# Tracer Aids Interpretation of Pumping Test

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*Abstract.* The nuclear research center at Mol, Belgium, is underlain by clean quartz sand to a depth of about 30 meters. An accident at one of the nuclear facilities, which could contaminate the ground water, would entail serious consequences, since the movement of radioactive contaminants through the ground would be retarded or reduced only slightly by adsorption. Test drilling showed that the water table aquifer is composed of two sand formations, the upper Mol sand being somewhat coarser grained and therefore probably more permeable than the underlying Casterle sand. The lower part of the Mol sand contains a number of thin clay layers which make a partial hydrologic barrier between the two formations, dividing the water table aquifer into two parts. A test well was installed, screened through the full thickness of both sands, and test pumped. Drawdowns were measured in observation wells screened both in the Mol sand and in the Casterle sand. A tracer was added to four of the observation wells in turn, and the arrival of the tracer was measured in the pumped well. The average travel times in the Mol and Casterle sand were used to determine the amount of water being produced from each by the pumping, and these data, with the observed drawdowns, were used to calculate the transmissibility, the permeability, and the storage coefficient of each of the two formations. Using these parameters, the designs of several well systems for pumping contaminated ground water out of the aquifers are discussed. Pumping out, or scavenging, the contaminated ground water and decontaminating it appears to be a practical method of resolving some of the problems that would be raised by a nuclear accident in the Mol area.

## NATURE OF THE PROBLEM

The work described in this paper was done at the Nuclear Research Center (C.E.N.) at Mol, Belgium in the summers of 1965 and 1966. The center is in north central Belgium, about 50 kilometers east of Antwerp in the ancient floodplain of the Rhine and Meuse rivers. The area is drained by the upper branches of the Nete River, a tributary of the Escaut, which flows west through the city of Antwerp to the sea. The center is underlain by some 30 meters of pure quartz sand, and the ground water, which is everywhere near the surface, has a *p*H of from 4.0 to 4.5 largely due to the acids produced by the decay of pine needles. Consequently, many potential radioactive contaminants, particularly $^{90}Sr$, if they were to reach the ground water would be carried along with little delay due to ion exchange or adsorption.

The purpose of the work described in this paper was to define the geohydrology of the site in sufficient detail so that plans for remedial action might be made which could be used in the unlikely event that an accident at the site contaminated the ground water with radioactive materials. Two remedial methods were considered. The first, called scavenging [*de Laguna,* 1966], consists of drilling a well or wells into the contaminated ground water, pumping it out, and either treating it to remove the radioactive contaminations or injecting it into a deep permeable formation where it can do no harm, if such a formation is available. The second remedial measure would consist of constructing a chemical barrier. This is done by injecting reagents into the aquifer through suitably constructed wells which will build up thin, highly adsorptive layers on the sand grains. The treated sand will then be able to trap and hold the radioactive contaminants in the water that flows through it. The construction of such a barrier requires a detailed knowledge of the geohydrology of the area. Some of the chemical and hydrodynamic problems of barrier construction have been described by *Baetsle et al.* [1967] with whom the writer was privileged to work while at Mol.

The surface drainage of the area around the

Nuclear Research Center at Mol has little to do with the pumping test, which is the principal subject of this paper, but it has much to do with complicating the hydrology of the area so that such conventional methods of studying the hydrology as the construction of a water budget or material balance are impractical.

The Nuclear Research Center is on a slight rise of land that forms the low divide between the Groote Nete on the north and the Mol Nete to the south (Figure 1). In general the ground-water flow is toward one or the other of these two streams. The low divide is also followed by the Meuse-Escaut barge canal in which the water level drops to the west in a series of steps of about 2 meters at each of the locks. In the area just south of the canal occupied by the center proper (C.E.N.), and in the area immediately to the north of the canal occupied by the Eurochemic nuclear fuel reprocessing plant, both just to the east of lock 6, the water level in the canal is nearly 2 meters above the adjacent water table. The canal leaks considerable water through and under the Eurochemic plant; this water joins the flow of the Groote Nete. The canal also leaks water to the south, which would go under the site of the center were it not intercepted by an interior canal dug primarily to drain an old sand pit into the canal to the west of lock 6, where the water level is some 2 meters lower. The center

