The Geological Conditions of Municipal Water Supply in the Driftless Area of Southern Indiana.

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I. Introduction.
- Description of the driftless area.
- Character of the rocks and topography.

II. The Knobstone area.
- Peculiarities of the rock formations.
- Topography and soil.
- Water-bearing qualities.
- Water-producing qualities of the alluvial valleys of the region.
- Climatological data of the driftless area.
- Relation of rainfall to runoff.
- Conditions affecting the impounding of water in the Knobstone region.
- Proper construction of dams.
- Indiana University dam.

III. The limestone area.
- Peculiarities of the rock formations.
- Topography and soil.
- Cavernous character of the rocks and development of underground drainage.
- Difficulties of impounding water.
- Character of the springs of the region.
- General inadequacy of springs without impounding the water.
- Deep and shallow wells.
- Valley alluvium.

IV. The Chester-Mansfield area.
- Peculiarities of the rock formations.
- Topography and soil.
- Intermediate character of the region.
- Conditions affecting the impounding of water.
- Wells.

V. Relation of forests to water supply in the driftless area.
   Runoff and ground water.
   Erosion.
   Silting of ponds.
VI. Summary.

I.

The problem of municipal water supply involves a large number of factors, among which the geological conditions enter with varying importance, and have received a varying degree of emphasis at the hands of water-supply engineers. Some, as for example Vermeule[1], have been inclined to assign to the geological factors an importance second only to that of the fundamental factors of rainfall and run-off. Others, as Rafter[2], assign only secondary importance to the geological conditions. This difference of opinion is very probably attributable, in some degree, at least, to the sort of regions that have fallen most under the study of the respective students of these problems. In the glaciated portion of the United States, for example, where the geological conditions are apt to be measurably uniform over large areas, and where, at all events, the country rock is apt to be so deeply buried as to have little effect on the character and movements of surface waters, it is altogether likely that the geological factors, other than topography, would have received a relatively small amount of attention. In driftless areas, on the other hand, such as the area at present under consideration, the character of the rock formations may powerfully affect the case; and as a matter of fact, in this region, the geological factors are, next to rainfall, the most important factors to be taken into consideration.

The driftless area of southern Indiana comprises all of the counties of Floyd, Harrison, Perry, Crawford, Orange, Lawrence, Spencer and Warrick, and portions of the counties of Clark, Washington, Jackson, Brown, Monroe, Greene, Martin, Dubois, Pike, Gibson, Vanderburgh and Posey. It is a region of varied, but on the whole of rather strongly accentuated topography. The eastern portion of this area, the region of

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[1] *Vermeule, C. C.*, Geological Survey of New Jersey, Report on water-supply. Vol. iii of the Final Report of the State Geologist, 1894.

[2] *Rafter, G. W.*, Hydrology of the State of New York, New York State Museum, Bull. No. 85, 1905.

the "Knobs," compromising the counties of Floyd, eastern Washington, Jackson and Brown, and lapping over into eastern Lawrence and Monroe, is a region of mature topography, with deep, steep-sided valleys, very little level upland, and broad flat valleys only on the larger streams. To the west of this lies the great limestone region (Mississippian limestones) in Harrison, western Washington and eastern Orange, central Lawrence and Monroe, and northeastern Owen counties. The topography of this region is rolling, with deeper valleys on the eastern and western edges only. It is the region of caves and sinkholes, and consequently, to a marked degree, of underground drainage[1]. It is also the region of chief interest in the present connection.

To the west of the limestone belt lies the region of the Chester (Huron) formation and the Mansfield sandstone, which for our present purposes may be treated as a unit. Topographically this region bears considerable resemblance to the region of the "Knobs." In places it is even more rugged, as in Martin and Crawford counties. One important point of difference, however, from the standpoint of the water-supply engineer, is the fact that in this region of the Chester formation, the larger streams cut through the shales and sandstones to the limestone beneath, while in the region of the "Knobs," the valley floors are always in the same material as their sides. This type of valley in the Chester region is well exemplified by Richland Creek, in Monroe and Greene counties, and by French Lick Creek in Orange County.

To the west still of the region of the Chester and Mansfield formations, is the region of the Coal Measures, which presents no points of special interest to the present discussion.

Broadly speaking, we may say that the driftless area presents, from the standpoint of the water-supply engineer, two main types of geo-

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[1] For descriptions of the geology, topography and caves of this region see: *Blatchley, W. S.*, Indiana Caves and their fauna, 21st Ann. Rept. Indiana Dept. Geol. and Nat. Res., 1897, pp. 120-212; *Hopkins, T. C.*, and *Siebenthal, C. E.*, The Bedford Oölitic limestone of Indiana, *Ibid.*, pp. 289-427; *Newsom, J. F.*, A geologic and topographic section across southern Indiana, *Ibid.*, 26th Ann. Rept., 1901, pp. 227-302; *Ashley, G. H.*, and *Kindle, E. M.*, The geology of the Lower Carboniferous area, *Ibid.*, 27th Ann. Rept., 1902, pp. 49-122; *Shannon, C. W.* and others, The Indiana Soil Survey, in the 32d to 34th Ann. Repts., *Ibid.*, 1907-10; *Cumings, E. R.*, On the weathering of the Subcarboniferous limestones of southern Indiana, Proc. Ind. Acad. Sci. for 1905, pp. 85-100; *Greene, F. C.*, Caves and cave formations of the Mitchell limestones, *Ibid.*, for 1908, pp. 175-183; *Beede, J. W.*, The cycle of subterranean drainage as illustrated in the Bloomington, Indiana, quadrangle, *Ibid.*, for 1910, pp. 81-111.

logical formation, and a type intermediate between them. One of these principal types, the Knobstone formation, consists of compact, insoluble, impervious sandstones and shales; and the other, the Mississippian limestones, consists of conspicuously fissured and jointed, highly soluble, and consequently pervious limestones. It is also apparent that these two principal types of formation present interesting differences of topography, which are of importance to the student of water-supply problems.

II.

The first of these, the Knobstone formation, consists of a considerable thickness of fine-grained sandstones, with clay cementing material; and of sandy shales, becoming more argillaceous toward the base of the formation. Both sandstones and shales are impervious to an unusual degree. The evidence of this is seen in the general absence of springs in the region of the Knobstone formation, in the impossibility of obtaining good wells, either deep or shallow in the rock, and in the small dry-weather flow of the streams in the area underlain by this rock. An indirect evidence of the minute size of the pores of the Knobstone sandstones, is the damage that the rock suffers when exposed to freezing. Experiment and microscopical examination reveal the same thing. If a sample of the rock be tested, it will be found to absorb water rather readily, but to transmit it very slowly. As a matter of fact the purely geological evidence already presented, of the imperviousness of the rock, is altogether more satisfactory than the experimental evidence mentioned, because it deals with the formation in masses commensurate with those with which the water-supply engineer has to deal.

What the Knobstone formation lacks in water-bearing qualities, it more than makes up in its perfection as a substratum for reservoirs and ponds. Its qualities in this respect will be brought out in the description of a typical water-supply plant—that belonging to Indiana University—and need not be further discussed at this point. It is sufficient to say here that wherever the conditions are such that an adequate supply of pure water can be impounded, the Knobstone formation may be depended on, with properly constructed works, to hold the water with a minimum of leakage, and with perfect security to whatever structures are placed upon it.

The soil cover in the region of the Knobstone is usually rather thin, owing to the steepness of the slopes. It is of a sandy character, more or less mixed with clay, and is not in its usual state a fertile soil. As a consequence of this last fact, it is apt to be covered with a rather open and scanty vegetation. Where under cultivation, unless great care is observed, the steeper slopes gully badly[1]. Where this soil is fairly sandy and of some thickness, good well water may be obtained for domestic supply. Owing to its usual thinness and indifferent permeability, however, it is not a good conserver of the ground-water, and consequently, in common with the underlying rock, constitutes a poor reservoir for equalizing the flow of streams.

