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FLOW PROCESSES BELOW A GRAVELLY RIVERBED

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ABSTRACT

Laboratory results are given of permeability and small particle movement in gravel/sand mixtures and of permeability in sand. Interpretation of the data is aided by certain field measurements of infiltration in channel beds and ground water contours. Data are presented on anisotropy, porosity and air entrainment. The information leads to a definition of a 'shell' or zone of low permeability at the margins and below a river bed or channel.

INTRODUCTION

The objective of this study is to investigate flow processes below the gravelly Waimakariri river bed near Haklett, some 30 km from the coast, with a view to gaining a better understanding of the mechanism of recharge of ground water taking place from that site. While ground water recharge from the river here has been well established (Wilson, 1976), there is sparse literature on flow processes below a gravelly river bed. Field conditions restricted field work to identification of sediment deposits, some infiltration measurements, and to surveys of ground water contours. One item of interest, the permeability of the river bed sediment, was studied in the laboratory using disturbed samples. As sediment in the river bed is subject to continuous shifting and re-deposition, an objection to the use of disturbed samples does not seem serious.

Definition of Permeability

For laminar flow in porous media permeability is defined by the Darcy equation:

$$\text{where } Q = AV = AKi, \tag{1}$$

Q is the flow through the sediment body, m^3. day; A is the cross sectional area of the sediment body perpendicular to the direction of flow, m^2; V is velocity, m. day; K is the proportionally factor, sometimes also referred to as intrinsic permeability or hydraulic conductivity, m. day; i is the hydraulic gradient, defined as $(h_1 - h_2)/l$ where h_1 and h_2 are respectively the head at the inflow and outflow end of the sediment body; and l is the length of the flow path between h_1 and h_2.

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In accordance with this definition, the *K* values given in this report ignore the fact that flow takes place through part of the cross sectional area only, namely through the pores. Thus, the cross sectional area should be reduced and the velocity correspondingly increased for arriving at the velocity in the pores, V_p, which is thus defined as:

$$V_p = \frac{K i}{p} \tag{2}$$

where *p* is the estimated percentage pore space in a horizontal or vertical plane.

Sediment Description

The sediment near Halkett consists of a mixture of gravel and sand with local lenses, pockets and films of sand and of 'glacial silt' (very fine sand, Fig. 1). The gravel particles are smooth surfaced and somewhat flattened. They range in size up to 30 cm along their longest axis.

In the field, we distinguished several types of deposit:

(1) Deposits laid down from variable flows that are typically sorted and stratified and occur in any position.

(2) Deposits laid down by receding flood flows. These consist of gravel/sand mixtures in any position, lacking clear signs of sorting or stratification; sand deposits commonly laid down in 'over-channelbank' positions; and 'glacial silt' deposits at the surfaces of 'abandoned' channels and pools.

(3) Wind-blown deposits that are typically sandy. They are encountered in inter-channel islands where the sand is 'caught' by vegetation.

The deposits under (1) are further referred to as stratified; those under (2) as 'flood-dumped', or merely 'dumped'. On collecting material no distinction was made whether gravel/sand mixtures were stratified or dumped in their field state or whether a sandy deposit was dumped or wind blown.

METHODOLOGY

Trailer loads of gravel/sand mixtures, and bags of sand and of 'silt' were collected from several sites. The samples were mixed in the laboratory to arrive at representative samples. The mechanical composition of samples used is shown in Fig. 1.

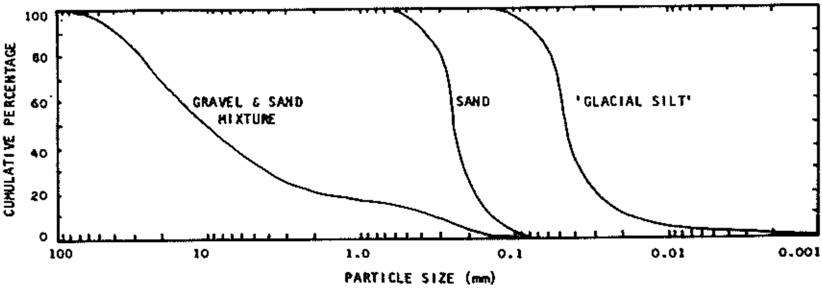
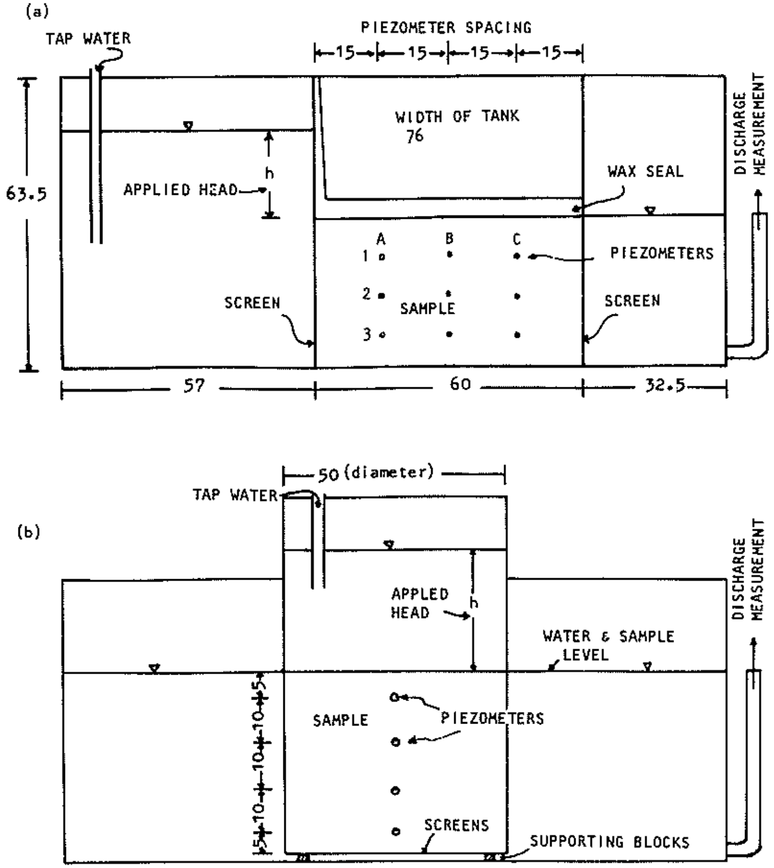


FIG — 1 Particle-size distribution in the composite samples of gravel and sand mixture, of sand and of very fine sand ('glacial silt') used for laboratory measurements.