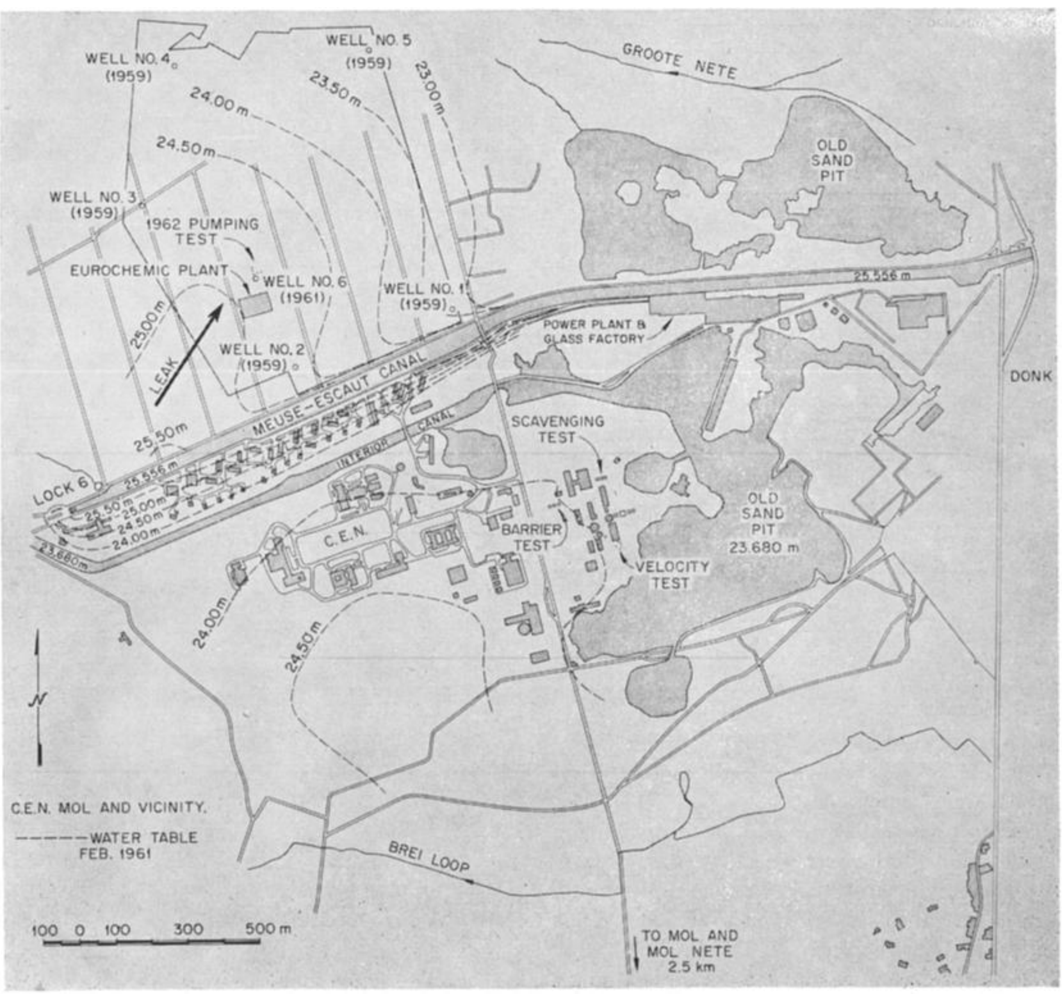


**Fig. 1. Index map.**

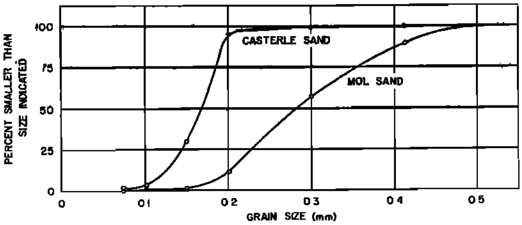


Fig. 2. Comparison of grain size distribution, Mol and Casterle sands.

itself is therefore on a peninsula surrounded by the interior canal on the north and by the old sand pit on the east and southeast. Infiltration of rainfall has built up a low water table mound on this peninsula which drains into the interior canal and the sand pit and to the south to the Mol Nete. However, some of the shallow ground water flowing to the south is intercepted by a small drainage ditch called the Brei Loop and carried far to the west, eventually to flow into the Nete River. Not only is the area one in which the contamination of the ground and surface water would involve consequences of unusual complexity, but the complicated pattern of water flow makes difficult any study of the geohydrology.

## STRATIGRAPHY OF THE MOL AREA

Test drillings at the Eurochemic site in 1959 and 1961, as interpreted by *Gulinck et al.* [1963], showed that the strata underlying this area are arranged as follows:

*Pleistocene cover, 0 to 4.5 meters.* Fine wind blown sand and medium fine sand, poorly sorted, grading into coarse sand with pebbles at the bottom.

*Mol sand, 4.5 to 14.5 meters.* Generally medium grained, moderately well sorted white quartz sand. Thin layers of white clay at about 8 meters and brown clay containing roots between 9.5 and 10 meters. Locally contains traces of lignite (finely divided carbonaceous material). Age, Upper Pliocene.

*Casterle sand, 14.5 to 32.5 meters.* Similar to the above but finer and better sorted. A few lenses of silty clay below 21.5 meters. Traces of glauconite in lower part. Lignite not reported. Age, Pliocene.

*Diest sand, 32.5 to 109 meters.* Medium to coarse quartz sand with much glauconite and more or less clay, depending on depth. Clay layers between 33 and 35 meters, including at least 12 cm of tough brown clay. Relatively coarse sand with little clay between 60 and 80 meters; this part of Diest supplies water to wells at Eurochemic and C.E.N. Age, Upper Miocene.

*Antwerp and Rupel formations, 109 to 178.5 meters.* Glauconitic clayey sands, in general similar to the Diest but finer grained. Clay-rich layer at 149 meters. Age, mid-Miocene to Oligocene.

*Boom clay, 178.5 to 200 meters.* A tough dark clay, believed to be about 200 meters thick in this area.

In 1965 a test well was drilled to a depth of 40 meters in the eastern part of the C.E.N. area. This well later became the pumped well of the scavenging pump test (Figure 1). The beds in this area dip very gently to the north so that the several stratigraphic units were found about 5 meters higher in this well than in the well described above. The log of this well is given in Figure 3.

*Pleistocene cover, 0 to 1.5 meters.* Poorly sorted yellow sand with a few well rounded pebbles at 1.5 meters.

*Mol sand, 1.5 to 9.0 meters.* Medium grained sand, fairly well sorted, no glauconite or lignite visible. Color, yellow to 4.0 meters; deeper, very light gray, almost white. Ten to fifteen layers of tough white clay, 2 to 3 mm thick, between 5 and 9 meters.

*Casterle sand, 9.0 to 25.0 meters.* Fine to medium grained, well sorted sand; color, very light gray. No clay layers and very little inter-

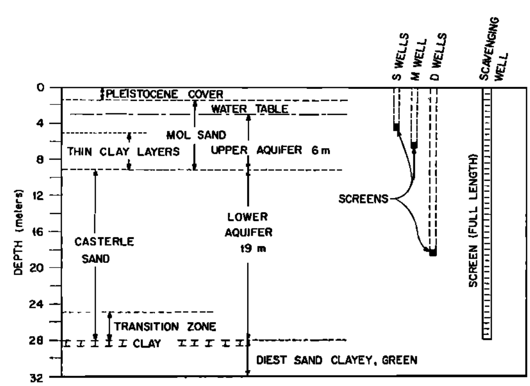


Fig. 3. Stratigraphy and well depths, scavenging test site.

stitial clay to 20 meters; slightly more interstitial clay and color slightly darker from 20 to 25 meters, but difference is believed insignificant.

*Casterle–Diest transition, 25 to 28 meters.* Medium fine sand as above, but content of fine grained glauconite and gray clay increases slowly with depth in this zone. Color grades downward from light green to medium green. This sand is part of the Casterle containing, with depth, increasing amounts of material reworked from the underlying Diest. Although probably slightly less permeable than the main body of the Casterle, it will be considered part of the Casterle hydrologic unit.

