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G. E. Eddy, *State Geologist*

TECHNICAL REPORT NUMBER TWO
Ground-water problems of the Iron River district, Michigan

by
W. T. Stuart, C. V. Theis, and G. M. Stanley

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ABSTRACT

This report discusses the ground-water phenomena near Iron River, Michigan, the center of an iron-mining district which ships about 3 million tons of ore annually. The purpose of the study was primarily to explore the possibilities of applying a knowledge of these phenomena to reduce the direct and indirect costs of mining caused by water in the mines. The investigation was carried out by the U. S. Geological Survey in cooperation with the Michigan Geological Survey Division of the Department of Conservation.

The iron-formation of the district forms a poorly permeable sequence of beds about 150 feet thick included in other, nearly impermeable, formations of the Huronian series. The formation typically occurs in complexly contorted structural basins. The bedrocks crop out in only a very few places, being covered almost everywhere by an overburden of glacial drift from a few to a few hundred feet thick.

Water, in some places saturating the overburden to a depth of 200 feet or mores apparently seeps into the underlying iron-formation and follows the formation to the mine openings within it. In some localities where mining is done by caving methods a more direct method of ingress is through the broken ground where the mine has caved to the bedrock or "ledge" surface.

A map of the ledge surface underlying the glacial materials of the district, made from data given by several hundred test borings and wells, kindly furnished by the operating companies, indicates several deep ledge valleys in which the iron-formation is known or suspected to appear at the ledge surface.

A study of the glacial geology of the area has developed much Interesting glacial history. The glacial materials are a complex of inter-lensing till and outwash. No principles could be developed to indicate, except in a very rough way, the localities of relatively permeable and impermeable materials.

A map of the water table shows that the ground water everywhere moves toward the Iron River and its tributaries except in the vicinity of heavy pumping where cones of depression have been developed. The recharge is predominantly from rainfall and, apparently amounts to about 7.3 inches per year or about 22 percent of the normal precipitation, as determined from fluctuations of the water table and from a number of seepage measurements of the Iron River. Of the difference between a loss of about 340 gallons of water a minute where the river crosses the edge of the cone of depression centering around heavy pumping in the Mineral Hills area, and a normal gain of about 860 gallons a minute in stretches of the river of similar length, elsewhere, all, or a large part, represents a decrease of the normal-pick-up of the stream diverted to the pumps. No large leakage from the several ditches of the district was found, but in Sunset Creek losses of as much as 650 gallons of water a minute were measured when the creek overflowed its banks. A percolation test showed that water carrying fine suspended iron ore pumped from the mines rapidly sealed the ground through which it percolated.

A study of-the record of pumpage from the mines and from the glacial overburden indicates that the lowering of the water table in the Mineral Hills area has decreased the inflow into the mines, presumably by drying up the "ledge" or bedrock surface where the iron-formation meets it.

A number of chemical analyses show (1) the water in the glacial overburden is a moderately mineralized calcium carbonate water, (2) the water entering the mines in considerable quantity is of similar character, but (3) that from drips and seeps, in lower levels is more highly mineralized and contains considerable quantities of sodium and/or calcium chloride.

A theoretical study of movements of ground water in a steeply inclined contorted aquifer, such as is represented by the iron-formation, indicates that in general larger amounts of water will move to lower, as opposed to upper, openings, but the tendency will be modified or reversed by competing openings in the same

geologic structure, by folds and degree of inclination of the strata, by the topography of the bedrock surface, and by depth of saturation in the overburden. As a general rule, however, exploratory openings at lower levels and at the ends of-a level would probably diminish the quantity of water coming into working openings above and between these openings. The amount of water entering the new Johnson lease of the Spies mine suggests that the transmissibility of the iron-formation is about 350 gallons of water a day per lineal foot of the formation and that the average permeability, through fractures, vugs, and pores, is about 2 gallons a day per square foot.

Pumping tests of wells in the Mineral Hills area indicate a transmissibility of the overburden of about 100,000 gallons a day per square foot. A discussion of the theory of movement of water in the overburden indicates in general that smaller wells than those now in use, placed nearer the critical areas where the iron-formation is at ledge surface or where the bedrock is broken through caving, probably would diminish more efficiently the quantity of water entering the mines. However, because of the complexities of the shape of the ledge troughs and of the hydrologic properties of the overburden, many problems concerning the best location of wells remain unsolved.

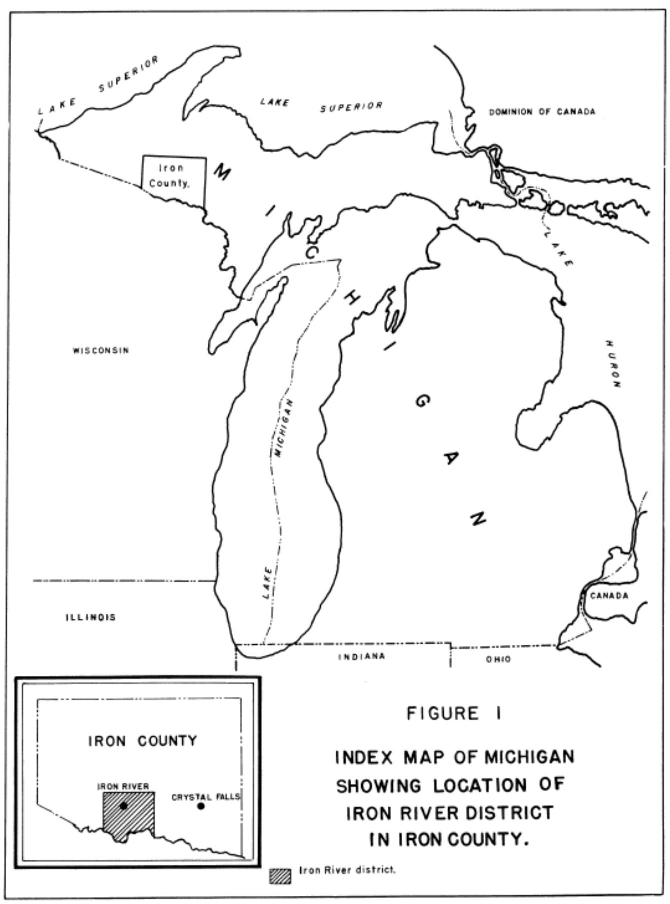

Figure 1. Index map of Michigan showing location of Iron River district in Iron County.

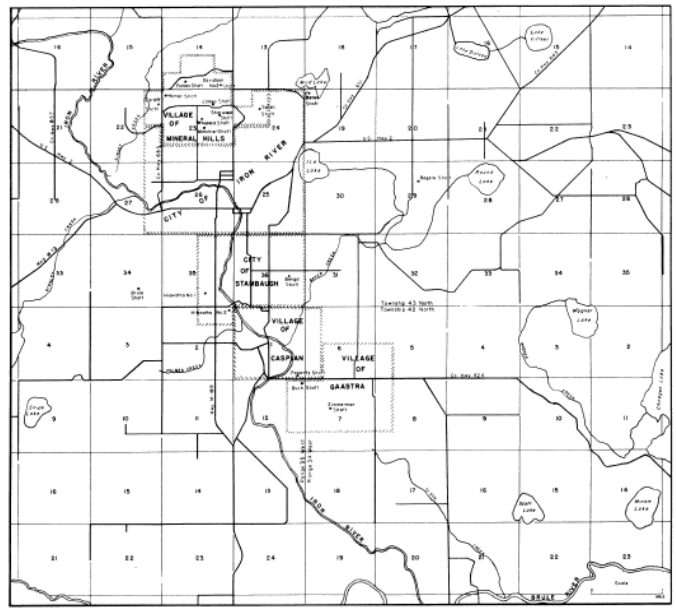

Figure 2. Iron River district, Michigan.

INTRODUCTION

For almost a century the Michigan ore-bearing districts have furnished a considerable part of the iron ore to the steel industry of the United States. During this period most of the areas containing the high grade ores have been extensively developed, and now, in general, the remaining harder-to-develop ores are being mined to maintain the continuous high production of ore necessary for the national economy. As existing mines penetrate deeper in search for ore and new developments are undertaken where the water table is above the ore body, the control of ground-water has become a major factor, in the fact that complete drainage of the surface reduces the operating hazards and permits a greater tonnage to be taken from the mine by reduction of the size of the pillars that must be left in place to support the surface. Not only are the direct costs of drainage increasing, but also the indirect operational costs of working a wet mine are becoming a larger proportion of the mining costs. For some wet mines the direct costs of pumping and drainage may range from 20 to 30 cents per ton of ore produced, but the increased mining costs due to handling wet ore and controlling the water may be 5 to 10 times this amount.

In recognition of the facts that the costs of drainage are increasing and that water is no respecter of political or property lines, the U. S. Geological Survey in cooperation with the Michigan Geological Survey undertook this investigation to determine whether knowledge of the hydraulic principles involved in the movement of water into the mines could lead to better engineering control and to a decrease in the cost of pumping water from the mines.

The problem has a direct bearing on and is interrelated with the broader country-wide and state-wide problem of mine drainage. Inasmuch as this is the first large-scale study of its kind, the methods of study were formulated as the work progressed and should serve as a guide for the solution of similar problems in other mining areas. The Iron River district was chosen for a pilot study because in this district the longest records of mine pumpage and water-level observations were available for study, including as they do the records for the Homer mine where pumping from surface wells began in 1930.

Location of area

The Iron River district of the West Menominee range is located in the south central part of Iron County, which is in the western part of the Northern Peninsula of Michigan. (See fig. 1.) The district, as the term is used in this report, includes the mined areas in the vicinity of Mineral Hills, Iron River, Stambaugh, Caspian, and Gaastra. (See fig. 2.) The twelve operating mining properties within the district ship an average of about 3 million tons of ore a year.

Cooperating parties and acknowledgements

The study of the relation between the ground water in the glacial drift and the water in the consolidated rocks, particularly the iron-bearing formations below the drift in the Iron River district, was undertaken by the Geological Survey, U. S. Department of the Interior, in cooperation-with the Geological Survey Division, Michigan Department of Conservation.

The study was made possible by the assistance of the mining companies who permitted underground examination of their properties and testing their wells on the surface, and contributed information from their records of diamond drill explorations, water-level observations, and pumpage. The operators in the district include the M. A. Hanna Company (Bates, South Homer, Homer-Cardiff, Minckler, Wauseca , and Hiawatha mines), Pickands Mather & Company (Baltic, Buck, Berkshire, Zimmerman, James, and Davidson mines), Cleveland Cliffs Iron Company (Spies-Virgil mine), and Inland Steel Company (Sherwood mine). F. G. Pardee, State Mine Appraiser, and F. E. Brown, of the Mineral Mining Co., also provided information on drill explorations.

Personnel

Field work was started in July 1945. Wilbur T. Stuart has devoted his full time to the collection, tabulation, and interpretation of the data obtained in the investigation. Charles V. Theis has spent more than 12 months in the development of the principles and formulas governing the movements of ground water below "ledge" (In the Lake Superior region the term "ledge" is used to designate the bedrock surface.) and the relation of the ground water above ledge to the circulation in the formations below ledge. George M. Stanley spent about 6 months studying the glacial geology of the area and the relationships of the water-bearing sands and gravels as contributors of water to the formations below ledge. C. S. Dutton and H. L. James of the Geologic Branch of the U. S. Geological Survey in Iron River have engaged frequently in consultations on the work and have furnished information concerning the geology of the consolidated rocks below ledge.

STRATIGRAPHY AND STRUCTURE OF AQUIFERS AND ASSOCIATED BEDS

The Iron River district has been almost completely covered with a coat of glacial materials, ranging in thickness from a few feet, on the buried bedrock hills to a few hundred feet in the buried valleys. Infiltration from precipitation and from surface water has saturated these materials, and maintains a water table in the buried valleys. Iron-bearing beds are in contact with the saturated glacial materials below the water table in many places in the district. All the rocks below ledge are highly and intricately folded and have steep dips. The iron-formation is the main water-bearing bed below ledge, although in many places permeable zones in the hanging wall beds are transmitting water. As openings are made in the formations below ledge through mining, water percolates into them and must be removed. The more extensive the exploration by the mine the greater the possible accretion of ground water to the mine.

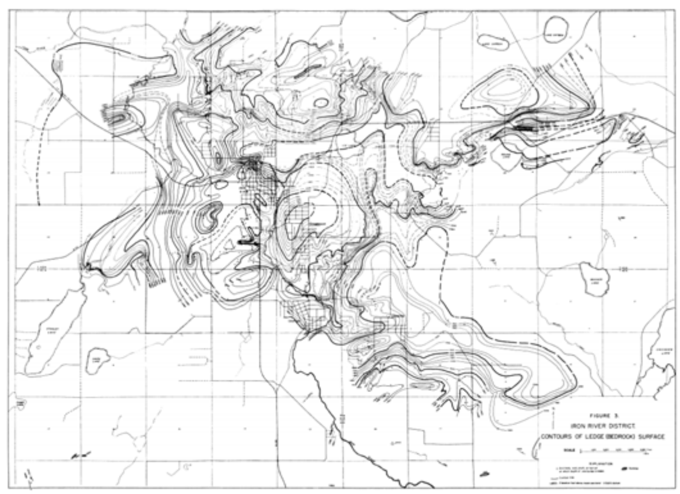

Figure 3. Contours of ledge (bedrock) surface, Iron River district.

Bedrock

The bedrocks of the district that are of interest in the problem of mine drainage are of pre-Cambrian (Huronian) age. They include the following typical stratigraphic succession, according to H. L. James (informal communication):

	Feet
Hanging well	
Magnetic slates	300-700
Silty gray sideritic slates and graywacke	
Sideritic graywacke and some slate and/or sideritic breccia, and locally black graphitic slate	
Iron-formation	
Iron-formation	50-160
Footwall	
Black graphitic, pyritic slate	30-40
Slate breccia	0-50
Gray sideritic slate, locally silty	more than 100
Graywacke, fine grained	

The geology of Mineral Hills section, has been described by Dutton and others, 1/ the Ice Lake - Chicagon Creek area by James and others, 2/ and the eastern and southeastern parts by James and Wier. 3/

Studies of the hydrology of the bedrock show the footwall formations to be almost impermeable to the flow of water, and only rarely do mine workings in the footwall intercept water; when they do the water is generally carried along fracture zones or vugs. However, in the iron-formation and in the hanging-wall formations small water flows in fracture zones and vugs are rather common, especially in the Mineral Fills area, where in some cases, the vug systems may be recharged from the saturated glacial drift at the sub-outcrops. (Points where bedrock strata meet the buried bedrock surface.) The iron-formation and the graywacke formations of the hanging wall that transmit water into the mines are considered poorly permeable to water when compared to the sands and gravels of the glacial drift. However, considering the formations as a whole unit, the length, thickness and dip, and the head of water over them; create favorable conditions for the movement of considerable water into openings made at depth in these formations.

Van Hise and Leith 4/ estimate the porosity of the iron formation to average 35 percent, and to contain an average of about 10 percent free moisture by weight. The porosity of the ore can be inferred from the comparison of the cubic contents of the ore in the ground (generally estimated as 12 cubic feet to the. ton) with the computed value of non-porous material of the composition of ore (which is estimated to be about 8 cubic feet to the ton). From this comparison it may be deduced that the porosity is equivalent to a volume of about 4 cubic feet per ton or about 33 percent. No laboratory tests to determine the porosity and water-transmitting characteristics of the rocks below ledge were made during this investigation, but values for these factors are discussed in a later section under the heading, "Movements of ground water into mines."'

Bedrock (ledge) topography

The topographic surface of the buried ledge is shown by the contours in figure 3. The information used in the construction of the ledge contour map was obtained from the exploratory drilling by the mining companies, from depth to ledge in existing mine shafts, from elevations of outcrops noted by the geologists, and from the records of water wells in which ledge was found. Many exploration holes have been drilled in the vicinity of known ore bodies and along lines parallel to the trends of the known bodies, but between these concentrations of drill holes the information is insufficient to define the ledge as closely as is needed.

In general, the map indicates a ledge topography of moderate relief. The Mineral Hills ridge and Stambaugh Hill are structural synclinal hills separated by a valley where the softer iron-bearing formations have been eroded. Other ridges and valleys of the district may have similar origins, but the trapping of the bedrock geology in most parts of the area discussed is quite incomplete. The contours of the bedrock surface show several valleys which drain in an easterly and southerly direction. A poorly defined valley west of Sunset Creek heading southeast of Iron Lake probably drains the ledge west of Mineral Hills to the south through sec. 34, T. 43 N., R. 35 W., and sec. 3, T. 42 N., R. 35 W. Connected to the Sunset Creek channel through a low saddle is a southeastward-draining valley passing south of the Homer and Minckler shafts in sec. 23. This valley trends southeast and, includes the area north of the Iron River within the City of Iron River and continues northeast of Ice Lake, where it is joined by a tributary from the vicinity of the Bates mine in sec. 19, T. 43 N., R. 34 W. The main valley continues eastward, including a basin in the vicinity of the Rogers mine, in sec. 29 and may either turn northeastward or southeastward from this point to the Chicagon Creek drainage. A tributary valley under the present bed of Baker Creek in the tillage of Caspian apparently drained northeast through sec. 31 and joined the main valley in the Rogers mine.

At present, the Iron River drainage does not follow the main preglacial drainage pattern. West of the City of Iron River and above the mouth of Sunset Creek the river flows across the preglacial drainage. Immediately below the mouth of Sunset Creek the Iron River valley is eroded almost to ledge and east of this point the river flows along the southern edge of the main ledge valley draining eastward, from the Homer and Minckler shafts. From the site of the East Genesee Street bridge, southward to the Hiawatha mines, the Iron River flows on ledge through a low gap in the preglacial surface. From the Hiawatha mines the river flows southeast and. south over the upper section of the ledge valley under the Village of Caspian to the bridge on County Road 424 west of Gaastra, where the ledge rises locally to the land surface. From this point the river, in general, follows the preglacial drainage southeastward to its junction with the Brule River at the southern boundary of the district.

It may be well to look backward and construct a mental picture of the surface topography just prior to glaciation. Before the deposition of the glacial materials the surface of the Iron River district presented a somewhat rugged aspect. The total relief was some hundred or more. feet greater than at present. The ancient hills did not present the smooth and rounded outlines of the present ones, but were bolder and rougher and in many places had steep slopes. Sheridan hill, a bedrock hill, with a present altitude of 1,860 feet, rises almost 600 feet above the bottom of the ledge valley north of Iron River.

In preglacial time there were probably no lakes or swamps. The land was dissected by stream channels and was completely drained. The area had been subjected to stream erosion for long ages end a considerable thickness of strata had been worn away. This is shown by the occurrence of flat-lying remnants of Ordovician limestone and sandstone on Sheridan Hill 6/ and along the Brule River. These strata formerly may have covered the entire district and above them still younger strata possibly once existed. These rocks were almost entirely removed before glacial time and the old erosional surface of the rocks of Algonkian type, on which the Paleozoic deposits rested and which now forms the rock surface beneath the glacial drift was again exposed. To accomplish this required a long period of erosion. Preglacial drainage was probably southeastward as now, as the rock surface seems to slope in that direction.

In the following section the geology of the glacial deposits above ledge is described.

GLACIAL GEOLOGY STUDY IN THE IRON RIVER DISTRICT, MICHIGAN, by George M. Stanley

Introduction

The excessive inflow of water to some of the iron mines in the vicinity of Iron River, Michigan, has been a-detriment to mining and a financial burden to the companies whose mines are so affected. Seeking some way to alleviate these difficulties, the United States Geological Survey in 1945 began an investigation, in cooperation with the Geological Survey of Michigan, of factors influencing ground-water inflow to mines in the Iron River district. As a part of this program, a study of the local glacial geology was undertaken by the writer. Field work was done during the summers of 1945 and 1946.

Previous glacial investigations had been made over larger regions including the area of this report, by Russell, 5/ Allen, 6/ Leverett, 7/ 8/ and Bergquist. 9/ 10/ It was hoped that further study might disclose enough regularity or systematic arrangement of the permeable and impermeable elements of the cover of glacial drift to outline the shapes and dimensions of the aquifers in the region. For this primary purpose the results of this study are negative. The variations in the gravelly, sandy, and clayey layers in the subsurface drift are so complex that no systematic presentation of their continuities and discontinuities can be given at this time.