FIG—2 Apparatus used for measuring horizontal permeability (top) and vertical permeability (bottom). Dimensions in cm.

Permeability

Samples of gravel/sand mixtures were prepared in two ways:

(1) Within the central compartment of the apparatus shown in Fig. 2, for the measurement of horizontal permeability;
(2) Within a cylinder placed within this central compartment, for the measurement of vertical permeability.

The apparatus was filled with water prior to sample insertion. To prepare stratified samples, handfuls of material were released just below the water surface so that the material descended through water and settled with longest axes on a horizontal plane. Larger gravel particles were individually bedded by hand, making an attempt to adjust sand insertion in such a way that each gravel particle became embedded in sand. Dumped deposits were simulated by merely dumping material from a shovel into the water-filled containers.

The upstream and downstream side of the sample body in the central compartment and the lower end of the sample body in the cylinder were separated from the water body in the apparatus by a double, metal–framed screen, one screen of 4 by 4 and one of 40 by 40 mesh (40 apertures per inch). The head loss across this set of screens was negligible in comparison to the head loss across the samples. Piezometers, consisting of 0.5 cm o.d. perforated plastic tubing, were inserted in the samples in the positions shown in Fig. 2.

The hydraulic gradient across a sample was determined on the outflow side by the level of the discharge pipe, which was set level with the upper surface of the sample. Any measurable head that formed during outflow above this level was taken into account in calculations. For measuring horizontal permeability, the maximum head at the inflow side was determined by the strength of the paraffin wax seal on top of the sample. For measuring vertical permeability, the inflow head was determined by the height of the cylinder used. Outflow was measured volumetrically. For the measurement of the permeabilities in sand and in very fine sand, a smaller version of the same apparatus was used.

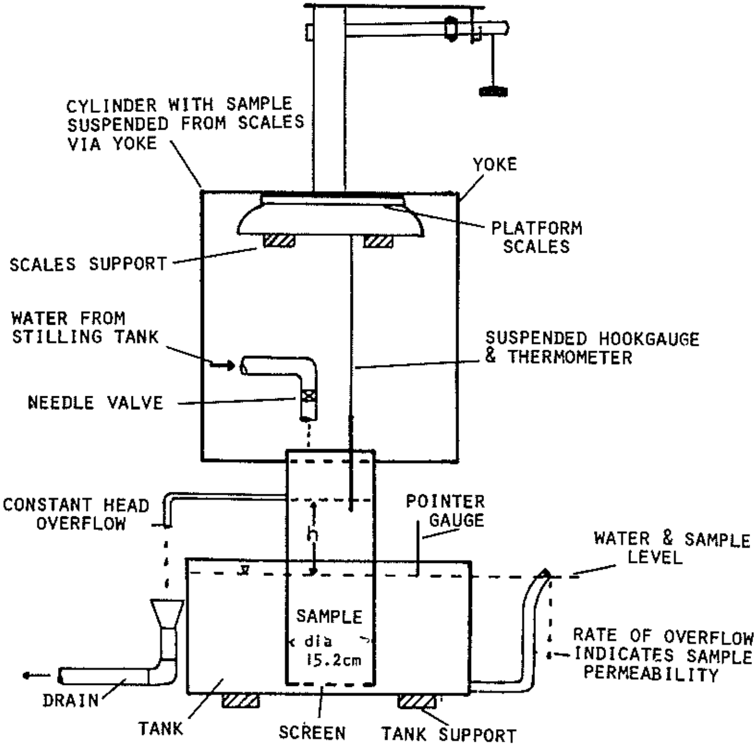


FIG – 3 Weighing mechanism for measuring air entrainment within gravel and sand mixture during infiltration of tap water.

Pore Space

Pore space was measured by (1), water displacement and (2), the outflow from gravel/sand mixtures following completion of vertical permeability measurements, after the head above the samples had subsided to exactly the sample surface.

Air Entrainment

A possible effect on permeability by air entrainment was assessed from weighing a cylinder with sediment in it while tapwater flowed through the sediment at a constant head and virtually constant temperature (Fig. 3).

RESULTS AND DISCUSSION

The horizontal and vertical permeabilities measured after sustained outflow had been attained at each head, as a function of the hydraulic gradient in gravel/sand mixtures are shown in Fig. 4, and those in sand and in very fine sand in Fig. 5.

Assessed pore space is shown in Table 1. Fig. 6 shows the volume of water in pores in a gravel/sand mixture that was displaced by air during percolation and the corresponding decrease in infiltration that occurred during the given time.