*Diest sand, 28.0 to 40 meters.* Medium fine sand, 25 to 50% glauconite, pores largely filled with fine grained glauconite and gray clay. Several thin brown-gray clay layers between 28 and 31.5 meters with total clay thickness about 10 cm. At 35 meters general color changes from bright green to brownish green due to presence of brown clay mixed with the sand. The Diest sand in this well is very poorly permeable compared with overlying beds.

The Mol-Casterle contact was set with confidence at a depth of 9 meters in this well on the basis of mechanical analysis of samples taken every half meter, which showed at 9 meters a change identical with that found 5.5 meters deeper in the 1961 Eurochemic well (Figure 2). The Casterle–Diest contact was set with confidence at 28 meters on the basis of the abrupt marked increase in glauconite and clay, which clearly greatly reduces the permeability of the Diest.

These investigations made possible a description of the geohydrologic environment at Mol sufficiently precise so that the field tests described below could be planned with some measure of confidence. This description may be summarized as follows:

The water-table aquifer consists of two parts: the upper Mol sand is relatively coarser and less well sorted; the lower Casterle sand is somewhat finer grained and very well sorted. Although the two might well be treated as a single hydrologic unit in studies of water supply, they differ sufficiently in permeability and in hydrologic homogeneity to require treatment as separate units in studies involving the movement of contaminated water through the aquifer.

The bottom 4 meters of the Mol sand has a number of thin clay layers which impede the movement of water between the Mol and Casterle sand. Therefore the lower half of the Mol sand has a vertical permeability that is reduced significantly by the thin clay layers, but the horizontal permeability is much the same throughout the entire unit. The field studies described below were designed in part to investigate this inference. If the thin clay layers in the lower Mol sand are indeed effective hydrologic barriers, then the Casterle sand must be an artesian or semiartesian hydrologic unit and certainly should be treated separately from the Mol sand in all questions regarding the movement of ground-water contaminants.

*Previous hydrologic studies.* Following the drilling of the test wells at the Eurochemic site in 1959 and 1961, piezometers were installed at various depths down to 80 meters and the wells backfilled. A slow progressive drop in head with depth shows that in this area the shallower aquifers are recharging the deeper ones, but at a very slow rate.

From 1961 to 1963 a number of somewhat generalized water table maps were made [*Simpson*, 1962] showing the gradient of the water table in the C.E.N. area to be about 0.002. The velocity of the ground water, as measured in a few shallow tracer tests of short duration, was about 5 to 10 cm per day. In 1962, variations in the barometric pressure were found to affect the water level in a dug well 2 meters deep, which just penetrated the water table at the barrier test site (Figure 1). The indicated barometric efficiency varied from 100% in winter when the ground was frozen, to 65% in the spring when the ground was very wet, to 50% in August when the ground was damp. The moisture greatly reduces the permeability to air of the fine sand and thin soil zone in the Pleistocene cover so that the Mol sand acts much like an artesian aquifer, even though a careful search has failed to find any clay layer at this site above a depth of 5 meters.

A pumping test was attempted at the Eurochemic site in late May and early June 1962. This was the first such test in the area and owing to lack of previous experience to guide the work the test wells were installed without sufficient regard for the complexities of the aquifer. The tests themselves were either stopped too soon, or in those cases where pumping was continued, little data were recorded during the latter part of the test, and calculation of the results was made without sufficient attention to the limitations of the methods used.

Recalculation of the results suggested that the most serious problems resulted from partial penetration of the aquifer by the pumped well and from the installation of the observation wells which had been screened by chance across the Mol–Casterle contact with the upper half of their screens in the lower part of the Mol sand which contains the thin clay layers.

The permeability of the composite water table aquifer, as determined from the pumping tests of 1962, ranged from 7.6 cm per minute to 0.23 cm per minute. Part of this wide variation is due to a failure to differentiate between the Mol sand and the underlying Casterle sand, a distinction first emphasized in print by Gulinck a year after the pumping test had been run.

Values for the storage coefficient determined from the test varied from 0.42 to $9 \times 10^{-5}$, but the apparently more reliable determinations ranged from 0.01 to 0.07. If the aquifer were under typical water table conditions, the storage coefficient should be about 0.20; if truly artesian, the storage coefficient should be $10^{-3}$ to $10^{-4}$. The apparently more reliable values from the 1962 pumping test are therefore intermediate between those characteristic of a water table and of an artesian aquifer, a somewhat surprising result except that it is in accord with the finding that the moist surface sands act as a partially confining layer. The combined Mol and Casterle sands are referred to as the water table aquifer in this report.

*Plan of pumping test with tracer.* In 1965 the complexities of the water table aquifer were better understood, and it was realized that the Mol and Casterle sands would have to be tested separately. If the thin clay layers in the lower part of the Mol sand had given the appearance of providing an impermeable hydrologic barrier, the problem would have been easy. The two sands could have been tested separately using two pumped wells, one screened in each of the aquifers, and also using two separate sets of observation wells. However, it appeared likely that the creation of an artificial drawdown in one of the sands but not in the other would pull water across from the unpumped sand into the pumped formation in sufficient volume to distort the results. Therefore the pumped well was screened the full thickness of the water table aquifer from the land surface down to the Casterle–Diest contact, so that the two sands were pumped simultaneously, and a tracer was used to determine what proportion of the pumped water was coming from each sand. Although the drawdowns in the Mol and Casterle sands were not identical, the head across the thin clay layers in the base of the Mol was much less than if the sands had been pumped separately.

Tracers can be used in conjunction with pumping tests to obtain answers to other problems; for example, those associated with a partially penetrating screen on the pumped well [*Warren et al.*, 1968].

## PREPARATIONS FOR PUMPING TEST AND UNDERLYING ASSUMPTIONS

After the 200-mm casing of the 1965 test well near the east border of the C.E.N. site had been sunk to 40 meters, it was jacked back to 28 meters (to the Casterle–Diest contact), and the open hole backfilled to this level with clay. A 150-mm plastic well screen 28 meters long was then lowered inside the casing, the annulus filled with pea gravel, and the outer casing removed, leaving a gravel packed well. The well was pumped through a drop pipe that extended nearly to the bottom of the screen so that the full saturated thickness of the Mol and Casterle sands was subject to essentially the same pumping head. An electrically driven centrifugal pump was used, and the discharge was carried by light tubing to the edge of the old sand pit about 200 meters to the southeast. Six plastic observation wells (in the Low Countries virtually all wells now are plastic casing and screens) were installed in pairs at distances from the pumped well of 5, 10, and 15 meters. One well of each pair was shallow and was screened from 4.0 to 4.5 meters deep in the Mol sand just above the thin clay layers. One well of each pair was deep and was screened from 18.0 to 18.5 meters deep, near the middle of the Casterle sand. Later a seventh well was installed 10 meters from the pumped well and screened from 6.0 to 6.5 meters deep, about in the middle of the lower part of the Mol sand containing the thin clay layers (Figure 3).