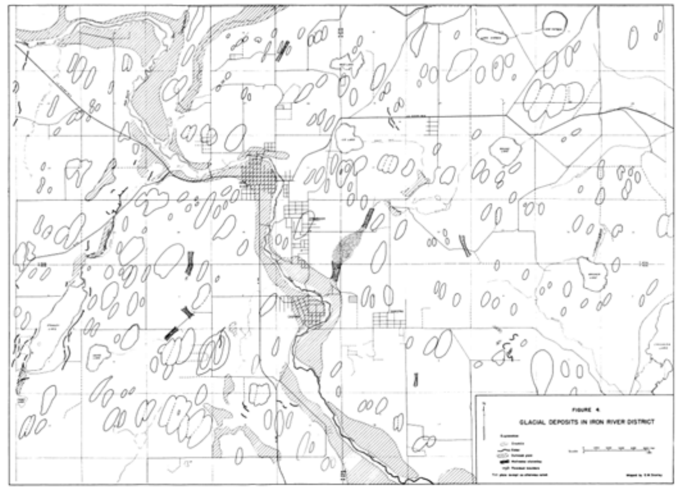

Figure 4. Glacial deposits in Iron River district.

This report includes a map of the surface formations of the Iron River and Gaastra quadrangles. (See fig. 4.) The areas of outwash are only roughly shown in some places. Their relatively poor development outside the Iron River valley and the wooded character of much of the country handicap identification of their boundaries. The eskers are more distinctive because of their sharp topography, and many previously unreported ones are shown. A number of other features relating to drainage during stages of deglaciation, to glacial erosion, and to drumlin formation are discussed.

General distribution of drift

Iron County is the central part of a highland area which obstructed expansion of the late Pleistocene ice sheet over areas to the south. The glacier of the Wisconsin stage, growing southwestward from the center in Labrador, did override this relatively high plateau, but it made easier progress and more extended advance through the basins of Lake Superior and Lake Michigan in two great lobes directed roughly-west-southwest and southward, respectively. There seems little doubt that the escape of southwestern Wisconsin from invasion by the ice sheet was directly due to the obstacle formed by the high area centering in Iron County.

Leverett 8/ has shown that the latest or Wisconsin stage of glaciation included five recessional substages. In the first two of these the ice reached the southern and central parts of Ohio and Indiana and corresponding latitudes in Illinois. In the third substage the ice of the Michigan, Huron, and Erie lobes reached only to northern Ohio, Indiana, and Illinois, and by the end of this period it had melted back far to the north and uncovered most, if not all, of lower Michigan. Also during the third substage, the ice from the Lake Superior basin had advanced over the Iron County highland and for about 100 miles into the north part of central and western Wisconsin, apparently beyond its limits in these areas during substages 1 and 2. The growth of a center of ice accumulation north of Lake Superior during this period is believed to have produced this greater expansion. After the retreat during substage 3, there was a readvance which inaugurated substage 4. At its greatest extent, the glacier of this substage covered all the upper peninsula of Michigan except for an area of about a dozen townships confined largely to the south-central part of Iron County between Elmwood and Crystal Falls. Both to the east and to the west the ice reached south of the present State line into Wisconsin. Thus the highland area, referred to before as an obstacle to ice movement, this time completely resisted incursion by the ice.

Iron County may thus be divided into two areas of drift of slightly different age. The boundary between them trends north-northeast from the middle of T. 44 N. on the Gogebic County line to the headwaters of Paint River, and then approximates the course of Paint River to the east and south down to Brule River and the Wisconsin State line. The older drift is, therefore, overlapped on the northwest, north, and east by the younger.

The older area in the south part of the county, of drift of substage 3, seems to lack distinct terminal moraines, but drumlins and eskers ore numerous. In a general way the presence of drumlins is one of the main features distinguishing this section from the area of more recent drift in the northern and eastern parts of the county.

It is striking that most of the lakes in the south part of the county are elongate in the same direction as the drumlins, and many of these lie in valleys of much greater length than the lakes themselves. Plainly the glaciation of this district during the third substage was very vigorous, as it shaped the landscape along contours conformable to southwestward glacier movement. However, apparently as a result of the expenditure of energy necessary for the glacier to surmount and scour over this plateau, it was unable to attain the southerly extent reached by the lobe in the Lake Michigan basin. From the absence of terminal moraines it must be presumed that the ice in this area became stagnant during the retreat phases of substage 3, the ability for forward motion being dissipated "by melting down and thinning of the mass. Many eskers were formed in the south part of Iron County during the time of ice a stage in substage 3.

	Direction	Location
(1)	S. 3° W. S. 1° W.	NW¼SE¼ sec. 21, T. 42 N., R. 35 W., about 1,000 feet NE of farm house. (See note at end of table.)
(2)	S. 4° W. S. 5° W. S. 7° W.	300 feet east of (1).
(3)	S. 5° W. S. 6° W. S. 13° W.	600 feet ENE of (2).
(4)	S. 7° W. S. 8° W. S. 11° W.	About 100 feet west of farm house referred to in (1).
(5)	S. 8° W.	SW¼ sec. 36, T. 43 N., R. 35 W., about 400 feet south of Stambaugh High School. (See note.)
(6)	S. 14° W.	About 100 feet SW of new school addition; and north of (5).
(7)	S. 34° W.	NW¼NE¼ sec. 13, T. 42 N., R. 35 W.
(8)	S. 0° W.	NE¼SW¼ sec. 8, T. 44 N., R. 35 W., on summit of high outcrop ½ mile west of Gibbs City; striae and chattermarks convex to north.
(9)	S. 43° W. S. 48° W. S. 51° W.	SW¼ sec. 13, T. 45 N., R. 37 W., outcrop on east edge of Forest Highway
(10)	S. 81° W. S. 83° W.	Center of sec. 19, T. 43 N., R. 31 W., in cut of road to Michigamme Falls, 1.9 miles north of State Highway 69.
(11) (a)	S. 86° W. S. 84° W. S. 81° W. S. 79° W.	SW¼ sec. 19, T. 43 N., R. 31 W., 1.25 miles north of State Highway 69 on same road as (10). (See note.)
(b)	S. 41° W. S. 48° W.	Earlier striae on same outcrops as (a).
(12)	S. 83° W. S. 81° W.	SW¼ sec. 18, T. 43 N., R. 31 W., NW of Mansfield
(13)	S. 20° E. S. 35° E.	Center of sec. 2, T. 46 N., R. 37 W., on east side of road.
(14)	S. 52° E.	NW¼ sec. 2, T. 46 N., R. 37 W., on prominent moutonnee on hill south of creek and old slate quarry.
(15)	S. 30° E. S. 35° E.	South of center of sec. 9, T. 46 N., R. 37 W., deep grooves in outcrop on NW side of road.

(1) These grooves on ,"roche moutonnee" outcrops of greenstone breccia are accompanied by faint tail-like ridges of the greenstone trending south from light-colored inclusions in the breccia. The inclusions obviously offered greater resistance to glacial abrasion and buttressed the tails of greenstone in their lee.

(5) A few crescentic chatter marks on this outcrop at the south end of the athletic field are convex to the north, affirming southerly ice movement.

(11) The striae listed in (b), showing a much more southerly direction of ice movement than those in (a), are found only in small remnant patches en the west slopes of outcrops where they were not eradicated by the later abrasional work which product the striae listed in (a).

Table 1. Direction and location of observed glacial striae.

Glacial Striae

The writer's observations of striae are in harmony with Leverett's interpretations of ice movement in the region. Those in localities (1) through (9), table 1, are in the area of the drift of substage 3 and are directed consistently a little west of south, in conformity with the trend of the drumlins. Those in set (b) at locality (11) are also associated with substage 1, though striae (11-a) of substage 4 predominate on the same outcrops. The other sets of striae, which are related to substage 4, trend close to west in the eastern part of Iron County and about southeastward in the northwest part of the county. Following the tabulation of striae below, a few additional notes are given on those at localities (1), (5), (6), and (11).

Drumlins

The drumlins in this area range from a few hundred feet to about a mile in length, but most of them are from a quarter to half a mile long, and from about 30 to 60 feet in height. Their trend ranges from south to about S. 40° W. and the typical trend in Iron River quadrangle is about S. 25° W. In the eastern part of the Gaastra quadrangle they bear a little nearer south than do those farther west.

There are many variations from the typical drumlin shape. Some adjacent drumlins are laterally merged. Several small ones may be seen perched on one large drumlin or on a drumlinoid mass. Some of the drumlins show gentle curvature of the long axis. Similarly, some interdrumlin troughs, shaped by the same vigorous glacial molding as the drumlins themselves, also exhibit slightly curved courses. Most of these characteristics are represents in figure 4. The general parallelism of the drumlins with most of the elongate lake basins and valleys of the district is striking. On the other hand. Sunset Lake trends almost at right angles to them. Emily, Iron, and Stanley Lakes, all elongate, are in almost perfect alignment with neighboring drumlins. So are Golden, James, and Smoky Lakes in the southwest part of Iron County. Across the Wisconsin line from Smoky Lake, Sand Lake trends more to the west-southwest, obliquely cutting across the ends of bold drumlins which show no tendency to divert locally from their trends elsewhere.

As in other regions, the drumlins are composed largely of glacial till, but beds of sand and gravel occur in some of them as in the SE¼ sec. 27 and in the center of sec. 25, T. 34 N., R. 35 W. In both these cases the exposed stratified beds are at the northern ends of the drumlins, and none have been seen by the writer at their southern ends. Their presence indicates that these drumlins were formed not entirely by a process of plastering on of till, but partially at least by sculpturing in drift deposited previously. Some of the drumlins have cores of bedrock. It seems likely that molding of the drumlins may have combined a sculpturing or erosion of debris from the stoss or northern ends simultaneously with additions of till to the lee or southern ends. In a number of exposures of drumlin till there is a faint bending or alignment of stones, the lines conforming more or less to the surface slopes. This suggests an accretion process in shaping the drumlins, but it is by no means a general nor a conspicuous feature of the till. Perhaps the clearest bend of stones within the till is on the north wall of the Zimmerman mine cave in the NW¼ sec. 7, T. 42 N., R. 34 W.

A striking example of the debris added to the lee end of a drumlin was found near .the center of the SW¼ sec. 36, T. 43. N., R. 35 W. Great quantities of till have been excavated from the tail of a drumlin here and used for stope fill in the Hiawatha mine. The large boulders are discarded. One of these, of chert breccia, is of such size that it has been moved but slightly from its original position in the till. It is elongate, with the long axis parallel that of the drumlin. The shovel operator succeeded in rolling the boulder over, with rotation about the long axis, so that it is now bottom side up from its natural position, but still trending in the same direction. Rarely does one encounter a transported rock which exhibits such a profusion of glacial markings. These include striations, signs of plucking and abrasion on the lee and stoss ends of chert fragments, chatter marks, and the shadow-like tails of matrix rock in the lee of resistant, buttressing inclusions. This last feature; is shown on two different scales in the same rock. The tails are several inches in length behind some of the chert inclusions. Tiny quartz crystals within the chert also protected delicate little cherty tails, less than an inch long, in their lee.

It is clear from all the observed phenomena that the exposed surface of the boulder was rubbed from its southern toward its northern end. This is just what would have been expected to occur while the boulder, originally the other side up and imbedded in the base of the glacier, was scraped over the subjacent surface during southward travel.

Sluiceways

Throughout the drumlin areas of the Iron River and Gaastra quadrangles there are many local bouldery tracts which appear to be residual from vigorous scour by small streams of melt water during deglaciation. Most of these are in the beds of channels between drumlins and along the south sides of basins enclosed by drumlins. Examples are shown in figure 2 in the NE¼ sec. 3, T. 42 N., R. 35 W., in the SE½ of the same section, and in the sec. 10, also in the SW¼ sec. 13, T. 43 N., R. 35 W. In all these places the amount of scour seems greater than could occur under modern conditions.

In some other localities the concentrations of boulders are so topographically situated as to be beyond the reach of any modern drainage, and therefore they must represent the work of running water that was confined to hill slopes by stagnant ice masses. A typical boulder-strewn channel courses south from the southwest corner of sec. 24, T. 42 N., R. 35 W. East of it and about 40 feet higher, another band of boulders lines the west slope of a drumlin in a course parallel to the channel below. Presumably this was formed by meltwater from the same source as for the channel bottom but at an earlier time, while the channel was still half filled with ice.

A similar concentration of boulders occurs half a mile to the south, along an easterly slope, and on the line between sec. 25 and 26. Similar occurrences are shown along a slope south to a swamp in the NE¼NW¼ sec. 9, T. 42 N., R. 34 W., and on a southeasterly slope in the SS¼SE¼ sec. 4 to the north.

The confining agency of ice seems necessary also to explain some belts of boulders concentrated on lowland flats where, without such restraint, the stream would have dissipated its water and energy over the surroundings. One such pavement of large rounded cobblestones courses along the flat between two esker ridges in the NE¼SW¼ sec. 33, T. 43 N., R. 35 W. Another leads south to the northeast corner of a large swamp, in the SW¼SW¼ sec. 8, T. 42 N., R. 34 W. A more extensive train of boulder pavement occurs along the line between sec. 34 and 35, T. 43 N., R. 34 W., near its midpoint, and can be followed south almost to Mahoney Lake by means of scattered boulders.

The most striking concentrations of boulder in the area are along Baker Creek, east and southeast of Stambaugh. Baker Creek collects water from Ice Lake and Round Lake and broad marshes in the northern parts of sec. 30 and 32, and the western part of sec. 29, T. 43 N., R. 34 W. It flows in this broad a lowland to the NW¼ sec. 31 where it passes through an abrupt gorge over a quarter of a mile long and 40 feet deep. Leaving this gorge, it continues through an open basin in the SW¼ sec. 31, leaves this by a second and smaller gorge, and enters Iron River in the eastern part of the town of Caspian.

Along the lower part of the upper gorge and a few hundred feet west of the center of sec. 31, boulder strewn or gravelly benches up to 20 feet above creek level indicate erosion by a larger stream, than modern Baker Creek. The boulders are so concentrated and free of finer debris in some places n these benches that grass and shrubs do not grow. Farther downstream and over considerable areas in-the northern and western parts of the SE¼ sec. 31, such bare stony patches are common, though here of a less coarse texture and a tract of perhaps 50 acres is mantled with cobblestone and coarse gravel. Apparently a flood of considerable volume eroded out the gorge in the northern part of sec. 31 and spread smaller stones in an extensive fan over the basin to the south of it. These conditions are duplicated, though less conspicuously, at and below the lower gorge in the northeastern part of Caspian.

There are faint benches just above the head of the upper gorge, in the NW¼NE¼ sec. 31, at elevations of 1,505 and 1,570 feet and from less than 2 to 25 feet above present creek level. They are on the north nose of the drumlin, which water currents had to pass around in order to enter the gorge. As glacial ice melted out of the low basins in secs. 29, 30, 31, and 32, a body of water must have been ponded in this lowland to the level of an interdrumlin trough which was scoured down to the present upper gorge.

A bouldery, scoured channel in the SW¼ sec. 32, leading southwest from the same system of basins, has an elevation somewhat above 1,580 feet where it crosses the divide, quite above the reach of present drainage. This sluiceway was an earlier outlet for the same lowland referred to above, while stagnant ice obstructed some of the lowland area from draining by the route Baker Creek follows. The threshold of this channel is about 15 feet higher then the uppermost bench at the head of Baker Creek gorge.

Eskers

There are many eskers throughout Iron County associated with both of the later substages of the Wisconsin glaciation. They occur most commonly in the larger valleys or lowlands which trend with the directions of glacier motion.

The valley of Stanley Lake and Stanley Creek contains the most complete esker system in the area of the Iron River and Gaastra quadrangles. It follows the valley floor from the south part of sec. 28, T. 43 N., R. 35 W. almost to the southwest corner of sec. 33, with a few minor gaps. In this stretch the main ridge is 10 to 25 feet high and is accompanied at a few points by short, auxiliary ridges, parallel or branching. On the east side of Stanley Lake, three short ridges, near the line between the secs. 4 and 5, T. 42 N., R. 35 W., 40 to 50 feet up the steep slope away from the lake and merge into a single ridge continuing thereafter on high ground, parallel to the lake shore, and southward into sec. 8. It would seem that the esker stream made this ascent under considerable hydrostatic pressure, without regard for the topography beneath the ice. Several eskers of shorter extent occur along the southwest shore of Stanley Lake.

A short esker courses along the crest of a drumlin in the NE¼ sec. 19, T. 43 N., R. 35 W. An esker is also perched on a drumlin in the NW¼ sec. 11, T. 42 N., R. 35 W. A most curious circumstance here is an echelon arrangement of short gravelly ridges on the lower north slope of the drumlin, close to the north line of the section. These ridges, just north of a continuous esker ridge, trend southwest following the general contour of the drumlin here, and are separated from one another by distant swales. That they might have become disjointed from an originally continuous ridge by some glacial movement, after deposition of the esker, seems unlikely from the even character of the ridges. More probably they were stream deposited in their present positions.

A somewhat similar arrangement of esker ridges occurs in an almost identical topographic situation about a mile to the south, in the SW¼SW¼ sec. 11. In each case the eskers are built on the north nose of a drumlin, just south of side valleys opening eastward into a larger north-south valley continuous along the east sides of both drumlins ad slightly oblique to the drumlin trends. Within this larger valley a current of glacial ice must have been directed more nearly southward than was characteristic over the adjacent drumlins and the region as a whole. The side valleys north of each drumlin offered escape southwestward for some of the ice confined elsewhere to the north-south valley. These escape currents, trending somewhat across the general ice movement at higher levels in the glacier, would have facilitated formation of crevasses about where the off-set esker ridges are situated, thus leading to deposition of these gravels.

Another chain of esker ridges trends south from sec. 23, T. 42 N., R. 35 W., and swings from south-southeast in sec. 26 to the east-southeast in secs. 25 and 36. Over most of the distance they are descending a general land slope toward the Brule River. From the fact that they turn east in approaching the Brule Valley, as does also a small esker in sec. 21, T. 42 N., R. 35 W., it is to be inferred that, by the time these eskers were formed, glacial drainage, perhaps beneath the ice, was following down the Brule Valley as does the drainage today.

The eskers in the Iron River and Gaastra quadrangles are not as large as some others in Iron County. A complex esker chain trends south toward Ottawa Lake along the line between secs. 23 and 24, T. 43 N., R. 36 W. and some of these ridges are very high and bulky. A conspicuous esker crosses U. S. Highway 2 in sec. 29, T. 43 N., R. 33 W. about 2 miles, east of Chicagon Creek, and contains a great number of large boulders, a detriment to the gravel operations that were formerly carried on in the north part of sec. 29. Two miles farther north the same esker is a very pretty pine-clad ridge along the east side of Long Lake.

During Leverett's substage 4 of the Wisconsin stage, the ice moving southeast into Iron County from northern Gogebic County left a splendid example of an esker along the valley of Tamarack Creek. It trends southeast from the northern part of sec. 23, T. 45 N., R. 38 W. through sec. 24, skirting the west shore of Ottawa Lake (Gogebic Co.), and across sec. 25 into Iron County sec. 30, T. 45 N., R. 37 W. It terminates close to the east edge of sec. 31 where Tamarack Creek turns its course from northeast to northwest, and only a little short of the ice margin of substage 4. Its length is 3½ miles, and in this distance it is near both Tamarack Creek and the Chicago and Northwestern Railroad, all three sharing the same valley. In sec. 24 the esker has a flattish top for half a mile; through secs. 30 and 31 it is a narrow crested ridge supporting, among smaller growth, a few clusters of stately pine trees.

Outwash

While glacial ice was melting out of the area of the Iron River and Gaastra quadrangles late in substage 3 of the Wisconsin stage, and probably following closely the formation of the eskers, meltwater must have drained southward along some of the larger valleys. The valley of Stanley Creek and Stanley and Camp Lakes offered a continuous depression south-southwest from Iron River Valley to the Brule River and along it are patches of outwash. Due south of the town of Iron River, a lowland through secs. 2, 11, 14, and 24 and 25, T. 42 N., R. 35 W. afforded another meltwater escape and contains patches of outwash. The limited extent and fragmentary character of these gravelly areas indicate that these routes were only temporarily used, and scarcely anywhere were they aggraded into plains of more than a few acres.