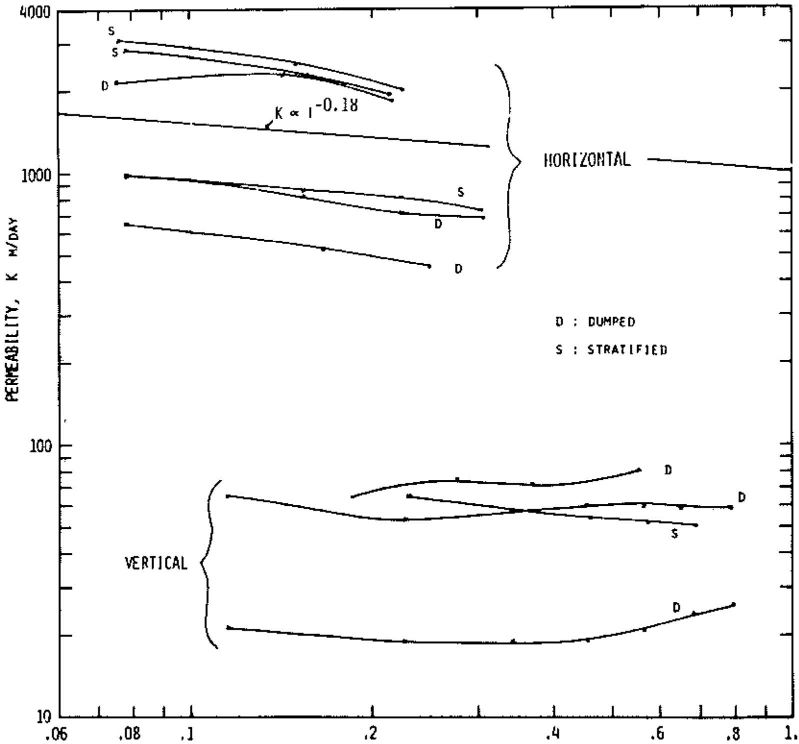
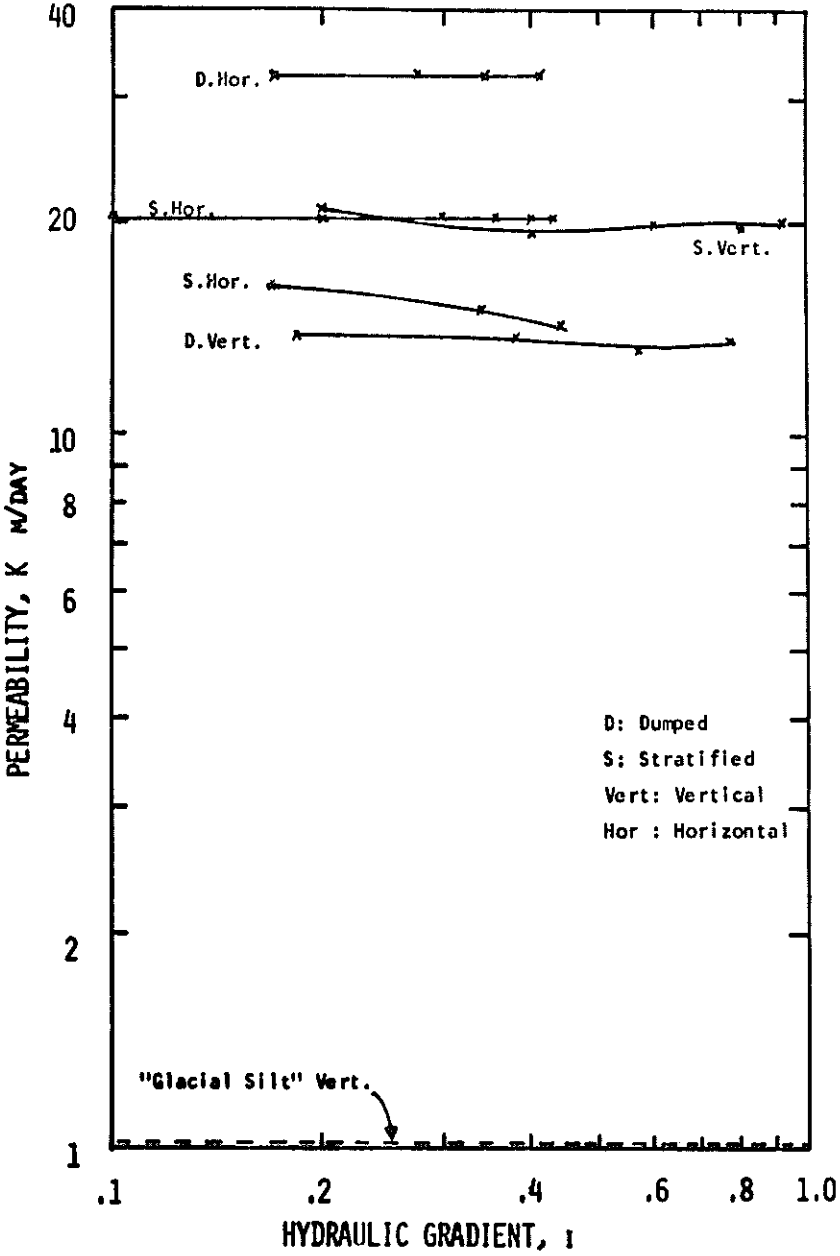
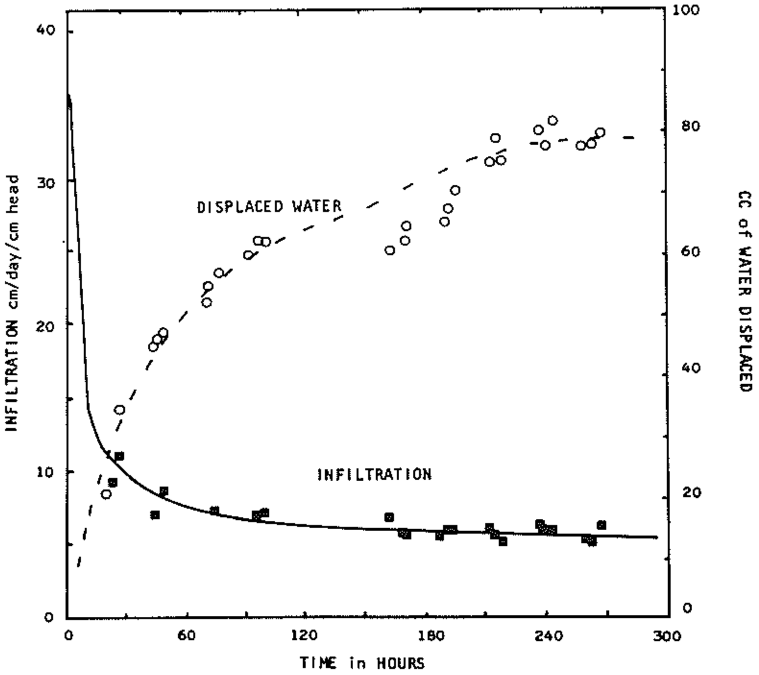