Four test pumpings were made during May and June 1966. On each occasion a chemical tracer was added to one of the observation wells, and its arrival in the pumped well detected by periodic measurement of the electrical resistance of the water in the pump discharge. The tracer used was a mixture of ammonium chloride, methanol, and water, in such proportions that the mixture has essentially the same density as the ground water. In the first test, during which about 500 cubic meters of water was pumped, the tracer consisted of 8 kilos of ammonium chloride, 20 liters of methanol, and 32 liters of water. In the fourth test, during which 4840 cubic meters of water was pumped, the tracer consisted of 50 kilos of ammonium chloride, 100 liters of methanol, and 200 liters of water. This represents an average concentration of chloride ions in the pump discharge of about 10 parts per million; the peak concentrations were several times the average. The constant temperature of the ground water makes it possible to measure these changes in concentration with confidence. A loose internal connection in the one conductivity cell available was responsible for a large part of the apparently erratic variations in the curves. In later tests in which this chemical tracer, tritiated water, and $^{89}Sr$ were employed simultaneously, all three tracers arrived at the same time, showing that in these clean sands the chemical tracer is not retarded by adsorption.

For the purposes of the following discussion, we will consider that the water table aquifer is actually composed of two separate aquifers. The upper is the saturated portion of the Mol sand, which extends from 3 meters below the land surface to a depth of 9 meters and so is 6 meters thick. The lower is the Casterle sand, which extends from 9 meters to 28 meters and hence is 19 meters thick. We will assume that during the several tests water flowed radially in towards the pumped well and that although the drawdown was greater in the lower aquifer than in the upper, only a negligible amount of water moved down from the upper aquifer into the lower. This is equivalent to assuming that during the short time required for one of these tests the thin clay layers in the lower part of the Mol sand were effectively impermeable. The longest test lasted only for 220 hours (about 9 days), and the difference in head across the clay layers 10 meters from the pumped well was only a little over 0.1 meter, so this is not at all the same as assuming that the clay layers are completely impermeable and that over a period of years and over wide areas the Casterle receives no recharge from the Mol.

This assumption that the Mol and Casterle sands may be considered as separate aquifers, at least over limited periods of time, is so vital to the whole hydrologic study described here that a short additional test was made to investigate the question in more detail. To this end a seventh observation well was installed 10 meters from the pumped well and screened from 6.0 to 6.5 meters below the surface, that is, about in the middle of the lower part of the Mol sand containing the thin clay layers. The main well was then pumped for a little over 8 hours, and the drawdown was recorded in all three wells 10 meters from the pumped well. Figure 4 shows the results plotted on rectangular coordinates. There is slightly more drawdown in the 6.5-meter-deep well (10*M*) than in well 10*S*, but the plots are generally similar and clearly differ from the plot of the drawdown in the 18.5-meter-deep well (10*D*). Of considerable interest is the almost instantaneous drawdown of 0.2 to 0.3 meter in well 10*D* when pumping started, a feature characteristic of an artesian as opposed to a water table aquifer. In any case this test tends to confirm the validity of dividing the water table aquifer into two separate aquifers.

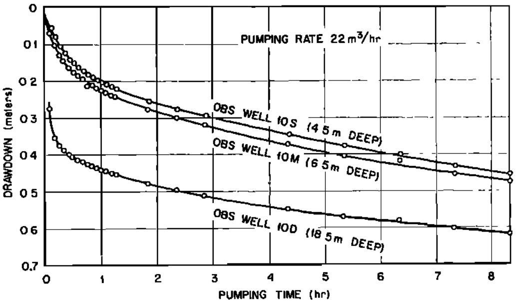


Fig. 4. Comparison of drawdowns in observation wells 4.5, 6.5, and 18.5 meters deep located 10 meters from scavenging well.

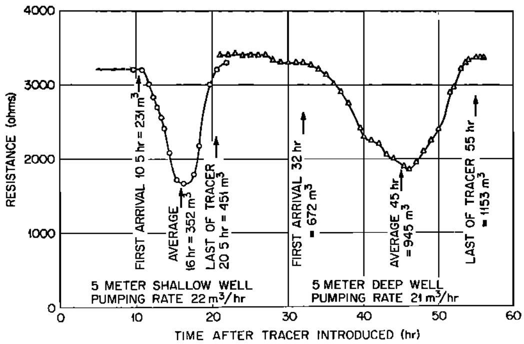


Fig. 5. Tracer breakthrough curves, wells *5S* and *5D*.

### OPERATION OF THE TEST

In the first test the tracer was added to the shallow well 5 meters from the pumped well (well *5S*). The pumping rate averaged 22 cubic meters per hour. The tracer was first detected after 10.5 hours, or after 231 cubic meters of water had been pumped. The last of the tracer was seen after 20.5 hours and 451 cubic meters. The average travel time, which came slightly ahead of the peak of the tracer concentration because the peak on this occasion was not quite symmetrical, arrived after 16.0 hours when 352 cubic meters of water had been pumped. This last value is the one that is most useful (Figure 5).

A vertical cylinder of the upper aquifer 6 meters high, with a radius of 5 meters (the distance to the observation well used for tracer injection) and with a porosity of 35%, contains 165 cubic meters of water. However, to pump out this much water from the upper aquifer it was necessary to pump 352 cubic meters from the well, since both the upper and lower aquifers contributed water. Therefore the lower aquifer contributed 187 cubic meters while the upper aquifer was contributing 165 cubic meters. The pumping rate from the upper aquifer was 165 cubic meters divided by 16.0 hours, or 10.3 cubic meters per hour. The pumping rate from the lower aquifer was 187 cubic meters divided by 16.0 hours, or 11.7 cubic meters per hour. The upper aquifer is 6 meters thick, and the lower aquifer 19 meters thick. The ratio of their permeabilities is consequently the ratio of 165 divided by 6 to 187 divided by 19, or 2.78. The pumping rates determined from this tracer test were used in the interpretation of the pumping test described below; the three other tracer tests were used only to check the validity of the results of the first tracer test.