In this respect, the trains of level outwash which follow the Iron River Valley are far more fully developed. Although the Iron River has dissected the highest outwash surface along the valley, there are graded remnants of it that extend for a mile or more. Probably at one time the graded surface filled the valley almost completely, but there are some basins contiguous to the valley which give no indication of ever having been aggraded to the highest level.

One of these is a triangular area of about 80 acres in the NW¼ sec. 25, T. 43 N., R. 35 W., skirted by the main highway between Iron River and Ice Lake. This is below the 1,500-foot contour and fully 20 feet below the gravel plain on which the town of Iron River is situated. This depression has not the shape one would expect had it been eroded out by the Iron River subsequent to aggradation. Moreover, a gravel bar built eastwards part way into this basin, from the southeast edge of the Mineral Hills residential district, into the SW¼NW¼ sec. 25, illustrates a partial attempt at filling it. The position of the bar also negates any presumption that the basin, or at least the eastward part of it, is due to erosion by Iron River. Erosion by short-lived hillside streams is also out of the question. A somewhat analogous situation occurs north of the Iron River quadrangle, between Iron River and Iron Lake.

In general it seems that the failure of the Iron River meltwater stream to aggrade these basins with gravel is due to the behavior of the river rather than to occupancy of the hollows by stagnant ice masses, and that, while aggradation was preceding in neighboring parts of the main valley, pools of deeper water were present in some basins.

The Iron River outwash has a summit elevation of about 1,540 feet in the center of sec. 16, T. 43 N., R. 35 W. in the north part of Iron River quadrangle; in the south part of Gaastra quadrangle it is 1,445 feet near Scott Lake R. R. Station. The difference of 95 feet between these points, 11 miles apart along the valley, would suggest a gradient of almost 9 feet per mile for the aggrading stream. This seems very high for the large stream it must have been. About 22 feet (4 feet per mile times 5½ miles along the tilt line) may be subtracted from this fall for that part of the postglacial uplift which deformed the Algonquin beach of the Lake Superior and Lake Michigan basins. The remaining drop of 73 feet would give a gradient of 6½ feet per mile for the glacial stream.

The outwash consists of sandy gravel with localized lenses of pure sand and of very coarse gravel.

Diversion of Paint River to Iron River Valley

The size of the broad gravel plain at Beechwood, at the head of the North Branch of Iron River, indicates formation by a volume of water comparable with that which graded the gravel terraces farther down the Iron River Valley. The Champion Gravel Company has left, large pits in sec. 1, T. 43 N., R. 36 W., after excavation of this gravel. In the NW¼ sec. 1, a pit wall shows current bedding of the gravel to the south-southeast, down Iron River Valley. The Beechwood gravel plain extends about 2 miles north-northeast to the valley of the South Branch of Paint River, bordered by an eroded bluff along its western edge. The plain contains a swampy channel, with a width in places of a quarter of a mile, floored with peat and 15 feet or so below the outwash level; the channel courses south and southeast from the edge of Paint River Valley across secs. 25, 35, and 36, T. 44 N., R. 36 W., to the head of Iron River, which lies in it.

It is evident that the Iron River Valley formerly deceived from the South Branch of Paint River a copious meltwater stream crossing the present divide north of Beechwood. Undoubtedly such a diversion would be expected temporarily during the northward recession of the' ice of substage 3. From the position of the moraine substage 4 on the maps of Leverett 7/ and Bergquist, 9/ lying as it does everywhere to the north and east of the Paint River and its South Branch, it would appear that this river could have pursued its present course during substage 4 without disturbance. However it may be that the ice of substage 4 advanced across the Paint River Valley in some place, such as along the valley of Net River, causing a recurrence of this diversion.

Laminated silts

In the eastern part of sec. 22, T. 43 N., R. 35 W. along the valley of Sunset Creek, there are laminated silts at shallow depth. They seem to be annually deposited layers of alternately coarser and finer silt, each pair of summer and winter layers constituting a varve. These varves were exposed in a trench and in a boring made by the writer in the NE¼NE¼ sec. 22, about 800 feet west-northwest of the Cardiff mine shaft. The trench was on the bank of Sunset Creek and 3 feet above it, and exposed the following section:

18 inches	Yellow sand (about 2 feet to be added to this for previous excavation of railroad grade.)
5 inches	Coarse sand with some gravel.
25 inches	Laminated fine gray silts alternating with coarser silts or very fine sand. About 95 to 100 pairs of these laminae or varves. The upper 15 inches of the, finer, or winter, layers slightly reddish.

An auger boring was made to a depth of 6½ feet below the bottom of the trench. The material brought up appeared to be identical with the 25 inches of laminated silt above, and contains probably more than 300 additional varves.

A second auger boring, half a mile farther north, on the south quarter line of sec. 15 and about 400 feet east of Sunset Creek, showed essentially the same laminated silts covered by a few inches of sand, to a depth of 7 feet, except that between depths of 4 and 4½ feet scattered pebbles (up to 3/4 inch in diameter), probably ice rafted, were encountered in the silt.

A third boring, near the west edge of the SE¼NE¼ sec. 22, went to 10-foot depth and showed 4 feet of pebbly sand overlying 6 feet of stratified silts like those mentioned above.

A house excavation in the SE¼ sec. 15, about 600 feet north and 100 feet west from-the corner of secs. 14, 15, 22, and 23, T. 43 N., R. 35 W. shows more of the stratified silts. Here they are overlain by 3 inches to 10 inches of coarse gravel and by about 2 feet of loess. The silts are coarser in texture, here, with thicker laminae and much interbedded sand. As shown by an auger boring below the floor of the excavation, they have a thickness of at least 14 feet.

All the silts referred to above must have been deposited in rather quiet water, incapable of transporting fine pebbles, and while melting ice was in the vicinity. In every case the silts are covered with a layer of coarser material, either sand or gravel. Presumably the valley of Sunset Creek was filled with a broad pool of deep water in .which the silts settled, and when this pool was drawn down by better drainage, there was opportunity for a more vigorous flow, and the overlying sand and gravel was deposited. It would seem reasonable that the pooled condition might have been contemporaneous with the development of outwash along Stanley Creek and other valleys, and before integration of drainage along Iron River Valley, which brought an end to the pool.

In relation to ground water, the stratified silts along Sunset Creek probably are only slightly permeable to vertical movement of water, but somewhat more permeable in the horizontal direction.

Former valleys of Paint River

In the western part of Iron County two abandoned valleys indicate changes in drainage by Paint River. They show remarkably well on aerial photographs and have been studied only by this means.

They lie close to the boundary where the drift of substage 4 laps on to that of substage 3, but seem to be within the area of the latter, for the terrain they traverse, within about 4 miles north-northeast of Elmwood, shows the characteristic fluted and drumlin molded topography from northeast to southwest. The ice during substage 4 advanced toward this region from the northwest, at the same time pushing southward farther east toward Gibbs City, and probably it thereby cut across and obstructed the present eastward drainage of the North Branch of Paint River.

East of Elmwood the South Branch of the Paint makes an abrupt turn northward for a mile and loops back to the south again. Within a mile and a half farther north one of the abandoned valleys describes an almost parallel course, about 4 to 5 miles in length, shaped much like a horseshoe. Its western, beginning is in the SE¼ sec. 34, T. 45 N., R. 37 W., close to the "Forest Highway." It cuts through high land and is much gullied along the side walls. In its eastern part the valley is occupied by one of the headwaters of Bush Creek, with drainage to the North Branch of Paint River.

The second valley is about 3 miles north of the South Branch of Paint River and shows a tendency to the same delineation as the present river and the abandoned valley already described, as it makes a long curve convex northward. It has about the same length as the other old valley but traverses lower ground.

It seems likely that both these valleys were made by the same melt-water stream that built the large esker along Tamarack Creek, farther to the west. This esker trends southeast and terminates half a mile northeast of Tamarack Lake and only about 3 miles from the head of the first described abandoned valley, separated from it by channeled outwash.

Very likely this stream of meltwater made and used these two abandoned valleys in the same order in which they have been mentioned, by diversion northward as melting out of the ice permitted it to occupy lower ground.

Subsurface glacial drift

Good exposures of the drift to a moderate depth may be seen in two pits recently excavated by the M. A. Hanna Company in the east part of sec. 22, T. 43 N., R. 35 W. One of these is a pit from which material is taken to fill abandoned stopes in the mine, and is a few hundred feet south of the Cardiff mine shaft. At the south end of this pit the section is as follows:

<u>Section at Cardiff stope-filling pit</u>

0 - 4½ feet	Loess and weathered till
4½ - 20½ "	Till
20½ - 44½ "	Sand and gravel
44½ - 55½ "	Stratified sand with clay streaks
55½ - 65½ "	Coarse gravel

This section varies considerably along the walls of. the pit, which reaches north and south for about 250 feet and is less than half as wide. Along the east wall of the pit the till rapidly thins and disappears about 60 feet to the north, the underlying sand and gravel showing a corresponding thickening. After a hiatus of 3 to 4 yards the till reappears and gradually thickens again toward the north end of the pit. The till is 2 feet thick on either side of the discontinuity and at one-time was probably continuous here. A channel 5 feet deep, floored with boulders and filled with gravel, occupies this hiatus; it is covered over with the same even mantle of loess which elsewhere covers the till, leaving no break in the ground surface to distinguish it. The channel seems to trend from northeast to southwest, as it is exposed farther south on the west wall of the pit, and it was probably eroded and filled by a minor stream of subglacial drainage along this course.

Another excavation, known as Sauerman pit, was made half a mile to the southwest in the bed of Sunset Creek. The creek was diverted for the purpose through a small canal to the west. Seepage feeds a small pond in the bottom of the pit, and this is intermittently pumped out into Sunset Creek to maintain a lowered water table in the area near the Homer and Cardiff mines. The following section is exposed in the east wall of the pit beside the ladder down to the pump raft:

<u>Section at Sauerman Pit</u>

0 - 5 feet,	Loess, with stones and some boulders
5 - 9½ "	Gravel, sand, and boulders
9½ - 20½ "	Horizontally bedded sand, with pebbles
20½ - 22 "	Band of boulders and cobblestones, very much water-worn and pocketed, with admixture of hematite-stained sand and fine gravel
22 - 29½ "	Till with many striated stones; upper foot of till stained with hematite from overlying gravel
29½ - 38 "	Horizontally stratified sand with some streaks of reddish clay

Slumped material conceals the base of the section down to pond level at depth of 52½ feet.

In the above section the band of water-worn boulders is obviously a residue from wash on the underlying till. This band, together with the till surface, declines northward about 12 feet in a distance of 100 feet along the pit wall, with a correspondingly increased thickness of the overlying sand. The number of residual boulders in the band over the till decreases somewhat along the higher part of the till surface. Exposures on the west side of the pit are poorer, but the water-scoured zone of boulders above the till may be made out at a number of places sloping north and south from a high point, which is south-southwest of the high point on the east wall of the pit. Thus there seems to be a gentle ridge of till here, parallel to the drumlins of the country, eroded by running water and buried by stream-deposited gravels.

Another well-exposed section is afforded by a "cave" or collapsed area on the James mine property in the NW¼NE¼ sec. 23, T. 43 N., R. 35 W. Resembling an hourglass in plan, this cave consists of two circular areas of collapse, merged together. The following sequence was noted in its west wall.

Section in James mine "cave"

0 - 3 feet,	Loess, with stones
3 - 6 "	Weathered till
6 - 16 "	Till
16 - 46 "	Gravel and sand
46 - 64 "	Coarse gravel

Slump obscures lower walls to bottom of collapse pit at depth of 81 feet.

There are numerous other caved areas along the north edge of sec. 23, but because of less depth and much more advanced slumping the exposures are not as good as the one detailed above. They suggest that the till layer at James cave continues several hundred feet to the north.

Local variations in thickness of beds and in slope of contact surfaces, as in the Cardiff and Sauerman pits, and typical also of many of the gravel pits and caves near Iron River, caution against attempts to correlate buried, beds of till and gravel between places of exposure, or to infer that continuities exist from one place to another.

With a view to the possibility of tracing the buried till and gravel beds, considerable time was spent in studying the logs of wells and borings in the Mineral Hills district. Profiles were drawn in various directions between the more closely spaced and more recent holes. The correlation or continuity of beds between points of record in these profiles proved to be so dubious a matter and involved so many alternatives that no statement of positive findings can be made in this regard. Although a great number of borings have been made in the district, many of them had no logs for the glacial drift. Some of the more recent holes were made with very detailed records of the drift, but older ones tend to supply meager information. When correlations along even a single profile are extremely doubtful, it seems futile to attempt to portray a three-dimensional picture of the permeable and impermeable elements that comprise the drift.

In general, it is not possible to predict the occurrence of the permeable or impermeable elements in the - overburden. Although the determinations of permeability made in the pumped wells indicate the water-bearing areas to be of rather uniform permeability, these wells were located after an extensive program of exploratory test drilling had determined the most favorable sites. This study of the glacial drift further emphasizes that the detailed character of the overburden can be determined only by adequate exploration.

GROUND-WATER CIRCULATION

Between certain levels, water occupies the large and small openings in the rocks of the earth's crust. The upper surface of the zone saturated with ground water is known as the water table. It rises in response to additions from rainfall or surface water and declines in response to withdrawals by pumping or natural discharge. The ground-water zone extends downward to a considerable depth, where the rock pressure is so great that water-bearing openings cannot exist.

In the Iron River district, materials of the earth's crust that contain ground water can be divided into two main groups; (1) the unconsolidated sands, gravels, clays, and hardpan of the glacial drift which covers the area more or less thickly; and (2) the consolidated bedrock, which includes the iron-formation and associated rocks in which the mining of the district is taking place.

The water table

The water table that is found in the glacial materials above the consolidated bedrock or ledge is the surface at which free water stands in the pore spaces of the pervious granular material and indicates the level to which the subsurface reservoir is filled. The pores or interstices are. intricately connected. The size of the interstices and the degree of interconnection are governed by the type of the material and the manner by which it was deposited in its present state. In the Iron River district under natural conditions the water table lies close to the bedrock where the bedrock extends above the surface drainage level, and slopes gently to the surface drainage where the bedrock lies at some depth below the surface drainage.

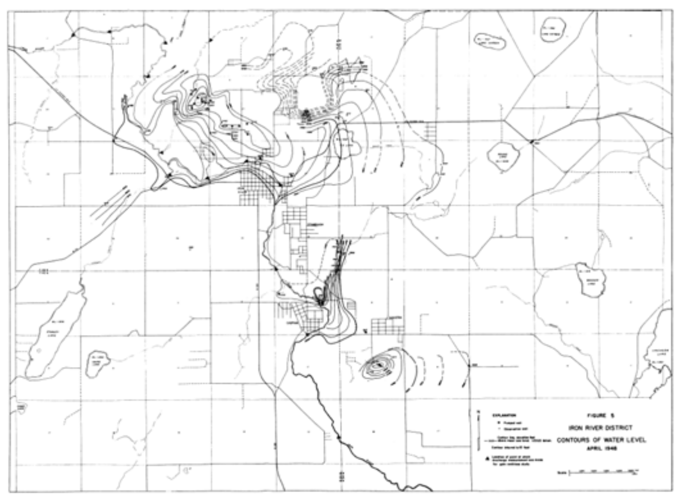

Figure 5. Contours of water level - April 1948, Iron River district.

The contour map of the water table

A contour map of the water table is a graphic representation of the slope of the water table and forms a basis for the study of the direction of movement, rate of motion of the water, and zones of recharge to, and zones of discharge from, the area; and it may indicate changes in permeability of the underlying saturated materials. The general ground-water movement is down the slope normal to the contour lines.

Contours of the water table as shown in figure 5 represent the height above mean sea level at which water will stand in wells drilled into the glacial overburden.

The contours of the water level as shown in figure 5 were constructed from the elevation of the water table as measured in all the accessible observation points in the area as of April 1, 1948. On this date the static levels were at low points after steady declines during the preceding fall and winter periods. The mean air temperature on this date was below freezing, so that recharge from the accumulated snow and ice on the ground surface had not started. The major features of the water table change noticeably only slowly and over long periods of time, although the water levels in wells are fluctuating continually owing to variations in the rate of pumping the wells, changes in barometric pressure, and recharge from various sources.

The contour map shows the water table to be sloping toward the Iron River along natural drainage channels in areas distant from the influence of the municipal or mine pumping. In the northwestern and western parts of the district the ground-water drainage is toward Sunset Creek and Stanley Creek and then toward the Iron River. In the north-central and northeastern parts of the district the ground-water drainage is toward Baker Creek, a tributary of the Iron River near Caspian. In the vicinity of Caspian and Gaastra the ground-water drainage is toward the Iron River.

The contour map shows three cones of pumping depression, in the Mineral Hills-Iron River area, the Caspian Pit area, and the Zimmerman-Degrasse area south of Gaastra. The Mineral Hills-Iron River cone is the largest and represents the effect of the combined withdrawals of ground water by the mines (above and below ledge) and by the Cities of Iron River and Stambaugh. The shape of this cone is influenced by the ledge valleys in which the pumping is taking place. The cone extends from west of Sunset Creek to east of Ice Lake in parts of two ledge valleys heading against each other. The deepest points are under Sunset Creek, southwest of the-Homer-Cardiff mines, and in the SW¼ sec. 23, at elevations below 1,430 feet. At the western edge of the cone ground water is found at an elevation of 1,480 feet, or about the level of the water surface of the Iron River, whereas on the eastern edge of the cone the ground-water divide has an elevation of about 1,550 in the vicinity of the Rogers mine in the center of sec. 29, T. 43 N., R. 34 W.

The cone in the Homer-Cardiff section is rather steep on the southern side, owing to a high ledge ridge at the SE¼ sec. 22 and an apparent source of recharge in the buried valley of Sunset Creek in the SW¼ sec. 22. This source of recharge may possibly be induced infiltration from the lower reach of Sunset Creek or from the Iron River. As the gradient in the vicinity of the Iron River is rather flat, it may be that most of the infiltration is from downward percolation from Sunset Creek nearer the cone. The cone of pumping in the Homer-Cardiff area has seemingly spread outward in a northerly direction in the N½ sec. 22, indicating that the most effective dewatering has taken place north and west of the Cardiff shaft.

In the South Homer-Minckler area in the S½ sec. 23 the cone is elongated, owing to the shape of the ledge valley in which the pumping takes place. Further dewatering could be accomplished by means of additional wells in the SW¼NW¼ sec. 23, and in the NW¼NW¼ sec. 26. Wells in the SE¼ sec. 23 would assist in dewatering the Minckler property overburden but would increase the existing gradient of ground-water flow from the east.

The cone of ground-water depression in the Caspian Pit area is due to the dewatering of the Caspian Pit and the Bengal mine property in the SW¼ sec. 36, T. 43 N., R. 35 W. This cone is located between two ledge hills, Stambaugh Hill and the hill north of Gaastra. The cone has steep sides where the ledge is high but extends outward under the Iron River on the south and extends north in the Baker Creek ledge channel. Although complete information is not available, it is probable that the cone of influence has created a ground-water flow toward this area from south of Ice Lake and from the Rogers mine in sec. 29. As the cone in the vicinity of the Caspian Pit grows southward, it is possible that recharge to it will be developed when it extends beneath the present bed of the Iron River.

The Zimmerman-Degrasse cone of depression south of Gaastra shows the effect of a well pumping from the glacial overburden to decrease the pressure of the ground water over an area where the iron formation sub-outcrops below the water table. The cone is steep on the northwest side, owing to a nearby ledge hill.

In the Mineral Hills area a water table with steep slopes is shown on a buried ledge hill, which indicates that ground water occurs in the form of sheet flow percolating down the ledge hillside toward the buried valley. Although adequate information on the depth of water above ledge is not available for the whole area, a few scattered wells and drill holes indicate that a few feet of water may be found on those ledge hillsides that have not been artificially drained through mining operations. Similar conditions of percolating water on ledge hills may be expected on Stambaugh Hill, and on the hill southwest of the City of Iron River, but inadequate information prevents contouring pf the water table in those areas.

Recharge

Recharge to the glacial drift cover of the Iron River district takes place by downward percolation from precipitation falling on the land surface, and from percolation from the surface water in those areas where the water table is below the surface-water level and where geologic conditions are favorable for such a movement to take place.

