WATER RESEARCH CENTRE

II.27.7

ARTIFICIAL RECHARGE THROUGH A BOREHOLE

LIBRARY
International Reference Centre
for Community Water Supply

The construction and performance of a recharge borehole in the Bunter Sandstone, Nottinghamshire

K. J. Edworthy

August 1978

MEDMENHAM LABORATORY
P.O. Box 16, Medmenham,
Marlow, Bucks. SL7 2HD
Tel.049 166 531

STEVENAGE LABORATORY
Elder Way, Stevenage,
Herts. SG1 1TH
Tel.0438

2 12.2-78AR

II. 277

Technical Report TR86

August 1978

212.2
78 AR

ARTIFICIAL RECHARGE THROUGH A BOREHOLE

The construction and performance of a recharge borehole in the Bunter Sandstone, Nottinghamshire

by

K. J. Edworthy

Resources Division
Water Research Centre

Medmenham Laboratory,
P.O. Box 16, Medmenham,
Marlow, Bucks, SL7 2HD
Tel: 049 166 531

Stevenage Laboratory,
Elder Way,
Stevenage, Herts. SG1 1TH
Tel: 0438 2444

The contents of this report are the copyright of the Water Research Centre and may not be reproduced in part or in whole without prior written consent.

© Water Research Centre, 1978

CONTENTS

PREFACE

Artificial groundwater recharge has been widely practised overseas, but only to a limited extent in the UK. It has been recognised, however, that the technique could be used to augment water resources economically in some areas. To assess its potential usefulness in this country, a number of pilot-scale recharge schemes have been studied. This report describes the construction and performance of a recharge borehole in the Bunter Sandstone, one of the most important UK aquifers. Tests showed that a long-term recharge rate of 2.9 Ml/d could be achieved at this site using treated water.

The work reported here was initiated by the Water Resources Board and carried out under the general guidance of H.J. Richards. The detailed work was undertaken by R.L.H. Satchell and K.J. Edworthy with important contributions from J.M.A. Pontin, R.A. Monkhouse, and E.R. Price.

Water quality analyses were carried out by the Trent River Authority, Nottingham (now the Divisional Laboratories for the Lower Trent Division of the Severn-Trent Water Authority), and considerable help during the planning and construction phases was given by the Central Nottinghamshire Water Board (now part of the Severn-Trent Water Authority). The help and co-operation of both these organisations is gratefully acknowledged.

Following re-organisation of the Water Industry on 1 April 1974, and the disbanding of the Water Resources Board, the Water Research Centre assumed responsibility for the site and further experimental work.

This report is published by the Water Research Centre as it is felt that the construction and performance details of this recharge facility will be of value to WRC Members.

1. INTRODUCTION

This report describes the design, construction and operation of an experimental borehole recharge project in the Bunter Sandstone at Clipstone Forest, Nottinghamshire. The investigation was complementary to basin recharge and spray irrigation experiments carried out by the Water Resources Board as part of the Trent Research Programme(1). The borehole was constructed and tested by the Water Resources Board as part of the Board's extensive study of the applications of artificial groundwater recharge techniques in the United Kingdom. After re-organisation of the UK water industry in 1974, responsibility for the Clipstone Forest recharge site passed to the Water Research Centre.

The recharge borehole is constructed in the Permo-Triassic Bunter Sandstone of Nottinghamshire. Currently the aquifer yields about 600×10^3 m^3/d for public water supply, mainly for Mansfield and Nottingham.

While this is thought to be approximately equal to the long-term mean natural recharge rate of the aquifer, groundwater development has not been systematic. In consequence some parts are overdeveloped and groundwater levels have fallen considerably; in other areas there is still a small amount of further development possible(2).

It was believed that artificial recharge could have an important part to play in the future use of the aquifer and that there was, therefore, the need to investigate the most appropriate recharge techniques.

The Water Resources Board decided to design and carry out the present pilot recharge study and in 1969 a site was selected. Site investigations and construction took place between September 1970 and June 1971 and recharge experiments followed until March 1973.

The principal objectives of the experiment are listed below:

(a) to determine the rates at which potable water would pass into the aquifer from a recharge borehole for a range of head conditions in the borehole;

(b) to observe any long-term changes in the recharge capacity under constant flow conditions and determine the cause of such changes;

(c) to develop methods of restoring recharge rates, should any decline occur as a result of clogging;

(d) to obtain guidance on design criteria for recharge boreholes in the Permo-Triassic Sandstones of Nottinghamshire and elsewhere in the UK by measuring the development and decay of the recharge 'mound' within the aquifer.

Artificial recharge through boreholes for storage augmentation is practised extensively in Israel(3) and in parts of the USA, mainly into sandstones but also into limestone and basalt aquifers. Elsewhere, experience is limited, though some work has been done in France(4), Holland(5), and Spain(6). In Britain, experimental recharge was successfully carried out in the London Basin Chalk in existing large diameter wells at total rates up to about 45 × 10^3 m^3/d(7) during the 1950s and again in the 1960s. Between 1962 and 1965 a well in the Keuper Sandstone at Birmingham racecourse was recharged in order to secure summer supplies for irrigation. Rates of recharge were low at about 0.14 × 10^3 m^3/d and the experiment was abandoned when the racecourse was sold(8).

Recharge of treated effluent through wells, either for later reclamation or disposal, is widely practised in Israel and the USA. In many other countries, including the United Kingdom, a variety of effluents, ranging in quality from warm water to toxic industrial wastes, have been injected underground through wells and boreholes for many years. In most cases, no scientific study of the effects of the waste disposal practices on aquifers or on groundwater quality has been made, though there are some notable exceptions to this, principally in the United States(9,10). Deep-well disposal, mainly of toxic materials, is a separate field of study(11). Further consideration of waste and effluent recharge is beyond the scope of this report, however.

Experience overseas has shown that the efficiency of well or borehole recharge is a function of many factors(12,13,14,15). The most important potential problems were found to be associated with suspended solids, bacterial growth, gas entrainment, and chemical interaction between the recharged and native water, and with the well structure.

2. SITE SELECTION AND PRELIMINARY DRILLING

2.1. PLANNING AND SITE SELECTION

During the planning of the investigation, a literature survey of borehole recharge showed that there are many factors which may cause poor recharge performance, although the precise effect of each factor may not be fully understood. Therefore it was decided to minimise the possibilities of obtaining results that would be difficult to interpret, firstly by adopting sound practices and, secondly, by reducing the variables to be examined initially to as small a number as possible. This was done principally by using a supply of recharge water of a quality similar to that naturally present in the aquifer in order to avoid any of the hazards of bacteriological clogging, or of chemical incompatibility. It was also considered that recharge above the water table as well as below should be examined, though there were no previous examples of recharge of unconfined aquifers in this situation to act as a guide.

The site ultimately chosen, at Clipstone Forest, Nottinghamshire (NGR SK 604 623) shown in Figs 1 and 2, was near to a 450 mm diameter Central Nottinghamshire Water Board supply main carrying potable water abstracted from the Bunter Sandstone approximately 4.5 km to the north-east. At the design stage the main had ample spare capacity for the recharge work and a supply of up to 6.75×10^3 m^3/d was arranged with the Water Board. The water table, believed to be more than 25 m below surface, allowed ample scope for investigation of recharge using the unsaturated zone together with the saturated part of the aquifer.

2.2. GEOLOGY OF THE AQUIFER

The Bunter Sandstone, overlying marls, dolomitic sandstones, and limestones of Permian age, make up the Permo-Triassic succession in south Nottinghamshire (Fig. 3). At the Clipstone site the Permian succession is estimated to be 25 m thick. The permeable Bunter Sandstone, which directly overlies the Permian sediments, can be subdivided in this area into a Lower Mottled Sandstones unit directly overlain by the Pebble Beds. Immediately down the stratigraphic dip from the site, the full thickness of the Bunter formation is estimated to be slightly in excess of 200 m(16). The base of the Bunter Sandstone at Clipstone is approximately 120 m (-15 m AOD) below surface so approximately 80 m of the upper part of the sequence has been eroded. Superficial sediments are absent. The effects of weathering extend more than 30 m below the surface, as judged from the extreme lack of cohesion of the sandstones penetrated at the site.

The Lower Mottled Sandstone comprises a series of red-brown friable sandstones, generally of fine to medium grain size, and thin, laterally impersistent siltstones. Overall, the Lower Mottled Sandstones are finer-grained than the overlying Pebble Beds and are lithologically transitional between the Permian rocks and the Pebble Beds. It is unlikely that the Lower Mottled Sandstones were penetrated at Clipstone. The Pebble Beds are typically red-brown, poorly indurated medium-grained sandstones,

