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GROUND WATER RESOURCES OF MISSISSIPPI BASIN IN ILLINOIS, IOWA, MINNESOTA, AND WISCONSIN

by

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GROUND WATER RESOURCES OF MISSISSIPPI BASIN IN

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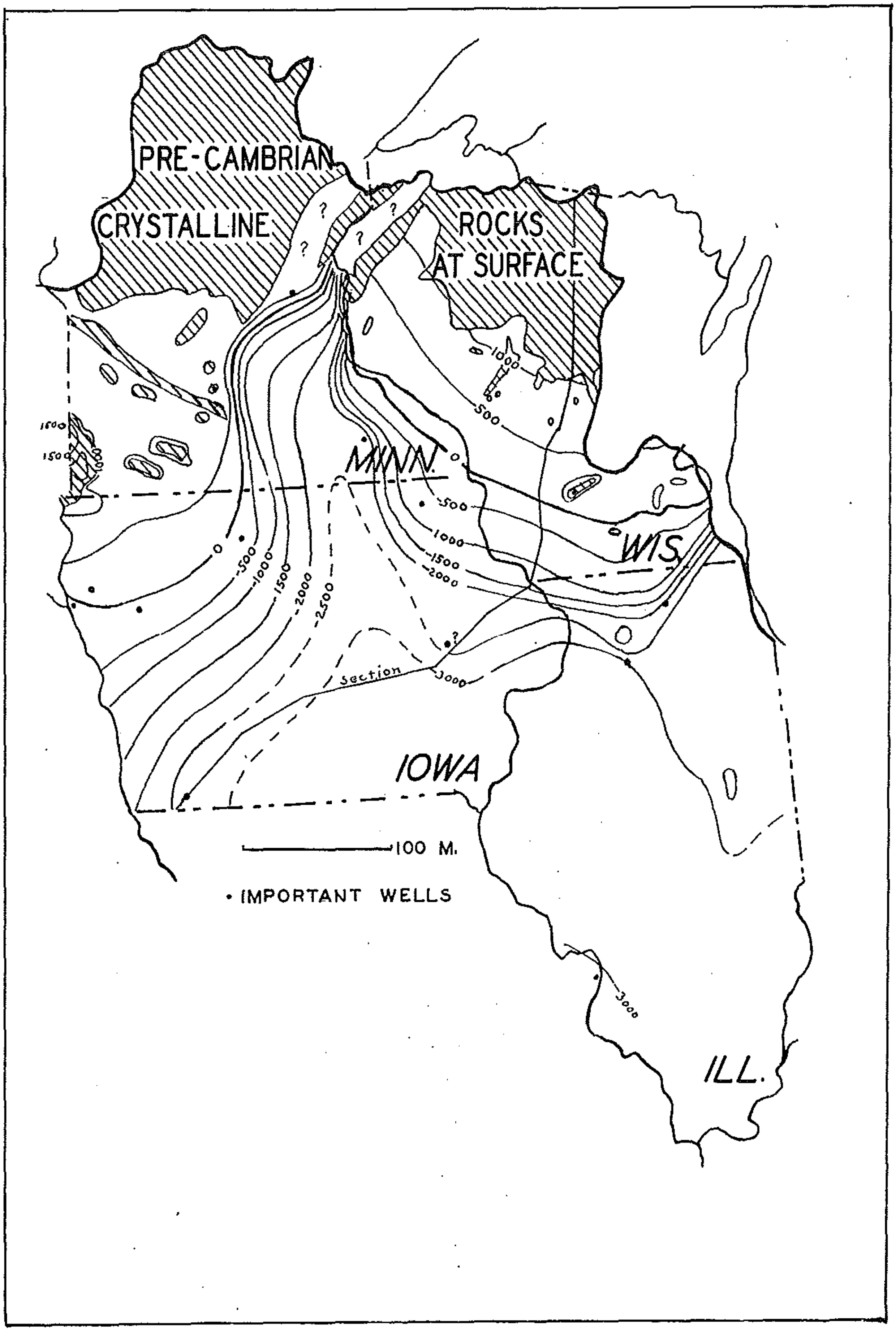
Introduction.– On September 7, 1934 the writer was instructed by Professor Howard E. Simpson to prepare a report on the ground water resources of the portion of the Mississippi Basin within the states of Illinois, Iowa, Minnesota, and Wisconsin. In the time allotted, two weeks, it was impossible to do any significant amount of field work; consequently the material of the report was drawn from the results of previous investigation by the writer and others. Letters were sent out to representative well drillers and engineers throughout the territory and much information was obtained verbally from engineers and officials in Madison and by correspondence with the chairmen of the State Planning Boards at Springfield, St. Paul, and Ames.

LOCAL HORIZONS OF UNDERGROUND WATER

Introduction.– The accompanying table of formations summarizes the geological conditions under which underground waters occur in the district under discussion. These formations can be broadly divided into (a) loose unconsolidated surficial deposits, chiefly glacial drift, which cover almost all of the district to variable depths; (b) "soft rocks", many of which are water-bearing and which range in age from Cretaceous to Cambrian; and (c) "hard rocks" of pre-Cambrian age which contain little water. Plate I shows the areas where the hard rocks occur immediately below the glacial drift and their approximate surface beneath the overlying soft rocks. Plate II is a section demonstrating how the different layers of soft rock slope away from the outcrop areas of the pre-Cambrian. Plate III presents by means of contour

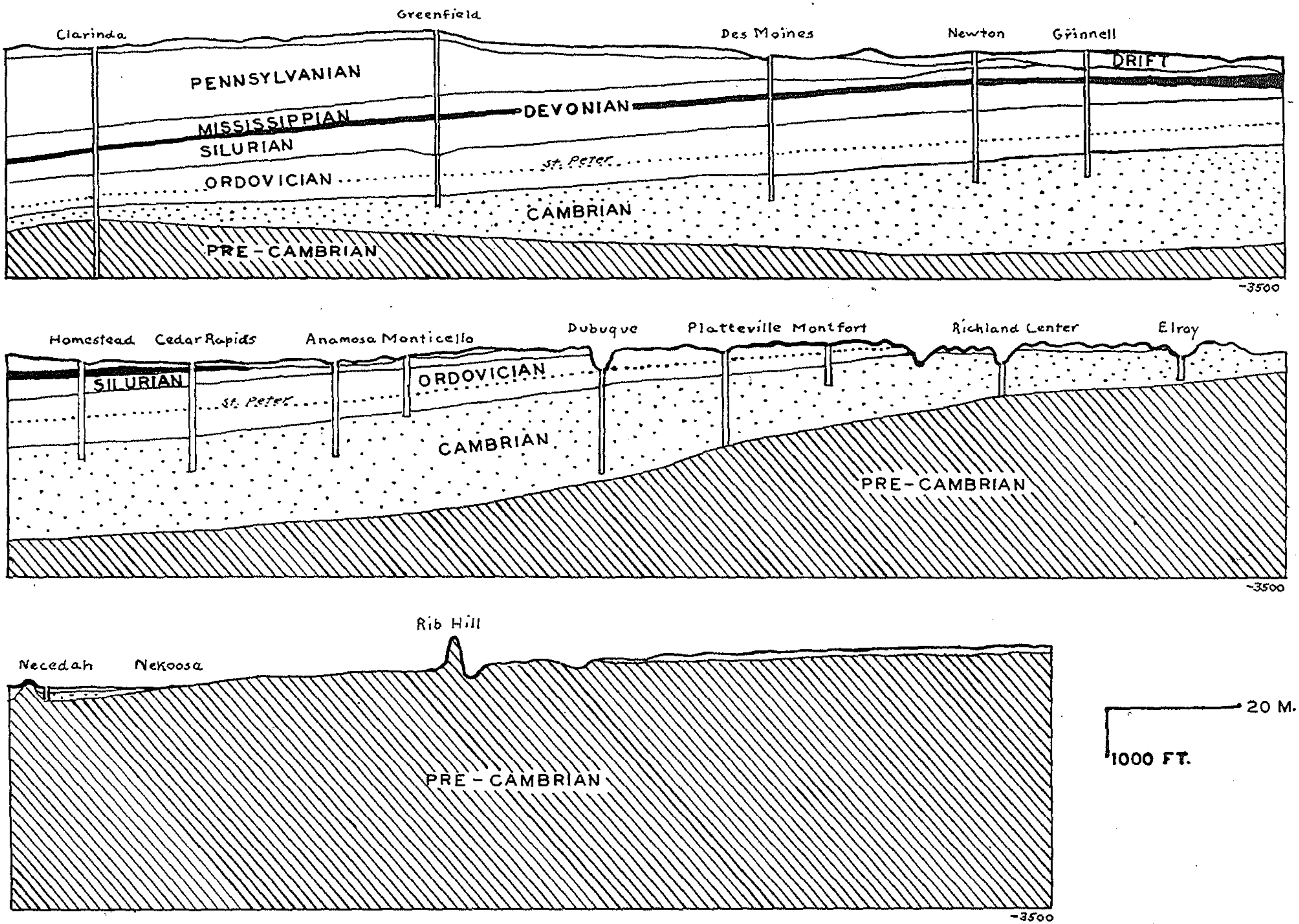


SURFACE DISTRIBUTION OF PRE-CAMBRAIN CRYSTALLINE ROCKS AND THEIR BURIED EXTENSION

contour interval 500 ft.