In the second test the tracer was added to well *5D*, the small diameter well, 5 meters from the pumped well and screened between depths of 18.0 and 18.5 meters. The average pumping rate was 21 cubic meters per hour. The average arrival time for the tracer was 45 hours, during which time 945 cubic meters was pumped (Figure 5). A saturated cylinder of sand with a radius of 5 meters, a height of 19 meters, and a porosity of 35% contains 522 cubic meters of water. The pumping rate from the upper aquifer was 9.4 cubic meters per hour and from the lower aquifer 11.6 cubic meters per hour. This time the upper aquifer provided 45% of the water, and the lower aquifer 55%. The ratio of the average permeability of the sand in the upper aquifer to the sand in the lower aquifer is 2.56.

In the third test the tracer was introduced into well *10S*. The average arrival time of the tracer in the pumped well was 78 hours, or after 1560 cubic meters of water had been pumped (Figure 6). The average pumping rate for this test was 20 cubic meters per hour. The upper aquifer at a pumping rate of 8.5 cubic meters per hour supplied 42.4% of the water, while the lower aquifer, at a pumping rate of 11.5 cubic meters per hour, supplied 57.6%. The ratio of the average permeability of the upper aquifer to the lower aquifer was 2.32.

In the fourth and final test of the series, the tracer was introduced into well *10D*. The aver-

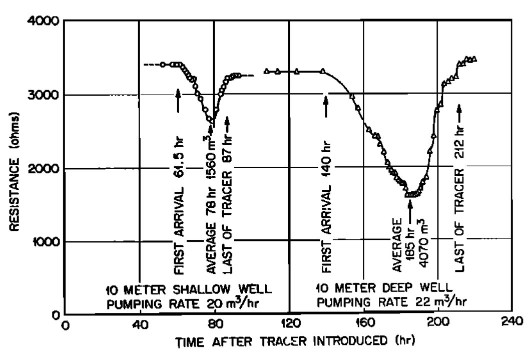


Fig. 6. Tracer breakthrough curves, wells *10S* and *10D*.

age arrival time of the tracer in the pumped well was 185 hours, or after 4070 cubic meters of water had been pumped. The average pumping rate for this test was 22 cubic meters per hour. The upper aquifer at a pumping rate of 9.3 cubic meters per hour supplied 45% of the water while the lower aquifer at a pumping rate of 11.3 cubic meters per hour supplied 55% (Figure 6). The ratio of the average permeability of the upper aquifer to the lower aquifer was 2.75.

The ratio of permeabilities ranged from 2.78 to 2.22, and the percent of total water pumped furnished by the upper aquifer ranged from 47% to 42.4%. This relatively small variation in results, which depends in part on the validity of the assumptions used in the calculations, suggests that the assumptions are justified for the conditions of the test.

During the first test, in which the tracer was introduced into well 5S, the changes in water level with time were measured at frequent intervals in all six observation wells then available. This, with the pumping rates as determined with the aid of the tracer, made it possible to calculate the transmissibility, permeability, and storage coefficients for both the upper and the lower parts of the water table aquifer, that is, for the Mol and the Casterle sand.

CALCULATION OF RESULTS

Figure 7 shows the drawdown observed in the shallow observation wells located 5 meters, 10 meters, and 15 meters from the pumped well. The drawdown is plotted in meters on a linear scale, and the time in hours on a logarithmic scale to permit determination of the transmissibility, permeability, and storage coefficient by use of the *Jacob* [1950] method. When the points representing the individual water level readings in an observation well are so plotted, in general it will be found that after a certain time they fall on a straight line. In the case of Figure 7 the readings taken prior to about 3 to 10 hours of pumping do not fall on this line and should be disregarded. Two values are obtained from each straight line drawn through the later points. One is the intercept of the

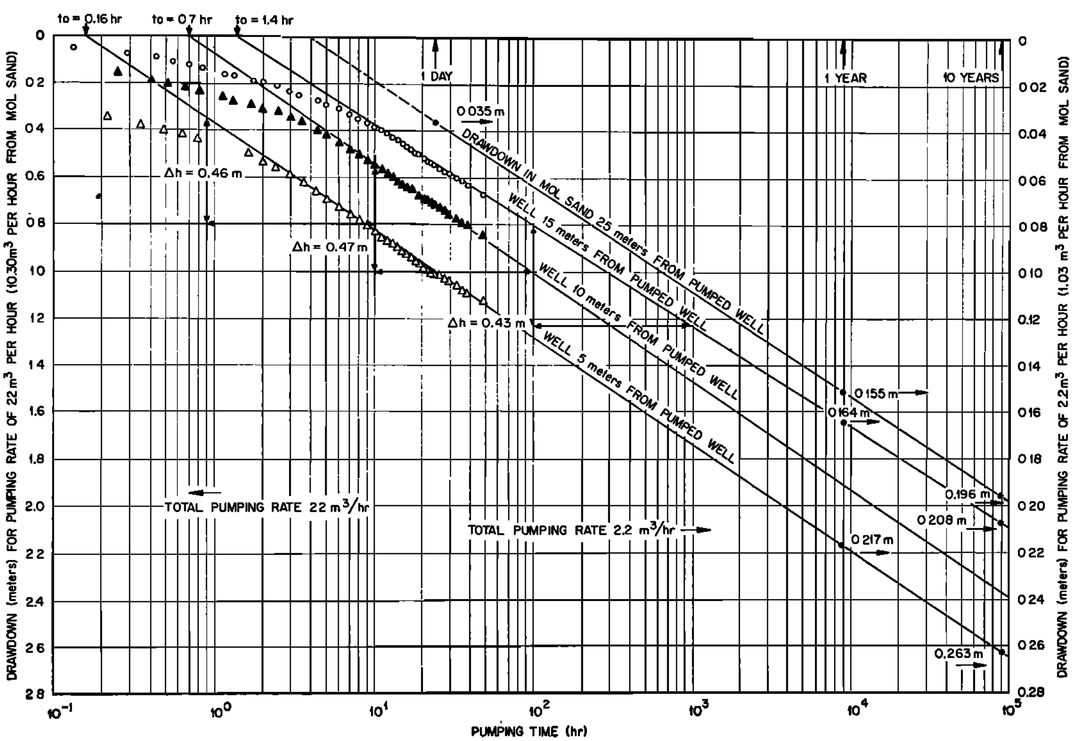


Fig. 7. Drawdowns, wells 5*S*, 10*S*, and 15*S*.

