HYDROLOGY, WATER QUALITY, AND SIMULATION OF GROUND-WATER FLOW AT A TACONITE-TAILINGS BASIN NEAR KEEWATIN, MINNESOTA

By Charles F. Myette

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MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
702 Post Office Building
St. Paul, Minnesota 55101

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon (gal)	3.7854	liter
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	2.54	centimeters
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
square mile (mi^2)	2.590	square kilometer
ton, short	0.9072	megagram
ton, short	0.9072	metric ton [only commerical usage]
ton, long	0.9972	metric ton [only commerical usage]
ton per day (ton/d)	0.9072	megagram per day
degrees Fahrenheit (^{o}F)	(^{o}F - 32)(1.8)	degrees Celsius

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

HYDROLOGY, WATER QUALITY, AND SIMULATION OF GROUND-WATER FLOW AT A TACONITE-TAILINGS BASIN NEAR KEEWATIN, MINNESOTA

By Charles F. Myette

ABSTRACT

Taconite tailings, a waste product from processing of iron ore, have been deposited in a 2.5-square-mile containment basin near Keewatin, Minnesota. The basin, which is bounded by earthen dikes of compacted drift and clayey bouldery till, contains saturated tailings consisting of chert and other silica-rich particles that range from clay to coarse-sand size.

Runoff from the tailings is slight and occurs only after heavy rains and snowmelt. Average discharge from the basin from April 1982 through June 1984 was about 0.6 cubic foot per second. Instantaneous discharge ranged from zero during much of the period to about 140 cubic feet per second following snowmelt in spring 1982. Daily mean discharge from the basin exceeded 20 cubic feet per second on two days during the period of study.

Water levels in wells range from 0 to 25 feet below the tailings surface; seasonal fluctuations range from 2 to 8 feet. Ground water flows radially from a mound in the north-central part of the basin under a hydraulic gradient of 4.7×10^{-3} feet per foot. Vertical flow also is downward to drift deposits beneath the tailings. Vertical gradients range from 7.0×10^{-3} to 6.0×10^{-1} feet per foot.

Saturated thickness of the tailings ranges from about 1 to 35 feet. Estimated horizontal hydraulic conductivity ranges from about 1 to 500 feet per day. Transmissivities range from about 25 feet squared per day in fine tailings to about 350 feet squared per day in coarse tailings. Ground-water recharge from precipitation was 11.8 inches from October 1982 through September 1983. Ground-water outflow as leakage to the underlying drift deposits was 9.9 inches for the same period.

Water collected from wells completed in the tailings and from the drainage ditch at the basin outlet is of a mixed type in which the magnesium concentration only slightly exceeds concentrations of calcium and sodium plus potassium, expressed in milliequivalents, and concentrations of sulfate and bicarbonate, expressed in milliequivalents, are equal. Concentrations of arsenic, fluoride, and nitrite plus nitrate in water from the tailings were notably greater than in water from adjacent aquifers. However, only fluoride, manganese, and nitrite plus nitrate concentrations equalled or exceeded State drinking-water standards. Suspended-sediment concentrations in streamflow ranged from less than 1 milligram per liter during low-flow periods to about 4,600 milligrams per liter following snowmelt in the spring of 1982.

Numerical-model simulations of ground-water flow near the vicinity of the tailings basin indicate that, if areal recharge were doubled during

spring and fall, water levels in wells could average about 4 feet above 1983 levels during these periods. Model results indicate that water levels in the tailings could possibly remain about 5 feet above 1983 levels at the end of the year. Water levels in the tailings at the outlet of the basin could be about 1 foot above 1983 levels during the spring stress period and could be nearly 1.5 feet above 1983 levels during the fall stress period. Under these hypothetical climatic conditions, ground-water contribution to discharge at the outlet could be about 50 cubic feet per second during spring and about 80 cubic feet per second during fall.

INTRODUCTION

Since the early 1880's, about 150 mi^2 (square miles) of northern Minnesota have been disturbed by open-pit mining of iron ore. Shipment to date of 3.4 billion tons of iron ore represents only about one-sixth of the State's ore reserves that are recoverable by open-pit mining. Long-range forecasts by the Minnesota Department of Natural Resources (MDNR), Division of Minerals, indicate that stockpiles, open pits, and tailings basins will occupy as much as 700 mi^2.

State regulatory actions and judicial decisions require that all future disposal of iron-mine-waste tailings be on land in manmade holding basins. Further, State regulations require that, after filling and before abandonment, the downgradient dike of a taconite-tailings basin must be breached to assure that the abandoned basin does not impound water. It has been suggested, however, that the filling and abandonment of these basins may create long-term pollution problems resulting from sediment erosion and chemical leaching of heavy metals. Additionally, State agencies also are concerned about potential effect of these tailings basins on the hydrology and geochemistry of adjacent aquifers.

Reclamation actions to incorporate the abandoned basins into the natural ecosystem require adequate knowledge of ground-water and surface-water interactions. Consequently, the MDNR and the Minnesota Pollution Control Agency (MPCA) need hydrogeologic information on which to base criteria for proper reclamation and abandonment of filled tailings basins. As a result, the U.S. Geological Survey, in cooperation with the Iron Range Resources and Rehabilitation Board (IRRRB) and the MPCA began a study to supply the needed information.

Purpose and Scope

The purpose of this report is to describe the hydrology of a 2.5-mi^2 taconite-tailings basin near Keewatin, Minnesota. The report describes (1) the hydrogeologic setting of the basin, including a description of the tailings within the basin, (2) the surface-water discharge at the outlet of the basin and its response to rainfall on the basin, (3) the ground-water system at the tailings basin and its response to rainfall on the basin, (4) the quality of the ground water beneath the basin and in the surrounding drift,

(5) the quality of surface water and sediment discharging from the basin, and (6) the results of a finite-difference-model simulation of the ground-water flow system.

Surface-water discharge measurements were made at the outlet of the tailings basin. Data from 62 test holes, 53 observation wells, and an aquifer test were analyzed to determine the hydraulic properties of the tailings and the adjacent drift. Ground-water-quality data were collected from four wells--two outside the basin, one in the tailings, and one in the outwash below the tailings. Surface-water quality data were collected from a pond in the tailings basin and at the outlet of the basin.

Model simulation of ground-water flow was limited to deposits in the tailings basin and parts of the adjacent and underlying glacial-drift aquifers. The model was developed to evaluate estimates of hydraulic properties obtained from field data and to provide a better understanding of the effects of climatic stresses on ground-water levels and ground-water flow in the basin and on discharge from the basin. The model was calibrated for steady-state (assumed long-term average) conditions and evaluated by comparison with measured water-level changes and an estimate of the water budget for the basin. The model was used to simulate the hydrologic response to above-normal precipitation during spring and fall.

Location and Description of the Study Area

The study area, in western St. Louis County near Keewatin, Minnesota, (fig. 1) is a 2.5-mi^2 tailings basin located at a taconite-ore-pellet plant. At full capacity, the plant is capable of producing 5.8 million long tons of taconite-ore pellets per year. In the process, about 32 thousand long tons of waste taconite tailings are produced each day. After processing, a slurry of waste tailings and water is pumped to a thickener for water removal. The thickened slurry is then pumped into a basin for disposal of the tailings. The disposal system consists of the plant's initial and stage-two tailings-disposal basins. For the purpose of this investigation, only the temporarily unused initial basin was studied.

By 1979, the initial basin was filled with tailings and reclamation of the newly created land surface had begun. In 1982, about 75 percent of the basin cover was exposed tailings, 20 percent undisturbed drift, and 5 percent ponded water (over tailings and drift areas). Reclamation of the tailings basin mainly included the planting of alfalfa, brome grasses, sweet clover, and a variety of trees (hardwoods). Eventually, the initial basin will be covered with new tailings as larger tailings basins downgradient fill during stage 2 and engulf the initial basin. At the present (1983) deposition rate in stage 2, the initial basin will not be reused for several years.

Short, mild summers with long, cold winters characterize the climate of the area. Average annual precipitation in the vicinity of the tailings basin is 26 in. (inches), of which about 20 in. is lost through evapotranspiration and about 6 in. runs off as streamflow (Oaks and Bidwell, 1968, Sheet 1). Runoff includes the ground-water contribution to streams. Average annual

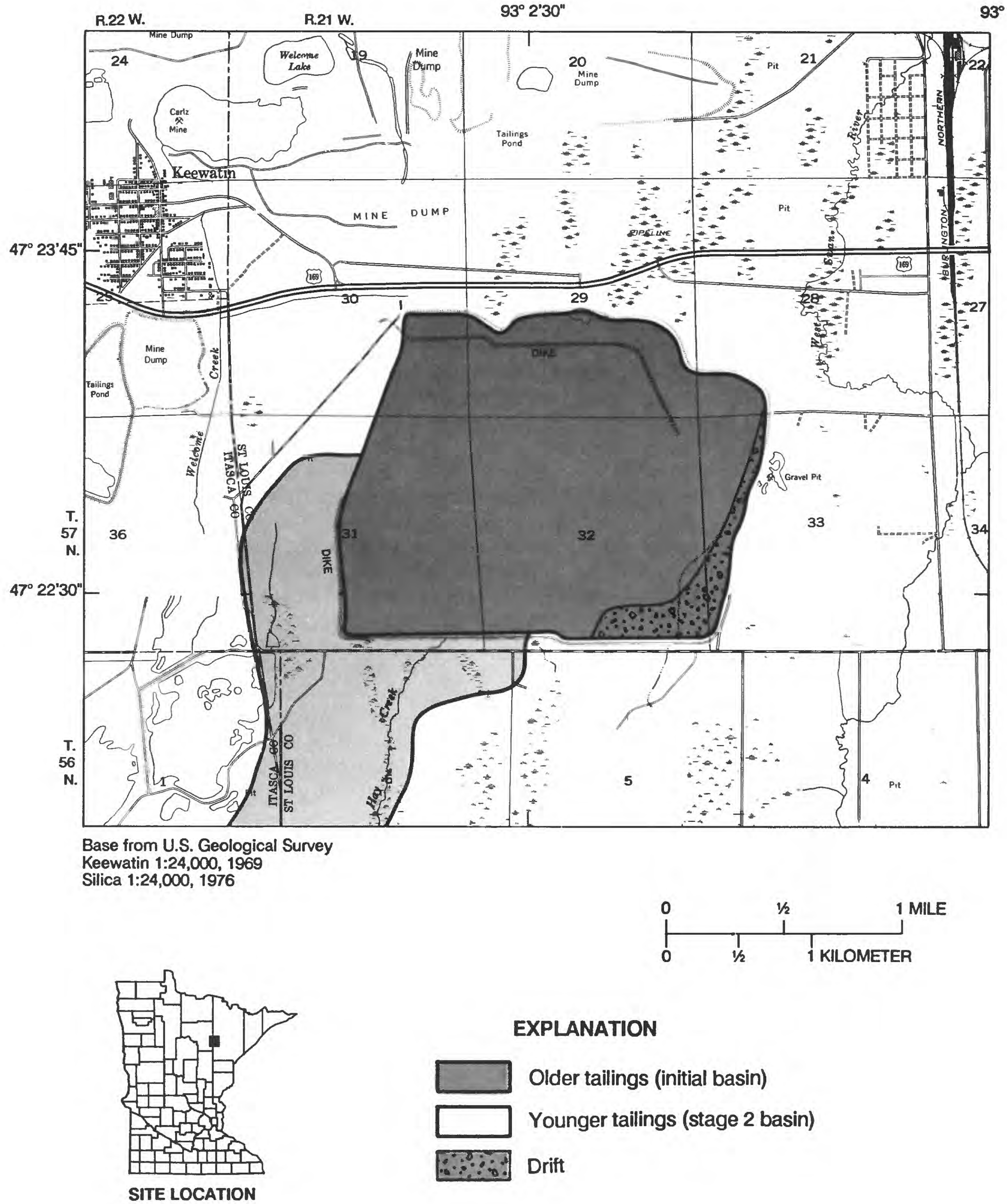


Figure 1.--Location of study area and areal extent of tailings in the vicinity of the initial tailings basin near Keewatin, Minnesota

temperature is 39.2 °F (degrees Fahrenheit) with monthly averages ranging from 9.8 °F in January to 64.6 °F in July. Regional drainage is part of the Mississippi Headwaters watershed. Local drainage is to West Swan River and Hay Creek. Streams generally flow from north to south, draining to the Swan and Mississippi Rivers.

Previous Investigations

Winchell and Upham (1899) provide one of the earliest accounts of surface drainage and geology in the study area. Early surficial geologic and general climatic conditions were described by Leverett and Sardeson (1917). Principal geologic structure was described by Leverett (1932), Thiel (1947), Oakes (1964), Minnesota Geological Survey (1970), and Sims and Morey (1972). Sequence of glaciation was described by Winter (1971). Winter and others (1973) described the petrography and stratigraphy of the glacial drift of the Mesabi-Vermilion Iron Range area. Studies of minerology and geologic structure of the Mesabi Range were conducted by Gruner (1924, 1946). Early studies of ground-water resources were by Thiel (1947) and Cotter and others (1965). Their reports described water availability, municipal water supplies, and water quality with respect to major constituents. Some of the latest hydrological studies of the area were by Oakes and Bidwell (1968) and Winter (1973), who describe appraisals of water resources and interpret water quality and quantity data.

Methods of Investigation

A total of 62 test holes was drilled by power auger in the vicinity of the initial tailings basin to provide geologic data. Of these test holes, 53 were completed as observation wells (piezometers) to provide information on (1) the water table and potentiometric surfaces of the tailings and underlying drift and (2) seasonal changes in water levels. Hydraulic properties were estimated at each of the test holes based on grain size and water-level data. Additional hydraulic properties of the aquifers and confining layers were calculated from results of aquifer tests. Hydrographs from the observation wells were analyzed for aquifer recharge-discharge characteristics.

Surface-water data were collected at two locations in the basin to determine storage capacity of the pond and runoff characteristics of the tailings. Measurements of stage at the tailings-basin outlet were obtained from either periodic readings of a staff gage or from a continuous water-stage recorder. Measurements of pond stage were obtained by an automatic stage recorder that provided data at 30-minute intervals. Measurements at the tailings-basin outlet were made only during ice-free periods. Based on stage-discharge relations, a rating table was developed for the outlet to estimate discharge from stage data. A stage-capacity table was developed for the pond based on stage-area relation curves defined by surveys.

Samples of ground water and surface water were collected periodically and analyzed for major chemical and physical characteristics. The data were used to evaluate the quality of water in the basin.

Some of the chemical concentrations measured for this study were less than the reporting limit; these are called censored values. Mean concentrations were determined by assuming the actual concentration for censored values was at the reporting limit.

A numerical model was constructed to simulate ground-water flow in three dimensions. The model was used primarily as a tool to improve the conceptual model of the flow system. The model was used also to simulate hydraulic response of the aquifer to hypothetical climatic conditions.

Test-Hole and Well-Numbering System

Test holes and wells in this report are identified by the prefix letters "KTB" (Keewatin Tailings Basin) followed by sequential numbers that correspond to the order in which they were drilled. Thus, well number KTB-5 was the fifth well or test hole drilled in this study.

Acknowledgments

The U.S. Geological Survey would like to thank the owners of the tailings basin, National Steel Pellet Company, for their cooperation.

HYDROGEOLOGIC SETTING

Bedrock

Granite, iron formation, and argillite of Precambrian age form the basement structure in the study area. Depths to these formations range from outcrops of granite a few miles north of the basin to greater than 200 ft (feet) to argillite southwest of the basin (Winter, 1973, pl. 1). Conglomerate of Cretaceous age also underlies parts of the study area. Depths to the conglomerate generally range from 150 to 200 ft (Winter, 1971). Bedrock formations typically are dense with fractures providing the only storage space for water. Maximum yields of bedrock wells are obtained by drilling where fractures intersect, but yields rarely exceed 10 gal/min (gallons per minute).

Glacial Drift

Three identifiable glacial advances have left the study area covered with drift of Pleistocene age (Winter, 1971). Thickness of drift in the vicinity of the study area ranges from 0 north of the tailings basin to greater than 200 ft in the vicinity of the tailings basin near Keewatin (Winter, 1973, pl. 1). The drift is composed of sandy and bouldery till and sand and gravel outwash. The outwash, where present, generally is surrounded by till or occurs in outwash channels that rarely exceed 30 ft in thickness (Winter, 1973, p. A9). Predominant features of the drift are drumlins found throughout the basin area. Figure 2 shows the surficial geology in the vicinity of the tailings basin prior to emplacement of the tailings. Yields of water from wells in the drift are highly variable. Till has low hydraulic conductivity

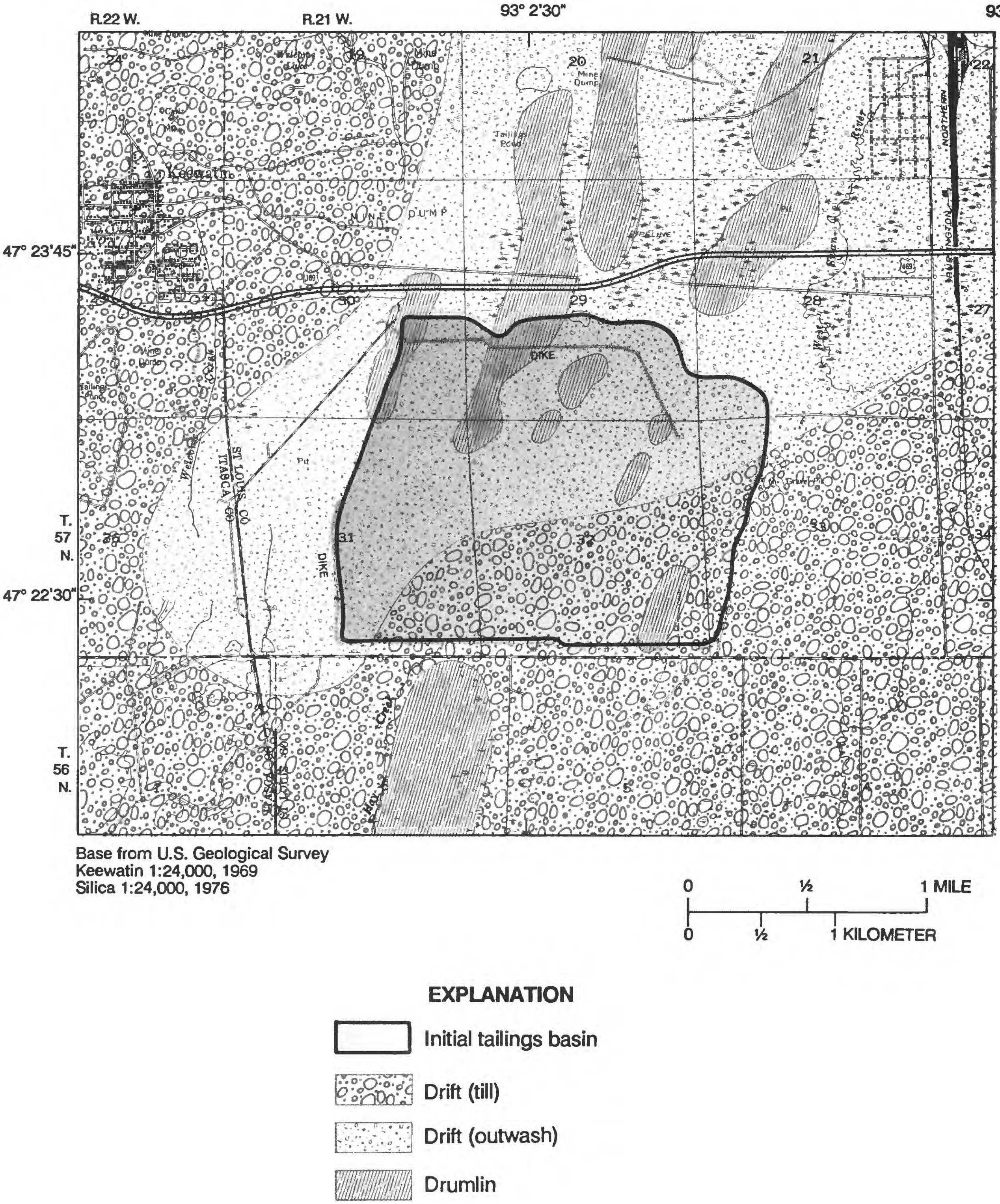


Figure 2.--Surficial geology prior to emplacement of tailings in the basin near Keewatin, Minnesota.

and yields very little water to wells. Outwash has a high hydraulic conductivity in relation to till and well yields of several hundred gal/min are possible to properly constructed wells.

