Operation of a recharge borehole

J. K. MARSHALL, A. SARAVANAPAVAN & Z. SPIEGEL

Mr Marshall

The Paper itself is of limited, rather specialized interest, but much interest is being shown in the subject of artificial recharge generally. The Paper is therefore presented as a vehicle for discussion on current prospects for the use of artificial recharge particularly in Britain, and the practical and economic problems envisaged.

93. In connexion with the work described at the Birmingham Racecourse some interesting facts have been determined since the Paper was written.

94. Contrary to expectation, the rest level in the borehole has risen steadily some 40 ft over the last six years. This appears to be partly the result of progressively reduced annual abstraction in this area of the Birmingham aquifer and partly the result of increased winter rainfall in the latter half of the period.

95. A continuous recording of rest water level in the borehole over a period of four weeks has recently been obtained. This showed that intermittent pumping operations in neighbouring boreholes causes regular changes of rest water level amounting to several feet at the racecourse borehole. Such changes would explain irregularities in the recharge performance curves, for example between points C and G and the sharp dip at point D in Fig. 5. The recording also showed that there is a definite correlation between changes of rest water level and barometric pressure. Barometric efficiency, as defined by Jacob,³ works out to be very close to unity, which implies that the storage coefficient of the aquifer derives mostly from elasticity of the water and very little from elasticity of the sandstone. On this basis the storage coefficient of the aquifer should be of the order of 1×10^{-4} , which supports the kind of explanation offered in § 44.

96. Some investigation of the porosity and permeability of the sandstone has also provided useful information. Analysis of the pumping test referred to in § 4 together with the results obtained in §§ 31 and 42, show that the permeability increases with depth in the borehole from 7×10^{-7} to 2×10^{-5} ft/s. Laboratory tests of small samples of sandstone from the borehole gave results in this range, which tends to confirm that water flows through pores in the aquifer rather than along fissures. On this basis the effective diameter of the pore passages can be estimated to range from about 5 microns to about 25 microns. These dimensions are of critical importance in the mechanism of plugging of the borehole by solids in the recharge water.

97. Laboratory tests of the porosity of small samples of sandstone from the borehole gave a minimum value of 0.142. From this value it can be estimated that the water recharged during operation of the scheme never travelled further than about 100 ft from the borehole. In light of this, § 62 needs qualification. While 100 ft is hardly 'a considerable distance from the borehole' in relation to the nearest neighbouring borehole, it is still very considerable in relation to the diameter of the pore passages of the aquifer.

Mr A. Hunter Blair, Water Research Association

The standard Theis curve analysis was not applied to the pumping test figures in the Paper since this analysis is strictly applicable to confined aquifers and steady pumping rates. The following analyses, summarized in Table 1, were applicable.

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Theis curve analysis: variable pumping rate

99. On log-log paper the drawdown divided by the pumping rate (s/Q) was plotted against the reciprocal of the time since pumping commenced ($1/t$), and matched with the Theis curve. It should be noted that this method is only approximate and is superseded by the step drawdown analyses.

Specific yield analysis

100. Curves have been plotted showing the relationship between the specific yield of a borehole (yield divided by drawdown) and the transmissivity.⁹ By extrapolation of the water levels to a steady state during the final period of pumping, values of transmissivity were found for:

- (a) an unconfined aquifer, and
- (b) a confined aquifer.

Step drawdown analysis 1

101. On log-log paper the drawdown (Z) due to the difference in pumping rates ($Q_1 - Q_2$) was plotted against the reciprocal of the time since pumping commenced ($1/t$) and matched with the Theis curve. For values of Z and $1/t$ corresponding values of $W(u)$ and u were obtained and substituted in equations (1) and (2):

$$T = \frac{114.6(Q_1 - Q_2)W(u)}{Z} \quad \dots \dots \dots (1)$$

$$S = \frac{uTt}{1.56r^2} \quad \dots \dots \dots (2)$$

This analysis was applied to (a) the initial step and (b) the final step. The increasing values of transmissivity may imply development of the borehole.

Step drawdown analysis 2

102. The drawdown s in a borehole is given by equation (3).

$$s = \frac{2.3Q}{4\pi T} \log \frac{2.25Tt}{r^2 S} + CQ^2 \quad \dots \dots \dots (3)$$

or

$$s = BQ + CQ^2 \quad \dots \dots \dots (4)$$

where B and C are well loss coefficients. For each period during a step drawdown test, equation (4) may be written as:

$$\frac{\Delta s_i}{\Delta Q_i} = C \left\{ \frac{Q_i^2 - Q_{i-1}^2}{\Delta Q_i} \right\} + B \quad \dots \dots \dots (5)$$

B and C were found by plotting $\Delta s_i / \Delta Q_i$ against $(Q_i^2 - Q_{i-1}^2) / \Delta Q_i$ for various values of Q_i . T and S were obtained by substitution in equation (4).

Step drawdown analysis 3

103. Equation (4) may be stated in the more general form:

$$s = BQ + CQ^n$$

$$\therefore \frac{s}{Q} - B = CQ^{n-1} \quad \dots \dots \dots (6)$$

The left hand side of equation (6) was plotted against Q for various values of B . For the specific value of B which gave a straight line plot C and n were found from the intercept and slope. T and S were found by substitution of these values in equation (7).

$$B = \frac{2.3}{4\pi T} \log \frac{2.25T}{Sr^2} \quad \dots \dots \dots (7)$$

DISCUSSION

Resources Board has the major responsibility. The location of the site is at Edwinstowe, 10 miles NE of Nottingham. For the pilot scheme we will be using water from the River Mourne, a tributary of the Trent, which flows across the boulder sandstone outcrop near Edwinstowe. This stream is similar in quality to the River Trent. The object of the experiment is to investigate recharge techniques as well as the improvement in water quality which might be expected as a result of recharge.

