USE OF GRAVITY SHAFTS FOR GROUND WATER RECHARGE

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More and more interest is being shown in artificially recharging ground water sources. The advantage of ready-made storage reservoirs and transmission facilities, free from evaporation and protected against pollution and nuclear fallout, is being evaluated by more and more engineers. In addition to the increasing necessity to conserve our natural water resources by replenishing overdrafts on our ground water sources, and to prevent saline water intrusion, ground water recharge is also practiced for the prevention of subsidence and for the reclamation of wastewater.

Many problems accompany the injection of water into an aquifer. The depth of cover over a previous formation limits recharge methods applicable in an area. Simple spreading may be used where the aquifer is exposed at the surface. Trenches or variously shaped pits may be used when the aquifer is found at a relatively shallow depth. Tubular wells are necessary, however, where the depth of the impermeable cover makes the pit or trench method impractical or too costly.

Pressure injection wells have been most commonly used for these deep formations. This type of well has an advantage in that it may be used as a production well and as a recharge well. Factors that tend to reduce the effectiveness of pressure injection wells are: the "air binding" of the aquifer, which results from gases released from the injected water; the restructuring of the aquifer due to the pressure and velocities inherent in the system; and the penetrating of solids deep into the aquifer that reduce the permeability of the formation. Other problems associated with recharge systems are biological clogging and movement of chemical and bacterial pollution. Problems such as these must be evaluated through continuing research in the laboratory and in full-scale field experiments.

Shafts bored through the impervious cover, penetrating the total depth of a suitable aquifer and filled with a granular material, provide a "natural" type of recharge and should be given careful study. It is anticipated that the "air-binding" associated with pressure injection systems will not be a problem in recharge by the gravity method. The recharge rate for a gravity shaft will be proportionately less than for the pressure type, due to the limited available head. The head loss for the laminar region is proportional to the flow, however, and if the turbulent region is encountered in pressure systems, the head losses will be a function of the square of the flow. Simple gravity shafts will cost less to construct and have fewer or no operation and maintenance costs.

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Study Undertaken

The city of West Fargo, N.D., derives its municipal and industrial water supplies from glacially deposited gravel formations. These water-bearing deposits range in thickness from 70 to 250 ft. and are overlain with approximately 50 to 150 ft. of clay and silt, formerly the bottom of glacial Lake Agassiz. The annual drop in the water table over the past quarter-century has exceeded 1.5 ft., and the city has been considering the construction of a surface-water treatment plant and the extraction of water from the Sheyenne River. Another possible solution under study is a joint surface-water expansion program with the city of Fargo, which has been obtaining its water from the Red River. A third alternative is the recharge of the glacial aquifer with water from the Sheyenne River.

The North Dakota State Water Commission has also been concerned about the depletion of ground water sources in the West Fargo area, as well as throughout the state and, in 1967, co-sponsored a study of gravity shafts. The project was financed through a matching grant from the Office of Water Resources of the U.S. Department of Interior and administered through the North Dakota Water Resources Research Institute. A laboratory study of gravity shafts was conducted by the Department of Civil Engineering of North Dakota State University at Fargo.

Laboratory Investigation

The objective of the study was the evaluation of the hydraulic characteristics of model gravity shafts, prior to possible full-scale field experiments. Model gravity shafts consisting of uniformly graded sands were tested to observe permeability, head-loss gradients, and clogging patterns. Each shaft was filled with a different size sand, and trials were run using waters having specific levels of turbidity.

A 4-in. ID shaft, 4-ft. high, was constructed of plexiglas and fitted along its length with piezometers. The sand was graded into uniform sizes designated as No. 20, 30 and 40 by sieving consecutively through U.S. Standard Sieves No. 16, 20, 30 and 40 and by separating the portions retained on the last three sieves. The shaft was filled to a depth of 3 ft. with one size sand, and then the shaft was backwashed with clean water until the turbidity of the backwash effluent, as measured on a spectrophotometer, indicated 100 per cent light transmittance. The flow of clear water was then reversed until the sand had stabilized and the flow rate had become constant.

Test water having a specific level of turbidity or sediment density was then applied to the shaft, and the head losses were recorded along the shaft length at periodic time intervals. During the first trials, Sheyenne River water was used. The practice of hauling river water to the laboratory by tank truck later proved impractical, and artificially prepared turbid water was substituted. The substitute water was prepared using a mixture of Kaolin and Illite that had a range of particle sizes, as determined by electron microscope analysis, comparable to particle sizes observed in samples of the Sheyenne water. Eighty per cent of the clay particles in the prepared turbid water were determined to be 1–2.5 u and 20 per cent 3–5 u.

Sediment density levels of the applied water were controlled by turbidity measurements and maintained at the following levels (Table 1):

Table 1. Sediment Density Levels.

