities of the leading edge and peak concentration of the tracer are 2,500 and 2,100 feet per year, respectively. Using measured values of 6.7×10^{-5} feet per second (about 2,100 feet per year) for average horizontal velocity, 9.1×10^{-3} (dimensionless) for ground-water head gradient, and 0.35 (dimensionless) for volumetric porosity in the following equation:

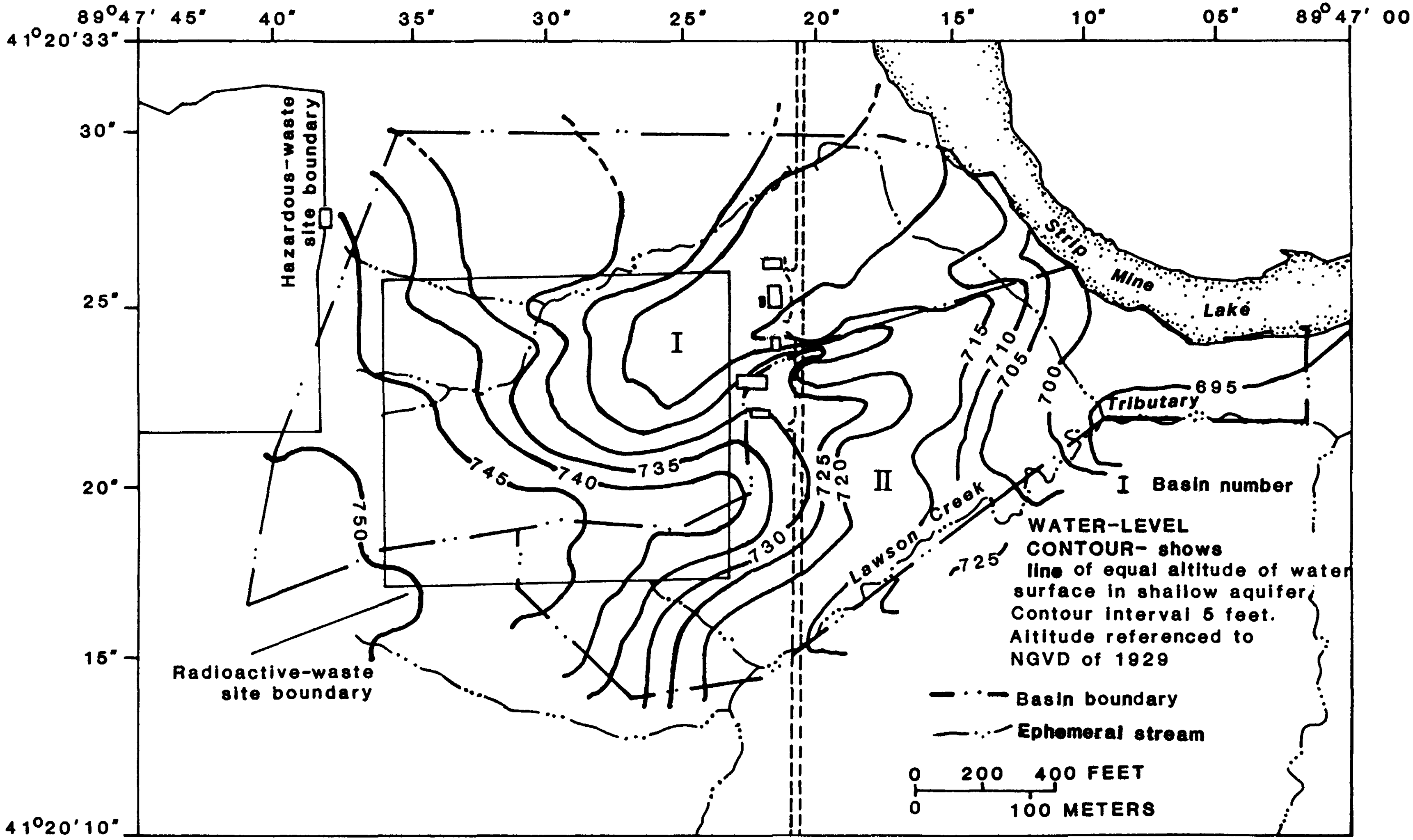


Figure 10.--Ground-water altitudes measured in June 1982.

$$v = \frac{K}{n} \times \frac{dh}{dl} \quad (1)$$

where v = average linear velocity,

K = hydraulic conductivity,

$\frac{dh}{dl}$ = ground-water head gradient, and

n = volumetric porosity,

the computed hydraulic conductivity is 2.6×10^{-3} feet per second. This agrees well with previously determined values of hydraulic conductivity for the sandy portions of the Toulon Member (Foster and others, 1984b).

On site, the Duncan Mills Member is limited to the bedrock valley. Although saturated through its extent, its low vertical hydraulic conductivity, on the order of 2×10^{-8} feet per second, prevents it from conveying significant amounts of ground water (Foster and others, 1984b).

The Hulick Till Member is saturated everywhere except near the tunnel and the area near wells 578 and 584, where only the lower part is saturated. Hydraulic conductivities of tills generally range from about 10^{-6} to 10^{-12} feet per second (Freeze and Cherry, 1979, p. 29). Measured values of hydraulic conductivity in the study area ranged from 5×10^{-7} to 9×10^{-7} feet per second. Even though saturated, these low conductivites indicate that the Hulick Till Member does not rapidly convey ground water. In those areas where the sand is either absent or unsaturated, such as in basin II, the Hulick Till Member conveys ground water, though at low velocities.

Quaternary materials overlying the Toulon Member are unsaturated throughout their extent. The thickness and hydraulic conductivities of those units overlying the Toulon Member affect the ground-water system by governing recharge to lower units and providing potential pathways for unsaturated flow.

North of the site, strip-mine spoils extend from the strip-mine lake west past the site. The spoils act as a relatively impermeable barrier to ground-water flow north of the site.

South of the site, the valley of the tributary to Lawson Creek is filled with Cahokia Alluvium. This unit is saturated at least in part throughout its areal extent. Ground-water flow through the alluvium is toward the strip-mine lake. The tributary to Lawson Creek is the southern boundary of the shallow aquifer.