108. It is proposed to have a recharge basin of about 10 000 sq. ft in area and to recharge this with about $\frac{1}{2}$ m.g.d. of water from the River Mourne. There will also be an irrigation plot of about 1 acre in extent. The site will be surrounded by 25 monitoring boreholes. The capital cost of this scheme is about £65 000. The running costs will be about £7000/year for the two-year period of the experiment. We have estimated that a prototype scheme using water from the River Trent, designed to produce 60 m.g.d., would cost about £12 million, and the indications are that water produced in this way would be competitive in price with water produced from other sources.

109. At Birmingham, the River Tame is clearly unsuitable as a source of recharge water in view of the very high quantity of sewage and industrial effluents which this river carries. The obvious alternative seemed to be the River Severn.

110. In 1967, we approached the Birmingham Corporation to see whether they could provide us with a supply of off-peak water from their mains at a suitable off-peak price. It appeared, however, that their distribution system does not have any surplus water. This is because of local service reservoirs, which are filled by their distribution system during off-peak periods at night, and so on. They had a surplus of water for only a few days each year at Christmas and during industrial holidays. Their aqueduct from the River Severn would have a gradually diminishing surplus as their own requirements increased, and this was expected to disappear completely in about five years' time. Their distribution mains would also require augmentation and the water would receive full treatment and would have to be pumped 700 ft from the River Severn.

111. The Nottingham experiments may, however, show that the feasibility of laying these additional mains from the River Severn, or, indeed, from the Dee estuary, may well prove attractive in the future, and this is certainly being borne in mind in our present series of experiments.

112. This Paper is the only recent work on recharge in the Trent River Authority's area and is, therefore, extremely welcome at this stage, when our own experiments are about to get under way.

Mr G. Fox, Imperial College

In § 72, the Paper refers to upward flow. I am not quite sure what is meant. The recharge water was fed to the bottom of the borehole, and the Authors state that there is an upflow during recharge. I wonder whether this means that it was better to get an upflow through the aquifer rather than a horizontal flow. From our very limited knowledge about horizontal flow through aquifers I would have thought it better for the flow to be horizontal, but it may be simply a matter of flushing the deposit in the borehole itself.

114. I recently talked to one of the Authors' co-operators, Dr Dadd, concerning the iron bacteria problem. He mentioned that iron bacteria from the Birmingham water supply could have been a source of infection. Apparently, chlorination will not kill off these iron bacteria as it will the pathogens. Certainly, in my pre-war experience with the Birmingham aqueduct, there was an enormous amount of iron nodule growth. I am still not sure whether this was due to bacteria, but I remember it cutting down the original 1904 aqueduct pipes to something like two-thirds of their discharge.

115. One should emphasize that this recharge is very important. Mr Boniface

did a great deal of good when he transmitted his information on the recharge of the London chalk basin.¹⁰ Presumably, if we succeed in this, we will more or less have solved the storage problem of SE England.

Mr E. S. Boniface, Metropolitan Water Board

Mr Fox has suggested that the problem of storage in SE England might be solved if artificial recharge were to be successful in the Inner London Basin. From the experience of the Metropolitan Water Board, I do not think that it can be solved by that alone, but the potentialities of the basin present a tremendous challenge.

117. In the Metropolitan Water Board, as probably many of you know, we pass filtered water in winter into several of the wells from which, in summer, we extract water. We find that we ourselves are able to recover about 40% of the water used in recharge.

118. It is a relatively small operation in relation to the whole basin, but it is a success under special circumstances. The circumstances are these. There are filtration works adjacent to the wells, which have large and extensive underground works and, in winter, at off-peak periods, we can put down water which is of really good quality. If there is anything that I have learned on artificial recharge, it is that the recharge water must be of good quality, for one has to consider many other well owners in an area like London.

119. Without large filtration works, with water to spare in off-peak periods, I very much doubt whether, even today, recharge is a really economical proposition in the rather unusual conditions which prevail in the overpumped area of the basin.

Mr H. C. Bowen, Thames Conservancy

The subject before us is one in which I have much to learn and little to offer. But the Authors did cast a rather tentative fly over the assembly when they asked for the reactions of river authorities to the problem of aquifer recharge in general, and the contribution by Mr Boniface has high-lighted the difficulties that river authorities, at any rate in SE England, will encounter in approaching it.

121. The big basic difficulty is that artificial recharge is a slow process, particularly when applied through boreholes. To be effective on any considerable scale a large number of boreholes will be required, together with an assured supply of water so that the recharge process can be as continuous as possible. This supply can only come from surface run-off. The difficulty is that, in SE England, demands on surface run-off are already so high that for long periods there is no surplus available. Therefore the recharge process could only be an intermittent one, and the quantities that could be recharged would be severely limited by this factor.

122. Where artificial recharge is applied on a large scale, as in Southern California, an essential first step is the storage of heavy run-off, in impounding reservoirs built in the mountains. This stored water is then transferred underground, by recharge, as rapidly as circumstances permit, leaving the mountain reservoirs drawn down and ready to capture the next heavy run-off that occurs. In this way the process of recharge is made almost continuous.

123. In SE England there are no sites for mountain reservoirs of this sort. As Mr Boniface has remarked, the London Basin is a depleted aquifer available for recharge. But in addition to the practical difficulties of refilling it that he mentions, there is the further difficulty of finding the water to do so in a reasonably continuous process. The Thames could furnish large quantities for limited periods, but these would be interspersed with long periods when no recharge could take place at all.