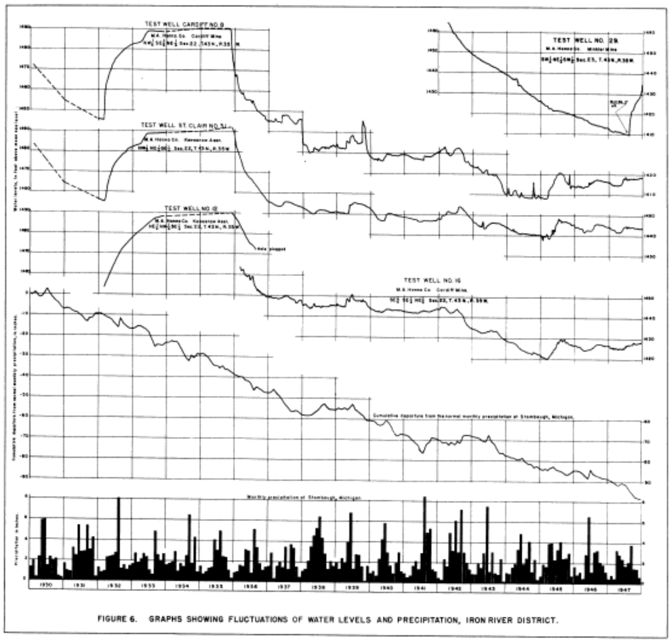

Figure 6. Graphs showing fluctuations of water levels and precipitation, Iron River district.

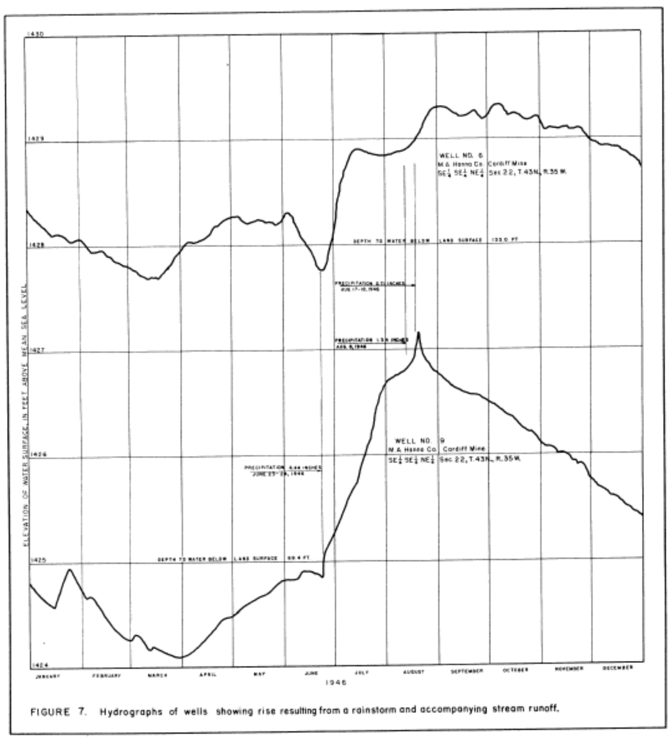

Figure 7. Hydrographs of wells showing rise resulting from a rainstorm and accompanying stream runoff.

Recharge from rainfall penetration

Recharge by absorption of water from precipitation is the major source of ground water in the district. Where the precipitation occurs on permeable formations the water seeps beneath the surface and percolates downward, and in some cases laterally, until it reaches the water table. The locations of the outwash plains, which are the most permeable of the glacial formations, are shown on figure 4.

The effects of the additions of recharge to the water table are indicated by seasonal rises in the water levels in the wells in the period within a few months after the ground surface thaws and the snow melts each spring. There is considerable variation from one year to another, owing to differences in the snow and frost conditions as well as irregularities in precipitation. The hydrographs of wells in figure 6 show seasonal rises due to the recharge resulting from the melting of the accumulated winter snow. Figure 7 shows the rise due to a period of heavy rainfall in which 4.44 inches fell in 36 hours on June. 23 and 24, 1946.

A detailed correlation of the spring rises of the water table in the Mineral Hills area with precipitation during the past 10 years indicates that, if an effective porosity or specific yield (The amount of water that will drain by gravity from a unit volume of saturated material.) of 0.30 is used, an average of about 60 percent of the precipitation occurring in the months of December, January, February, March, April, and May reaches the ground-water reservoir each year as recharge. In a normal year this would amount to about 7.3 inches. As the wells used in this correlation lie in a buried valley to which the recharge percolating down the buried ledge hillside is also added, the above value for normal recharge is an upper limit, dependent upon the ratio of valley area to hillside area in the zone being considered.

Data on the flow of the Iron River at the mouth, as measured during seepage runs, show the discharge at low flow to be about 78 cubic feet per second, of which about 24 cubic feet per second represents pumped water or other artificial inflow. If the drainage area is about 125 square miles and if the remainder of 54 cubic feet per second may be assumed to be equal to the average ground-water runoff, the average annual ground-water runoff is about 5.9 inches from the drainage area. Of the 24 cubic feet per second of pumped water, probably only about 50 percent is being derived from storage and the remainder is a diversion of ground water that probably would reach the river if it had not been intercepted by the wells. If the inflow under natural conditions is, therefore, 54 plus 12 or 66 cubic feet per second, the recharge would be 7.2 inches per year. Both values of recharge are in the general order of magnitude of that obtained by study of the rises in the water table due to the addition of the percolating water from precipitation.

In the case of the Davidson and James mines, where the rate of flow into the mines seems to be limited to the flow through the glacial drift down the ledge hillside on which the sub-outcrop of the iron-formation lies, the mine pump age should have a relation to the ground-water recharge in the contributing area. As the contributing area for these two 'mines appears to be about 400 acres on the basis of incomplete data on the ledge surface, and as the average pumpage from both properties is about 300 gpm, the average rate of ground-water recharge appears to be 144 inches per year. This value is considerably higher than that obtained by other methods, but this area has many large zones of subsidence which provide greater facilities for percolation, and the vegetative cover is missing which would have transpired a portion of the precipitation before it percolated below the root zone.

The cumulative departure from normal monthly precipitation at Stambaugh has been included in figure 6. This diagram was constructed by adding algebraically the monthly departure from normal, as reported by the Weather Bureau, to the cumulative total obtained for the previous month. The fluctuations of the diagram show in general how much above or below the average the rainfall has been in a given period.

Recharge from surface water

Recharge to the ground-water reservoir from water flowing over or standing on the land surface has been investigated by means of gain or loss measurements on the river and ditches, percolation studies, and correlation of lake stages with fluctuations of the ground-water levels.

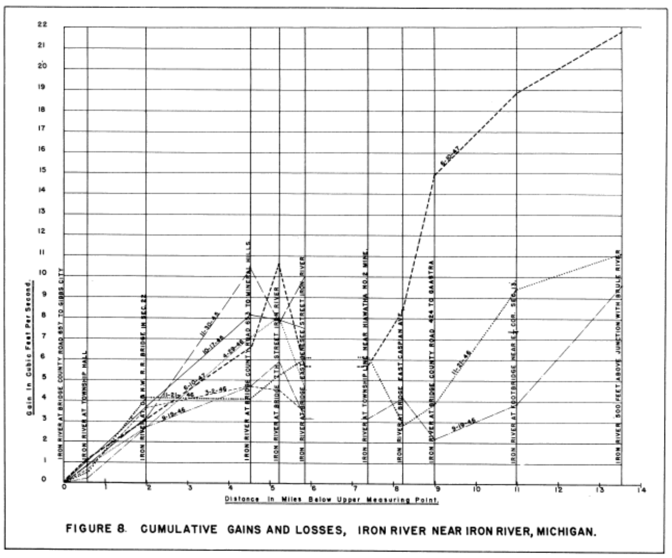

Figure 8. Cumulative gains and losses, Iron River near Iron River, Michigan.

Seepage investigation of flow of Iron River

In order to investigate the relation of the flow in Iron River to the ground-water reservoir, seepage investigations were made several times in each of the years 1945, 1946, and 1947 by measuring the flow of the river at intervals from half a mile to 2½ miles. Measurements were made on the river at the bridge on County Highway 657 to Gibbs City, at the Iron River Township Hall, at the C. & N. W. R. R. bridge in sec. 22, at the bridge on County Highway 653 to Mineral Hills, at the Seventh Street bridge in the City of Iron River, and at the bridge on East Genesee Street east of the City of Iron River. In 1946 additional measurements were made at the south township line near the Hiawatha No. 2 mine, at the bridge on East Caspian Avenue in Caspian, at the bridge on County Road 424 south of Caspian, near the E. cor. sec. 13, T. 42 N., R. 35 W., and above the junction of the Iron River with the Brule River. The locations of the points of measurements are shown on figure 5. Inflow in the upper section of the river was measured at Stanley and Sunset Creeks and at the two mine drainage ditches which discharge into the river near the water pumping plant of the City of Iron River. Iron Lake Creek was flowing at its mouth on only one day during these measurements. Inflow in the lower section was measured at Holmes and Baker Creeks and inflow from mine pumpage was measured from the Caspian Pit and from the Buck mine.

The gains and losses are tabulated in table 2, and figure 8 has been prepared to show where the gains and losses occur. The gains and losses were obtained by subtracting the sum of the measured discharges at the upper end and all the measured inflow in the reach from the measured discharge at the lower end. Thus the gain is ground water which entered the river through seeps and springs along the banks and in the bed of the river. The losses are the sum of all the losses that may occur within the river reach. The above method of determination of gains and losses is subject to the hazard of an error of measurement of flow at any point.

DISCUSSION OF RESULTS

The cumulative loss and gain diagram shows gains in the two upper reaches of the river totaling 1.99 miles in length, ranging from 2.76 to 4.20 sec.-ft. (cubic feet per second). The river banks on both sides are outwash gravels, and the heavy growth of swamp-type vegetation indicates that ground-water levels are at or above the normal stage of the river. There is an outwash plain extending from Iron Lake to the river which may contribute underflow from that direction. A few diamond-drill records indicate that ledge is more than 100 feet below the land surface. The gains for these reaches average 3.34 sec.-ft. in the total length, or 754 gpm per mile.

In the next reach of 2.55 miles, from the C. & N. W. R. R. bridge to the County Road 653 crossing to Mineral Hills, the seepage investigations show changes ranging from a loss of 0.05 sec.-ft. to gains of 7.28 sec-ft. The river banks on both sides are outwash gravels and the ground-water levels are expected to be at or. above the normal river stage. Although the river flows above a ledge valley ranging from 90 to 190 feet below the land surface, the river bed is the lowest topographic point to which the saturated materials filling the ledge valley can drain under natural conditions of flow. The river bed is almost at ledge near the lower measuring point, as there are outcrops on the south bank and diamond-drill holes indicate ledge to be higher than the river north of the crossing. Therefore, most of the underflow of the stream is forced to the surface at this point. Pumping in this ledge valley in the Homer-Cardiff mine area has lowered the water levels below the normal river stage in the immediate vicinity of the pumps, but the area of diversion of the pumps probably is not large enough to divert water from the river, although it does intercept water that would normally reach the river. The run of measurements of November 21, 1946, shows a loss of 0.05 sec.-ft. for this reach of river, whereas the other runs indicate this to be a gaining section. The gains indicated by all the measurements average 3.20 sec.-ft., or at the rate of 563 gpm per mile; or, excluding the measurement of November 21, 1946, they average 3.75 sec.-ft., or at the rate of 660 gpm per mile for the reach.

The next two reaches - from the crossing of County Road 653 to Mineral Hills to the Seventh Street bridge in the City of Iron River, and from this point to the bridge on East Genesee Street, are 0.67 and 0.66 mile in length, respectively. These short reaches involve different geologic conditions of river bed. Above the Seventh Street bridge the river bed is very close to ledge and there is little opportunity for losses, and the gains are limited to that ground water percolating down the ledge hillsides near the present river channel. The section shows changes ranging from losses of 2.63 sec.-ft. to gains of 4.04 sec.-ft., but an average of all the measurements indicates an average gain of 0.61 sec.-ft., or at the rate of 408 gpm per mile of reach.

From the Seventh Street bridge to the bridge on East Genesee Street the river flows over glacial-outwash materials which, north of the river, fill an old ledge valley to a depth of more than 212 feet. Within half a mile south of the river, ledge rises above the elevation of the river bed. In this section the ground-water accretion of the river would be derived from recharge from precipitation flowing down the ledge hillside from the south. North of the river the accretion would be the discharge from the ledge valley. However, pumping by the mines and the Cities of Iron River and Stambaugh have lowered the water levels in this ledge valley until they are below the river stage, thereby preventing a gain by the river from the north side. The section shows changes ranging from gains of 2.23 sec.-ft. to losses of 4.94 sec.-ft., but an average of all the measurements indicates an average loss of 1.36 sec.-ft., or at the rate of 925 gpm per mile of reach.

If the section of the river from the County Road bridge to Mineral Hills to the "bridge on East Genesee Street is considered as one unit, an average of all the measurements shows a loss of 0.76 sec.-ft. or about 341 gallons a minute. Although unknown irregularities in the ledge topography may affect this inference somewhat, it appears that the total amount of water that the pumps have diverted from the river in this section is the 341 gallons a minute plus the ground-water inflow that the section would have gained had the pumps not been in operation.

No computations were made of the gain or loss of the section from the bridge on East Genesee Street to the south township line, as unmeasurable quantities of sewage and mine drainage are discharged into the river in this section. The river bed is almost at ledge and outcrops are bound on both sides of the river. Small gains would be expected in the upper part of this section, but, owing to the widening and deepening of the topographic valley at the lower measuring point, these probably would be offset by losses occasioned by the opportunity for greater percolation and underflow past the lower point in the wider and deeper ledge valley.

In the next reach, from the south township line to the East Caspian Avenue bridge, geologic conditions are favorable for a slight rate of loss by the river to the ground-water reservoir. The ledge is about 30 feet below the river bed and the whole ledge valley is over 1,000 feet wide. The section shows changes ranging from losses of 3.28 sec.-ft. to gains of 2.77 sec.-ft., but an average of all the measurements indicates an average gain of 0.18 sec.-ft., or at the rate of 95 gpm per mile of reach.

From the Caspian Avenue bridge to the County Road 424 bridge south of Caspian, the river flows over the upper end of a ledge valley, but in places there is more than 80 feet of glacial material below the river stage. Pumping from the Caspian Pit area depresses the water table below the river stage, thus providing favorable conditions for the river to recharge the ground-water reservoir. This section show losses ranging from 2.02 sec.-ft. to gains of 6.49 sec.-ft., but an average of all measurements indicates that an average gain of 1.83 sec.-ft., or at the rate of 1,080 gpm per mile of reach.

The next two reaches of the Iron River, from County Road 424 bridge to the junction with the Brule River, would be expected, from the geologic and hydrologic characteristics of the drainage basin, to be gaining sections. In these sections the rate of gain should be of the same magnitude as in the two uppermost reaches of the river, as the topographic and geologic conditions are similar, except that ledge is probably shallower in the lower sections. These two sections are 4.54 miles long and showed a gain averaging 7.23 sec.-ft., or at the rate of 715 gpm per mile.

Although the seepage runs could not be made at regular intervals throughout the year, because of weather and high-flow conditions, they indicate that gains are greater in the fall than in the spring months. The hydrographs of wells distant from the river indicate that recharge from precipitation causes the ground-water levels to be highest in the summer.

These measurements show average figures as to the ground-water gains and losses, and, although each individual run of measurements may not be representative of conditions throughout the year, the average of all the runs shows that the river is not yet a major factor in contributing water to the increasing mine pumpage.

<u>Seepage investigation of flow ditches</u>

The losses in flow through downward percolation in Sunset Creek, the Minckler-South Homer Ditch, the James-Sherwood-Minckler Ditch, and the Spies-Virgil Ditch were determined by comparing the measured flow at the upper ends with the flow at the lower ends.

Losses in Sunset Creek were studied by placing a water-stage recorder on a company-installed weir at the County Road 653 bridge in the SW¼NW¼ sec. 14, to determine continuously the inflow at the upper end, and by building a temporary gaging station at the company weir site southwest of Sauerman pit in the NW¼SE¼ sec. 22, to determine the outflow. The artificial inflow from mine pumpage was determined daily by instantaneous readings of weirs or orifices on each pump. Table 3 shows the losses or gains determined on days when the flow was not influenced by precipitation or changes in pumpage, but includes no correction for channel storage.

Date	Flow at upper weir, gpm	Pumpage inflow within reach, gpm	Outflow at lower end, gpm	Gain (+) or loss (-), gpm
11-30-45	128	3,220	3,300	-48
3-2-46	345	3,055	3,260	-135
4-29-46	2,390	3,120	4,880	-630
9-18-46	381	3,227	3,649	+41
9-20-46	685	3,213	3,807	-92
9-29-46	628	3,196	3,850	+26
9-30-46	528	3,210	3,769	+31
10-1-46	489	3,178	3,679	+12
10-2-46	465	3,223	3,666	-22
10-4-46	433	3,326	3,773	+14
10-5-46	422	3,162	3,704	-120
10-6-46	404	3,183	3,645	+58
10-11-46	459	3,307	3,668	-97
10-12-46	402	3,277	3,655	-24
10-13-46	386	3,326	3,521	-191
10-14-46	390	3,330	3,542	-178
10-18-46	413	3,348	3,602	-59
10-19-46	395	3,254	3,628	-31
10-20-46	383	3,189	3,519	-53
10-21-46	390	3,256	3,560	-94
10-22-46	391	3,238	3,518	-111
10-23-46	388	3,253	3,441	-200
11-21-46	406	3,020	3,780	-254
6-10-47	3,360	3,198	5,880	-678

Table 3. Gains and Losses in Sunset Creek.

The gains and losses shown in table 3 indicate that when the Sunset Creek is confined to its low-flow channel the losses are small, but when the creek overflows its banks the losses may become a larger source of recharge to the ground-water reservoir of the area.

Seepage losses in the Minckler-South Homer ditch were investigated by comparing the total inflow to the ditch with measurements of the outflow near the mouth at Sunset Creek. Three comparisons of flow made in the fall of 1945 indicate the losses to be less than one percent of the flow. As this ditch traverses a loess-covered flat whose surface is rather impermeable to water, no large losses by downward percolation should be expected.

Seepage losses in the James-Sherwood-Minckler ditch were determined by continuous measurements of flow at weirs located about 1,000 feet south of the James mine and at a point northwest of the football field in the Iron County Fairgrounds. The losses determined in table 4 cover a period when the flow was not influenced by precipitation.

Date	Flow at upper weir, gpm	Pumpage inflow within reach, gpm	Outflow at lower end, gpm	Loss, gpm
4-15-46	191	1,605	1,710	86
4-16-46	173	1,600	1,685	88
4-17-46	185	1,600	1,680	95
4-18-46	162	1,600	1,690	72
4-19-46	207	1,605	1,700	112

Table 4. Gains and Losses in James-Sherwood-Minckler ditch.

The losses from this ditch, which is only about 3,500 feet long, are rather high, considering the small flows carried in the upper parts. However, the total loss is not as yet a large factor in recharging the ground-water reservoir.

Percolation studies

A field experiment to determine the sealing qualities of the iron sludge carried in the water pumped from below ledge in the Homer mine was made by allowing these waters to flow over and through selected sands and gravels similar to those found along drain ditches.

This was done by filling sheet-metal vessels or permeameters 12 inches in diameter and 18 inches deep with a 2-inch layer of washed gravel at the bottom and a 12-inch layer of the selected material above. Water carrying iron sludge was flumed to each vessel in excess of the amounts needed for downward percolation. The excess water overflowed from each vessel through a pipe 2 inches above the surface of the selected sample. The water percolating downward was measured at a drain pipe in the center of the bottom of each vessel.

Three types of material were selected for the experiments Vessel No. 1 was filled with a clean fine sand obtained from a house foundation 600 feet north of the SE cor. sec. 15, T. 43 N., R. 35 W., at an elevation of about 1,520 feet. This material is typical of the surface cover of the Sunset Creek channel upstream from the point at which the sludge-bearing waters are discharged into the creek. Borings described in the section on geology indicate that this sand extends to depths greater than 10 feet below the present creek channel.

Vessel No. 2 was filled with a mixture of sand and gravel that is found in the layer 6 feet thick in the wall of the Sauerman Pit at the same elevation as the present bed at Sunset Creek. This material is representative of that over which Sunset Creek flows from the point at which the sludge-bearing mine waters are discharged into the channel to the mouth of the Creek one mile below.