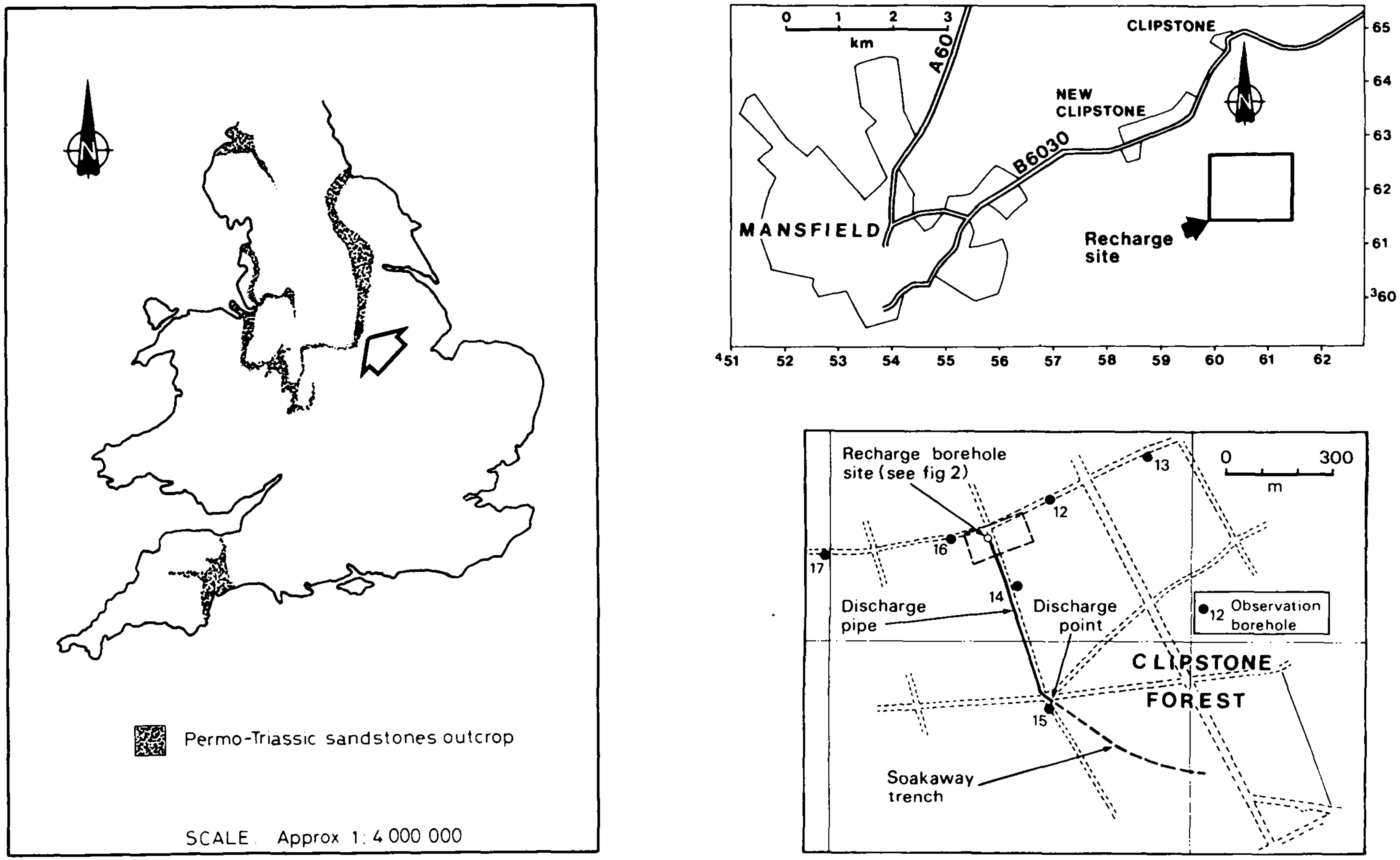


Fig. 1. Site location maps

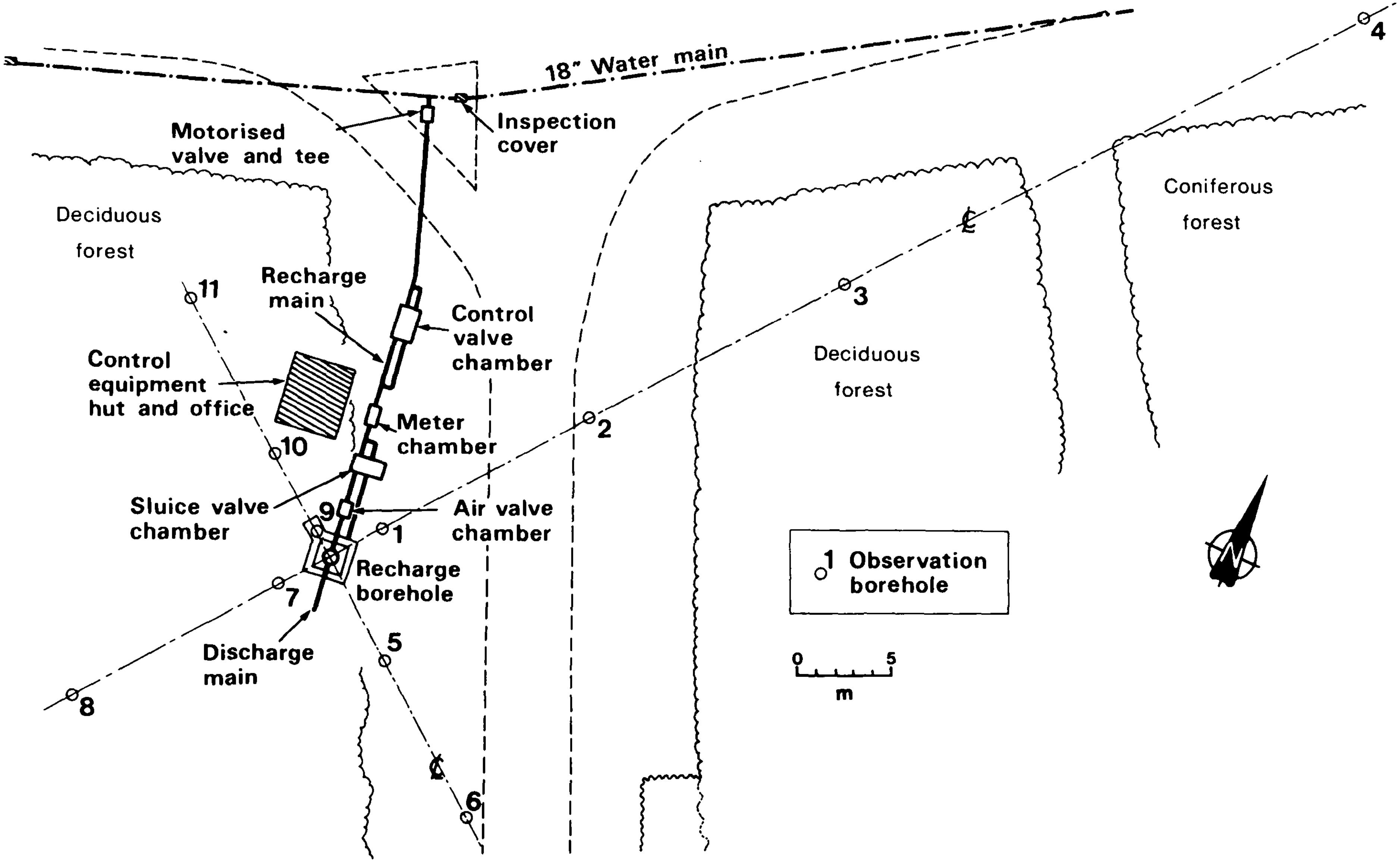


Fig. 2. Plan of site showing borehole positions

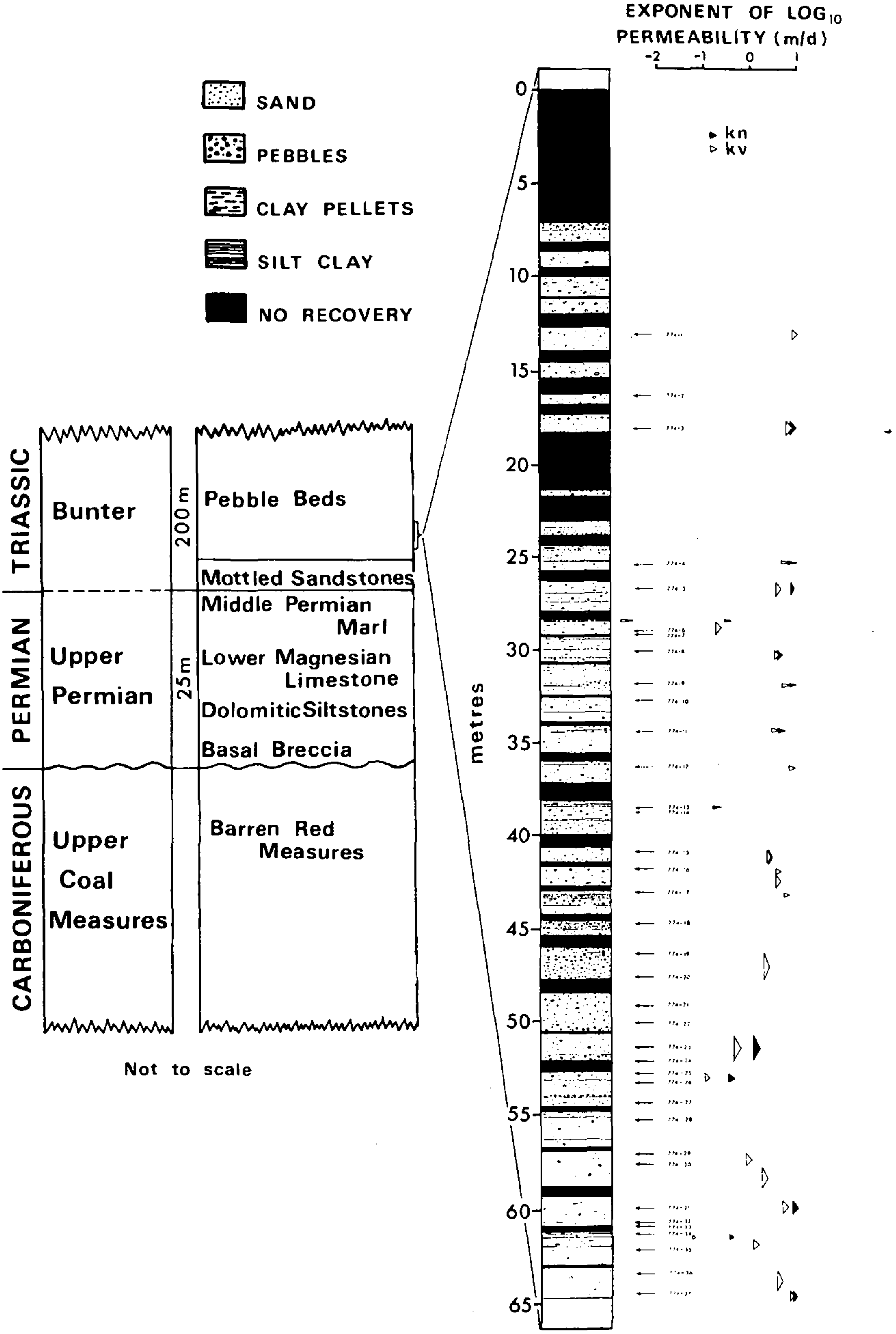


Fig. 3. The Permo-Triassic succession of South Nottinghamshire showing the section at Clipstone and permeability valves

with lenses of siltstone and mudstone and numerous pebbles.

Deformation of these strata is limited to gentle flexure and tilting which have produced some degree of jointing, as observed in nearby outcrops, and an overall easterly dip of about 1%. There is evidence nearby of large-scale fracturing due to mining subsidence but not at the recharge site.

2.3. OBSERVATION BOREHOLE DRILLING

The observation boreholes were drilled with two main objectives. First, it was necessary to determine the detailed nature of the aquifer locally and its particular physical and chemical properties. Secondly, the boreholes were designed to enable continuous monitoring of water table behaviour under recharge and abstraction conditions. Since the natural water level gradient was believed to be towards the north-east, eleven 200 mm diameter holes were drilled to a cruciform pattern with the long arm in this direction (Fig. 2). The recharge borehole is situated at the centre of the cross and the observation holes situated at distances ranging from 1.5 m to 60 m from it. Boreholes 1,7,9A and the recharge borehole were drilled to 65 m depth; 2 and 8 were drilled to 50 m and the remainder to 45 m. Boreholes 1,2,7,8 and 9A were all extended in depth by 5 m when it was found that the natural water level was deeper than expected.

Four of the boreholes, Nos. 2,5,8 and 10, as well as the pilot recharge borehole, were cored to total depth. The remainder were drilled using a percussion rig except for borehole 9; this was particularly difficult to drill, being only 1.5 m from the centre of the recharge borehole, and was drilled by a rotary rig. All observation boreholes were lined with bitumen-coated mild steel at the surface, with 0.5 m left above the surface to be covered by a mild steel blank flange with a 25 mm screwed access plug. Borehole 9 was abandoned at 23 m due to excessive deviation, and replaced by borehole 9A on the directly opposite side of the recharge borehole.

To obtain an indication of the problems, if any, in coring the Bunter Sandstone at this site, it was decided first to drill one of the observation boreholes rather than the pilot recharge borehole. It was hoped that any fissuring in the sandstone would be identified in this first cored borehole and that any changes in the layout of the site which might become necessary could be made early in the programme. In drilling borehole No. 2 it was found that coring conditions using a 150 mm diameter double core-barrel with a rotating split inner and a tungsten-insert bit were very difficult and that recovery of the upper 10 m of the formation was impossible. The sandstone was largely unconsolidated and though the coring of borehole No. 2 was unsuccessful in recovering samples, it did serve to develop the coring technique necessary to achieve improved recovery in the remaining five cored boreholes. Borehole No. 2 was re-drilled in an attempt to obtain core from this location and greater success was achieved. Between depths of about 10 m and 30 m, the formation was slightly better indurated, and sample recovery was easier. This improved with depth, but the 90% recovery called for in the specification could not be attained, the final average being only 44%.

Several changes in drilling technique, drilling fluid, and the type of coring bit used were made. Using water-flush, various rates of flow were tried, and eventually the additive 'Revert'* was used. Numerous changes were also made to the core 'catcher' design in the course of the work. The formation was found to be extremely abrasive to the diamond and tungsten-insert bits to the extent of eroding the inserted elements; improvements in the shrouding of the inserts led to increases in coring bit life from 15 m to more than 50 m per bit.

2.4. INSTRUMENTATION

As soon as observation borehole 3 was completed in October 1970, a punched-tape water level recorder was fitted to measure the natural water level fluctuations at the site. When drilling and construction work was fully completed it was decided to monitor water levels as closely as possible along the section running south-west to north-east and five additional punched-tape recorders were mounted on boreholes 1,2,7,8 and 9A. Water level in the recharge borehole was monitored using a punched-tape recorder. Foil-backed tape was used in the recorders and a low-power light bulb was used as a heat source to combat the humid conditions at the recharge well-head. Recharge and abstraction experiments differ from normal pumping tests in that extremely large ranges of water level fluctuation often have to be accommodated by the recording instruments. This was an important point to consider in setting up the instrumentation, since inadequate provision for this could easily mean the loss of valuable data. The range in the recharge borehole was particularly large, reaching a maximum of about 45 m.

2.5. DRILLING OF ADDITIONAL OBSERVATION BOREHOLES

As the experimental programme progressed into 1972 it became clear that the recharge 'mound' had attained a radius of influence considerably beyond the limits of the site and analysis of the data showed that measurable effects could extend as far as 1.0 km from the recharge borehole. It was decided that at least six further observation boreholes were required, and these should be drilled within 0.5 km of the site to a depth which was predicted to give a penetration of the saturated sandstone of at least 3.0 m (see Table 1). These boreholes were drilled by the shell and auger method and were cased to 6 m below ground level with 150 mm diameter mild-steel casing. The casing top was set in a concrete plinth and completed with a screwed cap.

---

* Registered name of drilling fluid additive manufactured by Union Oil Products, Johnson Division.

Table 1. Observation and recharge borehole details (on completion)

BH No.	Total depth (m)	Elevation (m)*	Depth to water (m)	Distance from recharge borehole (m)	Depth to bottom of casing (m)
1	66.0	1.862	36.80	6	6.1
2A	45.0	0.977	36.74	15	12.2
3	45.0	0.573	36.25	30	6.1
4	45.0	0	35.92	60	6.1
5	50.0	1.739		6	12.2
6	45.0	1.189	37.06	15	6.1
7	66.0	1.752	34.35	6	6.1
8	45.0	2.191	37.72	15	6.1
9A	66.0	2.053	36.83	1.5	12.2
10	50.0	1.739	37.30	6	12.2
11	45.0	1.577	37.16	15	6.1
12	42.0	-2.683	33.47	170	6.1
13	42.0	-6.103	33.19	485	6.1
14	37.0	-0.973	33.46	155	6.1
15	31.0	-15.983	17.92	515	6.1
16	37.0	-0.747	34.79	105	6.1
17	43.0	-4.183	26.97	510	6.1
Rech.BH	65.8	0.132**	36.8	-	13.7

* Elevation of borehole No. 4 used as datum

** Well-head chamber floor

3. RECHARGE BOREHOLE CONSTRUCTION

3.1. DRILLING

In order to determine the precise nature of the aquifer at the site, a cored 200 mm diameter pilot hole was drilled to a depth of 65.8 m below surface on the centre line of the recharge borehole. The groundwater level was found at 36.8 m below surface. Once it had been confirmed that the location of the hole was acceptable in that there was no evidence of major fissuring, the pilot hole was reamed to 915 mm diameter using reverse circulation equipment. 'Revert' drilling fluid additive was again used. It was expected that the use of this combined with high circulation rates during drilling would prevent a permanent mud cake forming on the borehole wall. After drilling, however, closed circuit television followed by physical inspection showed that a slurry approximately 6 mm thick had adhered to the wall. This was removed by dry-reaming the hole 25 mm oversize down to 5 m below standing water level.

3.2. BOREHOLE COMPLETION

An outer mild-steel casing of 900 mm internal diameter was placed and cemented to 13.7 m below ground surface. The remainder of the hole was left open to receive the screen, inner casing and gravel pack. Apart from recharge, it was envisaged that the borehole would be pumped from time to time both to assess the effect of recharge on aquifer properties and to develop performance. Although the hole appeared to be stable over the unlined length, it was decided to install a gravel pack and screen immediately after the preliminary pumping test to maintain stability and to allow full development by pumping and surging.

A 450 mm outside diameter, stainless-steel, wire-wound screen was installed in 6 m lengths and joined by welding. Stainless-steel was selected in order to ensure the chemical inertness of the system, as far as possible. Comparison of the grain-size analyses of the aquifer and the commercially available gravel-pack media indicated that a slot size of 1 mm should be adopted for the screen, using conventional abstraction borehole design criteria. Grain-size analyses of aquifer and gravel pack are shown in Fig. 4(b).

As the screen was lowered into the borehole, and each successive length welded, a series of spacers was built into the outside, to ensure correct central positioning of the screen. Four pairs of 25 mm internal diameter uPVC pipes were attached to the spacers and positioned at 90° intervals around the screen to enable recharge water levels in the gravel pack to be measured. The lower end of each pipe was finished with a perforated section 300 mm long filled with fine gravel. One pipe from each pair was positioned 75 mm from the screen, and the other 150 mm. The four pairs terminated at 17.4 m, 29.6 m, 41.8 m and 58.5 m below original ground level. A set of six 75 mm uPVC backwashing pipes, also attached to the spacers were positioned in the pack at a distance of 50 mm from the face of the aquifer and equidistantly spaced around the screen. The pipes were each perforated with groups of three 4 mm diameter inward-facing holes at 250 mm centres, as indicated in Fig. 4(b). The perforations extended to between 14 m and 43 m below the surface.

The top of the screen at 13.7 m depth was welded to the lower end of the 450 mm blank, mild-steel, bitumen-coated casing.

The recharge water supply was taken from a 200 mm tapping on the 450 mm Central Nottinghamshire Water Board main (see Fig. 4(c)). A 200 mm diameter uPVC pipe took water to the borehole either directly or alternatively through a constant velocity electrically-operated control valve, and through a 150 mm diameter impeller-driven water meter. It was possible for the Central Nottinghamshire Board to determine the rate of flow using a 'Datafonic' link installed in the nearby site hut and to control or shut off the water supply to the recharge borehole if this were ever necessary to ensure supply to consumers.

From the meter, water could be fed directly to the recharge borehole or to the backwashing system through a manifold in the well-head chamber. The recharge pipe was suspended from rolled-steel channels set in a concrete well-head chamber and extended to 47.5 m depth or 9.5 m below initial standing water level. An air-valve was installed to allow trapped gases to escape from the recharge pipe, but the valve was found to be defective and removed during the early part of the experiments.

A single-stage submersible pump was installed 60.8 m below original ground surface so that the borehole could be periodically test pumped. The pump, with a discharge capacity of 12 l/s at a head of 58 m, discharged to a soakaway trench at the end of a 200 mm diameter 500 m long uPVC main (Fig. 2).

The total cost of the recharge borehole pipework, ancillary equipment and eleven observation boreholes was £38 492. The works were constructed between September 1970 and June 1971.