FIG — 4 Measured horizontal (top) and vertical (bottom) permeability versus hydraulic gradients in gravel and sand mixtures.



FIG—5 Measured horizontal and vertical permeability in sand (top) and of vertical permeability in very fine sand ('glacial silt') versus hydraulic gradients.



FIG—6 Measured air entrainment and related infiltration as a function of the duration of tap water application to a gravel and sand mixture.

Permeability

The ratio of the highest to the lowest permeability rate is about 4 in the gravel/sand mixtures and about 2 in the case of sand (Fig. 4 and 5 and Table 2). Nevertheless, an interesting order of magnitude shows up. At, for instance, a hydraulic gradient of 0.1, the average horizontal and vertical permeability in the gravel/sand mixtures were respectively 1600 and 50 m. day, giving a ratio of over 30:1. The vertical permeabilities in terms of *K* in the gravel/sand mixtures (20 to 80 m. day) overlap with, and are only slightly higher than those in sand (15 to 37 m. day). The latter values are in line with those measured by De Ridder and Wit (1965) in undisturbed sand cores. No clear distinction could be detected in any category between permeability in stratified and dumped samples.

A layer of very fine sand ('glacial silt') of merely a few millimetres thickness, placed on top of a sand column caused the permeability of the total column to be reduced to between 0.4 to 1.0 m. day, in line with observations made by Donaldson and Campbell (1977).

The Nature of Flow

The *K* versus *i* curves for the vertical permeability in gravel/sand mixtures and those for sand and very fine sand are essentially horizontal, indicating *K* to be independent from the hydraulic gradient and, therefore, indicating laminar flow.

TABLE — 1 Pore space in river bed sediment samples based on:
(1) water displacement (samples 1-10; and
(2) outflow from saturated sediment bodies (sample 11)

Sample No.	*Sample description*	*Passed by screen of mesh size (cm)*	*Retained by screen of mesh size, (cm)*	*Pore space, % of volume of in situ sample*
1	Clean-washed, soaked gravel		8	53.7
2	Ditto	8	5.5	37.7
3	Ditto	5.5	3.8	41.3
4	Ditto	3.8	2.1	37.9
5	Ditto	2.1	1.0	35.5
6	Gravel-free sand			40.0
7	Very fine sand ('glacial silt')			39.0
8	Gravel of composition shown in Table 3			34.1
9	Ditto			31.3
10	Ditto, but saturated with sand introduced by flowing water			20.2 20.0
11	Gravel and sand samples used for vertical permeability measurements			4.6 7.9 11.9 12.6

TABLE 2 — Range and average of measured rates of horizontal permeability in gravel and sand samples.

Sample no.	*i = 0.083*	*i = 0.167*	*i = 0.25*
	K, m. day		
1	640	532	450
2	919	753	637
3	922	784	762
4	1839	2301	1900
5	2747	2072	1764
6	2900	2450	1975
Average	1661	1482	1248