124. The Authors have presented an interesting and important Paper. For the reasons indicated, artificial recharge does not appear to offer a general solution to the immediate problems confronting river authorities; nevertheless it is sure to be used in many particular cases, and the experience they have gained and described will be of great value to other engineers working in the same field.

DISCUSSION

Written contributions

Mr F. W. Sherrell, Consulting Engineering Geologist

The sinking of the borehole was accomplished by the reverse-circulation process, so presumably it would not have been possible to make any detailed study of the lithology, degree of cementing, jointing or fissuring of the sandstone. The fact that the lower portion of the bore is unlined suggests a degree of cementing of the aquifer in which calcium carbonate is playing a part, judging from the hardness of the water. Presumably joints are present which may as a result of stress relief following drilling have dilated, albeit only slightly. Such joints would be very significant to the hydraulic conductivity of the aquifer.

126. During recharge work it is possible that such joints may become rapidly bridged by sand particles eroded from the bore and thereafter blocked with silt. In this way it would appear that much less silt would be required than for the blockage of the face of the bore as a whole. Furthermore, such material would be rapidly expelled when the reversal of flow occurs again. I would welcome the Authors' comments on this suggestion.

127. Turning to the matter of iron bacteria, the thread-like nature and micro-straining properties which are suggested could readily function across the very small openings of micro-fissures.

Mr R. F. Stoner, Sir M. MacDonald and Partners

The Authors' experience with the Birmingham Racecourse recharge well reflects similar experience with such wells in Long Island where ground water is pumped for use in central air conditioning plants and returned to the ground water via recharge wells.

129. Iron bacteria have given trouble in normal wells in several parts of the world. The problem has been faced particularly in West Pakistan, where some fifty thousand irrigation wells have been constructed over the past ten years. Several thousand of these have been large capacity wells installed as part of the extensive public programme for ground water development. Originally mild steel screens and casings were used, but failure due to corrosion and incrustation occurred within the first two years of operation. Various studies of the problem were undertaken and eventually the sulphate reducing bacterium *Sporovibrio desulfuricans* was positively identified as one of the causes of well failure. Sterilization with sodium hypochlorite did not prove to be effective. Several hypotheses for the origin of the bacteria were examined without a satisfactory conclusion being reached.

130. The solution to the problem in West Pakistan has been the adoption of resin bonded fibreglass well screens and casings. Some 4000 such wells have now been installed in the last four years and no cases of failure have yet been recorded, although the bacteria are known to be present in some wells and have attacked the shafts of the turbine pumps. It is anticipated that the use of non-ferrous materials throughout would provide the complete answer to problems with sulphate-reducing bacteria in normal wells in West Pakistan. Perhaps the performance of recharge wells could also be improved using a similar approach.

Mr C. H. H. Mercer, Sussex River Authority

I am at present concerned with work in relation to the possible artificial recharge of the Folkestone Sands near Pulborough. Although not specifically concerned with borehole recharge the work is related to that described in the Paper.

132. Some years ago it was realized that the structure of the rocks underlying the Hardham-Pulborough area might prove favourable for the development of water resources, and following initial exploration by the NW Sussex Water Board, six supply boreholes were sunk into the Lower Greensand formation at Hardham. At present,

the Water Board is authorized to abstract up to a maximum of 8 m.g.d. from these boreholes in addition to a further 6 m.g.d. from the River Rother.

133. However, in order to meet the estimated future demand in the Board's supply area, additional supplies will be required from this source before 1985. The preliminary survey of the area had suggested that the underground storage potential was considerable, but the actual capacity and the extent to which the basin could be developed were unknown factors requiring full geological exploration. If potential storage was as great as was first thought, then it was possible that in addition to supplying the increased quantities required by the Board, there could also be sufficient surplus water for transfer to other areas.

134. In the area in question an E-W fold, combined with a secondary NNE-SSW fold give rise to a periclinal structure in which lies the Lower Greensand formation, overlain in the centre by a variable thickness of impermeable Gault clay, and in parts by superficial valley and plateau gravels. The Lower Greensand is divided into four main series, the lowest of which is the impermeable Atherfield clay, followed by the Hythe sandstone and the more or less impermeable silty clay of the Sandgate and Bargate beds. These are succeeded in turn by unconsolidated brown, yellow and white coarse grained sands of the Folkestone series, which average 170 ft in thickness, and which have proved to be one of the more important aquifers in this area.

135. Within the basin, the aquifer is approximately four miles in length and just over a mile in maximum width. Estimates of its storage capacity vary within a range of 8000 million to 30 000 million gal, but the true capacity remains to be determined. The outcrop of the sands covers an area of 1679 acres, but in addition to this there is an area of 1590 acres which is liable to frequent flooding from the rivers Rother and Arun and which could be a source of natural recharge of the sands.

136. The investigation is being carried out in full co-operation with the NW Sussex Water Board, which has already drilled a number of exploratory boreholes and with the Water Resources Board which is grant-aiding the scheme. Assistance is also being given by the Water Research Association in the construction of a ground water analogue for the area.

137. Within recent months the River Authority has completed a further programme of exploratory drilling at the eastern end of the syncline, together with a 24 in. dia. test hole sited centrally. This latter borehole was test-pumped for 14 days at the beginning of December, yielding just on 2 m.g.d., in order to determine more accurately the storage coefficient and transmissivity constants. In 1969 it is intended to carry out long-term test pumping of this borehole to determine storage capacity, direction of flow, and other characteristics of the aquifer.

138. Once the results of the drilling and test pumping are fully evaluated, the next stage of the investigation will include detailed proposals for artificial recharge of the Folkestone sands, utilizing surplus flood water from the River Arun, mainly during the winter period. This water will be diverted into shallow basins sited at strategic points and as percolation proceeds the sands will act as a natural filter, resulting in a considerable improvement in quality. When re-abstracted for supply purposes, the water will require far less treatment than raw river water.