TABLE 1. Summary of Drawdowns in Six Observation Wells

| Well | $t_0$, hr | $\Delta h$, m | $Q$, m³/hr | $T$, m²/hr | $S$ |
|---|---|---|---|---|---|
| 5 *S* | 0.16 | 0.46 | 10.3 | 4.10 | 0.059 |
| 10*S* | 0.7 | 0.47 | 10.3 | 4.01 | 0.0631 |
| 15*S* | 1.4 | 0.43 | 10.3 | 4.38 | 0.0614 |
| 5*D* | 0.016 | 0.35 | 11.7 | 6.12 | 0.0088 |
| 10*D* | 0.11 | 0.34 | 11.7 | 6.3 | 0.0148 |
| 15*D* | 0.23 | 0.315 | 11.7 | 6.8 | 0.0156 |

line, extended, with the time axis, called $t_0$ (0.16 hour for well 5*S* in Figure 7), and the other is the slope of the line represented by the observed drawdown during one log cycle on the time scale, called $\Delta h$ (0.46 meters for well 5*S* in Figure 7).

The method of calculating the transmissibility, permeability, and storage coefficient by the Jacob method is well known and need not be explained here. The relevant equations in the metric system are

$$T = \frac{0.183Q}{\Delta h}$$

and

$$S = \frac{2.25Tt_0}{r^2}$$

where $T$ is the transmissibility in square meters per hour, $t_0$ is the intercept of the straight line with the time axis in hours, $r$ is the distance from the pumped well in meters, and $Q$ is the pumping rate in cubic meters per hour.

From the drawdown observed in well 5*S* (Figure 7) $t_0 = 0.16$ hr, $\Delta h = 0.46$ meter, and $Q$ from the tracer test $= 10.3$ cubic meters per hour. From these data $T$ may be calculated as 4.10 square meters per hour, and the permeability as 0.683 meter per hour or 1.14 cm per minute. The data obtained from the drawdowns in the six observation wells is summarized in Table 1, and the calculated results in Table 2. The semilogrithmic plots from the three deep wells are shown in Figure 8.

As a first approximation and as a rough check on the validity of the various assumptions on which these calculations are based, it is of interest to compare the relative proportions of the water pumped from the Mol and Casterle sand with their relative transmissibilities, as determined by the pumping test. From the four tracer tests the Mol sand appeared to furnish an average of 45% of the water pumped, while the Casterle furnished 55%. The average transmissibility of the Mol sand was calculated to be 4.16 square meters per hour, and that of the Casterle sand 6.41 square meters per hour, giving a combined transmissibility of 10.67 square meters per hour. The Mol sand contributes about 40% of this transmissibility and should therefore contribute 40% of the water, not 45% as determined by the average of the transfer tests. Similarly the Casterle contributes 60% of the total transmissibility but only 55% of the water, as measured by the tracer tests. Although closer agreement of these values would be a matter of satisfaction, so many assumptions, which are at best only approximations, must be made to carry out the calculations that even this rough agreement gives some assurance that we are justified in subdividing the water table aquifer into the Mol and the Casterle sand, and in treating these as essentially independent aquifers where short periods of time are involved. The agreement, although rough, also suggests that the permeabilities and storage coefficients as calculated are probably substantially correct.

## NATURAL GROUND-WATER VELOCITIES

Having determined these properties, the next question is: What conclusions of practical interest may we deduce from them? One use is

TABLE 2. Summary of Results of Pumping Tests, May 16, 1966

| | Transmissibility, m²/hr | Permeability, cm/min | Storage Coefficient |
|---|---|---|---|
| Mol Sand | | | |
| Well 5*S* | 4 10 | 1.14 | 0 059 |
| Well 10*S* | 4.01 | 1.115 | 0 0631 |
| Well 15*S* | 4.38 | 1.22 | 0 0614 |
| Average | 4.16 | 1.16 | 0 0612 |
| Casterle Sand | | | |
| Well 5*D* | 6.12 | 0.537 | 0 0088* |
| Well 10*D* | 6.30 | 0 552 | 0 0148 |
| Well 15*D* | 6.80 | 0 596 | 0 0156 |
| Average | 6.41 | 0.562 | 0 0131 |

* This value probably should have been disregarded in computing the average, since the values obtained from wells 10*D* and 15*D* should be more accurate, these wells being more distant from the pumped well.

to calculate the probable rate of movement of the ground water. Over much of the area of interest the water table gradients are of the order of 0.002. Therefore, taking the porosity as 35%, ground-water velocity $V$ (Mol sand) $= 1.16$ cm/min $\times$ 0.002 $\times$ 1/0.35 $\times$ 1440 min/day $=$ 9.55 cm/day, which is about the velocity measured over short distances with various tracers. In the Casterle sand the velocity will be reduced by the ratio of the permeabilities. $V$ (Casterle sand) $=$ 9.55 cm/day $\times$ 0.562/1.16 $=$ 4.63 cm/day. No tracer velocity tests have been made in the Casterle.

### DESIGN OF A HYPOTHETICAL SCAVENGING SYSTEM

Now that the hydrologic properties of the two parts of the water table aquifer have been quantitatively determined, it is possible to design a scavenging system.

If the hypothetical accident were to release a liquid contaminant in an area roughly 20 meters in diameter, the results of the test in which the tracer was added to well 10$S$ could be applied directly. There is some measure of assurance that the contamination would for a period of weeks, months, or even a year or so be largely confined to the Mol sand. A well 9 meters deep installed at the center of the contaminated area could then be pumped at any convenient rate, say 2 cubic meters per hour, until a total of 780 cubic meters of water had been removed from the Mol sand. This volume would not only remove the water in a cylinder of the Mol sand with a radius of 10 meters (660 cubic meters) but would also be sufficient to make allowance for the hydrodynamic dispersion, as represented by the trailing edge of the tracer, which came through with the pumped water after the peak concentration of the tracer had passed (Figure 6). Indeed, this direct determination of the amount of longitudinal dispersion to be expected under field conditions is of sufficient value by itself to warrant the use of the tracers.

