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The Use of Groundwater Surveys in the Diagnosis and Solution of a Drainage Problem

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Abstract

Groundwater investigations were carried out in a river valley area where drainage was unsatisfactory. A site was surveyed and water-table and piezometric gradients were measured. Hydraulic conductivity was determined by inversed auger hole, permeameter, pit bailing and aquifer pumping test methods. Drain spacing was determined from Ernst's, Hooghoudt's and Toksöz and Kirkham's equations.

The drainage problem was a high water-table in a two-layered unconfined aquifer with a gravel layer at 2 m depth. Distant drain spacings of 110-130 m were indicated where drains were in or connected to this gravel layer and close spacings of 10 m or less where the drains were in the upper more slow draining layer.

There was good agreement between hydraulic conductivity values from the pit bailing and aquifer pumping test methods. The study showed the value of test pits in diagnosing drainage problems and determining hydraulic conductivity. The pit bailing method was effective, cheap and quick and is recommended. The solutions showed the economy of placing drains in or in contact with fast draining soil layers.

Introduction

The study site was a 3.4-ha wet grassland field in the townland of Scart, Gortaclea about 6 km west of Castleisland (Fig. 1). It lies in the valley of the River Maine. This valley averages 6 km in width and stretches from 7 km eastwards of Tralee to about 6 km east of Castleisland. The mean elevation of the valley is 45 m OD although east from Castleisland it attains elevations of 75 m OD in places. The mean elevation of the study site is 22.5 m OD.

The valley is bounded on the south by the Old Red Sandstone mountains of Slieve Mish and on the north and east by

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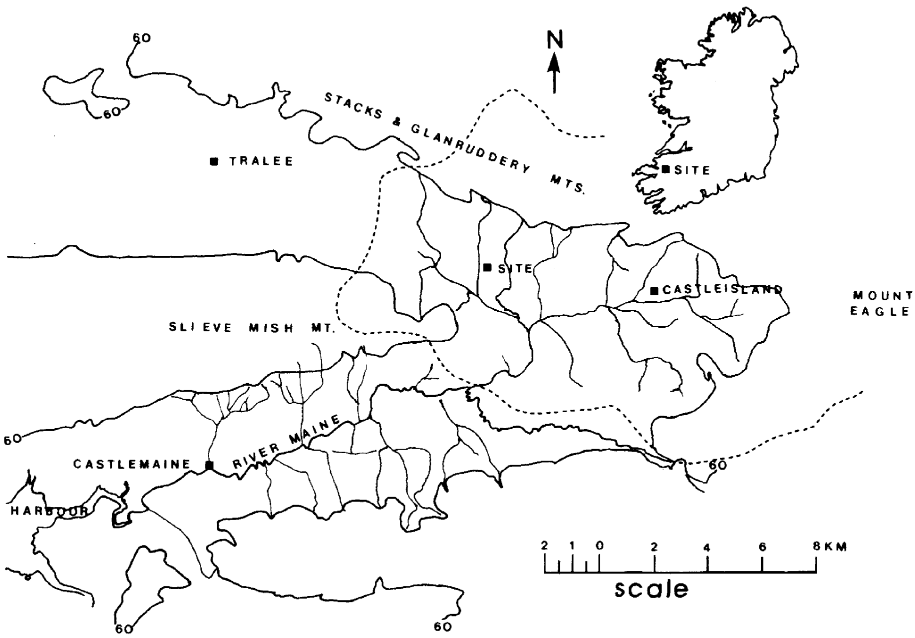

Fig. 1: The valley of the River Maine below the 60 m contour showing the location of the site; inset is a location map and broken line shows outline of western section of Fig. 2

the Coal Measure shale and flagstone mountains of Stacks, Glanruddery and Mount Eagle. The subjacent rock in the valley is limestone. The stratigraphical succession is Old Red Sandstone of Devonian Age, Ahane, Springmount, Castleisland, Rockfield, Cloonagh and Dirtoge limestone formations of Dinantian age, the Clare Shales formation of Namurian age and unnamed sediments of more recent ages including glacial drift and alluvium (Hudson, Clarke and Brennand, 1966).