139. The proposed recharge area is located where information at present available indicates that the upper horizon of the Folkestone sands is at approximately OD and where average ground levels are in the region of +10 ft OD. Assuming an infiltration rate of some 4 ft/day, an area of 18 acres in contact with the aquifer is required and the layout of lagoons or channels allows for this. The channels would have 30 ft bed width access berms thus allowing desilting operations to be carried out by dragline excavator. At the intake, provision will have to be made for pumping capacity of 30 m.g.d., but a gravity feed sluice will be included for use when levels permit. River water will be pumped into a distribution pool and thence into settling lagoons which can be used alternately, thus allowing desilting operations to be carried out as required. The settling lagoons are the only form of pre-treatment at present

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envisaged. The total area of land taken up by these proposals would be of the order of 60 acres.

140. Within the last 18 months the NW Sussex Water Board has undertaken a pilot study involving the construction of two small recharge lagoons 200 ft by 55 ft bed width and although not entirely successful, some useful information on potential percolation rates has been derived. It is, therefore, intended that more experimental work will be carried out in the near future on these basins, possibly supplemented by an experimental recharge borehole to determine the possible effects of air entrapment on downward percolating waters.

Mr R. C. Whitehead, City of Birmingham Water Department

The Authors are to be thanked for an important contribution to the newly developing water conservation technique of underground water recharge. In particular they must be congratulated on their courage in reporting on an operation that was only partially successful.

142. The work was handicapped from the outset by the requirement of the abstraction licence that the water to be abstracted was first to be charged into the borehole during the previous winter months. Possibly in a future case a river authority might in the interests of research be prepared to agree to the first season's abstraction preceding recharge where, as in this case, the quantity abstracted in a year is comparatively small. Considerable delay might then be avoided.

143. The recharge difficulties encountered appear to derive from three main causes:

- (a) suspended matter in the recharge water;
- (b) dissolved air in the recharge water;
- (c) iron bacteria.

With regard to the first point, it would appear desirable in a future operation to have a short period of test pumping at a high rate in order to clear the bore of drilling debris. Following that operation, choking of the borehole by suspended matter could only be caused by particles derived from the recharge water. This could originate either (a) from suspended matter passing the water undertaking's treatment works, or (b) from corrosion products (mainly iron hydroxide) derived from the corrosion of unlined cast-iron mains in the water undertaking's distribution system. In the case in question the water was double filtered, the second time being by conventional rapid gravity filters (without the use of coagulant) through sand, 99% of which passed BS Sieve No. 14 and was retained on BS Sieve No. 25. The permeability of well compacted sandstone rock would appear to be far less than that of an open sand filter; therefore it would seem that a build-up of recharge head would be inevitable in the circumstances under consideration, the only possibility of success appearing to be that the build-up of suspended matter might be removed by occasional pumping to waste.

144. With regard to the second difficulty, that is dissolved air, it is well known that fine air bubbles emerge from solution in well aerated mains water following a reduction in pressure. In fact, air binding of sand filters has been known to occur in filtering Birmingham water, when an excessive head loss in the filter causes pressure slightly below that of the atmosphere.

145. Although it was suspected that difficulty might arise from the first two causes, the third difficulty of iron bacteria was not expected. However, it was known that iron bacteria were present in the water in minute concentrations since cases had occurred of the proliferation of iron bacteria in hot water systems.

146. The reason why mains water could not be supplied at the high peak rate required for course watering was that the racecourse was situated on the eastern side of a distribution system into which the main supply was introduced from the west, and the high peak flow required would have absorbed the reserve capacity of the

distribution system. Since the abandonment of the racecourse, however, it and other adjacent sites have been developed for large-scale housing, fed from the same distribution system. The supply to the new development, which is sited on the periphery of the distribution system and remote from a service reservoir, could well do with the balancing effect of such a reservoir. This raises the question of whether the use of boreholes in connexion with recharge would be an economical alternative to a service reservoir in meeting peak demands and reducing peak flows in distribution trunk mains.

147. From the experience gained from the Birmingham Racecourse borehole it would appear that, although such a proposal might be feasible and economical in highly permeable strata, its successful operation will be likely to be prevented where the strata being recharged are insufficiently permeable to accept the mains water in supply without an expensive treatment plant at the well head. An additional objection in Birmingham is that the mains water is soft and the ground water hard. Is there any indication of the extent to which the recharged water remained soft when re-abstracted?

Dr N. S. Boulton, Emeritus Professor, University of Sheffield

The pumping test described by the Authors (§ 40) provides a noteworthy addition to the small amount of published data for such tests in Bunter and Keuper sandstone aquifers. The Paper is admirably presented, but owing to the uncertainties inherent in this kind of field study, I find it difficult to deduce from the test results the hydraulic properties of the aquifer.

149. The Authors show that the Theis equation gives a curve which fairly accurately fits the observed depths between 1 and 12 h with a storage coefficient of 0.012. This value is characteristic of unconfined (water table) rather than confined conditions. The section of the borehole (Fig. 1) suggests that confined conditions probably existed.

150. The recorded water levels are for the *pumped* borehole and my research has shown¹¹ that such levels are not correctly represented, even approximately, by the Theis equation during the earlier stages of pumping with *unconfined* conditions. In fact, for these conditions, the water level in the test being considered should remain constant for the first two hours of pumping. Therefore the fall in level in Fig. 7 is additional evidence that water table conditions did not exist.

151. I have attempted to account for the recorded water levels during the first two hours on the basis of the Authors' explanation in § 44, but without success.