GEOLOGICAL CROSS SECTION - SOUTHWESTERN IOWA TO NORTHERN WISCONSIN

PLATE II



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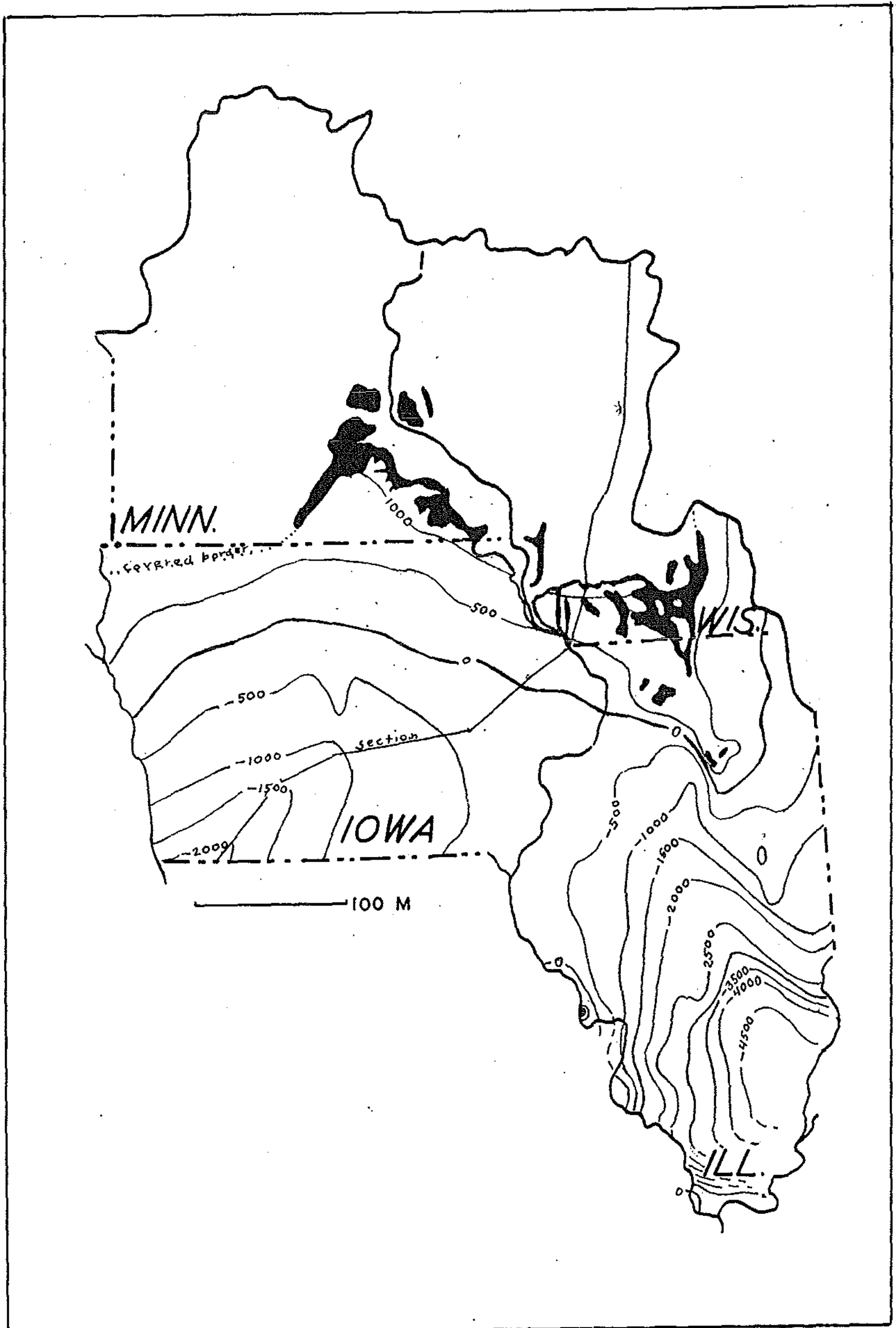


OUTCROP AREA (SOLID BLACK) AND CONCEALED EXTENSION OF ST. PETER SANDSTONE

Contour interval 500 ft.

Formation	Thickness, ft.	Description	Yield	Quality
SURFICIAL				
Pleistocene (drift)	to 600	Till, sand, gravel	Variable	Variable
Tertiary	to 50	Gravel	Large?	Soft?
BED ROCK-SOFT				
Cretaceous	to 500	Shale, sandstone	Variable	Some hard, some soft alkalie
Pennsylvanian (Coal Measures)	to 2100	Shale, sandstone, limestone, coal	Small	Fair to very poor
Mississippian				
(Chester)	to 1200	Sandstone, shale, limestone	Large	Hard
(Meramec)	400-550	Limestone	Variable	Hard
(Osage)	280-500	Limestone, sandstone, shale	Variable	Hard
(Kinderhook)	50-370	Shale, limestone	Small	Hard?
Devonian	to 300	Limestone, shale	Variable	Hard
Silurian				
(Salina)	to 500	Dolomite, salt, gypsum	None	-------
(Niagara)	to 500	Dolomite, limestone	Variable	Hard, some soft
Ordovician				
(Maquoketa)	75-300	Shale, dolomite	None	-------
(Galena, Platteville, etc.)	200-510	Dolomite, limestone	Variable	Hard
(St. Peter)	to 500	Sandstone	Large	Medium hard
(Prairie du Chien)	to 700	Dolomite, sandstone	Large	Hard
Cambrian				
(Jordan)	to 200	Sandstone	Large	Medium hard
(St. Lawrence)	100-350	Dolomite, silty	Small	Hard
(Franconia)	70-150	Sandstone, fine, dol.	Moderate	Medium hard
(Dresbach)	30-200	Sandstone, white	Large	Medium hard
(Eau Claire)	100-350	Sandstone, shale	Small	Hard, some soft
(Mt. Simon)	to 1000	Sandstone	Very large	Soft to hard
Age unknown (Red Clastics)	to 2250	Sandstone, shale, red	Small	Salty
BED ROCK-HARD				
Huronian	to 7000	Quartzite, slate, etc	Small	Soft
Igneous and metamorphic	-------	Granite, gneiss, etc	Very small	Soft

GEOLOGIC SECTION OF ILLINOIS, IOWA, MINNESOTA, AND WISCONSIN SHOWING WATER-BEARING QUALITY OF FORMATIONS
F. T. Thwaites, 1934

Note: All formations contain only salt water at depths of over 2000-3500 ft.

lines drawn on the top of the St. Peter sandstone, an important water-bearing formation, a more complete picture of the geological structure. Attention should be given to the two deep basins in Iowa and Illinois respectively in which the formations of soft rocks reach their lowest elevations.

<u>Surficial deposits - Pleistocene</u>.- The major part of the surficial deposits of the Upper Mississippi Valley was deposited either directly by glacial ice (till) or by the waters derived from its decay (sand, gravel, and clay). A relatively thin mantle was laid down by the wind (loess). These deposits are collectively called "drift". Their water-bearing quality varies widely. The tills vary from a mixture of boulders and sand in the regions underlain by hard pre-Cambrian rocks to dense clays with scattered stones in the districts of soft shale bed rock. In general, tills contain very little water although there were extensively drawn upon by the dug wells of the early settlers. The same remark may be made of the loess which contains water during humid seasons where underlain by impervious till. Although the silts and clays which were laid down in lakes of glacial time contain much water, the pores in them are so small that this water is not yielded to wells and they are of no practical importance. The sand and gravel deposits of the drift occur (a) above the till, (b) interstratified with it, and (c) between it and the underlying bed rock. In many localities where is more than one layer of sand and gravel, but in others no such deposits occur. Such deposits are much more abundant in regions of firm rocks like limestone or granite where the glacial drift is stony than they are in districts of very clayey till. Throughout northern Minnesota, much of Iowa, and large parts of Illinois, indeed almost all of the rivers which once

carried glacial floods, sand and gravel beds (outwash) are very important sources of water supply. Indeed, in many localities they are the only sources of water or the only sources of potable water. Not all layers, however, are productive; some lie above the water table and others do not communicate with the surface. Glacial outwash deposits occur within the unglaciated areas in southwestern Wisconsin and southern Illinois. The limits of the drift in these areas are for the most part ill-defined and are, therefore, not mapped.

Surficial deposits - Tertiary.- So far as the information available to the writer goes the gravels of Tertiary age which occur mainly in southern Illinois are not important as sources of water.

Soft rocks.- The soft rocks consist of limestone, dolomite (magnesian limestone), shale, and sandstone and include all degrees of mixture of the above types. All of these rocks are more or less broken by joints and fissures and this is best developed near to the weathered surface. All of them contain more or less water near to their outcrops. Many shales there produce enough water to supply farm wells. Where the openings in limestones have been enlarged by solution, immense amounts of water are present. But at depths of more than a few hundred feet weathering has not been appreciable in amount and the shales, limestones, and dolomites are not important producers. The sandstones are more uniformly porous, but down the dip away from the outcrop the amount of cementing minerals between the sand grains gradually increases and the porosity correspondingly decreases. The coarser grained sandstones, however, yield some water as far down as they have been penetrated by the drill.

Cretaceous.- Comparatively little is known of the details of the Cretaceous deposits of western Iowa and southwestern Minnesota. Their base contains more or less sandstone and some conglomerate, for the most part rather fine grained and charged with sulphides of iron. Only a few large wells have been obtained in these deposits.

<u>Pennsylvanian</u>.- The Pennsylvanian deposits contain many water-bearing sandstones, but the extent of individual layers is for the most part very limited and the rock is fine-grained. Both the sandstones and the adjacent rocks contain much sulphide of iron. In a few localities, however, good wells of fairly abundant yield have been obtained from Pennsylvanian rocks and it is probable that their possibilities have never received a thorough test. The best opportunities for water development lie near to sandstone outcrops.

<u>Mississippian</u>.- Near to the outcrop the Mississippian sandstones and limestones yield considerable amounts of potable water. In Illinois the steep dip carries these strata too deep for satisfactory yields within a few miles of their outcrop, but in Iowa the inclination is less and water may be found in the Mississippian for some distance under the cover of overlying beds.

<u>Devonian</u>.- Small amounts of water are found in the Devonian limestones of Iowa and northwestern Illinois. They do not rank as important sources for large supplies.

<u>Silurian</u>.- The fissures of the Silurian dolomite locally yield enormous amounts of water. Large wells are found in northeastern Illinois and northeastern Iowa, but the finding of such supplies is very uncertain. Where this formation rests on underlying impervious shale, springs are abundant wherever the contact is exposed. In portions of Iowa the salt and gypsum bearing beds of the Salina formation occur at the top of the Silurian but do not themselves yield a substantial amount of water.

Ordovician.-- The Ordovician strata above the St. Peter sandstone yield little water except on the outcrop. Some production is reported from the Galena-Platteville in northeastern Iowa and northern Illinois at considerable depths. Wherever there is a shale bed (Decorah) at the bottom of the Galena, important springs issue along the outcrop. In many localities the St. Peter sandstone is the first water-bearing bed encountered in wells. Although this formation is very persistent, it is of only moderately coarse grain and the thickness is variable. In eastern Wisconsin it is locally absent. Below the St. Peter one or more sandstone layers are found within the Prairie du Chien dolomite. The principal one is often called "New Richmond" and is an important source of water in parts of northern Illinois and northeastern Iowa and to some extent in southern Minnesota. The dolomite also yields considerable water especially where not covered by other formations.