The limestone formations are cut by a system of faults and joints (Wright, 1979), mostly small fractures, and some have been dissolved out to form caverns and sinks especially the reef limestones (Castleisland and Cloonagh formations). Water sinks are frequent at the junction of the Carboniferous Limestone and overlying Namurian Shales. The Cloonagh and Castleisland limestone formations tend to form belts of low irregular hills with thin dry soils and outcropping rock. In this geological framework, there could be a component of groundwater seepage in the lowlands of the river valley.

Geohydrology

In Pleistocene times the valley of the River Maine was glaciated. The ice covered the limestone plain with a layer of glacial drift consisting of clay, silt, sand, gravel and boulders. Debris of the Old Red Sandstone and Namurian formations were mixed with that of the limestone formations. When the ice margins oscillated during Midlandian times, parts of the drift were overlain with fluvioglacial deposits of sand and gravel. New drift then was overlain on these deposits so that they now occur as buried gravel layers in the drift.

Most of the soil overburden deposits are less than 3 m thick and are very variable (Scanlon, 1982). While the reef knolls stand out as low rocky hills, the valleys are covered with thicker glacial drift. Elevation differences along the peripheries of the valley result in hydraulic gradients forcing water to flow towards the streams and rivers on the low ground chiefly through the faulted and jointed limestones (Selim, Selim and Kirkham, 1975).

Fig. 2 shows a flow net constructed using well-water level contours as equipotential lines with streamlines drawn perpendicular to them (Scanlon, 1982). This shows that much of the recharge in the valley comes from the high ground and that the streams and river are effluent. Flow nets for 1980 and 1981 were similar but water levels in 1980 were a little higher due to higher rainfalls (Scanlon, 1982). While Fig. 2 shows the macro geohydrology, the hydrology of small catchments and farm fields within the valley may differ from the general trends. Moreover, a detailed investigation of farm fields is

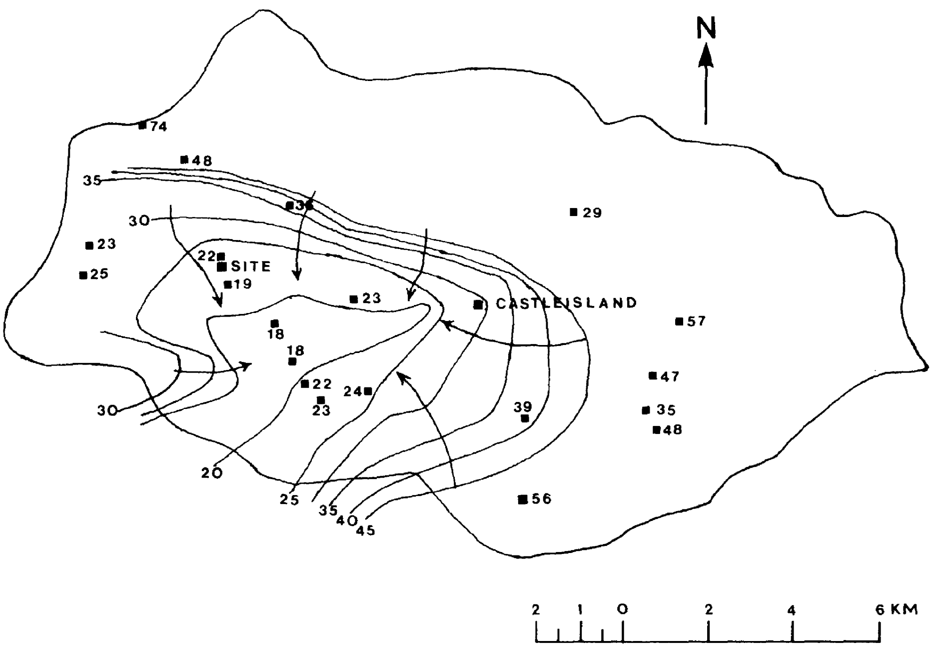

Fig. 2: Groundwater contour map derived from 116 wells (some shown) in the catchment of the River Maine, summer 1981; lines with arrows indicate the direction of flow; levels are shown in m OD (data from Scanlon, 1982)

required to establish the boundary and geohydrological conditions necessary to formulate a drainage solution.