Tailings

Tailings, consisting of wastes formed by processing iron ore, were deposited as a slurry in the initial tailings basin. Aggradation of the basin was similar in mechanical process to formation of a delta. Pipelines discharged the slurry at various locations along the northern edge of the basin, resulting in mounds of rapidly settling coarse-sand-sized tailings near the point of discharge. Finer silt and clay-sized tailings were deposited progressively farther downgradient near the southern edge of the basin. Evidence of variable discharge rates can be observed as interbedding of fine and coarse material throughout the basin. The tailings consist mostly of chert and other silica-rich material that range from clay to coarse-sand-sized particles. On a weight basis, the material is dominated by silica (SiO_2, 65 percent), hematite (Fe_2O_3, 11 percent), iron oxide (Fe_O, 8 percent), and other trace metals (16 percent) with manganese dioxide (MnO_2) dominating the trace metals (Berglund, 1983). Tailings deposits within the basin range in thickness from less than 1 foot in the east-southeast part of the basin to nearly 40 ft in the southwest corner. Newer tailings deposits from recent mining operations are found immediately west and southwest of the basin (fig. 1). Most of the tailings in the basin consist of fine-grained tailings interbedded with coarser tailings. The hydraulic conductivity of the tailings generally is low. Yields of wells completed in the tailings generally are less than 1 gal/min.

Deposition of the tailings at variable rates and locations, as a slurry, caused formation of textural zones in the basin that are difficult to delineate. Slack and others (1984,) differentiated coarse, medium, and fine zones by the predominant grain size, expressed as a percent. Approximate areal extent of the zones is shown on figure 3. Texture of the tailings was analyzed statistically by Berglund (1983) using two-way analysis of variance. Table 1 shows Berglund's results based on mean textural composition. The data indicate a significant difference in textural composition of coarse material deposited in the northern part of the basin (coarse zone, fig. 3). There is, however, very little difference (no statistical difference at 95-percent-confidence level) in textural composition between the medium and fine zones, which, therefore, are combined in this report.

HYDROLOGY

Surface-Water System

Runoff from the initial tailings basin generally occurs only following spring snowmelt or heavy rain. Runoff from the western part of the basin is to a drainage ditch along the western dike that drains to a pond in the southwest corner of the basin. Runoff from the central part of the basin is to several small channels at the south end of the basin and then to a drainage ditch along the southern dike that leads east to the breach in the dike (outlet). Runoff from the eastern side of the basin is from areas of undisturbed drift to the south and west to the breach in the dike (outlet).

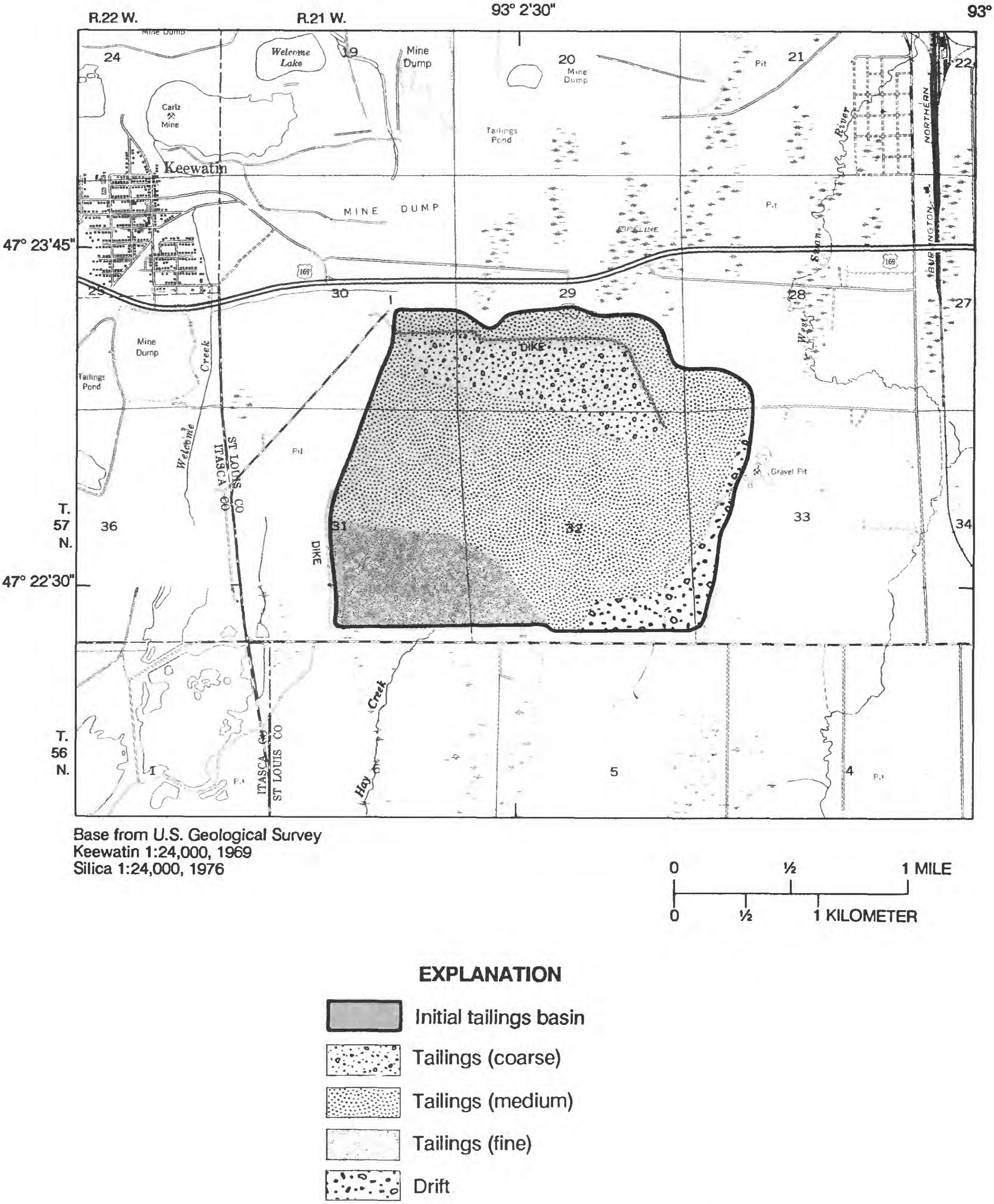


Figure 3.--Approximate areal extent of textural zones within the initial tailings basin on the basis of predominant grain size.

Table 1.--*Mean textural composition and zone classification of tailings from the initial tailings basin near Keewatin, Minnesota*

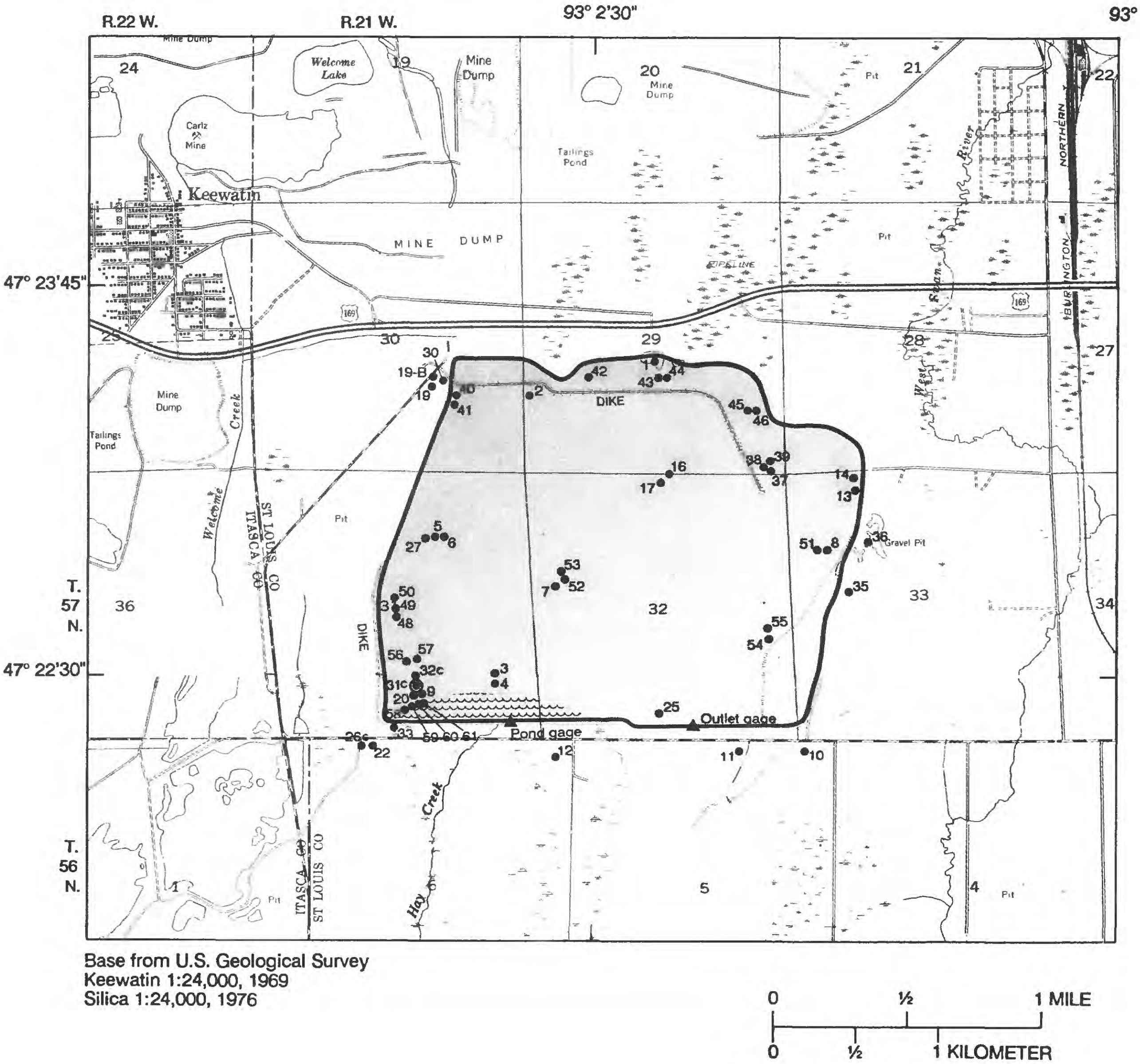
[Modified from Slack and others, 1984. <, less than; >, greater than; mm, millimeter]

	Mean textural composition (in percent)		
Zone	Sand (>0.0625 mm)	Silt (0.0625-0.004 mm)	Clay (<0.004 mm)
Coarse	85.19	12.24	2.57
Medium	20.53	69.37	10.10
Fine	28.02	64.58	7.40

Berglund's (1983) infiltrometer studies show that water from most storms infiltrates the tailings quickly. The data suggest that large storms, with several hours of heavy rain, can generate significant runoff from the fine-tailings zone. The data also show that infiltration capacity in each of the textural zones is high initially, decreases rapidly with time to an equilibrium rate. Infiltration rates remain high (4 to 20 in/h (inches per hour)) in the coarse zone if the silt content is less than 40 to 50 percent. Infiltration rates are greatly reduced (4 to 0.08 in/h) if the silt content exceeds 50 percent, as in the medium and fine zones of the basin (see Berglund (1983) for additional infiltration data).

A major feature of the drainage system is the shallow pond in the southwest corner of the basin (fig. 4). Dead storage of the pond was 39 acre-ft (acre-feet) at a stage of 1,493.76 ft in November 1983. Estimated peak storage of the pond was 150 acre-ft in April 1982, when snow and ice blocked the runoff channel. Depth of the pond normally is about 3 ft. The pond serves as a buffer that retains runoff and sediment and allows more infiltration and evaporation to occur. Surface-water flow out of the basin occurs only when the pond fills and spills to the runoff channel and the outlet.

Table 2 lists the storage capacity of the pond at various stages, based on the stage-area relation curves defined by surveys completed in November 1983. Comparison of different stages allows calculation of changes in storage that may occur daily, monthly, or yearly. Storage capacity, however, may be subject to slight change because of sediment deposition in the pond. The range in stage for the pond is from 1,490.98 ft (dry) to 1,494.0 ft. Water flows out of the pond at a stage of 1,493.76 ft. Data are insufficient to extrapolate storage at stages greater than 1,494.0 ft with any degree of accuracy. Pond-stage data are stored in District files and published in annual reports of the U.S. Geological Survey (1982-84).



EXPLANATION

Initial tailings basin

Pond

•¹ Test hole or observation well. Number indicates order of drilling. All numbers are proceeded by KTB.

◉ Aquifer test location (KTB-31)

▲ Surface-water gage

c Sampled for chemical analysis

Figure 4.--Approximate location of test holes, observation wells, and surface-water gages.

Table 2.--*Storage capacity of the pond at the initial tailings basin near Keewatin, Minnesota*

Stage (feet above sea level)	Storage (Acre feet)	Storage (Cubic feet)	Stage (feet above sea level)	Storage (Acre feet)	Storage (Cubic feet)
1490.98	0.0	0	1492.50	9.8	$4.3x10^5$
1491.00	.004	$1.7x10^2$	1492.75	14	$6.1x10^5$
1491.25	.2	$8.7x10^3$	1493.00	19	$8.3x10^5$
1491.50	.8	$3.5x10^4$	1493.25	25	$1.1x10^6$
1491.75	1.9	$8.3x10^4$	1493.50	32	$1.4x10^6$
1492.00	3.8	$1.7x10^5$	1493.76	39	$1.7x10^6$
1492.25	6.4	$2.8x10^5$	1494.00	48	$2.1x10^6$

Thirty-one discharge measurements were made at the outlet of the basin from April 1982 to June 1984 and a stage-discharge rating table was prepared. Measurements of stage were obtained from periodic readings of a non-recording staff gage prior to July 7, 1982, and from a continuous water-stage recorder thereafter. Daily mean discharge was computed from the stage-discharge rating table. Techniques used for determination of discharge are those described by Buchanan and Somers (1968), Carter and Davidian (1968), and Rantz and others (1982). Measurements of discharge are expressed in cubic feet per second (ft^3/s). Discharge data are published in the annual reports, U.S. Geological Survey Water-Resources Data for Minnesota (U.S. Geological Survey, 1982-84). Location of the outlet gage is shown on figure 4.

Average streamflow at the basin outlet during the 27-month period, April 1982 through June 1984, was 0.62 ft^3/s. Instantaneous discharge varied from zero during much of the period to a peak of 142 ft^3/s following snowmelt in 1982. Daily mean discharge exceeded 0.10 ft^3/s on 288 of 817 days of record, 5 ft^3/s on 21 days, and 20 ft^3/s on two days. About half the total runoff occurred during spring snowmelt.

A major factor affecting discharge from the basin is stage of the pond. If stage is low, as in September 1982, a 2-in. rain causes no discharge at the outlet; it simply increases the level (storage) of the pond. However, when the pond was full in May 1982, a 0.75-in. rain caused a daily mean discharge of 14 ft^3/s.

Following runoff, discharge at the outlet generally decreased to zero (or less than 0.10 ft^3/s) in a few days. Duration of runoff following storms depends on several factors such as the amount and duration of rainfall, antecedent soil moisture, stage of the pond, and evapotranspiration rates.

Occasionally, runoff from the drift area in the eastern part of the basin (fig. 3) was measured separately from the total runoff. The measurements, made in a small channel in the drift immediately above the outlet, show that runoff from the drift area ranges from 4 to 50 percent of total runoff; it averages about 28 percent. The greatest percentage contribution from the drift occurs during low-flow conditions. The percentage contribution decreases as flow from the basin increases.

In summary, surface runoff from the basin generally is low. Most precipitation on the basin either infiltrates the tailings surface and percolates to the ground-water system or evaporates from the pond. Water leaving the basin as surface runoff is a small percentage of the total annual precipitation (runoff of 1.6 in. from 29.7 in. of precipitation) as shown by the 1983 discharge records and a hydrologic budget.

Surface-water conditions observed during the study probably are not representative of long-term average conditions in the basin, nor are they necessarily representative of other tailings basins. Precipitation during the study period was 114 percent of normal with unusually wet periods followed by cool, dry periods. Seasonal flow patterns were unique and do not represent average flow conditions. Further, the prolific growth of vegetation as a result of reclamation efforts during the study changed runoff characteristics of the basin.

Ground-Water System

Recharge

Recharge of ground water in the initial tailings basin is mostly derived from the infiltration of precipitation. The amount of recharge depends on several factors, most important of which are runoff characteristics, infiltration rates, antecedent moisture conditions in near-surface materials, and seasonal variations in temperature that affect evaporation rates. For these reasons, the amount of recharge does not correlate directly to the amount of precipitation and is, therefore, difficult to predict for individual storms. Figure 5 shows the correlation between precipitation, cumulative departure from normal precipitation, and water-level fluctuations in well KTB-17 during 1982-84. For some wells, cumulative departure from normal precipitation may be used to predict water-level changes where data are incomplete.

Slack and others (1984) used double-ring-infiltrometer techniques to estimate infiltration rates in each of the three grain-size zones in the tailings (figure 3). Results indicate an average infiltration rate of 1.39 in/h in the fine tailings, 0.56 in/h in the medium tailings, and 12.86 in/h in the coarse tailings. Using analysis of variance and Kruskal-Wallis tests, no significant differences were found at the 95-percent-confidence level between infiltration rates in the fine and medium tailings. The rate in the coarse tailings is significantly different from those in the fine and medium tailings at the 99-percent confidence level. These data suggest that the coarse tailings have a significant capacity for infiltration of precipitation from most storms and that the lower infiltration capacity of fine and medium tailings causes precipitation from large storms to run off.