Cambrian.-- Throughout Iowa, Minnesota, and the western parts of Wisconsin and Illinois the Jordan sandstone at the top of the Cambrian is a very important water producer. To the east it grades into sandy dolomite and is of no practical importance. The underlying St. Lawrence and Franconia formations are of little importance except near the outcrop. Where there is a layer of so-called "shale" (siltstone) at the bottom of the Franconia sandstone the outcrop of this horizon is an important spring line. The very pure white Dresbach sandstone is an extremely valuable source of water throughout Minnesota, Wisconsin, northeastern Iowa, and northern Illinois. Underlying the Dresbach the fine grained, well cemented Eau Claire sandstones do not yield large amounts of water. The basal formation of the Cambrian, the Mt. Simon sandstone, is pre-eminently the best water producing formation in the area. It is much coarser grained than any overlying sandstone.

Red Clastic series.-- Along the margins of the soft rock area the Mt. Simon sandstone rests directly upon pre-Cambrian crystalline rocks. In the bottoms of the basins, however, several hundred to over 2,000 feet of pink and red sandstones and shales intervene between the light colored Mt. Simon sandstone and the crystalline basement. On the cross section no attempt has been made to separate these rocks. Their age is uncertain; they may be either (a) the downward extension of the Mt. Simon, or (b) the southwestward prolongation of the enormously thick red shaly sandstones which lie in the troughs between ridges of pre-Cambrian igneous rocks in northwestern Wisconsin and northeastern Minnesota. No attempt was made in Plate I to contour the bottoms of these troughs (See questions marks.).

Huronian.- The Huronian quartzites of the Baraboo region, Wisconsin, and of southwestern Minnesota yield small supplies of water from crevices.

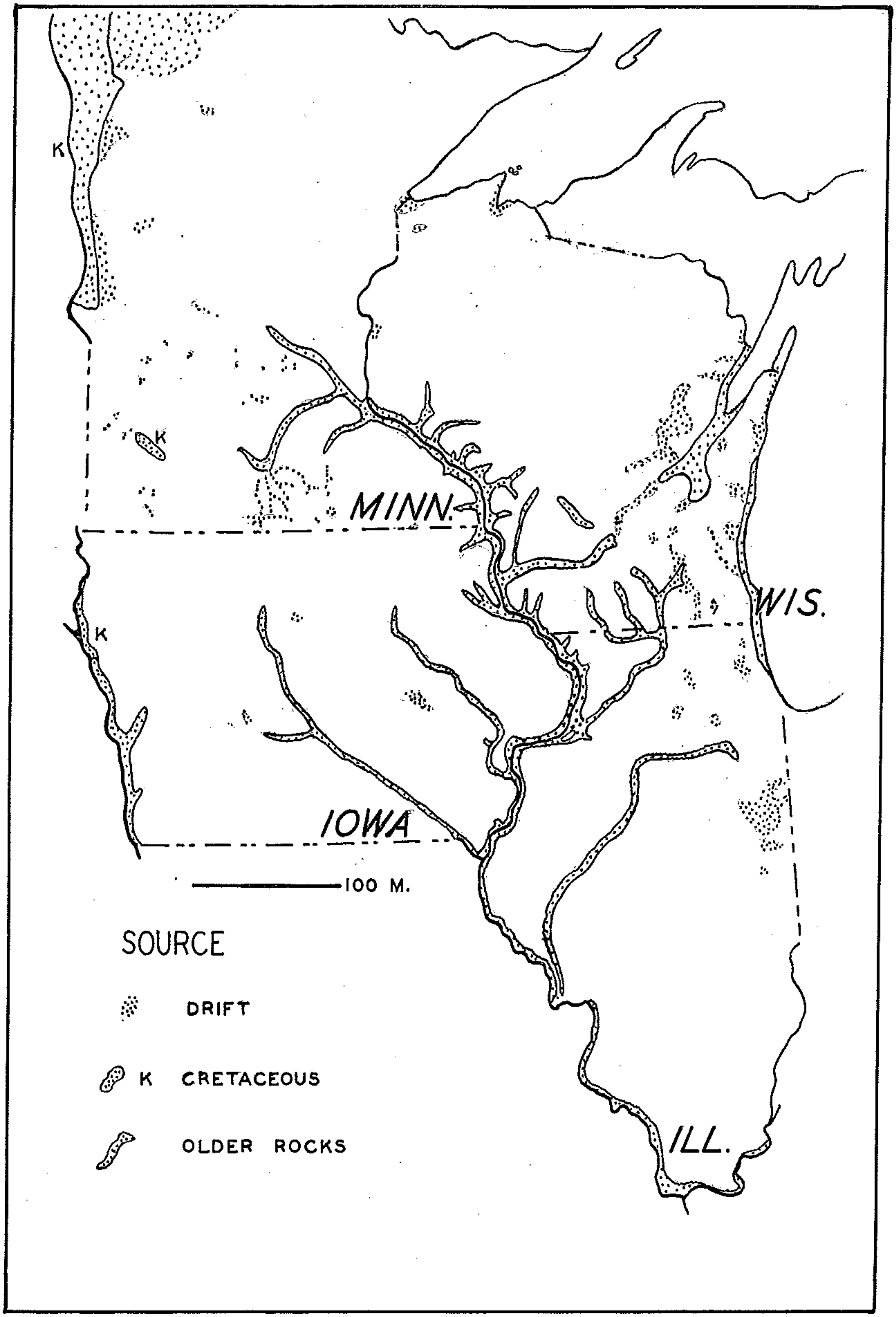
Igneous and metamorphic rocks.- Throughout much of Minnesota the top of the igneous and metamorphic rocks is deeply weathered and yields some water. Deep wells, however, in the formations invariably encounter little or no water. One driller informed the writer that if a well passes through more than 200 feet of hard rock without finding a water-bearing crevice, it was advisable to discontinue work and try another location. In Wisconsin few wells obtain more than a very meager supply of water from the hard rock formations.

FLOWING WELLS

Introduction.- Wells which flow at the surface were formerly called "artesian", but when geologists realized that these wells differ from adjacent ones which penetrate the same formations only by being located on lower ground where the static head lies above the surface, this term was so widely applied that it has lost the original meaning. The term "flowing well" is definite and is here used. In parts of Wisconsin such wells are commonly termed "fountains". Plate IV shows the distribution of flowing wells according to available data.

Cause of flows.- Flowing wells may be compared with taps in a city water system which is supplied from an elevated tank as long ago explained by Chamberlin. Recently Russell endeavored to show that flows might be explained by the weight of the overlying strata. When the water pressure was relieved by a well, settling took place with discharge of the contained water. This theory is doubtless true in part but it fails to explain either the character of many of the waters which are obviously derived from rain water and not deposited in the formation or the permanence of many flows. Although the pressure differs in different water-bearing formations in the same well, there is some evidence that considerable leakage occurs both into and out of the formation. For instance the flows in the Kickapoo Valley in southwestern Wisconsin occur higher than the outcrop of the formation to the north. They must be in part supplied by the high water table under the adjacent hills. In fact, most flows occur in deep valleys rather than out on the plains although in some places the valley is very wide. As shown by Slichter the water percolating from the high water level under the hills is largely moving upward below a valley where it escaped[5]. If there is a relatively impervious layer under the valley, then a well offers easier outlet than nature has afforded and a flow results.

Flows from drift.- The requisite conditions for flowing wells are common in the glacial drift and the mapping on Plate IV of such wells is not complete. The writer has observed scattered flowing drift wells in several places in southern Illinois. In most cases the water-bearing sand and gravel is covered either by till or by lake clays. In some places water



FLOWING WELLS

is confined in the bed rock by overlying drift. In few cases can the detailed stratigraphy of such deposits be worked out as may be done with the bed rocks and the probable extent of the basin cannot, therefore, be forecasted. One of the early discoveries was the famous "Jumbo" well at Belle Plaine, Iowa which ran wild for a considerable time. In many places it is difficult to drill such wells without getting leaks outside the drive pipe. Some drift flows are left uncased below 20 to 40 feet from the surface and are subject to bridging if the flow is stopped even for an instant.

Flows from bed rocks.- The map (Plate IV) shows that flowing wells can be obtained from the bed rock along most of the principal river valleys. No attempt has been made to map the artesian head. Underground leakage is so common that the head is dependent upon the method of casing the well and the effectiveness of the "shut off" as it is termed in oil well practice. The map does not attempt to separate areas of flows due to different water-bearing formations although some localities of flows from the Cretaceous have been indicated. These wells are similar to the famous Cretaceous (Dakota sandstone) flows of the Dakotas. No attempt has been made to separate flows of potable and non-potable water. There were formerly flowing wells near Chicago but heavy pumping has there lowered the head so that they have ceased. The same phenomenon occurs elsewhere but has not been shown.

DEPLETION OF UNDERGROUND WATERS

Introduction.- The problem of the depletion of underground waters is a complex one and is intimately tied up with questions of agriculture, forestry, and meteorology. Within the limits of this report it is impossible to follow all the ramifications of the subject or to summarize all the different opinions of previous investigators. This discussion is confined to the more important investigations of the subject and to actual observations within the area under discussion.

Origin of underground water.- Of the water which falls on the surface of the earth by far the larger part is returned to the atmosphere by evaporation both directly and through the medium of growing plants. Some runs directly into streams, and a part soaks into the ground so deeply that it reaches the underground water. It is difficult to estimate the relative proportions of these three dispositions, for such vary widely with weather, character of the vegetation, and local geological phenomena. The discharge of streams is larger than the storm run-off, for it includes much spring water. Minimum discharge records during long dry spells offer a fairly close approximation of spring flow except where the watershed includes lakes and swamps.

