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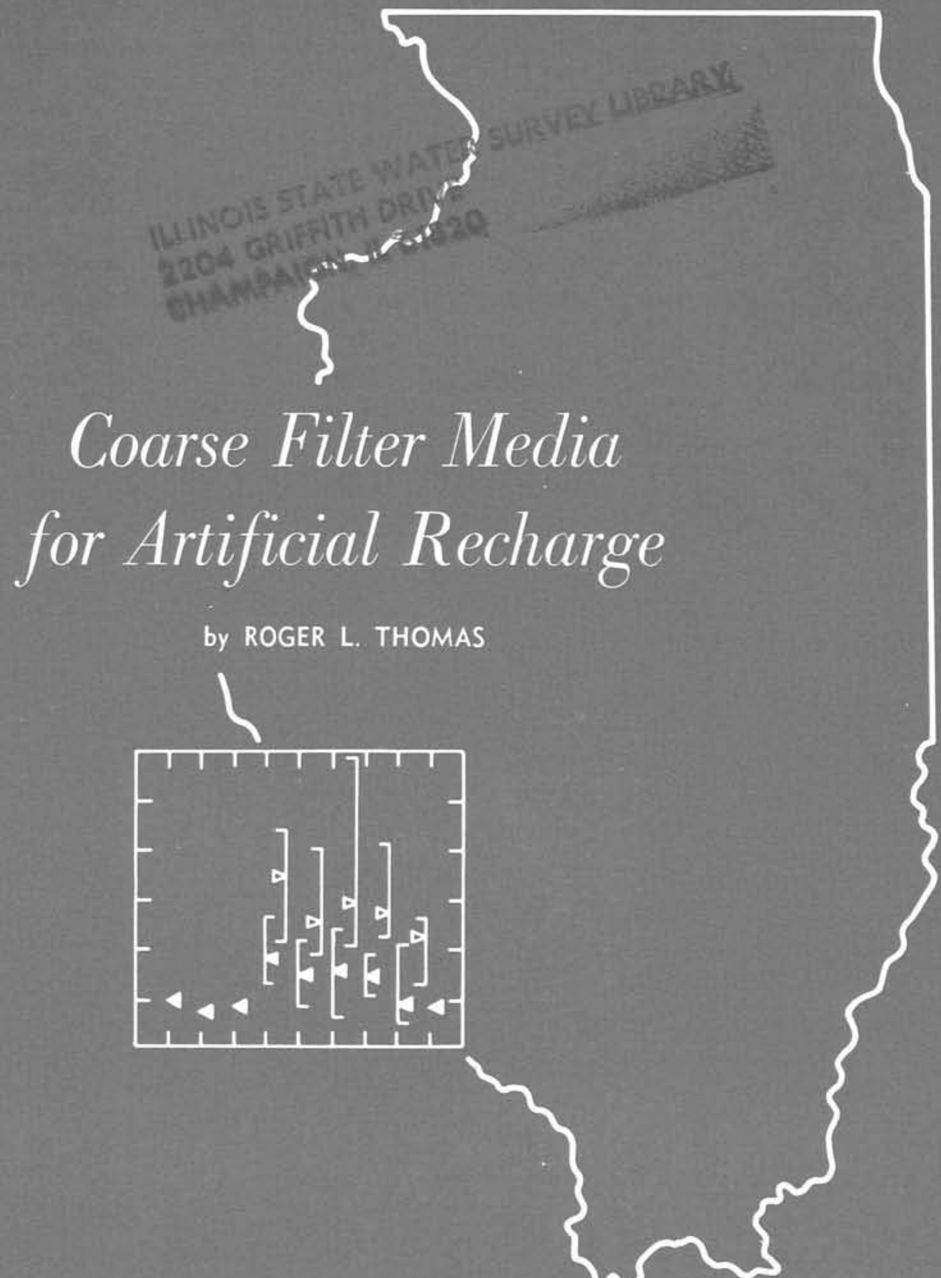

Coarse Filter Media for Artificial Recharge

by ROGER L. THOMAS

ILLINOIS STATE WATER SURVEY
URBANA
1968

REPORT OF INVESTIGATION 60

Coarse Filter Media for Artificial Recharge

by ROGER L. THOMAS

Title: Coarse Filter Media for Artificial Recharge.

Abstract: Artificial groundwater recharge has been used at Peoria for 17 years. The first recharge pit, built in 1951, operated for 3 years with a 6-inch sand filter layer. The filter medium was then changed from sand to a coarse-grained pea gravel, which resulted in increasing the average operating recharge rate from 0.41 to 1.09 mgd. A second pit was built in 1956, and use of the coarse-grained media has continued in both. However, the filtration performance of the coarse media is believed responsible for a continuous decrease in the average operating rate from 1.09 mgd to approximately 0.53 mgd. Laboratory research was conducted on the performance of various sizes and depths of coarse media, and to evaluate the effect on an aquifer of using coarse media filters. An equation relating filter performance to recharge rate, media size, and filter depth was formulated. This equation and operational experience at Peoria provide significant basis for planning future groundwater recharge projects.

Reference: Thomas, Roger L. Coarse Filter Media for Artificial Recharge. Illinois State Water Survey, Urbana, Report of Investigation 60, 1968.

Indexing Terms: artificial recharge, coarse media filtration, groundwater, Illinois, water supply.

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by Roger L. Thomas

ABSTRACT

In 1951 the State Water Survey began the practice of artificial groundwater recharge at Peoria, with one pit. Artificial recharge was needed to augment the depleted aquifer serving the Central Well Field and to maintain an adequate supply of cool, clean groundwater for heavy industrial demands. This first recharge pit was operated for three years with a 6-inch sand filter layer. Because of rapid clogging of the sand and the difficulty of obtaining suitable clean sand, a coarse-grained filter medium has been used from the fourth year on.

A second pit was built in 1956, and the two have operated simultaneously since then. With use of ⅜-inch pea gravel, clogging of the filter layer has been reduced, thereby permitting longer periods of operation and greater quantities of artificial recharge. Between 1951 and 1965, total recharge was over 8.5 billion gallons with 3.795 through Pit 1 and 4.717 through-Pit 2.

However, the advantages of higher recharge rates through the coarse filter media were being lost because of clogging in the underlying aquifer. This new problem called for additional research on the methods of operating artificial recharge pits.

The effects of using coarse filter media in conjunction with artificial recharge were investigated in a laboratory model. Illinois River water was applied to 4-inch lucite filter columns containing various sizes and depths of coarse filter media and aquifer materials. Water analyses were made primarily for cuspended solids and turbidity, although many other physical, chemical, and biological determinations also were made.

Recharge rate, coarse medium size, and coarse medium depth were found to be interrelated functions, from the standpoint of particulate removal efficiency. The relationship can be expressed by the equation:

$$\%\ \textit{Removal of suspended solids} = -34.5 + 29.8 \log D - 44.0 \log d - 35.2 \log R$$

where D = depth, d = diameter of particles, and R = recharge rate.

Very little change in recharge water chemical quality was ascertained during passage through coarse filter media. The depth of silt penetration into the aquifer appeared to be a function of recharge rate, although the major portion of the particulate passing through the fdter media was retained in the upper layers of the aquifer.

An evaluation of the data obtained in this investigation will aid in effective planning for utilization of coarse fdter media with artificial recharge and for prolonging the efficient life of an artificially recharged aquifer.

INTRODUCTION

Artificial recharge is the process whereby the rate at which water enters groundwater storage in a particular area is increased by man's modification of natural conditions. In this report, artificial recharge is considered to be the controlled infiltration of surface water, through recharge pits, into an aquifer.

Ever-increasing pumpage demands on existing groundwater sources, and development of new groundwater sources to meet industrial, municipal, and agricultural needs in the United States have illuminated the need for recharging groundwater aquifers to augment aquifers which are becoming depleted.[1] An industrial complex, with each industry withdrawing large quantities of groundwater for cooling purposes, was faced with the problem of declining groundwater levels some years ago at Peoria, Illinois. Through their cooperative efforts, together with those of the State Water Survey, groundwater conditions have been improved.[2]

Artificial recharge of Illinois River water into the Central Well Field, together with effective conservation measures, was an approach used in Peoria to attack the problem of declining water levels. The operation of high-rate recharge pits has been successfully and continuously maintained since 1951.[3,4] Although the concept of artificially recharging aquifers is not new,[5,6,7] it has not been extensively used in the United States until within the last two decades. And, although it has long been known that the quality of water is generally improved during passage through the soil, only recently have growing demands for improving and maintaining the quality of available surface water led to the practice of introducing surface water to the soil as a means of achieving a desired quality. Induced infiltration, water spreading, and injection wells are some of the commonly used methods of artificial recharge.[6-78]

The use of coarse-grained filter media with high-rate recharge pits has had a fairly recent introduction in this country.[9] The use of coarse-grained media, such as the so-called pea gravel used at Peoria, instead of the more conventionally used fine-grained filter sands, permits a higher recharge rate to be maintained in many cases, depending of course on the characteristics of the underlying aquifer.

Removal of particulates from water used for artificial recharge is a problem regardless of whether the source is surface water or treated waste water. Successful operation of the artificial recharge pits in Peoria, where the river source is often highly turbid, depends on the use of a filtering medium that will protect the aquifer from silt penetration and clogging and from contamination, and at the same time permit high rates of recharge. The balance between the abilities of coarse-grained filter media to prevent silt penetration into the aquifer and to maintain high recharge rates is finite; and if this balance is disturbed, the coarse media may not remove sufficient particulate matter from the influent water to prevent detrimental effects on the aquifer or eventual failure of the recharge operation.

In Peoria, partial and continuous passage of silt, and other suspended materials, through the coarse-grained filtering media has occurred over the years. Obviously, the effective life of the aquifer being artificially recharged with turbid water through coarse-grained filter media is significantly affected by the performance of the media; thus it is necessary that these performance characteristics be investigated, or known.

Purpose and Scope of Laboratory Research

Full-scale or field operations of the recharge pits at Peoria have not provided conclusive evidence of the effects on water quality and aquifer characteristics of using different kinds and sizes of filter media, nor have they defined the optimum balance required between such factors as media size, recharge rate, and amount of silt penetration occurring. Furthermore, there are considerable costs involved in conducting detailed field studies, and an inherent danger that groundwater quality may be unknowingly and unalterably affected. Therefore, controlled laboratory studies have been made in an attempt to determine such factors as the performance characteristics of coarse-grained filter media.

The purpose of this research was to determine the filtration efficiency of coarse-grained filter media used in artificial recharge, and to evaluate the effects of their use on the quantity of water recharged and on the performance of the recharged aquifer. Analyses were made to evaluate physical, chemical, and biological changes taking place in water recharged through coarse media filters and underlying aquifer soils. Factors which vary in field operations, such as intermittent or seasonal periods of recharge, fluctuating turbidity, and ponding or surcharge levels in the pits, were studied in the research, and their effects on recharge were evaluated.

Part 1 of this report presents a review of the artificial recharge operations at Peoria, emphasizing developments subsequent to the publication of Bulletin 48.[3] These developments indicated the need for the laboratory studies on coarse filter media which are reported in Part 2.

Acknowledgments

This research project was conducted under the general direction of William C. Ackermann, Chief, Illinois State Water Survey, and Dr. T. E. Larson, Assistant Chief. The entire staff of the Water Quality Section (formerly Peoria Laboratory) contributed to this project, and their cooperation, suggestions, and criticism are greatly appreciated. The planning and groundwork for this project were done by Mr. Robert H. Harmeson. The initial model construction, model revisions, test preparations, and analytical determinations were done by research assistants, Joseph S. Cutt, Arlin D. Dearing, Bennie E. Darrow, James P. Miller, Michael E. Gregg, and David L. Hullinger. The statistical analysis of the data leading to the design formula was made by Dr. James C. Neill, Survey Staff Statistician. The illustrations were prepared by J. W. Brother, Chief Draftsman. Mr. Ralph L. Evans, Head of the Water Quality Section, and Mr. Harmeson contributed to the final preparation of the manuscript, assisted by Mrs. J. Loreena Ivens, Technical Editor.

The information contained in the annual reports of operation of the Peoria recharge pits distributed by the Peoria Association of Commerce, and State Water Survey Bulletin 48, *Artificial Ground-Water Recharge at Peoria, Illinois*, have been used extensively for background and basic information.[34]

The laboratory research was -supported by Research Grant WP00447 from the Division of Water Supply and Pollution Control, U. S. Public Health Service.

Part 1. Review of Artificial Recharge at Peoria

HISTORY OF RECHARGE PITS

In 1967, there were three pits in operation at Peoria, all using chlorinated river water for artificial recharge. All penetrate the shallow sand and gravel aquifer in which the well fields serving the Peoria area are located, and all are used to supplement natural recharge to the aquifer.