The Carbondale Formation is assumed to provide a relatively impermeable boundary between the Quaternary deposits and the deeper regional aquifers. The shale and coal seams near the contact of bedrock and overlying units may, however, provide a pathway for ground-water movement. Fractures, fissures, and bedding-plane separations in the shale, and the usually permeable nature of coal found near the surface, may transmit water in a way so as to be considered part of the shallow aquifer system. Evidence for this is found in an area to the southeast of the site in the vicinity of well 602. In this area, the weathered bedrock surface and the lower part of the overlying Hulick Till Member are saturated while all units above these are not. In addition, tritium was found in well 602 and not in wells screened in more permeable materials between well 602 and the site. This area is near a bedrock high and is thought to have coal present in the bedrock that may act as a conduit for ground-water flow from the site. Therefore, although the strata of the Carbondale Formation act as a barrier between the shallow and deeper bedrock aquifers, the uppermost units of the bedrock may be in hydraulic connection with Quaternary materials and may be considered part of the shallow aquifer.

GROUND-WATER FLOW

Conceptual Models

Although the geologic units that comprise the shallow aquifer have complex configurations and diverse hydraulic characteristics, they can be consolidated into relatively simple models for each basin. Geologic units are grouped into conceptual elements for each basin on the basis of three hydrogeologic factors: (1) saturated ground-water flow, (2) infiltration and recharge, and (3) impermeable base units and ground-water divides. The simplest conceptual model for each basin would have three elements, one corresponding to each of the hydrogeologic factors used to group geologic units.

Basin I

The boundaries for basin I are shown in figure 4. The western and southern boundaries are ground-water divides. The northern boundary, at the contact of undisturbed strata and strip-mine spoils, is considered a ground-water divide. Although little data are available on ground-water levels north of the site, the low permeability of spoil material is thought to preclude movement of ground water from the spoils to the site. The strip-mine lake to the east serves as a sink for all ground-water flow.

The geologic materials in basin I are grouped into three elements: The first element is composed of the pebbly sand. The second element is composed of the units overlying the pebbly sand. These units are the Radnor Till and Berry Clay Members of the Glasford Formation, loess, and fill. The third element is composed of those units underlying the pebbly sand; these are the Duncan Mills and Hulick Till Members of the Glasford Formation.

Because it is the unit through which saturated flow in basin I occurs, the pebbly sand is considered the single, most important element in the conceptual model. The units overlying the pebbly sand are considered a single element because they function as a control on the amount and rate of recharge to the pebbly sand. The units underlying the pebbly sand form a relatively impermeable basal unit in basin I. The surface of the Hulick Till Member also provides structural control of ground-water flow.

Ground water in the southwestern part of the basin flows toward the center of the site, and then toward the channel-like depression east of the site. On entering the depression, flow is eastward to the lake. Because the depression is just to the north of, and abuts, the ridge-like structure in the Hulick Till Member, there is virtually no contribution to ground-water flow from the south in basin I to the east of the road. Ground-water flow in the northern part of basin I is eastward or southeastward toward the strip-mine lake or the pebbly sand-filled depression.

Basin II

Basin II is bounded by ground-water divides on all sides except the east, where the lake again is a sink for ground-water flow (fig. 4). A bedrock high, coincident with a topographic high near the southeastern corner of the site, forms part of the divide between basins I and II.

Basin II differs from basin I in that the pebbly sand is not a dominant factor in determining ground-water-flow direction or velocity. In this basin, four elements are considered. The fill, loess, Berry Clay and Radnor Till Members, and the pebbly sand to the south of the bedrock high at the southeastern part of the site are grouped into the first element. The second element is composed of the Hulick Till Member and the pebbly sand to the north and east of the bedrock high, and only the Hulick Till Member to the south of the bedrock high. The third element is composed of the Cahokia Alluvium in the valley of the tributary to Lawson Creek. The fourth element is the bedrock.

Element one is composed of geologic units that govern recharge to the saturated units in the basin. In basin II, the pebbly sand is included in this element where it is present to the south of the bedrock high. In this area, it is unsaturated, whereas units underlying it are saturated. Because of its superposition over saturated units, the pebbly sand affects recharge but not ground-water flow. The second element is composed of those units that convey ground water in the basin. To the north and east of the bedrock high, the lower part of the pebbly sand is saturated, as is the Hulick Till Member. As mentioned earlier, ground-water flow in the bedrock near its contact with overlying till may be occurring in basin II. Because of the probable hydraulic connection of bedrock and overlying till in the area to the south of the bedrock high, it is conceptualized as being integral with the Hulick Till Member and not treated as a separate element. The third element, the Cahokia Alluvium, has higher hydraulic conductivity than the Hulick Till Member and, therefore, provides a medium that can rapidly convey ground-water to the lake.

The first two elements may limit the movement of ground water, the third may provide a drain to the strip-mine lake, and the fourth provides an impermeable base to the aquifer.

Ground water in basin II can be thought of as flowing radially from the bedrock high toward the Cahokia Alluvium to the south and the strip-mine lake to the east. The direction of flow in the northernmost part is controlled by the divide that separates basins I and II. Flow in the southern part of basin II is to the south and southeast toward the tributary to Lawson Creek, then eastward to the lake.

Basin III

Basin III is located at the southwestern corner of the site (fig. 4)--the location of a bedrock high. The bedrock high is overlain by the Hulick Till, Toulon, and Berry Clay Members of the Glasford Formation; these are overlain by loess. The members of the Glasford Formation pinch out quickly to the south of the bedrock high, and the stratigraphy over the southern slope of the bedrock high consists of the Hulick Till and Toulon Members and overlying loess. The Toulon Member extends about one-half the distance from the bedrock high to an ephemeral stream channel.

The basin boundaries to the north, east, and west are along bedrock highs and are ground-water divides. The southern boundary of basin III, along the ephemeral stream, is a sink for ground-water flow.

Three elements can be conceptualized in basin III. First, the overlying fill material, loess, and Berry Clay Member determine recharge rates to the lower lying Toulon and Hulick Till Members and are grouped in one element. The second element is composed of the Toulon and Hulick Till Members, through which ground water flows from the site toward the ephemeral stream and to the alluvial material in the channel of the ephemeral stream. The alluvial material directs ground-water flow toward the tributary to Lawson Creek and then toward the strip-mine lake. Element three consists of bedrock.

Ground-water flow from the site in basin III is to the south and southeast to the valley of the ephemeral stream. Flow then continues eastward to the tributary of Lawson Creek, which also drains basin II. Ground-water-flow velocities can be expected to be equal to, or less than, those of basin II.