The water table.- The level at which water stands in openings in the ground is defined as the "water table." Most text books treat the subject as though there were only one water table. Actual field investigation shows, however, that in regions of diverse materials the distribution of underground water is extremely variable. Layers of impervious material underlying pervious substances hold underground water above them in "perched" water tables. In regions of alternating pervious and impervious materials in more or less horizontal position there may be several perched water tables. This is the case in many hills of western Wisconsin. In materials of low porosity such as the clay tills of Iowa and Illinois it is difficult to say that there is any definite water table. Many lakes, ponds, and streams do not connect with the subjacent water table but are perched. In other places deeply buried water-bearing layers contain water under pressure which when reached by a well rises far above its original position, and over considerable areas above the surface where the well was put down. (See flowing wells, p. 9) It follows, therefore, that wells within short distances of one another obtain diverse positions for the water table depending upon their depth and method of casing. Some may allow the drainage of underground waters which lie near the surface down into deeper waters of lower head. Others may permit the rise of high-pressure deep waters into strata where the water has lower pressure.

Variations in the water table.- The level of the water table varies with the amount of precipitation which reaches it and to some extent as the result of changes in temperature of the ground and in atmospheric pressure. Adjacent ground water flows toward the well. The ground retards the flow so that unless there are very large openings the net result is a fall in the level of the water table adjacent to the well during pumping and for some time after it ceases. This is called "draw down" and the yield per foot of drawdown is called "specific capacity". In the same way the water table slopes down toward springs and lines of seepage.

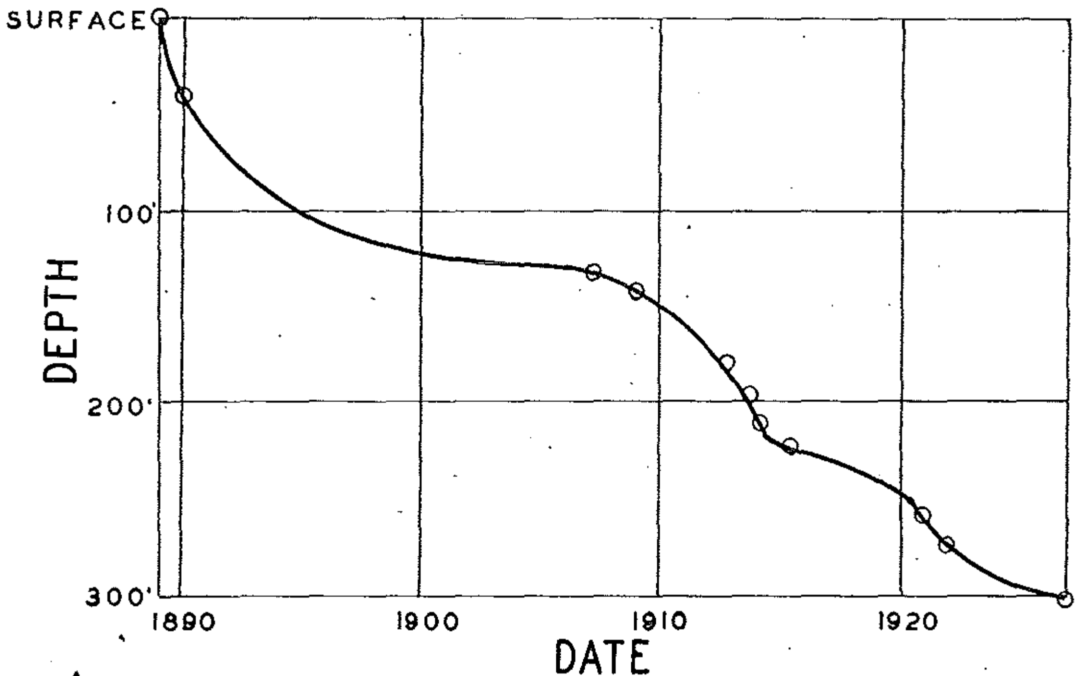
Recession of the water table.- The first settlers in the Mississippi Basin to a large extent obtained their water supplies from natural springs. Next dug wells, which for obvious reasons extended only a few feet below the water table, were made. Many of these continued in use until the prolonged period of subnormal rainfall during the nineties. Then drilled wells were widely introduced. Most of these were carried down into bed rock and, largely on account of their superior sanitary qualities, have almost entirely displaced dug wells, although driven and bored wells are used in many places. Many wells were also drilled in the effort to obtain flows. Most of these deeper wells were satisfactory until the drought which began in 1930. Since that date there has been continued recession of water levels so that now many farm and some village and city wells are dry for the first time. It is reported that in the last few years the water table has locally receded 40 to 50 feet and a sinking of 10 to 15 feet is very common. Apparently the recent lowering is most marked in (a) perched water tables, (b) narrow ridges, (c) sandy plains, and (d) relatively imperious materials such as till.

Causes of recession in shallow wells.— The writer has been able to find in print very few actual observations on the relation between ground water levels in shallow wells and adjacent precipitation. It is clear, however, that replenishment of the underground waters normally takes place chiefly during winter (except when the ground is frozen) and spring. Shortage of snow is probably much more important than summer droughts in lowering the water table. During the summers the greater demands of vegetation contribute to lowering the level largely by the prevention of replenishment. The effect of shortage in replenishment is cumulative and lags considerably behind changes in precipitation. The elaborate survey carried out by McGee which has been cited by most authors as positive proof of a permanent lowering of the water table due primarily to cultivation of the soil is open to several criticisms. First, no consideration was given to the factor of replenishment and the study was made shortly after the great drought of the nineties. Second, the evidence was necessarily based upon hearsay reports given from memory by old inhabitants and the experience of the writer is that few, if any, well owners know accurately the level of water in their wells. The writer himself does not know the present or past water levels in the four wells at his residence. Furthermore it must be realized that the wells of the early settlers for the most part never yielded very much water as judged by present-day standards. Stock was then watered almost exclusively at streams and ponds and the household use of water was much smaller than now. Many, possibly a very large fraction, of the early wells were little better than cisterns in which melted snow and spring rains accumulated. Others were supplied by such slow seepage that it would not be noticed in a modern well of only a few inches diameter but could be utilized because of the storage afforded in the large dug well. It is easy to see how any prolonged shortage of precipitation would cause the failure of such wells without the necessity of calling upon the effects of deforestation and cultivation. The writer does not deny that there are effects. The changed regime of the streams of today, the more marked freshets and floods, the development of gullies, and the drying up of many small springs and ponds are eloquent testimony of the evil effects of the march of civilization. But the replenishment of the main ground water is another matter and apparently does not depend to a large extent on the condition of the ground in the summer time. An attempt by Lees in 1927 to bring up to date in Iowa the survey of McGee failed to demonstrate any further change. In the opinion of the writer the changes wrought by man which may affect the amount of replenishment of the water table and bring about some permanent lowering are: (a) substitution of compact sod for loose forest mould, (b) tramping of ground by cattle rendering it less pervious, and (c) drainage of marshes. There is no data of trustworthy nature by which the effects of these factors can be evaluated and compared with effects of changes in precipitation. Wells put down for the sole purpose of observing the water level are needed, for it is useless to seek for accurate information in wells which are pumped to a considerable extent as are almost all wells at the present time, especially during a prolonged drought. Very important factors in governing the amount of recession of the top of the first or surface water are (a) porosity of the ground, (b) leaks in the restraining layer beneath perched bodies of ground water, and (c) the size of a given body of ground water. Low porosity makes a given loss or replenishment cause a greater absolute change in water level than in the case of high porosity. On the other hand high porosity allows relatively rapid leveling out of the water table down to the point of outlet when replenishment is slight or absent. The writer has known of the failure of wells in perched water tables even during periods of heavy rains ~~and naturally the effects of such are most conspicuous when replenishment is at a minimum.~~ It is obvious that small bodies of underground water are the first to be exhausted by use and by natural leakage.

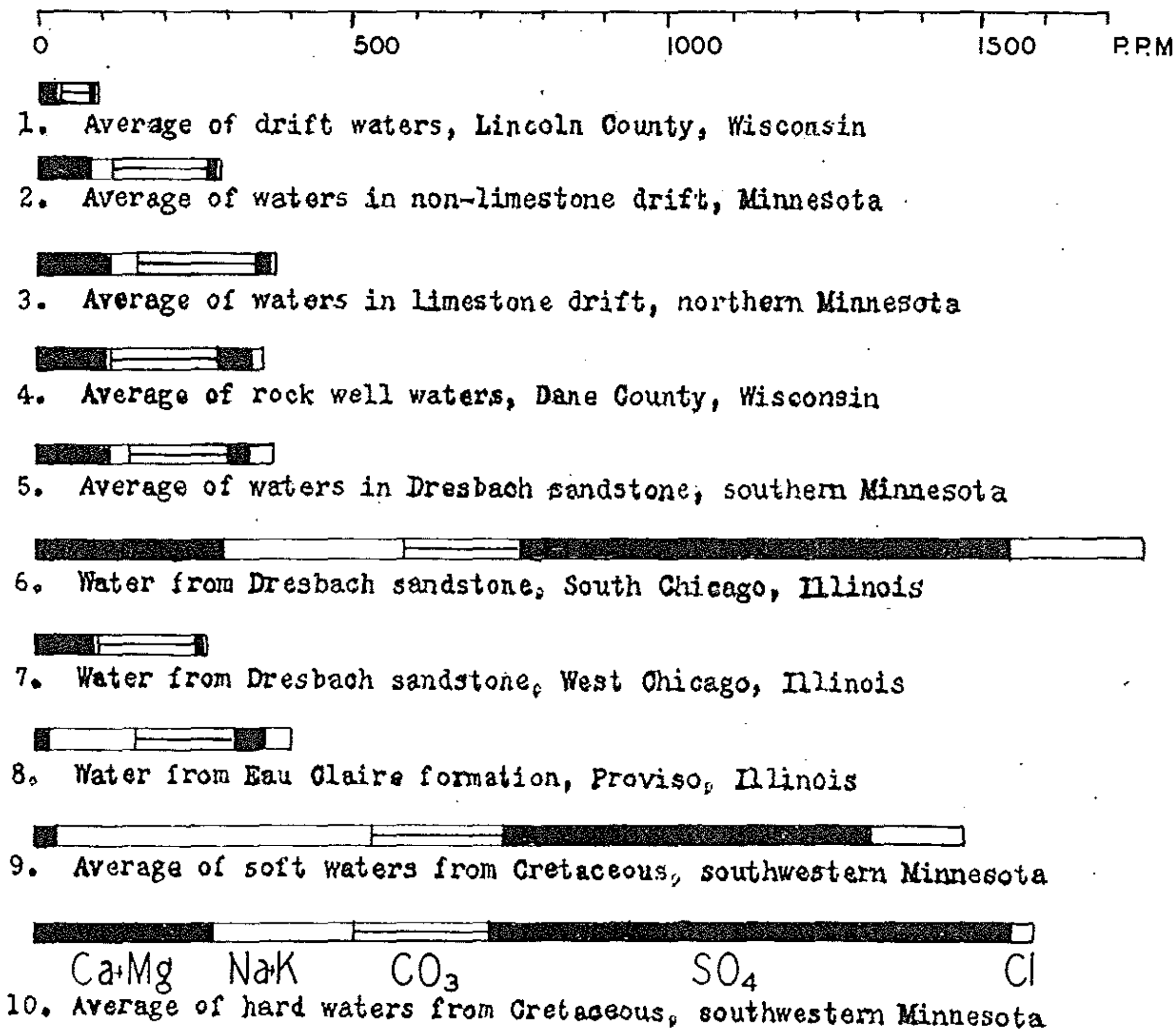
Examples of recovery of ground water level.-- One of the classic instances of ground water recession is in Portage County, Wisconsin, reported by Weidman and cited by Van Hise. In that region of sandy outwash plains Weidman reported that the water table had by 1900 sunk 20 to 40 feet. In 1927 the writer resurveyed the same region and found that the ground water had risen markedly again and that in many of the enclosed lakes which Weidman reported as permanently dry the water was killing trees over 30 years old! Similar observations have also been made by the writer in Dane County, Wisconsin. Beyond question if many of the old dug wells of the pioneers had been cleaned out during the time just before 1930, they would have yielded almost, if not quite, as much water as they ever did. An illustration of the permanent drying up of a stream due to lowering of the water table given by Weidman is also misleading. He cites a logging dam on what is now an intermittent stream apparently not realizing that such reservoirs were filled with the water from melting snow in the spring and not by summer flow.