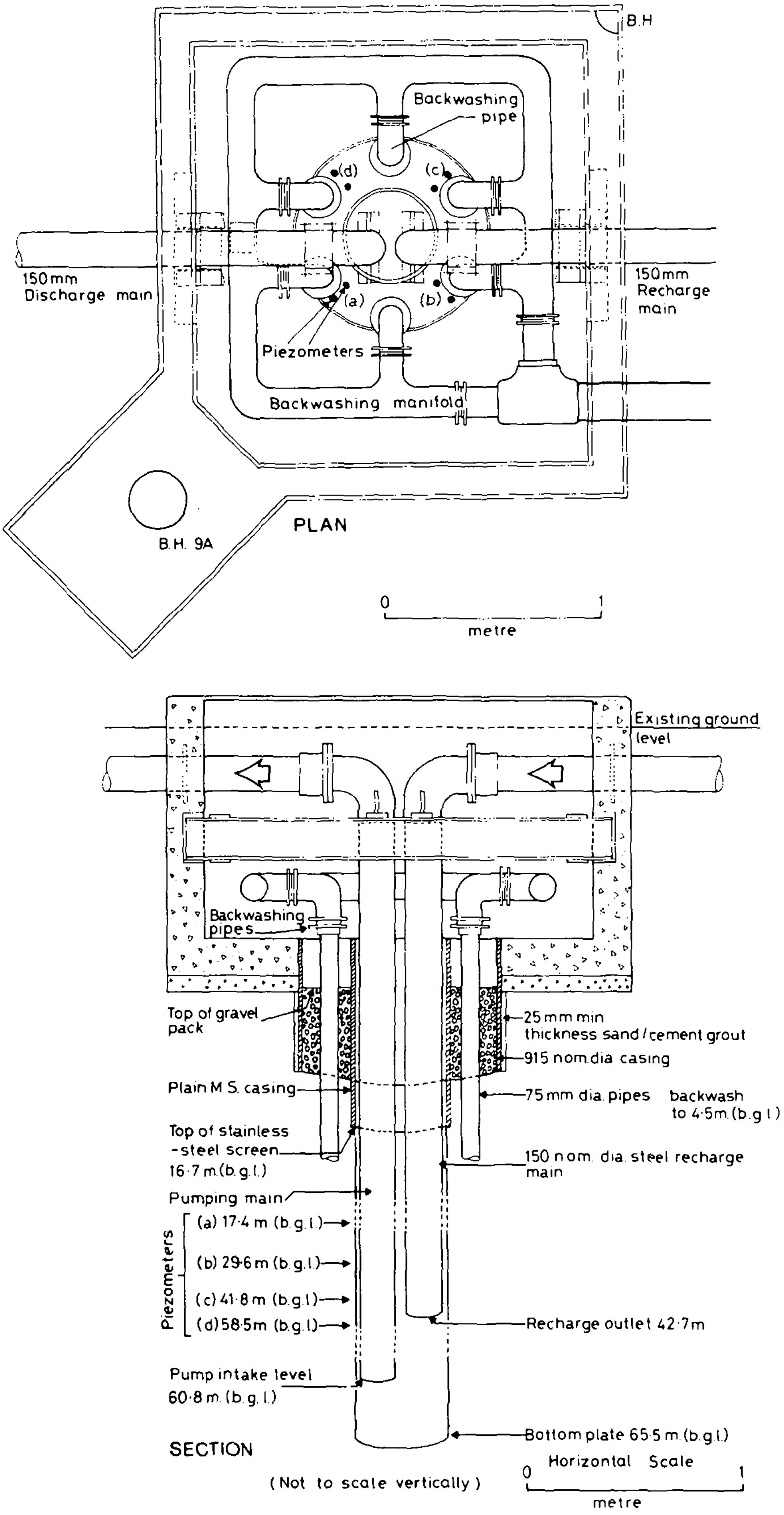


Fig. 4(a). Plan and section of recharge borehole and headworks

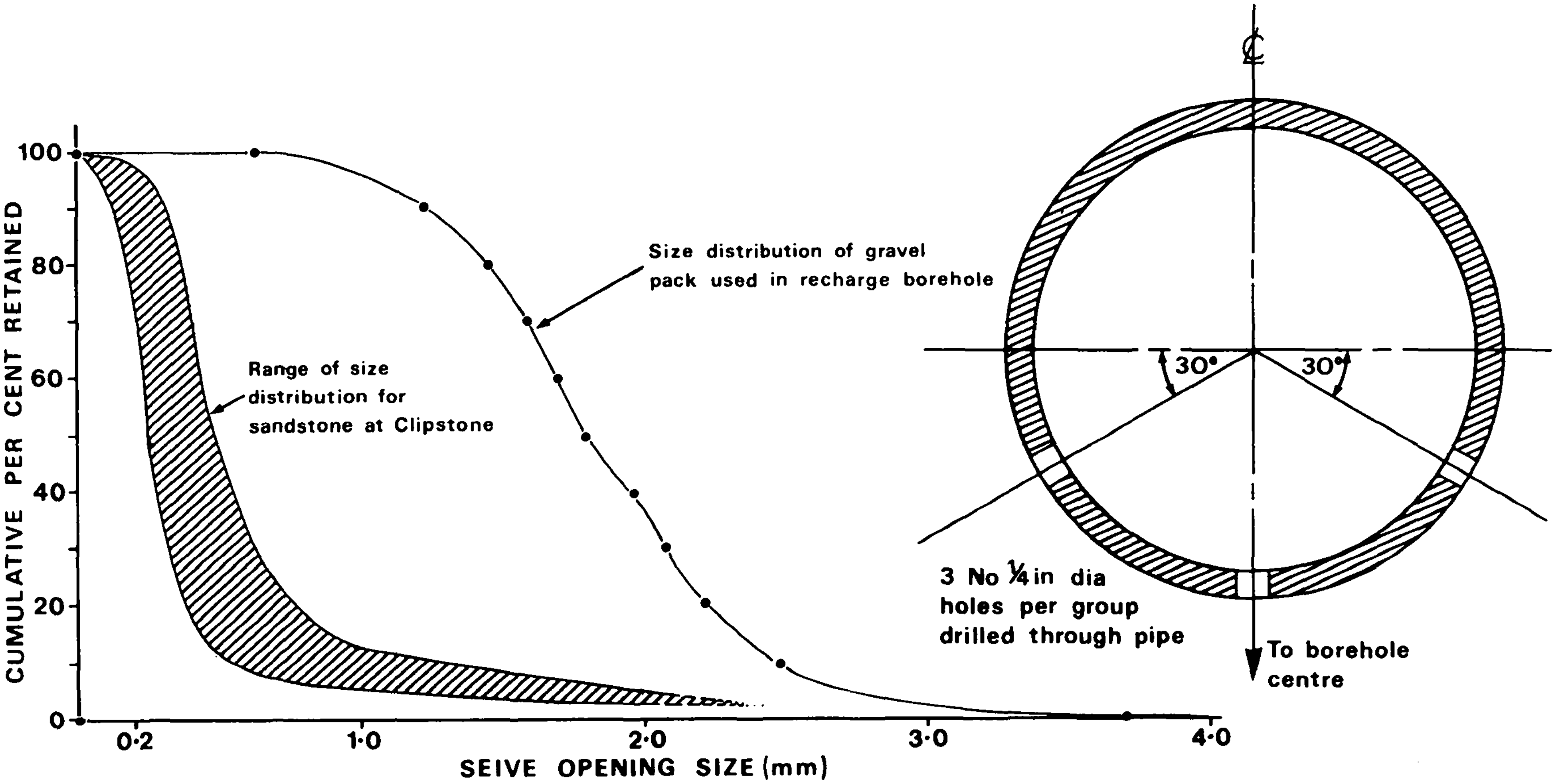


Fig. 4(b). Grain size analyses of aquifer and gravel pack, also showing section through backwashing pipe

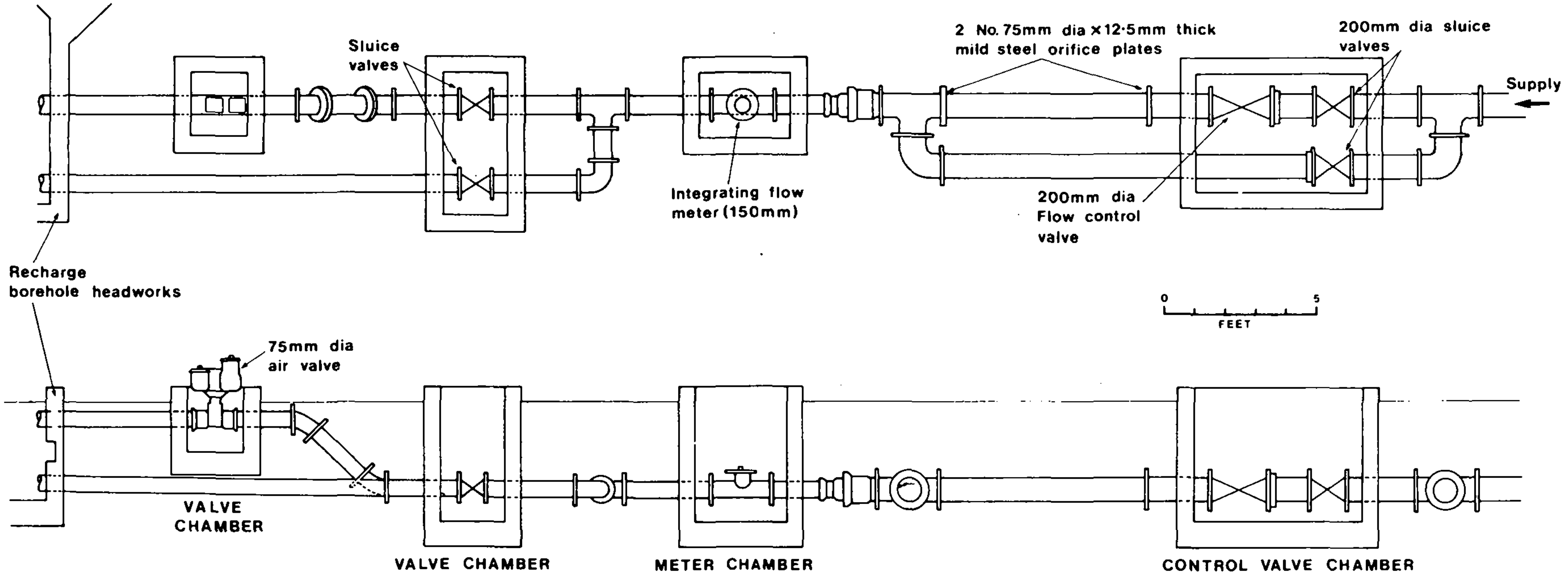


Fig. 4(c). Pipework layout of recharge water supply

4. HYDROGEOLOGICAL STUDIES

An adequate understanding of the processes involved in recharge is only gained by a full understanding of the geology and aquifer properties. The programme of investigation to provide the necessary information is described below.

Of the eleven boreholes drilled initially for observation purposes five, Nos. 2,5,8 and 10 and the recharge borehole pilot hole, were cored to their total depth. As indicated in Section 3 coring conditions were particularly difficult in the upper 30 m of each hole. While this improved below 30 m the average recovery was only 44% overall. Samples of cuttings were taken from the remaining boreholes. All cores and cutting samples were logged in detail.

The lithofacies present, identified by examination of the core samples, fall into three main categories:

(a) medium-brown to red-brown, thickly-bedded or cross-bedded friable to partly indurated, sub-angular to rounded, medium-grained(17), well-sorted orthoquartzites and subarkoses(18) with up to 5% clay; rare quartzite pebbles;

(b) dark red-brown to purple-brown, moderately hard, thinly-bedded fissile, micaceous very fine-grained protoquartzite(17);

(c) yellowish brown, pink, or pale orange, moderately- to well-cemented sub-angular to rounded, poorly to moderately-sorted, medium to coarse-grained pebbly orthoquartzite with clay pellet intervals.

Cementing media are of calcite and/or dolomite, and facies (a) is the most abundant with (b) and (c) together making up less than 20% of the thickness of the formation penetrated. However, these are believed to be of considerable hydrogeological significance due to their relatively low intergranular permeabilities.

Immediately after drilling, the boreholes were geophysically logged using electrical resistivity, spontaneous potential, and gamma-ray equipment. A caliper-log was also made for some of the boreholes. Correlation based on lithology alone has been particularly difficult, partly because of poor core recovery and partly because of the comparative uniformity of the sequence. Of the geophysical logs used, the gamma-ray profiles were of particular value in confirming the simplicity of the geological structure beneath the site and it was important that there was no evidence of faulting or dislocation in the strata.

Though it was difficult to relate samples precisely to the depths of their origin, due to the poor sample recovery, it was possible to establish a correlation between boreholes using the gamma-ray profiles across the site (Fig. 5). Facies (b) referred to above gave a maximum deflection on the gamma-ray log while facies (c) gave a minimum deflection. A number of clear maxima and minima correlated on this basis indicate that some of the strata are lenticular. The higher natural radioactivity associated with clay probably indicates horizons of lower permeability in the gamma-ray profiles. Average dip across the site appears to be 2^{o} to the east as a maximum, and thus slightly higher than the estimated regional dip.

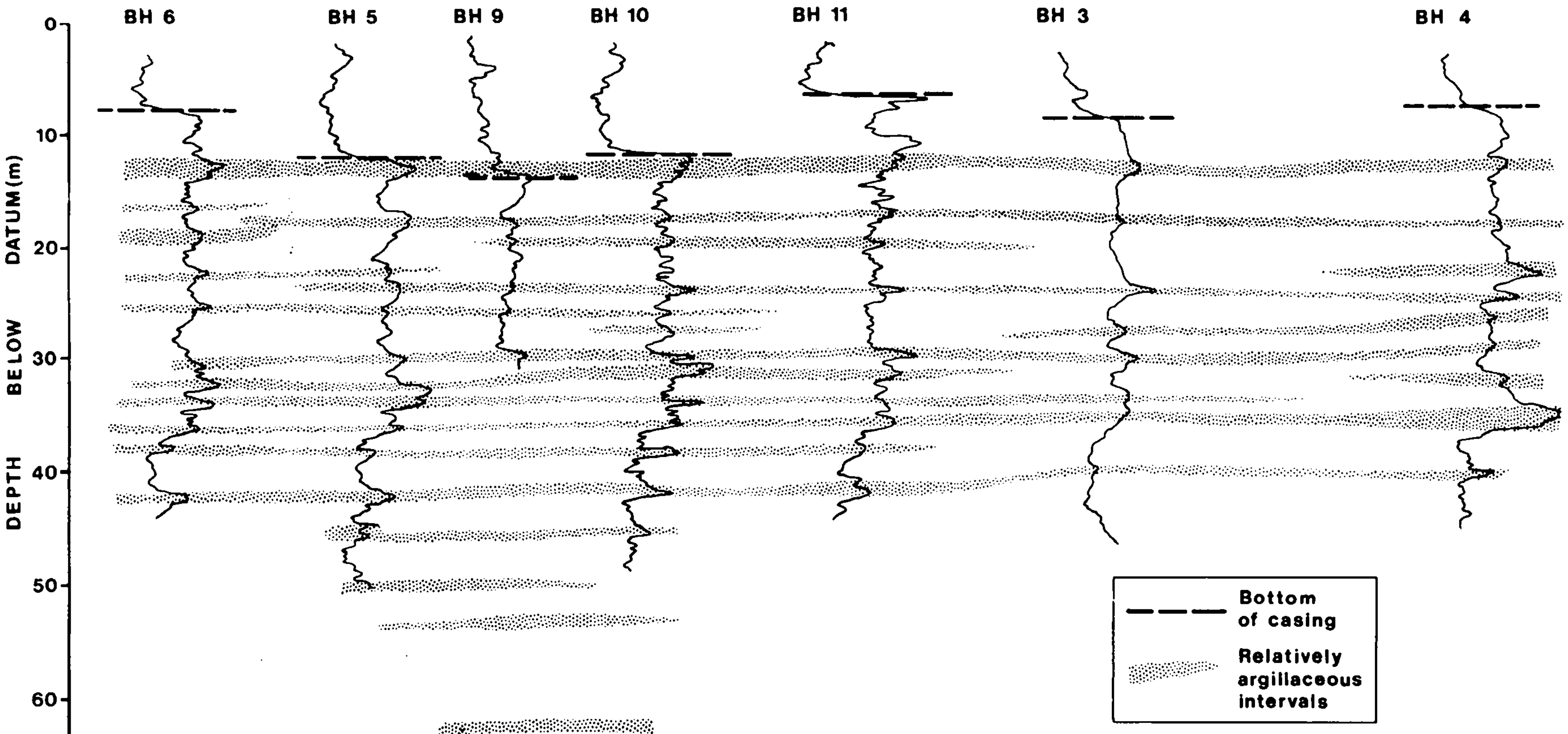
Immediately before experiments were started in March 1971, the water table was at a depth of between 36 and 37 m below surface (68-69 m AOD) and sloped downward to the north at a gradient slightly greater than 1%. A groundwater hydrograph for October 1970 to March 1971 showed that the natural range of water level during that period was not more than ± 50 mm. In March 1971, a step-drawdown pumping test was conducted at approximately 6.3 l/s, 12.6 l/s and 19.0 l/s. The last rate slightly exceeded the yield of the borehole, however, and the intermediate rate of 12.6 l/s was chosen for the constant rate test which immediately followed. An abstraction rate of 12 l/s attained within 5 minutes of the start of the test was maintained within ± 1% for three days, rising slightly to 12.3 l/s at the end of the test. The drawdown in the recharge borehole was 9.4 m.

Assuming that the aquifer was unconfined, but stratified and anisotropic, the log of distance plotted against drawdown for boreholes at 6.0 m or more from the recharge borehole gave a transmissivity value of 182 m^2/d and storage of 0.073. At the end of the test, the effects of delayed yield were insignificant and indeed appear to have become negligible after 1.5 days from the start. Using the analytical method developed by Boulton(19), data from boreholes at 15.0 m radius matched to type curves indicated an average transmissivity of 176 m^2/d and a storage co-efficient of 0.082. Losses at the aquifer-face rendered drawdown in the recharge borehole 85% higher than the theoretical value.