Peoria Water Works Company

The largest pit, owned and operated by the Peoria Water Works Company, is used to augment available groundwater in the vicinity of the company's main pumping station. This pit is adjacent to the Illinois River, and is underlain by the aquifer serving the North Well Field. This recharge pit is operated only when necessary to raise the water table in the vicinity of the main well, which is located about 350 feet from the recharge pit.

The groundwater table in this area is influenced by natural recharge from the river, especially during times of high river stage. Thus, the necessity for operating the recharge pit is principally dependent on river stages and rates of withdrawal from the main well.

The Water Company's recharge pit has been in operation since March 1956. Because its operation is based primarily on water table levels, it can and does operate at any time throughout the year, without regard for river water temperatures. Certain limits have been arbitrarily placed on other qualities of river water which can be used for artificial recharge. Operation of the pit is temporarily suspended if turbidity in the river exceeds 150 Jackson units (Jtu) and/or when the plankton biomass reaches proportions likely to clog the filter medium.

The filtering medium used in the Peoria Water Works recharge pit is a 6-inch layer of sand. Clogging effects are quite pronounced in the filter layer, hence the limitations on turbidity and algae of the applied water. The sand layer must be replaced approximately every two years at a cost of about $9000. The sand layer may be 'skinned' twice before complete replacement is necessary, as a temporary remedy to the clogging action of silt and algal growths. Each skinning, which is simply the removal of a relatively thin top layer of sand, costs approximately $100. The frequency of complete replacement of the sand layer depends on total recharge as well as on preventive operating conditions. Ordinarily, the pit is operated at a recharge rate of about 4.5 million gallons per day (mgd).

State Water Survey

The other two operating recharge pits in Peoria were built by the State Water Survey and are now operated by the city of Peoria engineering department under the direction of the Water Resources and Flood Control Committee of the Peoria Association of Commerce, in consultation with the Water Survey. Operating and maintenance funds are contributed by industrial water users located within the Central Well Field.

The first of these two pits was constructed as a research pit by the state in 1950. The second pit was added in 1956 at the request and expense of industrial water users. Both pits have been operated each winter since their construction. Both are located adjacent to the Illinois River, and within the boundaries of the Central Well Field. Much of the groundwater pumpage in this well field is used for industrial cooling.

Pit 1 has a rectangular bottom which measures 62.5 by 40 feet, and side slopes which are two horizontal to one vertical in the submerged area. The bottom of the pit is 30 feet below grade elevation and 10 feet below normal river pool stage. Water flows to this pit by gravity from the intake caisson, and water stage in the pit is approximately 9 feet, based on 1966-1967 operating season.

Pit 2 also has a rectangular bottom, measuring 73 by 20 feet, and side slopes which are set at three horizontal to one vertical in the submerged area. The bottom of this pit is 22 feet below grade elevation and 5 feet below river pool stage. A 3-mgd pump transfers water to this pit from the intake caisson. The resulting water stage in Pit 2 is approximately 10 feet, also based on the 1966-1967 season.

The bottoms and submerged side slopes of both recharge pits are covered with a 6-inch layer of ⅜-inch pea gravel. Water to be recharged is brought from the Illinois River by gravity flow into a circular intake caisson where it is chlorinated. Additional information and details of operation may be found in Bulletin 48.[3]

These two pits have been operated on a seasonal basis because the primary industrial demands for groundwater are for cooling. Hence, artificial recharge has been limited to those seasonal periods when river water temperatures are in the range between 32 and 65 F. Initially, an upper limit of 60 F was set on river water temperatures, but experience showed that this could safely be raised to 65 degrees. Groundwater temperatures in industrial wells near the recharge pits ranged between

50 and 69 F for the 5-year period 1947-1951. During the next 5-year period, 1952-1956, this range had changed to 39 to 67 F; and in the next 2-year period, 1957-1958, the range was 37 to 64 F.

In 1951, a 6-inch layer of sand was placed in Pit 1. During the first season of operation (1951-1952), this sand layer was cleaned with a swimming pool suction cleaner nine times, and was then replaced by a clean layer of sand midway in the operating season. The second season (1952-1953) was started with clean sand, and the suction cleaner was used, but the sand was not replaced until the beginning of the third season (1953-1954).

The sand filtering medium in Pit 1 was replaced with ⅜-inch pea gravel at the beginning of the fourth season (1954-1955), and this pea gravel was renewed annually for the next two seasons (1955-1956 and 1956-1957). The second pit was placed in operation in 1956. The clean pea gravel, which was placed in both pits at the start of the 1956-1957 season, was used for three operating seasons. Subsequently, the gravel filter layers have been replaced in 1959, 1963, and 1967. The use of sand as the filtering medium was discontinued in 1954, partly because of the difficulty experienced from rapid clogging, and partly because clean sand was hard to obtain from local suppliers.

The multiseason use of the coarse-grained filter medium was based on the premise that each cubic foot was capable of holding 12.5 pounds of silt before its void spaces were completely filled. Therefore, if at the end of a recharge season, the silt load in the pea gravel was determined to be significantly below that level, the gravel was left in place for another season's use. Unfortunately, at that time little was known about the filtration efficiency of the gravel, and considerable amounts of silt were being transmitted to the aquifer before the gravel became saturated. Consequently the ability of the aquifer to accept artificial recharge declined, as indicated in figure 1.

The quantity of recharge in Pit 1 is affected significantly by river stage because of gravity feed to the pit. Periods of high water are not unusual in the late winter and spring months and the water level in Pit 1 is proportionately higher during these periods. Artificial recharge is significantly increased at these times, and the increase is to some extent proportional to the height of the river stage. Apparently natural recharge through the submerged river bank areas is also considerable during high river stages.

Illinois River water used for recharge is chlorinated at an average rate of about 3.5 mg/1. During the 1951-1952 to 1954-1955 seasons, the chlorine application was

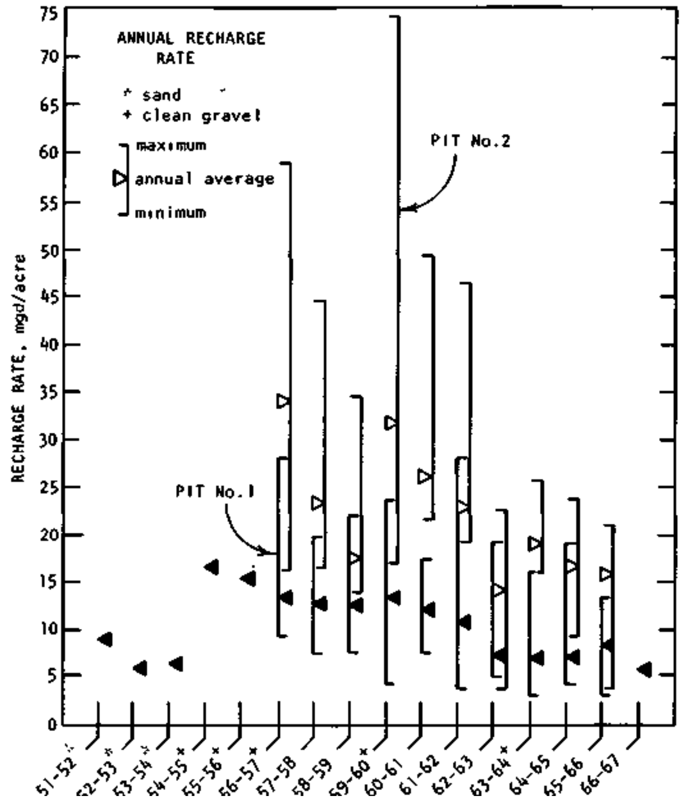

Figure 1. Artificial recharge rates at Peoria

8 to 9 mg/1 and a chlorine residual was found in the groundwater for a short distance from the pits. A well located in the State Water Survey laboratory building, a distance of 235 and 175 feet from the centers of Pits 1 and 2 respectively, is used to monitor groundwater for bacterial contamination. The criterion for acceptable chlorination practice in the pit operation is the absence of coliform group bacteria in samples of water taken from the well. Beginning with the 1954-1955 season and continuing to 1967, the chlorine was added at a rate of from 3 to 5 mg/1. Economic considerations were responsible for investigating the least amount of chlorination that would produce a water of satisfactory quality, and it was found that 3 to 5 mg/1 was adequate.

Because these two pits have been operated as a research facility, as well as a functional facility designed to alleviate a local problem, many data have been kept concerning operating methods and results. These data, together with the problems and phenomena observed during approximately 15 years of operation, furnished a basis for the research outlined in Part 2 of this report. Further mention of artificial recharge in Peoria in this report is intended to refer only to the State Water Survey's operations, and not to those carried on by the Peoria Water Works Company.

RESULTS OF OPERATING RECHARGE PITS

Achievements

Probably the most important result of artificial recharge at Peoria, at least from the industrial user's viewpoint, has been the addition of needed water to groundwater storage and the raising of groundwater levels. Overpumpage of groundwater was estimated to be between 8 and 10 mgd just prior to 1946,[10] and the water table was declining to critically low levels.

Because artificial recharge was only one of several factors responsible for improving conditions of groundwater storage and levels, its contribution has been rather difficult to evaluate and quantify. With one pit, operating only during the cooler months, the daily amount of recharge for a full year was approximately 0.71 million gallons (table 1). With the addition of the second pit, and continuing the same seasonal operation, this amount was increased to approximately 2.97 million gallons.

Table 1. Amount of Artificial Recharge at Peoria

Season	Days of operation	Volume of recharge (mil gal)	Rate per operating day (mgd)	Rate per calendar day (mgd)
Pit 1				
1951-52	146.0	260	1.78	0.71
1952-53	208.5	215	1.03	0.59
1953-54	199.3	208.2	1.05	0.57
1954-55	165.2	365.2	2.21	1.0
1955-56	195.8	422.6	2 16	1.16
1956-57	210.5	370	1.76	1.015
1957-58	213.1	359.2	1.69	0.985
1958-59	199.8	347.8	1.74	0.955
1959-60	225.6	345.6	1.53	0.95 '
1960-61	162.6	246.2	1.52	0.675
1961-62	163.1	234.6	1.44	0.635
1962-63	80.2	66.8	1.93	0.186
1963-64	178.9	171.5	0.96	0.47
1964-65	119.6	117.4	0.98	0.32
Pit 2				
1956-57	273.8	710	2.99	1.95
1957-58	215.7	623.6	2.89	1.71
1958-59	197.3	567.5	2.87	1.56
1959-60	226.7	616.7	2.72	1.69
1960-61	167.1	522.3	3.13	1.43
1961-62	178.2	597.1	3.36	1.64
1962-63	84.9	164.1	2.76	0.45
1963-64	181.8	529.5	2.91	1.45
1964-65	135.2	387.1	2.86	1.06

From a research standpoint, the first utilization of pea gravel as a coarse-grained filter medium in the Peoria recharge pits remains a noteworthy event. Fifteen years of actual field operations, in addition to laboratory research as outlined in Part 2 of this publication, have demonstrated that under controlled conditions, pea gravel can play an important role in the pretreatment of surface water used to augment groundwater reservoirs.

The cost of artificial recharge has been shown to be an economic practice. At Peoria, cost of operation in terms of 1000 gallons of water recharged has slowly decreased from $0.054 to $0.014. This excludes initial costs of land, equipment, and construction of pits. The amounts of artificially recharged water recovered by pumping have not been determined, and it is possible that losses would raise the cost of recovered water. Pumping costs have also been ignored here. With consideration of these factors, however, it is probable that the costs of 'delivered artificially recharged water' will be found at a very attractive level, and competitive with the cost of water from other sources.

Some design factors have been established by closely observing the Peoria pit operations, and basic questions concerning unconfirmed theories have been answered. Two small pits were constructed instead of one large pit so that the effects of interference between two pits could be ascertained. It was thought that a mound of water might be created between two pits from the large quantities of water flowing out from each pit. Test wells provided information indicating that there was no interference (or mound) between the Peoria pits, where the horizontal distance between waterlines is only 150 feet.

The investigation concerning pit interference also supplied data permitting some insight on the pattern of water flow from the pit. Except for recent years, during which the water table has risen so high that the groundwater level is penetrating the pit area itself, the ground immediately under the bottoms of the pits was not found to be saturated during artificial recharge. A free fall flow condition exists in this unsaturated aquifer when water-table levels are below the pit bottom elevation.

The second pit constructed in Peoria was deliberately given a more gentle side slope (3:1) than the first pit (2:1). The increased percentage of the submerged pit area included in side slope had the effect of substantially increasing the rate of water inflow per unit area.

Many observation wells drilled in the immediate and surrounding vicinity of the recharge pits were equipped with water-level recorders. These showed that the rise in groundwater levels within hours, days, and weeks at wells at various distances from the pits were predictably responsive to recharge operations. Start and stop of recharge, as well as increased recharge due to floods, were readily seen on the water-level plots.