Light Transmittance per cent	Sediment Density mg/1
80	125
60	265
40	435
20	680

Following each trial, the sand was removed from the shaft in layers, and the amount of sediment trapped in each layer was compared to the head-loss measurements previously recorded.

Test Results

The following curves (Fig. 1) show the variation in head loss, with time for reach of the three sand sizes. Most of the clogging occurred in the top 3 in. of the shaft, as shown by the upper, numbered curves, while the lower curves show a constant head loss, or a slightly increased permeability.

Sediment deposition patterns, as determined from measurements of trapped sediment in the shafts, were found to correspond with the head-loss characteristics recorded along the shaft.

Shaft permeabilities, using clean water prior to each trial, adjusted to a head-loss gradient of unity were found to be as follows (Table 2):

Table 2. Shaft Permeabilities.

Sand Size	Water gpd/sq. ft.
No. 20	14,400
No. 30	4,500
No. 40	3,400

Turbidity measurements on a limited number of water samples taken from the Sheyenne River

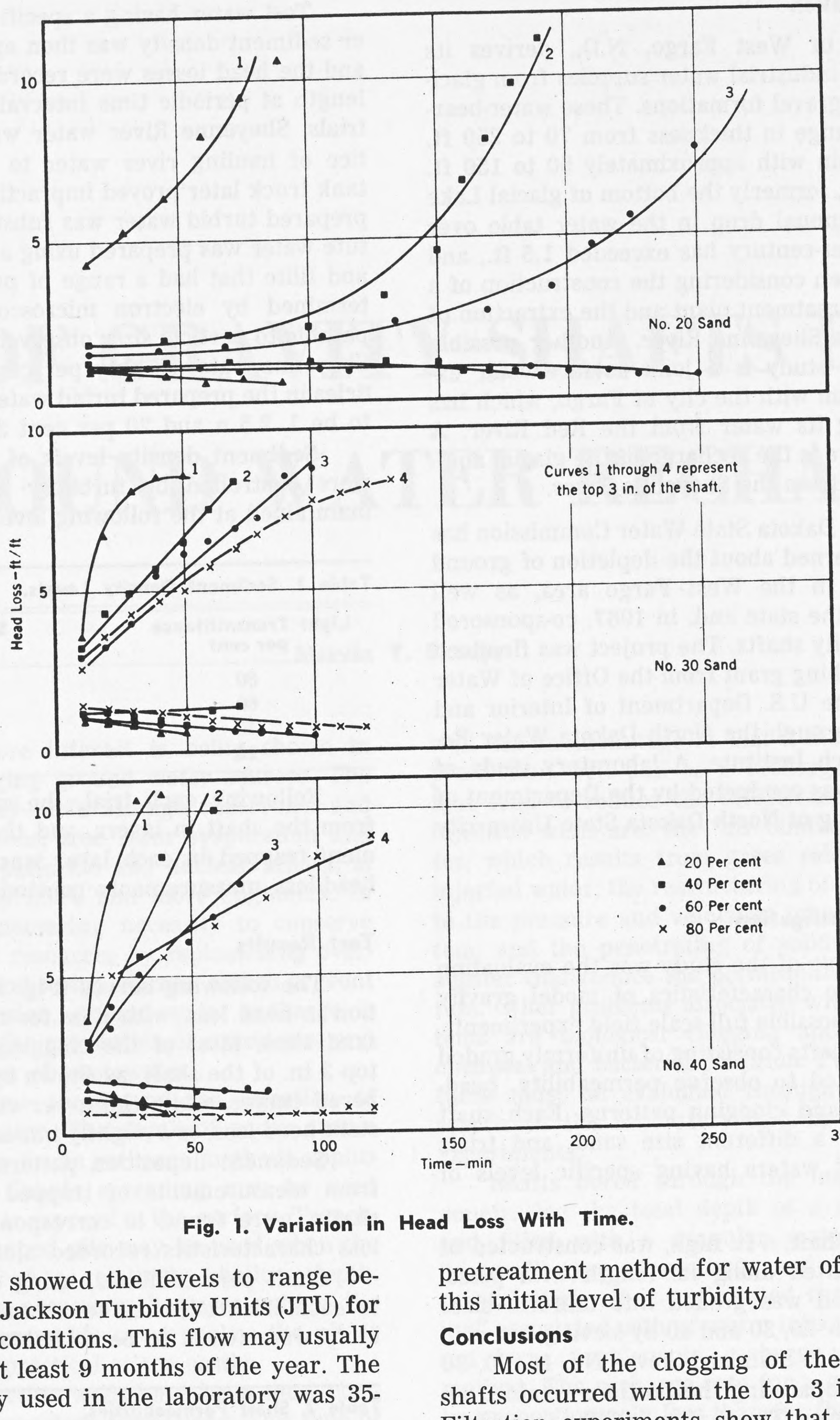

Fig. 1. Variation in Head Loss With Time.

during the study showed the levels to range between 60 and 130 Jackson Turbidity Units (JTU) for the average flow conditions. This flow may usually be expected for at least 9 months of the year. The range of turbidity used in the laboratory was 35-180 JTU.