After reaming of the recharge borehole to remove the mud-cake had been completed, and the screen and gravel pack were installed, further test pumping showed that the effect of these operations was negligible. Relatively deep invasion of the formation by fine material during drilling appeared to have taken place below the water table. The penetration was such that pumping during the first test had little or no effect, although highly turbid water was discharged initially. It was clear that the lower part of the borehole was affected by clogging and that this was likely to affect performance adversely.

An examination of all the data from both short-term pumping tests suggested a transmissivity value of 178 m^2/d and a specific yield of 0.09.

A pumping test of 28 days duration was carried out following the recharge experiments. For this test the transmissivity and specific yield were calculated to be 200 m^2/d and 0.17 respectively. Both values are higher than the short-term tests indicated. It appears that steady state conditions were not achieved until 15 days



Note: Not to scale horizontally (see fig.2)

Fig. 5. Correlation diagram based on geophysical profiles, indicating relatively argillaceous intervals

had elapsed. It is of interest that laboratory determinations of specific yield on samples taken from the Bunter Sandstone at nearby Edwinstowe are similar to the calculated field value(20).

On completion of drilling and coring, 89 representative samples of the various lithologies present in the sequence were selected for laboratory determination of porosity and permeability; 29 of these were from the recharge borehole. This work was undertaken by the Institute of Geological Sciences(21). It was clear at the time of sampling, that the sandstone was very poorly cemented and that in some cases there would be considerable difficulty in performing the laboratory work. Those cores which were too soft in their natural condition were frozen either with liquid nitrogen or dry ice before the small 25 mm cores for analysis could be drilled out.

Grain-size analyses were carried out on many samples which were unsuitable for direct laboratory determination of hydraulic properties. Indirect estimates of permeability were made from the grading(22). In this formation however, where there is some cementation and relatively small grain-size, a good relationship between the permeability and grain-size could not be expected.

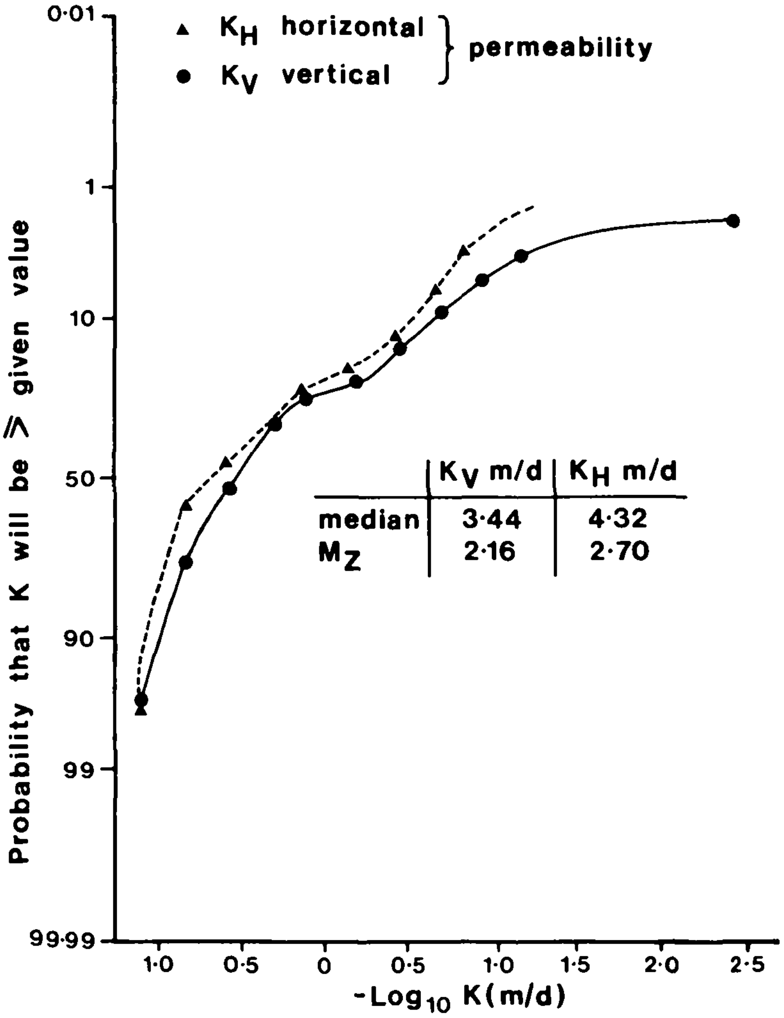
The only value of these particular data is that they provide confirmatory evidence of the order of magnitude of the laboratory values only.

The statistical distribution of hydraulic conductivity determined in the laboratory is illustrated in Fig. 6. The sample population on which these results are based was seriously affected however by the poor compaction of the coarser, more permeable lithologies, particularly in the uppermost 30 m. For this reason it is considered that the median value of permeability was more representative of the complete sequence. The horizontal permeability of samples from the lowermost 20 m of the borehole averaged over 4.0 m/d, and tended to support this. Furthermore they indicate a transmissivity similar to that measured in pumping tests. Over 300 samples from Edwinstowe, 4 km to the north-east, were tested in the laboratory and the mean values of K_v and k_h were 2.38 m/d and 3.13 m/d respectively(20).

It was hoped that a good quantitative impression of the hydraulic conductivity of the complete sequence might have been built up in this way. Largely because of the poor core recovery, however, it was generally difficult to attribute hydraulic conductivity values to specific features identifiable in the gamma-ray logs. All the evidence indicated that the succession is relatively uniform and that the combined laboratory and grain-size determinations of hydraulic conductivity can be used to characterise the formation adequately. Grain-size distribution data were analysed using the 'phi' size scale and the parameters defined by Inman(23).

It was found in the 40 samples that were studied, that the typical sandstone was well-to-moderately sorted, fine-skewed, and had a high or very high kurtosis. The median grain-size was in the 'medium sand' range(17) for 75% of the samples, 15%

were in the 'fine' range, and only 10% in the 'coarse' range. Finer-grained sandstones, (which have as much as 5% silt/clay) relate to gamma-ray maxima; the ill-sorted, generally coarser-grained sandstones, relate to gamma-ray minima.



	K_V m/d	K_H m/d
median	3·44	4·32
M_Z	2·16	2·70

Fig. 6. The statistical distribution

To obtain detailed knowledge about the condition of the inside of the borehole prior to insertion of the screen and gravel pack, a closed-circuit, downhole television survey was conducted, using both axial and radial scanning. Even allowing several days for the groundwater in the recharge borehole to clear, it was still too turbid to permit television inspection. Only the upper 60% of the borehole, above the water table, could therefore be examined on this occasion. A thick mud-cake was observed over most of the borehole wall. At two levels seepages from perched water bodies had penetrated the mud-cake, and at numerous points there were small areas where the mud-cake had been peeled off during the movement of drilling tools in the hole. The thickness of the mud-cake was estimated to be about 5 mm. The high reflectivity of the mud-cake suggested that the bulk of the material was of clay-sized particles.

In March 1972 a downhole TV survey of the nearest observation borehole, No. 9A, was carried out. It was clear from the information provided by this survey that a considerable proportion of the clay material within the formation occurred within clay-pellet intervals. Grain-size analysis, after careful separation of mud pellets from a medium-grained sandstone, showed that clay content was 2.4%. Including the mud-pellets, the clay content was 3.7%. This relatively permeable stratum could appear as a gamma maximum because of its misleadingly high total clay content.

In view of the fracturing encountered at the Edwinstowe site(1), it was decided that the vicinity of the recharge borehole should be carefully examined to determine whether this kind of feature was important. Flowmeter and temperature surveys were therefore conducted in borehole No. 9A during recharge. Several runs were made but no marked variations attributable to fissuring were found. Intergranular flow therefore appears to be predominant, an opinion also supported by the results of the permeability determinations.

5. RECHARGE EXPERIMENTS

5.1. FIRST RECHARGE EXPERIMENT

The first recharge period was carried out with the water level controlled electrically in the recharge borehole. The system did not operate efficiently and led to substantial water level fluctuation. This imposed practical problems with the water level measuring instruments and made analysis of the data difficult. For the main tests therefore, it was decided that the recharge rates would be fixed rather than the level in the recharge borehole. The recharge programme was planned and carried out as follows:

(a) Multi-step experiment: the recharge rate was increased in a series of steps each occupying not less than one month, and maintained until equilibrium conditions were established.

(b) Following the first recharge period, the borehole was tested by pumping, and the effectiveness of backwashing was determined.

(c) Constant rate experiment: recharging was at a constant rate, to determine how the recharge performance varied with time. The recharge rate used was selected on the basis of the results of the first recharge period. This period simulated the operational situation.

A low starting recharge rate of 256 m^3/d was selected for the first step. The fluctuations in mains supply pressure were detectable in the recharge borehole water level, but were considered unimportant. The average rates of recharge measured by an integrating meter during each step were essentially constant. The natural fluctuation in groundwater level was small (at most ± 50 mm), and at the start of the experiments the effects of previous tests were not evident. Water level in the recharge and observation boreholes at the start of recharge was therefore considered a suitable datum, and the water level rise measurements were based upon this.

In addition to the water level information provided by the seven punched-tape recorders, routine weekly measurements were made in the remaining observation boreholes (Nos. 4,5,6,10,11).

Recharge was undertaken at nine different rates, up to a maximum of 3500 m^3/d. The recharge borehole water level was taken up to as near the top of the borehole as practical. Special attention was paid to the changes in the level in borehole 9A, which was only 1.5 m from the recharge borehole (Fig. 7).

The increase in the water levels over the course of the first recharge experiment, around the borehole, showed increasing asymmetry with slight elongation in the direction of regional groundwater flow. The picture is not simple however, and within

15 m of the recharge borehole there is some variation in the detailed form of the 'mound' as illustrated by the profiles shown in Fig. 8. This does not affect the overall situation however. The development of the recharge mound is shown at three stages in Fig. 9 which clearly shows the 'near-well' variability.

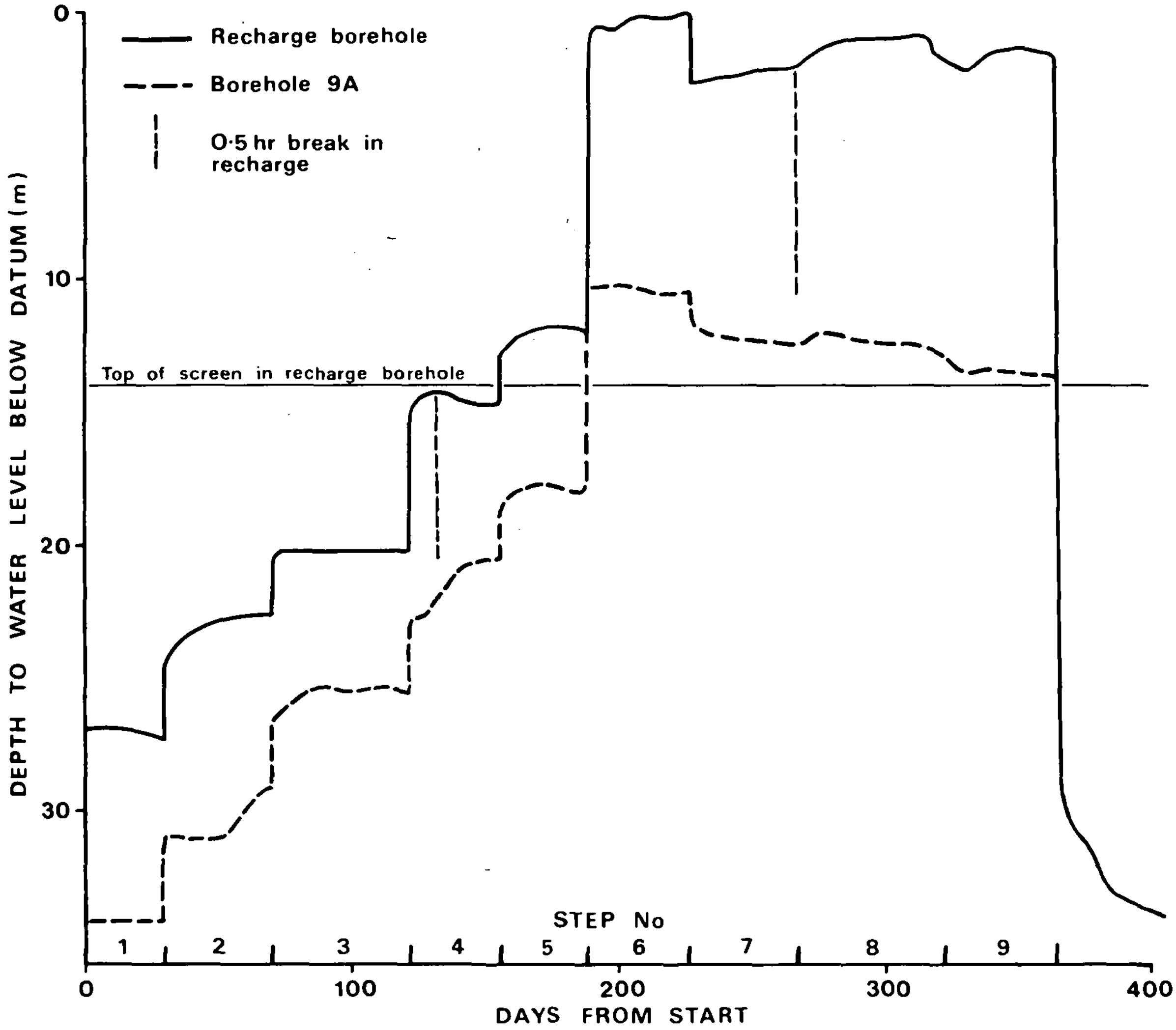


Fig. 7. Multi-step recharge experiment – water levels in recharge borehole and observation borehole No. 9A

The main increments in rate were in Steps 1 to 6 and the subsequent changes were relatively small. The important data relating to rate of recharge, quantity recharged and duration of the various steps, are presented in Table 2, and the observation borehole water levels are summarised in Table 3.

In an attempt to determine the specific recharge capacity for the recharge borehole, analogous to the specific capacity of an abstraction borehole, the rate of recharge was drawn as a function of the equilibrium water level rise in the well (Fig. 10). The progressive improvement of the specific recharge capacity is evident, particularly above a recharge rate of 1400 m^3/d.

Measurement of water level in piezometers, at different levels in the gravel pack, showed that a head loss of 80 mm was the maximum which occurred. There was however, a precipitous fall in head of up to 12.6 metres between the recharge borehole and borehole 9A, in the formation. The effective saturated depth of the aquifer is considered to be most accurately reflected by the saturated thickness in borehole 9A. rather than that indicated by the recharge borehole water level.