Some of the larger valleys of the Knobstone region contain considerable thicknesses of alluvium. Examples of this type of valley are the Bean Blossom and Salt Creek in Brown and Monroe counties, and the White and Muscatatuck rivers. All of these streams enter the area from the glaciated region, and their flood plain deposits are therefore composite, consisting partly of valley-train material, and partly of silt, pebbles and sand washed from the neighboring hills. The nature of these valley deposits, so far as concerns their water-bearing qualities, has not yet been investigated in a satisfactory manner. Some evidence obtained in the Bean Blossom Valley in the vicinity of Bloomington indicates that the valley train in that valley is both deep and amply provided with pervious water-bearing strata. The evidence referred to is the log of a well 70 feet deep, drilled about a year ago in the valley near Bloomington. This well passed through 10 feet of white sand and 15 feet of gravel before reaching the depth mentioned. No attempt has been made by the owners of the well to ascertain the maximum yield.

The geological history of Bean Blossom Valley and of other similar valleys coming out of the glaciated into the driftless area is such as to indicate that these strata of sand and gravel, revealed in the Bloomington well, are extensive. It is not necessary to enter into the details of this subject here. They may be found in the writings of Mr. Leverett[2] of the U. S. Geological Survey. At least one indication of the immense quantities of water that must be carried as underflow by these valleys is the fact that the majority of the smaller streams and gulleys that emerge upon the sides of the valley do not flow out to the main stream

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[1] *Shannon, C. W.*, Indiana soil types, Indiana Dept. Geol. and Nat. Res., 32d Ann. Rept., 1908, pp. 99-105.

[2] *Leverett, Frank.* The Illinois Glacial Lobe, Monog. U. S. Geological Survey, No. XXXVIII, 1899.

at all, but deliver their water to the pervious alluvium of the valley, and build their transported sediment into alluvial fans. These fans are a prime characteristic of the larger valleys of the driftless area.

In one instance the water-producing qualities of a valley of the Knobstone region have been carefully investigated by the writer, in connection with the investigations instituted with a view to obtaining the best available water-supply for Indiana University. This is the case of the valley of Griffey Creek at a point four miles due north of Bloomington. The valley at this point is about 1,000 feet wide, and the drainage area above the point where the tests were made is about seven square miles. The valley receives its water from steep slopes, and is entirely outside of the glaciated region. It contains no glacial drift of any sort. At the point named, four holes, about equally spaced across the valley, were drilled with an eight-inch soil augur through the alluvium to bed rock. The two nearest the west side of the valley reached a coarse impure gravel at a depth of eight feet. The two toward the east side of the valley passed through eighteen feet of fine silt, and very fine dark blue sand, and finally through two feet of coarse gravel to bed rock. All of these bores reached bed rock at a depth of about twenty feet.

At the second hole from the west side of the valley, a measurement of the rate of flow of the ground-water was made in the following manner: Four drive points were sunk into the gravel beds, so placed that one well was up stream and three down stream. The three downstream wells were two feet from each other and each four feet from the up-stream well. The middle down-stream well and the up-stream well were as nearly as possible in the main axis of the valley. The up-stream well was then dosed with fluorescein, and the interval that elapsed before the reagent could be detected in the down-stream wells was noted. At the end of six hours the fluorescein was first detected in the middle downstream well. It did not appear in the other two down-stream wells. It is believed that the fluorescein would not have diffused at a rate that would introduce any appreciable error into this computation, and consequently the rate of flow of the ground-water under this valley may be taken as about two-thirds foot per hour, or sixteen feet per day. Near this same spot a large test well, five feet in diameter, was sunk to bed rock. This well passed through eight feet of fine silt and twelve feet of fairly clean gravel. Careful tests of this well made by pumping it out and noting the rate of filling, indicate a capacity of 12,000 gallons per day, under a head of fifteen feet, the water-table being depressed five feet when the test was made. This is probably about the usual dry weather depression. Allowing 50 per cent. interference of wells, this valley should produce 50,000 gallons of water per day during the driest year. Such a supply would be sufficient for a town of 1,000 population, and would be of first-class quality.

There are many valleys of this type in the Knobstone region, that would be good water producers for small towns, or for manufacturing plants. The water would be of excellent character and exceptional purity. The larger valleys, such as Bean Blossom, should furnish sufficient well-water for cities of 10,000 inhabitants or less, or for extensive industrial plants.

The conditions affecting the impounding of water in the Knobstone region can not be adequately discussed without introducing certain climatological data. Since these data will also serve for the limestone region, they may properly be discussed in full at this point.

The following climatological data are obtained principally from the publications of the U. S. Weather Bureau. Between the coldest and warmest portions of this section of the State there is a difference of about 5 degrees in the mean annual temperature. The warmest localities are in the Wabash and Ohio valleys, the temperature increasing quite regularly from the upper to the lower portion of each valley. The mean annual temperature varies from about 52 degrees at the north end of the area, to nearly 57 degrees at Evansville.

The length of the growing season is somewhat greater in the southern than in the northern portion of the area under consideration. It is from two to three weeks longer at the Ohio River than in the northern part of Indiana.

The mean annual precipitation varies from about 40 inches to 55.21 inches (at Marengo). The maximum precipitation for any one year within the area was 97.38 inches at Marengo, in 1890. The maximum for any one month is 18.00 inches, also at Marengo, in August, 1888. The minimum for one month is a trace in October, 1908, at Mt. Vernon. Precipitations of 10 inches or more in one month are not uncommon, having been recorded an aggregate of 35 times at the seven stations reporting within the area. Ten of these were in the month of March, four each in January, July and August; three in September; and two each in February, June and November. Over ten inches have not been reported in any of the remaining months. . Six inches or more have been reported an aggregate of 233 times at these seven stations. Of these 18 were in January, 28 in February, 44 in March, 19 in April, 18 in May, 25 in June, 14 in July, 17 in August, 8 in September, 8 in October, 26 in November and 9 in December. Less than 1 inch has been reported an aggregate of 120 times at the seven stations. Of these, 6 were in January, 14 in February, 4 in March, 4 in April, 3 in May, 1 in June, 11 in July, 10 in August, 25 in September, 25 in October, 12 in November and 5 in December. These statistics by stations are as follows: At Bloomington there have been 10 inches or more of rain in one month, twice. There have been 6 or more inches 19 times; and less than 1 inch 11 times (indices, 1-78, 1-8 and 1-14)[1]. At Paoli, there have been 10 or more inches 2 times; 6 or more inches 16 times; and less than 1 inch 12 times (indices, 1-66, 1-8 and 1-11). At Jeffersonville there have been 10 or more inches 4 times; 6 or more, 34 times; and less than 1 inch 22 times (indices, 1-78, 1-9 and 1-14). At Marengo there have been 10 or more inches 18 times; 6 or more, 77 times; and less than 1 inch, 17 times (indices, 1-17, 1-4 and 1-18)[2]. At Evansville, there have been 10 or more inches 6 times; 6 or more inches, 51 times; and 1 inch or less 32 times (indices, 1-64, 1-7 and 1-12). At Rome there have been 10 inches or more, once; 6 inches or more, 8 times; and 1 inch or less, 5 times (indices, 1-68, 1-8 and 1-13). At Mt. Vernon, there have been 10 inches or more, 4 times; 6 inches or more, 36 times; and 1 inch or less, 21 times (indices, 1-66, 1-7 and 1-12). The mean annual precipitation for these towns is as follows: Bloomington, 43.43; Paoli, 43.47; Jeffersonville, 42.51; Marengo, 55.21; Evansville, 44.11; Rome, 44.62; Mt. Vernon, 42.65. The maximum annual precipitation for these stations is as follows: Bloomington, 52.15 (in 1898); Paoli, 55.86 (in 1907); Jeffersonville, 54.16 (in 1898); Marengo, 97.38 (in 1890); Evansville, 70.61 (in 1882); Rome, 57.12 (in 1905); Mt. Vernon, 57.46 (in 1890). The

[1] In order to compare the data of the several stations, it is necessary, since the length of record varies notably, to divide the number of times a given precipitation is reported at a given station by the total number of monthly reports for that station. Thus for Bloomington, where the length of record is 13 years, the divisor is 156. Since in each the numerator is made 1, these indices are only approximate.