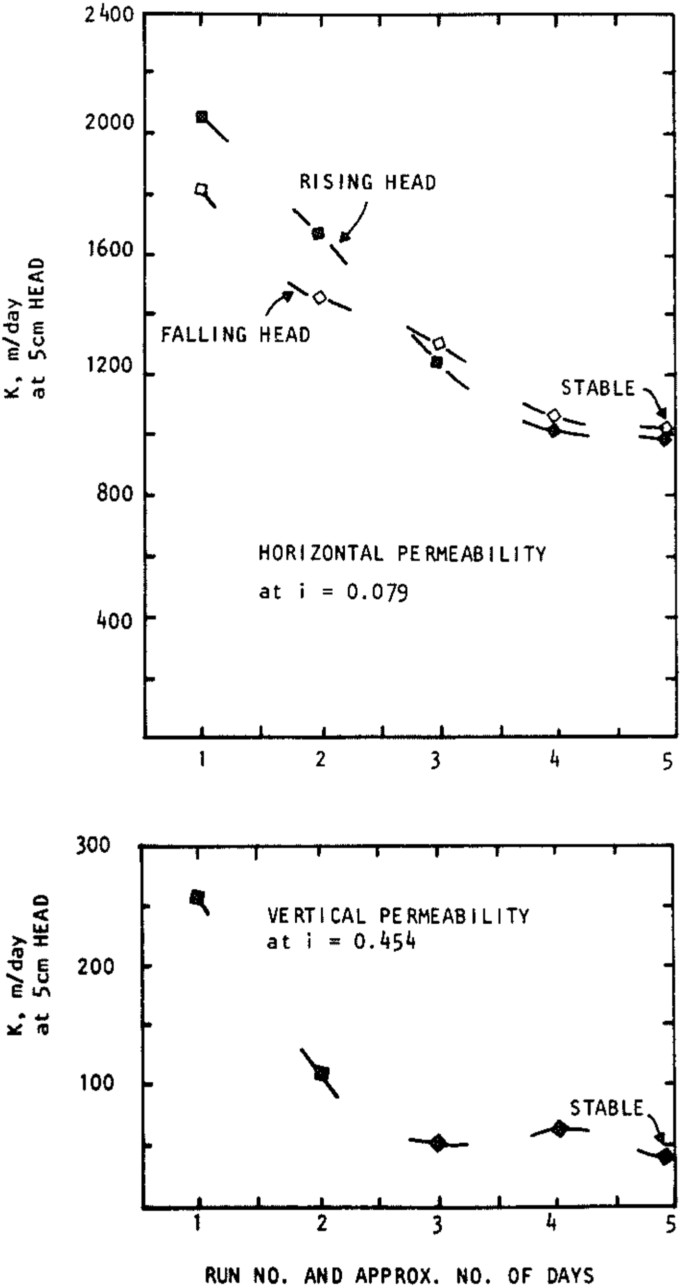
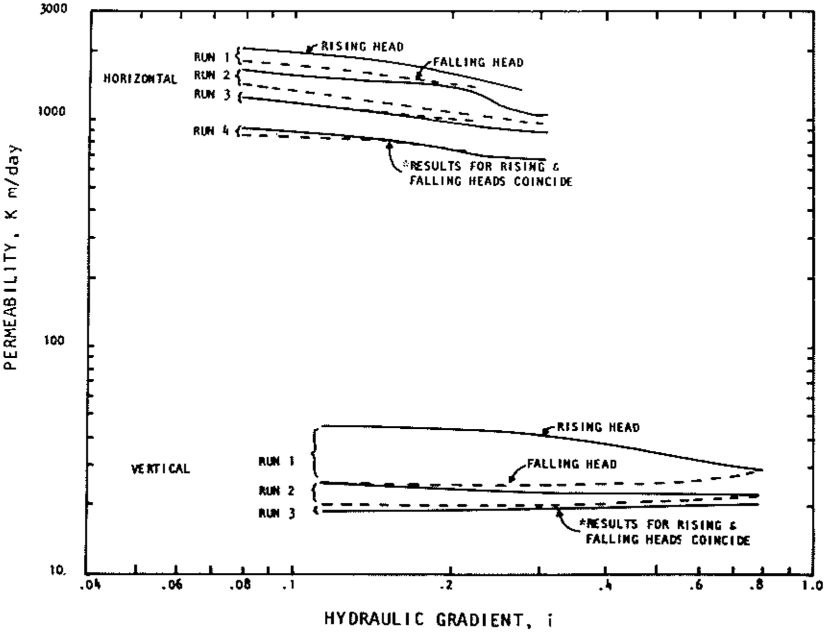


FIG – 7 Time-series of measured horizontal (top) and vertical (bottom) permeability in gravel and sand mixtures.



FIG—8 Measured horizontal (top) and vertical (bottom) permeability at rising and falling heads in gravel and sand mixture.

The K versus i curves for horizontal permeability in gravel/sand mixtures, however, show a trend such that $K \alpha\, i^{-m}$. This can be viewed as follows. When flow is turbulent, as commonly occurs in pipes m = 0.5, and when flow is transitional between turbulent and laminar m has a value between 0 and 0.5. The value of m = 0.18 which indicates that horizontal flow int he gravel/sand mixtures was not entirely laminar, perhaps laminar in narrow passages and turbulent in large pores.

Particle Movement

The continuous measurements allow permeability to be plotted as a time series (Fig. 7). A decline in permeability is observed over several days till ultimately, virtually constant outflow is measured. The decline is caused by changes within the sediment body.

If randomly selected gravel particles are placed side by side and in layers one above the other, the flattened shape of the gravel particles causes flow to be less obstructed in a horizontal than in a vertical plane. This gives rise to an initial anisotropy, clearly exhibited in Fig. 7. Further, pore space between adjacent particles is less subject to blockage by fines in a horizontal than in a vertical plane. The observed partly turbulent horizontal flow is less conducive towards the lodging of fines and more towards the freeing of fines than vertical laminar flow. Moreover, owing to gravity, vertical movement should exceed horizontal movement of fines. Thus, with passage of time, one can expect that horizontal flow becomes less obstructed than vertical flow and that vertical permeability declines more rapidly.

Samples were subjected to successively increasing heads, in about five centimetre increments, up to the maximum head possible. This was followed by the application of successively decreasing heads (Fig. 8). It is seen that successive rising and falling heads produced only a gradual decline in permeability during horizontal flow. However, during vertical flow an initial curious loop formation is observed. This has been interpreted to mean that during vertical flow, but not during horizontal flow, fine particles settle in positions at a rising head from which they cannot be dislodged at a falling head. Thus, obstruction to vertical flow may be increased by temporary high heads, when irreversible lodging of fines in niches can be expected.

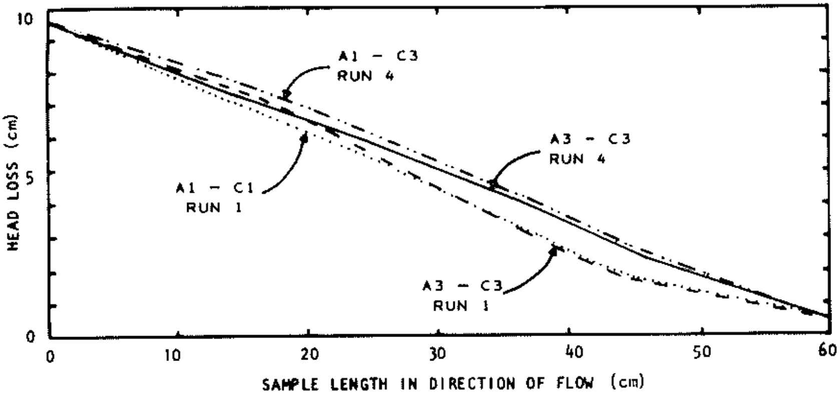


FIG – 9 Sequence in head loss from sample entrance to sample exit at 10 cm head application during continued horizontal flow through a gravel and sand mixture. See Fig. 2 (a) for piezometer position.