Digital Models

A digital computer model was used to simulate ground-water flow within basins I and II. Insufficient data precluded modeling basin III. The purposes of modeling were (1) to help understand the flow system; (2) to improve definition of the variation in hydrologic properties of the geologic units; and (3) to develop better estimates of ground-water velocities, which are important in estimating the transport of contaminants.

Several assumptions were made prior to modeling. Bedrock was considered to be an impermeable base to the ground-water system. The only inflow to the ground-water system was assumed to be recharge from precipitation falling directly on the basins. The ground-water system was assumed to be at steady state--that is, heads do not change with time at any location within the system.

The partial differential equation describing two dimensional steady-state ground-water flow in an isotropic aquifer (Pinder and Bredehoeft, 1968) is:

$$\frac{d}{dx} T \frac{dh}{dx} + \frac{d}{dy} T \frac{dh}{dy} + W = 0 \qquad (2)$$

where T = transmissivity (hydraulic conductivity x saturated thickness),

h = mean hydraulic head in the vertical (length),

x, y = cartesian coordinates (length), and

W = recharge rate (length/time).

A grid of nodes and elements was superimposed over the modeled areas. The model (R. L. Cooley, U.S. Geological Survey, written commun., 1977) approximates equation 2 at each node, using a finite-element technique. This produces a system of simultaneous equations which is then solved for the unknown values of head. The grid system was divided into different zones (fig. 11), where values of hydraulic conductivity and recharge were assumed to be uniform.

Initial estimates of hydraulic conductivity, saturated thickness, and recharge were based on previous laboratory and field analyses (Foster, Erickson, and Healy, 1984; Foster and others, 1984b). Using these data as input, the model computed estimated heads at all nodes. Computed heads were compared to heads measured on June 6, 1982, using the mean squared-error (MSE) term:

$$MSE = \frac{1}{N} \sum_{i=1}^{N} (\hat{h}_i - h_i)^2 \qquad (3)$$

where $\hat{h}_i$ = the measured head measured at node number i on June 6, 1982, in feet;

h_i = the computed head at node number i, in feet; and

N = the number of measured heads ($N = 60$ for basin I and 29 for basin II).

Values of hydraulic conductivity and recharge were changed on a zone-by-zone basis, and heads were recomputed by the model until a best fit was obtained. A best fit is defined as that set of parameters that produces a minimum value of the MSE term. Additionally, the differences between observed and computed heads, termed residuals, should be normally distributed with a mean of 0.

In evaluating the results of the modeling, it must be kept in mind that parameter values that produce the minimum value of the MSE term may be neither unique nor appropriately represent the hydrogeologic system. Different configurations of zonal boundaries and geometries, and other parameter values, could yield similar results. Sensitivity tests were performed on the best-fit model by changing parameter values and boundary conditions and by assessing

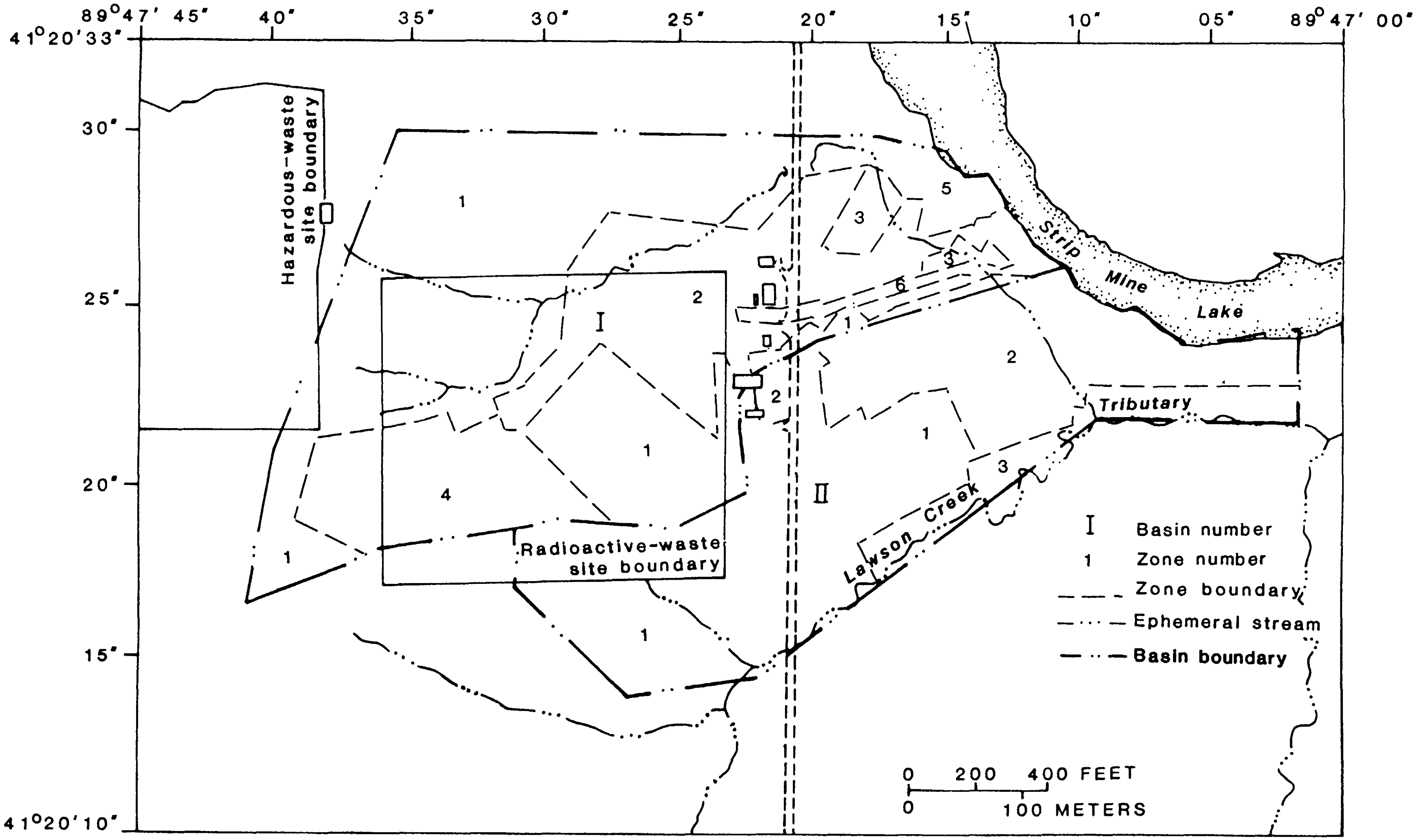


Figure 11.--Zone subdivisions in modeled basins.

the resulting changes in computed head values. Although this is not a sophisticated method of estimating the uncertainty of the model, it permits additional interpretation of model results.