__Recession of deep wells.__— For the purpose of the present study a deep well is defined as one which either (a) extends more than 20 feet below the normal water table or (b) encounters water under higher or lower head than is the surface water. The yield of such wells is best measured by their specific capacity and not by the static level of the water when not pumping. Specific capacity may be affected by (a) clogging of the pores of the rock close to the well by mineral or bacterial deposits, (c) reduction of the head supplying the water by recession of the ground water at the point of entry to the producing formation, (d) caving or bridging of the hole, (e) leaks below the surface, (f) drawing off of water by adjacent wells, and (g) clogging of screen. Changes in head of a deep well are due to (a) clogging or bridging of the hole, (b) subsurface leaks, (c) interference of adjacent wells, and (d) actual recession of the water at the source which change is probably very slowly transmitted because of the low rate of underground flow. In order to evaluate the several factors involved and see if there has been actual falling of the water level it is often necessary to do considerable expensive work on the well which involves taking it out of service for some time. Variations of head are most easily observed in flowing wells, ~~for in many pumped wells no device to measure the water level is installed.~~ Moreover few wells have any device installed in them by which the water level can be measured and the fact of recession is not noted until the pump sucks air. Data collected by the writer from engineers and well drillers fails to indicate any permanent lowering of water levels in deep wells or even any marked effect of the present drought.

__Examples of recession of deep well levels.__— The classic example of recession is around Chicago. Originally wells there flowed but as shown in Plate V-A there has been a constant decline down to 300 feet by 1927. The



A RECESSION OF WATER LEVEL IN DEEP WELLS AT CHICAGO, ILLINOIS



B MINERAL CONTENT OF TYPICAL UNDERGROUND WATERS rather abrupt drop between 1908 and 1915 took place before the war boom and may be the delayed effect of the drought of the nineties, but this is not proved. The major factor in causing the fall is the increase in amount of water pumped to the point where it is now estimated that 50,000,000 gallons a day is being raised in Chicago and suburbs. A case investigated by the writer involved recession of the static head of flows in the vicinity of Sparta, Wisconsin. Well drillers stated that the level to which water would rise fell on account of the drought of the nineties and had not recovered by 1917 to more than half the original distance above the ground. Recourse to written records by Moses Strong of the original head of wells, however, showed that the memory of the drillers was at fault and that aside from a rather slight fall due to the number of wells within the city, particularly abandoned wells discharging into the valley filling, there had been no permanent change. Possibly the drillers recalled some abnormal conditions due to the extremely heavy rainfall of the seventies, for such might easily have caused flows where normally there would be none. It was widely held that the supply of water from the Cambrian sandstones at Madison, Wisconsin was steadily diminishing and diagrams were published showing the progressive decline in static level. Then, following the advice of geologists, recourse was had to the unit well system. The new wells located more than two miles from the group at the waterworks discovered that the original conditions still prevailed and that the fall was due purely to local overdraft. The same story could be multiplied many times within the district under discussion. In many places new large diameter wells or repair work on old wells has restored original conditions. It is possible that acidizing now so successfully used in oil wells could be applied to the removal of carbonate deposits around water wells.

Compaction of strata.— The reduction of pressure in underground reservoirs near to a well in which pumping or flow lowers the original head to a marked degree undoubtedly causes the precipitation of more or less dissolved material. This is mainly accomplished by the breaking down of bicarbonates and may be seen to be still in progress after the water is brought to the surface. Encrustation is a common phenomenon in screen wells and is not remedied by acid treatment with an inhibitor to prevent action of the metal. The liberated carbon dioxide corrodes both casing and pumps. Another result of decreased head is thought to be compaction of the strata. It is evident that formations which contain water under pressure cannot be as compact as those which are dry, for the water supports a portion of the overlying burden. The effect of complete withdrawal of water from a formation of sand or very soft sandstone must certainly be considerable. (At New Orleans a lowering of 7 feet in the ground water level has caused marked subsidence at the surface.) When water is not completely withdrawn, the effect is proportional to the diminution of pressure. In the Chicago district the pressure in the water-bearing formations has been decreased by more than 130 pounds to the square inch. The rocks, however, are fairly firm and it seems unlikely that any sensible amount of compaction has taken place. Data on comparative specific capacities at different dates is not available except at Rockford, Illinois. There the decrease was ascribed by Slichter by organic growths in the pores (Anderson, p. 231).

Conclusions.— In the light of present information the following are established:

(1) The level of ground water has notably fallen as a result of the present drought and this is most pronounced in materials of low porosity and in situations where subsurface escape is relatively rapid.

(2) The yield of wells which enter small isolated or shallow bodies of ground water or do not extend more than a comparatively few feet into the ground water has been cut off or seriously cur-

tailed.

(3) In large bodies of ground water such as that within the major water-bearing formations the proportion of shortage to total amount in the ground is so small that the effect on the yield of wells is negligible.

(4) It has not been provedthat there is a large and progressive permanent fall in the water table due to the work of man although there has certainly been some effect due to deforestation and cultivation.

(5) In certain localities where large numbers of wells are in use the withdrawal of water is at a rate greater than can be replenished by underground flow and the water level is progressively falling; such fall may possibly result in compaction or cementation of the rock and thereby further slow up replenishment.

(6) Loss of capacity can be remedied at least in part in many, if not most, deep wells by reaming, shooting, acidizing, cleaning, replacement of screen, or recasing depending upon the circumstances.