Samples of water taken from these wells and direct measurements made in the wells established that the river water did not change very much in chemical quality after being recharged. Therefore, the recharged water could be traced. Generally, the recharged water was found to be flowing in a layer spreading out on top of the existing groundwater, rather than mixing, even though the recharged water was usually colder and thus more dense.

Problems and Questions

Many of the decisions regarding operational problems made in the course of 15 years of artificial recharge at Peoria were largely intuitive since no scientific basis was available. Some of these decisions were made in an attempt to solve immediate and obvious problems, with little thought to the indirect effects resulting from the problem solution.

Typical of this is the level of turbidity in the water used for artificial recharge and its several effects on the process and on the aquifer. Initially, whenever turbidity in the Illinois River exceeded 100 Jtu, recharge operations were temporarily suspended until the turbidity decreased to this limit. If this suspension of operation occurred for several hours during very cold weather, the pit emptied and the wet surface of the sand filter layer became frozen. When artificial recharge was resumed, the near-freezing temperature of the river water prevented the water from thawing the frozen sand filter layer for periods as long as several weeks, thus reducing the total volume of artificial recharge for the operating season.

Freezing of the empty pit surface and the recharge time lost because of this resulted in the decision to abandon turbidity limits and to operate continuously through the entire season. The consequence of this was a need for more frequent cleaning of the sand filter medium, and somewhat lower recharge rates. With the introduction of pea gravel as a filter medium, the recharge rates were greatly improved and measurements of silt retained in the pea gravel indicated that the gravel was not becoming saturated with silt. The consequences of transmitting silt through the coarse filter media and into the aquifer were largely ignored.

Fears of bringing high turbidity water into the pits were dispelled as very high recharge rates continued with the use of pea gravel as a filter medium. However, as was determined later, the resultant high recharge rate did not compensate for the increased penetration of silt into the aquifer. The amount of silt retained in a pea gravel layer, as a percentage of the theoretical silt saturation capacity of the gravel, is not a valid method of measuring the amount of silt penetrating the gravel layer and entering the aquifer. Therefore, elimination of turbidity limits of influent water at Peoria has resulted in a continual silt contamination of the upper portion of the aquifer underlying the pea gravel. It is believed that the pit freezing problem would be less severe with pea gravel than with sand.

Similar to high turbidity problems are problems due to high algae counts in the influent water. Algae and turbidity have the same clogging effect on the permeability of sand and the aquifer underlying pea gravel filters. The algae can be a particular nuisance in the summer and fall, when turbidity is likely to be very low. Algal conditions were reported as having a detrimental effect on recharge at Peoria in the first few operating seasons. Since then copper sulfate has been used when needed, with apparent success.

It has already been mentioned that the percent of silt saturation of a pea gravel filter layer is not a valid indication of the silt passing through the filter medium and into the underlying aquifer. The decision to make multiseason use of pea gravel without cleaning or replacement was based on estimates of the silt load contained in the pea gravel after each season of operation. It was estimated that the gravel used in Peoria would hold 12.5 pounds of silt per cubic foot of gravel, before becoming 'saturated.' Therefore, if at the end of a recharge season the gravel was shown to contain significantly less than this amount, the filter gravel was left in place and used for another season.

This practice has had a significant effect on the recharge rate, expressed in relation to unit area of surface utilized for recharge. Figure 1 depicts the progressive decline in recharge rates and the influence on the rates with each change of the pea gravel medium. It is clear that rate recovery has not occurred in spite of media renewal, suggesting the significance of silt penetration into the aquifer. It has been determined in the field that this clogging effect is confined to the upper portion of the aquifer, just beneath the gravel filter layer.

These findings, together with those of the subsequent laboratory research, strongly suggest that reestablishing some sort of turbidity limit on the water used for artificial recharge may be a necessary part of maintaining adequate and satisfactory operations.

Part 2. Laboratory Studies on Effects of Coarse Filter Media

Problems and questions arising from the Peoria field operations indicated the need for thorough investigation of the use of coarse-grained filtering media to achieve high infiltration rates in artificial recharge pits. The three-year laboratory research project was conducted to determine the principles involved in coarse media filtration and its effects during the recharge process.

These laboratory studies involved four general concerns. The first was for the physical improvement of recharge water by coarse media filtration. In this phase, evaluations were made of the effects of such variables as media size and depth and recharge rate on the efficiency with which coarse filter media might improve the physical characteristics of recharge water. The second concern was to determine any chemical or biochemical changes in the recharge water attributable to coarse media filtration. A third element for study was the effect of varying field operating procedures on the efficiency of coarse filter media. The final phase of the investigation concerned the effect on aquifer materials of the artificial recharge process when coarse filter media are used. On the basis of the findings from these studies, a design formula for the use of coarse filter media in artificial groundwater recharge was developed.

TEST APPARATUS AND PROCEDURES

Laboratory Model and Operation

The effects of coarse media filtration were studied in a series of six 4-inch-diameter filter columns constructed of lucite. These filter columns and some of the equipment and piping used in their operation are shown in figures 2 and 3.

Water for use in the study was pumped from the Illinois River to a 7300-gallon wet well in the laboratory basement, which continuously overflowed to waste. The water in the wet well was recirculated through an 1800-gallon constant head tank on the third floor of the building, and a small quantity of water was drawn continuously from this supply, taken through another small constant head box, and then to the filter columns. This small constant head box (figure 2) was on an adjustable stand to provide a choice of surcharge depths in the filter columns. Overflow from this box was returned to the recirculation system.

The header pipe feeding the six filter columns discharged through a recording turbidimeter, and this discharge was also returned to the system. Rate of flow through each filter column was regulated by an adjustable standpipe arrangement, and effluent from the filter columns was discharged to waste.

Overflow and recirculation of the river water provided a fresh supply with a minimal rate of change in water quality, particularly for turbidity. Heavy barge traffic near the river intake created extreme turbidity variations in the water which required stabilization for a successful laboratory study.

Table 2 lists the quality characteristics of the modified Illinois River water used during the test periods from August 16, 1963, through November 17, 1965. In this report all references to percent removal or reduction of quality parameters are based on the average influent conditions of water quality during the test period.

Table 2. Raw Water Quality Characteristics

Characteristic	Average	Range
Suspended solids, *mg/l*	48	0-236
Turbidity, *Jtu*	80	12-286
pH	7.9	7.5-8.5
BOD (5-day, 20C), mg/*l*	6.0	0.9-12.95
Ammonia nitrogen, *mg/l*	3.7	0.6-6.7
Nitrate nitrogen, *mg/l*	4.9	1.4-14.7
Dissolved oxygen, *mg/l*	9.0	4.1-16.2
Total alkalinity (as $CaCO_3$), *mg/l*	145	112-180
Temperature, *deg C*	13.1	5.0-23.7

The first test made with the research model was exploratory, to verify the reproducibility of results from the six filter columns. All columns were set up with a 24-inch depth of ⅜-inch coarse media and tested with the modified river water at a recharge rate of 0.4 gpm/sq ft. Three of the columns were continuously dosed with a strong chlorine solution, maintaining a concentration of 1 mg/l chlorine in the influent water. The similarity or reproducibility achieved was very good, as depicted in table 3. From this it was determined that the operation of the model itself would cause no variation in the test results.

The model had been constructed so that water samples could be taken through sampling collars at many points throughout the depth of a column (figure 3.) However, after the initial collection of silt in the filter layer, it was difficult to sample from within the gravel without pulling settled material from it, because of the velocity through the sampling collars. It became obvious

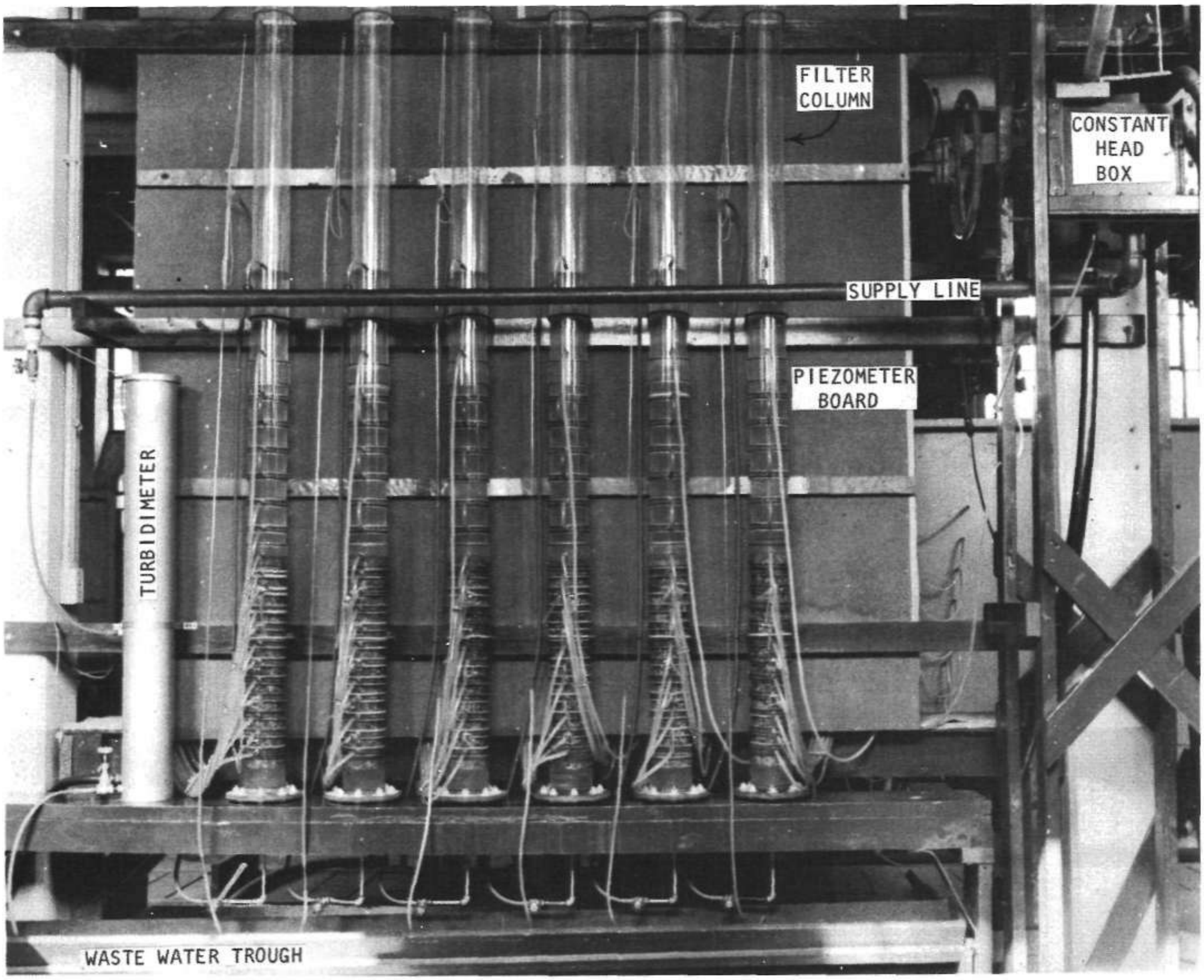

Figure 2. Laboratory research filter columns

Table 3. Results of Testing Six Filter Columns Under Similar Conditions

Characteristic	Col. 1	Col. 2	Col. 3	Col. 4*	Col. 5*	Col. 6*
Average effluent suspended solids, *mg/l*	24	22	22	19	22	20
Average effluent turbidity, *mg/l*	45	45	45	42	42	45
Average effluent total residue, *mg/l*	407	406	398	428	417	404
Average effluent pH	8.2	8.2	8.2	8.1	8.15	8.2
Average effluent BOD, *mg/l*	2.3	2.0	1.2	1.4	1.6	1.5
Average effluent DO, *mg/l*	5.7	5.6	5.5	7.2	7.2	6.8
Loss of porosity in filter media, *percent*	14	19	15	4	14	12
Material collected on filter, *grams*	107	114	115	83	92	106

**Influent maintained with a concentration of 1 mg/l chlorine*

after numerous attempts that it would not be possible to get an accurate sample through these sampling collars. Therefore all water samples for analyses were taken only from the influent and effluent ports of the columns.

An attempt also was made to collect composite samples, but the turbidity made control difficult so that a continuous sample could not be collected. Eventually, instead of the composite samples, grab samples were taken once or twice a day, and reported results are based on grab samples.

Test Procedures and Methods

During the three-year investigation, two series of tests were made. The first, series A, was conducted using the coarse-grained filter media alone. Background information thus obtained was then used in series B, conducted using aquifer material overlain with the coarse media.