152. The conclusion seems unavoidable that the aquifer behaved as if confined but with a high *apparent* compressibility associated with the storage coefficient of 0.012 which is difficult to explain in physical terms. The many marl beds (Fig. 1) may partly account for this compressibility. The comments of the Authors on this anomaly would be welcomed, since the question is of some importance for the correct interpretation of pumping tests in Bunter sandstone aquifers.

153. The large amount by which the observed water levels fall short of the Theis curve (Fig. 7) between 18 and 100 h can be theoretically accounted for by allowing a gradual increase in storage coefficient from 0.028 to 0.28 as the unconfined area described in § 44 becomes effective in contributing water to the borehole. For this purpose I used the theory of delayed yield¹² as a reasonable approximation.

Mr D. G. Davies, Mid. and SE Cheshire Water Board

In the world of water recharging there is still a great deal of synthetic analysis but very little practical work in Britain. It is for this last reason that the Paper is so welcome. As a nation the pressure on our natural resources is so great that we should be doing everything possible to optimize the utilization of our ground water resources through a proper integration of the ground and surface waters. As yet

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we have hardly faced the problem. It is strange how engineers throughout the world first build the more expensive dams when the nation is at its poorest and only when we become richer do we return to the economic development of ground waters.

155. Unfortunately there is a current belief that the recharging technique is simple, a mere matter of pushing water into the ground, whereas as the Authors have discovered it is a very complex problem, in which the natural ground water may in some cases be degraded by the return of clean but mineralized water.

156. The Paper explains well a growing resistance to the recharge of sandstone aquifer even by the relatively clean Birmingham tap water. Did they consider chlorinating the water before injection, in order to eliminate the development of biological slimes? Elsewhere in the world chlorination before borehole injection appears to be commonplace but despite injection of top quality water with 1.5 p.p.m. chlorine, many wells need redevelopment every two years because of clogging.

157. In California which has magnificent ground water resources, there is no tolerable alternative to recharge. Its absence would mean the penetration of the aquifers by saline waters. The present mechanics of consumer services connected to wells would have to be replaced by new connexions to aqueducts, new pipe networks, new large service reservoirs, for which potential sites are at near vanishing point and the great loss in underground storage as a regulator for aqueduct supplies. Unfortunately as they are now discovering, urbanization is a hazard to underground quality through the disposal of refuse in gravel pits and the lowering of the water table in some valleys which causes severe subsidence.

158. In order to optimize the ground water resources recharging is being intensified. California has one remarkable geological advantage in its vast areas of gravel beds of considerable depth which enable this state to use 21 000 m.g.d., half of which is supplied direct from the surface and the other half from the ground. I believe we shall find in our future developments in Britain that the most economic techniques will follow the Californian pattern, in that the winter river waters will have to undergo primary filtration before pouring on to gravel beds intermittently so as to eliminate undue clogging, which the Authors found to be their greatest impediment. Our problem is, have we sufficient gravel beds?

Mr H. Hirsch, Water Research Association

The divergence of observed depth to water level and calculated Theis curve (Fig. 7 of the Paper) after approximately 12 h pumping, suggests that the aquifer is limited by one or more recharge boundaries, for example, the River Tame, some 1000 ft distance from the borehole.

160. It has been shown¹³ that:

$$\frac{1.56S}{T} = \frac{u_p}{r_p^2/t_p} = \frac{u_i}{r_i^2/t_i} \quad \dots \dots \dots (9)$$

where subscripts p and i refer to pumping well and image recharge well respectively. If s_i , the departure of the Theis curve from the observed data, is chosen equal to s_p , the drawdown from the real well, then for constant discharge it follows that $u_p = u_i$. Therefore equation (9) may be restated as:

$$r_i = r_p \sqrt{(t_i/t_p)} \quad \dots \dots \dots (10)$$

From Fig. 7 a value of $s_i = 20$ ft at $t_i = 70$ h is evident. Given relevant values of Q , S and T one may solve for r_i : the recharge boundary is at a distance $r_i/2$. By applying this image well theory to the Theis non-equilibrium formula,¹³ and assuming that:

- (a) the aquifer is homogeneous;
 - (b) $Q = 131.7$ gal/min (Fig. 7; maximum pumping rate)
- $$\left. \begin{array}{l} T = 3.6 \times 10^2 \text{ gal/min per ft} \\ S = 1.2 \times 10^{-2} \end{array} \right\} \text{ see } \S 42$$

it may be shown that the distance to recharge boundary is only 90 ft, far short of the 1000 ft needed for pure river infiltration.

161. Repeating the calculation for values of formation constants given by Hunter Blair where:

$$T = 1.75 \times 10^3 \text{ gal/day per ft}$$

$$S = 1.4 \times 10^{-2}$$

the distance to recharge boundary becomes 137 ft, which again is far short of 1000 ft.

162. The above calculations assumed a constant discharge rate ($Q = 131.7$ gal/min); however, it may be shown that if the step-discharge rate is taken into account, the distance to recharge boundary would be less than the values arrived at above.

163. Three alternative explanations are:

- (a) the values of storage coefficient imply unconfined aquifer conditions; therefore if Jacob's correction¹⁴ for dewatering is applied most of the departure of observed from computed drawdown is explained;
- (b) transmissivity is increasing whilst the well is being developed which has the effect of increasing the effective well radius and reducing the incremental drawdown caused by changes in pumping rate later in the test;
- (c) a recharge boundary between the River Tame and the borehole may exist.

Mr Marshall, Mr Saravanapavan and Dr Spiegel

We would first like to thank all the speakers and writers for the contributions they have made, which add very greatly to the value of the Paper. We propose to reply to questions in a different order from the printed discussion; those on the pumping test we will answer together last.

165. We would particularly thank **Mr Butler** for his account of the work proposed by the Trent River Authority. This is of special interest in the context of the Paper because it will be the first major project to be carried out for recharging the Triassic sandstones of the Midlands.