Similar model results may be obtained if the ratio of recharge to conductivity is held constant while varying the values of those parameters. The reason for this is that there are no pumping wells in the study area. This is important to note because a best fit between observed and computed head values can be reproduced by applying any multipliers to hydraulic conductivity and recharge values as long as the ratio of those multipliers is equal to 1.

Basin I

The boundaries of basin I are those previously described. During modeling, no-flow boundaries were imposed along the periphery of the basin except along the lake, where constant heads equal to lake surface elevation were imposed. Basin I was divided into six zones. The grid in basin I consists of 716 nodes and 666 elements. Observed heads were available for 60 nodes.

Zone 1 represents all areas where the saturated zone consists of any geologic material except the Toulon Member. Although zone 1 contains many different geologic materials, an average value of hydraulic conductivity was assumed. As noted by Foster, Erickson, and Healy (1984, p. 24), the relative differences in hydraulic conductivity among the units within zone 1 are insignificant compared to the hydraulic conductivity of the pebbly sand. Zone 2 corresponds to the pebbly sand unit. Zone 3 also represents the pebbly sand in areas where it crops out at the land surface. Because it crops out, infiltration and recharge to the aquifer are greater in this area. Zone 3 was separated from zone 2 to account for this additional recharge.

Zone 4 represents the Toulon Member in the southwestern part of the basin. According to Foster and others (1984a), the Toulon Member here is characterized as a silty sand. The hydraulic conductivity of zone 4 was specified to be less than that of zone 2. Additionally, the depth to the top of the sand unit is significantly greater in this area than in zone 2, potentially reducing the amount of recharge to the sand. Zone 5 corresponds to an area where limited geologic information was available. The bottom of the sand unit is relatively high in this area (fig. 9) and may be above the saturated zone. The hydraulic conductivity of this zone also was specified to be lower than that in zone 2 to account for the areas where the sand may not be within the saturated zone. Zone 6 represents the channel-like depression discussed earlier. The aquifer in this area is comprised mostly of pebbly sand and has a hydraulic conductivity higher than that of any other part of the aquifer.

Table 1 shows the values of hydraulic conductivity and recharge for each zone that produced the best model fit. The MSE for the best fit had a value of 13.88 feet, whereas the average of the residuals was -0.39 foot. Values of hydraulic conductivity, determined in the laboratory and field--also shown in table 1--indicate good agreement with model values. Figures 10 and 12 show water levels measured in June 1982, and those computed by the model, respectively. Comparison of these two figures indicates a fairly good replication of observed heads by the model.

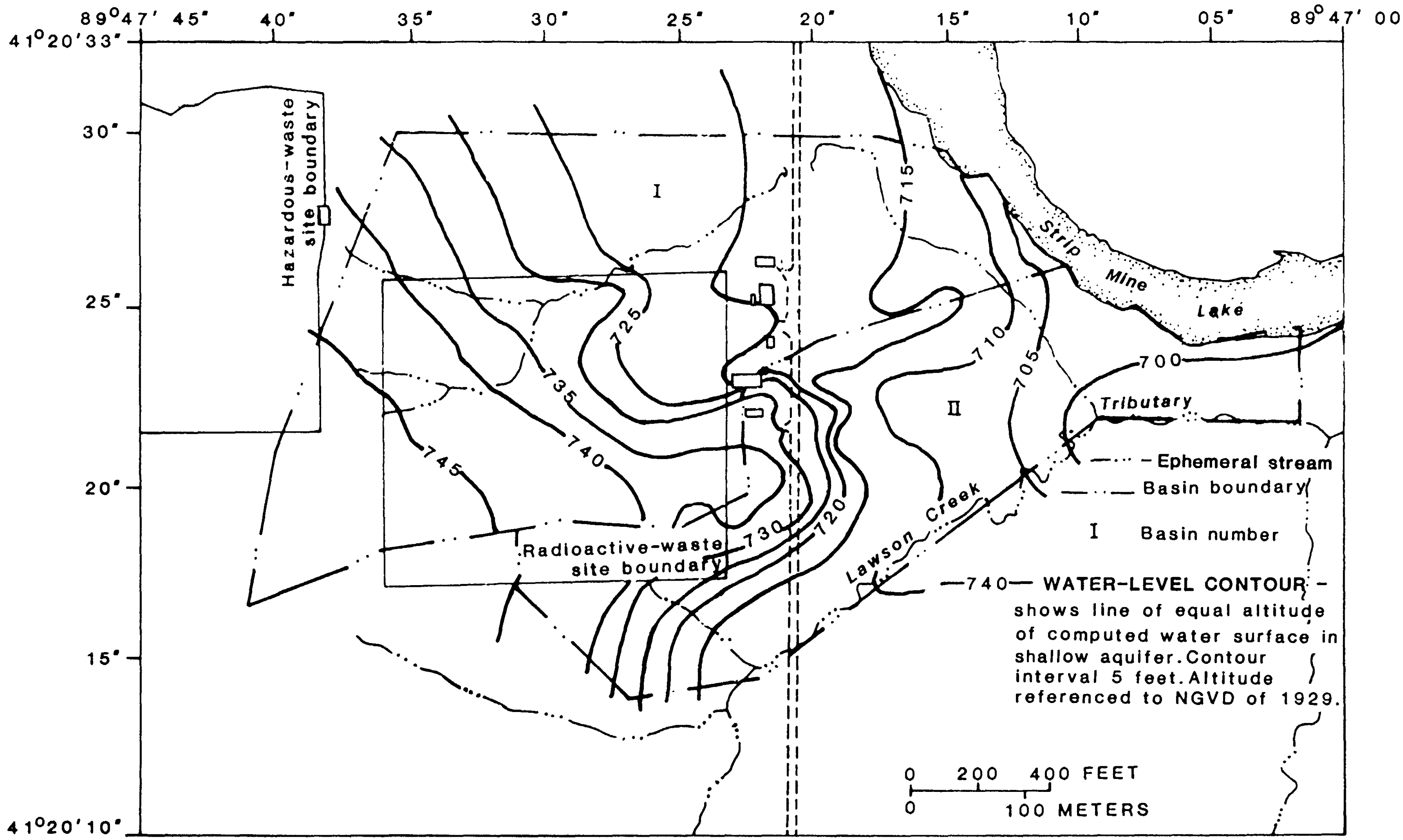


Figure 12.--Ground-water altitudes constructed from digital-modeling results.