[2] The unusual character of the record at Marengo arouses suspicion that some mistakes have been made in measuring the precipitation at that station.

minimum annual precipitation for these stations is as follows: Bloomington, 33.14 (in 1901); Paoli, 29.12 (in 1901); Jeffersonville, 30.18 (in 1904); Marengo, 32.37 (in 1901); Evansville, 28.65 (in 1887); Rome, 35.86 (in 1904); Mt. Vernon, 34.10 (in 1902).[1] At Indianapolis, which has a rainfall record going back without interruption to 1871, a period of forty years, the minimum recorded precipitation for any one year is 30.33 inches, in 1901.

An analysis of these data by seasons is interesting, and for our purposes more valuable than any other. Water-supply engineers are agreed on dividing the year into three periods, as follows: (a) The storage period, which in this latitude is ordinarily made to include the months from December to May, inclusive; (b) the growing period, from June to August, inclusive; and (c) the replenishing period, from September to November, inclusive. It is a well-known fact that in many years, and especially in dry years, the run-off is practically confined to the months from December to May, inclusive. It is important to ascertain, therefore, what is the minimum expectation of rain in these months. From the stations reporting there have been the following low precipitations during the storage period: Bloomington, 14.35 (Dec., 1895, to May, 1896) 16.58 (Dec. 1900, to May, 1901); Paoli, 13.03 (Dec. 1900 to May, 1901); Jeffersonville, 15.80 (Dec., 1888, to May, 1889), 13.02 (Dec., 1900, to May, 1901); Marengo, 14.58 (Dec., 1900, to May, 1901); Evansville, 11.83 (Dec., 1900, to May, 1901); Mt. Vernon, 12.70 (Dec., 1900, to May, 1901). The year 1901 will be remembered as one of the most disastrously dry seasons on record. It is clear, from the above data, that as low as 12 inches of rain may be expected within the area, during the storage period. A deficiency in this period is rarely made up by an excess of rainfall in the other periods of the year. In fact, a very considerable excess would be necessary to overbalance the effects of a deficiency in the winter and spring months. In other words, a relatively wet summer, following a dry winter and spring does not necessarily mean an ample supply of water for municipal use. During the summer months not only is all of the rainfall ordinarily consumed in the growth of plants and in other sources of evaporation, but in addition the groundwater is more or less extensively drawn upon, leaving a deficiency of ground-water at the end of the growing season, that must be made good

[1]1901, for which one month's report is lacking, was undoubtedly drier by several inches than 1902.

by the rains of the fall season (the replenishing period). If, now, there is a deficiency of rain in the replenishing season also, a greater or less proportion of the rainfall of the winter and spring months must go to fill up the ground, and the run-off of this period will be correspondingly decreased. The most unfavorable condition, therefore, is a dry fall, followed by a dry winter and spring. If, for example, such a fall as that of 1908, with as low as 2.2 inches of rain at several of the stations, for the three months, September, October and November, should be combined with such a winter and spring as that of 1900-1901 (a not impossible contingency), the probable catch of water, on the basis of 50 per cent. of the rainfall of the storage period, would be only 5 inches for the entire year[1].

The available catch of water in a dry season, that is, one of 30 inches of rainfall, will be a considerably smaller proportion of the rainfall than the catch of a wet season. In the latter case the run-off may be from 50 to 60 per cent. of the rainfall, while in a dry season it is likely to fall as low, in the region under consideration, as 25 per cent., or even lower.[2] From these data it appears that there will be years

[1] It is not deemed necessary to enter here into the technical discussion of the relation of rainfall to run-off. A very full discussion of these points may be found in the works of Vermeule and Rafter, cited above. Ordinarily, in this latitude the run-off of the winter and spring months may vary from 50 to 75 per cent. of the rainfall. For the remaining months of the year it will vary from 0.0 to 20 per cent. of the rainfall. Unfortunately there are no satisfactory run-off data for the region. The gagings at Shoals from 1903 to 1906, inclusive, are the only ones of a stream lying largely within the region under consideration. These indicate a mean annual run-off of 12.53 inches, which is about 30 per cent. of the rainfall of the region for the same interval. (The mean annual rainfall for the nearest station, Paoli, for this interval was 42.75 inches.) This interval includes two years of less than 40 inches rainfall, namely, 1903, with 35.18 inches, and 1904, with 39.09 inches. On the Muskingum River in Ohio, a stream lying in a region of similar topography and climatic conditions to the catchment of the east fork of White River, and like the latter, mostly in the driftless area, the run-off has been known to fall as low as 25 per cent. of the rainfall.

[2] The run-off formulæ of Vermeule are of interest in this connection. While designed to cover the conditions in New Jersey and southeastern New York, they are based on certain general considerations, such for example as mean annual temperature, etc., which are applicable to other regions as well. Vermeule's general formula is: $E=(11+0.29\,R)\,M$, where E stands for annual evaporation, R for rainfall, and M is a factor depending on mean annual temperature. The values of M are as follows for the mean annual temperatures noted in the present region: 52°, 1.14; 53°, 1.18; 54°, 1.22; 55°, 1.26; 56°, 1.30; and 57°, 1.34. Thus for a mean annual temperature of 52° the evaporation, with a rainfall of 30 inches, should be 22.46 inches, and this subtracted from the total rainfall would leave a run-off for the year of 7.54 inches. For the higher temperatures the run-off would be correspondingly less, and might, according to the formula, fall as low as 2 inches. It is not probable, however, that it ever does fall as low as the latter figure.

when we can not safely count on more than about 7.5 inches of run-off, at the northern end of the area, and possibly not more than two or three inches at the southern end. If several dry years occur in succession, as, for example, 1899, 1900 and 1901 at Bloomington, the problem of water-supply becomes all the more difficult.

We are now prepared to return to the conditions affecting the impounding of water in the region under discussion. That the flow of any except the largest streams of the region, such as the White, Blue and Ohio rivers, will be insufficient for municipal water-supply, without provision for impounding the run-off of the wet season, is a certain inference from the data presented above[1]. It has also been shown that there are no springs in the Knobstone area that are of use for other than domestic purposes; and in dry seasons it may be said that there is scarcely a spring of living water in the entire region. It will be necessary, therefore, for all towns, not located on one or other of the two or three largest streams of the area, to build reservoirs and impound water for municipal supply, except in those instances, already discussed, where the underflow of such valleys as the Bean Blossom, Salt Creek, etc., is available.

It has already been pointed out that for the purposes of impounding water the Knobstone formation is almost ideal. This is especially true of the upper portion of the formation, known as the Riverside sandstone. The latter, where it has not been exposed to the weather, and especially to frost action, is very firm, close-grained, impermeable, insoluble and strong. Its toughness and resiliency are remarkable. When the fresh rock is struck with the pick it is almost impossible to force off a clean spall, especially when the rock is wet. The rubber-like toughness of the rock causes blow after blow to spend itself with little effect. The writer has also noticed this same peculiarity of the rock in blasting. Instead of shattering the rock extensively, the whole charge will often enough spit out of the drill hole with little effect, or raise only a few fragments of rock in the immediate vicinity of the charge. This difficulty in blasting was experienced in the excavation of the cuts on the Illinois

[1] During the dry season of 1908, the writer observed the condition of the larger streams in the vicinity of Bloomington, drawing their water supply largely from the Knobstone region. In the Bean Blossom, the water stood in the deeper pools only. One mile from the mouth of this stream, with a drainage area of nearly 200 square miles, all of the riffles were dry. That is, all surface flow of the stream had completely ceased. The condition of Salt Creek was similar.