Table 2. Summary of multi-step recharge experiment data

	Period of recharge (days)		Volume recharged (m^3)		Recharge rate increase (m^3/d)	Average recharge rate (m^3/d)
Step No.	Step	Total	Step	Total		
1	30	30	7680	7680	256	256
2	40	70	23230	30910	324	580
3	51	121	38250	69160	170	750
4	35	156	44900	114060	530	1280
5	32	188	55370	169420	450	1730
6	38	226	133120	302540	1770	3500
7	44	270	131280	433820	-520	2980
8	52	322	163860	597680	170	3150
9	42	364	121670	719350	-250	2900

Table 3. Equilibrium water level rises (metres) in observation boreholes at each step of multi-step recharge experiment

Borehole No.	9A	1	7	5	10	2	6	8	11	3	4
Radius (m)	1.5	3		6		15				30	60
Days from start											
30	1.64	1.40	1.25	1.15	1.20	0.87	0.77	0.82	0.81	0.56	0.34
70	6.61	4.83	4.46	3.41	4.04	3.35	2.13	2.33	2.39	1.41	0.85
121	10.33	8.81	8.39	5.79	8.30	5.49	3.62	3.99	4.19	2.22	1.26
156	15.23	13.44	13.35	12.31	12.69	10.79	7.88	7.54	8.45	4.02	2.20
188	17.78	15.96	15.97	14.64	15.13	12.41	11.01	10.25	10.96	5.73	3.09
226	25.24	23.37	23.72	22.27	22.34	18.74	17.90	17.81	17.87	12.25	7.56
270	23.16	21.31	21.70	20.41	20.45	17.23	16.40	16.26	16.32	11.28	7.25
322	22.75	20.87	21.21	19.98	19.83	17.06	16.17	16.20	16.11	11.88	7.80
364	22.12	20.17	20.58	19.23	19.26	16.36	15.58	15.44	15.66	11.45	7.65

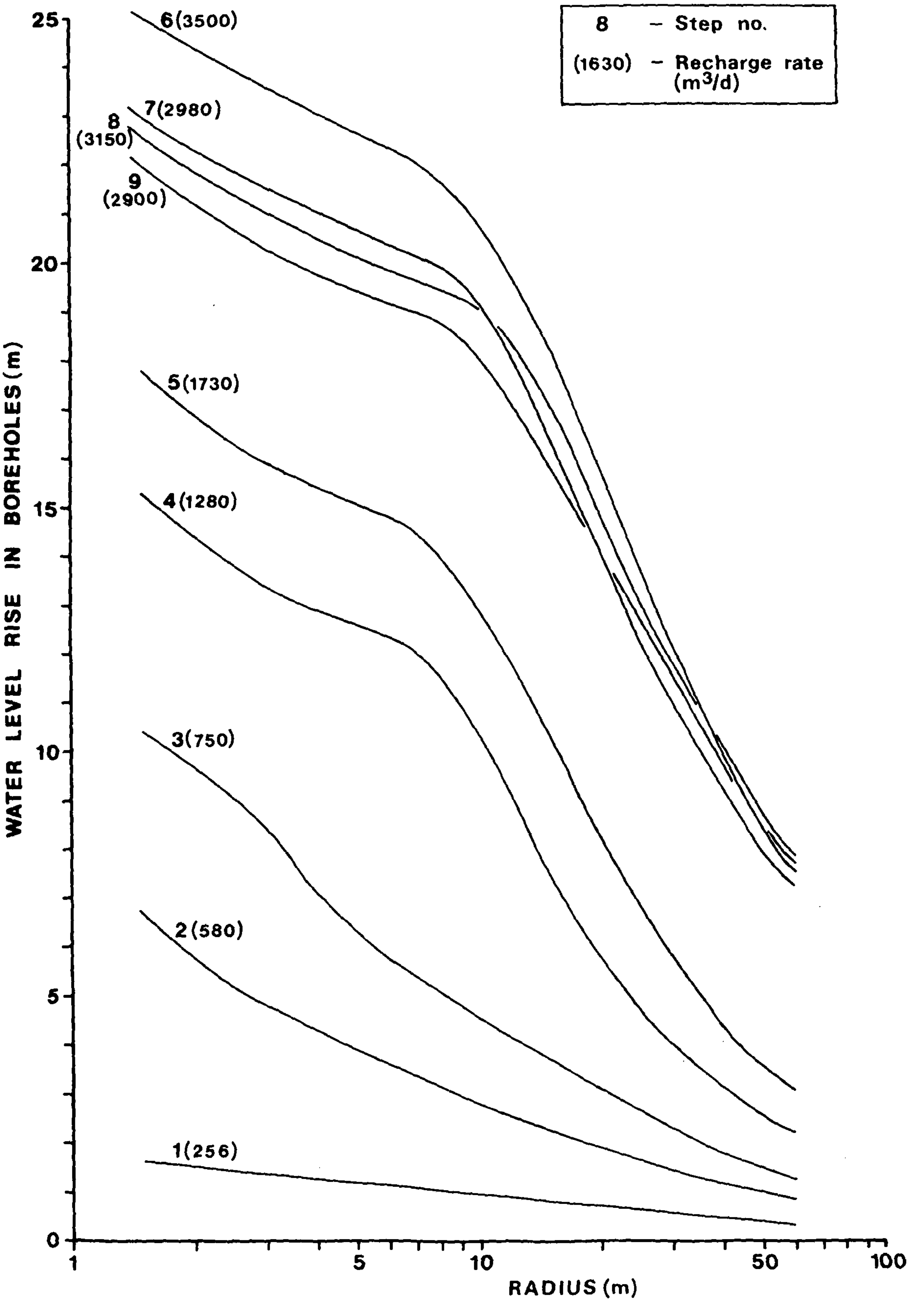


Fig. 8. Multi-step recharge – observation borehole water levels at series of recharge rates

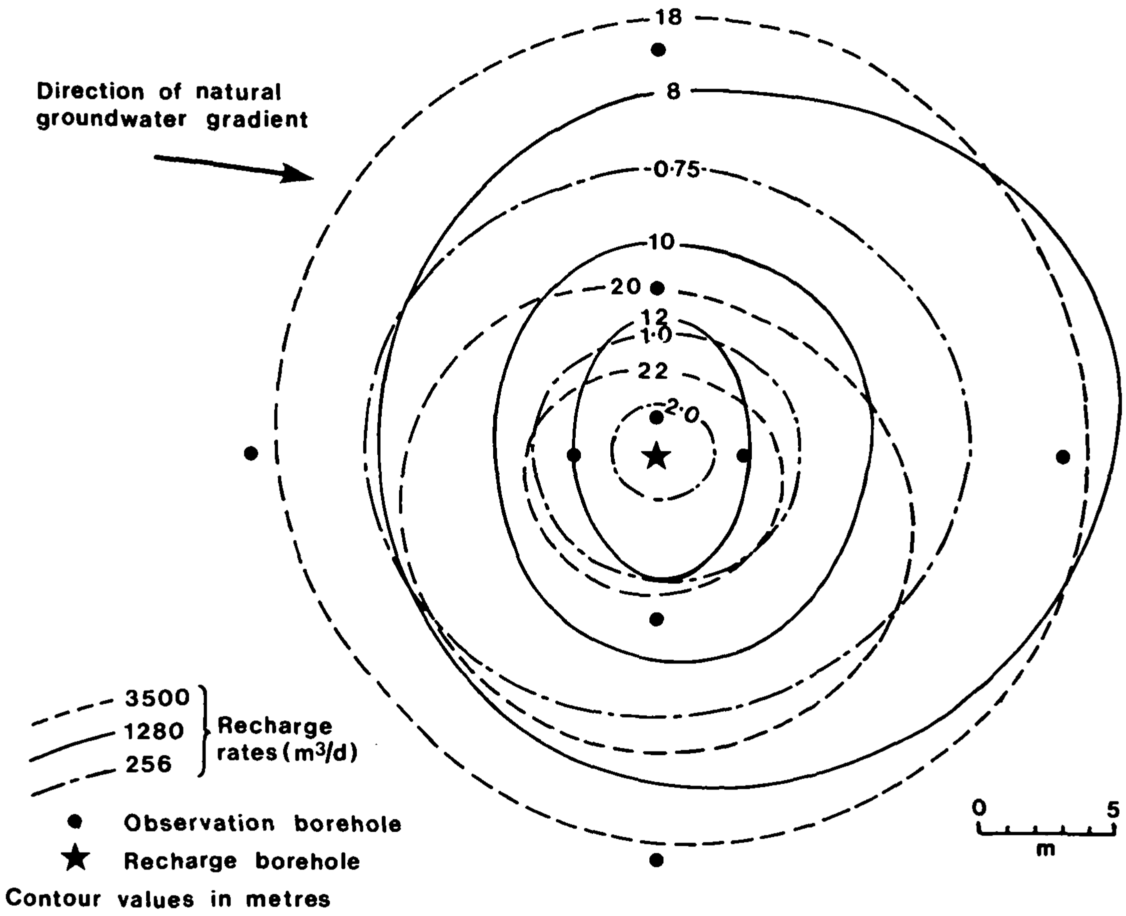


Fig. 9. Contours on the recharge mound at a series of rates during multi-step recharge

5.2. BACKWASHING

Backwashing was carried out one month after the end of recharge in preparation for the second period of experimentation.

Recharged water quality is discussed fully in Section 5.4. However, at this point it is relevant to consider suspended solids content separately. The supply for recharge was of potable standard and in 105 separate analyses the suspended solids concentration ranged up to 6 mg/l. The average value was less than 1.0 mg/l, but more accurate determinations using a sedimentation balance which obtained values of 0.05 mg/l suggest that a much lower concentration may be more representative. Samples of the solids recovered were of red-brown material.

At the end of the first period of recharge, backwashing, using the specially installed pipes, was carried out as follows:

(i) pumping from the recharge at 1080 m^3/d for one hour;
(ii) backwashing at 750 m^3/d for 1 hour;
(iii) rate increased to 1500 m^3/d for 1 hour;
(iv) two hours break in backwashing and pumping;
(v) pumping at 1080 m^3/d and backwashing at 1500 m^3/d for 1 hour;
(vi) pumping only, for 30 minutes.

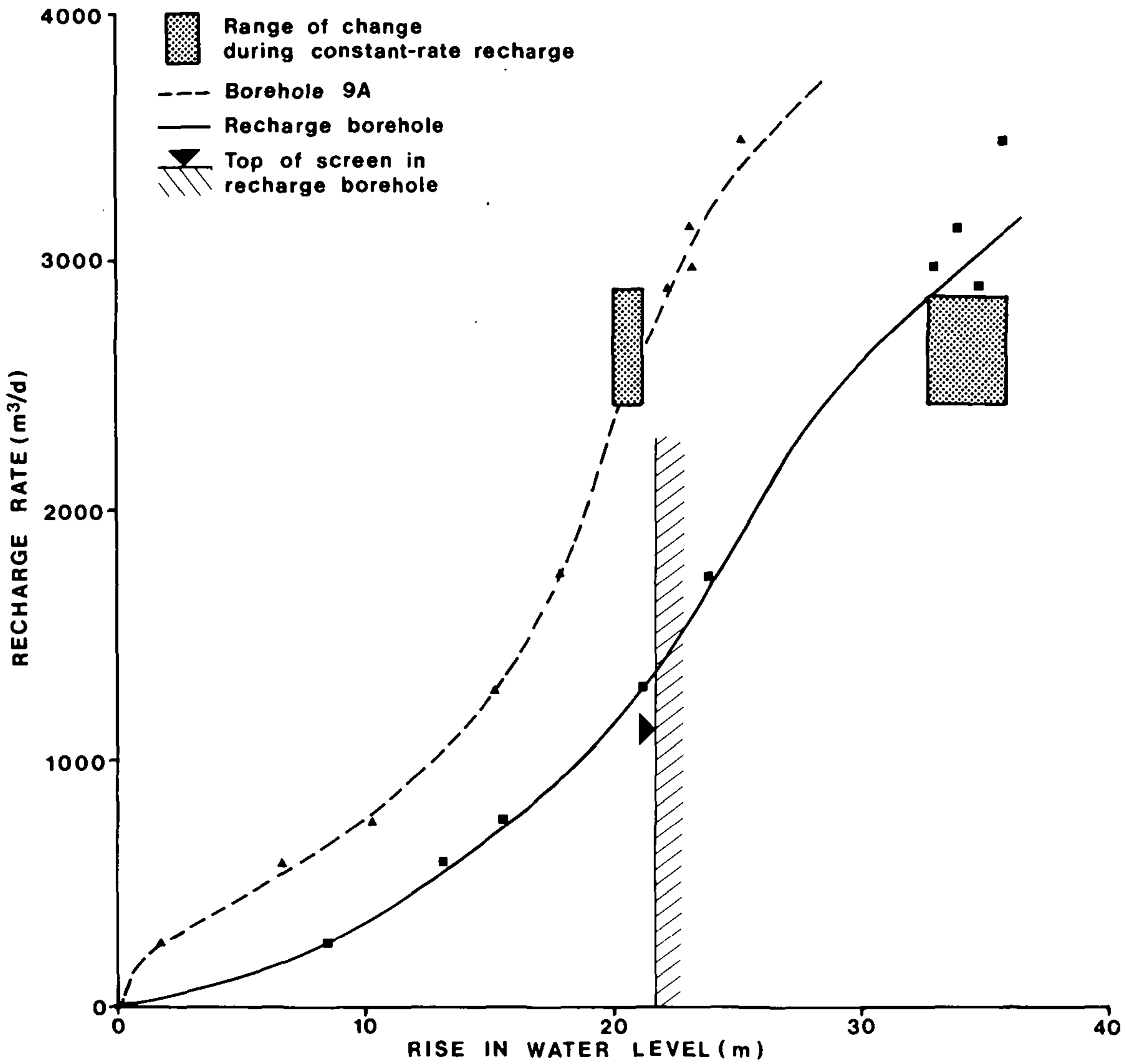


Fig. 10. Recharge rate and water level rise in the recharge borehole and observation borehole No. 9A

Samples of pumped water show that the highest concentrations of solids occurred at the start of the first pumping period.

Suspended solids in the sequence of samples taken are shown in Fig. 11. At the various changes in regime, the amounts of solid matter pumped with the water were large but the concentrations declined to less than 20 mg/l within one hour. If an average concentration of 25 mg/l is assumed for this short period, then more than 110 kg of solid matter were removed, as a conservative estimate. Some of the suspended solids in the discharged water were pale in colour and derived from the gravel pack. Most of the solids were, however, clearly derived from the Bunter Sandstone, but the proportions from the pack and from the mud-cake are not known. Samples taken from the pack inside piezometer tubes contained only traces of red-brown clay-sized material, and if this is taken to be typical of the entire pack then it could be assumed that the suspended solids in the discharged water come from beyond the pack. Pumping tests were carried out before and after backwashing to determine whether there was any clogging of the lower part of the aquifer. There was no measurable difference in performance between the two tests, but the higher starting water levels gave conditions which indicated a specific capacity some 20% higher than found in pre-recharge testing at similar discharge rates. The results of these tests gave no indication of the effects of clogging in the zone of aeration, and the results of further recharge were needed to examine this.

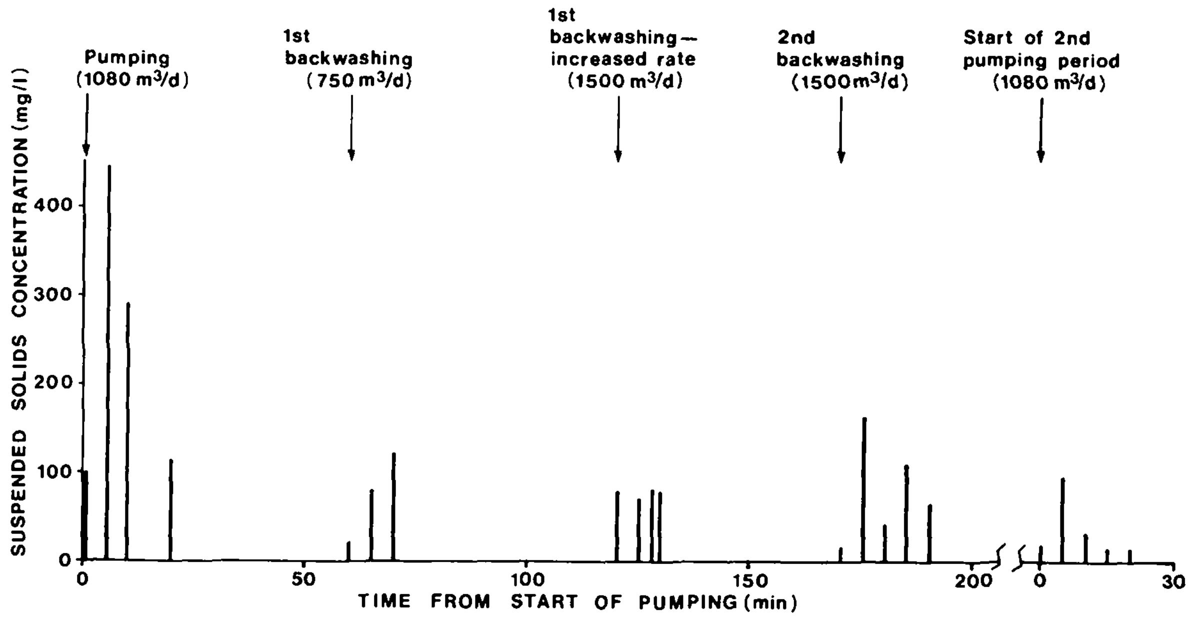


Fig. 11. Suspended solids concentrations during pumping and backwashing

5.3. SECOND RECHARGE EXPERIMENT (CONSTANT RATE)

The second recharge period started after a two-month recovery period, with an initial recharge rate of 2840 m^3/d, giving a recharge borehole water level rise of 34.0 m, which was about the maximum practicable. The head was maintained near to this level for three months, and it was necessary to reduce the recharge rate in steps by about 15% to 2420 m^3/d to maintain the same water level in the recharge borehole. Details are shown in Table 4.