Head loss during horizontal flow initially decreased towards the outflow end of a sample (Fig. 9), presumably because of the wash out of fines with discharging water from this end. However, prolonged flow caused a uniform hydraulic gradient to develop, indicating no obstruction to flow. On the other hand, Fig. 10 indicates that hydraulic gradients during vertical flow became steeper towards the outflow end of the sample and that the steepening increased on passing from 15 to 30 cm head.

Mechanical analysis of a gravel/sand mixture that had been subjected to a vertical permeability experiment showed that the percentage of very fine sand and silt (in the range from 0.01 to 0.001 cm) increased with depth below the surface (Fig. 11). This is in line with the inferred processes above.

Pore Space

Total pore space in gravel samples without fines ranged from about 36% to 54% (samples 1 to 5, Table 1). In gravel samples containing many small particles (for composition see Table 3), pore space was reduced to between 31% and 34% (samples 8 and 9). When sand was introduced into these samples by flowing water, the pore space was reduced to around 20% (sample 10). On the other hand, outflow from saturated samples after completion of vertical permeability

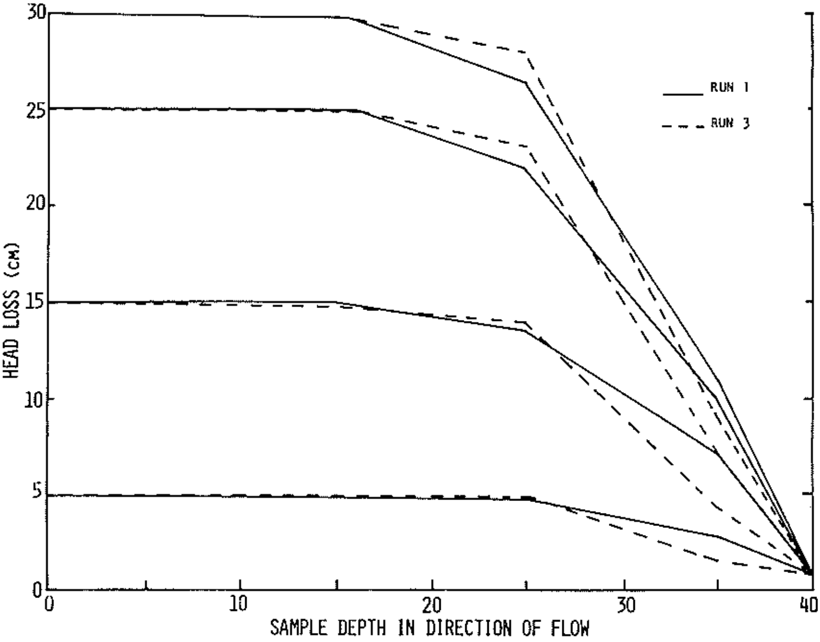


FIG – 10 Sequence in head loss from sample entrance to sample exit at 5, 15, 25 and 30 cm head application during continued vertical flow through a gravel and sand mixture. See Fig. 2 (b) for piezometer position.

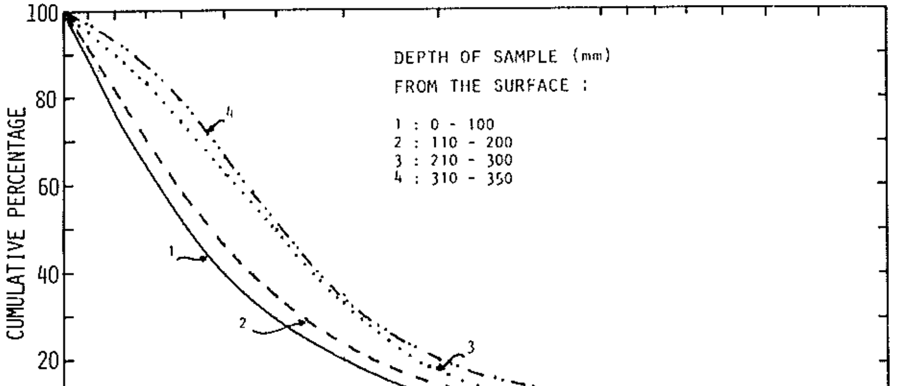


FIG – 11 Particle-size distribution at various depths below the surface of a gravel and sand mixture after completion of a vertical permeability experiment.

TABLE – 3 Particle-size distribution in a sample of gravel (samples 8 and 9 of Table 1) prior to sand being drawn into it by flowing water (with resulting pore space as shown by samples 10 of Table 1).

Passed by screen of mesh size, (cm)	*Retained by screen of mesh size, (cm)*	*Number of particles*	*Air-dry weight, (gm)*	*Percentage of total*
5	3.5	3*	351.5	4.1
2.5	2.0	*151*	4259	50.2
2.0	1.0	*734*	3510	41.3
1.0	0.476	*924*	332	3.9
0.476	0.280	*not counted*	32	0.4
Less than 0.280 cm			5	–
			8489.5	*99.9*

*sizes:2 × 5.5 × 8 cm; 3 × 4 × 8.3 cm; 3 × 5 × 7 cm

measurements indicated a pore space between 4.6% and 12.6% (sample 11).

Such low percentages can be explained, on the one hand, by replacement of water by air, and on the other hand, by outflow under gravity being obstructed by the blockage of passages by fines. Thus, the latter values may indicate 'effective pore space for vertical permeability', a term that is not yet accepted in the literature on the subject. The term 'pore space in a vertical plane' can be used instead. As air entrainment and passage blockage varies, a conservative estimate of pore space in a vertical plane could be 15%. The discussion of particle movement indicates that 'pore space in a horizontal plane' should be greater. A means for estimating it is not yet available and, for the time being, 30% is assumed.