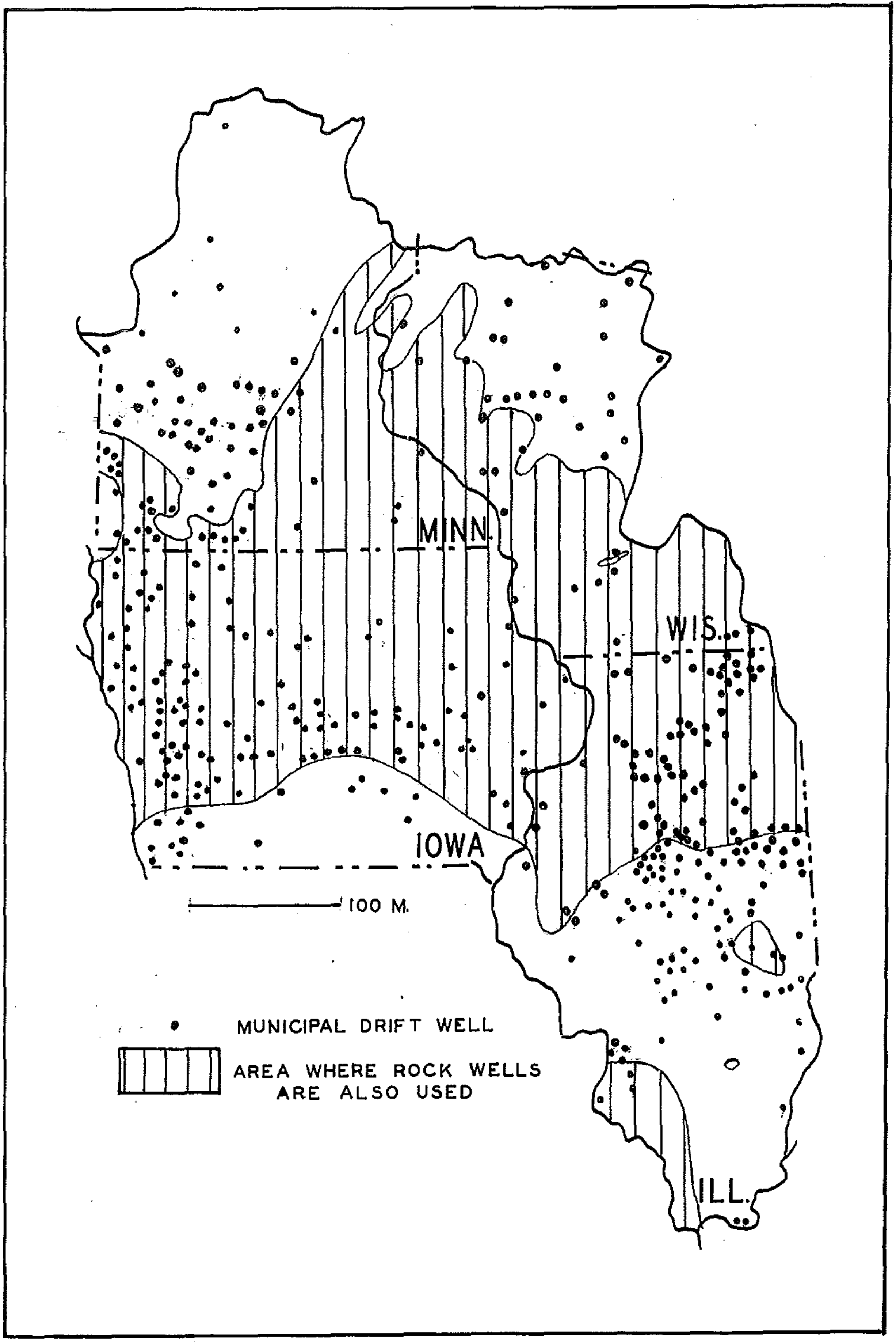
QUANTITY OF GROUND WATER AVAILABLE

General statement.- Many are the computations which have been made of the total quantity of ground water in the earth and the number of years storage of rainfall which it represents. All of the computations are based upon assumptions most of which are incapable of proof. Because they are expressed in figures they should not be regarded as more than guesses. As Artemus Ward is said to have written: "Figgers don't lie but some liers figger." Suffice it to say that in the district under consideration the depth of the "sea of underground water " varies from almost nothing where hard pre-Cambrian crystallines reach the surface to probably as great a depth in the deep basins of soft rocks as is anywhere known. The water-bearing formations of the Cambrian and lower Ordovician are among the greatest in the world. Over wide areas potable ground water extends to a depth of more than 2,000 feet below the surface. If we reckon that there is more than 1,000 feet of sandstones filled with fresh water beneath many thousands of square miles and that this sandstone probably averages over 5 percent prosity the enormous total reserves of ground water are apparent. But these reserves are by no means evenly distributed over the area and we must consider the several subdivisions.

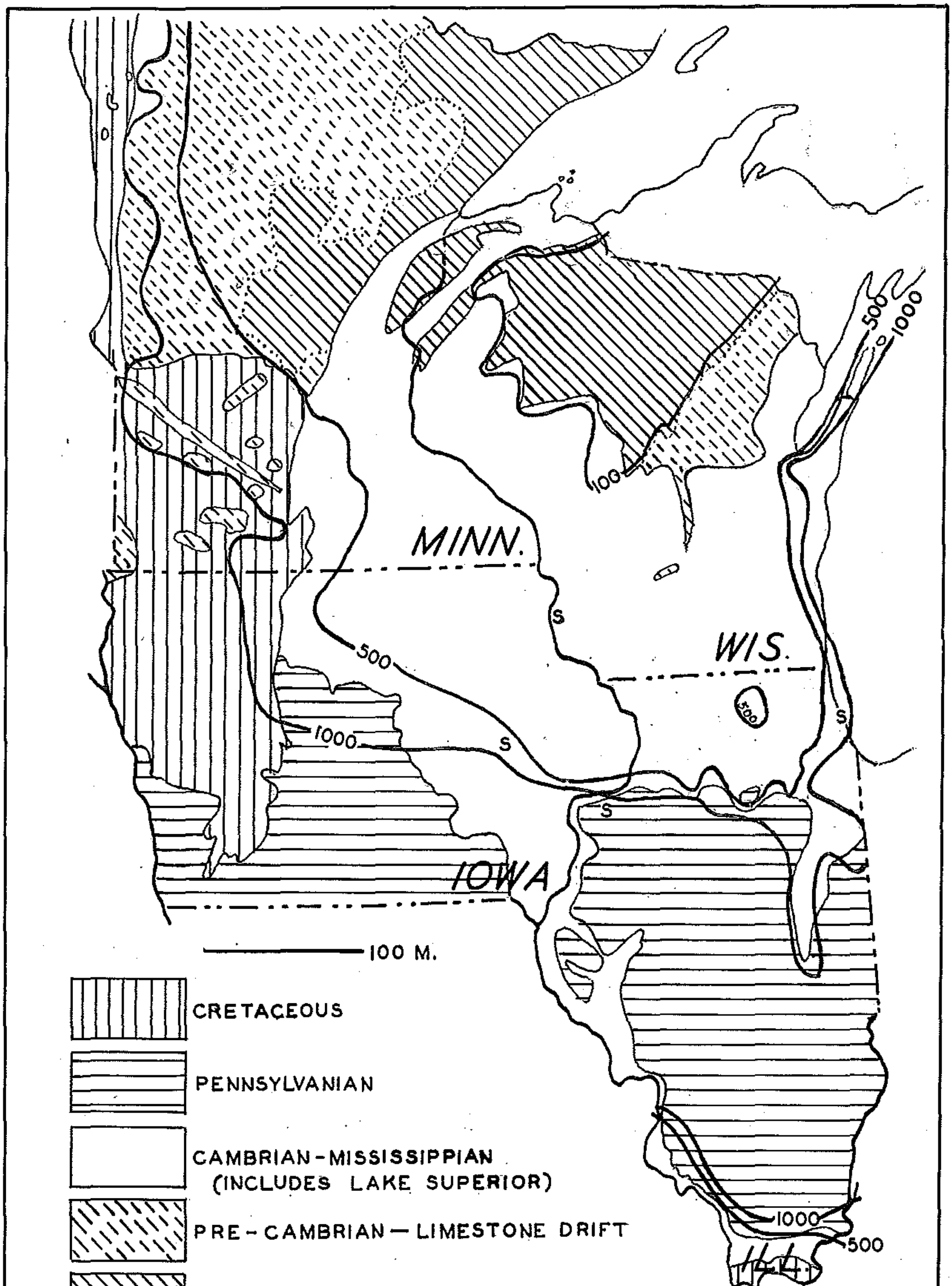
Drift production

Hard rock area. Where large deposits of sand and gravel extend below the water table wells with specific capacities of several hundred gallons per minute per foot of drawdown are common. Gravel is very abundant in this district but over considerable parts of it the bed rock extends clear to the surface. Plate VI shows the distribution of municipal drift wells so far as shown by available data.

Soft rock area. Within the area of soft bed rocks the drift is for the most part less stony than it is in hard rock districts. Much of it is so largely composed of clay that it contains too little water to supply wells of the modern type. Where there are extensive deposits of sand and gravel large capcity wells have been developed. Such deposits are more abund ant in the regions of limestone, dolomite, and sandstone than they are elsewhere. Because these distircts (see Plate VII area of rocks of Cambrian to Mississippian age) also afford good supplies in the rock (Plate VI) drift wells are not as abundant as in the regions underlain by bed rocks in which the water is of poor quality (see Plate VII areas of Cretaceous and Pennsylvanian rocks). In some areas, however, drillers have been prejudiced against such wells because they were not familiar with proper methods of development. In one locality (not in this district) the writer discovered that a driller had driven pipe through a gravel bed which later yielded 750 g.p.m. and finished a dry hole in the pre-Cambrian! The present drought has demonstrated, however, that many of the drift reservoirs are of



MUNICIPAL WELL WATER SUPPLIES



MINERALIZATION OF UNDERGROUND WATER IN RELATION TO GEOLOGY-TOTAL SOLIDS
Figures are parts per million of total solids

limited vertical and horizontal extent and are subject to exhaustion. Most of the wells in which trouble has been reported to the writer never extended many feet below the normal water table.

Rock production

Hard rock area. Where hard pre-Cambrian rocks extend above the water table the only underground water is that which is contained in the crevices. It follows that with very few exceptions the quanity of underground water in the bed rocks of this district is limited. Exceptions to this rule are very rare except where a well draws directly from an adjacent body of surface water. Some large open wells in the weathered portion of the granite yield as much as 75 g.p.m. but this is very uncommon and holes which are entirely dry are much more abundant. One well near Reeseville, Wisconsin, pentrated the pre-Cambrian for 1800 feet and did not obtain enough water to supply a hand pump. This and other deep dry holes should dispose of the idea still held by some drillers that all that is needed to obtain water in the pre-Cambrian is to drill deep enough. There are very few industrial or municipal supplies from the hard rocks. Four small towns in Minnesota are supplied from the Sioux quartzite and two in Wisconsin from granite or schist. Where slate is the bed rock small wells are possible. The well at Pipestone, Minnesota, in quartzite is reported to have had a specific capacity of 12.7 but this is exceptional and the storage underground is undoubtedly very small. Such wells are soon affected by a period of subnormal precipitation and there has been a notable recession of the water level throughout the district in recent years although the deeper wells which are not heavily pumped are still unaffected.

Soft rock area-limestone wells. Production of water from limestone and dolomite is almost entirely from crevices and opening. Solution openings are larger and more abundant in true limestone than in dolomite. As in the hard rocks crevices become progressively less and less abundant as the depth from the weathered surface increases. Wells in limestone or dolomite have very variable specific capacities with infinity as the upper limit provided the demand is not too great. Experience shows, however, that the yield of most limestone wells is small and that a point is soon reached where increased pumping fails to produce an amount of water in direct proportion to the amount of drawdown. Moreover, the storage capacity in crevices is in most places very limited and serious depletion follows upon drought. There are many municipal supplies in the district under discussion which are derived from wells in limestone or dolomite and there are still more where a portion of the production is from those rocks. On account of this fact it is impossible to map the areal distribution of limestone and dolomite supplies.

Soft rock area-sandstone wells. Sandstone has fewer crevices than limestone or dolomite because ~~these rocks~~ the latter are more brittle. Many of the sandstones of this district are cemented with the same material as makes up adjacent limestones or dolomites. The bulk of the water production in sandstone comes from the pores between the grains. It would be a mistake, however, to think that all sandstones are productive. Many are so fine grained and well cemented that little water enters a drill hole in them. In sandstone the yield of a well is directly proportional to the drawdown until the water level falls into the productive layer. An upper limit to production is forced in many wells by the pumping of sand which begins when the velocity of water entering the well is increased to a point where it disrupts and carries away the soft rock. The following table shows the maximum specific capacities of the several productive formations which may be expected where they are buried to a depth of a hundred feet or more.