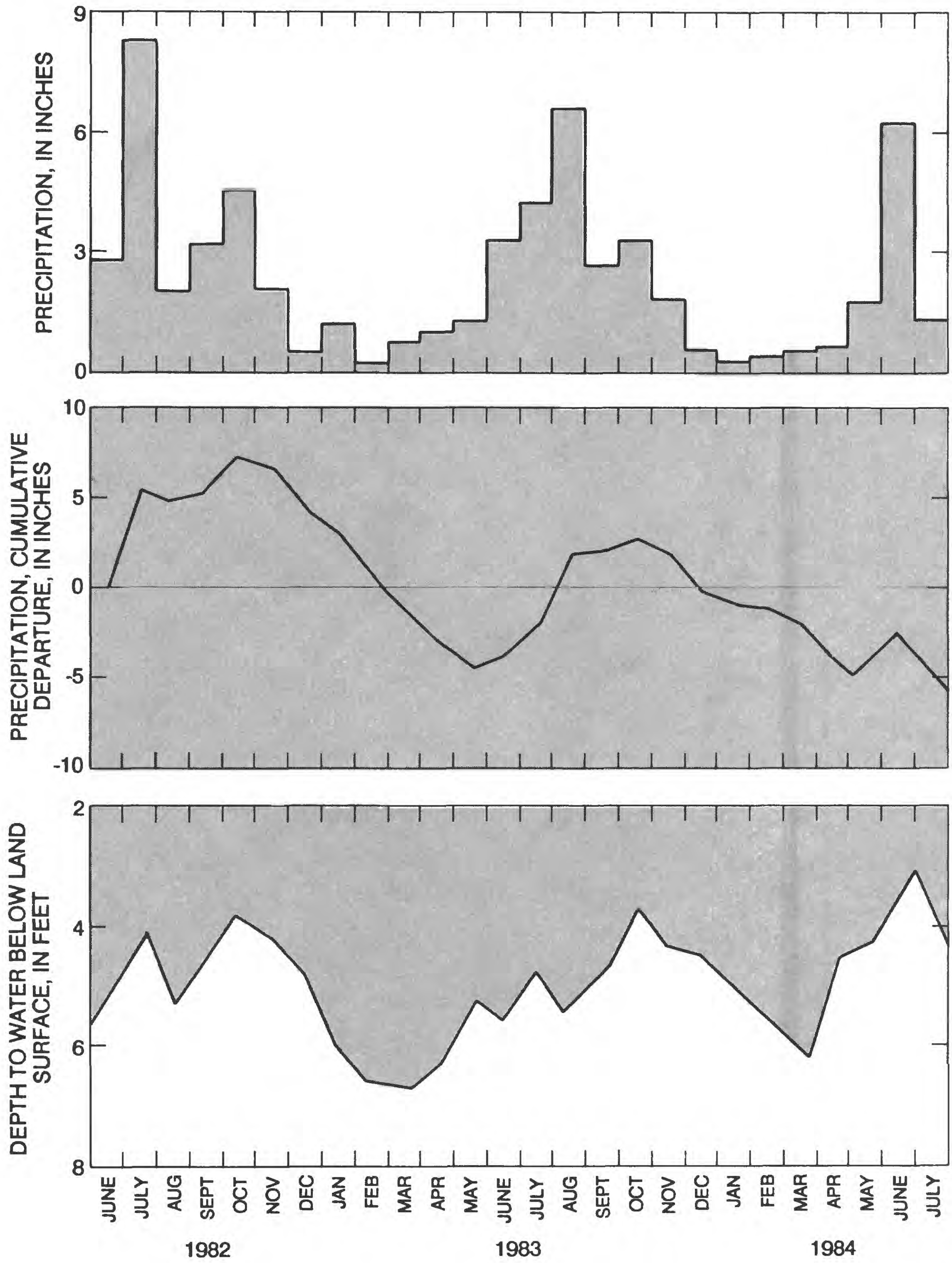


Figure 5.--Relation among precipitation, cumulative departure from monthly normal precipitation (1951-80), and depth to water in well KTB-17, 1982-84.

Relative amounts of recharge and changes in aquifer storage were estimated for the tailings by determining graphically the amount of water-level fluctuation and multiplying by the specific yield of the tailings at each observation well (Walton, 1970). Specific yield was estimated at each well site from the predominant grain size of the tailings (Todd, 1959, p. 25). Specific yield ranged from 6 percent in fine tailings to 20 percent in coarse tailings. Figure 6 illustrates the method used to estimate annual recharge at each well site, using well KTB-7 as an example. Applying this method at all well sites, recharge to the tailings aquifer in water year 1983 (October 1, 1982, to September 30, 1983) was estimated to be 11.8 in. Similarly, recharge in calendar year 1983 was estimated to be about 10 in.

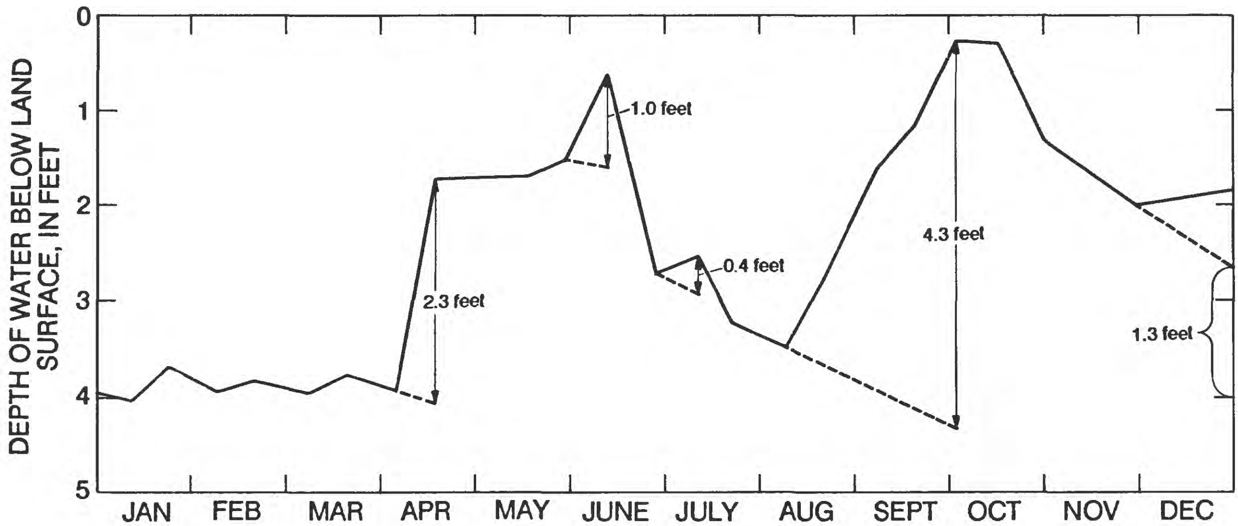
An occasional source of recharge to the tailings is vertical leakage from the pond when hydraulic head in the tailings falls below the hydraulic head in the pond. Leakage from the pond was estimated from stage/area data to be 4.0×10^{-3} ft^3/d (cublic feet per day) November 1-15, 1983, when evapotranspiration and precipitation were negligible and the temperature was above freezing. Leakage from the pond probably is less than 0.5 percent of the hydrologic budget in the tailings basin.

Hydraulic Properties

Data from 62 test holes, 53 observation wells, and an aquifer test were analyzed to determine the hydraulic properties of the tailings and the adjacent glacial drift.

Saturated thickness of the tailings was calculated by subtracting the altitude of the bottom of the tailings (tailings/drift contact) from the altitude of water levels in each test hole and observation well. Saturated thickness ranges from less than 1 ft in the topographically higher parts of the basin to about 35 ft in the southwestern part of the basin near the pond.

Horizontal hydraulic conductivity was determined by an aquifer test and by comparison of aquifer material with known grain-size analyses. Table 3 shows the relation between grain size (based on the Wentworth scale) and estimated horizontal hydraulic conductivity as used by Winter (1973). Horizontal hydraulic conductivities also were based on the degree of sorting. Tailings that were poorly sorted were assigned lower horizontal hydraulic conductivities than tailings that were well sorted. Estimated horizontal hydraulic conductivity of the tailings ranged from about 1 ft/d (foot per day) for silty clay in the southwestern part of the basin to about 500 ft/d for coarse tailings found along the ridge in the northern part of the basin. Stratification of the tailings was noted throughout the basin. Discontinuous layers of red clay-sized material were noted in test holes drilled in the topographically flat areas. More prominant clay layers were noted in the southwest part of the basin near the pond. This interbedding of clay layers with the tailings causes significant differences in vertical hydraulic conductivity in different parts of the basin. The vertical hydraulic conductivity in parts of the basin underlain by till was estimated to be 4.0×10^{-5} ft/d.



Specific yield = 0.08
Annual recharge = (2.3 + 1.0 + 0.4 + 4.3) feet x 12 inches per foot x 0.08 = 7.7 inches
Change in storage = 1.3 feet x 12 inches per foot x 0.08 = 1.2 inches

EXPLANATION

------- Projected water-level trends

Figure 6.--Hydrograph of well KTB-7 showing water-level changes used to determine recharge and change in aquifer storage at well sites during 1983.

Table 3.--*Estimated horizontal hydraulic conductivity of taconite tailings based on predominant grain size*

[Modified from Winter, 1973. <, less than; mm, millimeter]

Predominant grain size (Wentworth scale)	Estimated horizontal hydraulic conductivity (feet per day)
Clay (<0.004 mm)	<1
Silt (0.004-0.0625 mm)	1-10
Sand, very fine (0.0625-0.125 mm)	10-50
Sand, fine (0.125-0.250 mm)	50-100
Sand, medium (0.250-0.5 mm)	100-300
Sand, medium with gravel (0.250-72.0 mm)	200-400
Sand, coarse to very coarse (0.5-2.0 mm)	300-500

Using double-ring infiltrometers, Berglund (1983) estimated vertical hydraulic conductivity of the tailings in each of the three major zones shown in figure 3. Vertical hydraulic conductivities of 26, 1, and 3 ft/d were estimated for the coarse, medium, and fine tailings, respectively. Statistically, at the 95-percent-confidence level, there is no difference between vertical hydraulic-conductivities of the medium and fine tailings; therefore, these tailings were considered as a single hydrologic unit. A factor that complicates interpretation of results from infiltrometer studies is the formation of desiccation cracks as the tailings dry. Presence of the cracks, which may extend downward several feet, may account for some of the areal variability in hydraulic conductivity within the zones.

Horizontal hydraulic conductivity values for the adjacent glacial drift are estimated to range from about 0.1 to 32 ft/d in till to 10 to 3,200 ft/d in outwash (Siegel, and Ericson, 1980, p. 13). Test holes drilled by the U.S. Geological Survey penetrated peat below the tailings in most low-lying drift areas. Soils maps (Terry Weber, U.S. Soil Conversation Service, written commun., 1983) indicate that the peat is from 5 to 7 ft thick. Test drilling, however, showed peat thicknesses to range from 1 to 8 ft. The peat probably has been compacted where buried by thick tailings. This may have reduced the hydraulic conductivity of the peat. Siegel and Ericson (1980, p. 13) suggest that vertical hydraulic conductivities of peat range from 1.0×10^{-3} to 1.0×10^{-1} ft/d.

Transmissivity was calculated at each test-hole and observation-well location by summing the products of the saturated thickness of each lithologic unit and the horizontal hydraulic conductivity of the unit. Within the tailings, transmissivities ranged from 25 ft^2/d (feet squared per day) for the fine tailings in the southwestern part of the basin to 350 ft^2/d for the coarse tailings along the northern ridge. Transmissivities of the outwash below the tailings ranged from 700 ft^2/d in the northern section of the study area to 3,750 ft^2/d below the southwestern section of the basin. Transmissivities were not estimated for the till.

A 48-hour aquifer test was performed October 12-14, 1983 using well KTB-31, completed in outwash underlying the tailings, in the southwestern part of the basin (fig.4). Transmissivity and storage coefficient values for outwash, and the vertical hydraulic conductivity of the confining unit (peat) between the outwash and overlying tailings were calculated using methods described by Walton (1970, p. 149) and Lohman (1972, p. 30). The transmissivity and storage coefficient of the outwash, and vertical hydraulic conductivity of the confining unit were calculated to be 3,750 ft^2/d, 2.1×10^{-4}, and 1.4×10^{-3} ft/d, respectively. Table 4 supplies supplemental information for the test.

Ground-Water Flow

Depth to water in the tailings ranged from water above land surface in the pond in the southwest part of the basin to about 25 ft below land surface in the topographically high area along the northern part of the basin. Depth to water in about 30 percent of the basin is less than 5 ft below land surface. Depths to water in the adjacent drift aquifers generally are less than 20 ft below land surface.

Table 4.--*Aquifer test results at well KTB-31, October 12-14, 1983*

Lithology..	Sand, fine to coarse, with trace of fine gravel
Saturated thickness (feet)................................	27
Duration of test (hours)..................................	48
Pumping rate (gallons per minute).........................	50
Specific capacity (gallons per minute per foot of drawdown...	6
Transmissivity (feet squared per day).....................	3,750
Average horizontal hydraulic conductivity (feet per day).....	140
Storage coefficient..	2.1×10^{-4}
Vertical hydraulic conductivity of confining unit (peat) between tailings and outwash (feet per day)...............	1.4×10^{-3}

Figure 7 shows the approximate configuration of the water table in the tailings in August 1983. The unconfined ground water moves radially away from a mound in the north-central part of the basin. The mound is caused in part by topography and in part by the low horizontal hydraulic conductivity of the adjacent material. The predominant horizontal gradient is about 4.7×10^{-3} ft/ft (feet per foot) (25 ft/mi (feet per mile).

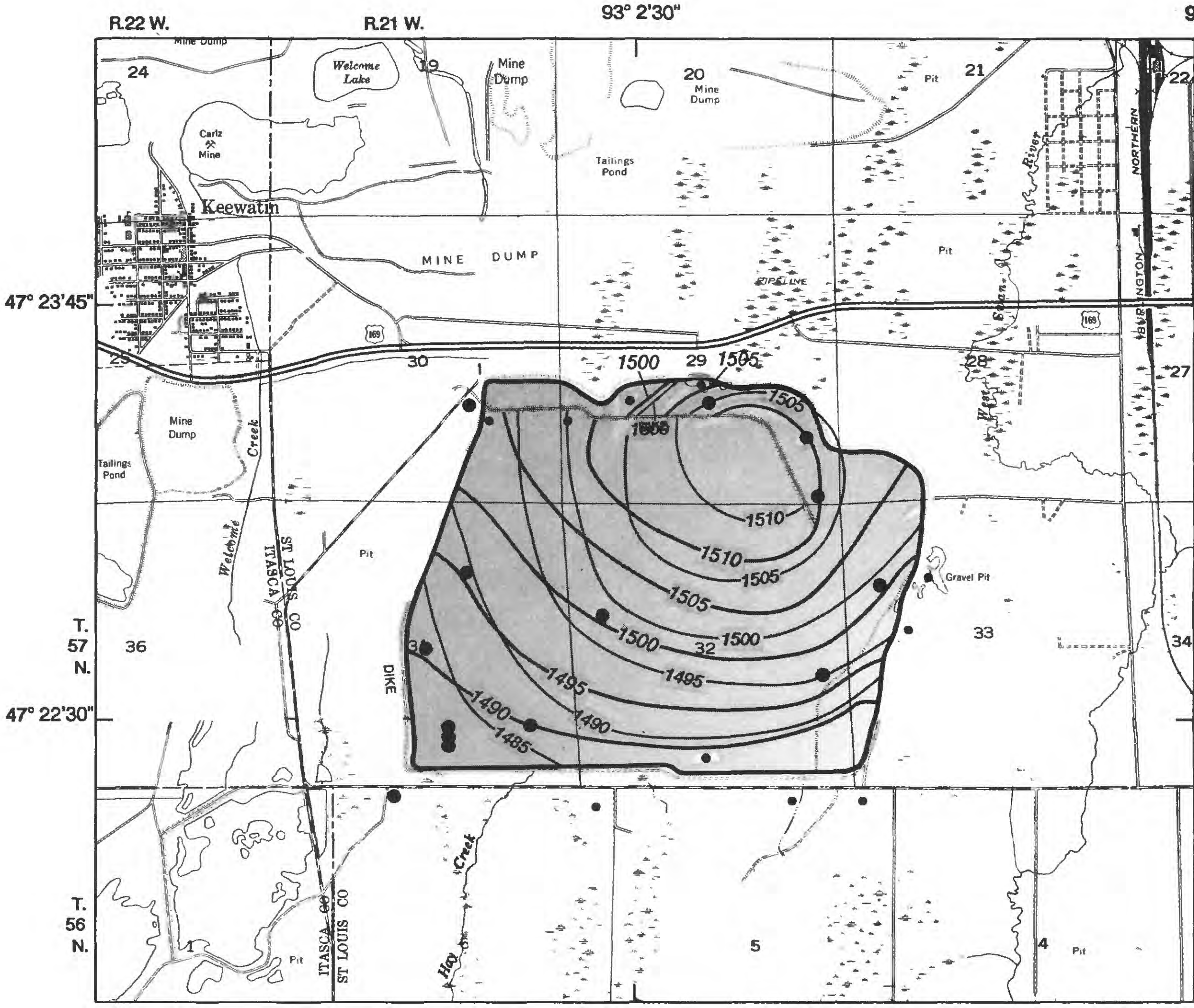
The approximate configuration of the potentiometric surface of the drift aquifer immediately below the tailings is also shown on figure 7. The direction of movement of the confined ground water is similar to that of water in the tailings. Average vertical head difference between wells completed at the water table in the tailings and wells completed in the underlying drift is 3.5 ft, heads in the drift aquifer are lower.

Water levels in nested wells (screened at various intervals within and below the tailings) indicate downward flow and vertical head loss, both within the tailings and between the tailings and the underlying drift aquifer. Actual differences in head ranged from 0.18 ft between wells KTB-7 and KTB-53 (fig. 4) to 11.0 ft between wells KTB-40 and KTB-41 (fig. 4). Vertical hydraulic gradients between wells screened in tailings and in the underlying drift, measured in August 1983, ranged from 7.0×10^{-3} ft/ft near the central part of the basin (wells KTB-7 and KTB-53, fig. 4) where tailings overlie 8 ft of peat over till, to 6.0×10^{-1} ft/ft in the northwestern part of the basin (wells KTB 40 and KTB 41) where tailings overlie 5 ft of peat over outwash. The average vertical hydraulic gradient between tailings and till was 1.3×10^{-2} ft/ft, whereas the average vertical hydraulic gradient between tailings and outwash was 2.4×10^{-1} ft/ft.

The relatively steep horizontal gradient in the tailings (as compared to land surface) and the steep vertical gradient suggest that (1) ground-water movement within the tailings is primarily downward and (2) ground-water discharge from the tailings is primarily as vertical leakage to the underlying drift. The greatest vertical leakage occurs where the tailings immediately overlie the outwash (fig. 2).

Ground-Water-Level Fluctuations

Water levels in the vicinity of the tailings basin are constantly changing, indicating that the basin is a dynamic inflow-outflow system. Water-level fluctuations result from seasonal imbalances between areal recharge from precipitation and ground-water outflow from the basin. Because areal differences in hydraulic characteristics of tailings and adjacent aquifers vary over space, the magnitude of the fluctuations is not areally uniform. Figure 8 shows water-level fluctuations during 1983 for selected wells in the vicinity of the initial tailings basin. Water-level changes ranged from about 1 ft in well KTB-2 (completed in outwash underlying the basin) to about 8 ft in well KTB-9 (completed in fine tailings near the pond in the southwest part of the basin). The average change in water levels in 1983 was about 5 ft in wells completed in fine tailings, 3 ft in wells completed in medium tailings, and about 2 ft in wells completed in either coarse tailings or outwash.



Base from U.S. Geological Survey
Keewatin 1:24,000, 1969
Silica 1:24,000, 1976

0 ½ 1 MILE
0 ½ 1 KILOMETER

EXPLANATION

Initial tailings basin

—1500— WATER TABLE CONTOUR--Shows altitude of water table in the tailings. Contour interval is 5 feet. Datum is sea level.

—1500— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of the drift aquifer underlying the tailings. Contour interval is 5 feet. Datum is sea level.

● Observation well-nested

• Observation well-single

Figure 7.--Water table in the tailings and potentiometric surface of the underlying drift aquifer, August 1983.