Most tests in both series were approximately 500 hours

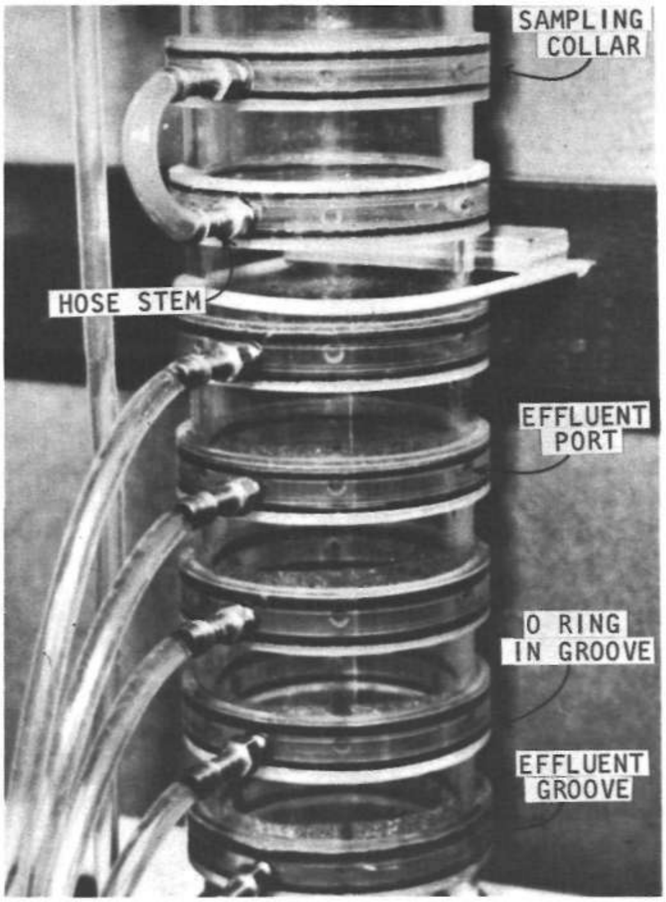

Figure 3. Filter column detail

in duration, although one extended test was run in each series (A-6 Ex, 6070 hours; B-2 Ex, 1822 hours). Table 4 provides a summary of all tests. Test conditions and methods used were as follows:

Sizes of Coarse Media. Local natural gravel was first washed, then graded by sieving. The gravel was passed through sieves of 1 inch, 3/4 inch, 5/8 inch, 1/2 inch, 2 1/2 mesh, 3 1/2 mesh, and 5 mesh. The gravels retained on the sizes under 1 inch were used in this project and designated as 3/4-inch, 5/8-inch, 1/2-inch, 3/8-inch, 1/4-inch, and 3/16-inch coarse media, respectively.

Recharge Rates. The recharge rates used, given in gallons per minute per square foot (gpm/sq ft) of surface exposed to recharge, were 0.05, 0.1, 0.2, 0.4, and 0.8.

Depths of Coarse Media. The depths of coarse media studied were 4, 8, 12, 16, 24, 32, and 45 inches.

Surcharges. Tests were made with free water above the coarse media at heights of 12, 24, 36, 44, 48, and 60 inches.

Chemical Analyses. Quantitative water quality determinations were made using methods outlined in *Standard Methods for the Examination of Water and Wastewater.*[11] Analyses were made for total alkalinity (as $CaCO_3$), residual chlorine, ammonia nitrogen, nitrate nitrogen, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH value, coliform group by membrane filter technique, residue on evaporation, temperature, total suspended matter, and turbidity given in Jackson turbidity units.

Material Collected on Filter. At the termination of each test, the columns were drained and all material in the columns carefully removed. The material was then dried (103-105 C) and weighed. The medium was washed of the accumulated silt and sand particulate matter. After some tests these washings were saved, dried, weighed, fired (600 C), and weighed again to determine volatile material. The washed coarse medium was dried and weighed again. The difference in weight of the medium before and after washing was considered the amount of particulate material collected during the test.

Head Loss. Pressure head readings were made from the piezometer tubes connected to various points on the research columns.

Permeability. Since the filter columns are essentially constant head permeameters, the permeability can be calculated in Meinzer units if the head loss through the material and the water temperature are known. A Meinzer unit is the flow in gallons per day through a cross-sectional area of 1 square foot, under a hydraulic gradient of 100 percent, at a temperature of 60 F. Flow was at a constant recharge rate in all tests and temperature was recorded continually, so permeability can be calculated at any point where head readings were taken during any test. All of these calculations have not been made, however, because of the insignificant head losses encountered.

Porosity. Porosity (n) of the gravel in a laboratory filter column is equal to the volume of the void spaces (V_v) in the gravel divided by the total volume (V) occupied by the gravel in the column. The volume of voids (V_v) in the gravel of a filter column was determined as follows: After all gravel had been placed in the filter columns, they were filled with enough water to completely submerge the gravel and were allowed to stand for 24 hours. Before the water in each column was drawn down to a level exactly at the top of the gravel surface, the columns were tapped gently to release as much as possible of the air and gases entrapped in the voids between and on the surface of the gravel. Then the water between the top and bottom levels of the gravel was drawn off, weighed, and its temperature noted. From the weight and temperature a volume was computed which was assumed to be V_v or the volume of the void space. Total volume of the gravel filter section was computed from the diameter and length of the column occupied by the' gravel. Porosity for each filter column was determined at both the beginning and end of a test in order to estimate change in porosity due to clogging of the void space by solids.

Table 4. Summary of Tests and Conditions*

Test number	A-1	A-2	A-3	A-4	A-5	A-6	A-6Ex	A-7	A-8	A-9	A-10	A-11	A-12	A-13	A-14	A-15	A-16	A-17	B-1	B-2	B-2Ex	B-3	B-4	B-5
Date of testing	1963	1963	1963	63-64	1964	1964	64-65	1964	1964	1964	1964	1964	1964	1964	1964	1965	1965	1965	1966	1966	1966	1966	1966	1966
Start	8/16	10/21	11/18	12/18	1/17	2/12	2/12	3/12	4/10	5/14	6/10	7/8	8/20	10/5	12/1	1/19	4/19	10/27	2/21	3/22	3/22	4/20	5/16	7/20
Stop	9/17	11/11	12/9	1/8	2/1	3/4	11/17	4/2	5/1	6/4	7/1	7/29	9/10	10/26	12/22	2/9	5/11	11/17	3/14	4/12	6/6	5/11	6/6	8/10
Total hours of test	767	508	505	504	386	507	6070	504	506	507	499	498	502	507	505	505	526	500	507	501	1822	502	504	506
Recharge rate	0.4	All	All	All	All	All	0.2	.05,.4, .8	.05,.4, .8	0.1	0.2	0.4	0.1	.2,.4	All	0.2	.1, .2,.4	0.2	All	Free	Free	0.1	Free	0.2, Free
Size of coarse media	3/8	1/4	3/8	1/2	5/8	3/4	1/4	1/4, 3/8, 1/2	1/2, 5/8, 3/4	1/4	3/8	1/2	1/4	3/8, 1/2	3/16	Mixed	1/4, 3/8, 1/2	1/4	1/4	1/4	1/4	1/4	1/4	1/4
Depth of coarse media	24	24	24	24	24	24	24	24	24	All	All	All	24	All	24	20,24	16, 32,45	12	12	8	8	8	6,8	8
Underlying aquifer depth																			21	21	21	All	36,48	All
Surcharge	44	44	44	44	44	44	44,65	44	44	44	44	44	All	44	44	44	44	56	36	36	36		33,46	
Special conditions	Cl_2	Cl_2	Cl_2															Cl_2						
Analyses made:																								
Turbidity	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Suspended solids	√	√	√	√	√	√	√			√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Head loss		√	√	√	√		√			√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Collected particulate	√	√	√	√	√	√	√	√	√	√	√	√		√	√		√	√						
Dissolved oxygen	√	√	√	√	√		√	√				√		√	√	√	√							
Biochemical oxygen demand	√	√	√	√	√	√	√	√	√	√	√	√		√										
Chemical oxygen demand							√			√	√	√												
pH	√	√	√	√			√							√	√	√	√							
Total alkalinity															√	√	√							
Ammonia nitrogen			√	√	√	√	√	√	√		√													
Nitrate nitrogen			√	√	√	√	√	√	√		√													
Coliform bacteria			√	√			√				√	√												
Media porosity	√	√	√	√	√	√									√									
Total residue	√				√								√						√	√				
Residual chlorine	√																	√						
Temperature	√	√	√	√	√	√	√	√		√				√	√							√		√

**Notes*

1) The word 'all' for the respective conditions includes the following:

Recharge rates — 0.05, 0.1, 0.2, 0.4, 0.8 gpm/sq ft

Media depths — 4, 8, 16, 32, 45 inches

Aquifer depths — 12, 24, 48 inches

Surcharges — 12, 24, 36, 48, 60 inches

2) The word 'free' indicates a self-regulating recharge rate

Factors Affecting Test Results

During this investigation of coarse media filtration, studies were made to determine the amount of turbidity-causing solids, suspended material, and particulate matter removed from recharge water by coarse media filter layers. Determinations were based on only the *amount* of solids removed, without regard to size or type of solids.

However, it soon became obvious that there was considerable variation in the characteristics (size, weight, shape, type) of the particulate materials in the river water. This would be expected in a surface water affected by river velocity, type of watershed, climate, precipitation, season, regulatory flow structures, and other variables. It is believed that the controlled laboratory studies have minimized the effects of these factors and that the conclusions drawn are reliable and representative descriptions of the overall effects of coarse media on artificial recharge.

The natural variations and fluctuation in the size and type of particulate material in the influent recharge water caused some deviation for individual tests, as is pointed out in the data discussions, but generally constant relationships were developed from the data as a whole.

Throughout the investigation, for a given set of conditions, the effluent turbidity and suspended solids were related to, and dependent upon, the influent turbidity and suspended solids. The graphical representation of suspended solids concentration for influent water versus effluent, shown in figure 4, depicts a linear relationship, indicating a generally constant range in the percentage of removal. Turbidity showed a similar relationship. The magnitude of the reduction expressed as percent removal varied with recharge rate, media size, and media depth, and was reflected graphically by a change in slope. This relationship within limits of observations was found to hold in all tests.

A consistent relationship between suspended solids and turbidity was found in this investigation. Because the research work was spread out over a period of about 36 months and included many types of river conditions, it provided a representative sampling of the Illinois River water. Comparison of analyses for turbidity and suspended solids during the project showed that the ratio between these two parameters was fairly constant, with a 10 percent variation. The data (table 5) indicate that the suspended solids, in mg/1, of Illinois River water

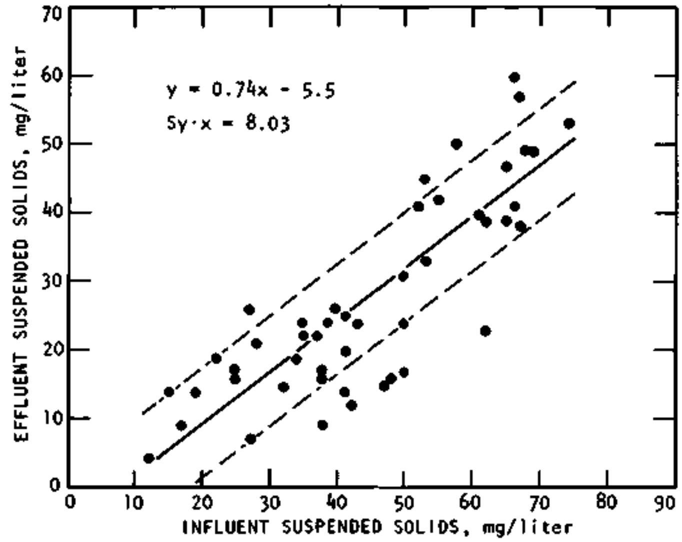

Figure 4. Relationship between influent and effluent suspended solids

is 63.4 ±10 percent of the turbidity level, on the average, for all conditions. Any consistent relationship for turbidity conditions should therefore hold fairly close for suspended solids, and the two parameters have been discussed interchangeably in this report.

Table 5. Relationship Between Suspended Solids and Turbidity

Test	Suspended solids (mg/l)		Turbidity (Jtu)		Ratio of avg. sus. solids to avg. turbidity
	Range	Average	Range	Average	
A-1	12–74	40	30–166	73	54.8
A-2	24–50	35	38–80	60	58.4
A-3	37–76	55	63–120	83	66.3
A-4	24–67	38	33–88	52	73 0
A-5	17–66	46	48–99	68	67.6
A-6	26–50	39	46–80	64	61.0
A-7			80–150	104	
A-8			63–173	119	
A-9	12–71	38	15–82	52	73.0
A-10	9–73	40	12–91	54	74.0
A-11	8–52	30	12–73	42	71 5
A-12	0–40	21	19–54	39	53.9
A-13	18–58	32	39–92	60	53.4
A-14	38–76	52	58–110	85	61.2
A-15	78–236	129	126–286	199	64.9
A-16	34–79	48	71–115	89	54.0
A-17	60–109	80	95–150	120	66.6
B-1	38–225	93	61–428	151	61.5
B-2	61–226	104	110–348	163	63.8
B-3	30–212	66	60–270	100	66 0
B-4	19–54	36	43–116	64	56.3
B-5	22–49	38	44–75	57	66.6
Average					63.4 ± 10.0

PHYSICAL IMPROVEMENT OF RECHARGE WATER

The usual objective in artificial recharge is to get as much good quality water into the ground as possible. To accomplish this, the aquifer must be protected from silt and particulate contamination so that the pathways to groundwater storage will not be obstructed. Physical improvement of recharge water is of prime importance in safeguarding these pathways. Laboratory tests were made to evaluate the relationships between recharge rate, media size, and media depth and the efficiency of coarse media filtration in improving the physical characteristics of recharge water.