Vessel No. 3 was filled with material selected from the deposits exposed in the Sauerman Pit, each layer in the vessel being proportional in thickness to that of the same bed in the exposure.

Each vessel was filled with water before the sand and gravel samples were introduced. Care was taken to avoid entrapping air, by placing small amounts of the sample in the vessel at a time and by agitating the sample with a rod to release the air and reduce the volume of the sample to approximately that of the undisturbed material. The material was further compacted by jarring the vessels when they were transported to the site of the test. Prior to the test, clear water from the Cardiff mine weir was allowed to percolate through each vessel to determine the rate of percolation for clean water. Values of the rate of percolation, in gallons per day per square foot of surface area at 60° F, are shown in table f for the clear water and at various time intervals in hours after the sludge-bearing waters were allowed to flow over and through the permeameters. A sample of loess from the SW¼ sec. 23, T. 43 N., R. 35 W., was also placed in the vessel to determine the rate of percolation. As the rate of percolation for clear water was low (17.4 gpd/sq.ft.), this sample was not included in the test with the others.

Discussion of results

Although there were considerable differences in the starting percolation rates of the three samples, as indicated by the rate of percolation of clear water, it is important to note that, after the sludge-bearing water had flowed over the vessels for more than 100 hours, each sample had approximately the same rate of percolation, and after 450 hours the rates became almost exactly the same. Thus it is evident that the film of deposited sludge on top of the sample governed the rate of flow through the vessel, regardless of the ability of the material below the film to transmit water. Readings of the rate of percolation were discontinued after 628 hours of flow, as toward the end of the period the sides of the vessels apparently froze each night and thawed each day, allowing water to percolate along the edge more easily than through the sample. Because of this freezing process the last readings may not be as small as expected. However, an extrapolation of the rate of percolation from the later data would indicate that the rate after 1,000 hours would be less than 2½ gallons per day per square foot and after a year's time would be about one gallon per day per square foot. Accordingly, the rate of loss of water through the bed of Sunset Creek where the iron-bearing sludge has covered the bed of the creek should not be of major importance.

Table 5 gives the percolation rates observed in the field experiment.

Time since flow started (hours)	Vessel No. 1	Vessel No. 2	Vessel No. 3
Clear water	252.0	47.5	169.0
2	166.2	33.3	97.2
5	52.2	31.8	54.8
24	27.7	21.5	27.8
30	23.5	18.2	22.3
48	18.8	14.6	18.8
98	10.4	8.9	11.3
124	9.3	6.8	9.8
148	7.9	6.4	8.0
196	6.8	5.5	6.7
267	5.2	4.9	5.1
316	4.5	4.4	4.3
364	3.7	3.6	3.6
460	3.2	2.9	3.1
628	3.1	2.9	3.0

Table 5. Percolation Rates in Gallons per Day per Square Foot at 60° F. in Permeameter Experiment.

A sample of the iron-bearing sludge was tested in the variable-head laboratory permeameter and the permeability was determined to be about 0.55 gallon per day per square foot of area with a unit gradient at a temperature of 60° F.

Seepage losses from lakes

The only lakes within the mine district investigated are Ice Lake and Mud Lake, although Sunset Lake, Iron Lake, Stanley Lake, and several others are located within a 5-mile radius of the Iron River district.

Correlation of the ground-water levels with the surface level of Ice Lake indicates that the lake level is. about 60 feet above, the ground-water level, but that the downward percolation through the bottom of the lake is small. The level of the lake as shown by a continuous recording gage shows rises due to rainfall and surface inflow, and after these, rises a steady decline to a level governed by the outlet works. Once the base level is reached no further decline is apparent that could be attributed to downward percolation. This is probably due to the fact that the lake bottom has been sealed by continued deposition of silt and clay, and that the silty clay till exposed at the surface of the plain extends for some depth below the lake bottom. It was reported that a well at the old Tyler residence on the north side of the lake, was dug to a level 70 feet below the lake surface and obtained insufficient water to maintain even a small domestic supply. According to C. A. Nelson, Manager-Clerk of Stambaugh, shortly after 1910 the City of Stambaugh sank a shaft 15 feet from the edge of Ice Lake on the southwest side in an attempt to develop a water supply, but no water was obtained and for a time the city took water directly from the lake. It was further reported that a dry ditch was dug across the east end of the lake by banking the spoil on the sides and ahead of the ditch. However, in the event that further mining operations are contemplated in the immediate vicinity of the lake, it is recommended that additional observation wells be drilled to obtain more detailed information on the position of the water table under the lake.

At some other lakes in the district the water table probably is close to the same elevation as the water surface of the lake, and the lakes may be points of ground-water discharge rather than points of recharge. Iron Lake and Sunset Lake are probably in this classification.

Natural discharge

The visible seeps and springs

Areas of shallow depth to ground water are found in the vicinity of all the surface streams in the district. These areas are characterized by swamp-type vegetation and a boggy condition of the ground. Many of the smaller creeks and intermittent streams head in these seep areas. No actual points of discharge of springs have been mapped except on the west side of the Iron River at the mouth of Baker Creek, where a flow of about 10 gallons a minute has been observed. However, many seep zones and former seep zones are found on the north and east sides of the Iron River in the reach from Sunset Creek to the bridge, on U. S. Highway 2 east of the town of Iron River. There is some evidence, which is supported by observations of local residents, that the flow from these seep zones in this reach has greatly decreased in quantity within the last 5 or more years. In two cases -- the area northwest of County Highway 653 and the swamp area in the NW¼ sec. 25, between the City of Iron River and Ice Lake -- the flow has ceased entirely. At the latter location, the reported nonpumping levels at the Stambaugh water plant show a decline in water level from about the land surface in 1932 to more than 20 feet below the land surface in 1948. Furthermore, examination of the contour map (figure 5) shows the water table to be generally below the river stage in these locations, owing to the pumping, and it is to be expected that, owing to reversal of the original gradients, that the flow should have been decreased at these points of natural discharge.

Large spring and seep zones still exist in the southeast part of the district, along Olson and Wagner Creeks. In many places these zones are where the ground water has collected in the buried ledge valleys and overflows to a surface drainage. As yet none of these buried valleys have been tapped by a mine dewatering operation.

Only in a limited area has the natural discharge been decreased or diverted through the artificial withdrawals of water by pumping, and the measurements of loss and gain on the Iron River indicate an inflow averaging about 328 gpm per mile for the length of stream studied.

Artificial discharge

Artificial discharge from the ground-water systems in the district is brought about both by the withdrawals of water from the glacial overburden by the pumping systems of the mines and municipal supplies and by the withdrawals of water from the formations below ledge during the processes of mining.

The first attempts to control water in the glacial overburden in the district were by means of water drifts in the bedrock at a shallow depth below the overburden. One such drift was driven in the form of a ring around the mining area at the now abandoned Rogers mine in sec. 29, T. 43 N., R. 35 W., about 2½ miles east of the City of Iron River. According to reports, the drift was successful in controlling the water in the mine and pumping from it affected water levels as far as Sunset Lake, about 2½ miles north of the mine.

A water drift was also constructed connecting the Homer and Cardiff shafts. This drift, about 500 feet long, produced a large quantity of water by natural percolation and through holes drilled upward to the bedrock surface. The first records indicate that this drift produced about 4,200 gallons of water per minute in the early part of 1930, before any pumping from wells was begun in the area. At that time the water table was standing at about 1,475 or 1,480 feet above sea level and the ledge around the Homer and Cardiff shafts and a part of the caved area lying north and east of the Homer shaft was submerged. Five wells in the general area were drilled between February 1, 1930, and August 1931, producing a total of 3,100 gallons a minute. Concurrently the pumpage from the water drift dropped to 1,800 gallons a minute and the pumpage from lower levels in the Homer mine dropped from 950 to 300 gallons a minute. The water table was lowered about 25 feet during this time, and the "shore line" of the water body in the ledge valley retreated from the caved area.

All pumping from wells and all pumping from the water drift, with the exception of about 20 gpm used as a water supply for the Mineral Hills location, was stopped on March 18 1932, and the mine was shut down until November 1935. Pumping from the seventh level of the mine, to keep it from flooding, increased from 200 gpm to 1,000 gpm during this period. The water table rose to an altitude of 1,490 feet, again "flooding" the caved areas. When operations were resumed in November 1935 the water drift produced about 7,300 gpm initially, and the wells about 4,000 gpm, but within a year the pumpage from the water drift had dropped to 2,100 gpm, that from wells to about 2,300, and that from the Homer seventh level to 200 gpm. The water table had declined to about 1,450 feet, and the "shore line" of the water body had retreated from the Homer shaft and the caved area.

New wells have been drilled since the reopening of the mine, until the total production of wells-was about 6,000 gpm in 1945, while that from the water drift was about 800 gpm and the total pumping from lower levels in the mine was about 1,000 gpm, the increase in underground pumpage doubtless being caused by the opening up of new areas for mining. The water table declined to an altitude of about 1,400 feet during this time, thereby unwatering a large part of the sub-outcrop of the iron-formation below the overburden. Table 6 shows the withdrawals of ground water in the district by classes.

	Above ledge			Below ledge		
Year	Public Supplies	Mineral Hills	Else-where	Mineral Hills	Else-where	Total
1936	513	6,324	No data	3,270	1,632	11,739
1937	531	5,623	No data	1,399	1,572	9,125
1938	491	6,075	1,429	1,336	1,857	11,188
1939	465	6,275	1,943	1,489	1,785	11,957
1940	507	6,029	1,057	1,936	1,842	11,371
1941	575	5,964	2,067	1,987	1,870	12,463
1942	742	7,092	1,963	2,271	1,917	13,985
1943	658	8,300	2,042	2,487	1,812	15,299
1944	631	7,902	397	2,387	1,340	12,657
1945	694	7,259	1,306	2,504	1,377	13,140
1946	690	7,904	2,010	2,671	1,239	14,514
1947	831	6,030	3,429	2,151	2,196	14,637

Table 6. Estimated average pumpage from Iron River district, in gallons a minute.

The estimates of pumpage given in this report are based on data obtained from various sources. The data for public supplies were obtained by calculation from the metered monthly power consumed and the power used to pump a measured quantity for a short test. The data, for the pumpage at the mines were obtained from the pump operators' records at the mines and from the records compiled by the engineering staffs of the companies. It is believed that the totals are essentially correct, although the underground pumpage figures may possibly be on the high side because many mines compute the pumpage on the basis of high pump efficiencies.

QUALITY OF GROUND WATER

In order to determine the chemical character of ground water in the Iron River district, samples of water were collected from all the wells pumping from the glacial overburden and from several types of iron-formation in the mines. The analyses made by the U. S. Geological Survey are shown in table 7.

The ground water in the glacial overburden is similar in chemical quality to that in other parts of the northern peninsula of Michigan and, except for hardness, is of good-quality for domestic and other common uses. The hardness ranges from 166 to 288 parts per million. The chloride content is low (generally less than 8 parts per million) as also is the iron content (generally less than 1 parts per million).

The character of the water found in the mines is variable. With one exception, the samples taken from the ore and from the oxidized iron-formation are no more highly mineralized than the water in the glacial overburden. On the whole, the samples taken from strata in the hanging wall, in all cases from drips in these strata, are slightly more highly mineralized than the water in the overburden. There appears to be a slight tendency for the sulfate to be higher and the bicarbonate lower in these mine waters, as compared with water in the overburden. Two of the samples from ore are high in sodium chloride.

The footwall samples are in general the most highly mineralized, an exception being that from a drill hole 350 feet long in the Hiawatha mine, in which the strata are so contorted that there is some doubt if the strata penetrated are all footwall strata. (Additional information obtained since the time of sampling indicates this drill hole penetrates the hanging wall sequence.) In the sample from a long drill hole in the Homer mine, the water is a calcium sulfate water. The high sulfate content is perhaps-to be correlated with oxidation of pyrite, a common mineral in the footwall. The sample from a drip from footwall strata in the Fogarty mine was the most highly mineralized sample found and was a sodium chloride water, with unusually large amounts of calcium and magnesium.

In general the samples that come from strata and localities in which the circulation is most vigorous differ the least from the water of the glacial overburden. The water that came from small drips and seeps from drill holes is rather highly mineralized, and the much higher chloride content of the water suggests strongly that it is an indigenous (connate) water now being forced out of the formations by the circulation set up by mining. The comparatively highly mineralized sample of water from the ore, that in the Hiawatha mine, was taken at the lowest level in the mine, -- the deepest in the vicinity -- that had just been opened and in which mining had not yet been actively begun. It is predominately a calcium chloride water. All the samples were comparatively low in iron, the highest containing 3.40 parts per million, and were rather low in fluoride and boron.

In general the presence among these few analyses of one sample from medium depth that contains mainly chlorides of sodium, and calcium, and magnesium, and one from the greatest depth, 566 feet below sea level, that is a calcium chloride water with little sodium, conforms to the generalization reside by Lane 16/ concerning the waters of the iron and copper mines of the Upper Peninsula. According to Lane, the waters of the mines can be divided into three zones of different chemical character; an. upper zone of relatively soft water, an intermediate zone of sodium chloride waters increasing in concentration with depth, and a lower zone merging in character with that above, in which calcium and chloride are the chief radicals.

THEORY OF MOVEMENT OF WATER INTO MINES

The iron-formation consists of somewhat porous ore, brecciated chert interbanded with more or less hydrated hematite, and brittle unoxidized cherty siderite. The jointing and brecciation of the chert make it permeable, probably in large measure permeable to the same degree both parallel and perpendicular to the bedding; that is, it is hydrologically isotropic. The iron-formation overlies stratigraphically some tens of feet of graphitic slate which in turn overlies gray slate. The formation underlies gray slate and in some places graywacke. The beds stratigraphically adjacent to the iron-formation are relatively impermeable, so that the iron-formation, in which the mining must be done, is in large measure an aquifer included between impervious walls.

The bedrocks are greatly contorted. On the whole, the ore in the Mineral Hills area lies in a trough where the average dip on the flank or folds is greater than 45°, but the dips vary from horizontal to vertical and the beds are even overturned in places. Hence, in these mines, we are dealing with an aquifer that is vertical or steeply inclined.

The bedrock surface is overlain by glacial drift from a few to a few hundred feet thick. In places the drift is coarse and permeable, especially in the valleys on the bedrock surface, where it is saturated with water to a depth of as much as 200 feet.

When a mine is opened the water in the iron-formation begins to drain into the underground openings. This water is replaced by water in the glacial drift above the sub-outcrop of the formation, and if there is a large body of water in the glacial drift a relatively rapid and continuous flow of water passes through the iron-formation to the underground openings. The first problem in the theory of mine drainage is, therefore, an investigation of the character of the movement of water in the iron-formation to the mine workings, including the effect of openings at different levels and different attitudes of beds and the effect of the head of water in the glacial drift above, with the end in view that a knowledge of the character of the movement will suggest the most feasible way of disposing of the water.

As the water drains from the glacial drift into the sub-outcrop of the iron-formations a trough will be formed in the water table in the glacial drift. A contour map of this depression of the water surface would show approximately elliptical contours. The shape of this depression is the second, element of the problem of mine drainage. We must inquire as to the rate at which the water level lowers, and how the local character of the ledge surface affects the rate of lowering.

Finally, inasmuch as it is possible to exhaust the water in the glacial drift by pumping, we must inquire as to the movement of water to wells, and how again the shape of the bedrock surface affects the rate at which water levels are lowered by pumping from wells.

Flow of water in the iron-formation

The iron-formation, where unoxidized, consists of interbanded chert and siderite. Where oxidized it consists of chert interbanded with red and yellow iron oxides (mostly hematite). The ore consists mainly of soft red hematite, though locally limonite predominates. It is typically underlain by some 200 feet of slate and overlain by interbedded siderite. The water in the mines comes, in the largest part, from the ore and the remainder of the. iron-formation, and in exploratory drilling the presence of water is considered a good indication of the nearby presence of ore. The iron-formation is therefore the aquifer.

Vugs are present in all the mines of the Mineral Hills district. These range in size from one approximately hemispherical in shape and about 15 feet in diameter found in the ninth level of the South Homer mine to those the diameter of a pencil or smaller. Ordinarily these vugs discharge water at a high rate when first struck, but the flow rapidly diminishes in most instances. The rapid "flush" production cannot be entirely ascribed to compressibility of the formation and the consequent squeezing out of water from the formation when the hydrostatic pressure is released, which is the usual reason for the flush production of an artesian well. The water seems to be stored in the vug and its tributary vugs. It may be that part of the diminution in flow of the vugs is due to the development of capillary menisci at the orifices of the capillary cracks and pores. Because the vugs following the bedding usually are steeply inclined, so long as a vug is full the water from capillaries will enter it freely; whereas, after the stored water in the vug is drained, water from capillary openings will not enter it unless under some pressure, and, inasmuch as the drift or other opening permits the escape of water, no great pressure can be built up in the capillaries a little distance above the drift. The fact that the flows of the vugs soon cease almost certainly indicates that the vugs are not continuous to the surface of the bedrock, as in many cases the formation sub-outcrops under a hundred feet or more of saturated glacial outwash. As a consequence, it appears that the main flow through the formation is through capillary openings.

How much of the water moves through the ore and how much through the remainder of the iron-formation is an unsettled question. It appears to be definite that it does not all move through the ore, despite the fact that the ore generally lies on the footwall and hence is in the most favorable position for carrying water. In many of the mines the main part of the water seems to come from the hanging wall. A recent flood of water struck in the Mather mine in the Marquette range, involving a total flow of over 10 million gallons in a few days from an old stope, was struck in the hanging wall of the ore, whereas prior to the breaking of the hanging wall the ore was reported dry (Boyum, Burton, in oral communication.). Inasmuch as the ore bodies are discontinuous in many places, it appears that the rest of the iron-formation must carry much and probably most of the water entering the mines. No adequate test of the permeability of the ore can be made, and inasmuch as the water in the iron-formation must be carried, to a considerable degree at least, in fractures, no laboratory test of its permeability can be made.

It is the aim of this investigation to describe the movement of the ground water as quantitatively as possible. To do so requires the application of mathematics. The use of mathematics necessarily involves simplifying assumptions. The permeability of the iron-formation is irregular, the formation lies steeply inclined or vertical, workings in it are irregularly shaped, and the formation is greatly contorted. No mathematical approach can hope to consider these irregularities adequately. Even models used for study necessarily would be simplified from the actual irregular details. Nevertheless, if we are to understand the movement of water, we must develop some criteria from mathematical study to use as a yardstick to measure observed phenomena. If, then, the phenomena do not conform to the mathematical deductions, we shall know at least that the assumptions on which the mathematical deductions were based are wrong. Without such criteria we have no way whatever of judging the meaning of our observed data. It is in this philosophy that the mathematical approach is presented.

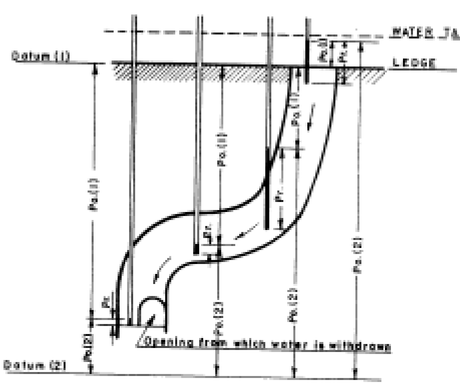

Figure 9a. Pressures and potentials in a steeply inclined aquifer.

General conditions of flow into a steeply inclined aquifer

Where water moves through capillary openings, and therefore in accordance with Darcy's law, its rate of movement is proportional to the rate of drop with its hydraulic potential. The hydraulic potential at any point would be measured by the position of the water level in a tightly cased well with its bottom open at this point, measured with respect to any arbitrary datum. In figure 9a and b, the potentials are shown in a folded but steeply inclined aquifer such as the iron-formation. Two sets of potentials are givens first with the datum of measurement taken at ledge and second with the datum taken arbitrarily some distance below the lowest point of interest in the diagram. The potential drop between any two points is of course the same no matter which datum is chosen, the only difference being that the potentials at all but the highest point will be negative if ledge is taken as datum, whereas with the lower datum the potentials at all four points will be positive.