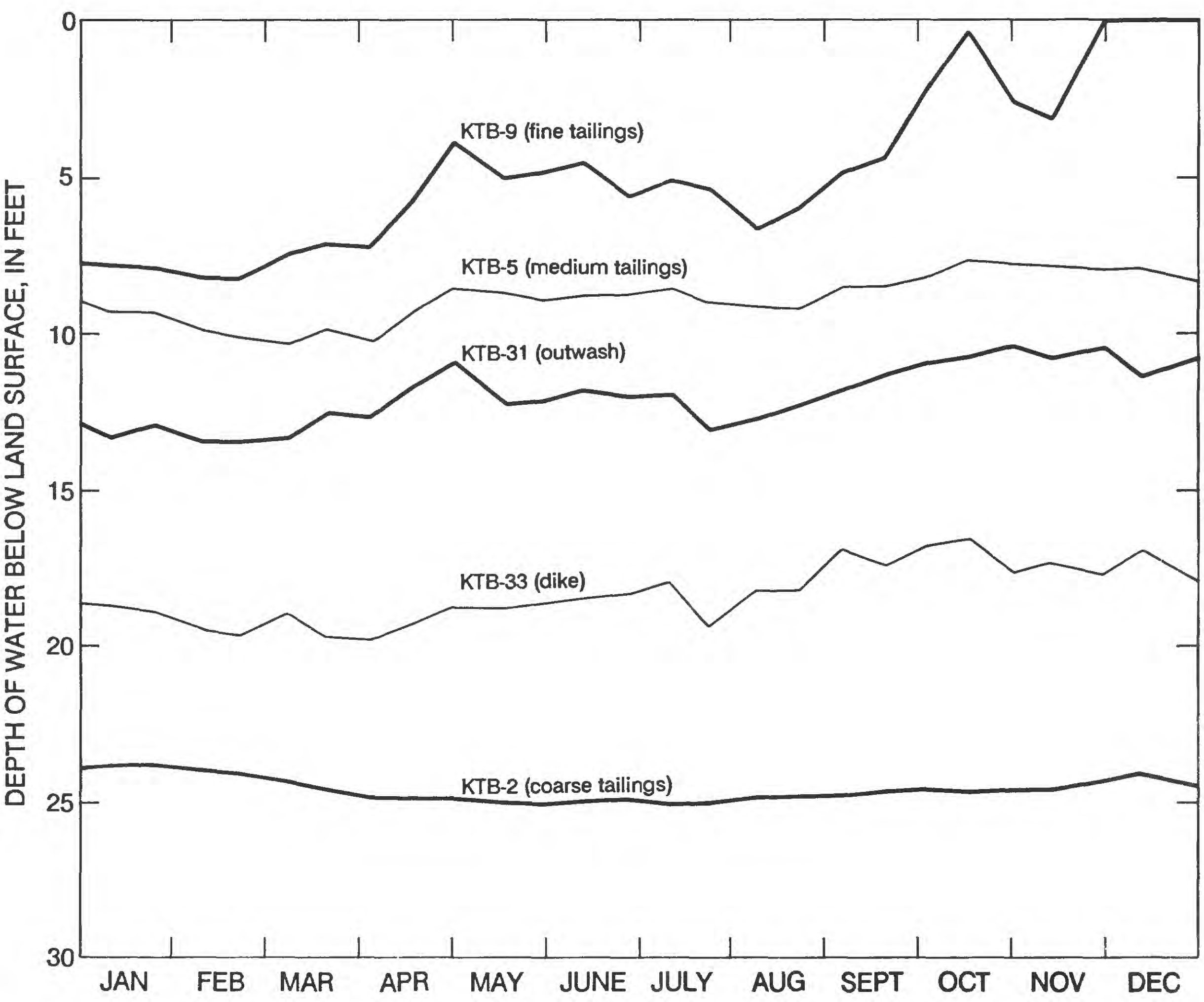


Figure 8.--Water level fluctuations in selected wells in the vicinity of the initial tailings basin, 1983.

Some of the water-level fluctuations in each well can be attributed to changes in barometric pressure. The observed water level in a cased well changes inversely in response to changes in barometric pressure--that is, water levels in the well decline as barometric pressure rises and rise as barometric pressure falls. The ratio of water-level change to barometric pressure change expresses the barometric efficiency of an aquifer (Todd, 1959, p. 158). Because of the interbedding of fine material within the tailings, all the wells in the tailings, including those screened at the water table, display some effect of barometric changes. Barometric efficiencies of the wells range from about 35 percent in well KTB-16 (completed in coarse tailings) to about 65 percent in well KTB-32 (completed in fine tailings). The hydrograph shown in figure 6 was developed and calculations were based on long-term changes, thereby eliminating the short-term effects of barometric changes.

Hydrologic Budget

An approximate hydrologic budget was developed for the initial tailings basin for the 1983 water year. Because historical water-level data do not exist and because unique hydrologic conditions occurred during that year, the budget is approximate and probably does not represent a long-term budget. The equation used for calculations of the budget was modified from Walton (1970, p. 375). Components of the hydrologic budget are:

$$P = R + Et + G \pm S,$$

where P is precipitation,
R is streamflow (surface-water outflow),
Et is evapotranspiration,
G is ground-water leakage out the bottom of the tailings, and
S is change in ground-water storage.

Estimates of each component of the budget are subject to errors because of areal differences in hydrologic properties, limits of instrumentation, and limited data. Data for this study are insufficient to estimate the percent error in each component; however, Winter (1981) suggests that errors in hydrologic budgets can range from 5 to 30 percent.

Precipitation and temperature data were obtained from records at the National Oceanic and Atmospheric Administration weather station at Hibbing Airport, and were assumed to be the same as at the tailings basin, 5 miles to the west. Precipitation totaled 29.7 in. during the 1983 water year. Evapotranspiration was calculated using techniques developed by Thornthwaite and Mather (1957) and described by Cruff and Thompson (1967, M7). Evapotranspiration for the 1983 water year was calculated to be 18.8 in.

Streamflow at the outlet of the tailings basin averaged 0.30 ft^3/s during the 1983 water year, which is equivalent to about 1.6 in. of runoff from the basin. Change in ground-water storage over the long term is assumed to be zero (Oakes and Bidwell, 1968). The change in water year 1983 was estimated by averaging the net change in ground-water level at each observation well during the year and multiplying by the specific yield of the aquifer. Using this method, the change in ground-water storage in the 1983 water year was calculated to be -0.6 in (net loss).

Ground-water leakage out of the tailings to the underlying drift aquifer was calculated as the residual to the balance equation, which amounted to 9.9 in. for water year 1983.

Components of the hydrologic budget for the tailings basin, using these values and the equation above, for the 1983 water year, are

$$P\ (29.7\text{ in.}) = R\ (1.6\text{ in.}) + Et\ (18.8\text{ in.}) + G + S\ (-0.6\text{ in.})$$

$$G = 9.9\text{ in. (calculated as the residual).}$$

The hydrologic-budget values for water year 1983 are used in this report because they generally agree with long-term values and are based on field data collected specifically for this study.

WATER QUALITY

Chemical composition of surface and ground water is influenced by the chemical composition of precipitation and by the material through which the water moves. The degree of influence depends largely on residence time, chemical and physical properties of soil or aquifer material through which the water moves, and, to some extent, chemical reactions, such as oxidation and ion exchange, which are affected by pH and temperature. Quality of water also can be altered by human activities, such as land-surface application of mine tailings, fertilizers, pesticides, and industrial wastes, and spills of chemicals and petroleum products.

Suitability of water commonly is determined by the intended use. In Minnesota, for example, the most stringent water-quality standards are applied to waters intended for domestic consumption or food processing. Standards also are established for other uses such as fisheries and recreation, industrial and agriculture, and wildlife. A complete set of water-quality standards is available from the Minnesota Pollution Control Agency. For this report, results of water-quality analyses are compared to recommended limits for domestic consumption as established by the Minnesota Pollution Control Agency.

The quality of water in the vicinity of the initial tailings basin was investigated by analyzing water samples collected from four ground-water and two surface-water sites. The ground-water sites are part of the well network installed in the vicinity of the basin to measure water-level fluctuations. The four sampling wells were constructed with plastic (PVC) casing and screens to avoid contamination of the samples by metals from the casing. Two of the wells were completed outside the tailings basin; one in the younger tailings and one, as a control, just below the water table in the outwash. Construction and lithologic data for sampling wells are provided in table 5. Surface-water samples were collected from the pond and the outlet of the basin. Samples were collected periodically during the 1982-84 study period. Locations of sampling sites are shown in figure 4.

Samples were collected, preserved, and analyzed following techniques outlined by Greeson and others (1977), Porterfield (1972), Skougstad and others (1979), and Wershaw and others (1983). Before sampling, each well was pumped until several times its volume of water was removed and values of pH, specific conductance, and temperature stabilized. All samples, with the exception of sediment, were filtered and preserved as appropriate and shipped for analysis to the U.S. Geological Survey's Central Laboratory in Atlanta, Ga. Sediment samples were collected in special glass bottles and shipped for analysis to the U.S. Geological Survey's Sediment Laboratory in Iowa City, Iowa. Sediment samples were collected and analyzed following techniques outlined by Porterfield (1972). Concentrations of chemical constituents are expressed either in milligrams per liter (mg/L) or micrograms per liter (μg/L). Sediment concentrations and loads are expressed in milligrams per liter and tons per day (ton/d), respectively.

Selected Chemical Constituents

Water-quality analyses listed and described below are representative of ground water and surface water in the vicinity of the sampling point. However, because of the variation in water quality, the extent to which data from the analyses may be interpolated or extrapolated to other sites is unknown. Therefore, analyses are only compared between sample sites. Table 6 shows chemical analyses of water for selected constituents collected periodically from representative sites in the vicinity of the initial tailings basin during 1982-84. Table 7 summarizes the suspended sediment collected at the continuous-record stream-gaging station located on the tailings basin outflow. Table 8 is a summary of the results of the chemical analyses for the wells.

Chemical constituents sampled for during this study were considered because they have potential to affect the human health or the well being of plants and animals. Standards and recommended limits for many of these constituents have been established by the MPCA (1988) for the protection of human health and plant and animal life.

Arsenic occurs naturally in many waters. The recommended limit for domestic consumption of arsenic is 10 μg/L (MPCA, 1988). The concentration of arsenic averaged about 5 μg/L in water from the tailings and about 1 μg/L in water from the adjacent drift, and did not exceed drinking water standards.

Barium also occurs naturally in water. The highest concentration of barium (100 μg/L) was observed in surface water at the outlet of the basin and was well below the MPCA (1988) standard of 1,000 μg/L for domestic consumption. The high concentrations in surface water may be related to the affinity of barium adsorption by oxides or hydroxides of iron and manganese (Ljunggren, 1955). The highest concentrations of iron also were observed at the outlet of the basin. Barium is not expected to be present in water from the tailings in concentrations sufficient to be a threat to health.

Table 5.--*Construction and lithologic data for water-quality-sampling wells*

Site number	Date of construction	Altitude of land surface (feet above sea level)	Altitude of water level (feet above sea level)	Date of water level	Diameter of well (inches)
KTB32	9-22-82	1,495.4	1,490.9	11-01-82	5
KTB31	9-21-82	1,495.4	1,484.1	11-01-82	5
KTB26	8-19-82	1,481.7	1,462.1	11-01-82	2
KTB30	9-20-82	1,495.0	1,478.6	11-01-82	5

Site	Lithology	Thickness (feet)	Depth interval (feet)	Length of casing (feet)	*Screened interval (feet)	**Measuring point (feet)
KTB-32	Tailings, very fine, sand, silty, gray...............	17	0 - 17	10	7 - 17 (tailings)	3.1
KTB-31	Tailings, very fine sand, silty, gray..............	38	0 - 38	48	45 - 60 (outwash below tailings)	3.0
	Peat, organic, black..............	3	38 - 41			
	Sand, fine to coarse, with fine gravel............	27	41 - 68			
	Till, sandy, red....	7	68 - 75			
KTB-26	Tailings, coarse, sandy, gray........	24	0 - 24	24	21 - 24 (tailings outside of basin)	3.3
	Till, sandy, gray...............	2	24 - 26			
	Sand, medium........	3	26 - 29			
	Till, gravelly, red................	8	29 - 37			
KTB-30	Sand, fine, silty with trace of clay...........	17	0 - 17	19	16 - 26 (outwash outside of basin)	3.4
	Sand, fine with some medium to coarse, silty......	9	17 - 26			
	Till, sandy with scattered rocks, red................	3	26 - 29			

* Feet below land surface
**Feet of casing above land surface

Table 6.--*Results of chemical analyses*

[MP, measuring point, generally top of well casing; ft^3/s, cubic feet per second; ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed for; <, less than. See text for a discussion of the terms (1) total, (2) total recoverable, (3) dissolved, (4) volatile solids, and (5) solids, residue at 180 °C.]

Site	Date of sample	Sampling depth (in feet) below MP	Streamflow, instantaneous (ft^3/s)	Specific conductance (µS/cm) field	Specific conductance (µS/cm) laboratory	pH (standard units)	Temperature (°C)	Chemical oxygen demand (high level) (mg/L)	Hardness (mg/L as $CaCO_3$) carbonate	Hardness (mg/L as $CaCO_3$) noncarbonate	Calcium (mg/L as Ca) recoverable	Calcium (mg/L as Ca) dissolved
Outlet	10/07/82	--	11	260	264	8.0	8.0	25	--	--	13	--
	06/08/84	--	26	230	269	6.9	18.0	43	120	0	12	12
Pond	08/10/82	--	--	390	402	8.9	14.0	--	200	50	--	14
KTB-32 (Tailings)	10/19/82	17	--	340	343	8.4	10.0	42	140	63	--	23
	11/01/82	17	--	405	388	8.5	10.0	--	150	46	--	24
	11/16/82	17	--	400	392	8.2	9.0	--	150	43	--	23
	11/29/82	17	--	380	375	8.6	8.5	--	150	39	--	23
	09/09/83	17	--	400	391	6.9	12.0	--	160	39	--	24
	05/17/84	17	--	420	372	8.3	10.0	--	160	69	--	20
KTB-31 (Drift)	10/19/82	60	--	440	464	8.6	7.0	46	220	10	--	57
	11/01/82	60	--	400	411	9.1	8.0	--	210	27	--	58
	11/16/82	60	--	380	304	9.3	8.0	--	120	4	--	30
	11/29/82	60	--	360	278	9.5	8.0	--	110	0	--	26
	09/09/83	60	--	550	477	7.7	6.0	--	210	0	--	58
	05/17/84	60	--	580	541	7.6	9.0	--	230	0	--	52
KTB-26 (Tailings)	10/14/82	24	--	760	794	7.8	9.0	49	320	58	--	30
	11/02/82	24	--	810	793	7.7	9.0	--	270	0	--	26
	11/16/82	24	--	750	740	7.9	9.0	--	260	0	--	25
	11/29/82	24	--	700	688	6.8	9.0	--	240	0	--	23
	09/09/83	24	--	980	980	7.8	10.0	--	360	110	--	32
	05/16/84	24	--	1200	1270	7.9	8.0	--	460	78	--	44
KTB-30 (Drift)	10/14/82	26	--	110	124	6.2	9.0	<10	46	0	--	13
	11/02/82	26	--	105	100	6.1	8.0	--	39	1	--	11
	11/16/82	26	--	105	97	6.1	9.0	--	40	2	--	12
	11/29/82	26	--	105	96	6.2	9.0	--	37	0	--	11
	09/09/83	26	--	110	97	5.8	8.0	--	36	6	--	10
	05/16/84	26	--	80	89	6.2	7.0	--	31	6	--	8.8

Table 6.--*Results of chemical analyses*--Continued

Site	Date of sample	Magnesium (mg/L as Mg) total recoverable	Magnesium (mg/L as Mg) dissolved	Sodium (mg/L as Na) total recoverable	Sodium (mg/L as Na) dissolved	Sodium percent	Sodium adsorption ratio	Potassium (mg/L as K) total recoverable	Potassium (mg/L as K) dissolved	Alkalinity, laboratory (mg/L as $CaCO_3$)	Sulfate dissolved (mg/L as SO_4)
Outlet	10/07/82	22	--	4.8	--	--	--	3.2	--	96	23
	06/08/84	24	23	3.3	3.3	5	0.1	1.9	1.8	131	9.8
Pond	08/10/82	--	39	--	14	13	.4	--	2.1	146	72
KTB-32 (Tailings)	10/19/82	--	21	--	15	18	.6	--	2.4	81	70
	11/01/82	--	22	--	19	21	.7	--	2.9	105	61
	11/16/82	--	23	--	15	17	.5	--	2.5	109	60
	11/29/82	--	22	--	16	19	.6	--	2.3	109	61
	09/09/83	--	24	--	15	17	.5	--	1.8	120	70
	05/17/84	--	26	--	13	15	.5	--	1.5	88	68
KTB-31 (Drift)	10/19/82	--	19	--	18	15	.5	--	3.9	211	26
	11/01/82	--	17	--	19	16	.6	--	3.9	188	19
	11/16/82	--	12	--	14	19	.6	--	4.3	120	21
	11/29/82	--	11	--	17	24	.7	--	4.3	117	19
	09/09/83	--	17	--	17	14	.5	--	4.2	215	22
	05/17/84	--	25	--	20	15	.6	--	5.5	239	17
KTB-26 (Tailings)	10/14/82	--	60	--	75	33	2	--	8.6	264	96
	11/02/82	--	50	--	62	32	2	--	9.1	304	89
	11/16/82	--	47	--	50	29	1	--	8.8	297	87
	11/29/82	--	44	--	57	33	2	--	8.6	280	74
	09/09/83	--	69	--	65	27	1	--	8.7	254	110
	05/16/84	--	84	--	110	34	2	--	14	378	220
KTB-30 (Drift)	10/14/82	--	3.2	--	3.8	15	.3	--	1.4	47	5.0
	11/02/82	--	2.8	--	3.5	16	.3	--	1.2	38	8.0
	11/16/82	--	2.4	--	2.6	12	.2	--	1.2	38	7.0
	11/29/82	--	2.4	--	3.3	16	.2	--	1.2	37	6.0
	09/09/83	--	2.6	--	3.6	17	.3	--	1.1	30	12
	05/16/84	--	2.1	--	2.7	15	.2	--	2.8	25	6.8

Table 6.--*Results of chemical analyses*--Continued

Site	Date of sample	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids (mg/L): residue at 180 °C, dissolved	Solids (mg/L): residue at 180 °C, total	Solids (mg/L): sum constituents dissolved	Solids (mg/L): volatile, on ignition	Solids (mg/L): volatile, dissolved
Outlet	10/07/82	2.2	--	4.6	--	--	--	80	--
	06/08/84	1.1	--	12	--	151[1]	140	75	72
Pond	08/10/82	5.2	0.5	.3	247	--	230	--	--
KTB-32 (Tailings)	10/19/82	19	1.5	23	243	--	220	--	58
	11/01/82	18	1.4	25	232	--	240	--	--
	11/16/82	14	1.3	24	250	--	230	--	--
	11/29/82	12	1.5	22	212	--	230	--	--
	09/09/83	16	1.3	21	231	--	250	--	--
	05/17/84	16	1.4	19	256	--	220	--	--
KTB-31 (Drift)	10/19/82	9.7	.30	29	312	--	290	--	52
	11/01/82	9.4	.30	27	251	--	270	--	--
	11/16/82	8.9	.30	25	219	--	190	--	--
	11/29/82	8.2	.30	25	203	--	180	--	--
	09/09/83	12	.30	32	295	--	290	--	--
	05/17/84	12	.40	31	342	--	310	--	--
KTB-26 (Tailings)	10/14/82	18	1.5	25	469	--	470	--	103
	11/02/82	16	1.5	22	463	--	460	--	--
	11/16/82	17	1.5	22	442	--	440	--	--
	11/29/82	12	1.7	22	414	--	410	--	--
	09/09/83	16	1.3	22	612	--	480	--	--
	05/16/84	13	1.2	22	849	--	740	--	--
KTB-30 (Drift)	10/14/82	1.4	<.10	23	74	--	80	--	17
	11/02/82	1.2	<.10	21	77	--	72	--	--
	11/16/82	.90	<.10	20	78	--	69	--	--
	11/29/82	1.0	<.10	20	110	--	67	--	--
	09/09/83	2.0	.10	20	75	--	70	--	--
	05/16/84	2.9	<.10	18	78	--	59	--	--