Table 4. Summary of recharge borehole performance during the constant-rate test

Recharge period (days)		Volume recharged (m^3)		Recharge rate (m^3/d)		Recharge capacity (m^2/d)	Water level rise in recharge borehole (m)
Interval	Total	Interval	Total	Increment	Average		
7	7	19830	19830	2840	2840	83.5	34.0
21	28	55400	75230	-200	2640	77	34.3
35	63	88020	163250	-120	2520	73	34.5
23	86	55280	218530	-100	2420	71	34.0

Table 5. **Mean concentration of groundwater and recharged water during 21.6.72 to 20.3.73, compared with initial groundwater composition (in mg/l)**

	Average pre-recharge groundwater	Borehole No.			Recharged water
		4	5	6	
Ca	24	34.9	33.2	34.4	28.9
Mg	11.5	22.1	22.8	19.0	18.5
Na	12.0	14.5	15.8	16.0	12.4
K	4.5	4.5	2.7	2.4	2.2
HCO_3	46	72.3	67.5	65	60.7
Cl	25	37.8	40.1	38.4	23.7
SO_4	42	45.4	43.4	41.5	40.9

The differential in water level between the recharge borehole and borehole 9A was sustained and remained almost constant throughout the period of recharge at between 13 and 14 m. The specific recharge capacity reached a final value of approximately 71 m^2/day. This is significantly less than that achieved during the first recharge period. The ranges of water level and recharge rate are shown in Fig. 12 for both 9A and the recharge borehole; the water level response in the observation boreholes is given in Figs 13 to 15. The shape of the recharge 'mound' showed considerable change during the course of the experiment. Contours on the 'mound' are given in Fig. 16 at two different times. It is of interest that no strong anisotropy is developed which might suggest important fracture permeability. The cone became considerably narrower and the basal portion broadened later in the recharge period.

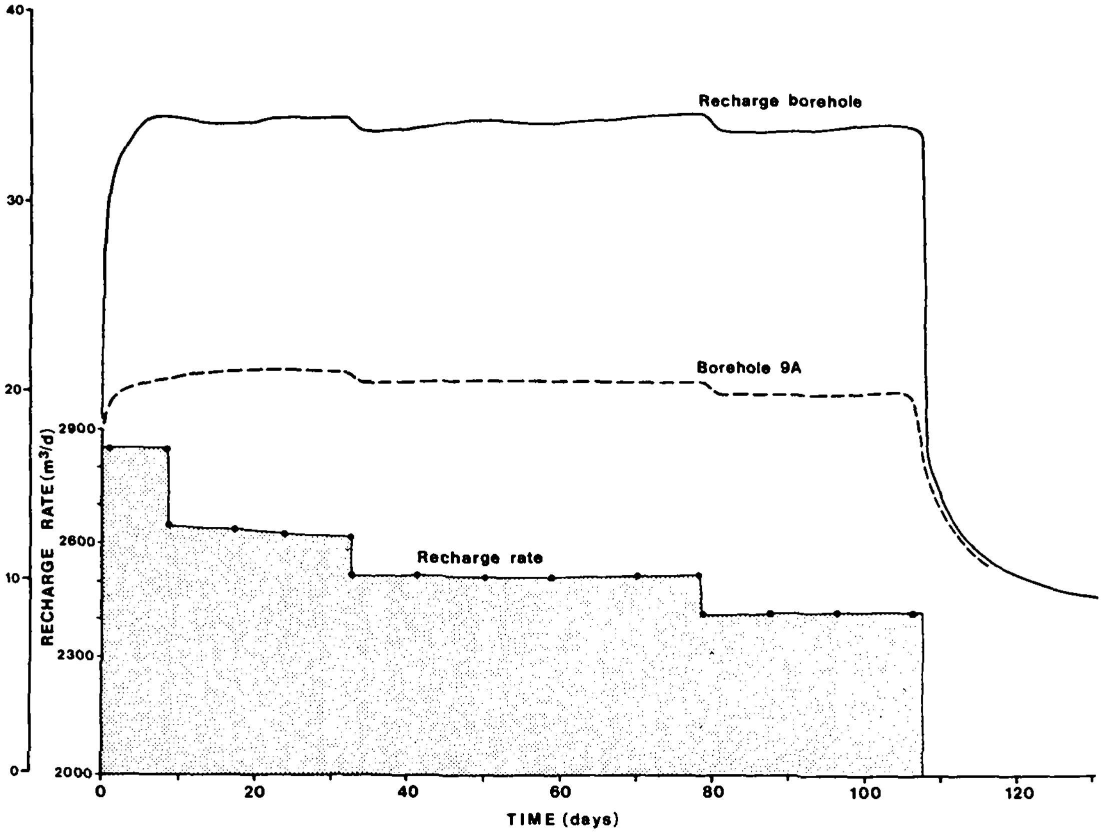


Fig. 12. Constant-rate recharge experiment – water-level recharge rate relationships

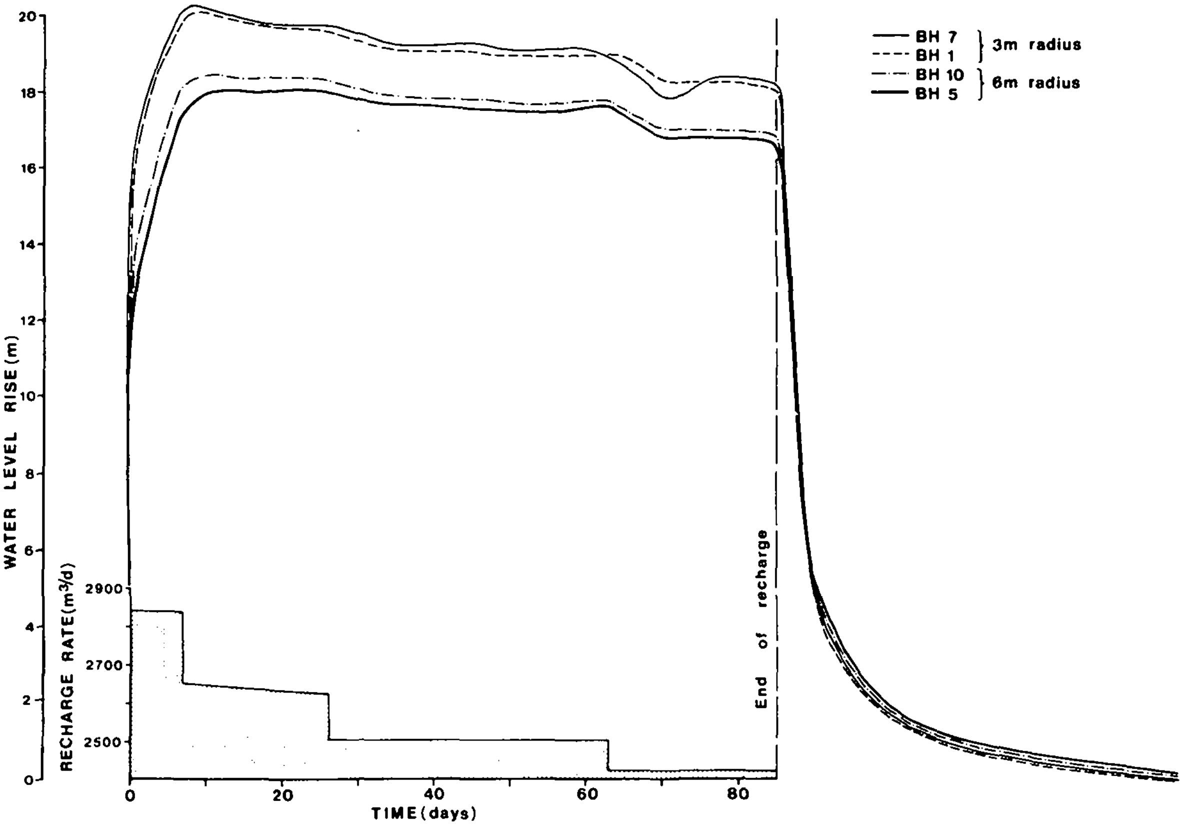


Fig. 13. Constant-rate recharge – observation borehole water levels

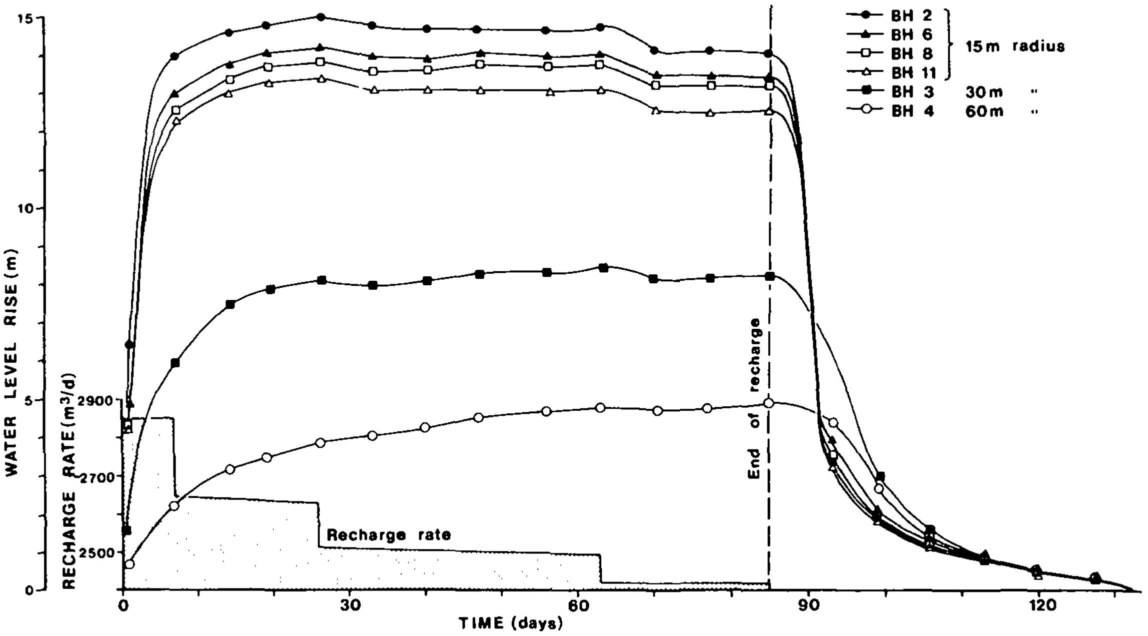


Fig. 14. Constant-rate recharge – observation borehole water levels (boreholes 2,3,4,6,8, and 11)

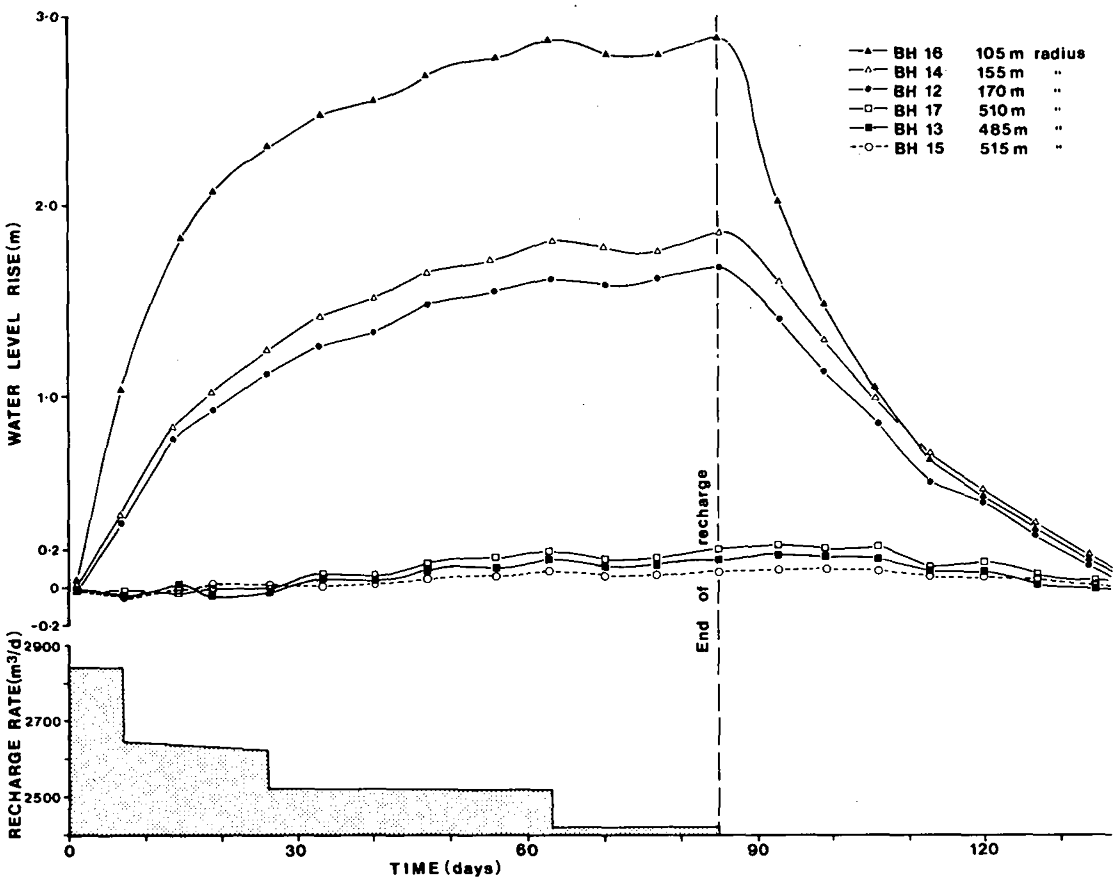


Fig. 15. Constant-rate recharge — observation borehole water levels (distant boreholes)

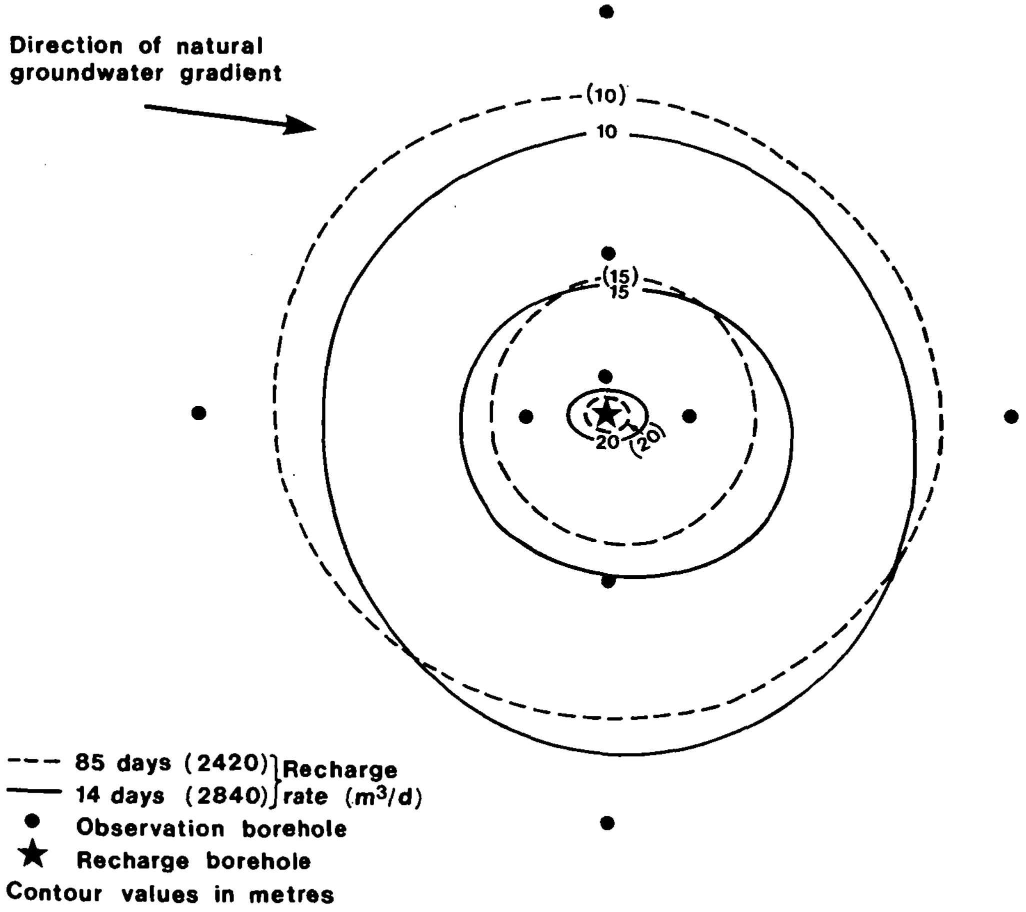


Fig. 16. Contours on recharge mound during constant-rate recharge

5.4. WATER QUALITY

A recharge water supply was chosen with a composition as close to that of the naturally occurring groundwater as practicable. This was done to avoid any chemical interactions that could affect the interpretation of the quantitative results of recharge. The pre-recharge composition of the groundwater and the mean composition of the recharged water, are given in Table 5. It is evident that the two waters are of closely similar composition.