Central Railway, and again in the excavation for the foundation of the Indiana University dam. When, however, the rock is exposed to the action of the sun in summer, and of frost in winter, the differential expansion and contraction in the one case, and the wedging effect of the freezing of interstitial water in the other, rapidly reduce the rock to a mass of fragments, which in turn slack down to a sandy soil. For this reason the sandstone is of no account as a building stone. The peculiarities of the rock, just enumerated, are due in large measure to the fineness of the grain, and to the fact that the cementing material is clay, which, when moist, gives the rock its unique toughness and impermeability.

Structurally also this sandstone is extremely favorable as a substratum for dams. It is singularly free from open joints and bedding planes. In the case of the University dam, which is 116½ feet long at the base and 34 feet high above the rock, there is not a single joint or bedding seam in the rock except near the top. The bottom and ends of the dam are in perfectly sound and unfissured rock. The thickness of weathered rock that it is necessary to remove in order to reach structurally sound material is usually slight. In the case of the University dam again, the maximum depth of excavation into rock was about five feet. On the crests of narrow ridges the rock will be found to be weathered to a greater depth than the above figure. But under the alluvium of valleys, and on the sides of steep hills, the depth of weathered and fractured rock should seldom be great[1].

The Riverside sandstone constitutes approximately the upper 100 feet of the Knobstone formation. Below this are alternating shales and sandstones, with the shale predominating. This shale is sandy or argillaceous, and toward the lower part of the formation, as may be seen in the quarries of the Lehigh Cement Company, at Brownstown, it becomes dark colored and somewhat carbonaceous. When unweathered the shale is firm and tough, and shows, on account of its sandy character, very little tendency to slip under heavy loading. In the excavation of the cuts on the Illinois Central, most of the shale required heavy blasting, and like the sandstone, described above, was tough and hard

[1] The reason for this is clear enough, when it is remembered that the only agents of weathering that materially affect this rock are mechanical, such as insolation, frost action, and the wedging action of tree roots; and that unlike the limestone, presently to be discussed, it is not at all affected by solution—an agent that acts to much greater depths.

to shoot. Like the sandstones, also, it will not endure frost action and insolation. Structurally and texturally it is very impermeable, and ideally free from objectionable joints and crevices. Sound rock will usually be found fairly near the surface, especially on steep slopes.

This shale formation is known to geologists as the New Providence shale. It is 400 to 500 feet thick. Where, in the eastern portion of the Knobstone area the larger streams cut through the New Providence shale, they enter the upper portion of the New Albany black shale, which is, like the former, a very impervious formation. It is evident, therefore, that any part of the Knobstone region will afford satisfactory foundations for dams of all sorts.

The proper type of dam for the Knobstone region will depend, of course, on the conditions at the particular site. In the majority of cases comparatively narrow, deep, steep-sided valleys will have to be dealt with; and this will be so in practically every instance where only a few square miles of catchment are needed.[1] For this type of valley where the breadth of the valley floor is not more than 300 feet, the most satisfactory, as well as the cheapest type of dam, is the concrete dam, arched up-stream to a radius of 200 feet or more. Such a dam, depending to a large degree on its curvature for its stability under water pressure, may be built with less material than any other type of safe, permanent dam. The construction should be such that the water face of the dam is perfectly tight. The balance of the dam may, however, be built of rubble concrete (uncoursed stone) i. e., large stone imbedded in a mortar of concrete. Some reinforcing steel to assist the structure in taking up the strains due to setting of the concrete and to thermal readjustments, will tend to prevent cracking. After the pressure of the water comes against the dam, there should be no tendency of an arch dam to crack. The ends and base of the dam should be mortised into the solid, unweathered rock, and every precaution should be observed to make these contacts perfectly water-tight.

[1]From the rainfall and run-off data given above, it will be seen that it is not safe in the present region to allow more than 25 per cent. of the rainfall of a dry season as available for impounding. This will approximate 300,000 gallons per day from each square mile of catchment with reservoir capacity sufficient to hold the entire run-off of the year. With reservoir capacity sufficient to hold the run-off of the three driest years—it is not economical to increase capacity beyond this point—the yield can be increased by about 50 per cent. A very full discussion of this subject will be found in the article on Water Supply in the 11th edition of the Encyclopædia Britannica, by Mr. G. F. Deacon. This article is a mine of information on most phases of water supply.

Earth dams will not ordinarily be feasible in the Knobstone region, owing to the general lack of clay of good puddling qualities for the core or the dam. In the edge of the limestone region such clay may be available, but would in most cases have to be moved down very steep slopes at considerable expense. Except on large contracts, where the construction of a cable-way would be worth while, the use of clay for short dams would probably be more expensive than concrete[1]. In some instances it might be advisable to use earth embankments with a reinforced concrete core, mortised well into the rock, and extending to the top of the structure. With this type of construction any sort of material, having the requisite stability, could be used for the embankments, since the waterproof qualities of the dam would depend entirely on the core. Great care is necessary in this type of dam to prevent settling of the embankments in such a way as to warp or crack the core. It is best that no water should be allowed to come against the dam until thorough settling has taken place. For long dams in the Knobstone region some such construction as that just described is almost a necessity.[2] It may be said finally that timber dams are only makeshifts, and should not be tolerated by any community.

As an example of a successful concrete arch dam in the Knobstone region, a brief description may be given at this point of the dam recently built by Indiana University. The cross-section of this dam is shown in the accompanying figure (Fig. 1), and photographs of the dam and pond in Figs. 2, 3 and 4. The length of the dam on the rock substratum is 116½ feet, and on the crest 200 feet. The thickness at the base is 28½ feet, and the total height subject to water pressure is 34 feet. The maximum height above the valley alluvium is 28 feet. The dam is stepped up in ledges on both the up-stream and down-stream faces, and the cross-section is such that ample stability is provided, even without any arching. The arching (to a radius of 340 feet) gives very greatly increased stability under water pressure, and vastly decreases the liability

[1] As a matter of fact, nearly all of the bids on earth dams for the University were higher than on the type of concrete dam constructed, and to be described later.

[2] A type of dam, consisting of a thin plate of reinforced concrete, supported by buttresses of concrete is described in Buel and Hill's treatise on reinforced concrete, and has actually been constructed, in a few cases. This type of dam uses a minimum of structural material, but demands a considerable outlay for forms. It would probably cost about the same as a good rubble concrete dam.

to cracking. The dam is mortised into the rock on both bottom and ends, and is also anchored to the rock by 1-inch steel bars, grouted into the rock and extending well up into the dam. Reinforcing bars of ⅝-inch section lap past these and extend to the top of the structure, being spaced four feet apart. The center of the crest and of all ledges is one foot lower than the ends, so that the water spills over the middle section of the dam. The pump installation is a triplex Deming pump, driven by a 25 H. P. Otto gasoline engine; and it works against a 220 to 240 foot static head. The water is pumped one mile to a reinforced concrete

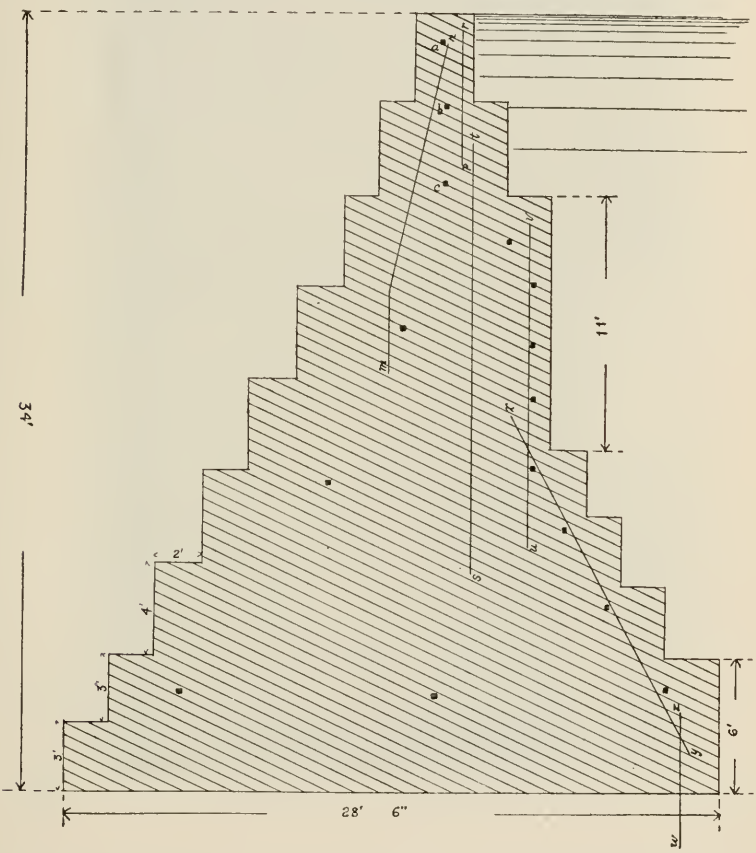

Fig. 1. Indiana University dam. Cross-section, showing dimensions, and distribution of reinforcing steel (a, b, c, etc., m-n, s-t, etc.). After a drawing by A. L. Foley.