Table 1.--Values of modeled recharge and of modeled and measured hydraulic conductivity, in feet per second

Zone	Recharge used in model	Hydraulic conductivity used in model	Range in measured hydraulic conductivity, field and laboratory methods
		Basin I	
1	1.0×10^{-9}	1.25×10^{-6}	7.9×10^{-4} to 4.5×10^{-7}
2	1.0×10^{-8}	1.40×10^{-4}	1.8×10^{-3} to 5.0×10^{-7}
3	7.5×10^{-8}	1.40×10^{-4}	None
4	8.0×10^{-9}	5.00×10^{-5}	7.5×10^{-7}*
5	1.0×10^{-8}	2.00×10^{-5}	1.3×10^{-5} to 9.5×10^{-6}*
6	5.0×10^{-9}	1.40×10^{-3}	5.6×10^{-4} to 3.6×10^{-5}
		Basin II	
1	5.0×10^{-9}	1.10×10^{-6}	6.2×10^{-6} to 9.0×10^{-7}
2	1.6×10^{-8}	1.35×10^{-4}	2.3×10^{-3} to 1.7×10^{-8}
3	1.3×10^{-8}	4.00×10^{-4}	9.0×10^{-7} to 6.2×10^{-6}*

* Indicates value(s) from one well.

In evaluating model results, it is helpful to view the areal distribution of the residuals. This can help to point out improper zoning or invalid residuals plotted over the model area (Cooley, 1979). The residuals appear to be evenly distributed throughout the area in terms of sign and magnitude. Three areas with significant deviation are shaded in figure 13. In each area, residuals are uniformly high in magnitude and have the same sign. All of these areas are adjacent to borders between different zones. The zonal boundaries used in the model may not correspond exactly to the boundaries that exist in the aquifer.

Several different zonal configurations were attempted and, for various reasons, rejected. Zone 5 originally was given the same model variable values as zone 2. However, this had the effect of greatly reducing computed head values throughout the entire system. It was concluded that the pebbly sand unit could not be in complete hydraulic connection with the lake. As mentioned above, it is assumed that, in much of this area, the pebbly sand unit lays above the zone of saturation. Subsequently, zone 5 was assigned the same parameter values as those of zone 1. This is equivalent to assuming that the sand has no hydraulic connection with the lake. This had the affect of greatly

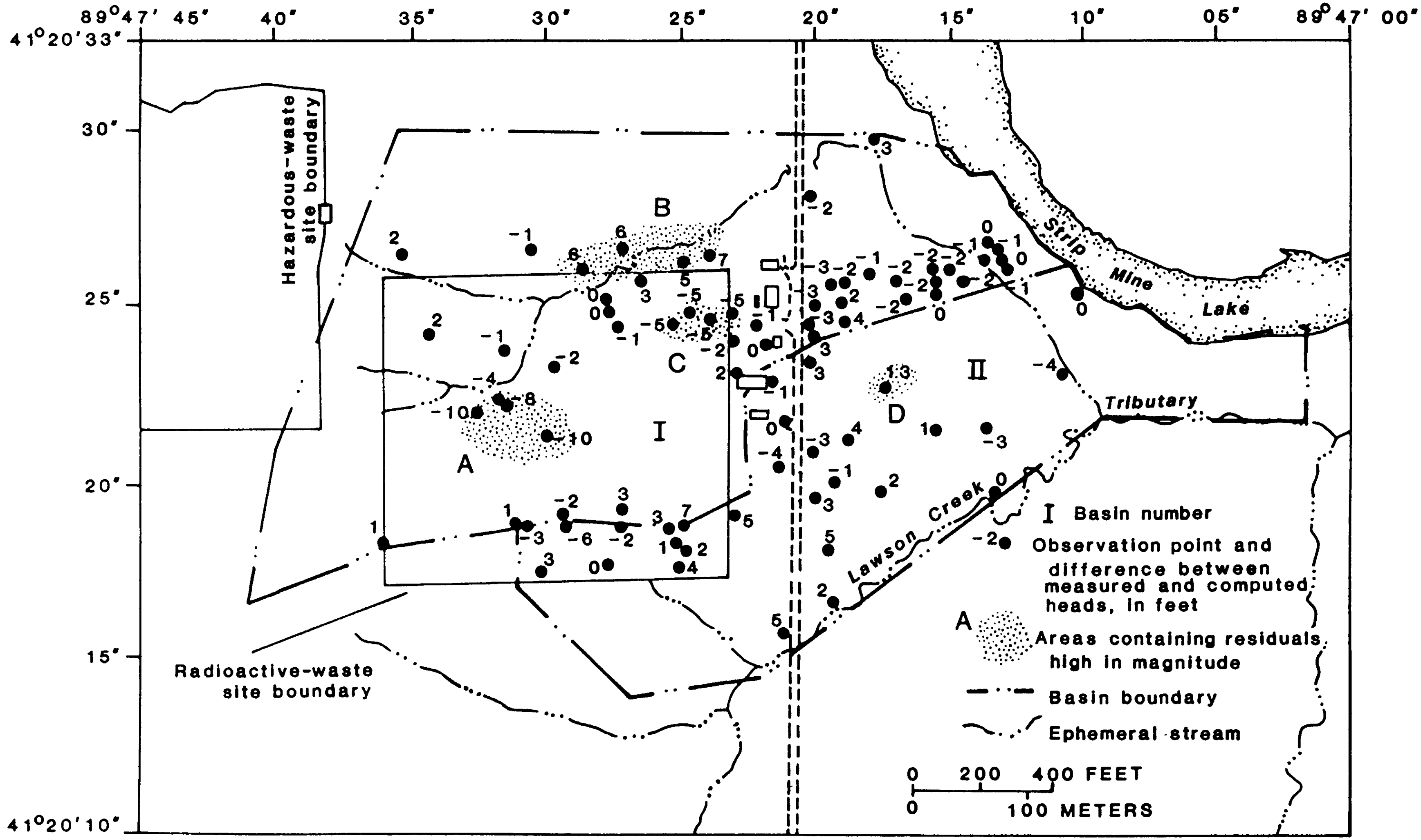


Figure 13.--Residual differences between measured and computed head in modeled basins.

raising computed heads in the northern half of the model area. It was concluded that the sand may be connected to the lake only in isolated locations; in these locations, the saturated thickness is probably quite small. A value of hydraulic conductivity between that of zones 1 and 2 was, therefore, assigned to zone 5.