Background to the study site

Farming in the valley of the River Maine is predominantly dairying. Intensive dairy farming requires dry ground with a high-bearing capacity to minimise treading damage. A dairy cow of 550 kg with a hoof area of 3.10^{-4} m^2 has a deadweight load of 1.7 bar. Wet topsoils have bearing capacities less than 0.2 bar and deform readily on treading by cows. This causes grass to be treaded in and gives rise to poor grass growth. Wet ground on many farms in the valley restricts the intensity of farming and increases management difficulties. Drainage is most important in improving farming conditions. Current drainage practice tends to be expensive and not fully effective. The site selected is typical of much wet ground in the valley and is grazed by dairy cows.

Annual rainfall of the valley is in the 1250-1500 mm range. Potential evapotranspiration is estimated at 500 mm (Smith, 1967) leaving an annual surplus of 750-1000 mm rainfall. Because of this, a high drainage criterion of 12 mm/d is used for the design of drain spacing for grassland in this valley. Field hydrological measurements for this study were carried out in September and October 1982 to cover dry and wet conditions. Up to September 21 the weather was fairly dry but heavy rain fell from then until the end of October. The total rainfall was 16.4 mm for September 21-23 and 311 mm for September 24–October 30 inclusive. The 311 mm of rain almost equals the 30-year maximum rainfall for a month at Valentia Observatory where the average annual rainfall is 1398 mm.

The study field itself (Fig. 3) is surrounded by open drains on the west and east sides and these discharge to the Little River Maine to the south (Figs. 1 and 3). The average gradient is 1/200 to the south-east. The field is wet, soft and waterlogged in wet weather and conventional drainage systems were only partially successful in

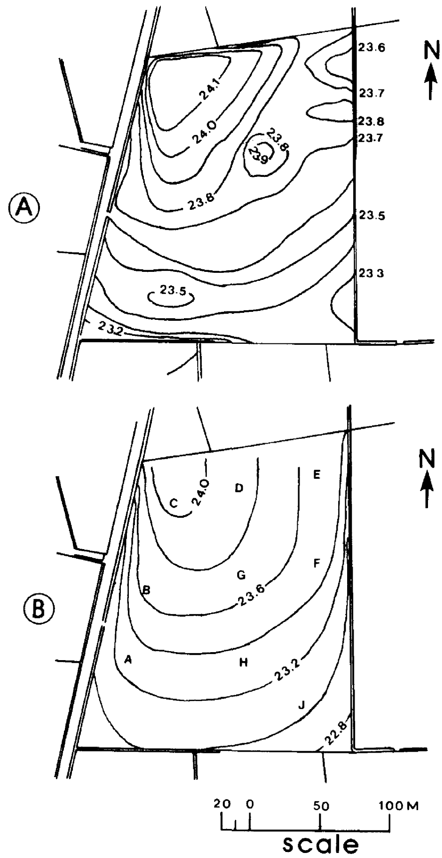

Fig. 3: Ground contour (A) and water table contour (B) map (24/9/1982) of the field investigated; A, B, C, D, E, F, G, H, J on the water-table contour map show the position of the test pits; levels are shown in m OD

abating the waterlogging in adjacent fields. The background hydrogeological information shows that the farm lies on the Castleisland reef limestone formation with an overburden thickness of 3-4 m. The water level in a domestic well where the ground level is about 24 m OD was at 22-23 m OD in summer. However, this well is not in the bedrock but in a gravel aquifer.

Investigations

Scope

The drainage on the site presented a problem in diagnosis. Therefore, the land was surveyed and test pits were excavated. Water-table and piezometric measurements were made in wet and dry periods to establish the nature of the water flows. Hydraulic conductivity measurements were made by field and laboratory methods. Drainage solutions were derived from these measurements using appropriate boundary conditions.

Water-table and piezometric gradients

The field was divided into a 30-m grid and surveyed, the contours are shown in Fig. 3. Nine test pits were excavated by a tracked excavator. Water-table and piezometer tubes were installed and read in the September-October period of 1982. There were 25 water-table tubes, 9 beside the pits and 4 rows of 4, which were used to assess the influence of the open ditches on the water-table. Water-table tubes were of 15-mm-bore steel drilled regularly with 3-mm holes. They were driven to a depth of 1.1 m below ground level and flushed out as recommended by Reeve (1965).