If the ground water under a larger area had to be cleaned up by scavenging, other factors must be considered, and more sophisticated methods employed. One properly located well could be used to scavenge an area much larger than 15 meters in radius, but if wide areas are to be cleaned up by one well, considerable time will be required to produce the drawdown depression, and some of the contamination may escape. Also, if only one well is used, there is a real danger in an area like Mol that the cone of depression will intercept one of the many

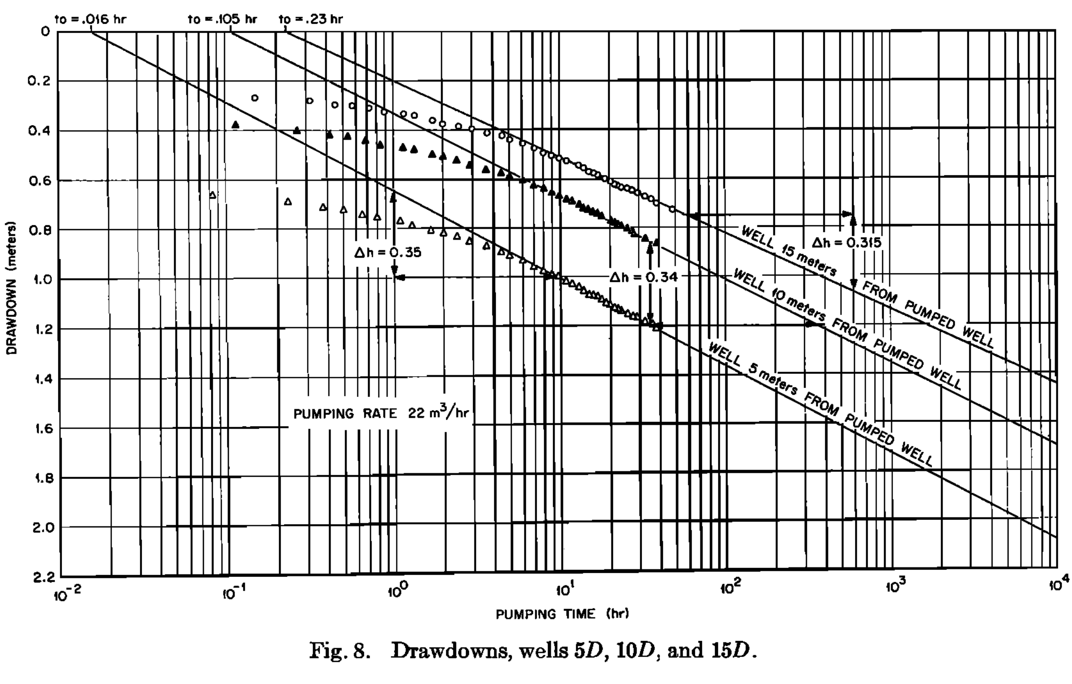


Fig. 8. Drawdowns, wells 5$D$, 10$D$, and 15$D$.

canals, lakes, or streams. For these and other reasons a row of wells is preferable.

Let us imagine a row of wells fully penetrating both sections of the water table aquifer and each pumped at a rate of about 2.2 cubic meters per hour. If 10 such wells were spaced 30 meters apart, they would form a hydrologic barrier about 300 meters long, to which we can apply directly the results of our field tests. The drawdown around a pumping well is directly proportional to the rate of pumping so that we can use the plots of the data from the pumping test by dividing the vertical scale by 10 (right side Figure 7). The effects of pumping for a longer period of time may be obtained by extending to the right on Figure 7 over several more log cycles the straight lines obtained by the semilogarithmic plots of the field test data. (This assumes that the storage coefficient will remain constant; see below.) Thus we see that after one year of pumping the drawdown in a shallow observation well 15 meters from the pumped well will be 0.164 meter and after 10 years the drawdown will be 0.208 meter. For a deeper (18.5 meters) observation well at the same distance, the equivalent drawdowns will be 0.144 meter and 0.175 meter (Figure 8). If the observation well is located halfway between two pumped wells 30 meters apart, the total drawdown will be just twice the values given, for drawdowns are directly additive. A 30-meter spacing would appear to offer more than enough drawdown to ensure a gradient toward each of the pumped wells sufficient to prevent contaminated water from passing between any two of them. In practice, two or more observation wells might be screened at different depths between each pair of pumped wells, and the pumping rate from each well adjusted to the minimum safe value. The minimum safe drawdown may be approximated rather easily. As can be seen from the spacing of the water table contours (Figure 1), the natural water table gradient would therefore be responsible for a drop of about 0.03 meter at a distance of 15 meters. The change in water level at 15 meters from a single pumped well after only one day is over 0.05 meter, more than enough to overcome any natural gradient. However, as discussed in the final section of this report, this value must be used with caution.

For the drawdown at a point more distant from the pumped well, one need only return to the basic formulas. Remembering that

$$S = \frac{2.25Tt_0}{r^2}$$

then

$$t_0 = \frac{r^2S}{2.25T}$$

For the Mol sand, at distance of 25 meters from the pumped well,

$$t_0 = \frac{625 \text{ m}^2 \times 0.0612}{2.25 \times 4.16 \text{ m}^2/\text{hr}} = 4.06 \text{ hr}$$

The value of $t_0$ is independent of the pumping rate. If the fully penetrating well is being pumped at a rate of 2.2 cubic meters per hour, the Mol sand is contributing water at a rate of 1.03 cubic meters per hour.

$$T = \frac{0.183Q}{\Delta h}, \quad \text{or} \quad \Delta h = \frac{0.183Q}{T}$$

$$\Delta h = \frac{0.183 \times 1.03 \text{ m}^3/\text{hr}}{4.16 \text{ m}^2/\text{hr}} = 0.0453 \text{ m}$$

Actually, $\Delta h$ is the same for all observation wells regardless of their distance from the pumped well. All the lines on Figures 7 and 8 should be parallel. Also, $t_0$ is proportional to $r^2$, so it may be calculated more easily than is done above.