St. Peter sandstone	5 g.p.m.	Dresbach sandstone	5 g.p.m.
New Richmond sandstone	2 g.p.m.	Mt. Simon sandstone	15 g.p.m.
Jordan sandstone	5 g.p.m.		

At Madison, Wisconsin the specific capacities of wells in the Dresbach, Eau Claire, and Mt. Simon varyes from 15 to 22. In the Chicago district wells drawing on the St. Peter and upper parts of the Cambrian rarely have a specific capacity of more than 5. Near the outcrop where cementing minerals have largely been removed by weathering and crevices are more common the capacity is higher. At great depths the reverse is true and some wells have found almost no water in formations elsewhere productive. Wherever the sandstone is thick and the well enters far into or passes through it, the storage reservoir drawn upon is so large that the effects of even a long series of dry years are ironed out and have little significance. There is little reason to fear any shortage of water in the major formations of water-bearing sandstone.

<u>Present production of ground waters</u>.- Any attempt to estimate the total production of ground waters within the area is fraught with much uncertainty. The records of maximum capacity and actual use for public water supplies can be obtained, but no information is available on private supplies, some of which are very large. Most reports are silent on the important subject of yield and drawdown of wells. Habermeyer estimated the pumpage in the Chicago district at 50,000,000 gallons per day and for the entire state of Illinois at 70,000,000 to 75,000,000 gallons per day. This estimate does not include the amount pumped on farms. Lees estimates the total con-

sumption of water in Iowa as over 335,000,000 gallons per day, but the portions of this which comes from wells was not given.

Summary.- In recent years there has been a decided tendency to shift from deep well supplies to shallow drift wells largely on account of the less cost of pumping from the latter. The present drought will probably counteract this and cause a change to the deeper and more reliable sources. So far these have not been seriously affected and it seems unlikely that they will be. So far as the situation goes in regions of deep ground water where the soft rocks are water-bearing, the present emergency could easily remedied by deepening of wells. The only reason that more of that has not been done is the presence of financial stringency, for it so happens that in the two last periods of depression drought and poor business conditions seem to go hand in hand. In regions where the bed rock is shale as over the Pennsylvanian or the hard rocks of the pre-Cambrian area (Plate VI) and the ground water above the rock is shallow or scanty, the problem is much more serious. Efforts should be made to find the larger and deeper bodies of ground water in such areas: lenses of sandstone containing fresh water and valleys filled with gravel.

QUALITY OF UNDERGROUND WATERS

Introduction.- The underground waters of the district under discussion vary from almost as pure as rainwater to strong brine. This variation is in respence to different geological conditions and has been summarized in the table of geological formations. The primary controls are (a) nature of the surrounding rock, and (b) amount of mixture with rain water of the original waters which date from the time of deposition of the rock. Plate VII shows the relation between total mineralization and the surface distribution of different types of deposits. Plate V-B shows some typical waters.

Comparison of waters.— Waters may be classed according to different qualities which control their usefulness. Waters which contain large numbers of bacteria are not suitable for drinking by human beings because disease producing organisms may readily be among these. The bacterial safety of waters is determined by testing for the present of an organism Bacterium (B.) coli which is abundant in sewage. Mineral substances dissolved in water also affect its use particularly for industrial purposes and for washing, although few of these seem to have much if any direct effect on the health of persons drinking the water unless the water is very highly mineralized. The mineral character of water is stated as (a) total dissolved solids, (b) hardness computed either as if all due to calcium carbonate or given as pounds of encrusting solids for 1,000 gallons, or (c) by a complete analysis of the substances in it. "Hardness" is due to the presence of carbonates and sulphates of the alkalie earth metals, calcium and magnesium. Carbonate hardness or "temporary hardness" is often determined as "alkalinity"; it is removable by boiling whereas that due to sulphates is not, "permanent hardness". Alkalinity should not be confused with the compounds of the alkalies, sodium and potassium. These metals also occur as carbonates and sulphates. They do not affect soap but cause foaming in boilers and if present in large amounts impart a soapy taste to the water. Common salt, sodium chloride, if present to the extent of more than about 300 parts per million imparts a distinct taste to the water and even smaller amounts cause the water to kill plants.

Distribution of kinds of waters.— On account of the labor of recalculation the map in Plate VII shows only total solids and not hardness of waters from the deeper wells, except that where non-water-bearing pre-

Cambrian rock is close to the surface. There is also a close relation between the amount and kind of mineralization and the nature of the formation in which the water is found, but as most deep wells draw from more than one formation it is not possible at present to map the nature of the water in individual rock formations. It is known, however, that the nature and amount of dissolved minerals does vary in different formations so much that the source of a given water can often be fixed by its composition once the data is available. Efforts are now under way in Iowa to determine these facts. In every formation there is a change from relatively soft water near the outcrop through progressively more and more mineralized water to salt water at a depth which varies from a few hundred feet to over 3500 feet from the surface. The increase in mineral content is not at the same rate, however, for above 500 parts per million of total solids it rapidly increases. There is a considerable zone in which the total solids exceed 500 p.p.m. and then a rather abrupt increase in salt content at the depths noted above.

Kinds of mineralization. Plate VB shows graphically the most important difference between different types of mineralization in the ground waters of the area under discussion. No. 1 shows water from a region of crystalline rocks where the total solids dissolved do not saturate the water. No. 2 is from the non-limestone-bearing drift of north central Minnesota and shows much more mineralization, for possibly there is limestone in the deeper parts of the drift. No. 3 demonstrates the effect of limestone pebbles and rock flour where it is present throughout the drift. No. 4, from Dane County, Wisconsin, is a fair average of the waters from wells in limestone, dolomite, and sandstone not far from or at the outcrop. It is typical of waters in the 100 to 500 p.p.m. zone (Plate VII). Such waters are saturated with carbonates (CO_3) of calcium (Ca) and magnesium (MG) but contain only a little sulphate (SO_4) and chloride (Cl). No 6, from South Chicago, Illinois, is typical of the more mineralized fresh waters which are common in deep wells. In comparison with No. 4 it must be noted that the amount of carbonate is not very different but that a large amount of sulphate has been added. This is chiefly calcium sulphate with some magnesium sulphate thus adding to the bar representing those substances. There is also an increase in the amount of chloride chiefly sodium (Na) and potassium (K) chlorides. No. 5, from southern Minnesota is an intermediate type with a moderate amount of sulphate. No. 7 is from a well where water was taken from only one formation, the Dresbach sandstone. The low mineralization is due to the purity of the sandstone. No. 8 is a soft alkalie (Na + K) carbonate water which occurs in and adjacent to the Eau Claire shaly sandstone at considerable depths. Although low in scale forming material it is not good for boiler use because it foams. Nos. 9 and 10 are averages of the soft and hard waters from the Cretaceous of southwestern Minnesota. No analysis of the brines which occur at great depths is included. Some of these exceed 61,000 p.p.m. of total solids and contain chlorides of calcium and magnesium as well as common salt (NaCl).

<u>Cause of mineralization</u>. All of the soft rocks of the district under study were deposited either in the sea or in enclosed desert basins. When first deposited they were, therefore, filled with salty waters. Locally some salt and gypsum (calcium sulphate) were deposited in layers and apparently considerable gypsum, an abundant compound in sea waters, was scattered througout the rocks. After the deposits hardened and were upraised

above the sea and bent into the form shown in Plate III rain waters entered the exposed edges of the different formations. These rain waters washed away the salty water, This process went on fastest in the more porous rocks like the Cambrian sandstones. It is not yet complete in some of the impervious rocks like parts of the Pennsylvania. Carbon dioxide (CO_2) and oxygen attacked the more soluble materials of the rocks and so the newer fresh waters came to be themselves mineralized. The fresh waters are lighter than the original brine and float on top of it. Down to the line of 1000 p.p.m. of total solids circulation of the ground water with return to the surface is farily active. Below that down to the salt water contact the fresh waters are almost stagnant. It is not possible with present information to map the contact between the fresh and salt waters and the zone of transition, although itself abrupt, is marked by many irregularities in horzontal distribution as well as it depth. These are related to porosity of the rock. In a few places, marked by the letter S, salt waters have been found within the area which averages less than 1000 p.p.m. In the Chicago district salt waters are found at depths of 1700 to 2400 feet. To guard against drilling into salt water with the result of an expensive plugging back job it is well to take samples of water from the bottom of the hole with the bailer as work prgresses. When analysis shows over 150 p.p.m. of chloride drilling should be stopped. Even then, prolonged pumping may cause this "bottom water", as it is called in the oil fields, to rise into the well. Such seems to have happened at Davenport, Iowa (Norton, 1929, pp. 48-52). Much trouble is experienced with salt water in Chicago.

<u>Source of sulphates.</u> The sulphates which are so characteristic of the deeper waters might arise in two different ways: (a) from gypsum

deposited in the rocks or dissolved in the original sea water, or (b) from the decomposition of sulphides mainly of iron. The question may be answered by comparing the amounts of calcium and magnesium. Most of the carbonate rocks of the district are dolomite rather than limestone. If the sulphate came from the same source as the carbonates through action of sulphuric acid formed by oxidation of sulphides we should expect the ratio of calcium and magnesium to be about the same in the waters as it is in the rocks. Such is not the case and calcium is almost everywhere greater in amount. This demonstrates that much if not all of the sulphate came from gypsum.

<u>Soft waters</u>. A water is soft if the amount of calcium and magnesium compounds is small. Two types of soft waters occur in this are: (a) lightly mineralized waters such as occur in the hard rock area of northern Wisconsin, and (b) mineralized waters where compounds of the alkalies (Na, K) other than chlorides predominate over calcum and magnesium compounds. Waters of the second type (Nos. 8 and 9, Plate VB) occur in (a) the Eau Claire and adjacent Mt. Simon formations north and west of Chicago, (b) parts of the Cretaceous deposits apparently a different layer than contains the hard waters, and (c)(rarely)parts of the Niagara dolomite in Wisconsin and northeastern Illinois. It is thought that these waters were originally of the calcium-magnesium type but they they were alteed by exchange of these substances (base exchange) with sodium and potassium contained in the rocks. The exact nature of the minerals responsible for this change which is the same as that in a zeolite water softener, is not known.

