THE HYDROLOGICAL PROPERTIES OF DELTAIC SEDIMENTS

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Summary

This paper deals with the hydrological properties of deltaic sediments. Owing to the various environments of deposition in delta plains great variations in texture and other features of the sediments may be expected. The main stream and its distributaries shift over the delta and consequently there are rapid alternations between relatively coarse channel sand and the finer silt and clay of still water deposition. A detailed study was made of the geological history of part of the delta plain of the Rhine and Meuse. Such hydrological properties as thickness of aquifers and semi-permeable layers, transmissibility of the aquifers were determined. The methods of study and the results obtained are discussed. Finally, some observations are made on the quality of the groundwater encountered in the area investigated.

Introduction

In a previous paper the importance of geological knowledge in groundwater studies of delta plains was discussed in greater detail (DE RIDDER, 1962). It was shown that the configuration of the water table in an area of the interior of the Rhine- and Meuse delta is largely determined by the tectonic features of this area.

In most groundwater studies, however, it is essential to determine the hydrological properties of the sediments. These properties depend upon the aggregation of the particles and include porosity, permeability, thickness and structure. It is well-known that the coefficient of permeability depends on the grain-size and sorting of the sediment. A study of the variations in mean grain-size and sorting in an area affords a better insight into variations in such mass properties as horizontal permeability. Hence a study of such particle properties as grain-size and sorting may be very valuable.

In this paper the main subject of discussion is the determination and variation of certain of these properties, e.q. the thickness, grain-size and permeability of sediments found in the Deurne area. The location of the area is shown

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on map 1. The data to be discussed was obtained from a number of wells of which the location is also shown on the map. As groundwater samples were assembled in most of these wells and chemically analyzed, the results of these analyses will be discussed in the concluding section.

Summary of geologic history

The geological history of the area, which has already described in greater detail in a previous paper (DE RIDDER, 1962), may be summarized as follows (Fig. 1).

In the Middle Miocene the sea advanced and a thick layer of fine, glauconite-bearing sand, silt and clay was deposited. In the Pliocene subdivision of the Tertiary period the sea retreated and streams draining the southern highlands built coalescing alluvial fans (the "Kieseloölite" formation) that almost completely buried the marine Miocene deposits. This epoch is characterized as a period of violent crustal unrest resulting in a block-faulted area.

In the Pleistocene epoch the Rhine and Meuse alternately contributed to the formation of the delta. The course of these rivers was often determined by faults which were even active in the Pleistocene epoch. One of these, the Peel boundary fault, divides the area into an upthrown eastern part, the so-called Peelhorst, and a downthrown western part, the Roer valley Graben.

The oldest Pleistocene deposits found in the area were laid down by the Rhine and belong to the Tegelen formation. These coarse-grained sands have only been found in one part of the Peelhorst, near the village of Milheeze. This formation also occurs in the Roervalley Graben, but at a great depth.

The next younger formation was deposited by the Meuse during an interglacial period of the Lower Pleistocene. It is known as the Kedichem formation and is composed of fine sand and extensive layers of heavy clay, particularly in the uppermost part. Its presence could only be demonstrated in the Roervalley Graben.

The Kedichem formation is overlain by coarse, gravel-bearing sands derived from the Rhine and belonging to the Sterksel formation, of Middle Pleistocene age. Since this formation is only found in the Roervalley Graben it may be concluded that at this period the Rhine flowed through this graben.

In the Holsteinian (Needian or Mindel-Riss Interglacial) the Rhine gradually disappeared from the area and was replaced by the Meuse. In the subsequent Saalian (Riss-Glacial) period the Meuse deposited a layer of coarse-grained, gravel-bearing sand belonging to the Veghel formation. Aggradation of chiefly fine sands; loamy sands and loam continued during the Late Saalian, whereas in the Eemian (Riss-Würm Interglacial) peat layers were occasionally formed.