A straight line starting from $t_0 = 4.06$ hours with a slope of 0.0453 meter per log cycle (on the 2.2 cubic meters per hour total pumping rate scale) shows that for an observation well in the Mol sand 25 meters from the pumped well after one day the drawdown will be 0.035 meter; after one year it will be 0.155 meter; and after 10 years it will be 0.196 meter, if the fully penetrating (28 meters deep, all screened) scavenging well is pumped at a rate of 2.2 cubic meters per hour. This graphic solution, based on the Jacob method of handling pumping test data, will not serve to predict the drawdown to be expected for the first few hours or days of pumping, but it is satisfactory for the present problem. The results of the above calculation suggest that the scavenging wells could be located 50 meters apart. However, the total volumes to be pumped would be much the same if the goal is to scavenge all of a given body of contaminated ground water, and in practice the added flexibility of the closer spacing would far outweigh the small cost of the additional wells required.

The volume that would have to be pumped from a line of wells along one side of a contaminated area may be calculated on the assumption that half of the water comes from each side of the barrier. A line of wells is suggested because the calculations are simple; in practice a more complex pattern might be used. If the contaminated area is contained within a square area 300 meters on a side, the total volume of water contained, assuming the actual thickness and porosity of the water table aquifer at Mol, will be 300 meters × 300 meters × 25 meters × 35%, or about 800,000 cubic meters. Since an equal volume of water will have to be pumped from the other side of the barrier, the total to be pumped will be 1,600,000 cubic meters which at a rate of 22 cubic meters per hour from the 10 wells will require about 82,000 hours, or nearly 10 years. To make allowance for longitudinal hydrodynamic dispersion this volume should be increased by roughly 25%.

A line of wells along one margin of the contaminated area has been assumed to avoid the need of drilling in contaminated ground. If the wells can be installed directly in the contaminated area, the volumes of water that would need to be pumped and treated could be reduced by about one half.

In the above discussion we have imagined that each of the small scavenging wells would be screened through the full thickness of the water table aquifer, as was the case with the actual pumped test well. As we have seen, such a well draws almost as much water from the Mol sand as from the Casterle sand, but because the saturated thickness of the Casterle is almost three times as great, the pumping would produce a faster rate of flow in the Mol and so scavenge over a wider area. However, if the contamination at its source spread down into both the Mol and Casterle, it would spread more rapidly in the Mol, for the natural rate of movement of ground water in the Mol is faster. Under these circumstances, a line of fully penetrating scavenging wells would clean up both aquifers almost simultaneously. If the Mol aquifer alone were contaminated, the scavenging wells would need to be screened only in this upper sand; if the pumping rate from each well were reduced to 1.03 cubic meters per hour, the values for drawdown and pumping time required would remain unchanged.

Let us assume that 22 cubic meters per hour of contaminated water is to be pumped continuously for 10 years and decontaminated sufficiently so that the effluent can be discharged to the environment. The plant described by *Blanco et al.* [1966] in the proceedings of the conference on treatment of intermediate and low-level wastes may be used as a guide.

Twenty-two cubic meters per hour is about 138,000 gallons per day; the plant Blanco describes has a capacity of 750,000 gallons per day. We may still use this same plant, however, since the extra capacity would offer certain advantages and since reducing its size would not greatly reduce the capital cost, which Blanco places at $388,000. Including the scavenging wells, observation wells, and pumps, we may arbitrarily raise this capital cost to $500,000. The cost of complete treatment with overall decontamination factors of over 1000 for both strontium and cesium is estimated by Blanco at $0.80 per 1000 gallons, or $110 per day at a rate of 138,000 gallons per day. However, at this lower rate the cost per gallon would be higher, so that we may arbitrarily assume a cost per day of $200, to include also the cost of operating and maintaining the scavenging pumps and wells. This represents a cost of $73,000 per year, or $730,000 for 10 years. Including the capital cost of the plant and wells of $500,000, the total cost of scavenging after a major accident would be $1,230,000. This total cost should not be taken too seriously, however, since some real costs, such as those for the many analyses of water samples, have not been included. These calculations do, however, suggest that scavenging would be a practical countermeasure in the unlikely event of serious ground water contamination in the Mol area.

### EFFECT OF TIME ON STORAGE COEFFICIENT

The calculations and conclusions presented above are based on a series of tests, the longest of which lasted little more than a week. The remedial scavenging, however, might well require a period of some 5 to 10 years in the event of a serious accident, and it seems prudent to look for defects in the line of reasoning due to this difference in time scale. A possible or even probable change in the value of the storage coefficient is one example.

As shown, the unsaturated but moist sand lying between the water table and the land surface is poorly permeable to air and gives the Mol sand some of the properties of an artesian aquifer. Since pumping removes water and lowers the water table, sufficient air cannot come in from above to maintain normal air pressure in the partially drained pore spaces above the water table. This prevents normal drainage and reduces the storage coefficient from an estimated possible value of 0.20 to an observed value in the Mol sand of 0.0612. Over a period of months or years, however, air is certain to enter and the pores above the water table will drain to a specific retention of perhaps 0.20. If this happens, how will this change the values calculated for observed drawdown, using the predicted values at the 15-meter shallow well as an example?

The observed drawdown depends on pumping rate, transmissibility, storage coefficient, and time; we are changing only the storage coefficient $S$. The line showing projected drawdown for the 15-meter shallow well in Figure 7 depends on only two calculated values, $\Delta h$ and $t_0$. As we have seen,

$$\Delta h = \frac{0.183Q}{T}$$

and so is independent of $S$; however

$$t_0 = \frac{r^2 S}{2.25T}$$

so that if $r$ and $T$ remain constant, $t_0$ is directly proportional to $S$, the storage coefficient. Therefore if $S$ changes from 0.06 to 0.20, $t_0$ will change from 1.4 to 4.66 hours, or a little more than the value of 4.06 hours, which was the $t_0$ value for a well 25 meters from the pumped well. After one year of pumping the drawdown at the 15-meter shallow well will be 0.150 meter rather than 0.164 meter if the storage coefficient goes from 0.0612 to 0.20, and after 10 years of pumping the corresponding values will be 0.192 meter rather than 0.208 meter. This suggests that an increase with time of the value of the storage coefficient will have no drastic effect on the drawdowns produced by the barrier of pumping wells, but of course these drawdowns should be carefully monitored in any case. The time necessary to establish the pumping depression may be more critical than absolute drawdown.

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