During the first few years the Peoria recharge pits were operated with a 6-inch layer of fine-grained filter medium (sand) to protect the underlying aquifer from silt penetration. The sand soon clogged, however, and the recharge rate was reduced to less than the rate that could have been accepted by the underlying aquifer. Hence, the recharge rate was being determined by the overlying filter medium. Since a higher recharge rate was desirable, a gravel filter medium, largely decided upon arbitrarily, was brought into use.

The laboratory tests consistently showed that coarse media (depths of 4 up to 45 inches) contributed no head loss over short periods and over an extended period caused no significant head loss that would tend to alter the recharge rate. When coarse filter media were utilized in the recharge pits, the recharge rates appeared to depend solely on the permeability of the underlying aquifer. The aquifer then must be protected to avoid decreasing this limiting permeability. The best possible filter medium must be used to remove the maximum amount of applied particulate matter, and this entails a choice of size, depth, and type of media appropriate to the desired recharge rate.

Coarse Media Efficiency and Recharge Rate

The laboratory studies showed that the removal of suspended solids from influent recharge water by coarse filter media is dependent on the recharge rate, as depicted in figure 5. The percent removal of solids increased as the recharge rate decreased. Material collected by the filter media, measured on a weight basis, indicated the same dependency, as shown in figure 6. The data in figure 6 represent removal within the interstices of the filter bed itself and does not include any re-

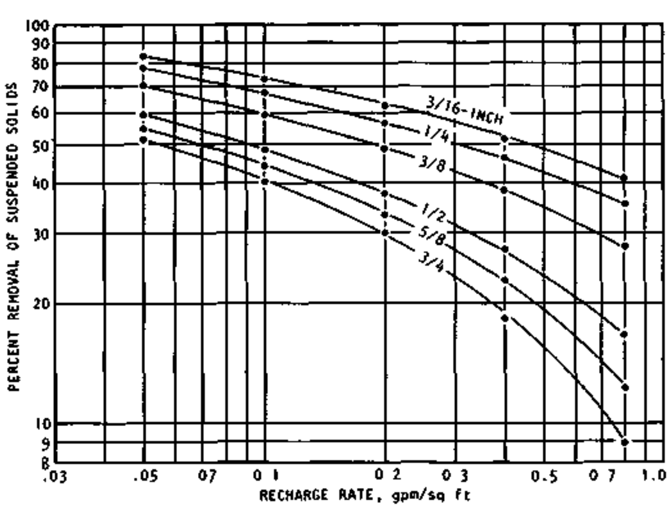

Figure 5. Effect of recharge rate on suspended solids removal

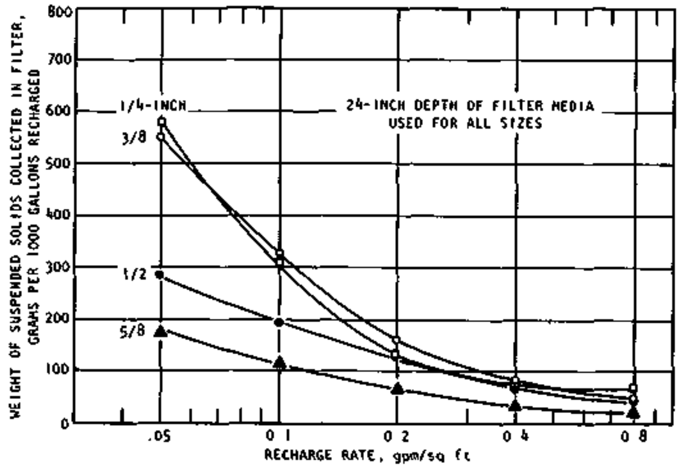

Figure 6. Effect of recharge rate on weight of material collected in filters

moval by deposition on top of the filter that would occur with ponding (see Surcharge, page 15). The data in figure 6 were derived from computed weights based on the weight of suspended solids (mg/1) applied to, and in the effluent of, the filter column and the rate of recharge. The somewhat erratic depiction may be accounted for in part by weight variations in the suspended solids material. Both graphs indicate that low recharge rates tended to yield a greater range of suspended solids removal efficiencies for various coarse media sizes than did high recharge rates.

It was thought that measurement of the media porosity before and after application of recharge water might show a porosity change related to recharge rate, indicative of particulate matter filling the voids of the media. Porosity determinations did not substantiate this, however. The results were irregular (table 6) and the values of porosity change (generally less than 4 percent) were considered insignificant because of the inaccuracy of the porosity determination.

Subsequent testing showed that although a decrease in porosity frequently occurs during infiltration, the percent particulate removal remains constant for given conditions of recharge rate, media size, and media depth. Porosity, then, is indirectly affected by recharge rate, but a change in rate causes only a very small increment of

Table 6. Effects of Recharge on Changes in Porosity in Coarse Media

Recharge rate (gpm/sq ft)	Percent change in porosity for given media sizes*					
	3/16-inch	1/4-inch	3/8-inch	1/2-inch	5/8-inch	3/4-inch
0.05	+1.8	+0.45**	–2.2	–1.5	+0.4	–0.6
0.1	–0.1	–1.3	–2.7	+0.8	–1.1	–1.2
0.2	–0.9	–6.8	–2.2	–3.8	–2.7	–1.5
0.4	–2.4	–4.2	–9.1**	–2.6	–2.4	–3.1
0.8		–6.4	–2.9	–3.7	–2.8	–2.8

* *Media depth in all cases was 24 inches -*
Plus sign (+) indicates an apparent increase in porosity from beginning to end of test; minus sign (—) indicates an apparent decrease
** *Average of two*

porosity change, and these changes are indistinguishable from changes caused by inherent variations in conditions.

Coarse Media Efficiency and Media Size

The relationship between coarse media filtration efficiency and media size was tested on uniform-sized media of various sizes. Such uniformity probably would not be available in a commercial gravel, but the range of sizes used covers quite thoroughly any effective (mode) size, as shown by sieve analysis, of local gravel likely to be used for a filter layer.

The investigations showed that the smaller the coarse media size, the more efficient the filter characteristics of the medium. Figure 7 shows that as the coarse media size is increased, the percent removal of suspended solids decreases. The weight of material collected in a coarse media filter also is dependent, in general, on the size of the media, as shown in figure 8. The scatter of data may be attributed to both natural variation of material in the recharge water and inaccuracies inherent in the methods of weight measurement.

It was thought that, of all the factors, the size of the coarse media would have the most influence on any change in porosity in the filter media. That is, since all of the materials used were of the same type (rounded natural gravel), the small interstices between the media particles would tend to entrap turbidity particles from the water passing through it and fill up the voids in a manner dependent upon the size of the openings between the particles. As reflected in table 6, no general relationship was apparent to correlate porosity changes with media size, although some of the more erratic values are attributed to inaccuracy of the determination. As with recharge rate, there is an indirect relation, but the resultant change in porosity is too small to be distinguished from other changes.

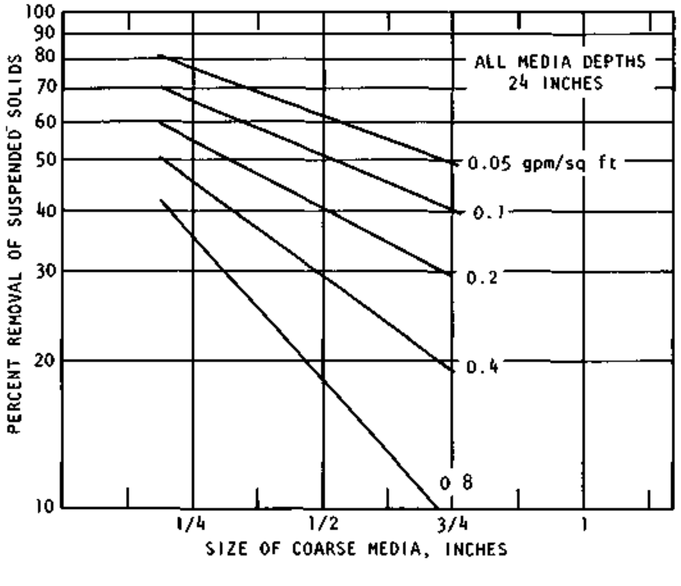

Figure 7. Effect of media size on suspended solids removal

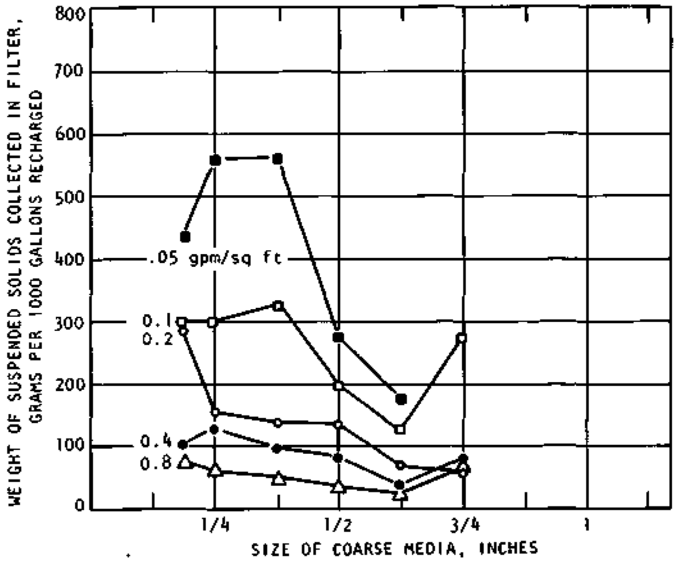

Figure 8. Effect of media size on weight of material collected in filters

Coarse Media Efficiency and Media Depth

It is axiomatic that the more filter media water passes' through, the more particulate matter the media removes. During this investigation, the buildup within the filter media of material removed from the recharge water could be observed visually. The initial few inches of filter media removed the bulk of the particulate, and at each increment of depth less removal occurred. Regardless of the depth of filter media, however, each portion of the bed indicated some buildup of collected material, and in all cases, the effluent was not free of turbidity, suspended solids, or observable 'cloudiness.' The object of this part of the study was not to determine if medium depth affected removal efficiency, but to determine the extent of removal under various conditions.

The relationship between physical removal of material suspended in water and the depth of coarse media used as a filter, as expressed by the percent of suspended solids removal and the weight of particulate material collected, is shown in figures 9 and 10.

The data in figure 10, relating filter depth to the actual grams of particulate material collected within the coarse media filters per 1000 gallons of water recharged, are somewhat erratic and in apparent disagreement with the data in figure 9. Frequently during the investigation there was no correlation between the weight of material as computed using average daily suspended solids removal data and the weight of material physically collected at the end of the test run. Table 7 shows some random comparisons where the values are off by as much as 57.5 percent.

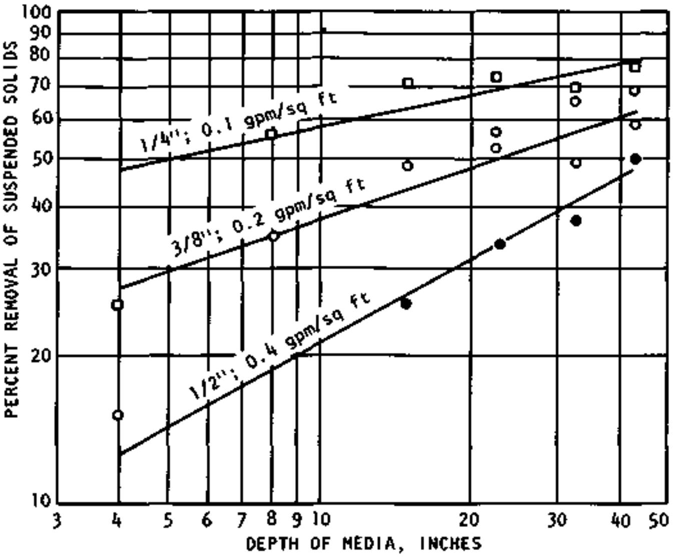

Figure 9. Effect of filter depth on suspended solids removal

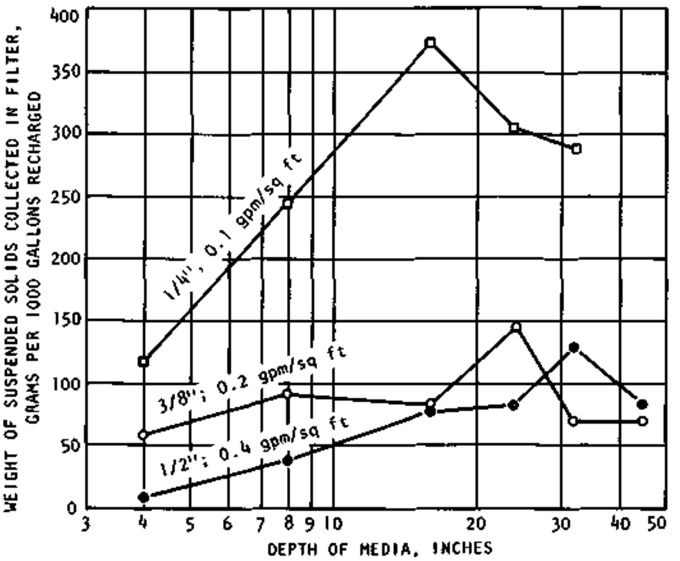

Figure 10. Effect of filter depth on weight of material collected in filters

Actual weight measurements of material in the filter column included particulate that had deposited on the top of the filter medium as well as that retained within filter voids. Computed weight measurements were based on suspended solids concentrations of the influent water, sampled at the interface of the deposited layer and filter media, and the suspended solids concentration in the filter effluent. Thus in most cases the actual weight of the collected material exceeded the computed weight.