In the Weichselian (Würm-Glacial) the remaining valleys were chiefly filled with fine sand and silt. Finally, an extensive sheet of cover sands was deposited during the Late Weichselian, resulting in a rolling plain of low relief. These wind-blown sands dammed up the valleys and in the subsequent Holocene period these topographical depressions were filled with vegetation and extensive areas of peat were formed. This whole complex of fine sand, loam, silt and peat is called Sand Diluvium.

HYDROLOGICAL PROPERTIES OF THE GEOLOGIC FORMATIONS

The impervious basement

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For practical purposes the marine Miocene may be regarded as the "impervious" basement of the area. This series is more than 300 m. thick and fine to very fine-textured. Its uppermost layers are often rich in clay (plate 1). Owing to its generally low permeability it only yields small quantities of water, often of poor quality. This series is unsuitable for supplying the area with water, so that it is no use digging deeper wells when these characteristic fine, clayey green sands have been reached.

The Miocene underlies the entire area, but its depth varies considerably (map 2). As the Miocene has sunk to a very great depth in the area west of the Peel boundary fault, the Pleistocene Kedichem formation should here be regarded as the impervious base layer. Layers of clay of considerable thickness are widespread in this fine-textured formation, particularly in the upper part.

In the area bounded by the Peel boundary and the Veghel faults the impervious basis layer may be expected at a depth of about 10 to 20 m. below sea--level at about 60 m. below sea-level in the area west of the Veghel fault.

In the remainder of the area, viz. east of the Peel boundary fault, the base layer is formed by the Miocene which owing to tectonic displacements varies in depth from 15 m. above to 30 m. below sea-level (Fig. 1). The depth is slightest on the horst bounded by the Griendtsveen fault and the Peel boundary/Milheeze faults.

To summarize the above data, it can be stated that the depth of the impervious base layer shows considerable variations throughout the area. These variations are generally abrupt owing to displacement of the layers along fault planes.

The aquifers

For the purpose of discussing the water-bearing formations we must divide the area into two parts, the boundary being formed by the Peel boundary fault. In the area east of this fault, the Veghel and "Kieseloölite" formations are the most important aquifers (Fig. 1 and plate 1). These two coarse-grained and gravel-bearing formations underlie the entire area. The Tegelen formation, intercalated between these formations, is also important as an aquifer, but it only occupies a small area. It is only found on the Milheeze wedge.

The thickness of the Veghel formation ranges from about 4 to 12 m., but a thickness from 8 to 10 m. is usually found. Owing to the great tectonic activity during the Pliocene the "Kieseloölite" formation varies considerably in thickness, viz. from nil to more than 30 m.

As both formations are in direct contact with each other and there is little difference in permeability, they may be regarded as being a single aquifer ranging in thickness from about 8 m. on the upthrown fault-blocks to more than 40 m. at certain points on some downthrown blocks.

It should be noted that the Pliocene "Kieseloölite" formation sometimes contains interbedded layers of clay or clay lenses which reduce the thickness of the aquifer (plate 1). Hardly any layers of clay are found in the Veghel formation.

In the area west of the Peel boundary fault we find the Veghel- and the Sterksel formations, these being the principal aquifers. Both consist of coarse, gravel-bearing sands. Taking these two formations together as a single aquifer, we find that the latter varies in thickness from about 20 to 30 m. on the fault-step of Deurne-Bakel, to 40 to 45 m. in the Roervalley Graben, west of the Veghel fault. This aquifer provides the water for several domestic and municipal wells (Helmond, Vlierden).

For practical purposes it may be useful to know the depth of the top of this important aquifer, and for this reason map 3 was compiled. This shows that the depth of the Veghel formation may vary from about sea-level in the western part of the area to 28 m. above sea-level at a point SE of Deurne.

As the Veghel formation is covered by the Sand Diluvium, an isopachous map of the latter may be useful as it shows the thickness of the fine-textured sediments, which have to be drilled in order to reach the aquifer (map 4). It can be seen that there is a considerable difference in thickness between the areas on either side of the Peel boundary fault.

Semi-permeable layers

The covering strata of the area are formed by Sand Diluvium sediments. The latter usually consists of fine sand, loamy sand, sandy loam, loam and peat. Owing to their heterogeneous character there are considerable variations in the physical and hydrological properties of these sediments.