<u>Iron, manganese, and hydrogen sulphide</u>. Substances which although commonly present only in small amounts are extremely troublesome are iron, manganese, and hydrogen sulphide (H_2S). The first two apparently come from (a) solution in the zone of abundant organic matter and (b) oxidation

of iron sulphide. Hydrogen sylphide may originate by (a) partial oxidation of sulphides or (b) reduction of sulphates by bacteria. The relative importance of these different processes is not known. The offending substances may be removed from water by proper chemical treatment. Drift wells are particularly apt to yield iron-bearing water and many of the deeper wells of the district, particularly those which reach the base of the Cambrian, are also. Hydrogen sulphide is most abundant in waters which pass through deposits of sulphides.

Control of water quality by casing. Most deep water wells have no casing below the drive pipe except where caving formations occur. In the great majority of cases no effort was made to learn the nature of the water in each formation. In the deep well drilled for the Chicago and North Western Railway Company at West Chicago, Illinois, in 1923 the waters were carefully sampled during drilling both by bailer and pumping tests. As a result of these tests it was found possible to case the well in such a manner as to greatly lessen the amount of scale-forming minerals in the water in comparison with the former supply. A number of similar soft water wells have been completed north and west of Chicago but no sucess has been met with in any other district within this area. It is very striking that in Plate VII the 1000 p.p.m. line roughly parallels the borders of the Pennsylvanian and Cretaceous deposits, both of which are known to contain highly mineralized waters. The question at once arises if it is possible to drill through these deposits and shut off their waters in order to obtain better water from the underlying formations. Some sucess has been attained in this effort in places not far removed from the border and it is suspected that were more water well drillers as skilled in making proper shut offs as are drillers in the oil fields the boundary of moderately mineralized waters might be shifted many miles to the west and south.

Effect of drought on mineralization. No quantitative information is available on the effect of the drought on the mineralization of the upper part of the ground water. However, the qualitative observations which the writer has made seem to show that both iron and hardness have markedly increased in such waters. This is in line with observations in arid and semi-arid regions where loss of ground water to the surface causes the uppermost water to be markedly more mineralized than is the lower water.

Effect of drought on safety of waters. It is generally believed that in dry periods well waters are less safe than normally. This is explained in two ways: (a) sinking of the water level at which bacteria seem to be most abundant brings contaminated water into wells, and (b) the larger radius from which wells then drain brings sources of contamination within range of the well which ordinarily are not drawn upon.

Summary. The following facts appear from present information to be demonstrated:

(1) The degree of mineralization of the waters is related to the materials through which they pass and to the efficiency of flushing of the original waters by percolating rain water.

(2) Within the zone of active circulation of ground waters and escape to the surface mineralization in few places exceeds 1000 p.p.m.

(3) Near the surface, waters contain mainly carbonates of calcium and magnesium; with a mineralization of over 1500 p.p.m. sulphates are present in important amounts much of which was derived from gypsum.

(4) At depths of 1500 to 3500 feet salt water which is not potable

appearswith a narrow belt of transition; such are original waters on which the fresh waters are floating and also occur in formations which have been imperfectly flushed up to very shallow depths.

(5) The border of water supplies with less than 1000 p.p.m. total solids roughly coincides with the surface border of the Pennsylvanian and Cretaceous rocks which themselves contain very highly mineraliged waters.

(6) It is possible by proper construction of wells to pass through formations which contain highly mineralized waters and obtain better water below; this method can considerably extend the area in which satisfactory deep well supplies can be obtained.

(7) Some of the deeper waters of both the Cretaceous and the Cambrian appear to have been softened by natural b ase exchange and proper casing of wells allows these to be secured.

(8) Tests of water from each productive formation can generally be obtained while wells are bing drilled and are invaluable guides to proper casing.

(9) Further studies of the causes of solution of iron, manganes, and of the formation of hydrogen sulphide are needed in order to guide exploration for waters free of these substances and avoid the expense of treatment.

(10) It appears that the current drought has increased both mineralization and bacterial contamination of the surficial ground water.

MEASURES OF CONSERVATION

<u>Introduction</u>. When the neighbor's house burns it is to be expected that sparks will fall on your house. The district under discussion lies close to the vast arid and semi-arid region of the West and we must expect

that every now and then the weather of that district will spread eastward and involve us in difficulty. Weather records have been kept for too short a time and at too few localities to enable use to decide definitely whether or not this occurs at regular intervals. The last severe drought in the Upper Mississippi Valley lasted (at Madison, Wisconsin) from 1887 to 1901, a space of 15 years. Let us hope that this one will not last as long! Meantime, we may rest assured that it is not a permanent affair.

Where the shortage of precipitation has been felt. The shortage of precipitation in the last five years has made itself manifest to users of (a) surface waters from reservoirs, streams, and small lakes, and (b) the shallower underground waters. It has not effected supplies from deep wells except where these were forced beyond normal capacity by the increased demand for water. For many years engineers seem to have preferred surface water supplies to ground water supplies partly because they felt more certain of an adequate supply and partly because of the lesser mineralization of surface waters. Where ground water was used they advocated shallow wells rather than deep wells because of lower pumping cost and somewhat less mineralization. The drought has shown the danger of dependence upon either surface or shallow well supplies. It has also demonstrated that the capacity of any water supply system should be made several times that ordinarilly needed so as to be prepared against emergencies like the present one. The value of deep well supplies which are properly constructed and maintained has now been made clear to all. They are insurance against drought. When a reservoir becomes dry or a shallow body of ground water disappears there is nothing to do but to wait for rain or snow. When a well which normally entered the ground water only a few feet or was bottomed in a perched water table fails, the logical course is to deepen it provided geological conditions indicate that the depth of potable ground water is sufficient. Many wells apparently fail because of internal defects as noted above. A vast number of wells now need deepening, cleaning, and repairing. Unfortunately financial conditions have made well drillers reluctant to do work for which they might have to wait a long time to be paid. Another obstacle has been the fact that prices of iron and steel, important elements in well construction, have not kept in line with those of other commodities. It is a time-consuming and expensive job to locate a new supply, to drill a new well, or to repair an old one. When water is short many persons do not dare to shut down the pumps long enough to find the cause of the trouble. The problem of well supplies is most acute in southern Iowa and southern Illinois where deep well supplies are not possible and the drift contains few large sand and gravel beds. Besides this the drought has been more severe in just those localities. In the pre-Cambrian area of the north the depth of underground water is also small but the considerable thickness of water-bearing glacial drift has saved the situation.

Summary. At such a time as the present it behooves us to see if there are any measures which may be taken to mitigate similar troubles in the future. Some of these follow.

(1) Detailed scientific search for more adequate ground water supplies is needed in the regions of greatest shortage; undoubtedly there are undeveloped gravel beds, and sandstone layers in this region from which water might be piped for considerable distances.

(2) Experiments are needed to see if any change in agricultural methods

such as larger wood lots which are not pastured, contour plowing, fall plowing, reflooding of marshes, or construction of impounding resevoirs will increase the amount of water which enters the soil.

(3) At present vast amounts of ground water are used for cooling and absorption because they are cooler in summer than are adjacent surface waters. Other industrial uses consume much ground water. Studies are needed to see where either surface water or non-potable ground water could be substituted for potable ground water thus conserving the latter for public supplies. For instance the stock yards in Chicago consume immense amounts of well water and have seriously curtailed the water supply of many suburban towns not far away. So far the difficulty of securing a right of way for a tunnel has prevented the use of cool water taken from the deeper part of Lake Michigan. In some places there are undeveloped water supplies in the drift and in other localities salt water from wells might be used for many purposes. Some form of public supervision is needed in some parts of the district to allocate water supplies to the most profitable use.

(4) In many places the interference of wells is marked and yet there is no legal remedy or public supervision. In Wisconsin flowing wells on low ground are allowed to rob their neighbors above them. Laws compelling the restriction of flow from wells to actual needs have been enacted and enforced in other states and are undoubtedly needed in this region as well.

(5) Improperly cased wells and abandoned wells are allowing the underground mixture of waters. For instance, at Prairie du Chien, Wisconsin, salt water from deep flowing wells is contaminating the fresh waters above. Public regulation with power to compel proper casing of wells and the plugging of abandoned wells is badly needed.

(6) Many attempts have been made to use wells with a low head of water to take either surface water from enclosed depressions or sewage effluent. Most of these efforts have been failures because of clogging but every effort should be made to discourage this dangerous practice. Use of sink holes to receive sewage should also be prohibited and "dry wells" should be confined to a shallow depth where the natural purifying agencies of the soil can do their work. Abandoned wells are also a menace as they often allow surface contaminated waters to enter the deep waters. Such should be discovered and plugged.

(7) It is now more important than ever to chlorinate all water supplies even if not intended for drinking but to which persons have access. Such treatment causes no taste in ordinary ground waters and the test for free chlorine shows at once whether or not dangerous contamination has occurred.

(8) Observation wells for study of ground water levels are needed.

Work of State Planning Boards. Telegrams were sent to the State Planning Boards of Iowa, Illinois, and Minnesota a d all these replied. No reply was received to a letter to the Wisconsin State Planning Board. The Illinois board has compiled much data on public water supplies and on methods of water treatment. During the C. W. A. the State Water Survey collected a great number of well records. Studies of underground water supply conditions are being constantly carried on by the State Geological Survey and the State Water Survey. Iowa has a very ambitious program. This includes (a) a report on the source and adequacy of all municipal water supplies, (b) analyses of surface and underground waters for both mineral and bacterial content, (c) study of well cuttings and other data on underground sources of water under direction of the State Geological

Survey, and (d) a proposed study of ground water levels. Six geologists are at work studying ground water conditions and locating test wells. Studies are planned in cooperation with the U. S. Geological Survey on underground leakage in deep wells. A preliminary report is in preparation. Minnesota is making some minor studies in the Twin City area and the reflooding of marshes which were once drained is under discussion. It is also reported that work is going forward to bring up to date the 1911 report on underground waters. Wisconsin is listing public water supplies. Some marshes have been reflooded although primarily as game refuges. Studies of ground water levels are being started by the Conservation Commission. Observation wells are to be installed at the ranger stations and test wells will be sunk to determine the depth to ground water in forest areas where temporary wells may be needed to fight fires. Studies of the geology of underground waters are being carried out by the writer under the auspices of the State Geological Survey.

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APPENDIX

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