[1] Value is for residue at 105 °C

Table 6.--*Results of chemical analyses*--Continued

Site	Date of sample	Nitrogen (mg/L as N) NO2 + NO3 total	NO2 + NO3 dissolved	ammonia total	ammonia dissolved	organic total	ammonia + organic total	ammonia + organic dissolved	total	(mg/L as NO3) total
Outlet	10/07/82	<0.10	--	0.03	--	.57	.60	--	--	--
	06/08/84	<.10	<0.10	.02	0.02	1.2	1.2	1.2	--	--
Pond	08/10/82	<.10	<.10	<.01	--	--	--	--	--	--
KTB-32 (Tailings)	10/19/82	.30	<.10	.48	--	.32	.80	--	1.1	4.9
	11/01/82	.20	<.10	.28	--	.02	.30	--	.50	2.2
	11/16/82	<.10	<.10	.50	--	.08	.50	--	--	--
	11/29/82	.40	<.10	.60	--	.08	.60	--	1.0	4.4
	09/09/83	<.10	<.10	.12	--	.58	.70	--	--	--
	05/17/84	<.10	<.10	.04	--	5.3	5.3	--	--	--
KTB-31 (Drift)	10/19/82	<.10	<.10	.15	--	.05	.20	--	--	--
	11/01/82	<.10	<.10	.18	--	2.3	2.5	--	--	--
	11/16/82	<.10	<.10	.24	--	.36	.60	--	--	--
	11/29/82	<.10	<.10	.33	--	.07	.40	--	--	--
	09/09/83	<.10	<.10	.21	--	.69	.90	--	--	--
	05/17/84	<.10	<.10	.52	--	5.7	6.2	--	--	--
KTB-26 (Tailings)	10/14/82	6.9	6.1	.09	--	1.0	1.1	--	8.0	35
	11/02/82	4.7	4.7	.10	--	.20	.30	--	5.0	22
	11/16/82	1.8	1.8	.12	--	.08	.20	--	2.0	8.9
	11/29/82	1.0	1.0	.12	--	.08	.20	--	1.2	5.3
	09/09/83	48	3.8	.06	--	.84	.90	--	49	220
	05/16/84	28	27	<.01	--	--	4.2	--	32	140
KTB-30 (Drift)	10/14/82	.80	.80	.06	--	.44	.50	--	1.3	5.8
	11/02/82	1.0	.99	.02	--	.18	.20	--	1.2	5.3
	11/16/82	1.1	1.1	.04	--	.26	.30	--	1.4	6.2
	11/29/82	1.2	1.2	.05	--	.25	.30	--	1.5	6.6
	09/09/83	1.4	1.4	.06	--	.64	.70	--	2.1	9.3
	05/16/84	1.0	1.1	.38	--	4.9	5.3	--	6.3	28

Table 6.--*Results of chemical analyses*--Continued

Site	Date of sample	Phosphorus (mg/L as P) total	Phosphorus (mg/L as P) dissolved	Phosphorus (mg/L as P) ortho, total	Arsenic (µg/L as As) total	Arsenic (µg/L as As) dissolved	Barium (µg/L as Ba) total recoverable	Barium (µg/L as Ba) dissolved	Beryllium (µg/L as Be) dissolved	Boron (µg/L as B) total recoverable	Boron (µg/L as B) dissolved
Outlet	10/07/82	.10	--	--	4	--	100	--	--	50	--
	06/08/84	.02	.02	--	2	2	<100	<100	--	30	20
Pond	08/10/82	--	--	<0.01	--	5	--	12	<1	--	80
KTB-32 (Tailings)	10/19/82	--	--	.28	--	5	--	15	<1	--	60
	11/01/82	--	--	.09	--	--	--	--	--	--	--
	11/16/82	--	--	.14	--	--	--	--	--	--	--
	11/29/82	--	--	.27	--	--	--	--	--	--	--
	09/09/83	--	--	<.01	--	--	--	--	--	--	--
	05/17/84	--	--	<.01	--	--	--	--	--	--	--
KTB-31 (Drift)	10/19/82	--	--	<.01	--	1	--	24	<1	--	30
	11/01/82	--	--	<.01	--	--	--	--	--	--	--
	11/16/82	--	--	<.01	--	--	--	--	--	--	--
	11/29/82	--	--	<.01	--	--	--	--	--	--	--
	09/09/83	--	--	.02	--	--	--	--	--	--	--
	05/17/84	--	--	.02	--	--	--	--	--	--	--
KTB-26 (Tailings)	10/14/82	--	--	<.01	--	5	--	60	<.5	--	150
	11/02/82	--	--	<.01	--	--	--	--	--	--	--
	11/16/82	--	--	<.01	--	--	--	--	--	--	--
	11/29/82	--	--	<.01	--	--	--	--	--	--	--
	09/09/83	--	--	<.01	--	--	--	--	--	--	--
	05/16/84	--	--	<.01	--	--	--	--	--	--	--
KTB-30 (Drift)	10/14/82	--	--	.01	--	1	--	30	<.5	--	20
	11/02/82	--	--	<.01	--	--	--	--	--	--	--
	11/16/82	--	--	<.01	--	--	--	--	--	--	--
	11/29/82	--	--	.02	--	--	--	--	--	--	--
	09/09/83	--	--	<.01	--	--	--	--	--	--	--
	05/16/84	--	--	<.01	--	--	--	--	--	--	--

Table 6.--*Results of chemical analyses*--Continued

Site	Date of sample	Cadmium (µg/L as Cd)		Chromium (µg/L as Cr)		Cobalt, dissolved (µg/L as Co)	Copper (µg/L as Cu)		Iron (µg/L as Fe)	
		total recoverable	dissolved	total recoverable	dissolved		total recoverable	dissolved	total recoverable	dissolved
Outlet	10/07/82	1	--	<1	--	--	6	--	450	--
	06/08/84	1	1	1	<1	--	3	3	690	180
Pond	08/10/82	--	<1	--	10	<3	--	<10	--	10
					--					
KTB-32 (Tailings)	10/19/82	--	<1	--	<1	<3	--	<10	--	91
	11/01/82	--	--	--	--	--	--	--	--	--
	11/16/82	--	--	--	--	--	--	--	--	--
	11/29/82	--	--	--	--	--	--	--	--	--
	09/09/83	--	--	--	--	--	--	--	--	--
	05/17/84	--	--	--	--	--	--	--	--	--
KTB-31 (Drift)	10/19/82	--	<1	--	<1	<3	--	<10	--	16
	11/01/82	--	--	--	--	--	--	--	--	--
	11/16/82	--	--	--	--	--	--	--	--	--
	11/29/82	--	--	--	--	--	--	--	--	--
	09/09/83	--	--	--	--	--	--	--	--	--
	05/17/84	--	--	--	--	--	--	--	--	--
KTB-26 (Tailings)	10/14/82	--	<1	--	1	<3	--	<10	--	16
	11/02/82	--	--	--	--	--	--	--	--	--
	11/16/82	--	--	--	--	--	--	--	--	--
	11/29/82	--	--	--	--	--	--	--	--	--
	09/09/83	--	--	--	--	--	--	--	--	--
	05/16/84	--	--	--	10	--	--	--	--	--
KTB-30 (Drift)	10/14/82	--	<1	--	1	4	--	<10	--	14
	11/02/82	--	--	--	--	--	--	--	--	--
	11/16/82	--	--	--	--	--	--	--	--	--
	11/29/82	--	--	--	--	--	--	--	--	--
	09/09/83	--	--	--	--	--	--	--	--	--
	05/16/84	--	--	--	--	--	--	--	--	--

Table 6.--*Results of chemical analyses*--Continued

Site	Date of sample	Lead (µg/L as Pb) total recoverable	Lead (µg/L as Pb) dissolved	Lithium, dissolved (µg/L as Li)	Manganese (µg/L as Mn) total recoverable	Manganese (µg/L as Mn) dissolved	Mercury (µg/L as Hg) total recoverable	Mercury (µg/L as Hg) dissolved	Molybdenum, dissolved (µg/L) as Mo)
Outlet	10/07/82	2	--	--	40	--	--	--	--
	06/08/84	2	1	--	70	20	.1	0.1	--
Pond	08/10/82	--	<10	<4	--	3	--	<.1	20
KTB-32 (Tailings)	10/19/82	--	10	<4	--	280	--	.4	100
	11/01/82	--	--	--	--	380	--	--	--
	11/16/82	--	--	--	--	360	--	--	--
	11/29/82	--	--	--	--	350	--	--	--
	09/09/83	--	--	--	--	1100	--	--	--
	05/17/84	--	--	--	--	780	--	--	--
KTB-31 (Drift)	10/19/82	--	<10	8	--	1400	--	.2	10
	11/01/82	--	--	--	--	1100	--	--	--
	11/16/82	--	--	--	--	610	--	--	--
	11/29/82	--	--	--	--	520	--	--	--
	09/09/83	--	--	--	--	1500	--	--	--
	05/17/84	--	--	--	--	1200	--	--	--
KTB-26 (Tailings)	10/14/82	--	<10	30	--	300	--	.3	130
	11/02/82	--	--	--	--	290	--	--	--
	11/16/82	--	--	--	--	270	--	--	--
	11/29/82	--	--	--	--	260	--	--	--
	09/09/83	--	--	--	--	300	--	--	--
	05/16/84	--	--	--	--	320	--	--	--
KTB-30 (Drift)	10/14/82	--	<10	<4	--	500	--	<.1	<10
	11/02/82	--	--	--	--	470	--	--	--
	11/16/82	--	--	--	--	400	--	--	--
	11/29/82	--	--	--	--	410	--	--	--
	09/09/83	--	--	--	--	130	--	--	--
	05/16/84	--	--	--	--	38	--	--	--

Table 6.--*Results of chemical analyses*--Continued

Site	Date of sample	Nickel (µg/L as Ni) total recoverable	Nickel (µg/L as Ni) dissolved	Selenium (µg/L as Se) total	Selenium (µg/L as Se) dissolved	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Zinc (µg/L as Zn) total recoverable	Zinc (µg/L as Zn) dissolved	Carbon, total organic (mg/L as C)	Phenols, total (µg/L as C_6H_5OH)
Outlet	10/07/82	3	--	<1	--	--	--	70	--	5.6	12
	06/08/84	<1	<1	<1	<1	--	--	20	20	7.8	3
Pond	08/10/82	--	<100	--	<1	44	<6	--	5	5.5	--
KTB-32 (Tailings)	10/19/82	--	2	--	<1	69	<6	--	<4	3.8	<1
	11/01/82	--	--	--	--	--	--	--	--	27	<1
	11/16/82	--	--	--	--	--	--	--	--	>90	--
	11/29/82	--	--	--	--	--	--	--	--	42	--
	09/09/83	--	--	--	--	--	--	--	--	60	--
	05/17/84	--	--	--	--	--	--	--	--	3.8	--
KTB-31 (Drift)	10/19/82	--	3	--	<1	140	<6	--	<4	6.2	<1
	11/01/82	--	--	--	--	--	--	--	--	7.5	<1
	11/16/82	--	--	--	--	--	--	--	--	5.9	--
	11/29/82	--	--	--	--	--	--	--	--	5.9	--
	09/09/83	--	--	--	--	--	--	--	--	7.4	--
	05/17/84	--	--	--	--	--	--	--	--	8.1	--
KTB-26 (Tailings)	10/14/82	--	3	--	<1	130	<6	--	<3	2.8	<1
	11/02/82	--	--	--	--	--	--	--	--	2.9	<1
	11/16/82	--	--	--	--	--	--	--	--	2.0	--
	11/29/82	--	--	--	--	--	--	--	--	1.8	--
	09/09/83	--	--	--	--	--	--	--	--	1.9	--
	05/16/84	--	--	--	--	--	--	--	--	1.4	--
KTB-30 (Drift)	10/14/82	--	10	--	<1	70	<6	--	19	3.3	<1
	11/02/82	--	--	--	--	--	--	--	--	3.7	<1
	11/16/82	--	--	--	--	--	--	--	--	1.8	--
	11/29/82	--	--	--	--	--	--	--	--	1.6	--
	09/09/83	--	--	--	--	--	--	--	--	3.3	--
	05/16/84	--	--	--	--	--	--	--	--	2.1	--

Table 7.--*Suspended sediment at tailings-basin outflow*

[μS/cm, microsiemens per centimeter; mg/L, milligrams per liter; °C, degrees Celsius; ft^3/s, cubic feet per second; mm, millimeter; --, no data]

Date	Temperature (°C)	Streamflow (ft^3/s) instantaneous	Streamflow (ft^3/s) daily mean	Specific conductance (μS/cm)	Suspended sediment (percent finer than) sieve diameter .062 mm	sieve diameter .125 mm	fall diameter .002 mm	fall diameter .004 mm	fall diameter .008 mm	fall diameter .016 mm	fall diameter .062 mm	fall diameter .125 mm	Suspended sediment (mg/L)
4/13/82	0.5	--	1.4	--	100	--	33	54	80	93	--	--	1580
4/14/82	1	--	13	--	100	--	33	43	62	79	--	--	1930
4/14/82	1	--	13	--	99	--	--	--	--	--	--	--	2380
4/14/82	1	--	13	--	98	--	--	--	--	--	--	--	2890
4/15/82	5	--	66	--	--	--	26	40	53	72	98	100	3430
4/15/82	7	--	66	--	--	--	28	35	45	60	98	100	2200
4/16/82	2.5	--	27	--	99	100	39	55	--	85	--	--	652
7/26/82	29	--	.28	--	100	--	--	--	--	--	--	--	1
4/ 6/83	.5	1.7	1.7	240	96	--	--	--	--	--	--	--	11
4/12/83	2	0.82	.3	340	93	--	--	--	--	--	--	--	5
4/19/83	3.5	.79	.79	384	86	--	--	--	--	--	--	--	7
5/ 2/83	9.5	.06	.06	570	88	--	--	--	--	--	--	--	5
10/ 3/83	13	--	5.8	--	62	--	--	--	--	--	--	--	2
4/ 2/84	8.5	.67	5.5	350	96	--	--	--	--	--	--	--	77
5/16/84	--	11	3.8	--	98	--	--	--	--	--	--	--	179
5/16/84	--	12	3.8	--	99	--	--	--	--	--	--	--	135
5/16/84	--	12	3.8	--	100	--	--	--	--	--	--	--	77
6/ 7/84	25	1.3	1.3	420	100	--	--	--	--	--	--	--	28
6/ 7/84	24	--	1.3	440	81	--	--	--	--	--	--	--	10
6/ 8/84	--	10	19	--	99	--	--	--	--	--	--	--	96
6/ 8/84	--	12	19	--	99	--	--	--	--	--	--	--	79
6/ 8/84	--	14	19	--	100	--	--	--	--	--	--	--	94
6/ 8/84	--	15	19	--	99	--	--	--	--	--	--	--	83
6/ 8/84	--	17	19	--	98	--	--	--	--	--	--	--	52
6/ 8/84	--	19	19	--	97	--	--	--	--	--	--	--	103
6/ 8/84	--	22	19	--	96	--	--	--	--	--	--	--	12
6/ 8/84	--	29	19	--	98	--	--	--	--	--	--	--	18
6/ 8/84	--	28	19	--	93	--	--	--	--	--	--	--	7
6/ 8/84	--	27	19	--	98	--	--	--	--	--	--	--	13
6/ 8/84	18	27	19	230	99	--	--	--	--	--	--	--	31

Table 7.--***Suspended sediment at tailings-basin outflow***--Continued

Date	Temperature (°C)	Streamflow (ft^3/s) instantaneous	Streamflow (ft^3/s) daily mean	Specific conductance (µS/cm)	Suspended sediment (percent finer than) sieve diameter .062 mm	sieve diameter .125 mm	fall diameter .002 mm	fall diameter .004 mm	fall diameter .008 mm	fall diameter .016 mm	fall diameter .062 mm	fall diameter .125 mm	Suspended sediment (mg/L)
6/ 8/84	--	26	19	--	96	--	--	--	--	--	--	--	33
6/ 8/84	--	25	19	--	84	--	--	--	--	--	--	--	13
6/ 8/84	--	24	19	--	97	--	--	--	--	--	--	--	4
6/ 8/84	--	17	19	--	93	--	--	--	--	--	--	--	10
6/ 8/84	--	14	19	--	97	--	--	--	--	--	--	--	10
6/ 8/84	--	12	19	--	93	--	--	--	--	--	--	--	4
6/10/84	--	11	12	--	98	--	--	--	--	--	--	--	36
6/10/84	--	15	12	--	98	--	--	--	--	--	--	--	23
6/10/84	--	15	12	--	93	--	--	--	--	--	--	--	10
6/10/84	--	16	12	--	92	--	--	--	--	--	--	--	5
6/10/84	--	17	12	--	89	--	--	--	--	--	--	--	5
6/10/84	--	16	12	--	96	--	--	--	--	--	--	--	3
6/10/84	--	15	12	--	86	--	--	--	--	--	--	--	4
6/10/84	--	12	12	--	88	--	--	--	--	--	--	--	2
6/12/84	--	9.7	11	--	92	--	--	--	--	--	--	--	408
6/12/84	--	26	11	--	92	--	--	--	--	--	--	--	76
6/13/84	--	11	11	--	90	--	--	--	--	--	--	--	4
6/13/84	18	10	11	330	93	--	--	--	--	--	--	--	5
3/25/85	1.5	.51	.51	390	92	--	--	--	--	--	--	--	52
3/25/85	--	--	.51	--	89	--	--	--	--	--	--	--	34

Table 8.--*Statistical summary of selected chemical constituents in water from wells in the vicinity of the initial tailings basin near Keewatin, Minnesota, 1982-84*

[The statistics are based upon six samples unless otherwise noted. °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; >, greater than; ---, no data]

Statistic	Well	Specific conductance (µS/cm) field	Specific conductance (µS/cm) laboratory	pH (standard units)	Hardness (mg/L as $CaCO_3$) carbonate	Hardness (mg/L as $CaCO_3$) noncarbonate	Calcium, dissolved (mg/L as $CaCO_3$)
Mean	KTB-32	376.8	376.8	---	151.7	49.8	22.8
	KTB-31	451.7	412.5	---	183.3	6.8	46.8
	KTB-26	866.7	877.5	---	318.3	41	30
	KTB-30	102.5	100.5	---	38.2	2.5	11.0
Median	KTB-32	402.5	381.5	8.3	150	44.5	23
	KTB-31	420	437.5	8.85	210	10	54.5
	KTB-26	800	793.5	7.8	295	29	28
	KTB-30	105	97	6.15	38	1.5	11
Maximum	KTB-32	420	392	8.6	160	69	24
	KTB-31	580	541	9.5	230	27	58
	KTB-26	1200	1270	7.9	460	110	44
	KTB-30	110	124	6.2	46	6	13
Minimum	KTB-32	340	343	6.9	140	39	20
	KTB-31	360	278	7.6	110	0	26
	KTB-26	700	688	6.8	240	0	23
	KTB-30	80	89	5.8	31	0	8.8

Statistic	Well	Magnesium, dissolved (mg/L as $CaCO_3$)	Sodium dissolved (mg/L as Na)	Sodium percent	Sodium adsorption ratio	Potassium, dissolved (mg/L as K)
Mean	KTB-32	23	15.5	17.8	.57	2.23
	KTB-31	16.8	17.5	17.2	.58	4.35
	KTB-26	59	69.8	31.3	1.7	9.63
	KTB-30	2.58	3.25	15.2	.25	1.48
Median	KTB-32	22.5	15	17.5	5.5	2.35
	KTB-31	17	17.5	15.5	.6	4.25
	KTB-26	55	63.5	32.5	2	8.75
	KTB-30	2.5	3.4	15.5	.25	1.2
Maximum	KTB-32	26	19	21	.7	2.9
	KTB-31	25	20	24	.7	5.5
	KTB-26	84	110	34	2	14
	KTB-30	3.2	3.8	17	.3	2.8
Minimum	KTB-32	21	13	15	.5	1.5
	KTB-31	11	14	14	.5	3.9
	KTB-26	44	50	27	1	8.6
	KTB-30	21	2.6	12	.2	1.1