Groundwater flow may be divided into three components, viz. a vertical, a horizontal and a radial flow. Vertical groundwater flow is often found in the upper soil layers when rainwater moves downward to join the groundwater at a greater depth, where the flow is mainly horizontal. Radial flow is found in soil layers surrounding open channels, rivers and brooks (ERNST, 1956; VAN HOORN, 1961). When groundwater moves it has to overcome a certain resistance, and with regard to the above three components it is possible to distinguish a vertical, a horizontal and a radial resistance. The vertical resistance is expressed by $c = \frac{D}{k}$, in which D is the thickness in m. and k the vertical hydraulic conductivity in m/day of the semi-permeable layer.

The value of c can be determined in various ways, viz. by determining the vertical hydraulic conductivity and the thickness of the covering strata, or by determining the intensity of the groundwater flow and the difference in head between the groundwater level and the piezometric level.

Unfortunately we were unable to carry out the required measurements in the field, so that only a qualitative description can be given. The thickness and lithology of the covering semi-permeable layers are known from the wells (plate 1). The isopachous map (map 4) shows that low to very low vertical resistances may be expected in the area between the Peel boundary and Griendtsveen faults, where fine-textured layers are thin or occasionally even absent. In a similar area south of Eindhoven ERNST (1956) computed c-values ranging from 50 to 400 days.

Generally speaking, much higher c-values may be expected in the area west of the Peel boundary fault, where there are thick layers of fine sand with intercalations of silty loam, clay or even peat. As these fine materials of low permeability are generally widespread it is estimated that c-values will be high in this area, i.e. probably ranging from a few hundred to over a 1000 days.

From these observations it is possible to draw some general conclusions on the recharge conditions of the area. In the first place it should be remembered that the area is located on, or almost on the divide. As a result of this location practically all water needed for groundwater recharge is supplied direct by precipitation.

In the eastern part of the area, viz. east of the Peel boundary fault, where the main aquifer is at the surface, or practically at the surface, recharge conditions are more favourable than in the western part. Here the groundwater reservoir is recharged by direct infiltration of precipitation.

Since the groundwater reservoir is relatively small on this raised fault-block, an increased use of groundwater for irrigation could exceed the mean annual recharge and lower the regional water table. In this area the infiltration rate would be high so that most of the water pumped for irrigation would infiltrate into the soil and rejoin the groundwater. For the same reason high seepage losses from channels and ditches may be expected if the area is supplied with water by pumping river-water through a new distribution system. These seepage losses will raise the water table to such an extent that certain parts of the area, particularly topographical depressions, may be subject to waterlogging.

Quite different hydrological conditions occur in the western part of the area, in the Roervalley Graben, where less permeable layers of great thickness and shallow beds of clay and peat of low permeability are partly responsible for the fact that most of the precipitation runs off direct.

These thick layers of low permeability tends to restrict infiltration of precipitation. Hence recharge conditions are, less favourable here than in the area east of the Peel boundary fault, but the great thickness of the aquifer and the large tributary area make the area suitable for pumping groundwater from wells in practically every part.

Grain-size distribution of the sediments

The grain-size distribution of sediments is very useful in sedimentary and hydrological work. The results of mechanical analyses can be used for describing the characteristic size-frequency distributions of the sediments, examining the horizontal and vertical variations in grain-size of the formations, determining the environment of deposition, examining the sorting features, and for gaining an impression of the over-all permeability of the sandy sediments.

The samples of all boreholes were analyzed and the results are shown in the appendix, in the form of graphs. Figure 2 shows the cumulative curves of a number of size-frequency distributions encountered in various geological formations. Since only remoulded (bailer) samples were available, it will be obvious that these graphs do not permit any far-reaching conclusions to be drawn. This is particularly the case for sediments with rapidly alternating grain-size in vertical sections. Although the curves should be interpreted with caution they give an over-all picture of the grain-size of the sediments.