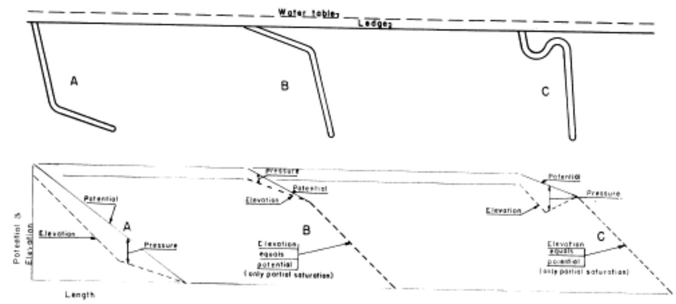

Figure 9b. Diagrams showing relation among pressure, potential, and elevation in steeply inclined aquifers.

The hydraulic potential is made up of two parts. The first is the gravity potential or that due to vertical position. This is merely a statement that water tends to move from a higher position to a lower one. The second part is the pressure of the water. The pressure is measured in ground-water problems most easily by the height of the water in a tightly cased well above the point in question. The diagram shows the pressures as well as the potentials at the several points. In short, water standing a foot deep in a pail is quiescent because the potentials at the water surface and at the bottom are both equal to one foot with respect to the datum of the bottom of the pail, although the water at the top is under no pressure but stands a foot above the bottom; whereas the water at the bottom is under a pressure equal to one foot of water and it stands zero feet above the bottom. The distinction between pressure and potential is important to the discussion of the movement of water in a near-vertical aquifer because (1) the pressure cannot fall significantly below zero and. (2) water can move horizontally only where a pressure gradient exists.

Consider the potential and pressure distribution in three distorted aquifers, each with an opening at the same depth below ledge. (see fig. 9b.) The first descends sharply for a considerable depth below ledge and then continues at a low dip to the opening. The second descends from ledge at a low dip and. then turns nearly to the vertical to descend to the opening. If we plot the hydraulic potentials at the points in the aquifer against their distances from the source of water at ledge, the potential in aquifer A (see fig. 9b.) will fall uniformly from the elevation of the water table at one end to the elevation of the opening at the other. A positive pressure, represented by the interval between the hydraulic gradient and the elevation of the points, exists at all points. The water will flow, therefore, at a rate proportional to the total vertical distance from the water table to the point of discharge, divided by the length of the path of water in the aquifer. In aquifer B, however, the potential can drop only from the height of the water table to that of the elbow in the aquifer, and the flow through the aquifer can be proportional to the hydraulic gradient only between these two points. Beyond the elbow a high gradient is available to carry the water. However, the amount flowing is determined by the amount that can flow through the relatively flat dipping part of the aquifer, and as a consequence the water cannot fill entirely the nearly vertical part of the formation and will collect on the footwall, leaving the hanging wall dry. Similarly in aquifer C, the flow of water is controlled by the potential gradient from the ledge surface to the top of the fold represented; and a high pressure is developed, at the bottom of the fold.

In sum, if we draw in hydraulic gradients from the ledge outcrop to various points in the formation above an opening in it, the distance of flow being considered that measured along the aquifer, and the difference in hydraulic potential being the difference in elevation between the water table and these points, the rate of flow through the aquifer to the opening will be proportional to the least gradient between the ledge outcrop and any point on the water surface above the opening.

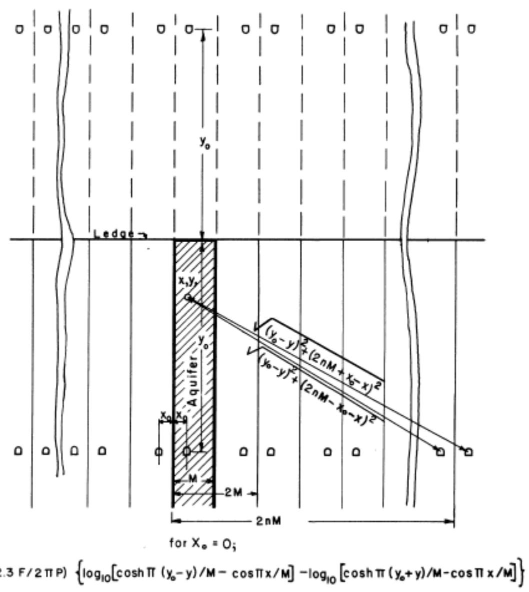

FIGURE 10. Image system for a long drift in a vertical aquifer sub-outcropping under saturated overburden.

Figure 10. Image system for a long drift in a vertical aquifer sub-outcropping under saturated overburden.

Flow of water in a cross section of a vertical aquifer

A study of the manner of flow of water in a vertical aquifer emerging into an opening at depth will be of value as an index of the movement in steeply inclined aquifers. The movements in inclined aquifers cannot be considered mathematically in any way known to the writers. In the case of vertical aquifers it will be considered that the water moves through capillary pores and cracks and therefore according to Darcy's law. As indicated previously, this seems at least approximately true, as movement through vugs seems quantitatively small, even though for a short time vugs sometimes yield spectacular flows.

Consider a vertical section of a vertical portion of the iron-formation, forming an aquifer of width M that sub-outcrops on a horizontal surface that is covered by a thin sheet of water of negligible but constant thickness (fig. 10). The other outcrop of the aquifer is considered sufficiently distant that its effects may be neglected. A drift of long lineal extent is made along the strike of the formation, with its center, represented by a point in this section, at a depth $-y_o$, and distant from one wall, which will be called the footwall, by x_o. The condition of having a constant supply of water at the surface to replace that which drains into the drift will be satisfied by piecing an image recharge point, delivering the same quantity of water that is being drained out below, at a point above the surface with coordinates x_o, y_o.

The hydraulic potential, v, or head of water measured with respect to a fixed datum taken as the surface of sub-outcrop, at any point x, y due to this pair of recharge and discharge points will be as follows:

$$v = (F/4\pi P)\ (\log_e r_D^2 - \log_e r_R^2)$$

In this equation F is the rate of discharge per unit length of the drifts, P is the permeability, and r_D and r_R are the distances from the point x, y to the points of discharge and recharge, respectively. However, as the aquifer has a finite thickness, it will be necessary to place an infinite number of similar pairs of points by multiple reflection in the walls of the aquifer, as shown in figure 10. The distances from the point x, y to any pair of the discharge points are:

$$\sqrt{(y_o-y)^2 + (2nM+x_o-x)^2} \text{ and } \sqrt{(y_o-y)^2 + (2nM-x_o-x)^2},$$

in which n is any whole number between -∞ and +∞. The distances to a pair of recharge points will be

$$\sqrt{(y_o+y)^2 + (2nM+x_o-x)^2} \text{ and } \sqrt{(y_o+y)^2 + (2nM-x_o-x)^2}.$$

Hence the hydraulic potential at the point x, y due to the infinite number of recharge and discharge points having all possible whole-number values is:

$$\begin{aligned} v = (F/4\pi P)\Big\{ & \log_e[(y_o-y)^2 + (2nM+x_o-x)^2] \\ & + \log_e[(y_o-y)^2 + (2nM-x_o-x)^2] \\ & - \log_e[(y_o+y)^2 + (2nM+x_o-x)^2] \\ & - \log_e[(y_o+y)^2 + (2nM-x_o-x)^2]. \end{aligned}$$

This may be reduced to the following form: 11/

$$v = (F/4\pi P)\left\{\log_e\left[\frac{\cosh \pi (y_o-y)/M - \cos \pi (x_o-x)/M}{\cosh \pi (y_o+y)/M - \cos \pi (x_o-x)/M}\right]\left[\frac{\cosh \pi (y_o-y)/M - \cos \pi (x_o+x)/M}{\cosh \pi (y_o+y)/M - \cos \pi (x_o+x)/M}\right]\right\}$$

If (1) the point is centered at the footwall an therefore $x_o = 0$, and if (2) instead of a sheet of negligible thickness over the ledge surface there is one that imposes a head v_e, by changing to common logs we get

$$v = v_e + (2.3\ F/2\pi P)\left\{\log_{10}[\cosh \pi (y_o-y)/M - \cos \pi x/M] - \log_{10}[\cosh \pi (y_o+y)/M - \cos \pi x/M]\right\}$$

If the discharge is given in gallons per day per lineal foot of drift and P is given in gallons per day per square foot, v will be given in feet of water. Table 8 gives values of the function $\log_{10}[\cosh\pi(y_o-y)/M-\cos\pi x/M]$. It is therefore necessary only to subtract the values given for $\pi(y_o+y)/M$, x/M from that for $\pi(y_o-y)$, x/M to obtain the quantity in braces above.

If there is a long drift or other mine opening along the strike of the footwall, extending out into the aquifer a fixed distance, the pressure of the ground water at the periphery of the opening will be 0 and the potential will therefore correspond to the elevation of the drift with respect to the ledge surface. As an example, if a long drift 15.7 feet wide extends along the footwall of a vertical aquifer 157 feet (50π) wide, the approximate thickness of the iron-formation in the Iron River district, 500 feet below ledge, ($\pi y_o/M = 10$), the algebraic difference of the values in table 8 for $\pi(y_o-y)/M = 0$, $x/M = 0.1$, and $\pi(y_o+y)/M = 20$, $x/M = 0,1$, which is -9.695, may be equated to the potential -500. From the ratio so found, the potential at other points can be computed. Table 9 gives the potential for various points in the aquifer under these conditions, the body of ground water above ledge being considered to be of negligible thickness.

The pressure in the water is equal to the potential minus the elevation of the point. Table 10 gives the pressures that would exist in the aquifer described above with the same size of drift, at a depth of 500 feet, in one case with a negligible thickness of water above the ledge surface and the other with a thickness of 200 feet. The table shows that, when there is no considerable body of water above ledge, little pressure is developed in the region above an opening and that, as a consequence, there will be comparatively little horizontal component to the movement of water, even if an intercepting gallery were present.

This point may be clarified perhaps by considering drifts at two levels on the footwall, both of the same size. The relative rate of flow into the two levels can be computed by solving simultaneously for two unknown flows into the two levels. Thus, if the two drifts are at depths y_o and y_o', and the discharges into them are F and F', the potentials at the inner sides of the drift will also be y_o and y_o'. If x is the width of both drifts, then at x, y_o,

$$\begin{aligned} v = y_o = v_e &+ (2.3\ F/2\pi P)\ \log[\cosh \pi(y_o-y_o)/M - \cos \pi x/M] \\ &- \log[\cosh \pi (y_o+y_o)/M - \cos \pi x/M] \\ &+ (2.3\ F'/2\pi P)\ \log[\cosh \pi (y_o-y_o')/M - \cos \pi x/M] \\ &- \log[\cosh \pi (y_o+y_o')/M - \cos \pi x/M] \end{aligned}$$

At x, y_o', we have,

$$\begin{aligned} v = y_o' = v_e &+ (2.3\ F'/2\pi P)\ \log[\cosh \pi(y_o'-y_o')/M - \cos \pi x/M] \\ &- \log[\cosh \pi (y_o'+y_o')/M - \cos \pi x/M] \\ &+ (2.3\ F/2\pi P)\ \log[\cosh \pi (y_o-y_o')/M - \cos \pi x/M] \\ &- \log[\cosh \pi (y_o+y_o')/M - \cos \pi x/M] \end{aligned}$$

Table 11 gives the results of the solution of these equations for the 157-foot aquifer previously considered with a drift 15.7 feet wide at 200 feet combined with another drift of the same size at 100 feet and, in another case, one at 300 feet. Results for conditions with 0, 100, and 200 feet of water lying above the sub-outcrop are given. The discharges are given in terms of the permeability P. If P is given in gallons per day per square foot the results are in gallons per day per lineal foot of drift.

Depth	At footwall	At middle of aquifer	At hanging wall
0	0	0	0
100	-90	-90	-90
200	-179	-179	-179
300	-270	-269	-268
400	-365	-358	-353
500	---	-433	-417
600	-455	-448	-442

Table 9. Hydraulic potentials, in feet of water, in a vertical aquifer 157 feet wide with a long drift 15.7 feet wide at the footwall, 500 feet below ledge; negligible head of water above outcrop.

	Negligible head of water above ledge			200 feet of water above ledge		
Depth	Footwall	Middle	Hanging wall	Footwall	Middle	Hanging wall
0	0	0	0	200	200	200
100	10	10	10	174	174	174
200	21	21	21	149	149	149
300	30	31	32	122	123	125
400	35	42	47	89	98	106
450	26	50	61	57	89	105
500	--	67	83	--	95	116
550	81	105	116	96	123	130

Table 10. Pressures, in feet of water, in vertical aquifer 157 feet wide, with drift 15.7 feet wide along the footwall, 500 feet below ledge.

	Depth of water above ledge (feet)		
	0	100	200
Single drift 200 feet below ledge:	122 P	183 P	244 P
Drifts at 200 feet and 100 feet below ledge:			
200 feet	112 P	140 P	167 P
100 feet	26 P	107 P	189 P
Drifts at 200 feet and 300 feet below ledge:			
200 feet	31 P	104 P	145 P
300 feet	114 P	100 P	125 P

Table 11. Relative discharge per unit length in long drifts 15.7 feet wide, at footwall, at different levels in vertical aquifer 157 feet wide.

If P, the permeability, is in gallons a day per square foot, above results are discharges per lineal foot of drift in gallons per day.

These figures show that, in a nearly vertical aquifer, the efficacy of intercepting galleries may be expected to vary greatly with the height of water above ledge. The introduction of an interceptor at 100 feet would decrease the water entering a, 200-foot-level drift about 30 percent if there were 200 feet of water above ledge but would increase the total amount of water to be handled about 45 percent. With a negligible thickness of water above ledge, the interceptor would decrease the water in the 200-foot level less than 10 percent and would increase the total water by about as much. With negligible thickness of water above ledge, a drain at the 300-foot level would be much more efficacious in draining the 200-foot level, reducing the water in that level about 75 percent, although the total cost of lifting the water would be greater. This suggests the possible desirability in some cases of exploration and preliminary opening at lower levels.

It should be pointed out that this analysis is not pertinent if the aquifer is not vertical. If the aquifer departs markedly from the vertical, the advantages of high-level interceptors are increased. Further, if the aquifer is folded above the opened levels, in many cases the hanging part of the aquifer would be dry, and the upper levels would divert a greater part of the water than is indicated here. Anomalies of this kind may possibly suggest in certain cases the structure of the aquifer above the opened levels.

Flow of water in an inclined aquifer

If the aquifer is inclined the foregoing analysis is not valid. Consider an inclined formation serving as an aquifer, dipping at an angle α and overlain by water in an overburden above ledge. The water above the upper opening will be moving approximately parallel to the walls of the formation but, as shown in the discussion of the vertical aquifer, with a slight component toward the footwall, at which are the drifts and other openings. This tendency to move toward the footwall is intensified in the case of an inclined, aquifer, inasmuch as the distances to an opening from the outcrop of the hanging wall of the beveled formation are shorter than those from the outcrop of the footwall. Neglecting the component toward the footwall, we can consider as a limiting case that the water is moving parallel to the walls and with a velocity proportional to gravity times sin α, the vector component of gravity in the direction of movement. When any front of water reaches the opening the particles of water in it will fall vertically, and a proportion of them equal to the height of the opening measured along the dip times cotangent α will fall into the upper opening, the remainder descending to the footwall and leaving the upper (stratigraphically) part of the formation unsaturated. The component of pressure toward the footwall neglected in the discussion will cause still more water to be intercepted by the upper opening. Hence the upper stopes or other openings will get a larger part of the waters and the more gentle the dip the larger the portion of water that will be intercepted by the upper openings. In fact, when the dimension of the opening along the dip is somewhat less then the thickness of the formation times the tangent of the angle of dip, the formation would be completely unwatered if the formation were equally permeable both parallel, to and perpendicular to the bedding. The fact that the upper levels in a mine do not, in general, intercept nearly all the water where the formation is inclined is probably due in part to greater permeability parallel to the bedding and in part to emergence at lower levels of water originating at some distance from the opening.

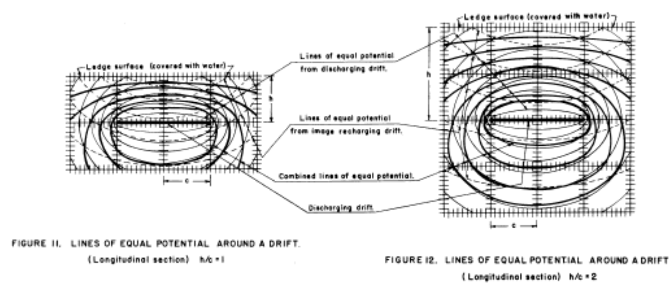

Figure 11. Lines of equal potential around a drift h/c = 1.

Figure 12. Lines of equal potential around a drift h/c = 2.

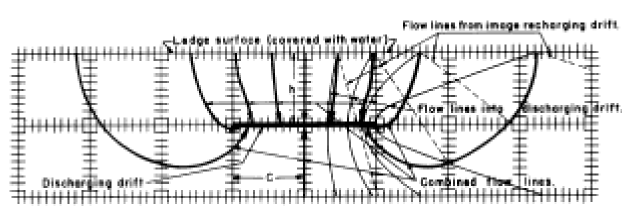

Figure 13. Flow lines into a drift h/c = 1.

Flow in a longitudinal section of an inclined aquifer

The preceding discussion dealt with flow in a cross section of a vertical or inclined aquifer. The formation and the drift were considered to extend indefinitely perpendicular to the plane of the paper. It seems impossible to consider mathematically the flow in three dimensions to a drift of finite length. However, by considering the drift to unwater effectually the whole thickness of the formation -- theoretically to extend entirely through it -- it is possible to consider the movement of water in the plane of the formation. The following discussion applies both to inclined and vertical aquifers, not being restricted to vertical aquifers alone as was the case in the discussion of flow in the direction of dip of the aquifer.

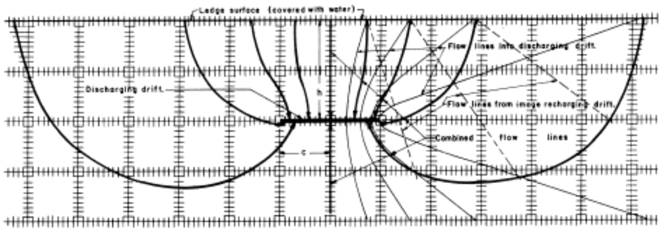

Figure 14. Flow lines into a drift h/c = 2.

Consider an aquifer of extensive length in which a long horizontal opening is cut of a length 2c at a distance h below the ledge surface as measured along the dip. Overlying the ledge is a water body of negligible thickness. Water will now drain from the ledge into the opening. Near the center of the opening the water will move almost perpendicular to the opening, but there will also be water draining from the ledge at a considerable distance from the opening which will move by circuitous paths to the opening. The effect of having the water continually replaced at the surface of ledge will be simulated by placing a similar image opening recharging the aquifer to the same extent that the real opening is draining it, at a distance h above the ledge.

Consider for the moment the distribution of potentials in the vicinity of the linear withdrawing opening if it were placed in an aquifer of infinite areal extent. The lines of equal potential would then be ellipses with the long axes lying along the opening and the short axes perpendicular to it and the total flux would be: 12/

$$F = \frac{2\pi T(p_e' - p_o')}{\log_e (b_e + \sqrt{c^2 + b_e^2})/c}$$

in which,

F is the rate of flow into the opening
T is the transmissibility
p_o' is the potential at the opening
p_e' is the potential on an ellipse with a semiminor axis, b_e
c is half length of opening

Transposing and setting $A = b_e/c$,

$$p_e' = p_o' + \frac{F}{2\pi T} \log_e (A + \sqrt{1+A^2})$$

If now we place a recharge opening as indicated above, and let the ratio between the semiminor axis of any ellipse around this opening and the half length of the opening be equal to B, the potentials at any point due to the opening will be

$$p_e'' = - p_o'' - \frac{F}{2\pi T} \log_e (B + \sqrt{1+B^2})$$

Within certain limits to be discussed below, the potential at any point due to both these openings may be taken as the sum of the potentials due to each

$$p = p' + p'' = \frac{F}{2\pi T} \log_e \frac{A + \sqrt{1+A^2}}{B + \sqrt{1+B^2}}$$

$$= \frac{2.3F}{2\pi T} \log_{10} \frac{A + \sqrt{1+A^2}}{B + \sqrt{1+B^2}}$$

Figures 11 to 14 show very closely the flow lines and potentials around typical linear openings located at depths below ledge equal to half the length of the opening in one case and to the length of the opening in the other. Approximately equal quantities of water pass between each pair of flow lines drawn. Only about half the water entering the opening leaves the surface directly above the opening and the remainder is drawn in from more or less distant points.