The rate of clogging increased as the turbidity level increased, and therefore it is desirable to reduce the turbidity level of the applied water. Sedimentation tests conducted on river water having an initial turbidity of 60 JTU produced only a 30 per cent reduction in turbidity, indicating that simple sedimentation is not very effective as a pretreatment method for water of this type with this initial level of turbidity.

Conclusions

Most of the clogging of the model gravity shafts occurred within the top 3 in. of the shaft. Filtration experiments show that the removal of suspended material normally tends to take place in the upper levels of a filter. In these tests, there was an additional factor that contributed to this result. During backwashing and subsequent recompaction of the sand, the sand became stratified in the upper level. Had the shaft been made longer so that a higher backwash rate could have been used, this stratification could have been reduced. Below this upper stratum, the permeability remained constant or was found to be slightly improved.

Theoretical considerations would indicate that the shaft should be constructed of granular material providing the maximum permeability required for flow considerations. The permeability, however, should not exceed that of the aquifer, so that sediment will be trapped in the shaft rather than enter the aquifer. With uniform sizes of sand, the laboratory tests showed the clogging to occur in the top few inches, so that periodic replacement of the upper level of sand may be all that is required to restore shaft permeability. The permeability of the sand, however, would be restricted to that of the aquifer. Increasing the sand size increases the permeability of the shaft and permits a deeper penetration of sediment and provides a greater capacity in the shaft for trapping sediment. These factors suggest two possible shaft designs, based upon either periodic restoration of the shaft by replacing the upper level of sand, or complete abandonment and shaft replacement. These designs provide for graded sands and gravels to maximize the shaft permeability and, at the same time, include a minimum sand size to prevent penetration of sediment into the aquifer.

Shaft Restoration

Assuming that shaft restoration based upon field experiments is the more economical, it would appear best to provide a shaft with coarse gravel and sands at the bottom of the shaft, reducing to a pea gravel and medium sand in the upper 10 to 20 ft. The size of the sand in the top portion of the shaft should be composed of sizes comparable to the aquifer grain size (in this study from 1/16 in. to No. 20 sand). This will provide a filtration level, which may be replaced, preceding the permeable lower level.

As the permeability of this upper layer will be a restricting factor on the capacity of the shaft, it is recommended that the area of this level be increased. This may be accomplishd by having a tapered pit at the top of the shaft filled with fine sand, or a larger diked area above the ground may be provided with a bed of fine sand centered over the shaft, not unlike a slow sand filter. A network of trenches may also be incorporated into the system.

Shaft Replacement

This shaft design would consist of essentially the same sand sizes, but in an inverted order, with the minimum sand sizes extending through the entire thickness of the aquifer. This minimum size should not be greater than the average size of the material contained in the aquifer. This reverse gradation would permit the maximum effective removal and storage of sediment in the upper part of the shaft and, at the same time, protect the aquifer against sediment penetration by filtration through the finer sand. When the shaft flow rate, due to clogging, falls below that required, a new shaft would be drilled. Each shaft however, could be used until the shaft is completely clogged.

Summary

Laboratory tests, in which water having various levels of turbidities were applied to gravity shafts constructed of uniformly graded fine sands, showed that the sediment was trapped in the upper few inches of the shaft. Piezometer measurements of head losses along the shaft during each run and sediment deposition patterns confirmed that the sediment removal was in the upper levels and that the lower levels maintained a constant permeability. The clogging rate was greater for the finer sands and with water having higher turbidities. No "air-binding" of the shafts was noted. Permeabilities of the three sand sizes designated as No. 20, 30 and 40 according to U.S. Standard Sieves were 14,400, 4,500, and 3,400 gpd/sq. ft., adjusted to a head-loss gradient of unity.

Two shaft designs are suggested for field experiments to determine whether periodic restoration of the upper level of the shaft is more economical than abandonment and complete shaft replacement. For shaft restoration, the material at the bottom of the shaft should be coarser to provide maximum permeability, with finer filtering material at the top. The cross-section area of the upper level containing the fine material should be increased to maximize flow rates.

For shaft replacement the gradation should be reversed, with the fine sand extending through the entire depth of the aquifer and the coarser material at the top. This coarse and medium sand will provide a greater storage capacity for sediment and extend the length of shaft operation. The fine sand should not be greater than the average size of the aquifer material, so that sediment will not be carried into the aquifer. Reduction in turbidity levels and sediment particle size will extend the life of the shaft. However, simple sedimentation of the river water having a turbidity level of 60 JTU did not indicate significant improvement in water quality in this study.