Figure 2 shows that the grain-size distribution of the marine Miocene sediments exhibits a high degree of uniformity. The bulk of the sediment is limited to a fairly narrow range of grain sizes (105 to 300 microns). The sediments of the "Kieseloölite" formation show strikingly different grain-size distributions which are anything but uniform. Several types of distributions may be distinguished, however, and some of these have a certain degree of uniformity. The flat, almost horizontal curves represent coarse to very coarse-grained, ill--sorted sands which are often found in river beds and broad flood cones of braided rivers. In addition to these, fine-grained, well-sorted sands and heavy clays are also found, indicating different environments of deposition.

The curves of the sediments from the Tegelen, Sterksel and Veghel formations are all similar in shape. Most curves are slightly undulating or almost horizontal, indicating coarse and very coarse, ill-sorted sands. These sediments probably represent stream-channel and braided-river deposits. Finally, the Sand Diluvium diagram shows the curves of five samples from the lower part of this formation. This diagram shows that the samples assembled in one borehole represent sediments of the filled-up channel of a former river. This channel filling consists of a sequence of sediments grading upward from coarse sands into progressively finer deposits of sands, silts and loam (graded bedding). During the final stage of degeneration of the channel, the chief materials deposited were silts and silty loams, or even clays. To this example may be added many others, all indicating the same phenomenon of graded bedding caused by degeneration of the river system of the Meuse. Several parts of the Sand Diluvium must therefore be of fluvial origin, although wind-blown sands are occasionally found, especially in the uppermost layers.

Transmissibility

The amount of water an aquifer will yield and the rate at which it will transmit water depend on its permeability. The horizontal resistance which groundwater flow has to overcome is expressed by L/kD, in which L is the distance in m. over which the water flows and kD = T = transmissibility of the aquifer in sq. m. per day (k is the average hydraulic conductivity in a horizontal direction in m/day and D the thickness of the aquifer in m.).

The transmissibility can be determined in various ways, for instance by field pumping tests, or by measuring the hydraulic conductivity in remoulded or core samples, or by calculating the hydraulic conductivity from results of mechanical analyses. Each method has its own difficulties and drawbacks, but as many analyses of borehole samples were available the transmissibility was estimated by the last method.

The mechanical composition of each sample was determined by the usual laboratory methods. The normal practice is to express such properties of the size-frequency distribution as average, sorting, skewness, etc. by means of a single number. The specific surface area or U-figure is often used in Holland to indicate the average grain-size. The U-figure shows the ratio between the total surface area of all particles and the surface area of an equal quantity by weight of particles of the same material having a diameter of 1 cm., it being assumed that the particles are spheroidal. Sands with U-figures smaller than 50 are termed coarse and those with U-figures larger than 50 are termed fine sands. Each group is subdivided, so that the U-figure forms a basis for the classification of sandy soils (plate 1).

It is well-known from the work of other investigators that particle diameter of the sand and hydraulic conductivity are closely related. There are several formulas showing the correlation between conductivity and particle diameter of the sand given as specific surface area (U). As FAHMY (1961) has recently discussed these problems again the reader may be referred to his work.

For each sample with a low clay content the hydraulic conductivity was calculated from the U-figure, and since the clay and gravel content and sorting of the sand fraction influence the conductivity in different ways, corrections were made for each of these parameters according to a procedure described by ERNST (unpublished report).

The thickness of each sampled layer is known and the transmissibility of the layer can be found by multiplying conductivity by thickness. The transmissibility of the aquifer can be determined by adding together all values obtained for the whole sequence of coarse layers.

Next to each borehole in the geological sections (plate 1) the transmissibility values, calculated by the above method, are shown for each formation. These sections show that the Veghel, Sterksel and Tegelen formations usually have high values, so that high yields can be expected. It should be noted, however, that the transmissibility may vary considerably in each formation, this being partly due to variations in grain-size of the sediments and partly to differences in thickness of the formation.

This is particularly the case in the (Pliocene) "Kieseloölite" formation which varies considerably in thickness and lithology and consequently only has local importance as a water-bearing formation.