Infiltration

Infiltration into two recently abandoned channel-bed sites, measured by a ring infiltrometer, was of the order of 0.02 m. day per cm head (Fig. 12). Such a low rate is obviously due to surface sealing as is evidenced by the effect of surface scarification. Field observations show a 'glacial silt' film at the surface of channel beds to play a role in the surface sealing.

Air Entrainment

When a rod is poked into sediment below flowing water in a channel bed near Halkett, numerous air bubbles rise to the water surface. However, where underflow intersects the ground surface in low spots, no such air evolution is observed. This means that the sediment below channel beds, but not the sediment through which underflow moves, is in an unsatured condition, implying that the rate of infiltration is lower than the rate at which water is

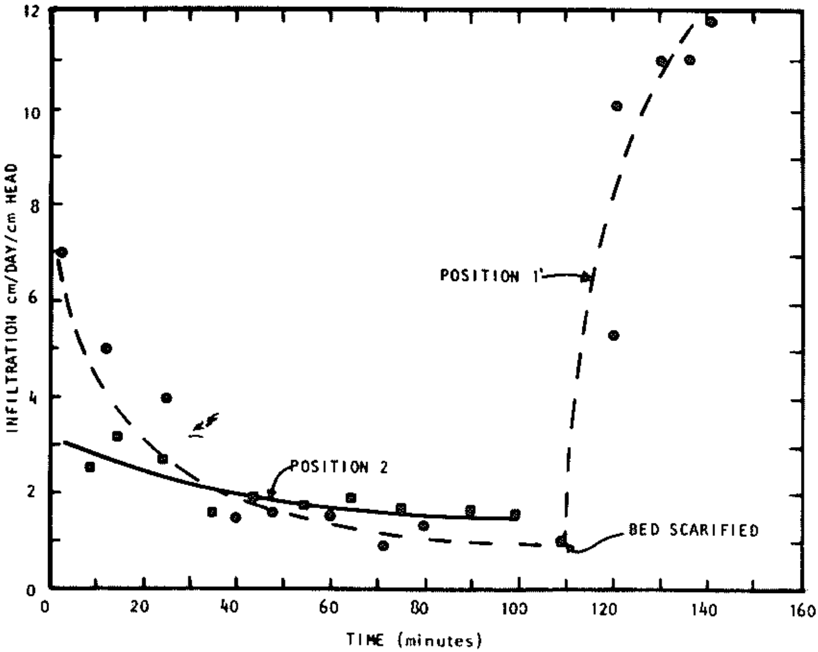


FIG — 12 Field infiltration rates measured by a ring infiltrometer in two channel bed positions. Note effect of surface scarification. Data collected by Zare (1977).

transmitted through the sediment after entering.

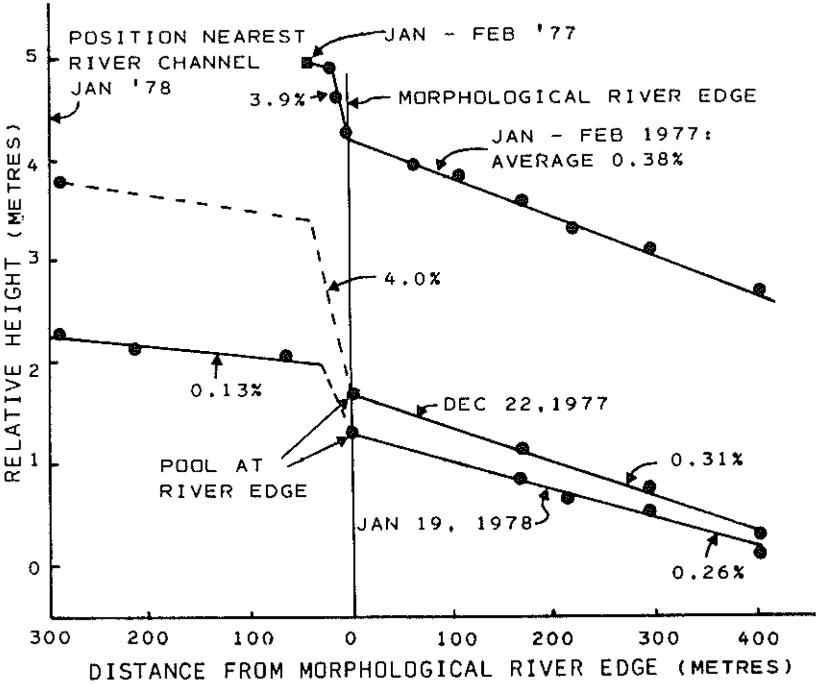
The principle of this subject was examined with the apparatus shown in Fig. 3 for which results are given in Fig. 6. It is shown that air separated from infiltrating tap water and accumulated in sediment in line with field behaviour. After 300 hours of flow through a gravel and sand mixture of 4600 ml at a head of 14.6 cm, 84 ml of water in the pores had been displaced by air, representing some 9% of an estimated 20% of the water content by volume in the sample.

The 'final' infiltration rate was 0.05 m. day per cm head, higher than the 0.02 m. day observed in the field, presumably because of a lack of opportunity for the formation of a 'glacial silt' seal on the sample. A qualitative explanation for an unsaturated condition of the sample arises from the assumption that passages at the surface were blocked more than passages within the sediment.