The total flow into a long opening can be computed approximately by considering the potential at the actual opening. Here the semiminor axis of the ellipse centering around the discharge opening is 0. The semiminor axis of the ellipse centering around the recharging opening (ratio B to the half-length of the opening) and touching the center of the actual, discharging, opening is 2h/c, and that of the ellipse cutting the ends of the actual opening is slightly larger. The fact that no ellipse centering around, the recharging opening will coincide with the discharging opening throughout its length indicates that the flow system proper for a single opening in an infinite aquifer is modified in the vicinity of another such opening or when the opening is relatively close to ledge. The flow lines are moved to some degree toward the center of the opening. However, if the depth below ledge is at least half the length of the opening s the distortion will be so small that the flow computed by the simple addition of potentials due to each opening will be less than a few percent. If the depth below ledge is at least equal to the length of the opening the error will be only a fraction of one percent. Hence, for our purposes, when the depth of the opening is at least equal to half its length:

$$p = \frac{2.3F}{2\pi T} \log_{10} \frac{1}{B + \sqrt{1 + B^2}}$$

$$F = \frac{2\pi T p}{2.3 \log_{10} 1/(B + \sqrt{1+B^2})} = - \frac{2\pi T p}{2.3 \log_{10}(B + \sqrt{1+B^2})}$$

in which B as before is equal to 2h/c.

The following table 12 indicates the approximate rate of total flow into long openings of various lengths at various depths below the surface in the absence of competing openings in the vicinity. For comparison the flow into a small drill hole 0.2 foot in diameter (about 2½ inches) is also given to show that preliminary test drilling might suggest a much greater quantity of water in the mine than would actually be produced. The computations are for a vertical aquifer with a negligible depth of water over ledge in which the potential p, in feet of water, equals the depth h, in feet. The flow of water in an inclined aquifer, or in one with a considerable depth of water in the overburden above ledge, can be obtained from these figures by considering the "depth below ledge" to equal the length from ledge to opening along the dip of the formation, and by multiplying the figure given by the ratio between the actual head of water above the opening and the "depth below ledge" in the table. Thus the ratio between, flow and transmissibility, where the flow is into an opening 400 feet long 1,000 feet from ledge along the dip in a formation dipping 45 degrees would be 2,100 x 700/1,000 = 1,470 and if there were 200 feet of water in the overburden it would be 2,100 x (700 + 200)/1,000 = 1,890.

		Length of opening (feet)				
Depth below ledge (feet)	Drill hole 2 ½" diameter	200	400	600	1,000	2,000
100	83	437				
200	152	600	874			
300	216	755	1,040	1,310		
500	341	1,050	1,360	1,640	2,180	
1,000	635	1,700	2,100	2,420	3,000	4,370
1,400	855	2,190	2,640	3,000	3,630	5,000

Table 12. Approximate ratio of total flow to transmissibility in vertical aquifer with a long opening at various depths below ledge.

These figures may be used to obtain an approximate figure for the transmissibility of the iron-formation in the Spies-Johnson workings. In the early stages of development a drift about 500 feet long with a few raises was run along the strike of the formation about 500 feet below ledge. The ratio of flow and transmissibility of such an opening should be about 1,500. The flow from the drift at this time was about 350 gallons per minute or 100,000 gallons per day. The transmissibility is indicated to be about 335 and the average permeability of the iron-formation, estimated to be about 150 feet thick, is about 2 gallons per day per square foot.

The values given in the foregoing pertain to a single exploratory drift in a formation that has a long sub-outcrop beneath saturated overburden. As is apparent from the diagrams of the flow lines, much of the water entering such a drift originates at ledge at a considerable horizontal distance from the drift. If a formation lies in a structural basin the sub-outcrop is limited in length. If mining is carried out throughout the structure it is obvious that there can be little or no lateral movement of the water to an opening, as each drift or other opening will intercept all or most of the water percolating from above. In such a case the amount of water percolating to an individual drift will be much less than that computed above and will simply approach the transmissibility of the formation times the length of opening. In other words, the ratios comparable to those in table 12 will be simply the length of opening.

The normal history of water production in a simple basin-shaped formation would be as follows. In the course of exploration the first diamond drillings into the formation should indicate a great deal of water, and, if the holes are put out from mines in another structure and therefore at some depth, the holes should in general flow an amount of water out of all proportion to the size of the opening represented by the hole. As development is begun by drifting and stoping the first openings normally would be exceedingly wet. During the course of development of the structure, either by the original mine or by other mines in the same structure, the amount of water would decrease in relation to the total amount of drifting and stoping in the structure. As the mines are carried to lower depths, the greatest amounts of water would probably seek the lower levels if the formation is steeply dipping, but might be largely intercepted in the upper mine levels if the dip is relatively gentle. Finally, as other areas in the same structure are mined out and the mines are abandoned and allowed to flood, the amount of water entering the remaining mines would increase probably beyond the original amounts because of the relatively easy movement of water through the abandoned workings.

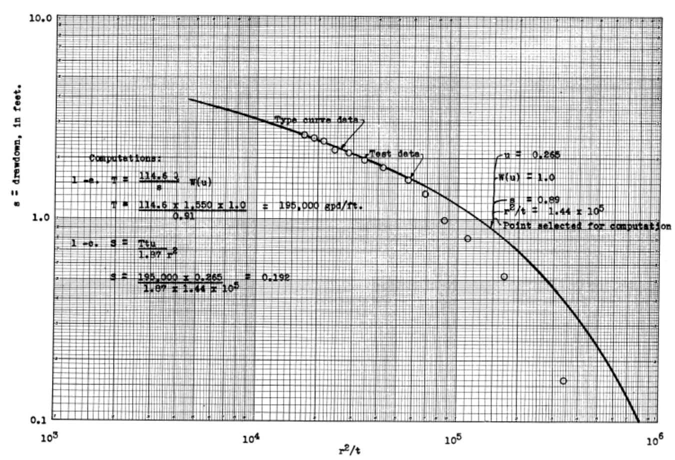

Figure 15. Logarithmic graph of the drawdown of water level in test well D. D. No. 7-44 caused by pumping M. A. Hanna Well No. 17.

THEORY OF CIRCULATION OF GROUND WATER WHERE THE OVERBURDEN IS BEING DEWATERED

Having just considered the manner of circulation of ground water in the vicinity of the mine openings in the ledge materials, we should investigate the relationships of the circulation in the overburden with reference to the various methods of dewatering. Perhaps the most common method of dewatering is by the use of vertical wells, although open pits, open trenches, and infiltration galleries below ledge have been used with varying degrees of success.

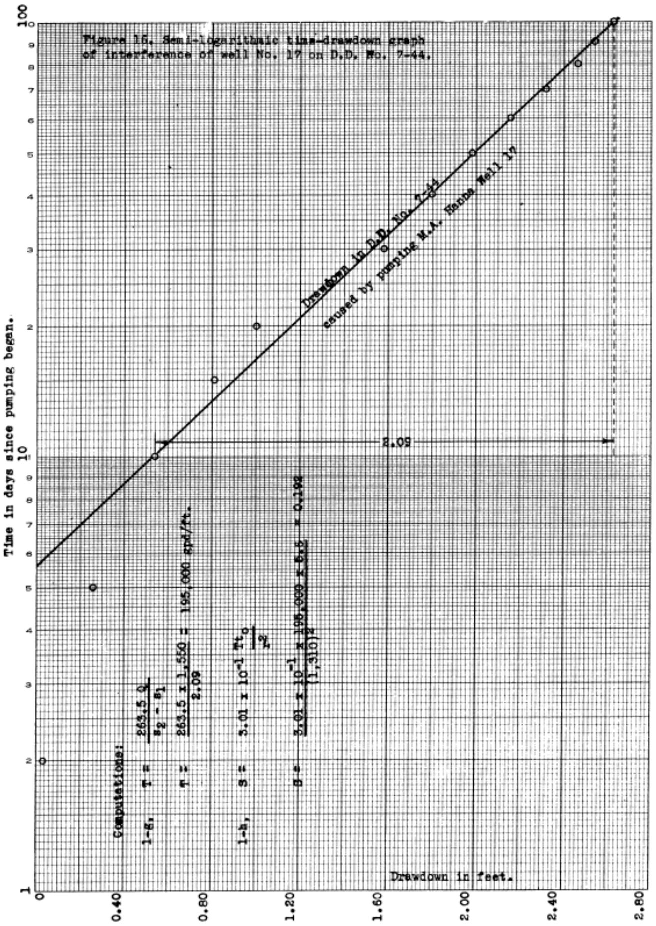

Figure 16. Semilogarithmic time-drawdown graph of interference of well No. 17 on D. D. No. 7-44.

Let us first consider the circulation around any system of dewatering the saturated overburden. The withdrawal of water from any aquifer causes the water levels to decline in the vicinity of the point of withdrawal. The water table or piezometric surface around a production well assumes the approximate shape of an inverted cone with the apex of the cone at the well. For an open pit, trench, or infiltration gallery the shape of the cone is modified or elongated to correspond to the shape of the dewatering structure. However, the over-all size, shape, and the rate of growth of the cone of depression created by the drainage structure are dependent on the rate and duration of drainage, the transmissibility and storage coefficients of the aquifer, the increase in recharge caused by the declining water levels, the natural discharge that is salvaged, and the boundaries of the aquifer. The lowering of water level at any point within the cone of depression is termed drawdown, and is dependent or. the variables mentioned, above and the distance from the point of withdrawal.

In order to express in a general equation the relationship among the variables that govern the magnitude of the dewatering effects, certain basic assumptions are made. It is assumed that the aquifer is constant in thickness, infinite in areal extent, homogeneous, and isotropic (transmits water with equal facility in all directions). It is assumed further that water may enter the structure from the full thickness of the aquifer.

The relationship among the hydraulic properties of the formation, the rate of pumping, and the change in water level caused by the withdrawal of water from a well or an open pit in a given formation is expressed by the following formula: 13/

$$s = \frac{114.6Q}{T} \int_{\frac{1.87r^2S}{Tt}}^{\infty} \frac{e^{-u}\,du}{u}$$

Where s = drawdown in feet at any point in the vicinity of a well pumped at a uniform rate.
Q = discharge of well in gpm.
T = coefficient of transmissibility in gpd/ft.
r = distance in feet from pumped well to point of observation.
S = coefficient of storage.
t = time in days that well has been discharging.

For a long open trench or infiltration gallery the equation is:

$$s = \frac{Qr}{2T}\left[\frac{e^{-z^2}}{\sqrt{\pi}\,z} - 1 + \frac{2}{\sqrt{\pi}}\int_0^z e^{-z^2}dz\right]$$

in which $z = \sqrt{\frac{1.87r^2S}{Tt}} = 1.3675\ r\sqrt{S/Tt}$

Where s = drawdown in feet at distance r and time t.
Q = quantity discharged from trench, in gpd per foot of trench.
r = distance of point from trench in feet.
t = time since discharge started, days.
T = coefficient of transmissibility in gpd/ft.
S = coefficient of storage.

In order to determine the effect or the water level at any distance from a drainage structure caused by a charge in rate of withdrawal of water it is necessary to know the water-bearing characteristics of the aquifer. These characteristics are commonly expressed as transmissibility and coefficient of storage. The transmissibility may be defined as the number of gallons of water that will move in one day through a vertical strip of the aquifer one foot wide having a height equal to the full thickness of the aquifer when the hydraulic gradient is 100 percent. The coefficient of storage is defined as the volume of water, measured in cubic feet, released from storage in each column of the aquifer having a base of one square foot and a height equal to the thickness of the aquifer when the head is lowered one foot.

The hydraulic properties of the undisturbed water-bearing formations in place are determined by means of pumping tests. A pumping test is made by changing the rate of withdrawal from a well and observing the effect on the recovery or drawdown of the water levels in other parts of the cone of depression. By analysis of these data, values of the transmissibility and storage coefficients can be obtained. Stated in another way, a pumping test is a means of determining the equation (the nonequilibrium formula with the proper coefficients) of a drawdown curve so as to be able to extend the curve over a longer period of time and for other distances by means of the same equation. In applying the equation over a longer period consideration must be given to the effects caused by boundaries and changes in the character of the aquifer. Such boundaries and changes are not taken into account for such short times as occur during the average pumping test, because their effects are generally negligible.

The effects of simple boundaries of the aquifer can be considered mathematically by the introduction of hypothetical image wells. In the case of a production well pumping in a ledge valley or in general in the vicinity of a straight boundary beyond which no water can pass, the introduction of an image production well, pumping an amount equal to that pumped by the actual production well and located at an equal distance on the opposite side of the boundary, will simulate mathematically the effects of the boundary. In this case the drawdown produced within the cone of depression will be the mathematical sum of the actual drawdown of the production, well plus the drawdown produced by the hypothetical image well at the same point.

Similarly, when a production well is operated near a. stream, or some source of induced recharge to the system, where the drawdown will be zero owing to addition of water to the hydraulic system as fast as it is being transmitted to the operating well, the addition of a hypothetical image recharging well will frequently permit this type of system, to be computed on a mathematical basis. In the case of a production well operated near a stream or line source of recharge, a hypothetical image recharge well is added to the system recharging a quantity equal to the yield of the production well and at a distance equal to that of the production well on the opposite side of the line soiree of recharge. In this case the drawdown at any point is that produced by the production well plus the drawdown (that is, minus the actual recovery) produced, by the simulated image recharge well on the same point.

With the introduction of several ledge boundaries and a source of recharge within the cone of depression of a ground«water system, as is found in the Iron River district, the computations of drawdowns may be mathematically so involved that the summation of the effects of all the hypothetical image production wells and image recharge wells will not be feasible. It is probable that electrical-resistance models constructed to simulate those conditions would provide data whereby these flow conditions can be analyzed accurately without the tedious and involved mathematical computations necessary at the present time.

In the Iron River district values of the coefficients of transmissibility and storage have been determined by the methods of Theis, 13/ and Cooper and Jacob, 14/ as applied to pumping wells. In the method of Theis the exponential integral of formula 1 is replaced by the term W(u) which is read "Well function of u", and the equation is rewritten as follows:

$$s = \frac{114.6Q}{T} W(u) \quad \ldots\ldots\ldots\ldots \quad (1\text{-a})$$

The value of the integral is given by the following series:

$$W(u) = \left(-0.577216 - \log_e u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} \ldots\right) \quad \ldots \quad (1\text{-b})$$

$$\text{in which} \quad u = \frac{1.87r^2S}{Tt} \quad \ldots\ldots\ldots\ldots \quad (1\text{-c})$$

Values of W(u) for values of u between 9.9 are 1.0×10^{-15} are given by Wenzel. 15/ The "well function of u" is plotted against u on log paper to form a type curve for determining the transmissibility and the storage coefficient of the formation tested. The observed drawdowns are plotted versus r^2/t on log paper. The graph of the observed data is matched with the type curve by superposition, keeping the axes of the two graphs parallel, and the values of r^2/t, s, W(u), and u are selected at any convenient point. The value of transmissibility is obtained from equation 1-a, and the value of the storage coefficient is then obtained from equation 1-c.

A more convenient nonequilibrium solution for transmissibility and storage coefficient is possible by a procedure described by Cooper and Jacob. 14/ For small values of u (small r or large t), W(u) given by equation 1-c is approximately

$$W(u) = -0.577216 - \log_e u \quad \ldots\ldots\ldots\ldots \quad (1\text{-d})$$

and

$$s = \frac{114.6Q}{T}\left(\log_e \frac{Tt}{1.87r^2S} - 0.577216\right. \quad \ldots\ldots\ldots\ldots \quad (1\text{-e})$$

The value of r is constant at a given observation well, and equation (1-e) may be written

$$s_2 - s_1 = \frac{114.6Q}{T}\left(\log_e \frac{Tt_2}{1.87r^2S} - \log_e \frac{Tt_1}{1.87r^2S}\right)$$

$$= \frac{114.6Q}{T} \log_e \frac{t_2}{t_1} = \frac{263.5Q}{T} \log_{10} \frac{t_2}{t_1} \quad \ldots\ldots \quad (1\text{-f})$$

where s_2 and s_1 are drawdowns observed at t_2 and t_1 respectively. Drawdown is plotted against the log of t on semilog paper, producing a straight-line graph. If an interval of one logarithmic cycle is selected from the time-drawdown graph of the observations made in any observation well near the pumping well, the value of transmissibility can be obtained from the following equation:

$$T = \frac{263.5Q}{s_2 - s_1} \quad \ldots\ldots\ldots\ldots \quad (1\text{-g})$$

where $s_2 - s_1$ is the difference in drawdowns through one log cycle. The storage coefficient is obtained from equation (1-h)

$$S = 3.01 \times 10^{-1} \frac{Tt_o}{r^2} \quad (1\text{-h})$$

where t_o is the time where the drawdown is zero on the graph. To determine t_o the plotting of equation (1-f) is used and the line representing s versus t is extended to s = 0 and this value of time is substituted in the equation (1-h) for the determination of the coefficient of storage. The value of T has been determined in equation (1-g) and r is the distance from the pumping well to the point of observation.

Both methods of solving the nonequilibrium formula (log and semilog plots) have been used in analyzing pumping-test data, as each has advantages not possessed by the other.

These methods were used in determining the transmissibility and coefficient of storage on the Minckler-Aronson properties in the S½ sec. 23, T. 43 N., R. 35 W. As the pumped well itself (M. A. Hanna Well No. 17) was not equipped with a means of measuring the depth to water, the drawdown in an observation well D.D. No. 7, about 1,310 feet away, caused by the initial pumping of well No. 17, has been used to show the method of computation of the values for transmissibility and storage. Well No. 17 was pumped at an average rate of 1,550 gallons a minute.

Figure 15 shows the logarithmic plotting and the use of formulas 1-a and 1-c; and figure 16 shows the semilogarithmic plotting and the use of formulas 1-g and 1-h.

Table 13 shows the values of the coefficients of transmissibility and storage obtained during the pumping tests in the district. Considerable range in values was to be expected, owing to the type of formations being tested. In the South Homer-Minckler field, where there is a large saturated thickness of water-bearing materials, large values of transmissibility were determined. Near Homer Well No. 1 and in the Sunset Creek area, where pumping has been in progress for more than 10 years, the saturated thickness has been reduced and the values of transmissibility determined were found to be correspondingly small.

The computed coefficient of storage, reflecting the quantity of water drained from a unit volume, varies considerably with the duration of pumping. This is probably due to the very slow drainage of the water from the silty and poorly sorted water-bearing materials. It is also probable in certain cases that the stratified and lenticular sands and gravels behave as artesian aquifers during short periods of pumping -- that is, the water is drawn through them from a reservoir at some distance, and no actual dewatering of the particular bed takes place. As the pumping continues, slow seepage of water through the more clayey confining beds may take place. The coefficient of storage computed from these tests increases from a very small decimal fraction for short periods of pumping to values of 0.25 to 0.35, which approach the value for the porosity of the materials.

The effects that the ledge "shore lines" and the possible source of recharge from the Iron River may have or the pumping test of well 17 have not been evaluated in these determinations, because the changes in the rate of drawdown due to these factors are not apparent in the diagrams and therefore cannot be given separate consideration. Long-term pumping tests were made to provide relatively complete knowledge of the behavior of the water levels due to changes in pumpage and other factors, end it is probable that some of the effects of the various boundaries are present in the tests. Tests of short duration could not be made because in order to do so it is necessary to have the observation wells located much closer to the pumped well than was the case in the Iron River district. It will be noted in table 13 that the values of transmissibility are about the same regardless of the length of test, but the coefficient of storage increases with the length of test

Date of test	Pumped well	Observation well	Coef- ficient of trans- missibility (gpd/ft.)	Coef- ficient of storage	Duration of test (days)
		Sunset Creek Well Field			
11-22-45	Homer Well 1	Homer Well 6	17,100	0.045	11
	"	Test " 23	10,600	.081	11
	"	Cardiff " 8	21,300	.021	11
	"	Test " 17	17,900	.0123	11
1-15-46	Homer Well 2	Cardiff " 8	42,800	.011	18
	"	Homer Well 9	50,200	.047	18
9-18-45	Homer Well 4	Cardiff " 8	24,200	.147	18
7-26-46	"	"	24,400	.0007	¼
		South Homer-Minckler Well Field			
10-19-45	Homer Well 15	Test Well 33	93,200	.113	6
	"	Homer Well 17	155,000	.060	6
11-3-45	Homer Well 17	Test Well DD 2	215,000	.207	100
	"	" DD 3	207,000	.216	100
	"	" DD 4	235,000	.158	100
	"	" DD 5	210,000	.189	100
	"	" DD 6	186,000	.211	100
	"	" DD 7	195,000	.192	100
	"	" 32	274,000	.385	100
		Iron River City Well			
1-15-46	Iron River Well	Iron River Test Well	75,000	.130	1

Table 13. Coefficients of transmissibility and storage of the glacial overburden as computed from pumping tests in Mineral Hills Area.