It is also found that even where the Sand Diluvium reaches a great thickness, it has low transmissibility values. Low yields can be expected from this formation. Although the geological sections give a fairly good impression of the occurrence, depth, distribution and importance of the various aquifers, it was considered useful to show the magnitude and variations in transmissibility of the aquifers in map form. For this reason a transmissibility map was compiled for the whole area (map 5). A map of this kind also enables us to determine the amount of water available for immediate use (MARGAT, 1960).

This map shows that the lowest transmissibility values (< 500 sq. m/day) are found on the elevated block bounded by the Griendtsveen fault and the Peel boundary/Milheeze faults, and to the east of the Ysselsteyn fault. Much higher values (500 - 1500 sq. m/day) occur on the downthrown blocks between these raised blocks, e.g. the areas of Griendtsveen-Ysselsteyn and Deurne. But the highest values (> 1500 sq. m/day) are found west of the Veghel fault, in the Roervalley Graben and occasionally near Deurne, and on the downthrown wedges of Griendtsveen and Milheeze where the aquifers reach their largest thickness.

This map clearly shows the close relationship between the structural geology of the area and the transmissibility values of the aquifers.

As the calculations discussed above are based on mechanical analyses of remoulded samples, the results obtained should not be regarded as showing a high degree of accuracy and need to be checked by one or more field pumping tests. Unfortunately we were unable to carry out such a test, but the Government Institute for Water Supplies had already carried out a field pumping test near Vlierden (borehole 672/8), SW of Deurne. The transmissibility calculated from this test came to 2200 sq. m/day, a value which shows a fairly close correspondence with the order of magnitude calculated by us for the area west of the Veghel fault.

In conclusion, it can be stated that the transmissibility values show considerable variations throughout the area, viz. from approximately 200 to over 2000 sq. m/day. These variations are both due to lithological variations within the aquifers and to tectonic activity which is the cause of considerable variations in thickness of the aquifers at opposite sides of the faults. As a result the lowest values are usually found on the upthrown blocks, whereas the highest values are shown to occur in the Roervalley Graben, where the aquifers are many times thicker than on the upthrown blocks. In the central zone, which is characterized by low transmissibility values, pumping of groundwater for irrigation will only be possible on a limited scale.

Chemical quality of the groundwater

As part of this investigation, 27 samples of water from various wells were assembled and thoroughly analyzed by the Government Institute for Water Supplies, The Hague. Only one or two samples were collected from each well. The depth of each screen is shown on the sections of plate 1. Most screens were installed in sediments of the Veghel formation. Two screens (well N74 and N75) were installed in the Sterksel formation and four (wells N71, P16, P18 and P35) in the "Kieseloölite" formation. Hence most groundwater samples were taken from the Young Pleistocene Meuse deposits; two samples were taken from middle Pleistocene Rhine deposits and four from Pliocene deposits. The results of analyses are shown in table 1. In general the groundwater is soft and very aggressive. This aggressivity is caused by low pH and low alkalinity. Chloride concentrations are low, ranging from 11 to 76 mg per litre, except in well P11 where a fairly high concentration (113 mg per litre) was found. Sulfate is also found in low concentrations, although one sample (well N70) showed a fairly high concentration (127 mg per litre). All samples have low concentrations of sodium (9-83 mg per litre).

A characteristic feature of the groundwater is the high concentration of iron, ranging from 3 to 36 mg per litre. Its presence in water in large amounts may render the water unsuitable for many purposes. Concentrations as low as 0.5 mg per litre are conducive to the growth of certain organisms ("iron bacteria") which form incrustations on the inside of pipes. Some crops are also very sensitive to iron. Sprinkling irrigation with groundwater rich in iron causes rust spots on foliage and hamper plant growth.

Manganese reacts in much the same way as iron, producing black or brown stains if more than about 0.1 mg per litre is present. To overcome all such drawbacks, the total iron and manganese content should be less than about 0.3 mg per litre for domestic and industrial use, whereas for agricultural use a content of more than 3 mg per litre may cause rust spots on foliage and fruit, thereby reducing the economic value of the crops.

It will be clear from the above and from map 6, which shows the iron concentrations of each water sample, that the groundwater in the Deurne area is unsuitable for most purposes unless precautionary measures are taken.