Table 8.--*Statistical summary of selected chemical constituents in water from wells in the vicinity of the initial tailings basin near Keewatin, Minnesota, 1982-84*--Continued

Statistic	Well	Alkalinity, laboratory (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)
Mean	KTB-32	102	65	16	1.4	22
	KTB-31	182	21	10	.32	28
	KTB-26	296	110	15	1.4	22
	KTB-30	35.8	7.5	1.6	<.10	20
Median	KTB-32	107	64	16.0	1.4	22
	KTB-31	200	20	9.55	.3	28
	KTB-26	288	92	16.0	1.5	22
	KTB-30	38	6.9	1.3	<.10	20
Maximum	KTB-32	120	70	19	1.5	25
	KTB-31	239	26	12	.40	32
	KTB-26	378	220	18	1.7	25
	KTB-30	47	12	2.9	.10	23
Minimum	KTB-32	81	60	12	1.3	19
	KTB-31	117	17	8.2	.30	25
	KTB-26	254	74	12	1.2	22
	KTB-30	25	5.0	.90	<.10	18

		Solids (mg/L)		Nitrogen (mg/L as N)						
Statistic	Well	residue at 180 °C, dissolved	sum constituents dissolved	$NO_2 + NO_3$ total	$NO_2 + NO_3$ dissolved	ammonia, total	organic total	ammonia + organic, total	total	Total (mg/L as NO_3)
Mean	KTB-32	237.3	231.7	.20	.1	.23	1.0	1.4	* .87	* 3.8
	KTB-31	270.3	255	.1	.1	.27	1.5	1.8	---	---
	KTB-26	541.5	500	15	7.4	.09	.04	1.2	16	72
	KTB-30	82.0	69.5	1.1	1.1	.10	1.1	1.2	2.3	10
Median	KTB-32	237.5	230	.15	.1	.38	.17	.60	* 1.0	* 4.4
	KTB-31	273	280	<.1	<.1	.22	.52	.80	---	---
	KTB-26	466	465	5.8	4.2	.10	.20	.6	6.5	28
	KTB-30	77.5	69.5	1.0	1.0	.01	.35	.40	1.4	6.4
Maximum	KTB-32	256	250	.4	<.1	.60	5.3	5.3	* 1.1	* 4.9
	KTB-31	342	310	<.1	<.1	.52	5.7	6.2	---	---
	KTB-26	849	740	48	27	.12	1.0	4.2	49	200
	KTB-30	110	80	1.4	1.4	.38	4.9	5.3	6.3	28
Minimum	KTB-32	212	220	<.10	<.10	.04	.00	.30	* .50	* 2.2
	KTB-31	203	180	<.10	<.10	.15	.05	.20	---	---
	KTB-26	414	410	1.0	1.0	<.01	.08	.20	1.2	5.3
	KTB-30	74	59	.80	.80	.02	.18	.20	1.2	5.3

* Only three analysis were made for this constituent.

Table 8.--*Statistical summary of selected chemical constituents in water from wells in the vicinity of the initial tailings basin near Keewatin, Minnesota, 1982-84*--Continued

Statistic	Well	Phosphorus, ortho, total (mg/L as P)	Manganese, dissolved (µg/L as MN)	Carbon, total organic (mg/L as C)
Mean	KTB-32	.13	540	38
	KTB-31	.01	1,060	6.8
	KTB-26	.01	290	2.1
	KTB-30	.01	320	2.6
Median	KTB-32	.115	370	34
	KTB-31	<.010	1,150	6.8
	KTB-26	<.010	300	2.0
	KTB-30	<.010	400	2.7
Maximum	KTB-32	.280	1,100	>90
	KTB-31	.020	1,500	8.1
	KTB-26	<.010	320	2.9
	KTB-30	.020	500	3.7
Minimum	KTB-32	<.010	280	3.8
	KTB-31	<.010	520	5.9
	KTB-26	<.010	260	1.4
	KTB-30	<.010	38	1.6

Chloride, a naturally occurring ion, is essential to both plants and animals. Elevated concentrations usually can be attributed to the influx of saline ground water, applications of fertilizers, use of road-deicing salts, or sewage effluent. The limit for domestic consumption is 250 mg/L (MPCA, 1988). Chloride concentrations in both surface and ground water from the vicinity of the tailings basin were below 20 mg/L. Chloride is a conservative ion that does not interact appreciably with other chemicals and, thus, may be used as a tracer of flow (Kimmel and Braids, 1980). Slightly elevated concentrations of chloride in outwash below the tailings may be indicative of vertical movement of ground water from the tailings to the underlying drift. Concentrations of chloride in the tailings range from 12 to 19 mg/L and in the adjacent drift from 0.9 to 12 mg/L.

Dissolved solids consist primarily of major ions and silica. High concentrations of these constituents do not generally pose any direct problems to human health, but may cause incrustation of well screens and plumbing. The limit of dissolved solids in waters for domestic consumption is 500 mg/L. This limit was exceeded in two samples from well KTB-26 (fig. 5).

Concentrations of dissolved fluoride were substantially higher in water from the tailings than from the drift. Fluoride concentrations in water from the tailings generally were at or slightly above the limit of 1.5 mg/L established by the MPCA (1988) for domestic consumption.

Lead and dissolved iron concentrations in all samples analyzed were far below domestic-consumption standards established by the MPCA (1988). Manganese concentrations, however, exceeded the domestic consumption standard of

50 $\mu g/L$ in most samples of ground-water. The highest concentrations, five times the recommended limit in one sample, were observed in wells screened in the drift. Concentrations in surface water were all below standards.

Concentrations of nitrite plus nitrate nitrogen, most of which usually is nitrate, were elevated in two of the wells sampled. Nitrate in the drift well KTB-30 averaged more than 1.0 mg/L. Nitrate in the tailings well KTB-26 was much higher, and concentrations in two samples far exceeded the MPCA's (1988) domestic-consumption standard of 10.0 mg/L.

Concentrations of phenols were below detection limits (1 $\mu g/L$) in each of the ground-water samples. Phenols were detected in surface water at the outlet of the basin in October 1982 and June 1984, and exceeded the MPCA's (1988) domestic-consumption standard of 1 $\mu g/L$. Presence of phenols may be derived from a tar-base emulsion used while seeding alfalfa in the vicinity of the pond.

Concentrations of sulfates all were below the domestic-consumption standard of 250 mg/L. Sulfate concentrations, however, were higher in water from the tailings (220 mg/L maximum) than from the outwash (90 mg/L maximum), probably because of oxidation of sulfide minerals in rocks from which the tailings were derived.

Surface-Water Quality

Degradation of surface-water quality from suspended sediment has varied throughout development of the tailings basin, depending on active deposition of tailings, runoff rates, and basin cover. During formation of the basin, runoff probably carried concentrations of sediment in the tens of thousands of milligrams per liter. A sample of slurry discharge from an adjacent basin one-half mile downstream from the discharge point contained a sediment concentration in excess of 50,000 mg/L, and 99 percent of the sediment was less than 0.125 mm in diameter. Runoff following snowmelt in April 1982 and prior to seeding of alfalfa in the southern part of the initial basin contained concentrations exceeding 4,600 mg/L of suspended sediment, and 96 percent of the particles were less than 0.062 mm in diameter. However, since that time, sediment concentrations in runoff generally have been less than 100 mg/L (U.S. Geological Survey, 1982-84).

Time-incremented data collected by automatic samplers indicate that sediment concentrations rise and peak prior to peak streamflow. Concentrations drop quickly after peaking and remain fairly low for the duration of runoff. Data collected for this study are insufficient to develop a relation between discharge and sediment concentration; however, in general, the magnitude of peak flow is directly proportional to sediment concentration.

Elevated concentrations of sediment in streamflow occur only after the pond spills over, suggesting that most of the sediment discharge is derived from erosion of the runoff channel between the pond and the outlet (fig. 4). However, numerous small channels are eroding in the more steeply sloped parts of the basin and contribute to the sediment discharge.

Erosion and sediment transport in the basin are controlled by three main factors. First, the slopes flatten in the lower reaches of the basin, which slows runoff significantly. Secondly, vegetation now covers most of the tailings and is particularly heavy in the lower, flatter areas and in the drainage channels where alfalfa and grasses grow prolifically, further reducing runoff velocities and providing a root system to better hold soil. Thirdly, runoff is temporarily stored in the pond where sediment settles out. As the vegetation continues to grow, erosion and sediment transport would be expected to become minimal.

During runoff in June 1984, samples were collected at the outlet and split to determine the influence of sediment on the chemical composition of the water. Samples collected and analyzed included (1) a sample with no filtering or sieving (to observe total concentrations of constituents), (2) a sample sieved through a 62.5-μm (micrometer) sieve (to observe adsorption effect of particulates less than 63 μm), and (3) a sample filtered through a 0.45-μm filter (to observe dissolved characteristics). In general, chemical concentrations of most of the constituents were similar for each of the three methods. However, significantly lower concentrations of iron and manganese were observed in the filtered sample, indicating precipitation of the constituents and, possibly, adsorption on the suspended sediment. A higher lead concentration was observed in the sieved sample, probably because of contamination from solder used to construct the sieve. Iron, manganese, and lead concentrations for the unfiltered and unsieved sample and for the filtered sample are 690, 70, and 2 μg/L and 180, 20, and 1 μg/L, respectively (table 6). Iron, manganese, and lead concentrations for the sieved sample are 620, 60, and 13 μg/L, respectively.

Comparison of Quality of Water from Tailings and Drift

Understanding of the differences in water quality and the potential for mixing of water types requires information about ground-water-flow patterns in the vicinity of the tailings basin. As mentioned earlier in the report, ground-water flow in the basin is radially away from the mound at a gradient of 25 ft/mi. The steepness of the gradient across the dike suggests that little water moves laterally through the dike. Vertical gradients between the tailings and the underlying drift indicate downward flow and suggest that most ground water leaves the basin by vertical leakage rather than by lateral flow. Therefore, chemical constituents dissolved in ground water in the tailings move with the water into the outwash beneath the tailings.

The effect of the tailings basin on ground-water quality in the area depends on the concentration of dissolved constituents in water in the tailings, the flux of water from the tailings, and the degree of mixing of tailings water with water in the outwash below. Quantitative comparison of results indicates that water collected from wells completed in the tailings (wells KTB-26 and KTB-32, fig 4) generally is more mineralized than water from either the outwash below the tailings (well KTB-31) or outwash outside the basin (well KTB-30). In general, most of the inorganic and trace-metal concentrations are greater in water from the tailings than from the underlying outwash, probably because of the chemical composition and accelerated weathering (in the slurry) of the rock from which the tailings were derived. Despite the generally higher mineralization of water from the tailings, manganese was found at higher concentrations in water from the drift than from the tailings.

Stiff diagrams of selected chemical constituents (fig. 9) indicate that water from the tailings and from the outwash are of two distinctive types. The patterns in figure 9 show that water from the outwash (wells KTB-30 and KTB-31) is a calcium bicarbonate type and that magnesium is the secondary cation. In contrast, water from the tailings (wells KTB-26 and KTB-32) is a mixed water type in which magnesium is only slightly dominant over calcium and sodium plus potassium. Also, water from the shallower well in the tailings (well KTB-32) contains equal milliequivalents per liter of sulfate and bicarbonate (calculated from laboratory alkalinity).

A Piper diagram (fig. 10) further illustrates the similarities and differences between the ground-water samples analyzed. Chemical concentration clustering indicates that water from the outwash underlying the tailings and from outwash outside the basin are very similar in chemical composition and probably represent the same aquifer. Water from the tailings is distinctly different in chemical composition from water from the outwash, particularly in calcium, magnesium, and sulfate content. However, the diagram shows that water from the tailings is variable in chemical composition, particularly in sulfate content. This variation may be due to differences in sample depth, residence time, and oxidation-reduction reactions. The plot of data for water from outwash below the tailings (KTB-31) indicates that some mixing probably occurs.

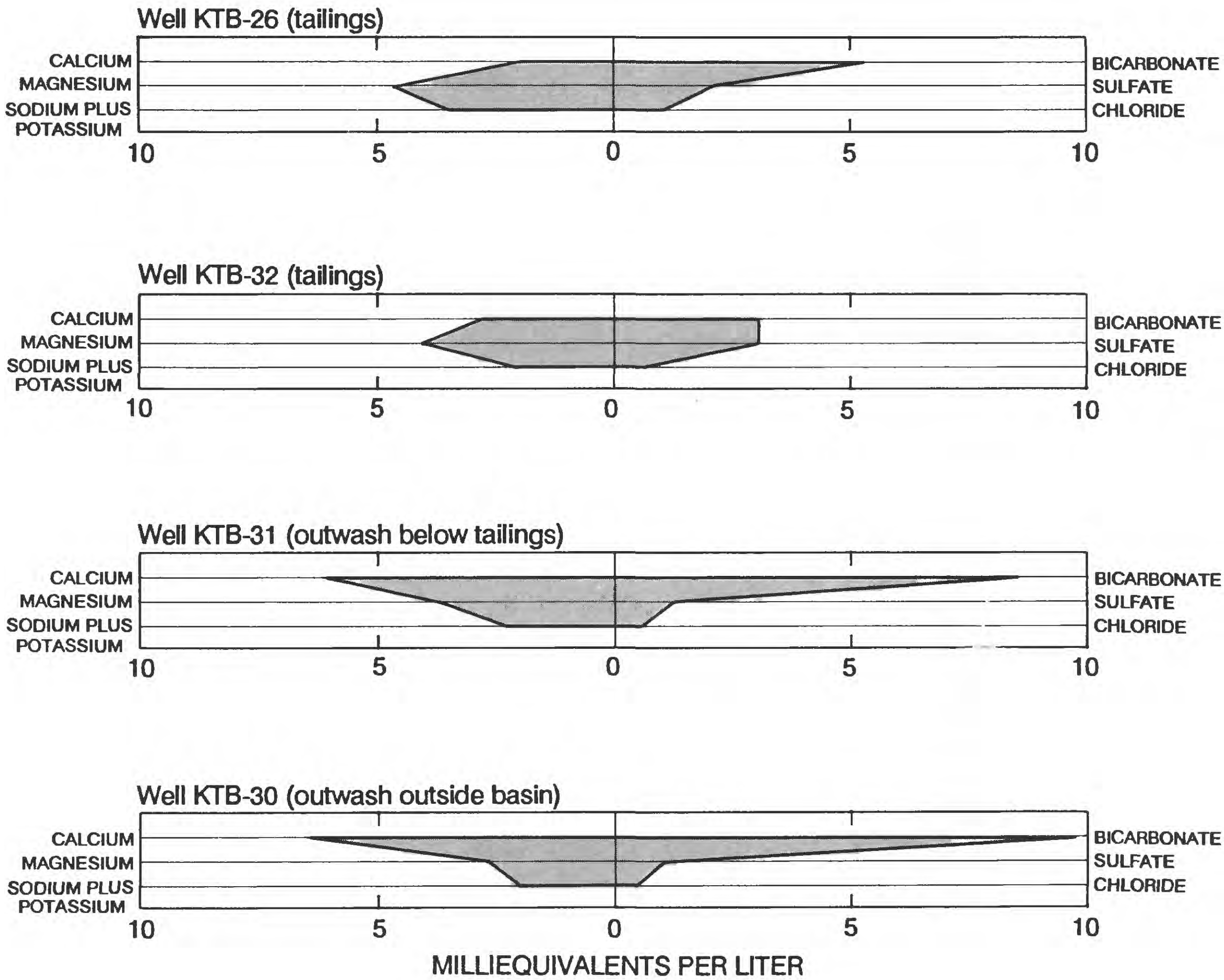
SIMULATION OF GROUND-WATER FLOW

The ground-water-flow system in the vicinity of the tailings basin was simulated using a numerical finite-difference model developed by McDonald and Harbaugh (1984). The model simulates ground-water flow in the aquifer system in three dimensions. Three-dimensional ground-water flow is simulated by the model using the partial-differential equation

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right] - W = S_s\left[\frac{\partial h}{\partial t}\right],$$

where

x, y, z are Cartesian coordinates aligned along the major axes of hydraulic conductivity Kxx, Kyy, Kzz;
h is the potentiometric head (L);
W is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1});
S_s is the specific storage of the porous material (L^{-1}); and
t is time (T).



EXPLANATION

WATER ANALYSIS PATTERN--Pattern is based on water analyses from indicated observation wells. Concentrations, in milliequivalents per liter, are plotted for calcium, magnesium, sodium plus potassium, bicarbonate, sulfate, and chloride. The larger the area of the pattern, the greater the chemical concentration.

Figure 9.--Stiff diagrams of water quality from wells completed in tailings and outwash in the vicinity of the taconite tailings basin, October 1982.

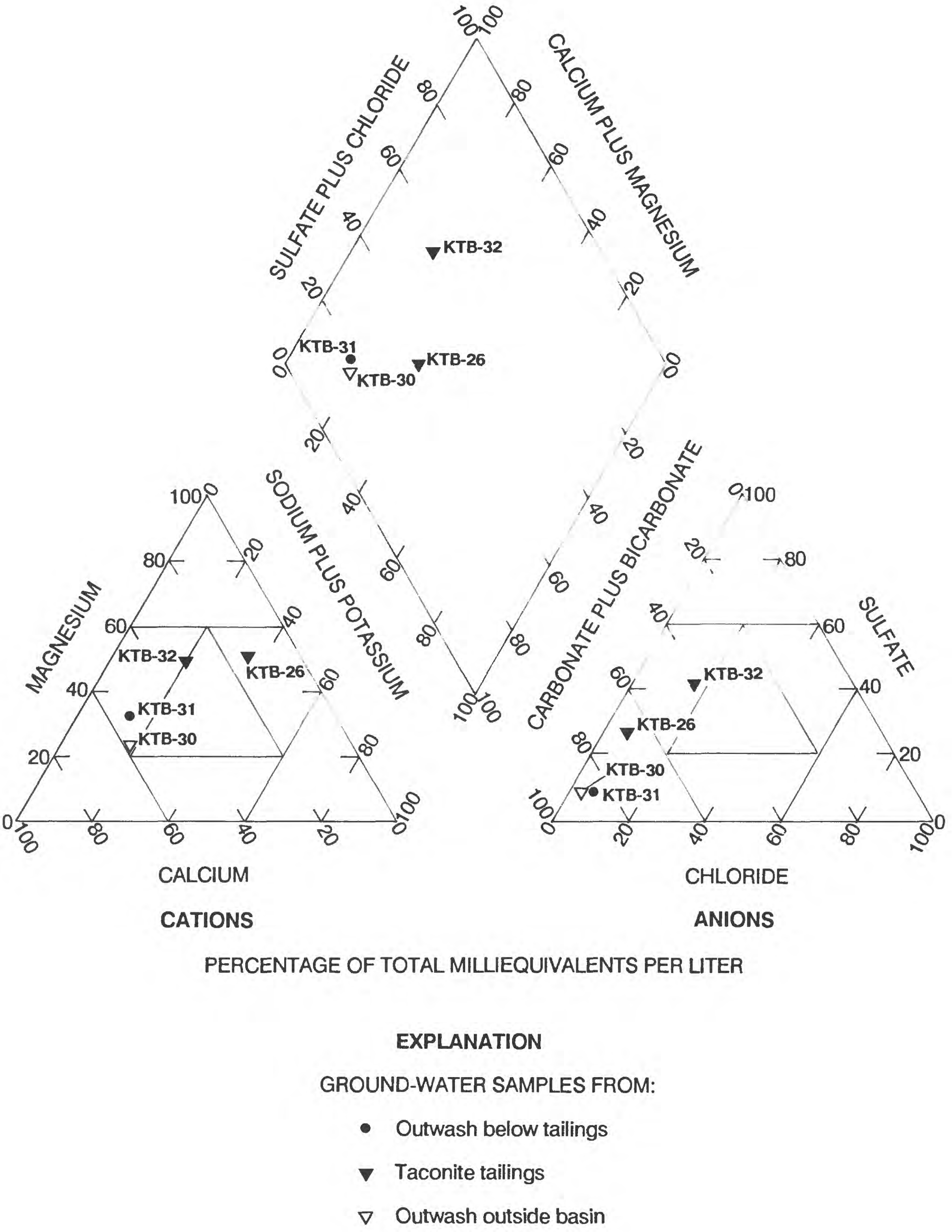


Figure 10.--Piper diagram of water-quality data from wells near the taconite-tailings basin, October 1982.