Fig. 2. Indiana University dam, seen from the valley below the dam. Each ledge is 4 feet high. Three ledges are concealed beneath the ground.

Fig. 3. Indiana University water-works dam from above north end, showing arching up-stream.

Fig. 4. Indiana University water-supply pond, looking from the dam toward the head of the pond.

tank of 120,000 gallons capacity, and 100 feet above the University campus. The main pipe lines are of 8-inch asphalted cast iron with leaded joints, and for the heavy pressure near the pump-house are of double strength. For the present consumption of 30,000 gallons per day, a few hours' service every three or four days is all that is required of this pump.

The pond formed by this dam has a water surface of four acres, and is deep and narrow. Its estimated capacity is 20,000,000 gallons. The area of the catchment is approximately 200 acres, most of which is characterized by steep, sparsely wooded slopes.

The dam was completed in July, 1911, and the pond began to fill in September. There was very little run-off, however, till the 15th of September, when a three-inch rain raised the pond from a nearly empty condition to within eight feet of the top of the dam. During the remainder of September the pond completely filled, and by the first of October was spilling over the crest. The total rainfall of this period was ten inches, from the first five inches of which there was no immediate run-off of any consequence. In other words, five inches went to replenish the groundwater, after the severe drouth of the summer. No leakage has developed in any part of the structure of the dam, nor in any part of the contact between the dam and the bottom and sides of the valley.

III.

The geological conditions of water supply in the limestone region are radically different from those just described for the Knobstone area.

First of all the slopes are much less steep, and the soil is less permeable than in the Knobstone region. The soil is also of greater thickness and more fertile. Originally the region was heavily forested, and a few examples may still be seen of virgin forest, as for example, on the University farm at Mitchell.

The central portion of the region, away from the deep valleys to the east and west, is nearly level, and is the area of the Mitchell limestone, preëminent as a cave-bearing formation. In this central portion of the limestone region, nearly all of the drainage is underground, and springs and sinkholes abound[1]. In many instances the entire headwater portions

[1] It is the sinkhole region of Newsom, the Mitchell plane of Beede. See *Newsom, J. F.*, A Geological Section Across Southern Indiana from Hanover to Vincennes, Proc. Ind. Acad. Sci. for 1897, pp. 250-253; *Beede, J. W.*, The Cycle of Subterranean Drainage as illustrated in the Bloomington, Indiana, Quadrangle, Proc. Ind. Acad. Sci. for 1910, pp. 81-111.

of streams have been taken underground and diverted from their ancient channels to new and alien outlets in great springs on the eastern and western borders of the area[1].

Remarkable examples of this are to be seen in the underground capture of the headwaters of Indian Creek in Monroe County, by Salt and Richland creeks. In the case of the famous Lost River, in Orange County, some twelve miles of the surface channel have been abandoned in favor of a subterranean course.

The depth to which these underground channels penetrate the rock is limited only by the thickness of the limestone formation and its elevation above the main lines of drainage[2]. Near the Ohio River, where the main drainage is deeply intrenched into the Mitchell plain, the rock is cavernous to a depth of 300 feet[3]. In the northern portion of the area, where the main streams have not cut so deep, and where also the limestone formations are thinner, the underground openings in the rock do not go so deep, but even in this part of the area the limestone may be cavernous to depth of more than 100 feet[4].

Nor is the cavernous character of the region confined to the higher portions, well above drainage. In all but the deeper valleys, the valley-floor itself may be riddled with solution holes and underground channels. This is exemplified in the valley of French Lick Creek. The extremely free underground communication of the waters underneath this valley has been repeatedly proven by the interference of wells in the valley with the flow of the mineral springs. The testimony taken in the case of the French Lick Springs Co. vs. Howard et al. showed this so conclusively that it may not be out of place to review it at this point.

[1]Beede, *loc. cit.*

[2]Cumings, On the Weathering of the Subcarboniferous Limestones of Southern Indiana, Proc. Ind. Acad. Sci. for 1905, pp. 85-100.

[3]Greene, Caves and Cave Formations of the Mitchell Limestone, Proc. Ind. Acad. Sci. for 1908, p. 106.

[4]Most people do not realize the depth to which limestone formations may be affected by solution. In the remarkable treatise by Martel on the cave regions of Europe (Les Abimes), there are described many well-like solution holes that go almost straight down into the rock to depths of 600 feet or more. Into many of these Martel actually descended by means of rope ladders, and explored the caves at the bottom. The famous region of the Karst, on the eastern side of the Adriatic, has been literally honeycombed with caves and sinkholes to great depths. A more extraordinary region could scarcely be imagined. The Recca, in Austria, flows in a subterranean channel, which is in places more than 1,000 feet beneath the surface.

At one time and another a number of wells have been sunk in this valley at West Baden and French Lick. These wells are the Ritter well on the bank of Lost River north of West Baden (388 feet deep); the Howard well on the east side of the valley, opposite French Lick (529 feet deep); the Caves and Wells well (510 feet deep); the two wells of the Colonial Hotel Company (each 93 feet deep); and a well near the French Lick station, known as Cerberus (465 feet deep). The most noted of these, and the most important in the present connection, is the Ritter well. This well had at first a strong artesian flow, that very soon affected all the springs of the valley. Those at French Lick, the famous Pluto, etc., were the first to be affected, because their outlets are highest above that of the well. These springs are a mile and a half away from the Ritter well. Later even the springs at West Baden ceased to flow. The same result, so far as the French Lick springs were concerned, was experienced from the wells near French Lick station (later purchased and plugged by the French Lick Springs Company), and especially from the wells of Howard and Gagnon. The pumping of these latter wells interfered so seriously with the flow of Pluto spring that the Springs Company was driven to resort to the courts for relief, and succeeded in obtaining an injunction against the pumping and wasting of the water. The injunction was granted by the court sitting at Paoli and at Salem, and was afterwards confirmed and made permanent by the Supreme Court of Indiana.

It was brought out in the hearing on this case that the pumping of the wells of Howard and of Gagnon immediately affected the flow of the Pluto spring at French Lick, three-quarters of a mile away, and that as soon as the pumping ceased, the spring resumed its flow. This effect was noticed repeatedly[1].

Another evidence of the same thing is the frequency of sinkholes in the valley floors themselves. This is illustrated in many of the valleys to the west of Bloomington, as on the headwaters of Richland Creek, Blair Hollow, etc. In the excavation for the foundations of the bottling works at the French Lick Hotel, cavernous rock was met with under the

[1] The distances of these various wells and springs from Pluto are as follows: Pluto to the wells near French Lick depot, 1,500 feet; Pluto to the Gagnon (Colonial Springs) wells, 4,000 feet; Pluto to Howard well, 4,000 feet; Pluto to Ritter well, 8,000 feet; Pluto spring to Bowles spring, 950 feet; Pluto spring to Pagoda spring at West Baden, 5,000 feet; West Baden Hotel to Ritter well, 3,000 feet.