There were 45 piezometer tubes placed in clusters of 3 beside test pits A, B, C, D, F, G, H (Fig. 3) and in clusters of 4 beside test pits E and J and one beside each of the water-table tubes in the 4 rows of 4. The piezometer tubes at each location were driven to different depths to determine gradients in soil-water pressure.

Hydraulic conductivity by the auger-hole method

The soil in the field was found to be three-layered with two permeable layers resting on an impervious layer. The hydraulic conductivity of the upper layer was measured at 9 sites by the inversed auger-hole method as the water-table, which was at 1.2 m, was deeper than the base of the hole (Kessler and Oosterbaan, 1974). Moreover, it was found impossible to bore a uniform hole deeper than 60 cm and even then the diameter of each hole had to be measured because the disturbance by stones resulted in a slightly larger diameter than the 8 cm drilled. The holes were filled with water to a depth of 20 cm and the time for a fixed increment of fall was noted 7 times.

Hydraulic conductivity by laboratory methods

Attempts were made to take 10-cm-diameter undisturbed samples of the gravelly sandy loam below 60 cm for laboratory measurement of hydraulic conductivity by the falling head method. Only one sample was successfully taken. Remoulded samples were taken by packing and compacting gravel-free loam in layers in the 10-cm-diameter samplers until the 13 cm deep cores were full. Attempts were made to simulate the field density of the soil. The samples swelled after pre-soaking and they had to be further trimmed. The hydraulic conductivity of one sample of the second layer (a sandy gravel) was measured in a 3-m-long, 70-mm-diameter permeameter at various gardients using a constant head for each gradient.

Hydraulic conductivity by pit-bailing and pumping test methods

The hydraulic conductivity of the soil slab overlying the impervious layer was measured by the pit-bailing method (Bouwer and Rice, 1983; Boast and Langebartel, 1984) and by aquifer pumping tests (Kruseman and de Ridder, 1970). The aquifer pumping tests also served to classify whether the aquifer was unconfined, semi-unconfined or semi-confined. The transmissivity of the second layer was derived from the results of the hydraulic conductivity tests. Two pit sizes, 2-m and 5-m diameter approximately, were used for the pit bailing tests. The depth to static water was 96 cm and 101 cm respectively and the depth to the impervious layer was 0.25 m below the bottom of each pit. The water level was lowered to 112.5 cm (16.5 cm drop) and 115.5 cm (14.5 cm drop) in the 2-m and 5-m pits, respectively. The rate of recovery was measured at intervals of 1 hour.

For the aquifer pumping tests, a test well approximately 3 m in diameter was excavated to the impervious layer and was pumped out at a constant rate of 20.5 m^3/day by a submersible pump fitted with 50-m of discharge pipe. At distances of 7.5, 15, 30 and 120 m from the well a piezometer and water-table tube was installed after the recommendations of Reeve (1965). The piezometer tube was driven to 210 cm into the gravel layer and the water-table tube to 120 cm into the upper layer. All tubes were tested for sensitivity and were installed some days before the tests began. Depth to water-table was measured by a sounder and readings were taken over a 20-hour period. Equilibrium conditions were not attained over this period as the drawdown continued to increase. Consequently, the data were analysed by methods for unsteady state flow (Kruseman and de Ridder, 1970).

Results

Description of soils and water relations

The soil on the site is three-layered. An upper layer of variable composition rests on a sandy gravel which in turn rests on a tightly packed impervious sandy loam. Two types of upper layer could be distinguished, a sandy loam and a sand; and typical profiles of these are described. These tended to occur in plan in blocks of up to 5-m sides. However, there was great variation and profiles with gradations between the two types were very common. In some test pits there was an intricate distribution with wedges and lenses of various sand sizes and sandy loam. Essentially, the soil is a two-layered aquifer.

Sandy loam profile:

0-25 cm Dark-brown organic sandy loam topsoil, loose and crumby.

25-85 cm Grey-brown sandy loam with shale grit and stones, a few limestone boulders, tight with cracks, iron staining along cracks. No water.

85-200 cm Grey-brown mottled sandy loam with grit and stones, tight with few cracks. No water.