The strongly implicit procedure (SIP) was used to solve the finite-difference equations simultaneously.

Certain simplifying assumptions were made about the study area to facilitate model simulation. Therefore, model results are considered an approximation of the real system. These assumptions are:

1. flow is predominatly horizontal in aquifer units and predominatly vertical in confining units,
2. dikes surrounding the basin are impermeable,
3. runoff from the basin is through a single location (outlet),
4. ground-water leakage from the basin is vertically downward through the bottom of the basin, and
5. some ground water is lost to evapotranspiration.

Description of the Model

The model was designed to simulate ground-water flow within the initial tailings-basin aquifer and adjacent drift aquifers. A block-centered finite-difference grid was used to divide the modeled area into discrete cells and blocks. Discretization of the modeled area is necessary to represent local variations in hydraulic properties. The model solves the flow equation at the center of each block (referred to as a node) using average hydraulic properties and stresses as specified for each cell. The modeled area was discretized into a 4-layer, 8,000-block (40x50 cells per layer) model. Cell size throughout the model is a uniform spacing of 300 by 370 ft (approximately 2.5 acres). Axes of the grid are oriented approximately parallel or perpendicular to the primary directions of ground-water flow. Figure 11 shows the areal extent of the model and the finite-difference grid.

The aquifer system was represented by four layers of blocks to simulate ground-water flow in the tailings and in adjacent drift. Because of the high vertical hydraulic gradient within the tailings, the tailings material was represented by more than a single layer. Layer 1 (uppermost layer) represents most of the saturated thickness of the tailings and includes the water table. The transmissivity of layer 1 was computed by the model as the product of horizontal hydraulic conductivity and saturated thickness. Layers 2 and 3 simulate flow in the lower part of the tailings and are equivalent in areal extent to layer 1. Layers 2 and 3 were modeled as confining layers in which transmissivities equal the horizontal hydraulic conductivity of layer 1 times 1 ft of thickness. Layers 2 and 3 represent the vertical hydraulic properties of the tailings and of the peat separating tailings from the underlying drift aquifer. This design simulates vertical leakage from the tailings to the underlying drift. The blocks outside the basin in layers 1, 2, and 3 are inactive.

Layer 4 represents the glacial-drift aquifer in areas surrounding and underlying the tailings basin. Some of the blocks in layer 4 represent sand and gravel, whereas others represent till.

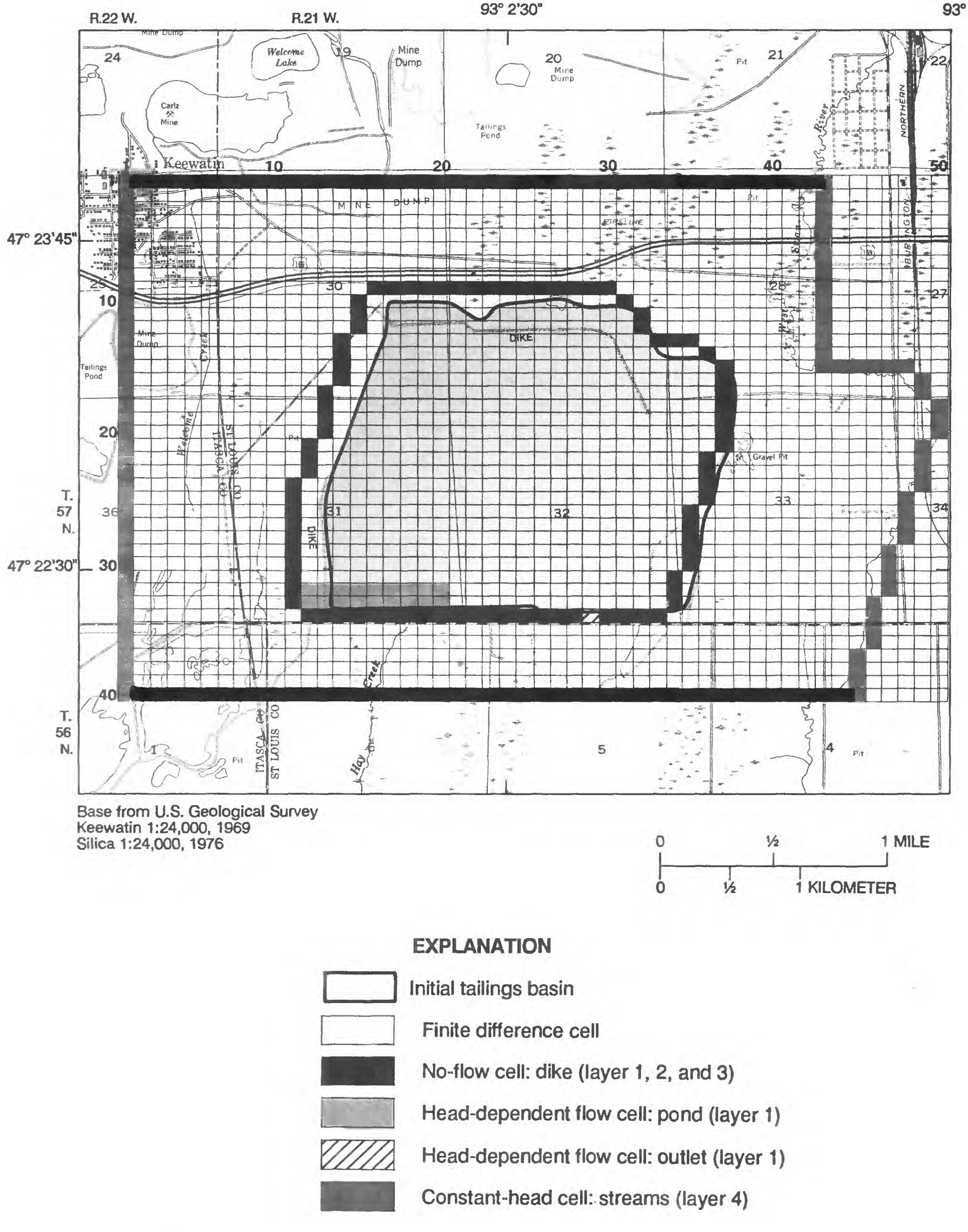


Figure 11.--Finite-difference grid and boundaries for ground-water-flow-model.

Model Boundaries

Hydrologic boundaries within the modeled area were simulated using: (1) constant-head cells, (2) no-flow cells, and (3) head-dependent flow cells (fig. 11). Constant-head cells allow sufficient flux (water flow) across model boundaries to maintain initial water levels at that boundary regardless of the hydraulic stress simulated in the model. No-flow boundary cells simulate impermeable boundaries, which allow no flux across the boundary. Head-dependent-flow cells simulates flux across a boundary in response to change in head caused by stress of the system. The amount of flux into or out of head-dependent-flow boundary cells is computed based on the hydraulic conductance and the difference between model-computed head at the boundary and specified head outside the boundary.

Constant-head boundaries were assigned in layer 4 along the eastern and western boundaries of the grid. These boundaries represent the West Swan River and Welcome Creek, respectively, which are natural discharge boundaries for the local ground-water system. No-flow boundaries were assigned in layer 4 along the northern and southern boundaries of the model area because ground-water inflow from the north and outflow to the south were assumed to be negligible.

Dikes around the basin, and the inner dike in the northern part of the basin, are comprised of compacted silt, sand, clay, and rock that have low permeability. No-flow boundaries were assigned to cells in layers 1, 2, and 3 to represent the dike that surrounds the tailings basin. Leakage at the toe of the dike is included as total leakage out the bottom of the tailings basin.

Head-dependent-flow cells were used in layer 1 to simulate flow between the tailings and the pond in the southwest corner of the basin. The head-dependent-flow cells are used to simulate flow into or out of the tailings as leakage through the bottom of the pond.

Ground-water contribution to streamflow at the basin outlet was represented as discharge through a hypothetical drain in the dike wall. The base of the drain was set to 1,488 ft (base altitude of the outlet of the basin). The conductance of the interface between the cell and the drain was assigned a large value to simulate open-channel flow. Flow out of the drain is computed by the model only when the water-table altitude in the tailings is above the base altitude of the drain.

Steady-State Calibration of the Model

In the initial model simulations, values of horizontal hydraulic conductivity of the tailings were assigned based on grain-size analyses. Values assigned to layers 1, 2, and 3 ranged from 1 to 100 ft/d. Values of transmissivity of the outwash underlying the tailings were assigned on the basis of the product of saturated thickness and estimated horizontal hydraulic conductivity from grain-size analyses. Values of transmissivity assigned to layer 4 ranged from 700 to 3,750 ft^2/d. To simplify the initial simulations, the tailings and the confining unit between the tailings and the underlying drift were assumed to have uniform vertical hydraulic conductivity of 1 ft/d.

Calibration of the model at steady-state was made by successively adjusting input values of hydrologic properties (within reasonable limits consistent with the uncertainty in the values) until model-computed heads acceptably matched water levels measured in the field. Calibration was considered acceptable when (1) computed heads matched measured water levels within 5 ft at each observation well and (2) computed differences in head between the tailings and underlying drift were within 2 ft of those measured at well-nest locations. Water levels measured in September 1983 were used for steady-state calibration because they were considered to be representative of average conditions in the ground-water system.

Initial model-computed heads for layers 1 and 4 generally matched the measured water table in the tailings and potentiometric surface of the drift aquifer, respectively, to within $\pm$ 6 ft. Computed vertical differences in head between layers 1 and 4, however, initially differed from field measurements by as much as $\pm$ 20 ft. Therefore, values of selected hydraulic properties were adjusted until acceptable matches were obtained.

In general, only minor adjustments were made in horizontal hydraulic conductivity and transmissivity (layers 1 and 4). Adjustments included (1) the horizontal hydraulic conductivity of the coarse tailings along the northern boundary of the basin was reduced from 25 to 20 ft/d and (2) transmissivity of the outwash beneath the tailings in the vicinity of the pond was reduced from 3,750 to 2,000 ft^2/d.

Extensive adjustments were made to values of vertical hydraulic conductivity to achieve an acceptable steady-state solution. Vertical hydraulic conductivities of the tailings between layers 1 and 2 and layers 2 and 3 were assigned on the basis of the horizontal hydraulic conductivity of the surficial tailings, assuming isotropic conditions. For example, coarse tailings were assigned a vertical hydraulic conductivity of 20 ft/d, whereas finer tailings were assigned vertical hydraulic-conductivities of 1 and 3 ft/d in the fine and medium zones, respectively. Vertical hydraulic conductivities between layers 3 and 4 were assigned on the basis of the lithology of the confining layer and the underlying material--that is, areas where peat overlies outwash were assigned a vertical hydraulic conductivity of $1.4x10^{-3}$ ft/d (based on aquifer-test data (table 4)). In other areas, where peat overlies till, a vertical hydraulic conductivity of $1.0x10^{-2}$ ft/d was assigned on the basis of work by Siegel and Ericson (1980). Sediment in the bottom of the pond was assigned a vertical hydraulic conductivity of $4.0x10^{-1}$ ft/d. This value was estimated from pond-leakage data in November 1983, and is based on the difference in head between the pond and the water table and the thickness of the pond sediments.

Table 9 is a comparison of model-computed and measured heads at each observation well screened at the depths represented by layers 1 and 4 (no wells were screened at depths represented by model layers 2 and 3). All the computed heads were within $\pm$ 4 ft of measured heads. Table 10 compares computed and measured vertical differences in head at well nests. For each of the well nests, the computed head difference is within 2 ft of the measured head, and most are within 1 ft of the measured head.

Table 9.--*Comparison of computed and measured water levels in observation wells for the calibrated steady-state simulation*

Node number (row, column)	Well number	Model-computed head (altitude in feet above sea level)	Measured head September 1983 (altitude in feet above sea level)	Difference (computed minus measured, in feet)
		LAYER 1		
10,26	KTB-1	1,507	1,506	+1
11,26	KTB-44	1,507	1,507	0
13,16	KTB-41	1,503	1,505	-2
13,19	KTB-2	1,505	1,509	-4
13,31	KTB-46	1,509	1,509	0
17,26	KTB-17	1,514	1,515	-1
17,32	KTB-39	1,511	1,510	+1
18,36	KTB-14	1,503	1,504	-1
21,14	KTB-6	1,495	1,498	-3
22,35	KTB-8	1,501	1,501	0
24,21	KTB-7	1,500	1,499	+1
25,12	KTB-50	1,492	1,491	+1
26,33	KTB-55	1,501	1,500	+1
30,18	KTB-3	1,494	1,491	+3
31,13	KTB-32	1,489	1,491	-2
33,25	KTB-25	1,492	1,489	+3
		LAYER 4		
11,21	KTB-42	1,496	1,494	+2
11,26	KTB-43	1,502	1,502	0
13,16	KTB-40	1,491	1,494	-3
13,31	KTB-45	1,504	1,504	0
17,26	KTB-16	1,509	1,512	-3
17,32	KTB-37	1,506	1,507	-1
18,36	KTB-13	1,500	1,502	-2
21,14	KTB-5	1,491	1,495	-4
22,35	KTB-51	1,498	1,500	-2
24,21	KTB-52	1,498	1,499	-1
25,12	KTB-48	1,485	1,483	2
26,33	KTB-54	1,498	1,497	1
31,13	KTB-31	1,482	1,484	-2

Table 10.--*Comparison of computed and measured vertical differences in water levels at observation-well nests for the calibrated steady-state simulation*

Node number (row, column)	Well number	Computed difference (feet)	Measured difference (feet)	Difference (computed minus measured in feet)
11,26	KTB-43,44	5	5	0
13,16	KTB-40,41	12	11	+1
13,31	KTB-45,46	5	5	0
17,26	KTB-16,17	5	3	+2
17,32	KTB-37,39	5	3	+2
18,36	KTB-13,14	3	2	+1
21,14	KTB-5,6	4	3	+1
22,35	KTB-8,51	3	1	+2
24,21	KTB-7,52	2	0	+2
25,12	KTB-48,50	7	8	-1
26,33	KTB-54,55	3	3	0
31,13	KTB-31,32	7	7	0

An additional check on model calibration was made by comparing the model-computed steady-state budget components to estimates of hydrologic budget for the 1983 water year. The model-computed water budget for the steady-state calibration is shown in table 11. Common components of both the ground-water-flow model and the hydrologic budget are areal recharge and vertical leakage. Model-computed areal recharge was 9.6 in. annually compared to 10.0 in. estimated by hydrograph analysis for 1983. Model-computed leakage was 8.8 in. annually compared to 9.9 in. estimated from the hydrologic budget for water year 1983.

Following steady-state calibration, the sensitivity of the model to changes in values of the hydraulic properties was tested. Sensitivity analysis provides insight to the uniqueness of the accepted steady-state solution and demonstrates how much values of hydraulic properties could be changed before the solution becomes unacceptable.

Values of each hydraulic property at each node were halved and doubled to observe relative effects. The model was most sensitive to changes in values of areal recharge and transmissivity and least sensitive to uniform changes in vertical hydraulic conductivity.

Solutions obtained by the model are based on the simplifying assumptions for the hydrologic characteristics of the aquifers and are not unique. Similar results might be obtained using other combinations of input values. However, the model was developed consistent with available data. Improvement in the model simulation might be obtained by collection and use of additional field data.

Transient Simulation

Once the model was calibrated at steady-state conditions, estimated values of aquifer storage coefficients were added to the model for simulation of transient (time-dependent) conditions. Transient simulation was necessary to determine how well the model could simulate major seasonal hydrologic changes. Because of the absence of historical water-level data prior to this study, the model was not calibrated to long-term transient conditions. However, a model simulation of the 1983 calendar year was compared to field data for that year.

In order to simulate 1983 hydrologic conditions, the year was divided into five periods. Period 1 represents the late winter months of January, February, and March (90 days) when there was virtually no areal recharge or evapotranspiration. Period 2 represents the spring months April and May (60 days) when areal recharge was high and evapotranspiration was low. Period 3 represents early summer months June and July (60 days) when areal recharge was low and evapotranspiration was high. Period 4 represents the late summer and early fall months of August, September, and October (90 days) when areal recharge was high and evapotranspiration was low. Period 5 represents the early winter months of November and December (65 days) when there was virtually no areal recharge or evapotranspiration.

Table 11.--*Model-computed water budget for the steady-state calibration*

Hydrologic component	Cubic feet per day	Inches per year
	INFLOW	
Ground-water flow	2.3×10^{3}	9.0×10^{-3}
Areal recharge from precipitation	1.52×10^{5}	9.61
Leakage from pond	1.3×10^{1}	7.0×10^{-3}
Total	1.54×10^{5}	9.62
	OUTFLOW	
Downward vertical leakage	1.4×10^{5}	8.80
Evapotranspiration	1.3×10^{4}	0.81
Leakage to pond	1.5×10^{-1}	9.0×10^{-3}
Total	1.53×10^{5}	9.62

In the initial transient simulations, the specific yield of the tailings and storage coefficient of the underlying drift aquifer were set at 0.2 and 0.002, respectively. Results indicated that the model could simulate the timing of water-level fluctuations in the tailings reasonably well. However, the magnitudes of the model-simulated fluctuations were not as great as those measured in wells. These results suggested that the specific yield simulated in the model for the tailings was too high. Therefore, in a series of successive simulations, the specific yield for layer 1 of the model was incrementally reduced until the best match between model-computed and measured water-level fluctuations was achieved. The final value of specific yield for the tailings simulated in the model was 0.10. The final values for storage coefficients were 0.01, 0.001, and 0.002 for layers 2, 3, and 4 respectively.

Figure 12 presents comparison of model-computed and measured water levels at several locations in the tailings basin in 1983. The figure shows that although there are some significant differences between simulated and observed heads, such as at well KTB-32 (November-December), the model generally simulates the timing and magnitude of water-level fluctuations reasonably well.