Inasmuch as the prime purpose of pumping from the overburden is eventually to drain the glacial materials down to ledge and thus stop the flow of ground water in the ledge depressions, consideration should be given to the behavior of well yields as the water table is successively lowered. It is obvious from the study of nonequilibrium formula No. 1 that, as the cone of depression around a well widens and deepens, the saturated thickness of the water-bearing materials becomes less and less for a constant yield. As the saturated thickness reaches a critical point beyond which it can transmit only a given quantity of water for the maximum gradient that can be developed, the yield of a well must decrease if the water table continues to lower. The decrease in yield as a result of this condition has been noted in all the drainage wells of the Mineral Hills area, and in the case of Homer Well No. 1 the decline in yield has ranged from a starting yield of 1,800 gpm on November 20, 1935; to 927 gpm in November 1936; to 742 gpm in November 1940; and to 152 gpm in November 1947, after 12 years of continuous pumping. This decrease in yield has been due not only to the pumping from the well itself, but also to the addition of many other drainage wells in the system, and to a deterioration in the well screen and pumping machinery.

The mathematical equation for the decrease in yield of a well with a constant drawdown has not been worked out for the unconfined aquifers (water-table conditions) such as exist in the Iron River district, but a study of certain wells indicates that the yield decreases as some constant divided by the logarithm of the product of some other constant and the time since pumping began $\left(\frac{K}{\log kt}\right)$.

Surface drainage structures

Unwatering the glacial overburden in the Iron River area has involved the use of both circular and longitudinal types of drainage structures, depending on the conditions of ground-water flow toward them. Open pits, large-diameter wells, and small-diameter wells are of the circular type, in which the water flows radially inward toward the structure; and open-trench drains and infiltration galleries are of the longitudinal type, in which the ground water flow is mostly from the sides. Circular types, particularly wells of various diameters, are most commonly used because of the ease and economy of their construction.

Because wells are commonly used as drainage structures and size is an economic factor in their construction, a comparison of size and yield and size and drawdown is necessary to determine the advantages of large diameter wells over those of small diameter. From equation 1-e (p. 49), if two wells of radii r_1 and r_2 in the same formation have the same drawdown, the following relation holds at a given time:

$$\frac{114.6Q_1}{T}\left(\log_e\frac{Tt}{1.87r_1^2S} - 0.577\right) = \frac{114.6Q_2}{T}\left(\log_e\frac{Tt}{1.87r_2^2S} - 0.577\right)$$

from which,

$$\frac{Q_1}{Q_2} = \frac{\log_e(Tt/1.87r_2^2S) - 0.577}{\log_e(Tt/1.87r_1^2S) - 0.577}$$

$$= \frac{\log_{10}(Tt/1.87S) - 0.251 - 2\log_{10}r_2}{\log_{10}(Tt/1.87S) - 0.251 - 2\log_{10}r_1}$$

Similarly, for the same pumping rate the drawdowns in the two wells vary as follows:

$$\frac{s_1}{s_2} = \frac{\log_{10}(Tt/1.87S) - 0.251 - 2\log_{10}r_1}{\log_{10}(Tt/1.87S) - 0.251 - 2\log_{10}r_2}$$

Tables 14 and 15 show the relation in yield and drawdown in wells of various sizes to the yield and drawdown of a 12-inch diameter well. The value of transmissibility (100,000 gpd/ft.) and the coefficient of storage (0.20) used in this comparison are an average of those conditions to be found in the Iron River district. The comparison assumes that the wells would be located in an isotropic, homogeneous aquifer of infinite extent and that the transmissibility does not change during the period of pumping. These assumptions are justified in the initial stages of pumping before the water level is drawn down considerably, and are satisfactory to give qualitatively the general effects of wells of different practical sizes throughout the period of pumping.

The following conclusions may be drawn from a study of the .tables in regard to the advantages of large-diameter wells.

1. Under conditions in which the depth of water in the aquifer is not greatly decreased by the pumping, the ratio of the quantity pumped by a large well to that by a small one is something less than the ratio between the logarithms of their respective radii. Under these conditions, which are typical for the early stages of pumping, the advantage of large wells is therefore small.

2. Under conditions in which a large part of the drawdown is caused by loss of head within the well, as by defective or corroded screens, wells of medium diameter are probably justified, inasmuch as the flow through the screen is proportional to the diameter.

3. As the water level is drawn down to the bottom of the aquifer, because of the very rapid decrease in transmissibility near the well the above equations do not hold, and a large well will have a much greater advantage than is indicated by the equations. However, even in this case, two or more smaller wells may be more economical.

Longitudinal types of drainage structures have not been widely used in the district because of the expense of constructing surface' drains and the hazards encountered in underground construction. Long trench drains to be effective in the removal of large quantities of water require considerable depth of expensive excavation below the water table. However, the trench is an effective dewatering device, especially as it intercepts flow from all the water-bearing formations in a heterogeneous aquifer in which a well might miss the most permeable zones.

Drainage structures below ledge

Infiltration galleries below ledge have not been used to a great extent because of the risk and hazards involved in working in the highly folded and fractured rocks below the ground-water reservoirs. The hydraulic effectiveness of an infiltration gallery below ledge is as great as a trench penetrating the full saturated thickness of the overburden.

Location of drainage structures

Within the cone of depression around any well or pit the drawdowns vary inversely approximately as the logarithm of the distance from the structure. Consequently, in the case of water moving vertically into a mine it is evident that the maximum reduction in flow could be obtained by a drainage structure at the point of a sub-outcrop or at a cave-in where vertical movement of water is taking place. Because many of the wells in the district cost about $20,000, the mine operators are loath to risk losing an expensive installation by placing it near a cave-in or possible area of subsidence. The physical problem becomes one of determining the critical place in which to locate a structure to accomplish the greatest decrease in the flow of rater into the mine without jeopardizing the investment. With this physical principal the economic problem is presented: Would not less expensive wells of shorter life pieced in areas of subsidence be more economical than the more expensive installations located where they are less effective in accomplishing their purpose?

When the water level has been drawn down to the bottom of the over-burden and the cone has extended some distance outward, the increased efficiency of a large well is only proportional to the ratio of the logarithm on the radius of the large well to the logarithm of the radius of the small well. When the cone has reached equilibrium form as far away as 1,000 feet, and the water table at the well has been drawn down 100 feet, for instance, a 3-foot well would lower the water table at a distance of 100 feet about 5 feet more than a one-foot well. When the cone has grown to an effective radius of 10,000 feet and the drawdown at the well is 100 feet, the larger well would produce about 3 feet more drawdown at a distance of 1,000 feet than the smaller well. As has been shown in tables 13 and 14, the advantage of a large well over one of a smaller diameter decreases with time, and the effectiveness of any well in lowering the water table diminishes rapidly with the distance.

It therefore becomes evident that some system of smaller, less expensive drainage structures, somewhat expendable so far as investment is concerned., would be as effective as more expensive permanent installations in reducing flow into the mines, and thereby would reduce the unit cost of pumping water in mine areas.

These conditions of location apply in all cases where the sub-outcrop or cave-in is under a considerable thickness of water-bearing materials, but where the sub-outcrop is near the "shore line" of the ground-water reservoir it is possible that large wells located in. areas of greater saturated thickness may dewater the critical area by drawing the ground-water "shore line” toward the well.

CONCLUSIONS

The primary aim of this investigation of ground-water conditions near the iron mines is to acquire enough data and develop sufficient theory to predict with some degree of confidence how successful a program of pumping from the overburden will be and how much water must be pumped, to determine the best location for pumps, and to indicate the principles for the control of water underground.

To accomplish this aim requires a knowledge of (1) how water enters and moves through the iron-formation, (2) the location of the outcrop of the iron-formation on the ledge surface, (3) the transmissibility and storage characteristics of the overlying glacial materials, (4) the character and shape of the ledge surface, and (5) the theory of movement of water in these materials over that surface. An inventory of our knowledge of these various phases of the investigation will indicate the progress made and point out the remaining problems.

It is rather clearly indicated that the water enters the iron-formation through the surface of contact between it and the overlying glacial blanket. This is indicated by several lines of evidence. First, almost all the water enters the mines through the workings in the iron-formation. Water entering drifts through the other bedrock strata is minor in amount. Second, the water of the actively opened parts of the iron-formation is similar in chemical character to the water of the glacial overburden, whereas water from, the other strata are in general more highly mineralized and of a different chemical character. Third, those mines in ore bodies in a part of the iron-formation which comes to the ledge surface on a hillside having only a small ground-water tributary area, such as the James and Davidson mines in the Mineral Fills area, are relatively dry mines.

The exact manner of entry of water into caved ground needs further study. It is not definitely known which element: the rapidity of inflow through the broken bedrock surface, or the rapidity with which water can move laterally through the overburden, controls the quantity of water entering the workings below the caved area. Inasmuch as the broken ledge is not exposed, and sufficient observation wells are not available to give a detailed picture of the water table near any collapse area in the Iron River district further studies are needed. The present continuation of ground-water work on the Marquette range will give an opportunity to follow up this problem.

However, the present studies in the district indicate that the lowering of the head of water over the uncaved contact of the iron-formation with the glacial overburden does not produce a similar decrease in the quantity of water to be pumped from the mine workings, except where the "shore lines" of the ground-water reservoir retreat from the contact area.

Theoretical work done on the movement of water within the iron-formation has indicated that in most mines working under a saturated, overburden, some relief from water in the working openings may be had by making exploratory openings at lower levels and in developing from, the extremities of a level toward, the center. However, where flexures in the iron-formation in its upper parts limit the ground-water flow and where the formation lies at a low or moderate inclination, the upper openings will intercept more water; and where there are other mines in the same geologic structure, or where the formation at ledge is not under saturated overburden for a considerable distance beyond the mine, the flow into the openings from, the sides will be reduced, and openings at the extremities will be less efficacious.

The location of the contact of the iron-formation with the overburden is only imperfectly known because, on the one hand, the ore cannot be mined close to the ledge, owing to the hazards of caving, and on the other hand the structure cannot be predicted ahead of the actual mining. In the Mineral Hills area, as shown in a map prepared, by the Geologic Branch of the U. S. Geological Survey, the formation comes to ledge approximately as an arcuate band, extending from the Homer shaft to the Davidson No. 3 shaft, and also appears between the Spies and the Wauseca shafts. Very probably these two bands are parts of an oval band representing a horizontal section of the formation deformed into an irregular trough-shaped structure. Elsewhere in the district the location of the iron-format ion on the ledge is known only roughly. As a consequence, the critical areas to be unwatered can, in many cases, be determined only approximately, and the correlation of the occurrence of water in the mines with that in. the glacial overburden also can be only approximate. Continuing studies by the Geologic Branch of the Survey doubtless will define the contact of the iron-formation with the overburden much more closely.

The transmissibility of the glacial overburden has been determined from the pumping tests that have been made in those areas where water-bearing materials have been found. It ranges from about 50,000 to 100,000 gallons a day per foot of aquifer, depending largely on the depth of saturation. The average permeability is about 1,000 gallons a day per square foot. In other parts of the district the glacial overburden is often poorly permeable and mines in these areas experience little difficulty from ground-water circulation.

The shape of the ledge surface has been closely defined in the immediate neighborhood of the mines by means of a great number of test borings. In areas at a distance from the mines, only the general features can be determined and the continuity of some of the troughs in the ledge surface cannot be definitely established. Hence there is sufficient information to define the immediate effects of the ledge topography upon the cones of depression around the pumps, but some of the distant and eventual effects cannot be predicted with certainty. Exploratory drilling now actively under way by several companies will increase our knowledge in this regard.

The general theory of the movement of water through the overburden has been given. It is indicated that the maximum reduction of-water level in the critical areas requires wells close to those areas, and that such wells would divert the maximum amount of water from the points of entry into mines with the least amount of pumping. It is suggested that a system of cheaply constructed wells near collapse areas, even though they might be eventually lost through further collapse, might be more economical as an unwatering device than large wells of greater capacity located some distance from the collapse areas.

Several important theoretical problems connected with movement of water through the overburden demand further study. These deal with movement in a very irregularly shaped aquifer such as is formed by the deposits in the ledge troughs. The effects of pumping in a gently shelving trough end in tortuous channels reed further consideration. The exact manner of movement into broken collapse areas must be studied further. These problems are being studied by means of an extension of the present investigation into the Marquette range. Many of the problems apparently will need study by means of electrical or other models.

BIBLIOGRAPHY

1. Dutton, C. E., Park, C. F., and Balsley, J. R., General. character and succession of tentative divisions in the stratigraphy of the Mineral Hills district, Iron River, Iron County, Michigan: U. S. Geol. Survey Strategic Minerals Investigation, 1945.
2. James, H. L., Clark, L. P., and Smith, L. E., Magnetic survey and geology of the Ice Lake - Chicago Creek area, Iron County, Michigan: Strategic Minerals Investigation Prelim. Rept. 3-213, 1947.
3. James, H. L., and Weir, K. L., Magnetic survey and geology of the eastern and southeastern parts of the Iron River district, Iron County, Michigan: U. S. Geol. Survey Circ. 26, 1948.
4. Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior regions U. S. Geol. Survey, Mon, 52, p. 480, 1911.
5. Russell, I. C., The surface geology of portions of Menominee, Dickinson and Iron Counties, Michigan: Geol. Survey Mich., Ann. Rept. for 1906, pp. 7-91.

6. Allen, R. C., The Iron River iron-bearing district of Michigan: Geol. Survey Mich., Pub. 3, Geol. Ser. 2, pp. 11-27, 1910.

7. Leverett, Frank, Surface geology of the northern peninsula of Michigan: Geol. Survey Mich., Pub. 7, Geol. Ser. 5, 1910.

8. Leverett, Frank, Moraines and shorelines of the Lake Superior basin: U. S. Geol. Survey Prof. Paper 154-A, 1928.

9. Bergquist, S. G., Glacial geology of Iron County, Michigan: Michigan Acad. Sci. Papers, vol. 165 pp. 363-372, 1932.

10. Bergquist, S. G., Valley train deposits in the northern peninsula of Michigan: Michigan Acad. Sci. Papers, vol. 20, pp. 4 39-447.

11. Muskat, M., The flow of homogeneous fluids thru porous media: p. 190, McGraw Hill Book Co., 1937.

12. Muskat, M., The flow of homogeneous fluids thru porous media: pp. 181-185, McGraw Hill Book Co., 1937.

13. Theis, G. V., The relation between the lowering of the piezometric surface and the rate and duration of the discharge from a well using ground water storage: Am. Geophys. Union Trans., pp. 519-524, 1935.

14. Cooper, H. H. Jr., and Jacob, C. E., A generalized graphical method for evaluating formation constants of summarizing well field history: Am. Geophys. Union Trans., pp. 526-534, vol. 27, no. 4, 1946.

15. Wenzel, L. K., Methods for determining permeability of water-bearing materials, with special reference to discharging well methods: U. S. Geol. Survey Water-Supply Paper 887, pp. 88-89, 1942.

16. Lane, A. C., The Keweenaw series of Michigan: Michigan Geol. Survey Pub. 6, Geol. Ser. 4, vol. 29 pp. 774-778.

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DEPUTY DIRECTOR

December 28, 1949

Mr. Olaf P. Senkins, State Mineralogist
Div. of Mines, Dept. of Natural Resources
San Francisco 11, California

Fellow State Geologist:

The attached Technical Report #2 is the publication I referred to and promised you at the San Francisco 1949 meeting of the A.A.S.G. With the possible exception of a recent report by the United States Bureau of Mines, which pertains chiefly to water-handling methods, I believe this is the first report of its kind in which is discussed the geology and hydralics of ground water movements through both man-made and natural underground workings. The conclusions are necessarily broad and generalized. Many factors are as yet unknown. However, the study is being continued in the Marquette Range, and it is anticipated that future reports will be of even greater value to geologists and engineers working with problems of mine drainage.

Sincerely

G. E. Eddy

GEOLOGICAL SURVEY DIVISION
G. E. Eddy
State Geologist

GEE:nvd

$\pi(Y_o \pm Y)M$	X/M										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0	-∞	-1.3103	-.7199	-.3851	-.1605	0	.1169	.2008	.2574	.2903	.3010
1.	-.2651	-.2277	-.1342	-.0200	.0914	.1884	.2677	.3286	.3714	.3969	.4054
2.	.4413	.4489	.4703	.5016	.5382	.5754	.6097	.6385	.6600	.6733	.6778
3.	.9575	.9598	.9666	.9768	.9894	1.0029	1.0161	1.0275	1.0365	1.0421	1.0441
4.	1.4201	1.4209	1.4232	1.4268	1.4314	1.4363	4.4412	1.4455	1.4490	1.4512	1.4519
5.	1.8646	1.8649	1.8657	1.8670	1.8687	1.8705	1.8723	1.8739	1.8752	1.8760	1.8763
6.	2.3026	2.3027	2.3030	2.3035	2.3041	2.3048	2.3054	2.3060	2.3065	2.3068	2.3069
7.	2.7382	2.7383	2.7384	2.7386	2.7388	2.7390	2.7393	2.7395	2.7397	2.7398	2.7398
8.	3.1730	3.1730	3.1731	3.1732	3.1732	3.1733	3.1734	3.1735	3.1736	3.1736	3.1736
9.	3.6075	3.6075	3.6075	3.6075	3.6075	3.6076	3.6076	3.6077	3.6077	3.6077	3.6077

For all values of X/M

$\pi(Y_o \pm Y)M$		$\pi(Y_o \pm Y)M$		$\pi(Y_o \pm Y)M$	
10.	4.042	20.	8.385	30.	12.728
11.	4.476	21.	8.819	31.	13.162
12.	4.910	22.	9.253	32.	13.596
13.	5.345	23.	9.688	33.	14.030
14.	5.779	24.	10.122	34.	14.465
15.	6.213	25.	10.566	35.	14.899
16.	6.648	26.	10.990	36.	15.333
17.	7.082	27.	11.425	37.	15.768
18.	7.516	28.	11.859	38.	16.202
19.	7.950	29.	12.293	39.	16.636

Table 8. Values of function log10 [$\cos\pi(Y_o \pm Y)$ / M-$\cos\pi$X/M].

Time in days of continu-ous pumping.	2½ inches	4 inches	6 inches	12 inches	24 inches	60 inches	10 feet	50 feet	100 feet	200 feet
1	0.81	0.86	0.91	1.00	1.12	1.32	1.53	2.43	3.25	4.92
10	.83	.88	.92	1.00	1.10	1.26	1.42	2.00	2.44	3.13
100	.85	.89	.93	1.00	1.08	1.21	1.34	1.78	2.04	2.44
1,000	.86	.90	.94	1.00	1.07	1.19	1.30	1.63	1.84	2.11
10,000	.88	.91	.94	1.00	1.07	1.17	1.25	1.54	1.69	1.89

Table 14. Ratio of yield of wells of various diameters to that of a well 12 inches in diameter.

Time in days of continu-ous pumping.	2½ inches	4 inches	6 inches	12 inches	24 inches	60 inches	10 feet	50 feet	100 feet	200 feet
1	1.24	1.16	1.10	1.00	0.90	0.76	0.65	0.41	0.31	0.20
10	1.20	1.14	1.09	1.00	.91	.79	.70	.50	.41	.32
100	1.17	1.12	1.08	1.00	.93	.82	.74	.56	.49	.41
1,000	1.16	1.11	1.07	1.00	.93	.84	.77	.61	.54	.48
10,000	1.14	1.10	1.06	1.00	.94	.86	.80	.65	.59	.53

Table 15. Ratio of drawdown in wells of various diameters to that in a well 12 inches in diameter.