On the basis of experience derived during this entire investigation, the relationship between removal of suspended solids and filter depth is reliably depicted in figure 9.

Table 7. Random Comparison of Actual and Computed Silt Load

Test	Column number	Total hours	Actual weight *(grams)*	Computed weight *(grams)*	Percent error
A-l	1	767	107.4	102.2	4.8
A-3	4	505	104.9	72.3	31.1
A-5	3	386	27.6	23.2	15.9
A-6	3	507	33.0	22.0	33.3
A-6Ex	6	6070	589.4	603.9	2.5
A-9	4	507	18.0	27.1	50 6
A-14	3	505	156.0	66.2	57.5

CHEMICAL AND BIOCHEMICAL CHANGES IN RECHARGE WATER

It was desirable to establish the extent of change that might occur in river water quality during artificial recharge. Conceivably, the water quality could be changed by various factors, including the removal by settling and filtration of solids containing organic matter, chemical reaction between the water and the filter medium, biological breakdown of waste material in the water by bacteria and organisms living in the filter medium, and mineralization of the water by dissolving materials through which it passes.

Determinations were made to measure changes in pH, dissolved oxygen, biochemical oxygen demand, ammonia and nitrate nitrogen, and several other facets of water quality as were listed in table 4. From the mass of analyses made, very little was derived in the way of conclusions, and only the pertinent analyses are discussed here.

An effort was made to relate the observed chemical and biochemical changes in water quality to the time of contact, which is dependent upon recharge rate and filter media depth. Values for contact time are given in table 8 for various conditions investigated.

Changes in pH

No significant change in pH was found to occur in water during passage through coarse media. The average change for all tests was a decrease of 0.075 pH units, and

Table 8. Contact Time of Influent Water in Coarse Media

Depth of media *(inches)*	Contact time *(minutes)* for given recharge rate *(gpm/sq ft)* 0.05	0.1	0.2	0.4	0.8
4	49.87	24.93	12.47	6.23	3.12
8	99.74	49.87	24 93	12.47	6.23
12	149.61	74.80	37.40	18.70	9.35
16	199.48	99.74	49.87	24.93	12.47
24	299.22	149.61	74.79	37.41	18.67
32	398.96	199.48	99.74	49.87	24.93
45	561.02	280.51	140.26	70.13	35.06

all changes were within 0.25 pH units. Most of the changes were within the range of error possible in using a pH meter. There was no significant pattern to the changes. Essentially no change in pH occurred at the high recharge rates, and a slight, but non-uniform, decrease in pH was noted at the lower rates.

It was observed that a significant pH change sometimes occurred for a day or so immediately after the beginning of a test run. This may have been caused by powdered rock dust placed in the model along with the coarse media. Such material, created by the grinding action in washing the coarse media after the previous test, could have been readily dissolved thereby creating a pH change, but this is just speculation.

Oxygen Relationships

Measurements of dissolved oxygen (DO) levels were made before and after passage of the river water through coarse filter media to determine the extent of change in DO concentration. Unfortunately the lower recharge rates allowed sufficient contact time to increase the water temperature during passage through the coarse media, especially in winter months. Because of the temperature changes and corresponding fluctuation in DO saturation limits, it was not clearly determined whether the actual change in DO level was due to physical release of DO from solution, or to a chemical or biochemical oxygen demand.

It appears that a 10 to 20 percent decrease in DO occurs in conjunction with the low recharge rates (longer contact time) and is due to biological activity. No evidence was found to indicate that coarse media filtration, in itself, caused a change in DO level.

Analyses of the water passing through coarse media were made to determine changes in 5-day BOD (20 C). It was suspected that most of the organic substrate present in the water would be associated with suspended solids. The 5-day BOD decreased from 25 to 74 percent during passage through coarse media and averaged 45.2 percent, a substantial reduction. The evidence is sufficient to say that this is associated with physical removal of suspended solids. Although investigation failed to reveal any conclusive relationship between dissolved oxygen or biochemical oxygen demand and coarse media filtration, apparently 40 to 50 percent of the influent BOD is eliminated during this process.

Nitrogen Relationships

The ammonia level of the influent water ranged from 0.6 to 6.7 mg/1 and averaged 3.7 mg/1. The filtration tests indicated ammonia concentration changes ranging from an increase of 1 mg/1 to a decrease of 1 mg/1 as the water passed through the coarse media. This increase and decrease in ammonia would indicate that the change is not dependent on the particular medium used in the recharge operation. At very low recharge rates, a continual decrease in ammonia was noted, to a maximum of 35 percent.

No relationships were evident between change in ammonia content and coarse media size or depth. Very little consistent change in ammonia occurred. Any changes seemed generally to be slight decreases, particularly at low recharge rates. Apparently the long contact time, or perhaps more accurately, the long oxidation time, at the low recharge rates is the only factor influencing the ammonia level of water during artificial recharge.

The nitrate level in the influent water ranged from 1.4 to 14.7 mg/1 and averaged 4.9 mg/1. Whereas the ammonia showed a slight decrease at low recharge rates, the nitrates increased as much as 88 percent at low recharge rates. Generally there was an increase in nitrate concentration under all flow rate conditions. These analyses also showed a slight trend toward a relationship between nitrate increase and recharge rate.

Other than an inverse relationship between nitrate and ammonia at low recharge rates, indicating the possibility of nitrification, there were no consistent findings involving nitrogen.

EFFECTS OF FIELD OPERATING PROCEDURES

Some of the changes in operating procedures at the Peoria artificial recharge pits had been made without knowing the effect on the recharge process or on the aquifer. For example, there was no precedent for the use of coarse gravel instead of sand as a filter medium, nor for the use of the same gravel in consecutive seasons without cleaning. These and other changes did bring about improved recharge rates and desirable economies, but little was known about the mechanisms involved. In this part of the laboratory project, studies were made to determine the effects on coarse media filtration of various field operating procedures including surcharge depth, chlorination, combined media sizes, intermittent operation, and extended use of filter media.

Surcharge

In artificial recharge, surcharge is the depth or 'head' of water which forms the pond overlying the filter bed. The laboratory model limited the surcharge depths that could be studied, and the maximum depth tested was 60 inches. Surcharge depth (up to 60 inches) was shown

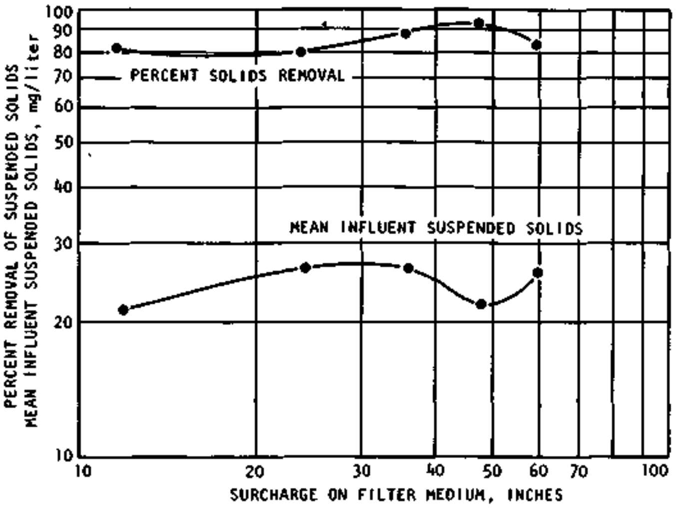

Figure 11. Effect of surcharge on suspended solids removal and on influent suspended solids

to have no effect on the water improvement taking place in the coarse filter media. Figure 11 shows that percent removal of suspended solids was relatively constant, regardless of the surcharge. The slight variations are apparently due to corresponding variations in influent suspended solids, as shown by figure 11.

Observation of the surcharge water standing in the model showed that: 1) turbidity and particulate gradually settled out of the water and was deposited on the surface of the coarse media filter bed, the deposition increasing with decreasing recharge rate; 2) the water entering into the coarse media was, therefore, somewhat cleaner than at its entrance into the column and contained less of the larger particles of previously suspended material; and 3) the thin deposit which built up on the surface of the coarse filter media bed tended to act as a strainer or prefilter, since it was finer than the coarse media.

These actions tended to have two effects: they allowed only the finer turbidity particles to pass into the coarse media, and they concentrated the particulate matter *above* the coarse media.

The first effect may have decreased the apparent turbidity removal by allowing only the finer particles to pass into the filter media; since these finer particles are less subject to removal, a greater percent would pass on through the filter. The second effect, concentration above the media, would place the particulate where it could be easily removed in an actual recharge operation, thereby keeping the coarse filter media somewhat cleaner.

Thus surcharge is of some benefit, but this is not related to the depth of surcharge water so much as to the settling time available. The settling time is dependent on the recharge rate which governs the rate at which influent water moves into the surcharge pond. The slower the influent flow, the cleaner the water passing through the coarse media should be.

Chlormation

In the operation of the Peoria recharge pits, approximately 3.5 mg/1 of chlorine is applied to the Illinois River water before it enters the pits. For this reason, one of the areas of study in this laboratory project was the effect of chlorination on suspended solids removal and the consequent change in filtration characteristics.

In the first test on the reproducibility of the six filter columns operated under identical conditions, chlorine had been added (1 mg/1 concentration) to the influent water for three columns. As indicated by the results that were given in table 3, the chlorinated columns averaged 7.6 percent more suspended solids removal, but the average weight of material collected in the filter media was 18.5 grams (16.5 percent) less than that collected in the unchlorinated columns.

Continued research indicated that suspended solids removal in coarse media varied over a range for a given set of conditions, so that the apparent effect of chlorine was probably the result of natural variations in water quality (see figure 4).

During the summer months an aqueous solution of calcium hypochlorite was added to the raw water as a control for algal growth (chlorine was used rather than copper sulfate because it was already on hand). Table 9 compares the data from these tests with that from comparable tests without chlorination. Except for the fact that the chlorinated columns generally showed less removal of suspended solids, the results were inconclusive.

Table 9. Data For Chlorination Study

Residual chlorine *(mg/l)*	Media size* *(inches)*	Recharge rate *(gpm/sq ft)*	Suspended solids *(% removal)*	Turbidity *(% removal)*	Weight of material collected **	Average influent turbidity *(Jtu)*
0	3/8	0.4	36.2	42.9	70	73
1	3/8	0.4	39.8	49.9	58	73
6	3/8	0.4	23.8	34.0	100	83
0	3/8	0.2	45.6	57.5	125	60
6	3/8	0.2	35.2	50.8	159	83
0	1/4	0 4	28.7		136	104
6	1/4	0.4	25.8	40.0	70	60
0	1/4	0.2	46.3	52.5		64
6	1/4	0.2	43.3	59.4	218	60

* *Media depth in all cases was 24 inches*
** *In grams per 1000 gallons recharged*

Much of the difference between data from chlorinated and unchlorinated columns could conceivably be caused by differences in the average amount, size, and type of influent solids for the various test periods. It was felt, however, that the differences were too great to be the result of a single factor, and an additional test was made to determine the effects of chlorination. Again, identical columns were set up but this time each column received a different dosage of chlorine, ranging from 0 to 12 mg/1 Cl_2. Figure 12 shows the data representing suspended solids removal plotted against initial residual chlorine

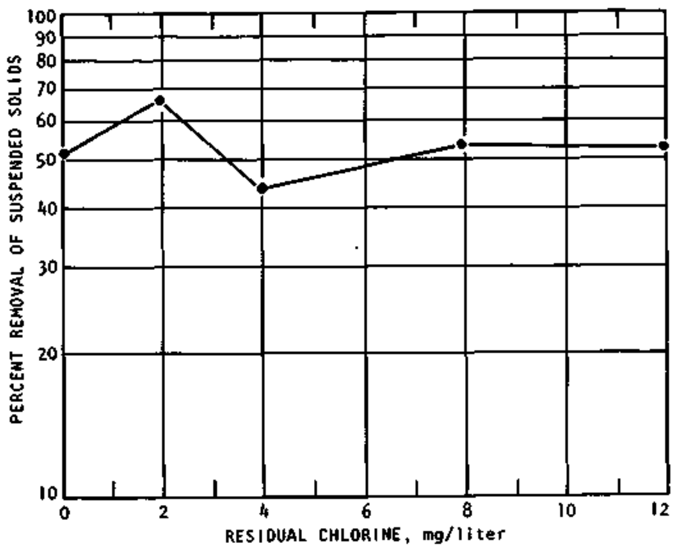

Figure 12. Effect of chlorinotion on suspended solids removal

concentration. Because all data in figure 12 fall within ±10 percent of the average, and because there is no apparent uniformity in the figure, it is concluded that no relationship exists between chlorination and physical improvement of recharge water by coarse media filtration.