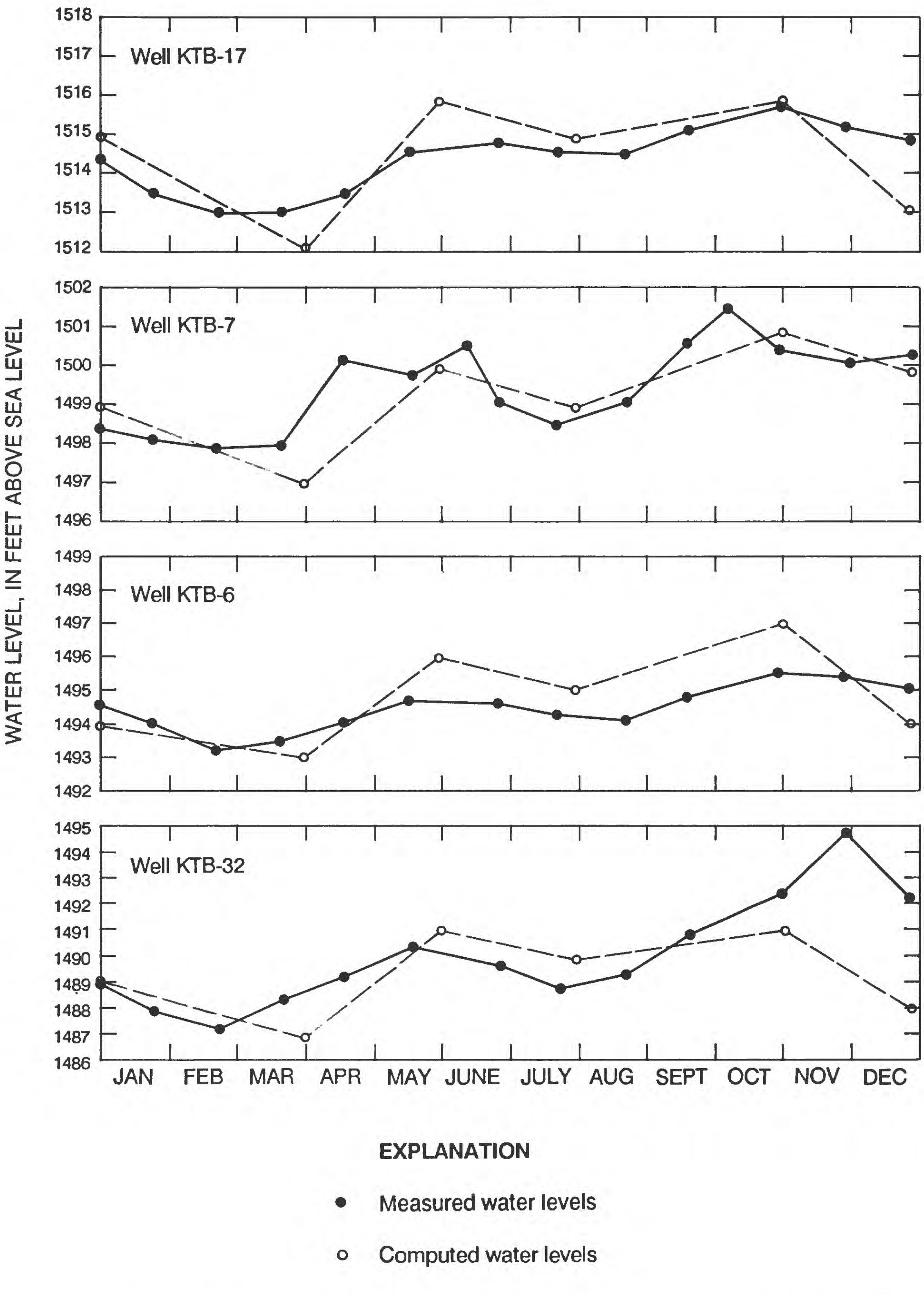


Figure 12.--Comparison of computed and measured water levels in layer 1 in representative wells in the tailings basin during 1983.

Simulation of Hypothetical Climatic Conditions

Following steady-state calibration of the model and transient simulation of hydrologic conditions during 1983, simulations were made to estimate hydrologic response of the tailings basin to hypothetical climatic conditions. Because the model does not simulate the system precisely and because the model was calibrated with short-term data, results can not be used for exact predictions of aquifer response and should be considered as approximations. The accuracy of the model could be determined by comparison of model results to actual hydrologic response observed in the field. The model could be refined and recalibrated as additional data become available.

Because of the runoff characteristics of the basin and the absence of pumpage, significant hydrologic changes in the basin occur only during snowmelt or intense storms. Therefore, for demonstrational purposes, two climatic conditions were simulated. Simulation 1 represents the response of the basin to increased areal recharge due to snowmelt and heavy spring rains. Simulation 2 represents a response resulting from increased spring and fall recharge and decreased evapotranspiration during the fall because of unseasonally wet and cool weather. For simulation 1, recharge was increased from 4 to 8 in. during the spring period (stress period 2). For simulation 2, recharge rates were increased during periods 2 (spring) and 4 (fall) from 4 to 8 in. and 3 to 6 in., respectively, while evapotranspiration rates were decreased from 1.4 to 1.0 in. for the same periods.

Figure 13 shows a comparison of model-computed water levels in layer 1, when recharge was doubled during the spring period, to model-computed water levels in 1983 (simulation 1). Model results for simulation 1 indicate that spring water levels in the tailings could average 4 ft above the 1983 levels, ranging from 1 ft above in areas of coarse tailings to 7 ft above in areas of gentle slopes and fine tailings. In addition, water levels could remain about 2 ft above the 1983 levels throughout most of the simulation.

Model results for simulation 1 indicate that water levels in the tailings in the vicinity of the basin outlet could be about 1 ft higher than 1983 water levels, or about 1 ft above the elevation of the basin outlet channel. An attempt was made to use this information to compute ground-water contribution to streamflow at the basin outlet using the drain simulator described previously. It was found that the computed discharge from the drain was artificially high because of the need to assign a large hydraulic conductivity to the drain node to mimic open-channel flow and, thus, these results were not interpretable. However, because the computed head in the tailings at the basin outlet seemed reasonable and the head was above the elevation of the basin outlet, this head was assumed to be equivalent to stage in the outlet channel. Using the stage-discharge relation for the channel outlet, the estimated flow would exceed 50 ft^3/s during the simulated spring period (stress period 2), but would recede to 1983 flows during the rest of the simulation. This discharge would be in addition to any surface-water runoff directly from the basin or produced as overflow from the pond.

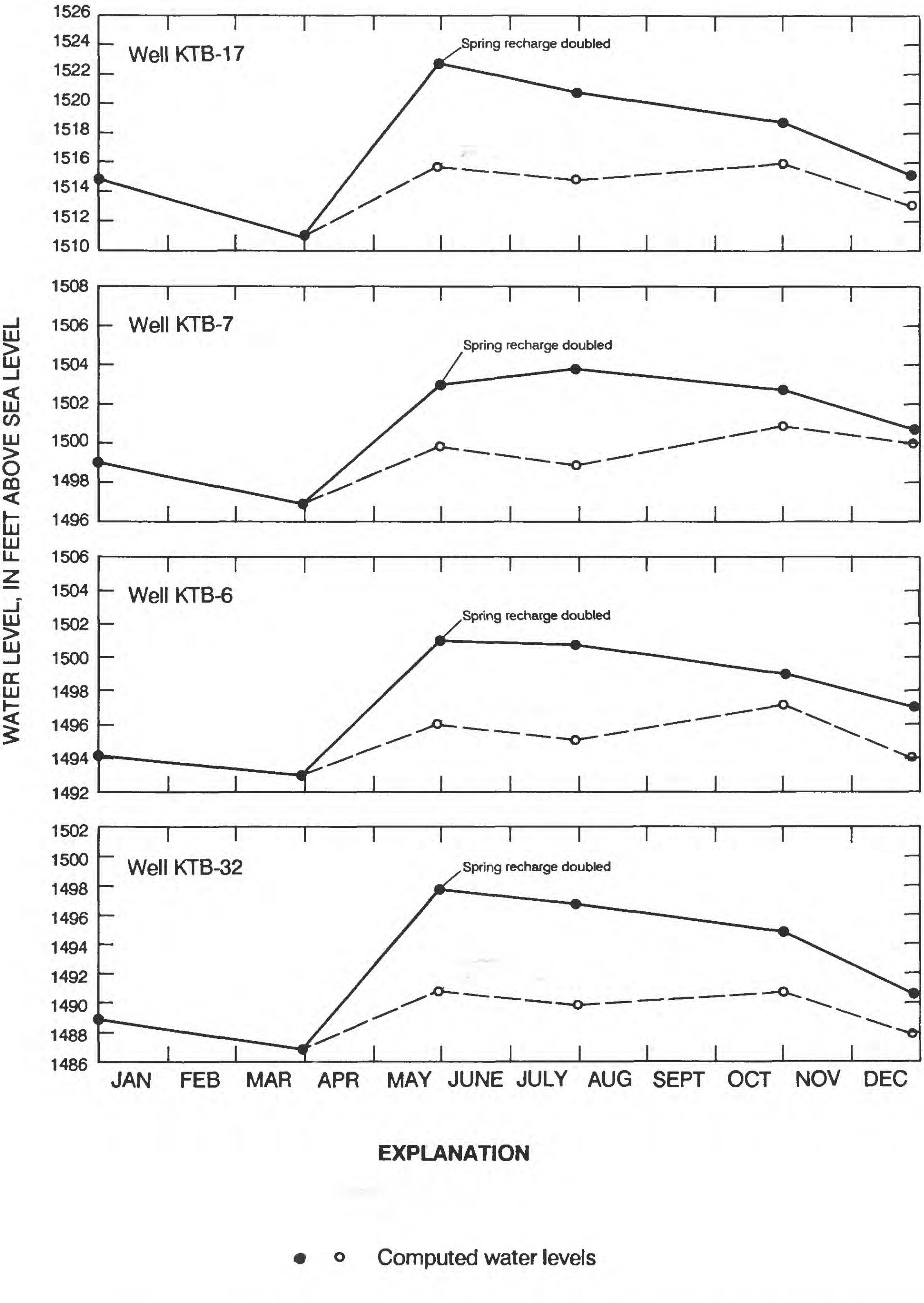


Figure 13.--Comparison of model-computed water levels in layer 1, when recharge is doubled during the spring stress period, to model-computed water levels in 1983 (Simulation 1).

Figure 14 shows a comparison of model-computed water levels in layer 1, when recharge is doubled during both spring and fall stress periods, to model-computed water levels in 1983 (simulation 2). Model results for simulation 2 indicate that water levels in the tailings could average 4 ft above 1983 levels at the end of the spring period, decline slightly during summer, and then average about 4 ft above 1983 levels during the fall period. By the end of the year, water levels could possibly remain about 5 ft above 1983 levels. Water levels at the outlet of the basin were about 1 ft above 1983 levels during the spring period, about 1.5 ft above 1983 levels during the fall period, and returned to near 1983 levels by the end of the year. Ground-water contribution to discharge at the outlet, estimated from the stage-discharge relation (as done for simulation 1), would exceed 50 ft^3/s during the spring period and 80 ft^3/s during the fall period. Table 12 is a summary of input data and results of simulations of hypothetical climatic conditions.

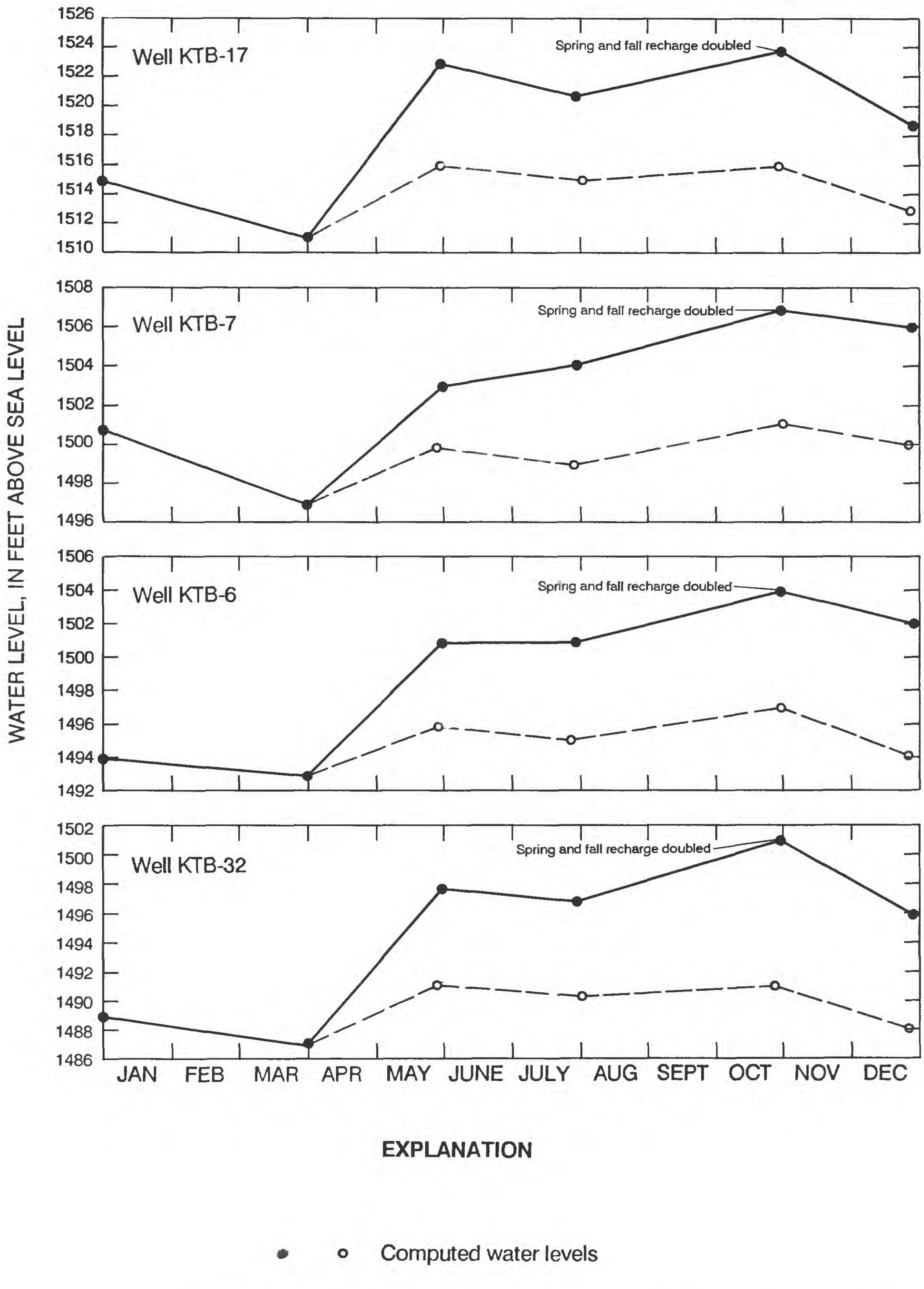


Figure 14.--Comparison of model-computed water levels in layer 1, when recharge is doubled during both the spring and fall stress periods, to model-computed water levels in 1983 (simulation 2).

Table 12.--*Summary of simulations of hypothetical climatic conditions*

Simulation	Conditions of simulation	Hydrologic response
Transient simulation	1983 hydrologic cycle	
	a. 10 in. of areal recharge b. 1.4 in. of ground-water evapotranspiration	Water levels and discharge closely approximate 1983 conditions
Simulation 1	Spring areal recharge doubled	
	a. 14 in. of recharge	a. Water levels average 4 ft above 1983 levels during spring period
	b. average ground-water evapotranspiration (1.4 in.)	b. Ground-water contribution to discharge from basin through outlet exceeds 50 ft^3/s during spring period
Simulation 2	Spring and fall areal recharge doubled	
	a. 17 in. of recharge	a. Water levels average 4 ft above 1983 levels during spring and fall periods
	b. 1.0 in. of ground-water evapotranspiration, reduced by 33 percent during both spring and fall periods	b. Ground-water contribution to discharge from basin through outlet exceeds 50 ft^3/s and 80 ft^3/s during spring and fall periods, respectively

SUMMARY AND CONCLUSIONS

Taconite tailings have been deposited as a slurry in a 2.5-mi^2 containment basin near Keewatin, Minnesota. The basin is bounded by earthen dikes composed of compacted drift and clayey bouldery till. Test drilling revealed considerable variability in tailings thickness and texture. Tailings thickness ranged from less than 1 ft in the east-southeastern part of the basin to nearly 40 ft in the southwestern corner. The tailings consist mostly of chert and silica particles that range from clay to coarse sand in grain size. Coarser material generally is found in the higher ridges at the points of slurry discharge along the northern boundary of the basin. The finest grain-sized material generally is found in the topographically low area near the pond in the southwestern corner of the basin.

Streamflow data indicate that runoff from the tailings is slight and occurs only following snowmelt or large rain storms. Average runoff to streamflow from April 1982 to June 1984 was 0.62 ft^3/s. Instantaneous discharge varied from zero flow during much of the period to 142 ft^3/s following spring snowmelt of 1982. Daily mean discharges exceeded 5 ft^3/s on 21 days and 20 ft^3/s on two days during the study. Runoff from the western side of the basin is stored temporarily in a small pond in the southwestern part of the basin. Dead storage of the pond is 39 acre-ft; estimated peak storage in the pond was 150 acre-ft in April 1982 when the runoff channel was blocked with ice and snow.

Ground-water-level data show depth to water in the vicinity of the basin ranges from 0 to 25 ft below land surface and is less than 5 ft below land surface in about 30 percent of the basin. Magnitude of water-level fluctuations ranged from about 1 ft in wells completed in outwash to about 8 ft in wells completed in fine tailings. The predominant pattern of ground-water flow is radially from a mound in the north-central part of the basin at a horizontal hydraulic gradient of 4.7×10^{-3} ft/ft (25 ft/mi). Water levels in nested wells indicate a vertical head loss both within the tailings and between the tailings and the underlying drift. Vertical gradients ranged from 7.0×10^{-3} ft/ft in areas where tailings overlie peat and till to 6.0×10^{-1} ft/ft in areas where the tailings overlie outwash.

Saturated thickness of the tailings ranges from less than 1 ft in the topographically higher areas of the basin to about 35 ft in the vicinity of the pond. Estimated horizontal hydraulic conductivity of the tailings ranges from less than 1 ft/d for silty clay found in the southwestern corner of the basin to as much as 500 ft/d for coarse tailings found along the ridge to the north near points of slurry discharge. Vertical hydraulic conductivity in the vicinity of the pond was estimated to be 1.4×10^{-3} ft/d. Transmissivity of the tailings was estimated to range from 25 ft^2/d in fine tailings to 350 ft^2/d in coarse tailings. Transmissivity of the outwash underlying the tailings ranges from 700 to 3,750 ft^2/d.

Average areal recharge to the tailings obtained from analysis of well hydrographs for each well from October 1982 through September 1983 was 11.8 in. The areal recharge rate calculated from well hydrographs ranged from 9.8 to 14.2 in. annually.

Precipitation at the tailings basin from October 1, 1982, through September 30, 1983, was 29.7 in., of which 18.8 in. left the basin as evapotranspiration, 9.9 in. left as ground-water leakage to the underlying drift aquifer, 1.6 in. left the basin as runoff to streamflow, and 0.6 in. was lost by a decrease in ground-water storage.

Qualitative comparisons of water quality show that water collected from wells completed within the tailings and from streamflow leaving the basin generally is more mineralized than water from adjacent aquifers. Water from the tailings is a mixed type in which magnesium is only slightly dominant over calcium and sodium plus potassium and milliequivalents of sulfate and bicarbonate are equal. Concentrations of arsenic, fluoride, molylebdenum, manganese and nitrite plus nitrate were high compared to adjacent drift. However, only fluoride, manganese and nitrite plus nitrate equalled or exceeded State drinking-water standards. Suspended-sediment concentrations in runoff ranged from less than 1 mg/L during low flows to greater than 4,600 mg/L following snowmelt in April 1982. During runoff, suspended-sediment concentrations generally are less than 100 mg/L and 90 percent of the sediment particles are smaller than 0.062[5] mm in diameter.

Numerical simulation of ground-water flow in the vicinity of the tailings basin indicates that, if areal recharge were doubled during both the spring and fall periods, water levels in wells could average about 4 ft above 1983 levels during both periods. Water levels by the end of the year could be about 5 ft above 1983 levels. Model results indicate that water levels at the outlet of the basin could be about 1 ft above 1983 levels during the spring period and nearly 1.5 ft above 1983 levels during the fall period. Under these hypothetical climatic conditions, ground-water contribution to discharge at the outlet could exceed 50 ft^3/s during the spring and 80 ft^3/s during the fall.

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