166. **Mr Boniface's** account of the recharge operations in the Lower Lee Valley¹⁰ had been published just before the start of the Birmingham Racecourse scheme and their success encouraged us at that time. Mr Boniface attributes their success to the extensive nature of the underground works, and to the really good quality of the water recharged. The superficial area of the aquifer exposed in his works is of the order of 300 000 sq. ft so that in this respect the operations resemble a basin recharge scheme more than one utilizing conventional boreholes. The total recharge rate reported was 7½ m.g.d. which indicates an average infiltration rate of 4 ft/day, although we understand that the figure varied widely in different parts of the works.

167. In the Birmingham Racecourse borehole the total area of the face was 1600 sq. ft. The average recharge rate during the last 6 months of operation was 14 000 gal/day, giving an infiltration rate of 1.4 ft/day; discounting marl layers, the rate would be 2.3 ft/day. The intended recharge rate required an infiltration rate of only 3 ft/day which seemed very modest on any basis.

168. In both schemes the waters recharged were fully treated and for public supply purposes would be regarded as being of really good quality.

169. **Mr Bowen** emphasizes that artificial recharge is a slow process. We agree that if no higher rate of infiltration were possible in boreholes than is commonly used in basin recharge, recharging by borehole would have very limited application, but we do not believe this is so. Water can be abstracted at high rates from boreholes in Bunter sandstone. Given an ideal fluid and a recharge head equal to drawdown, recharging should be possible at nearly similar rates. We think that an infiltration rate of the order of 100 ft/day ought to be possible in the ideal case.

170. In practice, water readily available for recharging is not an ideal fluid and the rate of infiltration obtainable will depend on how far it is economical to go in

treatment of the water so as to avoid rapid and possibly permanent reduction of the permeability of the aquifer. In this respect, suspended solids remaining after treatment may be much more significant in a fine grained aquifer than in a coarse one. Ives^{15, 16} has established the principles on which suspended solids are deposited in rapid gravity filters. Such filters have relatively large pore dimensions, but the principles which apply in a fine grained aquifer do not seem to have been studied so thoroughly.

171. We are grateful to **Mr Mercer** for his informative account of the Hardham scheme which must be the most important recharge project yet planned in Britain, and to **Mr Delwyn Davies** for his reference to the highly successful works which have been in operation for a number of years in California. Mr Delwyn Davies has emphasized the advantages of a coarse grained aquifer for recharging. We note that data given by Baffa¹⁷ indicate that sustained infiltration rates in boreholes in Los Angeles County are of the order of 60 ft/day.

172. Mr Delwyn Davies asks about chlorination at the Birmingham Racecourse borehole. The public water supply used in that case had already been chlorinated before distribution, and when the scheme was planned it was not thought necessary to re-chlorinate before injection. Re-chlorination was adopted for the last season as is described in § 58. In retrospect it would have been better to have used it from the start.

173. We thank **Mr Stoner** for his description of bacterial problems in West Pakistan and the remedy of using resin bonded fibreglass well screens and casings. We do not think that this material was readily available at the time tenders for the Birmingham Racecourse borehole were being obtained. The use of spun concrete lined steel casing was contemplated but an experienced firm of drilling contractors advised that the lining would become damaged by the passage of the drilling tools. Stow,¹⁸ writing in the following year, did not mention the use of any but steel casing. We fully agree with Mr Stoner that non-metallic casings could be used with advantage in future if the construction problem in deep wells has now been overcome.

174. In reply to **Mr Fox** 'upward flow' in § 72 refers to movement of water within the borehole and not to the direction of flow within the aquifer.

175. The technique of upward flow was devised to flush suspended solids out of the borehole at the end of a short pumping run. The borehole contained about 4000 gal below the pump suction level, and daily abstraction of enough water to remove all solids released from the face of the borehole would have represented a considerable loss to net recharge. The pump was run only for the few minutes required to draw the water level down to 300 ft depth, so as to free solids from the face. The recharge water supply was then turned on at the highest rate available, and its upward flow from near the bottom of the borehole was intended to carry the solids to the top.

176. Unfortunately, as flow into the aquifer increased with rising water level, once the rest level was passed, the upward velocity became smaller. More efficient flushing would have been obtained if the recharge water could have been supplied at a much higher rate, but it was limited by the 2 in. dia. supply main to about 2000 gal/h.

177. We are obliged to **Mr Fox** for the further information on the source of iron bacteria and the impotency of low-level chlorination to eradicate them. However chlorination at 5 p.p.m. (§ 58) achieved the largest single improvement in recharging, as is evidenced by Fig. 5.

178. **Mr Whitehead** has suggested that if the first year's abstraction could have been done without prior recharge, the work would have been less handicapped at the outset. It is true that because construction was not completed in time, the first winter's recharge period was curtailed. We would also agree that the conditions of the first licence were too inflexible. A revised licence was obtained later which limited annual abstraction to the amount recharged in that year but did not specify that recharging was to be done first. This allowed recharging to be done whenever water

was available. However we found no significant evidence that recharging after abstraction was easier in the long term than recharging before abstraction, probably because both operations were carried out under confined aquifer conditions. A significant difference might have been found in an unconfined aquifer.

179. Mr Whitehead has referred to suspended matter in the recharge water. For an experimental period in July 1964, the recharge water was passed through a Misselbrook filter before entering the borehole. The filter plates had 5 micron separation which was the smallest aperture size available for the experiment. The results of a run of the filter for 22 h showed that the recharge water contained iron hydroxide in suspension but the concentration of particles above 5 micron size was less than 1 p.p.m. As mentioned in § 15, iron hydroxide particles at a concentration of the order of 50 p.p.m. would have to have been supplied to account for the recharge performance observed during the first season.