During recharge experiments, chemical changes were not monitored in detail because of this similarity. A comparison of the average compositions of samples from three of the boreholes during recharge shows, however, that some recognisable changes have been caused. At least 15 samples have been used to produce these mean values. The standard deviation of ± 9.5 for the chloride value from borehole No. 4, is typical. The temperature of the recharged water varied by only ± 2 to $3^{o}C$, the supply pipeline being buried to approximately 1.0 m depth. Dissolved oxygen remained near saturation for the duration of the experiments and the nitrate concentration averaged 1.7 mg-N/l.

There were small increases in calcium and magnesium concentrations in the groundwater after recharge. These were probably due to leaching of cementing material from the zone of aeration which could have occurred even though the pH was relatively high.

The increase in chloride is difficult to explain, however, since chlorides appear to be too soluble to remain, or to become concentrated, in the zone of aeration. Addition of chloride at the time of chlorination could not account for this increase in concentration. The increase in concentration was relatively small, however, and of no significance in terms of potability. At present it must be concluded however, that leaching from the zone of aeration was the cause for the slightly increased chloride content.

6. DISCUSSION

The basic hydrogeological conditions found at Clipstone were essentially as predicted, except that the zone of aeration was approximately 5 m thicker. The geological succession was similar to the Bunter Pebble Beds at Edwinstowe but slightly more variable with more abundant mud-pellet intervals, and medium to coarse-grained sandstones. There was no evidence of jointing or other fracturing in drilling or in the cores taken and the indications are that the overall aquifer properties are similar to those found previously in the south Nottinghamshire area, and more particularly at the nearby Edwinstowe experimental site, Lovelock(21), Williams and others(22). The vertical anisotropy of the succession (k_h/K_v) which was expected to be particularly important for unconfined recharge, was relatively small at about 2. The <u>range</u> is the critical measure, however, and the thin lenses of argillaceous strata of low permeability ($<10^{-1}$ m/d) are important for their effect on the movement of water away from the recharge borehole at all stages of recharge. This is particularly so at the higher rates and near to the recharge borehole where the vertical component of the flow was greatest. More detailed information on the vertical component of flow, using piezometer points would be desirable in any future experiments.

The flow meters initially installed were not sufficiently accurate over the full range of flows. These were subsequently modified and additional metering incorporated. Metering arrangements could have been simplified if it had been possible to keep the main supplying the recharge borehole full, so that the amount of turbulence and the occurrence of air bubbles in the recharge borehole were reduced.

Even though special care was taken to avoid clogging during drilling, TV inspection of the borehole above water showed that clogging had occurred. The mud-cake was removed by dry reaming to a depth of 43 m, below which any clogging was believed to have been removed by pumping. Subsequent work has shown that this was probably not the case and that the use of a chemical conditioning agent in conjunction with jetting would have been beneficial. At that time, however, it was felt important to avoid introducing contaminants into the recharge borehole. Increase in the cumulative recharge capacity at progressively higher rates of recharge is shown in Table 6, which reflects the decrease in the relative proportion of unreamed, or uncleaned, hole as the saturated depth increases.

The specific recharge capacity for the first increment was relatively low at 28.9 m^2/d. The saturated depth included the lowermost, partly clogged section of the borehole. At the maximum rate, within the screened part of the hole, a specific recharge capacity over five times higher was achieved (160 m^2/d). The mean value of 'cumulative' (Table 6) specific recharge capacity, taken even as 60 m^2/d, is an encouragingly high rate when compared with the results achieved by Marshall and others(8) at Birmingham Racecourse using a similar gravity head and an aquifer penetrated to over 130 m compared with less than 50 m at Clipstone. The mean specific recharge capacity at Clipstone was almost 30 times higher than the maximum capacity achieved in the Birmingham Racecourse borehole. It was also double the value reported by Olsthoorn and others(5) in Pleistocene sands and closely similar to the value observed by Vecchioli and others(24) in recharging highly-treated effluent at a site on Long Island. It was approximately half that found as an equilibrium value in the Ogallala formation of Texas(25). The extremely high capacities which Israeli workers found possible in their coastal Pleistocene sand aquifers ranged as high as 2400 m^2/d, but these were coupled with permeabilities of up to 60 m/d (26,3).

The effects of continuous recharge on performance were difficult to detect at Clipstone even after one year, though a slight decline in cumulative recharge capacity probably reflects some degree of clogging. Analysis of suspended solids in a large sample (20 l) of recharge water showed that virtually all the solids were of clay size and less than 1.0 micron diameter. It is of interest to note that for a given rate of recharge as compared with abstraction under unconfined conditions, the entry velocity of recharged water will be considerably less with the present borehole design. Borehole losses due to turbulence are therefore implicitly smaller during recharge. The maximum entry velocity achieved during recharge at 3500 m^3/d was 3 mm/sec.

The decline in cumulative recharge capacity during the multi-step experiment appears, from the gradual fall in the level in borehole 9A, to be due to clogging. In the constant rate test, the fall in level of the recharge 'mound' during recharge appears to be most apparent at 3 m and 6 m radius so that some penetration of the aquifer to the region where flow velocity was near 0.1 mm/sec apparently occurred. Few laboratory studies under radial flow conditions have been made except for those of Rahman and others(27) and more recently of Bichara(15). Bichara's work has revealed that for a given cumulative amount of clogging material, high concentrations caused more rapid clogging than low, though the difference was progressively less the smaller the size of the suspended material. Furthermore, he also found that by doubling the thickness of the pack used, up to ten times the amount of suspended solids could be tolerated before the same degree of clogging was reached.

Table 6. Summary of recharge borehole performance – multi-step experiment

Step	Average recharge rate, R (m^3/d)	Recharge rate increment, r (m^3/d)	Effective* depth (m)	Water level rise increment, l (m)	Incremental recharge capacity, $^r/l$.	Total rise in recharge borehole, L (m)	Cumulative recharge capacity, $^R/_L$ (m^2/d)	% screen** saturated
1	256	256	31.2	8.87	28.9	8.87	28.9	59.8
2	580	324	36.1	3.78	85.7	12.65	45.9	69.3
3	750	170	39.7	2.77	61.4	15.42	48.7	77.0
4	1280	530	44.7	5.64	94.0	20.66	61.9	85.8
5	1730	450	47.3	2.80	160.7	23.46	73.7	90.8
6	3500	1770	54.7	11.90	148.7	35.36	99.0	↑
7	2980	-520	52.7	-2.80	-	32.56	91.5	fully
8	3150	170	52.7	1.0	-	33.56	93.9	↓
9	2900	-250	51.7	-0.8	-	32.76	88.5	99.2

* Saturated thickness estimated from level in borehole 9A

** Taken from level in borehole 9A

The cumulative effects of clogging as measured by the decline in specific recharge capacity (see Fig. 17) were almost unaffected by backwashing, pumping and surging between the two periods of recharge. Solids removed by backwashing were either an insignificant proportion of what had been introduced, or were already in the borehole (as clogging material concentrated by drilling, or as part of the pack). If the suspended solids concentration in the recharge water was 1.0 mg/l on average, approximately 700 kg of material would have been introduced. Backwashing removed approximately 15% of this amount but it is believed to have been at least partly derived from the pack. Actual removal of recharged solids therefore appears to be small as indicated by the lack of effect of backwashing on specific recharge capacity. Bichara(15) found that backwashing was not effective in his model experiments. Custodio(6), however, reports complete success in the operational use of backwashing in dual-purpose wells in coarse-grained alluvial deposits. In this special case flow velocities are comparatively high and sufficient to transport fine-grained silt, clay-sized inorganic and organic material. In the Netherlands, back-pumping to remove clogging material at 3 to 4 times the recharge rate has been found to be effective(5).

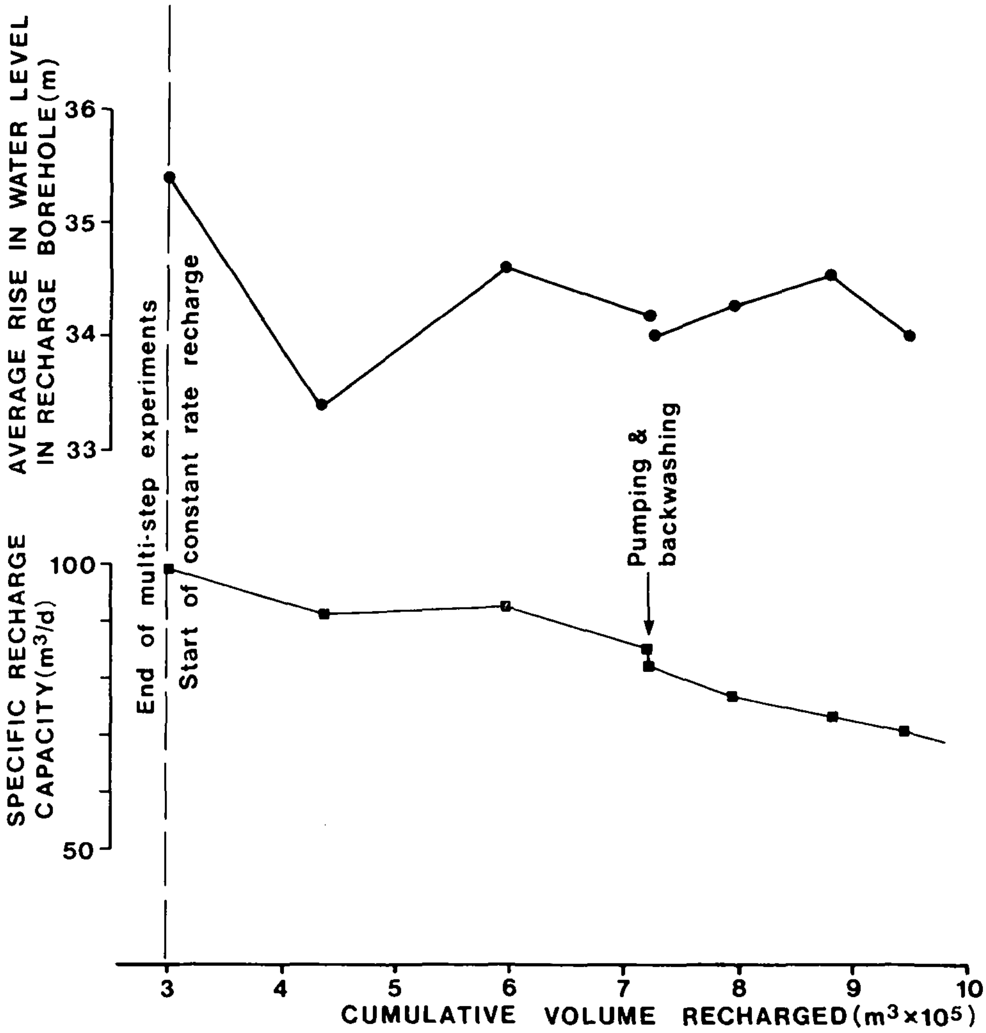


Fig. 17. Cumulative effects of clogging measured by the decline in specific recharge capacity

Clogging by air bubbles was not shown to have been important at Clipstone. The temperature contrast between groundwater and recharged water was only appreciable in summer when there was no danger of exsolution of gas from the relatively warm recharged water. The extremely deep recharge 'face' between the recharge borehole and borehole 9A tends to suggest that the turbulent flow into the well could have caused air bubbles to form fast enough to maintain some degree of 'binding' even though any such bubbles would be redissolved slowly back into the water. The efficiency of the borehole in the recharge mode was certainly very low at between 15% at 250 m^3/d and 45% at 2500 m^3/d. This problem with air, detailed by a number of workers(12,28,29) could be alleviated in a recharge borehole such as that at Clipstone by installing a foot valve, controllable from the surface, or simply putting a throttle on the lower end of the recharge main. The hazards of air entrainment should be avoided as far as possible by throttling flow in this way so that the recharge main stays full. Turbulence should be avoided as far as possible so that cavitation does not occur. If a temperature contrast between recharged water and groundwater cannot be avoided, particularly at the start of recharge, then a certain depth of water within the blank casing should be ensured. The depth required should be sufficient to produce a hydrostatic pressure at the top of the screen high enough to counteract the reduction on gas solubility due to the prevailing temperature contrast.

Reeder(30) reported the successful use of a recharge main which employed pipe friction to throttle flow and maintain 'full-pipe' conditions. Field experimentation is needed however to determine the recharge rate/head relationship and thus derive design specifications. For such experimental purposes it is vital in future work that a fully controllable foot valve is incorporated in the recharge main, so that full-pipe conditions can be maintained over a range of recharge rates.