The length of zone 6 also was varied. For alternative simulations, it was extended to the lake and farther onto the site. Extension to the lake produced a drastic reduction in computed heads within the entire system. Extension farther onto the site drew down computed heads to the immediate east and south.

Results of sensitivity analyses are shown in table 2. When model parameters were varied during the sensitivity analysis, the distribution of residuals became biased, and residuals in zone 1 had larger magnitudes than did other zones. The model should be considered relatively sensitive to overall changes in hydraulic conductivity and recharge. Although this is not ideal, a certain amount of inaccuracy is to be expected in any model representation caused by differences between the complexities of the modeled system and the necessary limiting assumptions inherent in digital models.

The model is less sensitive to changes in the head value of the constant-head boundary which is represented by the lake. The distribution of residuals was not noticeably affected by these changes. The best fit was reconstructed with different constant-head boundaries, simply by modifying the hydraulic conductivity of zone 1 and recharge of zone 2 by about 20 percent.

Ground-water velocities were calculated with equation 1 for parts of basin I using available values for head gradient and horizontal hydraulic conductivity, and typical volumetric porosities of 0.35 for sand, 0.40 for pebbly sand, and 0.05 for other units. Computed values range from 5 feet per year in till to 3,000 feet per year in the pebbly sand-filled channel. This latter value is in close agreement with velocities computed from analysis of the tracer experiment (Garklavs and Toler, 1985). Traveltimes from the site to the lake may be as little as 0.2 year.

Basin II

Similar assumptions to those used to model ground-water flow in basin I were used in basin II. A grid of 408 nodes and 403 elements was used to represent the system. The grid was divided into three zones (fig. 11). All of the boundaries in basin II were specified as no-flow boundaries, with the exception of the boundary at the lake. The boundary at the lake was specified as a constant-head boundary. The boundary along Lawson Creek Tributary was considered a no-flow boundary because the stream is ephemeral, and flow in the steam is negligible.

Zone 1 represents the same type of material as it did in basin I. Zone 2 is the pebbly sand unit. Zone 3 represents the alluvial deposits within the stream channel along the southern border of the model area. Computed water levels were compared to those measured during June 1982. Measured heads were available at 29 nodes.

Table 2.--Results of sensitivity analyses

Run No.	Hydraulic conductivity multiplied by	Recharge multiplied by	Change in constant head	Mean squared error, in square feet	Average residual, in feet
			Basin I		
1	0.50	1.00	+0.00	617	-21.5
2	1.00	2.00	+.00	617	-21.5
3	1.25	1.00	+.00	34.0	3.91
4	1.00	.80	+.00	30.3	3.52
5	1.00	1.00	-2.50	18.4	2.17
6	1.00	1.00	2.50	22.3	-2.94
			Basin II		
1	.50	1.00	+.00	652	-20.3
2	1.00	2.00	+.00	652	-20.3
3	1.25	1.00	+.00	56.3	6.05
4	1.00	.80	+.00	52.8	5.80
5	1.00	1.00	-2.50	31.1	3.94
6	1.00	1.00	2.50	16.8	-1.09

Values of hydraulic conductivity and recharge that produced the best model fit are shown in table 1. These values generally are in good agreement with measured values and those values that were used in the basin I model. The MSE for the best fit was 19.98. The average residual was +0.096. Contours of measured and model-computed water levels are shown in figures 10 and 12. The contours do not match exactly but do follow similar patterns. Figure 13 shows the residuals plotted on the model area. The areal distribution appears to be fairly even in terms of magnitude and sign, with the exception of a node in the north-central part of the basin. That node has a residual of 13 and corresponds to well 608. This well penetrates the pebbly sand unit. The high positive residual means that the measured head was much higher than computed head. This implies that the surrounding area may be incorrectly zoned. More likely, the pebbly sand unit in this area is not in complete hydraulic connection with the strip-mine lake. The bottom of the unit probably rises above the saturated zone somewhere east of well 608, as it does along the northern boundary of this basin.

Results of sensitivity analyses are shown in table 2. The basin II model is slightly more sensitive than the basin I model to changes in parameter values. This is not surprising because of the more complex geology and fewer data points within basin II. Changing the lake level had an unusual effect; raising the lake level 2.5 feet created a significantly larger MSE than lowering the level by the same amount. The reason for this is not apparent.

Velocities calculated from model-computed heads, assuming a porosity of 0.25 for the alluvial deposits and for other deposits as given in basin I, range from 40 to 1,600 feet per year. Ground-water traveltimes from the site to the lake, computed with these velocities, could be as great as 10 years.

TRITIUM MOVEMENT

The Illinois Department of Nuclear Safety has collected water samples for radionuclide analysis since burial of waste began at the site in 1967. The U.S. Geological Survey also has collected and analyzed water samples for tritium from wells and soil samples during the course of investigations at the site. Tritium was detected in observation wells on site in 1976 and off site in 1982. Tritium concentrations determined by the U.S. Geological Survey are published in Foster and others (1984b). Areas in which tritium was found are shown in figure 14. Concentrations ranged from the analytical detection limits of 0.20 nanocurie per liter to over 300 nanocuries per liter. The highest concentrations of tritium were found in basin II--an area in which a gradual increase in tritium concentrations was observed from 1976 to 1984. As an example, tritium concentrations from well 523 are shown in figure 15. Seasonal variations in tritium concentrations were observed in most wells, and dilution caused by infiltrating rainfall has been observed (Foster, Erickson, and Healy, 1984, p. 33).

It is virtually impossible to isolate individual trenches as sources of tritium in ground water. Because trenches were constructed in close proximity to each other, it was not possible to place observation wells between many of them. Tritium has been detected in all three basins, so it is apparent that tritium is moving from more than one trench.