Fig. 5. Spillway of the upper pond of Bloomington water-works, showing joints in the rock.

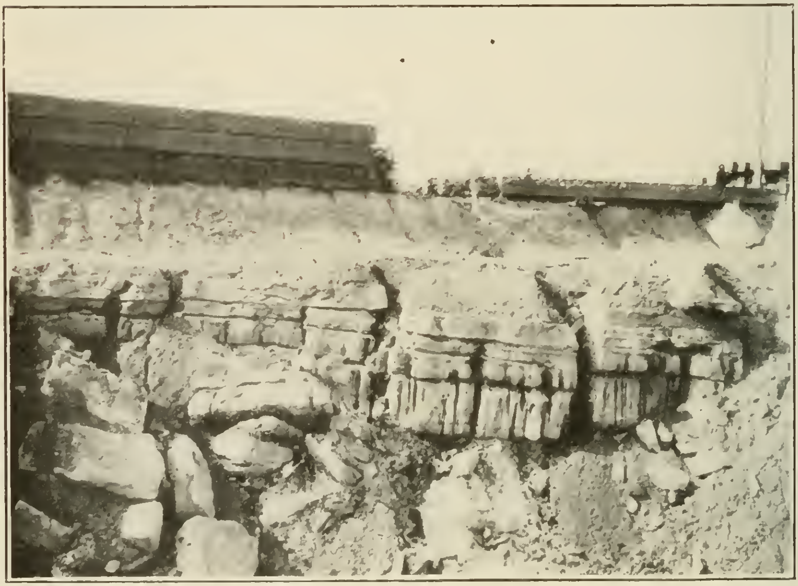

Fig. 6. Joints enlarged by solution. Cut on Illinois Central R. R., Bloomington.

valley. In the excavations for the foundation of the second dam of the Bloomington water-works, a joint, widely opened by solution, was traced down seventeen feet into the rock, without closing up. Some of these weathered joints are illustrated in the accompanying photographs (Figs. 6 and 7), and other illustrations may be found in the papers of the writer and Dr. Beede, cited above.

Fig. 7. A quarry ace in the Hunter valley region, Bloomington, showing joints widely opened by solution.

The valley sides in the limestone area are apt to be so leaky as to render them totally unfit to act as retainers of impounded water. This has been very thoroughly demonstrated in the case of the Bloomington water-works plant. The original dam at this plant has long been decrepit, and the extensive leakage is due to a variety of causes, among which the chief is probably faulty construction. A considerable quantity of water, however, finds its way into the joints and bedding planes of the rock, under the spillway (Fig. 5), and is recovered by the second pond, which is immediately below the first. In the case of the second pond, built in

1905, the dam was very carefully constructed of good clean clay, with a concrete core carried down into the rock far enough to prevent any likelihood of leakage through the substratum. As soon as this pond filled, nevertheless, severe leaks developed under the spillway, through the crevices of the rock, as in the case of the old dam. It is thought that some of the water appearing at this leak actually comes from the upper (first) pond, making the entire journey through the cavernous rock of the valley-side. An attempt was next made to repair this leak by tunneling into the valley side at the spillway. This excavation developed the fact that there is a mud-filled seam, extending back into the hill between two layers of limestone. This seam was followed back into the hill about 40 feet, and as it showed no sign of closing up, the portion excavated was filled with concrete, and the attempt at repair was abandoned. It is altogether likely that the entire hill is cavernous to an unusual degree, and that the only way to render the valley side tight would be to expose the rock along this entire side of the pond, and close all of the joints and seams with concrete. At the present time the entire water supply of Bloomington is pumped from the leak under the spillway of the lower pond, and an equal amount is pumped back into the ponds. That is, the leakage at present amounts to over a million gallons a day. Both of these ponds are located in the Mitchell limestone, the foundation of the dam of the lower pond resting on the top of the Oölitic limestone.

Enough evidence has now been cited to prove beyond any question that the general geological conditions in the limestone region are distinctly unfavorable to the impounding of water. One corollary to be drawn from this fact is that all towns within a reasonable distance (a few miles) of the Knobstone area, should utilize the latter for their water-supply systems. Where it is necessary to obtain water, if at all, from the limestone area, the portions underlain by the Oölitic limestone or the Harrodsburg limestone should be utilized in preference to the area underlain by the Mitchell limestone, and the Oölitic is to be preferred to the Harrodsburg. If it becomes necessary to utilize the Mitchell area, the following facts should be noted: First, it will be noticed by any one familiar with the Mitchell limestone that there is a layer or bed of rather impervious rock about 50 feet above the base of the formation. This layer serves as the floor of many of the caves of the region, and is the level at which many of the large springs emerge. Examples of this are the Leonard and Shiriey springs and the Stone spring (Bloomington water-works) near Bloomington. In some cases this layer might be made to serve as the substratum of a pond. Great care would then be necessary to make the sides of the pond secure, since they would be in an extremely cavernous part of the formation. Second, for ponds to be fed by springs of the type just mentioned, the top of the Oölitic limestone can be utilized for the bottom of the pond, and here again the sides of the pond must be made secure. The second pond of the Bloomington water-works is built on this layer, and all of the leakage is through the valley sides, and not through the floor of the pond. Where the valley sides are thickly covered with residual clay, and this is carefully puddled, ponds at this level should be fairly tight. Third, in a few cases the flow of the larger springs of the region, or of several springs combined, will be sufficient for small towns, without impounding. In such cases the flow of the springs should be very carefully gaged, through a period of years, before any money is spent on works to utilize the water.

In this connection it is proper to speak of the special characteristics of the springs of the limestone region, especially since they are usually very much overrated, and their nature and cause misunderstood. All of the large springs of the limestone region are the outlets of subterranean solution channels in the rock, and very often serve also as the mouths of well-defined caves. These caves and channels are in turn, as already shown, intimately connected with the sinkholes of the region. The sinkholes are the main gathering grounds of the waters that emerge at the springs. Or, to be more precise, they are the avenues through which the water is taken under ground. The sinks, like the caves themselves, are largely the work of solution. (See Fig. 8.) Where the sinks are open at the bottom, as is usually the case, storm water passes very readily and very quickly into the subterranean channels, and as quickly emerges at the springs. At such times the spring water is muddy, showing that it is merely surface water that has made a journey of greater or less length through an underground conduit. It is indeed possible in some cases to drop a handkerchief into a sinkhole, and to presently see it emerge at a distant spring. Sometimes the journey from the sink to the spring is very short, a few rods; at other times it may be many miles. In any case the storm water comes to the spring unfiltered.

Fig. 8. An open, funnel-shaped sink-hole, due to solution. Near Ellettsville, Indiann.

The drainage area of these springs can usually be defined with a fair degree of accuracy, and is as important to know as in the case of surface water, for it must not be forgotten that the water of these springs is just as certainly conditioned by rainfall, as the water of surface streams. The criteria of rainfall and run-off, discussed above, apply here with equal force, though it is probable that a somewhat larger percentage of the rainfall is available than in the Knobstone region to the east; at least the run-off is more regular.

If the element of catchment area be analyzed, it will be perfectly apparent why so few of the springs of the region are adequate for municipal supply without impounding the wet-weather flow. The great Shirley and Leonard springs, near Bloomington, drain an area of about six square miles. During the storage season the flow of these springs must be at times several million gallons per day. At the end of the dry season of 1908 the writer estimated their combined flow at less than 100,000 gallons per day. At that time the writer gaged the Hottel spring in Bloomington and found a flow of 12,000 gallons per day. At the same time also the Rogers springs, just east of Bloomington, had a flow of 10,000 gallons per day. All of these springs have the local reputation of being very strong springs. The Stone spring, at the Bloomington water-works, during the same season had an estimated flow of about 20,000 gallons per day. On the other hand, Wilson's spring, on Blue River, is estimated by Tucker[1] to have a dry-weather flow of nearly 10,000,000 gallons per day. It is said to be the largest spring in Indiana.