Comparison of Laboratory and Field Measurements

Field data have recently become available on tracer velocity in gravel and sand. From Hawke's Bay, Thorpe (1977) reported horizontal velocities of the order of 100 to 200 m. day and vertical velocities of 14 to 24 m. day. McCabe and Rowse (1977) reported 164 m. day from the Canterbury Plain. However, because of difficulties in ascertaining the field hydraulic gradients that applied, a comparison of laboratory results with these data should be done with reservation. If a K value of 1660 m. day at a hydraulic gradient of 0.083 is selected from Table 2, the V_p that applied in the samples was 460 m. day in a horizontal direction. Similarly, if a K value of 50 m. day at a hydraulic gradient of 0.2 is selected from Fig. 5, $V_p = 67$ m. day in a vertical direction. Values of 0.3 and 0.15 were assumed for pore space in horizontal and vertical planes respectively.

If the measured K values for horizontal permeability in the samples are used for calculating V_p at field hydraulic gradients, say 0.4% or 0.004 (see Fig. 13), K should be extrapolated to that hydraulic gradient from Table 2, giving 2700 m. day for K and 36 m. day for V_p. Thus, the measured K values in the samples should be conservative, but owing to the application of relatively steep hydraulic gradients to the samples, higher velocities were created than commonly occur in the field. This should not make the sample measurements unrealistic; the high velocities merely accentuated the movement of fines.



FIG—13 Ground water gradients away from nearest active channel on the south side of the river bed near Halkett. Jan-Feb 1977 data from Souhangir (1977).

Under field conditions one can expect such vertical permeabilities as measured to occur only where water is ponded on the ground surface and the water table is at considerable depth. Below channel beds this is unlikely to occur; rather, water filtering from a channel bed should move laterally in response to a horizontal hydraulic gradient. One can now consider again the infiltration measurements. If 1 m depth of water filters across the channel bed surface, the rate of transmission of the underlying sediment should be 6.7 m. day or

3.3 m. day, where 0.15 and 0.3 are assumed pore space values in vertical and horizontal planes respectively. This velocity is substantially lower than the 36 m. day calculated above to apply at a horizontal ground water hydraulic gradient of 0.4%. Thus, the transmission rate exceeds infiltration rate, explaining unsaturated conditions in the sediment below a river channel.

Shell Formation About the River Bed

Emphasis has been placed in this study on the movement of fines within a matrix of gravels. Fines were shown to move vertically, but no direct demonstration could be given of horizontal movement of fines. However, the latter movement can be inferred from various observations made.

A ground water hydraulic gradient of 0.13% was measured within the river bed perpendicular to the direction of channel flow (Fig. 13). This, however, is of little interest as ground water movement is governed by an upstream–downstream hydraulic gradient varying from 0.42% to 0.58% (van't Woudt, Whittaker and Nicolle, 1978), and a hydraulic gradient south of the river bed varying from 0.26% to 0.38% (Fig. 13). Thus, at the river bed margin a decrease in velocity occurs that should induce the deposition of fines in niches. Any initial deposition triggers further deposition with the result that a zone of relatively low permeability forms at the river edge as is clearly shown in Fig. 13. This is not an isolated observation as such a zone has also been observed by Rapier (1967) at the margin of the gravelly Ngaruroro river in Hawke's Bay.

Owing to the vertical movement of fines, such a zone can also be expected to form below a river bed or persisting channel. Evidence for this can be derived from the occurrence of a confined aquifer below the major abandoned river bed just south of the present one near Halkett (a river bed that guided Waimakariri flow farther to the south in the past). Such a 'local' confined aquifer can be explained from a continuation of the 'shell' at the river bed margin to below the river bed and this confirms the conclusion by Risk (1967) from resistivity measurements on the perched condition of the Waimakariri river bed. Such 'shell' formation seems widespread; it is needed to explain the occurrence of many rivers around the globe, perched above highly porous sediment. Without such a 'shell' many rivers would soak away like a desert stream. 'Shell' formation can explain a valley and ridge pattern in ground water contours near Halkett (van't Woudt, Whittaker and Nicolle, 1978) and the occurrence of preferred channels below the Canterbury Plain and in other gravelly sediment bodies elsewhere in New Zealand, signifying sites from which more than average ground water volumes may be extracted.

'Shell' formation below a river bed need not be continuous in one plane, but is more likely to be irregular in outline, depending on local differences in sediment at various depths. Near Halkett, 'shell' formation cannot be expected to extend to the northern margin of the river bed as ground water here moves towards the river bed (van't Woudt, Whittaker and Nicolle, 1978).

CONCLUSIONS

1. The ratio between horizontal and vertical permeability in gravel/sand mixtures was found to be 30:1. However, the measured vertical permeability seems to have little field significance because of an apparent

absence of vertical hydraulic gradients.

2. The vertical permeability in gravel/sand mixtures was found to overlap with horizontal and vertical permeability in sand.
3. A layer of 'glacial silt' less than 1 cm thick may reduce the vertical permeability of normally high–permeability gravels in which the 'silt' is embedded, to less than 0.01 m. day at a hydraulic gradient of 1.
4. An initial anisotropy in the sediment is accentuated by continued flow through it.
5. Horizontal flow through gravel/sand mixtures is not entirely laminar which has a bearing on the movement and deposition of fines during flow.
6. The movement of fines during flow through gravel/sand mixtures increases differences between the pore space in a horizontal plane and that in a vertical plane.
7. Air accumulates in sediment below flowing water in a river bed channel because the rate at which water is transmitted through a sediment exceeds the rate at which it enters. This situation results in negative pressures, unsaturated conditions and an opportunity for air accumulation in large pores.
8. The movement of fines within a matrix of gravel particles can give rise to a layer or zone of relatively low permeability, along the margin of and below a river bed or persisting channel. This can explain the occurrence of preferred ground water channels in gravelly sediment, conducive towards high yield of ground water.

ACKNOWLEDGEMENTS

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Corrigenda

Volume 16 Number 2 (1977)

Day, M. C. and Hunt, B. W.; Groundwater transmissivities in North Canterbury (note)

Page 158 paragraph 2 lines 4 and 5. Stream function symbol (Ψ) deleted.