In basin I, the principal pathway for tritium movement is through the pebbly sand unit which underlies about two-thirds of the site, and through which ground water and tritium flow eastward toward the strip-mine lake. Near the eastern border of the site, all flow in basin I converges into a channel-like depression filled with pebbly sand. This narrow depression is the principal flow path from the site boundary to the lake. Between the site and the lake, tritium was detected only in the wells in the narrow channel-like depression. Tritium has been detected in seeps along the final-cut wall at the western shore of the lake. These seeps are a point of discharge for water moving through the channel-like depression. No tritium has been found in observation wells to the east of the site in basin I beyond the confines of the channel-like depression and the seeps along the lake. The presence of the pebbly sand influences tritium concentrations on site by providing rapid transport from the site to the east that keeps concentrations from increasing with time. As an example, tritium concentrations from well 563 are shown in figure 15.

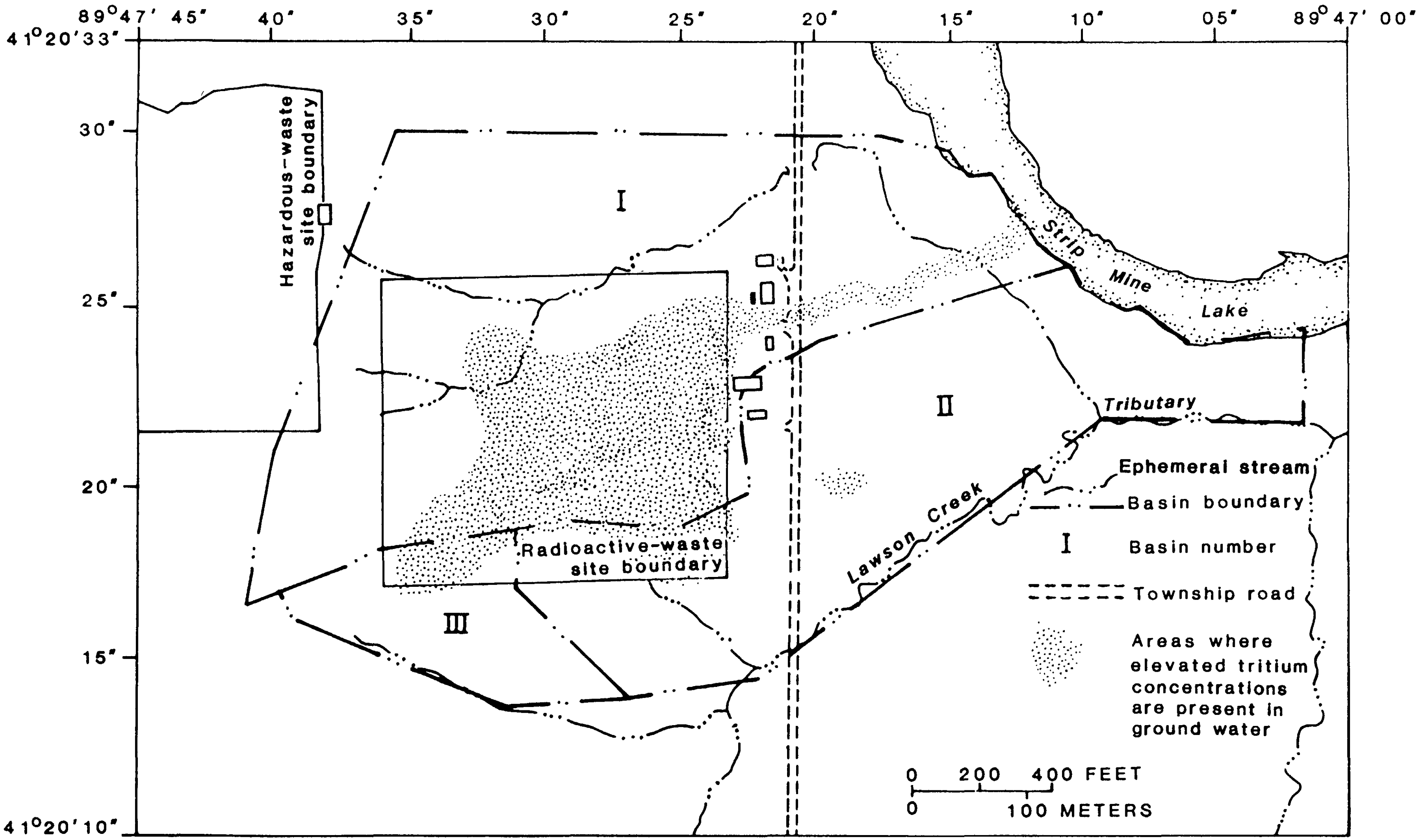


Figure 14.--Areas where tritium is found in study area.