Several attempts have been made to obtain water in quantity from deep wells in the limestone region. Invariably the water so obtained has been mineral water. The wells at French Link and West Baden are typical. The writer is unable to state definitely the yield of these wells, but from a rather intimate acquaintance with those that are still flowing, it would be safe to say that none of them, except the Ritter well, has a flow greater than that of the Pluto spring. The flow of this spring is said by Blatchley[2] to be nearly 26,000 gallons per day. The water contains about 300 grains of mineral matter per gallon. The flow of the Ritter well was at first much greater than this, and the water was less

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[1] *Tucker, W. M.*, Water Power of Indiana, 35th Ann. Rept. Indiana Dept. Geol. and Nat. Res., 1910, pp. 34-37.

[2] *Blatchley, W. S.*, Mineral Waters of Indiana, 26th Ann. Rept. Indiana Dept. Geol. Nat. Res., 1901, p. 102.

strongly impregnated with mineral matter, but was nevertheless unfit for domestic use. The Nashville well, 500 feet deep, flows about 29,000 gallons per day, and the water is strongly impregnated with sulphur. The White Sulphur well, in Crawford County, flows about 15,000 gallons per day. There are many other wells of this type in the region, but even if their flow were increased by pumping, none of them have a capacity sufficient to be of any consequence, and, moreover, they are all too strongly impregnated with mineral matter to be of use for domestic or municipal purposes. They vary in depth from a few hundred feet to 1,000 feet or more.

Attempts have also been made to obtain water from shallow wells in the limestone. There are three levels at which water may be expected in small quantities in the Mississippian limestones; namely, at the top of the Oölitic, at the top of the Harrodsburg limestone, and at the top of the Knobstone formation. The latter horizon is the most important. The writer is familiar with the history of a considerable number of such wells in the vicinity of Bloomington, and these are typical of the entire limestone region. The University has drilled, at one time and another, three wells on the campus in the hope of obtaining water for boiler-water. These wells vary in depth from 50 to more than 100 feet, and reach the top of the Knobstone formation. The city of Bloomington also drilled a well in the dry season of 1908, starting at the top of the Oölitic limestone and reaching to the top of the Knobstone. Private individuals in and about Bloomington have drilled a number of wells of a similar sort. None of these wells have produced a supply of water sufficient for even a small town, and some of them have been total failures. The reason for these failures is not far to seek. First of all the Knobstone formation, an impervious rock, underlies these limestones at a comparatively slight depth, constituting a level beneath which no water can be obtained, except small quantities of mineral water, as described above. Second, in the eastern part of the area, the extent and thickness of outcrop of the limestone above the Knobstone, are not sufficient to furnish gathering grounds for water in quantity, and the limestones are, in addition, very thoroughly drained out by the deep ravines that trench the eastern edge of the region. Third, in the central part of the area, where the limestones are thicker and more extensive, they are also so cavernous that shallow wells are a failure, except where they strike the underground streams, and deeper wells produce mineral water. Fourth, in the western edge of the area, where the limestone is under cover of the Chester formation, except in the deeper valleys, the rock-water is artesian, and more or less highly impregnated with mineral salts, as in the case of the water of the French Lick Valley. In this part of the area mineral water is constantly making its way from considerable depths to the surface, along the joints of the soluble limestone, and consequently mineral springs abound, and even shallow wells produce mineral water.

Except in the valleys of White, Blue and Ohio rivers, the limestone area contains, so far as known, no coarse deposits of alluvium, from which water can be obtained, as in the Knobstone region. The larger valleys of the area, with the exceptions already mentioned, are of two types. One of these is represented by the headwaters of Indian Creek in Monroe County, and by Lost River in Orange County, and Indian Creek in Harrison County. These creeks flow in broad shallow valleys on the limestone upland, and have lost many of their tributaries and much of their water by underground piracy to the deeper valleys on the east and west Their floors are leaky, and their deposits of alluvium are thin and very fine grained. The other type of valley is exemplified by Richland Creek in Monroe and Greene Counties and by the lower course of Indian Creek in Lawrence County, and by French Lick Creek. These valleys are deeply intrenched, having cut through the Mansfield and Chester formations into the top of the Mitchell limestone. They are broad, conspicuously terraced, and have well-developed alluvial deposits; but the character and water-bearing qualities of these deposits have not been carefully investigated.

IV.

Similar to the Knobstone region in topography, but differing considerably in type of geological formation, is the area occupied by the Chester and Mansfield formations. The Chester (Huron) formation consists of a series of limestones, shales and sandstones, varying from place to place in the thickness of its members, and in the details of its lithology, but presenting everywhere the following general sequence, in the ascending order: (a) Lower sandstone, ½ to 12 feet thick; (b) Lower limestone, thin-bedded, oölitic or lithographic, 2 to 5 feet; (c) Middle sandstone and shale, argillaceous or arenaceous shale and cross-bedded, soft sandstone, 45 to 62 feet thick; (d) Middle limestone, crystalline, generally light colored, occasionally oölitic, 6 to 21 feet; (e) Upper sandstone, ferruginous, reddish brown to white, laminated sandstone, 40 feet; (f) Upper limestone, grading from limestone at the bottom to shale at the top, 25 feet thick.[1] The limestones of the Chester are not unlike those of the Mitchell and Salem (Oölitic) formations. They are usually rather pure carbonate of lime, and hence soluble, as in the case of the limestones already discussed. Springs often occur at the base of the limestone beds. The sandstones are coarser grained than those of the Knobstone formation, and are cross-bedded and pervious, and conspicuously jointed, the joints often being widely opened by weathering. Springs occur at the base of the sandstone strata, where they rest on shale. The shales of the Chester formation vary from strongly bituminous to argillaceous or even arenaceous. The bituminous bands are very fine grained and impervious. The argillaceous shales are more pervious and grade into coarse grained pervious sandstones.

The Mansfield sandstone, forming the basal member of the Coal Measures of Indiana, and resting unconformably on the Mississippian formations, is a ferruginous, soft cross-bedded, rather coarse grained, sometimes conglomeratic pervious rock. It varies greatly in thickness. Where it is thick, as at Shoals, it produces a rugged topography, with cliffs and pinnacles. The deeply weathered joints and honeycombed weathered surfaces give it a very characteristic appearance. Small springs abound in the area of the Chester and Mansfield formations.

The soil of the Chester-Mansfield region varies from red residual clay, such as characterizes the limestone region, through sandy clay to almost pure yellow sand. In the more rugged portions of the region the soil is thin and poor, and the vegetation scanty. Some of the worst gullying seen in Indiana is to be found in this area. The rain water runs off very rapidly, carrying with it quantities of sediment. Greene and Martin Counties afford many excellent examples of this.

From the standpoint of the water-supply engineer this region is to be considered as intermediate in character between the Knobstone region and the limestone region. It is topographically similar to the former, but the greater permeability of the formations, and especially the presence of beds of cavernous limestone, and the fact that the deeper valleys are floored by the leaky Mitchell limestone, are all characteristics connecting

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[1] *Greene, F. C.*, The Huron Group in Western Monroe and Eastern Greene Counties, Indiana. Proc. Ind. Acad. Sci. for 1910, p. 270. This paper contains a full discussion of the Chester formation of the area under discussion.

it with the limestone region. Smaller amounts of water enter the ground than in the limestone area, however, owing to the steepness of the slopes, especially where these are not under forest. The run-off is concentrated more into the winter and spring months, flood stages are higher, and the streams carry a greater amount of sediment than is the case in the limestone region.