180. We agree with Mr Whitehead that suspended matter in the recharge water could be of first importance in any future scheme which is not dominated by our particular problems. We think that filtration of the recharge water to very fine limits would be needed before really high rates of infiltration could be achieved in the Triassic sandstones (possibly ultra-filtration through a semi-permeable membrane may prove to be an economic proposition eventually). However, we do not think that filtration would have been the complete answer at the Birmingham racecourse. Even if iron bacteria could have been eradicated, there remained within the borehole many beds of marl. Particles from these have a size of the order of $\frac{1}{3}$ to $\frac{1}{10}$ of the pore passage dimensions and these would very readily block the pores of the sandstone. Short of taking the roof off the pump house and fully lining the borehole with casing perforated in the right places, we could think of no practical remedy for this problem.

181. We agree that air entrainment appears to be a frequent difficulty in sand filters, but we do not think it was a significant factor in our case, at any rate during the last two seasons of recharging, for reasons explained in § 76. It may have been a contributory factor during the first season but other factors were so dominant that it is impossible to show what effect it may have had. There certainly did not seem to be any significant improvement in recharge performance from 1962/3 (Fig. 2) to 1963/4 (Fig. 5) which could be attributed to the change in the supply pipework mentioned in § 24 (d).

182. Mr Whitehead has asked whether there was any indication of the extent to which the recharge water remains soft when re-abstracted. In retrospect it would have been useful to have analysed the water abstracted at different times after recharging had last finished, but this was not done and the only information available is that given in §§ 26 and 27 which relates to a residence time of 8–11 months.

183. In reply to Professor Boulton, we agree that the pumping test results (Fig. 7) are difficult to analyse. We realized that the value of storage coefficient we obtained was not characteristic of a confined aquifer and therefore referred to it as an apparent value in § 42. We also appreciated that none of the explanations in §§ 42–44 were completely satisfactory, because of lack of sufficient data.

184. With reference to Professor Boulton's conclusion in § 152, the aquifer is certainly confined at the borehole because the top of the sandstone is 135 ft below the pump suction level. The nearest neighbouring borehole is 2400 ft to the north west, where the top of the sandstone is 300 ft higher. We understand that in 1962 the rest level there was 28 ft above the top of the sandstone and that the pumping water level would be about 97 ft below the top of the sandstone. We do not know the slope of the free water surface, nor whether the dip of the sandstone shown in the Geological Survey section (Fig. 6), can be relied upon—it has been suggested that there may be a N–S fault between the two boreholes, with a substantial throw. Another uncertainty is the influence of other boreholes in the area on the extent of the unconfined zone.

185. These uncertainties prevent accurate calculations being made in support or

rebuttal of § 44, but we do not think that the high apparent storage coefficient can be explained by compressibility of marl beds. It was to throw more light on compressibility that we recently conducted the barometric efficiency experiment mentioned in the introduction (§ 95). This indicated that the compressibility of the aquifer structure as a whole was small. While Jacob's equations⁹ may now be regarded by specialists in rock mechanics as not strictly valid for sandstones in the light of more recent research, for example that by Handin, Hager, Friedman and Feather,¹⁹ confirmation that the true storage coefficient of the aquifer is of the order of 1×10^{-4} was given by a Theis curve which fitted fairly closely the regular changes of water level observed during the barometric efficiency experiment. Although the precise rates of pumping at neighbouring boreholes were not known, reasonable assumptions could be made from the known annual abstractions and these showed that the storage coefficient was not smaller than 1×10^{-4} nor larger than 6×10^{-4} , the former being more probable.

186. In the Theis equation, the determination of storage coefficient from drawdown in the borehole depends on accurate knowledge of the borehole radius. The result mentioned in § 185 was based on the known distances from neighbouring boreholes, which suggests that the storage coefficient of 1×10^{-2} stated in § 42 was too large merely because the radius used for calculation was too small. We had used the actual radius determined in § 33. It now seems likely that the effective radius was very much larger. To account for the difference between the apparent and true storage coefficients, it would be necessary to postulate a zone of high permeability around the borehole having an effective radius of the order of 6 ft.

187. The formation of a high permeability zone during drilling is mentioned by **Mr Sherrell** and we are grateful to him for pointing this out. Although he put it forward to account for the recharge performance, it may explain both the storage coefficient error and other anomalies in the pumping test results.

188. **Mr Sherrell** refers to micro-fissures being formed around the face of the borehole as a result of stress relief during drilling. We think that cracks caused by stress relief may have been opened further by the forces applied during drilling and also by the passage of drilling tools afterwards, when the many marl beds present had been softened by exposure to water. Damage of this kind is illustrated by a piece of sandstone recovered during the bailing mentioned in § 24 (a). It had one concave cylindrical face of the same radius as the drilled hole.

189. A fissured zone around the borehole could explain most of the peculiarity of the shape of the drawdown curve. The peculiarity can be seen most clearly in Fig. 8(b) by comparing the March 1962 results with other pumping operations. We are grateful to **Mr Hunter Blair** and to **Mr Hirsch** for their suggestion about development during pumping, which we think provides a very reasonable explanation. They refer to an increase in transmissivity during development but we think that it is more accurate to describe the effect as a change in well loss, well loss being defined in this case as the head lost through the fissured zone.

190. Two types of development can be envisaged. Development proper would occur by flushing out and enlargement of the fissures created by stress relief and damage, particularly of fissures formed between sandstone and marl layers. The other type of development might be called redevelopment, and would occur by flushing out particles which had previously been forced into the fissures and pores of the aquifer during drilling.