Media Size Combinations

The coarse filter media chosen for the bulk of the laboratory tests were of uniform size, and because such uniformity of size would likely not be used in a field installation, some combinations of sizes were studied to help relate test results to field use.

One column was filled with 24 inches of coarse media composed of 4-inch layers of ¾-, ⅝-, ½-, ⅜-, ¼-, and 3/16-inch media, arranged in descending sizes from top to bottom. Another column was arranged with the media sizes in the reverse order. The results in table 10 show that the order of the coarse media gradation was not a significant factor in solids removal and did not affect water quality change. Probably a mixture of all the sizes would have given similar results, although this was not checked.

Some tests were made including layers of sand. Two columns were arranged with coarse media sizes in descending order with a layer of sand (between 4 and 6

Table 10. Effects of Filtration through Multi-Size Media Arranged in Layers According to Size

Characteristic	Largest size* layer at top	Smallest size* layer at top
Percent removal turbidity	35.7	35.2
Percent removal suspended solids	47.8	46.7
Percent decrease in total alkalinity	1.6	2.0
Decrease in pH	0.1	0.05
Head loss, inches	0.05	0.3

* *Media sizes—3/16, 1/4, 3/8, 1/2, 5/8, 3/4 inches*

inches thick) at the bottom. In this case there was significant improvement in water quality, but it did not approach the high level of improvement obtained in a number of previous tests made on single sizes of media. The sand rapidly collected suspended solids and soon clogged, so that within 3 weeks the head loss was so great (more than 6 feet, or greater than the combined depth of filter and surcharge) that the recharge rate fell below the preset rate of 0.2 gpm/sq ft.

Upon tearing down the columns at the end of the test, the sand was found to be literally filthy. This observation supported head loss readings which indicated that loss was occurring at the sand layer. This also indicates that there is a large amount of silt passing through a coarse media filter, under all conditions. The use of the sand caused a greater pH drop (0.2 pH units) and total alkalinity decrease (2.9 percent) in these columns than was observed in almost all other tests.

Another investigation performed was to compare 24 inches of ½-inch coarse media in one column with another column having 16 inches of ½-inch media overlain by layers of 3/16-, ¼-, and ⅜-inch media. It was thought that perhaps these layers of smaller sized coarse media would remove the bulk of the suspended material from the water as it initially entered the filter, thereby reducing the load on the ½-inch media. The results, in table 11, did not reveal any significant improvement by this arrangement.

Table 11. Effects of Filtration through One-Size and Multi-Size Media

Characteristic	One-size* media filter	Multi-size** media filter
Percent removal turbidity	30.3	32.6
Percent removal suspended solids	46.9	44.4

* *24 inches of 1/2-inch gravel*
** *16 inches of 1/2-inch gravel with 8 inches of smaller multi-size media on top*

The investigation of coarse media size combinations did not lead to any particular size or depth of medium that would be outstanding with regard to particulate removal, nor to any optimum recharge conditions. Rather, these tests fortified the data obtained earlier, both by the analytical determinations and by visual inspection, that removal of particulate material by coarse filter media is dependent on recharge rate, total filter bed depth, and surface area of the total filter bed.

The recommendation from these findings would be to use the greatest practical filter bed depth and the smallest available size of coarse media having a permeability greater than that of the aquifer to achieve the highest and most efficient silt and particulate matter removal for aquifer protection during artificial recharge.

Intermittent Operation and Extended Use of Media

The Peoria recharge pits have historically been operated on a seasonal basis, and for several years the coarse media filter was replaced before each season's operation. Since 1957, however, the coarse media layer has been left in place for three or four seasons before replacement.[4]

The seasonal operation of the pits and the multiseason use of the filter media produced an effect that warranted investigation. A short-lived 'recovery' in recharge rate and effective removal of particulate generally occurred at the beginning of a recharge season, the recharge rate being substantially higher than the rate at the end of the previous season. Efforts were made to find the cause of this recovery in laboratory studies.

One column was filled with 24 inches of ¼-inch coarse media and recharged with river water for 12 consecutive 500-hour test runs or 'seasons' without being disturbed. Each season was separated by from 150 to 1600 hours of preparation, during which the column was drained and the coarse media allowed to dry out. The progressive effects on the efficiency of the coarse media filter were observed.

Visually, the coarse media first showed a buildup of collected particulate in the first few inches of filter. Gradually the entire depth of filter showed a buildup, grading slightly heavier to lighter from top to bottom. This continued to increase until the media became completely obscured by particulate and growth (particularly algal).

Physically, several major effects were observed. The percent suspended solids removal tended to reach an equilibrium regardless of changes in the influent suspended solids (table 12). The continual removal of suspended solids is reflected by an increase in head loss. Although not great, head loss did increase progressively as shown in table 13. Under field conditions, this effect would be represented by a decrease in recharge rate. Also, if a continuing constant percent removal of influent suspended solids occurs in the coarse media, the remainder must pass into the aquifer.

Table 12. Effect of Extended Use of Coarse Media

Season	Average influent suspended solids *(mg/l)*	Average % removal sus. solids	Average influent turbidity *(Jtu)*	Average % removal turbidity
1	38	52.5	62	46.3
2			100	45.2
3			114	49.5
4	34	58.8	54	58.0
5	36	37.1	56	37.5
6	25	30.1	42	37.0
7	23	72.1	22	39.8
8	34	51.9	59	40.5
9	53	53.0	86	41.3
10	124	52.1	203	37.2
11	47	64.2	88	42.5
12	69	51.3	120	50.0
Average	48	52.3	84	43.7

Referring to table 13, it appears that the physical improvement of water quality did not decrease with time, but instead tended to stabilize close to a particular value. Thus, the long-term extended use of coarse media throughout several seasons does not seem to affect the efficiency of the coarse media.

It is concluded that intermittent or seasonal operation does not significantly affect the efficiency of the coarse media filter. Possibly the seasonal recovery seen in the Peoria pits is due to aquifer conditions, water table, or river stage.

Table 13. Changes in Quality Characteristics during 12 Seasons*

Season	1	2	3	4	5	6	7	8	9	10	11	12
Average % removal turbidity	46.3	45.2	49.5	58.0	37.5	37.0	39.8	40.5	41.3	37.2	42.5	50.0
Average % removal suspended solids	52.5			58.0	37.1	30.1	72.1	51.9	53.0	52.1	64.2	51.3
Maximum head loss, *inches*	0.0	0.2	1.3	3.5	1.2	1.5	2.0	1.2	1.1	6.9	4.6	3.1
Average change in pH	−0.07	−0.43	−0.22	+0.15	−0.08	−0.15	−0.13	−0.28	−0.45	−0.45	−0.20	
Average % change in DO	−24.6	−49.3	−32.4	−3.6	+5.2	−2.2	−1.3	−17.0	+32.0		−9.9	
Average temperature change, *deg C*	+3.4	+3.6	+2.2	+0.1							+0.8	
Average % change in BOD	−34.3	−34.2	−51.4	−67.7	−26.9	−21.2		−53.5				
Average % change in COD				−16.6	−7.1	−14.5						
Average % change in ammonia	+17.5	−51.9	−79.1	−34.8								
Average % change in nitrate	+3 0	+29.8	+12.3	+31.7								

* *Plus sign (+) indicates an apparent increase during the test; minus sign (—) indicates an apparent decrease*

EFFECTS OF ARTIFICIAL RECHARGE ON AQUIFER MATERIALS

Coarse media filtration does not remove all of the particulate materials from recharge water. Therefore silt, suspended solids, and some of the undesirable qualities of the raw river water are carried into the aquifer after the water has passed through coarse media. Although it is probable that certain changes occur in the chemical and biological quality of the water as it flows through the aquifer, these changes do not reduce the permeability of the aquifer material. The primary concern of this phase of the investigation was the physical character

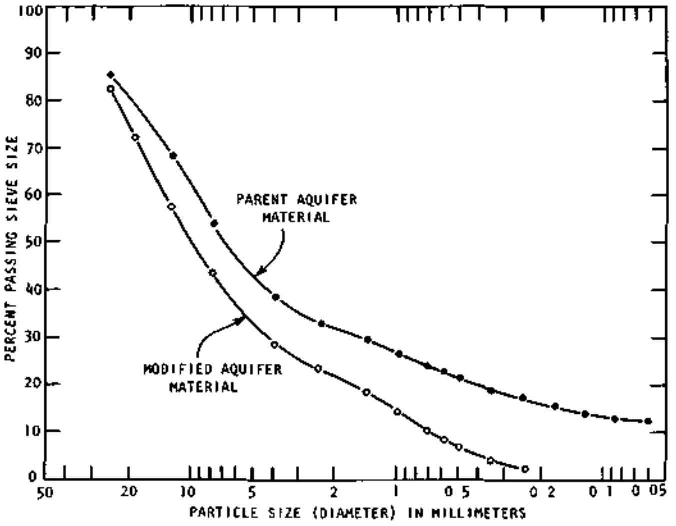

Figure 13. Analysis of parent and modified aquifer materials used in research studies

of the water passing through the coarse media and into the aquifer, and the resulting 'clogging' effect upon aquifer materials.

Attempting to duplicate natural aquifer conditions in a laboratory study is difficult. Preliminary tests with representative soil samples taken from the side slopes of the Peoria recharge pits indicated that" they contained lenses of fine material that formed barriers to water passage when placed in the research model. It was determined that 'placing' this aquifer material in the model in a way satisfactory for research tests was impossible. Therefore, the representative aquifer material to be used in the investigations was modified by washing through a number-60 sieve to remove the clay and fine sand sizes. This material used in the investigations differed slightly from the actual aquifer soil, as shown by the analyses in figure 13.

A preliminary test study showed that aquifer materials behave in a manner similar to coarse filter media in regard to the relationship between recharge rate and removal of suspended solids. Figure 14 shows that percent

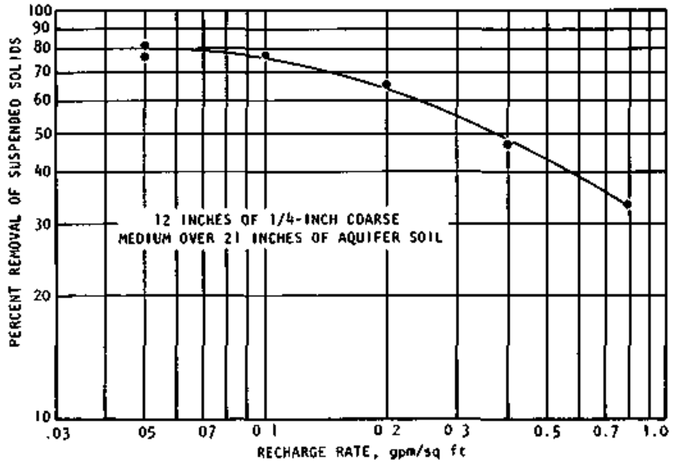

Figure 14. Effect of recharge rate on suspended solids removal in aquifer soils

suspended solids removal is related to the recharge rate through coarse media *and* aquifer, the percent removal decreasing with increasing rate. Since the figure is based on a specific depth of aquifer material, the depth to which suspended solids will penetrate into the aquifer is directly dependent on recharge rate.

In other tests, the columns were allowed to run uncontrolled or at a self-regulating rate, so that the recharge rate was limited only by the permeability of the modified aquifer material. The recharge rates at the beginning of the tests were at very high levels, but as time passed and some solids were removed in the aquifer material (causing a permeability decrease), the recharge rates progressively dropped. With the decrease in rate came a subsequent increase in percent removal of solids, which caused a decrease in permeability, a further decrease in the recharge rate, and so on in a cycle of interrelated reactions. Table 14 reflects the relationship between percent suspended solids removal and recharge rate with time.