Furthermore, there are, in contrast with the limestone region, beds of impervious shale in the Chester formation, that where favorably located might serve as foundations for dams. It should be noted, however, in this connection that these shales are less firm than those of the Knobstone formation, and would consequently be less capable of sustaining the weight of heavy structures.[1] Where the shales and sandstones are underlain by thick beds of limestone, they will often be found to have collapsed into large solution cavities in the latter, and consequently to present a confused and broken structure, wholly unfit for the foundation of a dam. Numerous examples of this collapse may be seen in the cuts on the Illinois Central Railroad near Stanford, Indiana.[2]

Because of their greater permeability the formations of this area will also be found to be weathered to a greater depth than those of the Knobstone area. In view of all these facts it will be seen that great care should be exercised, and very careful study of the geological conditions should be undertaken in every individual case before placing any impounding structures upon the rocks of the Chester formation. The Mansfield formation, while not as leaky as the limestones of the driftless area, is nevertheless not a favorable formation for impounding water, on account of its porosity.

In regard to deep wells, the Chester-Mansfield area is similar to the limestone region to the east. Deep wells ordinarily produce mineral water. In the western edge of the area, where the sandstones of the Chester or Mansfield are deeply buried, it may be possible to obtain from them water not too highly impregnated with mineral matter for domestic use. The writer is not in a position to speak with authority on this point. It is quite likely that the upward moving water from the limestones beneath would even here cause enough admixture to render the water of the sandstones unfit for use.

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[1] The recent failure of the Austin dam in Pennsylvania, was due to the presence in the substratum upon which the dam stood, of a bed of soft, slippery shale. The dam seems to have slid bodily forward, carrying the rock on which it stood with it. Even in this case, however, it is very doubtful if there would have been any failure had the dam been arched, as a dam of its length should have been.

[2] See Greene, *loc. cit.*

V.

Several times in this paper it has been necessary to call attention to the forest conditions of the driftless area. While this subject does not, in strictness, come within the view of a geologist, nevertheless the success or failure of a water-supply system, in a region where steep slopes preponderate, is so intimately bound up with forest problems, that it may not be out of place to devote a little space to the consideration of this topic.

Very little virgin timber is left standing in southern Indiana. Where the timber has not been removed entirely, it has been closely culled, and in many instances burned over, so that the stand is often thin and the forest cover poor. The writer has often been struck by the character of the woods in Brown County, which gives the impression of being largely under forest. And so it is, if one considers merely the area occupied mainly by trees; but when one notes carefully the character of the stand, one is immediately impressed with the fact that scarcely a tree can be found that appears to be over fifty years old, and much of the stand consists of mere saplings and inferior coppice. Cutting is still going on in the whole of the driftless area, and the writer has seen tracts of many acres of steep slopes denuded of their trees within the last five years. The fate of these slopes, under the type of farming generally practiced in the region, is pathetic (Fig. 9.). Gullying begins immediately, especially where the soil consists largely of clay, and absorbs the rainwater slowly, and in a few years the hillside is a scarred ruin. The regimen of the streams is radically changed. Floods increase in frequency and violence. Springs that formerly had a steady and abundant flow throughout the year, are reduced to dwindling threads of water throughout the dry season.

From the standpoint of water-supply, one of the most serious of these effects is the change of stream regimen. As Glenn[1] has pointed out in the southern Appalachians, whether or not the total rainfall of a region is affected by deforestation, it can be demonstrated that the regimen of the streams is notably changed. He has shown, and the same thing can be shown in southern Indiana, that in regions still under adequate forest cover, the streams are clear even at flood stage. He also points out the

[1] *Glenn, L. C.,* Denudation and Erosion in the Southern Appalachians. U. S. Geol. Surv., Professional Paper No. 72. 1911.

Fig. 9. Soil erosion on a moderate slope at the head of a deep ravine, near Clear Creek station, Indiana.

very significant fact that the former regimen of a stream is revealed in the character of its valley deposits. If a stream has been in the habit of depositing only very fine silt, the valley deposits (alluvium) will consist of fine material only. On the other hand if the stream has been in the habit of depositing coarse material, the valley deposits will reveal this fact. If furthermore a stream is now depositing coarse material where it formerly deposited only fine material, and if this change has come about *pari passu* with the deforestation of the region, and no other adequate cause can be assigned, it is a fair inference that the deforestation of the region has changed the regimen of the stream. This effect also finds ample illustration in southern Indiana. Torrential streams now emerge on the sides of broad alluvial valleys, building fans of coarse and sterile gravel out over the finer silt of the main stream flood plane. Deep scouring of fertile valleys by flood waters is only too common.

Now the importance of this change in stream regimen for the water-supply engineer is two-fold. First, if floods are notably increased in frequency and volume it will be necessary to build more massive structures to withstand them, and it will also be necessary to build large enough reservoirs to hold the flood water, since very little catch of water can be expected in the growing season. Second, the greatly increased erosion of slopes and valleys brings down immense quantities of sediment which tends to silt up reservoirs. The rapidity and completeness with which reservoirs are silted up, in the southern Appalachian region, as described by Professor Glenn, almost passes belief.[1] He says: "From the slopes along these streams a steadily increasing amount of waste is working its way down the channels, filling the dams and destroying their storage capacity; and this loss of storage means a decrease of efficiency that is calculated by the most experienced mill engineers to amount to 30 to 40 per cent. in plants that have been built especially for storage and a somewhat less marked decrease in other plants, the exact amount depending on the topography of the basin and the regimen of the particular stream on which the plant is located. So universal is this silting of storage basins that a prominent mill engineer of wide experience in his reports on the construction of power plants no longer calculates on power or anything except the flow of the stream, and he has increased his usual estimates by an allowance for increased storm waters that must be taken care of without endangering the dam or plant.

[1] Glenn, *loc. cit.*

"At one large plant storage basins that originally had a capacity to hold the water accumulated by several days of ordinary stream flow have been so filled that they cannot now hold the flow of a single night.

"At one dam where two years before, when the dam was first closed, there was a depth of 28 feet, an island has recently appeared. At another place, where a high dam had been built on a small stream, the pond has been so filled that its storage capacity has all been lost. . . . . A pond four miles long and forty feet deep at the lower end was in four years entirely filled in its upper part and near the dam was three-fourths full."

The differences between the southern Indiana region and the southern Appalachians are largely such as arise from the greater relative relief of the latter region. Plenty of examples on a somewhat less pronounced scale can be found in Indiana, of precisely the same process here so vividly outlined by Glenn.

There is only one remedy for this condition, and that is to remove the cause. The writer can vouch for the fact that where the forest cover is adequate, slopes in the Knobstone region, almost too steep to climb, are not suffering an appreciable amount of erosion. The steep slopes of water-supply catchments must be maintained in forest cover if reservoirs are to be kept free of mud. It would be a blessing to the future citizens of Indiana if large sections of the more rugged portions of the driftless area of southern Indiana could be protected by the State from further denudation, and if, furthermore, slopes which have already been denuded, and which are too steep for agricultural purposes, could be reforested. The great Knobstone region, with its innumerable deep valleys and ample rainfall, and impervious strata, must ultimately be called upon to furnish the water supply of great cities. It should be seen to that the one condition which alone can make this region unfavorable for such purposes, namely erosion of its steep slopes, is removed by early and adequate steps to forever maintain these slopes in forest.

VI.

Summary. The driftless area of southern Indiana comprises an eastern portion of impervious sandstones and shales and rugged topography; a central portion of cavernous limestone and mild relief, and a western portion of shales, sandstones and limestones, and similar in topography to the eastern region. The mean annual temperature and the mean annual rainfall are slightly greater in the southern than in the northern portion of the area. The minimum annual rainfall of the region is about thirty inches, and the run-off may, in dry years, fall as low as twenty-five per cent. of the rainfall. In the eastern region (Knobstone formation) water for municipal supply will have to be impounded, except where the underflow of the larger valleys may be used; and the conditions for building dams are ideal. In the central portion of the area the rock substratum is everywhere very cavernous and leaky, and tight ponds will be difficult to obtain. A few of the larger springs furnish sufficient water for small cities without impounding. All deep wells produce mineral water, and shallow wells are inadequate. In the western portion the conditions are intermediate between those of the eastern and central portions. To maintain the perennial flow of springs and prevent the silting of ponds the steep slopes of the area should be reforested, where necessary, and forever kept in forest.

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