The shape of the 'mound' created by recharge changed considerably as multi-step recharge progressed. Under constant rate recharge conditions the shape of the 'mound' as shown in Fig. 9 is almost radially symmetrical. The cause of the irregularity is thought to have been due to the marked vertical anisotropy which would impose a complex form to the wetted front. In the observation boreholes, which penetrated the aquifer by different amounts, the free water surface measurement was inevitably therefore slightly variable. The anomalously higher water level at borehole 2 is not understood, though it is not thought to have been due to fissure flow; the relatively slow rate of development of the level tends to indicate a local development of more permeable strata but this cannot be verified from the available core information. Neither is it possible to identify any distortion of the 'mound' due to the regional groundwater gradient even at the end of the constant rate experiment. The radius of influence of recharge extended well beyond the limits of the most distant observation boreholes to possibly more than 1.0 km from the recharge borehole (Fig. 18). At 510 m there was a water level rise of 0.2 m. Baumann(31) points out that the celerity of the wave created by recharge is much greater than the physical movement of water. Approximately 30 days elapsed before the influence of recharge was registered at 510 metres, more than 300 times

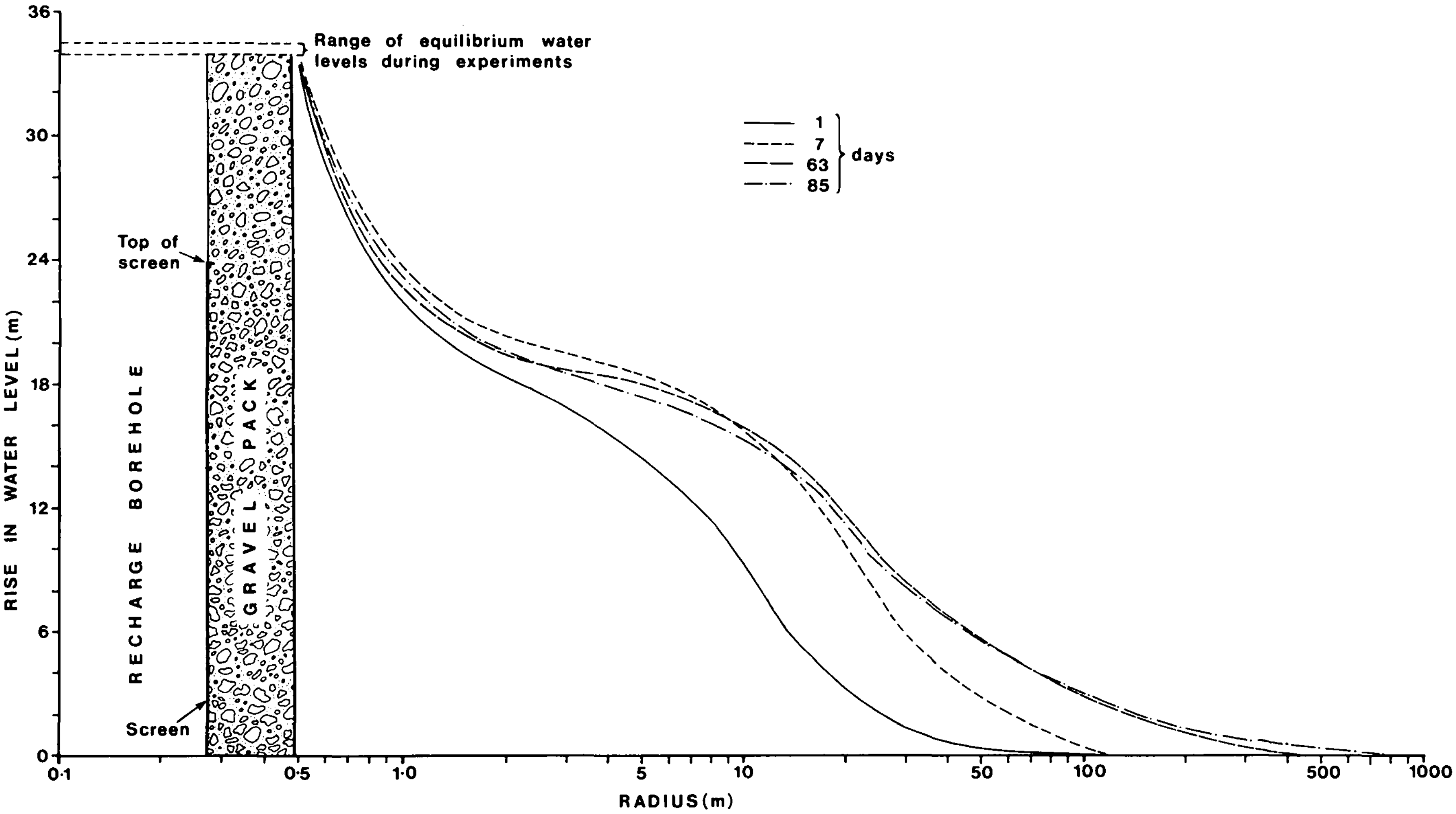


Fig. 18. Constant-rate recharge profiles across recharge mound at a series of times from the start

the rate of movement of groundwater even under the relatively steep gradient due to recharge.

A constant feature of the recharge 'mound' was the precipitous gradient between the recharge borehole and borehole 9A. There was no significant recharge 'face' developed between the recharge borehole and the pack, as observed by Baffa(32) in laboratory simulator experiments.

Some of the implications of experience at Clipstone for future recharge borehole design and construction are important. The residual clogging in the lower part of the borehole could have been largely avoided either by using an additive, or by using a continuous supply of fresh drilling water, instead of recirculating and concentrating the finest suspended solids in the drilling fluid. The use of the unsaturated zone has meant that good recharge rates have been achieved, in spite of clogging in the lower part of the borehole. The longer the screened part of the borehole, the lower the 'entry' velocity becomes. This can help to prevent deep penetration of clogging material into the pack and aquifer and backwashing is more likely to be effective. If clogging during drilling can be avoided then a shorter screened section may be appropriate, allowing an equally large gravity head to be applied but causing higher entry velocities for a similar rate of recharge. The opportunity to pump back through the recharged section of the borehole at high velocity may offset the disadvantage of deeper solids penetration that the higher recharge entry velocity might induce(5).

There can be a conflict in specifying the design of a single borehole for both recharge and abstraction. In unconsolidated aquifers, gravel packs are essential to retain the aquifer during abstraction. In the recharge mode, the over-riding priority is to protect the aquifer from irrecoverable damage by clogging material.

One approach, in designing a borehole to accommodate clogging during recharge, would be to use a pack of the same grain-size and permeability as the natural formation. Such a pack would retain clogging material near to the screen and allow easier cleaning by backwashing. It would be more capable of preventing the type of drastic irreversible clogging encountered by Schneider and others(32) in field experiments in Texas. The Bunter Sandstone is normally moderately, or well-consolidated and this was true for the succession below 30 m at Clipstone. A well-screen would be necessary in a consolidated aquifer only to ensure that any instability due to jointing or fissuring would not cause problems in the longer term. A pack in such a borehole would not be needed to retain the sand particles during abstraction as is normally the case. With accessibility of any clogging material as the main objective, then the optimum design would incorporate a very coarse pack (say 5 mm minimum diameter) of minimum practicable thickness (say 75 mm maximum). If stability of the formation could be absolutely guaranteed, then no screen or pack should be used.

If it is possible to retain clogging material near the screen by using the kind of pack outlined above, then any backwashing system must be installed so that it commands as much of the pack as possible. Flow velocities developed during pumping or backwashing should be at least as high or preferably much higher than those achieved during recharge.

The economics of the use of expensive screen material to maximise abstraction efficiency need to be considered carefully in a situation such as that at Clipstone. Entry velocities were very low and slotted uPVC would probably have served equally well, with only a small penalty in operational efficiency during abstraction. Chemical treatment with surging can be effective in improving clogged shallow recharge borehole performance as indicated by the experiments of Cormick(33).

The cost of the Clipstone recharge borehole and headworks only was £41 000 (adjusted to April 1977 prices). The relatively high cost was largely due to the experimental aspect of the work which required, for example, the use of stainless-steel screens. In an operational context it would be possible to reduce costs considerably. Using slotted plastic, or plastic-coated, screens instead of stainless-steel, a dual-purpose borehole of similar dimensions to the Clipstone recharge borehole could be constructed for an estimated £25 000. This cost includes the cost of a pump, assumes the borehole to be one of a series of between 10 and 20, but excludes connecting pipeline.

The results of the present work show that 2400 m^3/d could be recharged on a long-term basis through the Clipstone borehole. If there had been no damage by clogging during drilling it appears that a mean specific recharge capacity at least 85 m^2/d giving a mean recharge rate in excess of 5000 m^2/d could have been achieved.

If the water level in the recharge borehole had been increased to 10 m above ground level, saturation could have been caused at the surface within a radius of only 2 m, as proved by experimental results from borehole 9A. It may be advantageous to include an adequately anchored water-tight well-head platform to allow such increased heads to be achieved, and correspondingly higher recharge rates.

Well-fields capable of achieving optimum recharge rates and allowing maximum recovery can be designed from the field relationships derived, though such numerical data will be of limited value outside the Bunter Sandstone areas of south Nottinghamshire. The principles of unconfined recharge borehole design and possible operational problems, will however be more generally applicable.

7. CONCLUSIONS

The field recharge experiments have shown that the Bunter Sandstone can be recharged with potable supply water at an average rate of more than 2900 m^3/d over a period of 257 days, and at least 2400 m^3/d in the longer term. The driving head ranged from 33 to 36 m above natural groundwater level. The mean specific recharge capacity was 85 m^2/d. A maximum recharge rate of 3500 m^3/d was achieved over 38 days, which is equivalent to a specific recharge capacity of 100 m^2/d.

The decline in specific recharge capacity from the maximum of 100 m^2/d to 71 m^2/d took place over a total recharge period of 449 days during which 938 000 m^3 of water was stored in the aquifer.

The radius of influence in the 85 day constant-rate test, extended to 0.5 km with water level changes of less than 1.0 metre beyond 0.25 km radius.

The clogging of the borehole during construction was only partly corrected by reaming and the progressive rise in the 'incremental' specific recharge capacity has illustrated this with much higher values in the upper half of the zone of aeration. More intensive development of boreholes with, if necessary, chemical additives to the drilling fluid to help settle clay-sized material, should be used in future drilling. Recharged water was of high quality throughout the experiments with suspended solids of less than 1.0 mg/l. The particle size was predominantly less than 1.0 µm. Chemical quality of the recharged and natural groundwater was similar and no important changes were observed. Neither gas entrainment nor exsolution was detected but the design of the recharge supply pipework was such that such problems could have occurred and remained unidentified.

Water level changes in observation boreholes indicated some slight clogging, particularly during the constant-rate recharge period. This appeared as a progressive flattening of the recharge 'mound' within a 15 m radius of the recharge borehole. It is assumed that this was due to clogging by accumulation of suspended solids which have invaded the formation.

The backwashing facilities in the pack operated satisfactorily but since much of the clogging material appeared to have passed through the pack, their effectiveness in regeneration of performance was necessarily limited. More detailed work on the laboratory scale needs to be done to determine the optimum grain-size and thickness of gravel pack, and the most suitable position for backwashing equipment. If a pack is necessary in a consolidated aquifer, then a thin, very coarse type is probably most suitable. In poorly consolidated aquifers, packs of similar grain-size to the aquifer may allow more efficient recovery of clogging solids.

REFERENCES

1. SATCHELL, R.L.H., and EDWORTHY, K.J. Recharge of the Nottinghamshire Bunter Sandstone: Symposium on Advanced Techniques in River Basin Management. Inst. of Water Engineers, Birmingham, 1972.

2. LAND, D.H. Hydrogeology of the Bunter Sandstone in Nottinghamshire. Geol. Surv. Gt.Brit; Water Supply Papers; Hydrogeological Report No. 1. 1966.

3. HARPAZ, Y. Practical experiences of well recharge. Artificial Groundwater Recharge Conference, Reading; Water Research Association, Medmenham, Marlow, Bucks. 1970.

4. MARGAT, J. L'Alimentation artificielle des Nappes Souterraines en France. Conference sur l'Alimentation des Eaux Souterraines, Gottwaldov, June 1972.

5. OLTSHOORN, T.N. et al. Recharge of drinking water by means of a well. Report of the Working Committee on Injection Wells, Keuringsinstituut voor Waterleiding-artikelen, KIWA, Holland. 1975.

6. CUSTODIO, E. In 'Hidrologia Subterranea', Toms II. Section 19. Ediciones Omega S.A., Barcelona, Spain. 1975.

7. BONIFACE, E.S. Some experiments on artificial recharge in the Lower Lee Valley. Proc. Inst. civ. Engnrs, Vol 14, pp. 325 (Paper 6394). 1959.

8. MARSHALL, J.K., SAVANIPARAVAM, A., and SPEIGEL, Z. 'Operation of a recharge borehole' Proc. Inst. civ. Engnrs., Vol. 41, pp. 447-473 (Paper 7115). 1968.

9. VECCHIOLI, J. and KU, H.F.H. Preliminary results of injecting highly treated sewage plant effluent into a deep sand aquifer at Bay Park, New York. US Geological Survey. Prof. Paper 751-A. 1968.

10. KRONE, R.B. Borehole recharge: the compatibility of recharge water with the aquifer. Artificial Groundwater Recharge Conference, Reading 1970. Water Research Association, Medmenham, Marlow, Bucks. 1970.

11. EDWORTHY, K.J. Deep-well disposal. Water Research Centre TM 120, Medmenham, Marlow, Bucks. 1976.

12. SNIEGOCKI, R.T. Geochemical aspects of artificial recharge in the Grand Prairie region Arkansas. United States Geological Survey, Water Supply Paper 1615-E. 1963(a).

13. SNIEGOCKI, R.T. Problems in artificial recharge through wells in the Grand Prairie region. *United States Geological Survey*, Water Supply Paper 1615-F. 1963(b).

14. JOHNSON, A.I., MOSTON, R.P., and VERSAW, S.F. Laboratory study of aquifer properties and well design for an artificial recharge site. *United States Geological Survey Water Supply Paper No. 1615-H*. 1966.

15. BICHARA, A.S. *An experimental study of longterm artificial recharge of groundwater into confined aquifers using wells*. PhD Thesis, University of Strathclyde. 1974.

16. TAYLOR, F.M. In *'The Geology of the East Midlands'* pp. 149-173. Editors P.C. Sylvester-Bradley and T.D. Ford, Leicester University Press. 1968.

17. WENTWORTH, C.K. The terminology of coarse sediments. *Bull.Nat.Res. Council*. Pub. No. 98. 1935.

18. PETTIJOHN, F.J. *Sedimentary Rocks*. 3rd Edition. Harpendlow, New York. 628 pp. 1975.

19. BOULTON, N.S. Analysis of delayed yield from non-equilibrium pumping tests, allowing for delayed yield. *Proc. Inst. civ. Engnrs*, *26*, pp 469-482. 1963.

20. WILLIAMS, B.P., DOWNING, R.A. and LOVELOCK, P.E.R. Aquifer properties of the Bunter Sandstone in Nottinghamshire, England. Presented at the *24th International Geological Congress*. Montreal, Canada. 1971.

21. LOVELOCK, P.E.R. Core analysis results from Clipstone Forest, Nottinghamshire. *Institute of Geological Sciences Laboratory Tests*: Report No. 13. (Unpublished). 1971.

22. HAZEN, A. Some physical properties of sands and gravels. 24th Annual Report, Mass. State Board of Health. 1893.

23. INMAN, D.L., Measures for describing size distribution of sediments. *Journ. Sed. Petrol*. 22.125-145. 1952.

24. VECCHIOLI, J. Experimental injection of tertiary-treated sewage in a deep well at Bay Park, Long Island. N.Y. A summary of early results. *New England Water Works Assoc. Journ. 86:2 p. 87-103*. 1972.

25. BROWN, R.H. and SIGNOR, D.C. Artificial Recharge experiments and operations on the Southern High Plains of Texas and New Mexico. *United States Geological Survey*; Water Resources Investigations 10-73. 1973.

26. FAO. Underground Water Storage, Israel - Final Report. United Nations Development Programme; FAO Report FAO/SF:39/ISR-9. 1969.

27. RAHMAN, M.A., SMERDON, E.T., and HILER, E.A. Effect of sediment concentration on well recharge in a fine sand aquifer. Wat. Res. Research 5:3 pp 641-646. 1969.

28. PRICE, C.E. Artificial Recharge of a well tapping Basalt Aquifers, Walla Walla Area, Washington USA. State of Washington, Div. of Water Resources, Wat. Supply Bull. No. 7. 1960.

29. FOXWORTHY, B.L. and BRYANT, C.T. Artificial Recharge through a well tapping basalt aquifers in the Dalles Oregon. U.S.G.S. Water Supply Paper 1594-E. 1967.

30. REEDER, H.O. Injection pipe system for artificial recharge. US Geological Survey. Jnl. Research 3:4 July/Aug 1975 pp. 501-503.

31. BAUMANN, P. Theoretical and practical aspects of well recharge. Trans. Amer. Soc. civ. Engnrs, 128, pt 1, Paper 3442, pp. 739-764.

32. SCHNEIDER, A.D., JONES, O.R. and SIGNOR, D.C. Recharge of Turbid Water to the Ogallalah aquifer through a dual-purpose well. Texas A & M University, Texas Agricultural Experiment Station, Report MP-1001 August, 1971.

33. BAFFA, J.J. Injection well experience at Riverhead New York. Jnl. Am. Wat. Wks Ass. 62:1 pp. 41-46. 1970.

34. CORMICK, R.L. Filter pack installation and redevelopment techniques for shallow recharge wells. Groundwater 13:5, pp. 400-405. 1975.