The depth of aquifer affects the percent suspended solids removal, as did the depth of coarse media, so that percent removal increases as the depth of aquifer increases. Generally, each increment of aquifer depth removes a smaller increment of the suspended solids entering the aquifer. Table 15 indicates the removal efficiencies of aquifer material as the water passes into it.

Table 14. Time Effects on Recharge Rate and Suspended Solids Removal*

Time period *(hours)*	Average recharge rate *(gpm/sq ft)* Filter a	Filter b	Average suspended solids removal *(percent)* Filter a	Filter b
0–250	3.0	2.2	3.8	9.2
250–500	1.9	0.6	6.5	9.0
500–750	1.5	0.3	5.0	13.3
750–1000	0.5	0.08	24.8	42.5
1000–1250	0.13	0.06	33.2	79.9
1250–1500	0.12	0.04	45.4	88.2
1500–1750	0.11	0.03	49.9	87.7

* *Two filter columns of 8 inches of ¼-inch coarse media over 21 inches of aquifer soil; operated at uncontrolled recharge rate*

Table 15. Suspended Solids Removal in Coarse Media and Aquifer Soils

Filtration layers	Suspended solids removal *(percent)*
Case 1—recharge rate of 0.2 gpm/sq ft	
Top layer, 8 inches of 1/4-inch coarse media	57.1
Second layer, 12 inches of aquifer soil	12.1
Third layer, 12 inches of aquifer soil	22.1
Fourth layer, 24 inches of aquifer soil	4.7
All layers	96.0
Case 2—recharge rate of 0.1 gpm/sq ft	
Top layer, 8 inches of 1/4-inch coarse media	57.2
Second layer, 12 inches of aquifer soil	20.6
Third layer, 12 inches of aquifer soil	7.8
Fourth layer, 24 inches of aquifer soil	2.6
All layers	88.2

Apparently a high degree of solids removal (96.0 and 88.2 percent) takes place in only a few feet of aquifer.

Case 1 in table 15 indicates that more suspended solids were removed in the second foot of aquifer (22.1 percent) than were removed in the first foot (12.1 percent). This leads to the possibility that the higher recharge rates force more of the suspended solids in the recharge water deeper into the aquifer before removal is accomplished. Although the recharge rate in case 1 was not extremely high (0.2 gpm/sq ft), apparently it was high enough to cause more silt to penetrate deeper into the aquifer.

Table 16 indicates that when recharge starts and continues at a fairly constant rate in the range of 0.05 to 0.4 gpm/sq ft, much of the turbidity and suspended solids is removed. When recharge starts at a much higher initial recharge rate, however, and then slows to a fairly constant rate after a few weeks time, the resulting percent removal of turbidity and suspended solids at the final rate is less than if the rate had started lower and remained constant from the beginning.

Table 16. Controlled Low Recharge Rates Versus Uncontrolled High Rates

Case 1—filters with 12 inches of 1/4-inch coarse media over 21 inches of aquifer; operation controlled at 0.4 gpm/sq ft (a) and 0.05 gpm/sq ft (b)

	(a)	(b)
Average % removal turbidity during 500 hours of operation	35.3	76.5
Average % removal suspended solids during 500 hours of operation	46.9	78.7

Case 2—filters with 8 inches of 1/4-inch coarse media over 21 inches of aquifer; operation at maximum uncontrolled rates starting at 3.6 gpm/sq ft (c) and 5.2 gpm/sq ft (d)

	(c)	(d)
Recharge rate after 500 hours of operation, gpm/sq ft	1.6	0.4
Recharge rate after 850 hours of operation, gpm/sq ft	0.4	0.05
Percent turbidity removal after 850 hours of operation	21.8	39.5
Percent removal suspended solids after 850 hours of operation	29.5	67.8

DESIGN FORMULA FOR USE OF COARSE MEDIA

Statistical analysis of the data collected from three years of research on the behavior of coarse-grained filtering materials in artificial recharge has produced an equation expressing the filtration efficiency of the coarse media. It has been established that recharge rate, coarse filter media size, and coarse filter media depth are the variables that control the amount of turbidity, suspended solids, particulate, or other contaminants that will be removed from the influent recharge water when it is passed through a layer of coarse media.

The equation relating these parameters is

$$\%Removal = -34.5 + 29.8 \log D - 44.0 \log d - 35.2 \log R$$

where

- $\%\ Removal$ = that percent of the total suspended solids concentration of the applied water which is removed by the filter medium
- D = depth of the coarse medium filter layer, in inches
- d = mean diameter of the particles making up the coarse media layer, in inches
- R = rate of recharge, in gallons per minute per square foot

This equation has been established by tests which were about 500 hours in duration, and the data are reliable for this short time period. The standard error of the equation is 7.0 percent removal. The multiple correlation of the statistical data is 0.92.

The reliability of this formula with time was checked by the long-term test in which the one column was operated for 6070 hours in 12 segments of about 500 hours each. Measurements of turbidity during this extended test showed that the percent removal of turbidity in coarse-grained filtering materials remains constant over an extended period. Because of the consistent relationship that existed between turbidity and suspended solids (see table 5), the turbidity data can be used to verify the formula of suspended solids removal.

Figure 15 shows the percent turbidity removal data representing daily grab samples taken during the 6070-hour extended test. No overall increase or decrease in efficiency of the coarse filter media occurs over this period of time. Influent turbidity varied during this period, as seen in table 5. Two conclusions may be drawn from this extended test.

1) The percent removal of turbidity or suspended solids is constant for a given set of initial conditions, regardless of variations in influent water quality.
2) The percent removal of turbidity or suspended solids varies about a mean, but does not significantly increase or decrease over an extended period of time.

It was found in this study that recharge rate, media size, and media depth are all interrelated and interdependent. In an actual situation, local conditions would probably govern one of the three parameters. If a very high recharge rate was possible and only a very limited amount of land available, the only course to follow would be to utilize the high recharge rate and protect the aquifer with a deep layer of smaller sized coarse media. If a large land area was available so that a lower recharge rate could be implemented, a shallow depth of very coarse media might be sufficient.

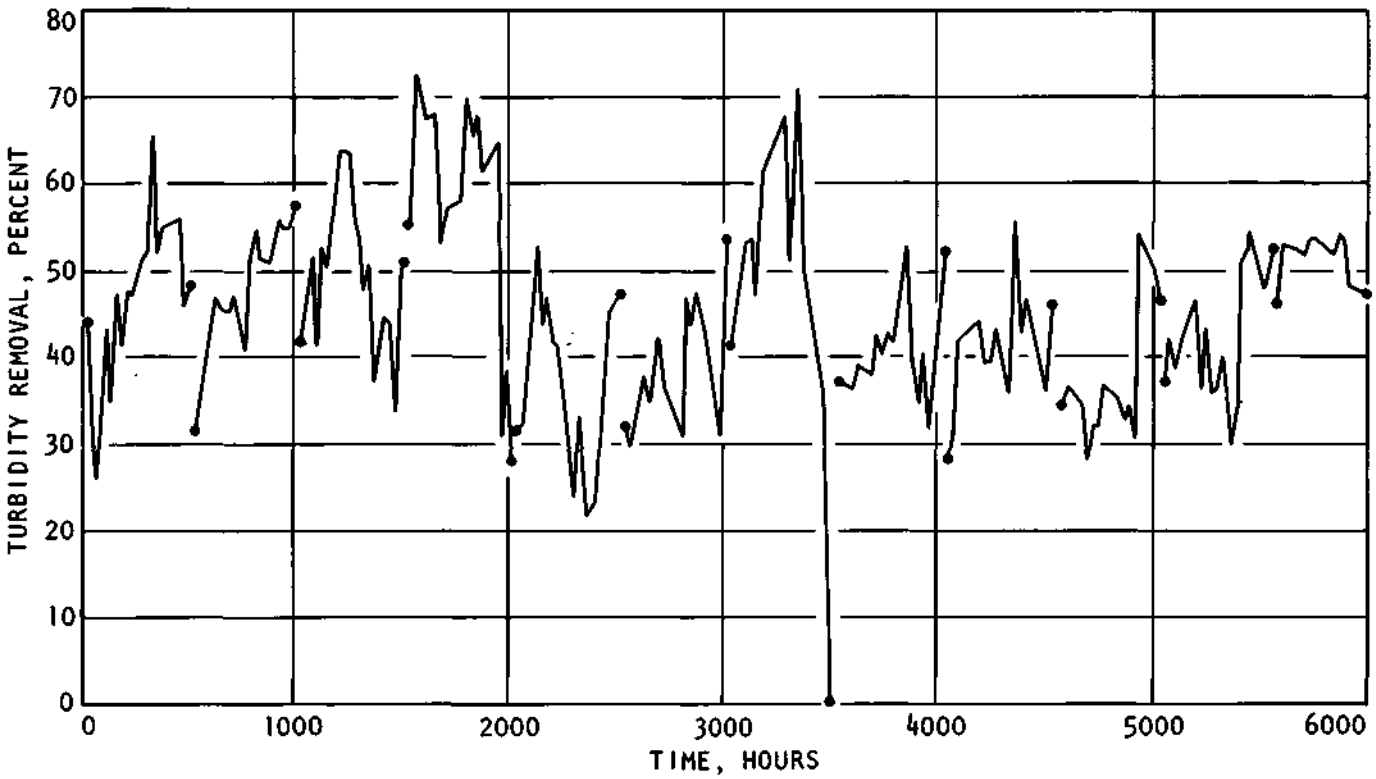

Figure 15. Turbidity removal variations with time

SUMMARY

Laboratory tests have shown the effects of such factors as size of filter media, depth of filter media, depth of surcharge on the filter, and rate of recharge through the filter media upon the general performance of coarse media filters.

Depth of surcharge has an indirect effect which, in the laboratory tests, was related to recharge rates. As recharge rates were decreased, for any given depth of surcharge, the amount of solids released from suspension in the water used for recharge and deposited on the top surface of the coarse media increased. Thus, if the removal of suspended solids within the filter media was computed on the basis of the difference in suspended solids in the influent and effluent water, the amount of solids deposited on the top surface of the media is ignored and the apparent internal removal efficiency is higher than the true value.

The separate, direct effects of other variables were more clearly shown. Removal efficiency was shown to be inversely related to recharge rate and to media size; and directly related to depth of the filter media. The effects of changes in one variable on other variables were also observed. The use of filter depths as great as 45 inches caused no significant loss of head over short periods of operation nor were recharge rates significantly reduced because of head loss during long periods of operation. Recharge rates were influenced more by the permeability of underlying aquifer materials than by conditions in the coarse filter media.

The removal of suspended material from influent water by coarse media filters was observed to take place mostly in the upper layers of the filters, regardless of the total removal efficiency of the filter, but no depths of media tested were successful in completely removing all suspended material from the water being recharged. In one test, sufficient material penetrated through 24 inches of coarse media to clog an underlying sand layer within three weeks.

No well-defined correlation between porosity changes in the filter media and recharge rate or media size was established. Very generally, it appeared that recharge rate affected the porosity more significantly than did media size.

Changes in water quality because of artificial recharge were about as anticipated. Very little change in mineral water quality occurred during all tests of artificial recharge through coarse grained media. Chlorination of the applied, water had no significant effect on such changes, nor did depth of surcharge. Dissolved oxygen content was sometimes decreased by 10-20 percent, particularly at low recharge rates, and apparently because of biological activity rather than a filtering mechanism.

Usually, about 50 percent of the 5-day 20C biochemical oxygen demand was removed during recharge through coarse media. This was presumably associated with the removal of suspended solids and with biological activity.

During all tests in which turbidity and suspended solids concentrations were compared, there appeared to be a relatively constant ratio between the two.

The intermittent use of coarse media filters does not seem to affect its filtration efficiency to any great extent. The percent removal of suspended solids remained fairly constant throughout such intermittent, long-period tests.

In filters made up of multi-size media arranged in layers according to size, the arrangement of the different sizes did not significantly affect the general filtration characteristics of the entire filter bed, during short test runs.

For tests of coarse media underlain by aquifer material, and for given depths and diameters of coarse media, the penetration of suspended solids into the aquifer was directly related to recharge rate. And, as with tests of coarse media alone, the major portions of the suspended solids penetrating into the aquifer materials were accumulated in the upper levels.

The effects of recharge rate, media size, and depth of media upon percent removal of suspended solids by coarse media filters are all interrelated. If influent suspended solids concentrations are ignored, an equation for percentage removal of suspended solids in a coarse media filter, relating to the variables of media diameter, depth of media, and recharge rate, has been developed.

Thus, for any allowable level of suspended solids concentration in the influent, and for a required recharge rate, the maximum protection to the underlying aquifer is afforded by the greatest practical filter media depth, and the smallest media size with a permeability greater than that of the aquifer.

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