191. The method used for construction was reversed circulation rotary drilling. A detailed description of this method has been given by Stow.¹⁸ A considerable quantity of fine particles from the marl beds encountered below 548 ft depth will have been forced into the aquifer, but they will not have travelled far because very little water was reported to have been lost.

192. It is a fair assumption that by the time drilling was completed the fissured zone had become fully plugged. Taking the effective radius of the borehole as the

outside radius of the fissured zone, the well loss caused by the plugging would be at its maximum value when pumping started.

193. We had assumed in preparing Fig. 8(b) that all the particles forced into the aquifer during drilling had been flushed out again in the first hour of pumping. We had therefore assigned zero value of 'specific well loss during pumping' to the Theis curve passing through the drawdown points between 1 and 17 h. If development were still proceeding, the upward steps in the drawdown points after 17 h could be the result of reduced well loss as particles were flushed out by the increased pumping rates between 17 and 24 h. A gradual clearance of the zone during the following 41 h would account for the flatter slope of the drawdown curve in that period.

194. If this explanation were correct, zero value of 'specific well loss during pumping' would have to be assigned to another Theis curve parallel to those shown in Fig. 8(b) passing through the last drawdown points. The values assigned to the Theis curves in Fig. 8(b) as drawn, and the values quoted in §§ 51–53, would all need to be increased by 2.5×10^{-3} ft. This is an arbitrary assignment inasmuch as the fissured zone may have been capable of further development. Zero 'specific well loss during pumping' for the purpose of Fig. 8(b) is merely the minimum value observed.

195. We would particularly thank Mr Hunter Blair for his comprehensive analyses of Fig. 7. The values of transmissivity in his Table 1 fall in the range 1.2×10^3 to 2.9×10^3 gal/day per ft, apart from a single value which is much lower. Our value in § 42, which is 1.4×10^3 in Mr Hunter Blair's units, is reasonably compatible and we think the results of other pumping operations shown in Fig. 8(b) tend to confirm its accuracy. All his methods of analysis, except for specific yield for which his tabulations of storage coefficient are presumably assumed and not calculated values, would be affected by an error in borehole radius so that we do not think the consistency of his values of storage coefficient in Table 1 invalidates our reply to Professor Boulton on this matter.

196. We are much obliged to Mr Hirsch for his calculations on the recharge boundary theory in elaboration of § 43. However if development occurred during pumping it would not now be necessary to invoke the recharge boundary theory to explain the departure of drawdown from the Theis curve.

197. We have already referred to Mr Sherrell's suggestion insofar as it would affect the test pumping results, but have not answered his question on recharging. It is difficult to theorize about a situation which could be very complex in practice, but if a simple model is envisaged in which regular fissures extend horizontally to a constant radius from the centre of the borehole, it can be shown that the effect of blocking these would be far from sufficient to account for the large specific recharge head observed.

198. If the fissures were perfectly clear of solids and were of sufficient size and number to carry the whole flow with relatively negligible loss of head, the effective radius of the borehole would extend to the end of the fissures. Quite small fissures would suffice to carry most of the flow. For example, one fissure $1\frac{1}{2}$ mm in dia. would have the same flow carrying capacity as 1 sq. ft of sandstone of the largest permeability mentioned in § 96.

199. Once the fissures had become completely blocked, all the flow would pass through the pores of the sandstone in the zone, and the effective radius of the borehole would become equal to its actual radius. We assume for this purpose that flow through the pores is unobstructed by deposition of solids on the face of the borehole until after the fissures are completely blocked.

200. The effect of blocking the fissures in the simple case described is therefore hydraulically equivalent to reducing the effective radius of the borehole. The maximum value of this effect depends on how large the effective radius could be initially. In our reply to Professor Boulton (§ 186) we postulated an effective radius of the order of 6 ft. After the development postulated in our reply to Messrs Hunter Blair and Hirsch (§ 194) the effective radius would apparently have become 16 ft

because r_w has to have this value in order that a Theis curve for $T=2.6 \times 10^{-3}$ sq. ft/s, and $S=1 \times 10^{-4}$ shall pass through the last drawdown points of the March 1962 pumping test. The curve for the same formation constants but for $r_w=0.565$ ft will plot on Fig. 8(b) between the Theis curves marked 6×10^{-3} ft and 7×10^{-3} ft. Reducing the effective radius of the borehole to the actual radius is therefore equivalent to introducing a specific well loss of about 6.5×10^{-3} plus $2.5 \times 10^{-3}=9 \times 10^{-3}$ ft. This is very small compared with the increase of specific recharge head of about 0.2 ft observed between points C and D in Fig. 2.

201. The foregoing reasoning suggests a physical explanation for the notional well loss described in § 50. The changes in the 'specific well loss during pumping' shown at different dates in Fig. 8(b) may be no more nor less than a record of changes in the amount of blocking of fissures by such solids and bacteria as ordinary pumping could not remove. According to the calculation in the preceding section, the fissures would be fully plugged when the 'specific well loss during pumping' reached 6.5×10^{-3} plus 2.5×10^{-3} ft. The fact that the specific well loss was rather larger than this in the early months of 1965 could possibly be explained by vertical circumferential cracks in the fissured zone. Such cracks, when plugged, would affect flow through the pores of the sandstone, contrary to the assumption made in the simple model previously mentioned.

202. We should mention that the 'specific well loss during pumping' defined in § 50 is equal to well loss coefficient C in equation (6) when $n=1$, which is only correct if flow in the fissured zone is laminar. Depending on the size and number of fissures, flow may have been turbulent in this zone. There do not appear to be any features of the results in Fig. 8(b) which suggest that this was the case, but the effect of turbulent flow may have been concealed because the flow rate was substantially constant for all pumping operations except that in March 1962, and except at early time as noted in § 49.

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