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Table 1. Chemical analyses of groundwater samples from the Deurne area in mg per litre

Aquifer: Ve = Veghel formation; Ster. = Sterksel formation; Plio = "Kieseloölite" formation

Well	Aquifer	Depth of screen in meters	Date of collection	Chloride (Cl)	Nitrate (NO_3)	Sulfate (SO_4)	Bicarbonate (HCO_3)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	pH
N70	Ve	6.5	19-2-1960	76	0	127.3	37	10.9	0.36	42.0	12.0	49.6	6.3
N71	Plio	12.5	19-2-1960	23	0	16.9	49	12.8	0.13	8.0	6.0	17.5	6.3
N72	Ve	12.5	19-2-1960	11	0	20.6	37	10.0	0.08	4.0	4.8	15.6	6.3
N73	Ve	21.0	19-2-1960	71	0	9.1	18	17.0	0.36	23.0	9.6	11.0	6.2
N74	Ster.	29.0	26-2-1960	33	0	47.8	37	9.2	0.20	17.0	4.4	29.1	6.2
N75	Ster.	33.0	26-2-1960	18	0	0	47.5	8.0	0.23	9.7	2.9	11.5	6.5
N76	Ve	12.0	19-2-1960	34	0	63.9	18	8.2	0.09	19.0	5.4	18.0	6.4
N77	Ve	8.5	19-2-1960	14	0	0	92	9.2	0.07	11.0	3.6	11.0	6.3
N79	Ve	16.5	26-2-1960	11	0	19.6	25	3.4	0	5.0	2.3	13.8	6.2
N80	Ve	9.5	19-2-1960	52	0	26.0	61	15.0	0.12	16.0	6.0	23.0	6.2
N81	Ve	16.5	19-2-1960	31	0	19.2	43	9.5	0.08	13.0	3.6	17.1	6.3
N82	Ve	20.0	26-2-1960	27	0	47.0	37	12.0	0.27	16.0	3.6	27.6	6.5
N83	Ve	29.5	26-2-1960	13	0	20.4	37	8.6	0.22	8.0	2.4	19.3	6.5
N87	Ve	10.5	9-3-1960	21	0	16.1	37	11.8	0.08	5.6	3.8	14.9	6.3
N93	Ve	22.5	26-2-1960	15	0	22.7	34	6.0	0.10	9.2	2.4	18.4	6.4
P10	Ve	18.6	23-6-1952	25.4	0	17.9	64	30.0	0.35	8.5	3.4	28.5	6.5
P11	Ve	17.5	1-7-1952	113.0	0	20.2	85	17.1	0.33	14.4	4.7	82.8	6.5
P16	Ve	11.1	27-2-1953	14.7	0	10.7	61	10.7	0.08	12.4	5.0	10.6	6.5
P16	Plio	19.5	27-2-1953	12.8	0	11.5	55	18.8	0.12	8.9	6.5	9.1	6.5
P17	Ve	18.5	3-2-1953	14.0	0	17.5	44	13.3	1.3	5.2	5.0	17.5	<6.6
P18	Ve	17.7	2-3-1953	28.7	0	4.1	78	16.7	0.22	10.9	6.8	19.7	<6.5
P18	Plio	28.5	2-3-1953	17.5	0	7.0	171	32.4	0.66	27.8	8.3	11.4	<6.5
P33	Ve	14.4	8-4-1954	39.0	0	30.5	18	28.6	0.27	8.6	3.4	15.8	<6.5
P34	Ve	17.7	22-4-1954	44.0	0	35.8	0	18.2	0.31	10.5	14.5	17.5	<6.5
P35	Ve	13.2	18-6-1954	58.0	0	93.9	11	36.4	0.19	4.0	10.9	35.7	<6.5
P35	Plio	32.8	18-6-1954	11.7	0	9.1	37	6.0	0	7.7	1.8	12.9	6.5
P40	Ve	11.4	4-2-1955	31.0	0	34.6	18	19.3	0.22	3.6	3.8	20.2	<6.5