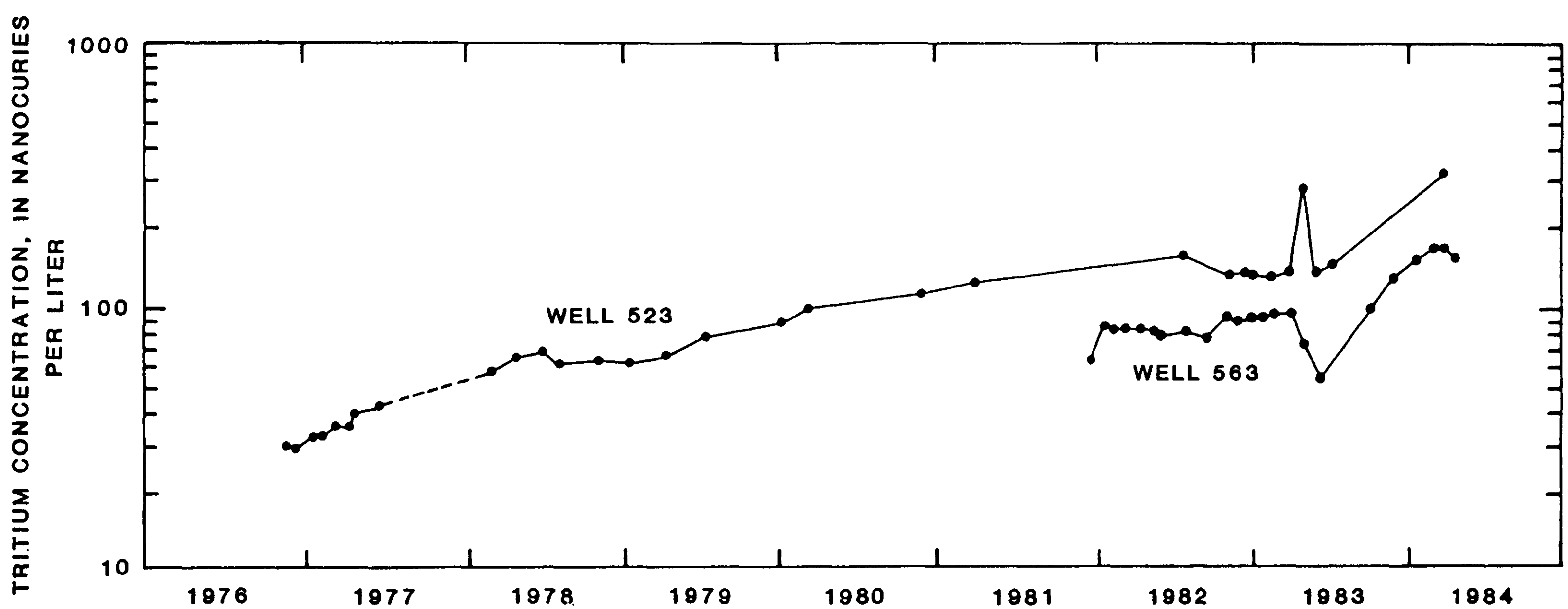


Figure 15.--Variation in tritium concentration in wells 523 and 563, October 1976 to April 1984.

Detection of off-site migration of tritium in basin II is restricted to the area near well 602. As discussed in the section describing the hydrogeologic framework of basin II, it is hypothesized that ground-water flow and tritium movement may be occurring at the bedrock/till interface. The bottoms of the trenches in the southeastern corner of the site are close to the bedrock surface. Saturation at the bedrock surface would, in the presence of joints, fractures, or coal seams, allow movement of both ground water and tritium off site.

The materials controlling ground-water flow in basin II also control tritium movement. The principal water-bearing units are tills and outwash silts. The relatively low hydraulic conductivites of these materials prevent rapid drainage from the basin. Consequently, tritium concentrations have tended to increase gradually on site in basin II, particularly near the southeastern corner of the site. Although ground-water flow in the southern part of basin II is directed toward the tributary to Lawson Creek, no tritium has been detected in water samples from the creek. The higher hydraulic conductivity of the alluvial material is thought to provide sufficient dilution of tritium transport through the Hulick Till Member so as to render it undetectable in the vicinity of the creek.

Tritium migration from basin III is difficult to define. The pebbly sand, where present, is saturated and is a likely unit for transport of tritium. Tritium has been detected in the pebbly sand in well 531. Because the pebbly sand unit does not extend to the ephemeral stream channel, the flow path for tritium from basin III has not been determined. Flow may occur at the pebbly sand/till interface, or a bedrock/till flow path, similar to that in basin II, may be present. Tritium has not been detected off site in basin III.

SUMMARY

Hydrogeologic characteristics of three ground-water basins control ground-water flow and tritium movement in the study area. The shallow aquifer is composed of Quaternary deposits that are diverse in lithologic character and have complex spatial and stratigraphic configurations. Most of the ground-water flow at the site is through a pebbly sand outwash deposit. The principal source of recharge to the shallow aquifer is from precipitation falling on the study area.

Conceptual models of ground-water flow for the three basins were developed from available data on geology and hydraulic properties of the geologic material. These models were tested by application of digital models for the three basins. In basin I, a pebbly sand is considered the most important element in controlling ground-water flow. In basins II and III, tills, sand, and alluvium are equally important in controlling ground-water flow.

The general direction of ground-water flow from the site is eastward toward a strip-mine lake. About 70 percent of the site is drained through basin I. A pebbly sand deposit is the principal unit through which ground water flows in basin I. To the east of the site, most of the flow is confined to a channel-like depression in the Hulick Till Member of the Glasford

Formation (Willman and Frye, 1970). Ground-water velocities, under hydraulic-head conditions measured during this investigation, are about 2,500 feet per year in the depression. Data gathered for several years indicate little change in altitude of the water surface within the pebbly sand unit. Because annual changes are minimal, the ground-water flow through the pebbly sand can be conceptualized as approaching a steady state. Ground-water flow through basin I discharges into the strip-mine lake. Ground-water-flow velocities are greater in basin I than in basin II or expected in basin III.

Ground-water flow in basin II is thought to be partially influenced by the nature of the bedrock/glacial till interface. In the area bounded by wells 602, 609, 610, and 611, the pebbly sand of the Toulon Member of the Glasford Formation is unsaturated. The Hulick Till Member, however, is fully saturated in this area. In addition, concentrations of tritium above background levels are found in well 602. No tritium is found in wells between 602 and the site. Ground-water flow may be through joints or bedding planes near the bedrock surface, or coal seams in the bedrock. Ground-water flow in such manner may be under sufficient head to saturate the overlying till. Ground-water flow in basin II is to the east and southeast--from the bedrock high at the southeastern corner of the site to the strip-mine lake and to the tributary to Lawson Creek.

Ground-water flow in basin III is to the southeast toward an ephemeral stream. Flow is directed through the alluvium in this stream channel toward the tributary to Lawson Creek, then toward the strip-mine lake.

Tritium movement in the shallow aquifer is governed by ground-water flow. Within the confines of the site, tritium movement through and from individual trenches is not defined. The area occupied by trenches, as a whole, is considered the source of tritium that enters the ground-water system. Tritium is assumed to move at the velocity equal to the water transporting it.

To the east of the site, in basin I, tritium movement is well defined. Tritium is confined to the channel-like depression in the Hulick Till Member. Because basin I is drained by an extensive sand unit, the Toulon Member, and because ground-water flow approaches steady-state conditions, tritium concentrations do not vary significantly at individual locations. What variation is seen can be attributed to seasonal recharge to the shallow aquifer. Tritium moving through basin I flows into the strip-mine lake.

Tritium movement in basin II generally is confined to the site. The exception is in the vicinity of well 602, where tritium may be moving through the upper part of the bedrock. Because ground-water velocities are much lower in basin II than in basin I, tritium has not moved off site as quickly and has been observed to increase in concentration in some wells near the southeastern corner of the site. Tritium moving through basin II flows into the alluvial material in the valley of the tributary to Lawson Creek, which, in turn, flows into the strip-mine lake.

Tritium movement through basin III is not well defined, but it is assumed to be toward the alluvium of an ephemeral stream to the south of the site. The tritium then follows the same flow path as tritium moving through basin II. Tritium has not been observed off site in basin III.

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