200-235 cm Dark-grey gritty gravel, badly graded, flat shale grit and some stones. Strong water breakthrough.

235+cm Dark-brown glacial drift, very tight, no cracks. No water.

Sand profile:

0-25 cm Dark-brown organic sandy loam topsoil.

25-130 cm Grey-brown mostly fine sand with some shale stones, loose.
130-190 cm Grey- and reddish-brown sandy and silty fine gravel with stones.
190-220 cm Grey gritty gravel both round and flat. Strong water breakthrough mainly at one wall.
220 cm+ Grey-brown sandy loam, tight, no cracks. No water breakthrough.

All profiles sampled had a sandy gravel layer, commonly 25-35 cm thick and beginning at a depth of about 190 cm but the sandy gravel layer was as shallow as 100 cm in one test pit. There was a strong breakthrough of water from this layer in all tests pits. This sandy gravel layer is the most important one from a hydrological standpoint. No textural analysis of the soil was made because of the great variation within individual test pits.

The water-table and potentiometric surfaces

The water-table follows the gradient of the land surface fairly closely except near the open drains at the east and west sides (Fig. 3). These drains are effluent as indicated by the sharp bending and configuration of the contour lines close to them. The fairly uniform spacing of the contour lines away from the influence of the open drains indicates that the field is hydrologically uniform. But the hydraulic gradient is small, varying about 1/200; this indicates that nearly static water conditions exist away from the open drains. Near the open drains the hydraulic gradient varied about 3-6/100.

Hartley's statistical method of sequential testing (Snedecor, 1962) was used to test the validity of using contour lines to plot the water-tables. This showed that all sites had significantly higher water levels than J (Table 1). A, H and B were not significantly different. C, D, E, F and G were significantly greater than A. E, F and G were not significantly different. C and D were significantly greater than F, and C was greater than D. Contours for 30/10/82 followed similar trends to those for 24/9/82 but they were higher at any elevation.

TABLE 1: Mean elevation of water in water-table and piezometer tubes at the different sites (m OD); sample standard deviation is 0.12261 m

Site	A	H	J
No. of pipes	3	4	4
Elevation	22.77	22.74	22.41
Site	B	G	F
No. of pipes	4	3	4
Elevation	22.73	22.94	22.97
Site	C	D	E
No. of pipes	4	2	4
Elevation	23.57	23.10	22.87

TABLE 2: Comparison of water table and piezometer elevations on 24/9/82

Tube[1]	No. of sites	Water level mean elevation (m OD)	$S\bar{x}$
W	8	22.94	0.045
P_1	8	22.82	0.045
P_2	10	22.66	0.039
P_3	10	22.66	0.039

$t = 2.571$ (P_1 v P_2); $t = 2.548$ (P_1 v P_3);
$t = 4.965$ {($W + P_1$) v ($P_2 + P_3$)};
$t = 1.874$ (W v P_1); $t = -0.026$ (P_2 v P_3).
[1]Tubes: W = Water table
P_1 = Shallow piezometer
P_2 and P_3 = Deeper piezometer.

At the end of the dry spell (21/9/82) most of the tubes were dry but after 16 mm of rainfall there was water in all tubes on 24/9/82. The water-table and shallow piezometer tubes showed a falling water-table which was a statistically significant result (Table 2). Hence the water-table is falling slowly and the water is moving out of the area both downslope and into the open drains as indicated by the water-table gradients in Fig. 3. Unlike on the 24/9/82 when conditions were dry, there was heavy rain from about 0800 hours on 29/10 to 0800 hours on 30/10/82. The field became ponded and there was no significant difference between the water-table or piezometer tubes, indicating near static water conditions in heavy rainfall. At sites E and F there was also a near static water-table on 24/9/82, suggesting some recharge of the gravelly layer from outside but this was not investigated.

The water-table and piezometer tubes together with the logs of the test pits indicate that the drainage problem is a high water-table problem and that the aquifer is either a semi-unconfined or an unconfined aquifer. A semi-unconfined aquifer is defined by Kruseman and de Ridder (1970) as an aquifer in which the hydraulic conductivity of the confining layer is large enough so that significant horizontal flow takes place through it.

Hydraulic conductivity

The mean hydraulic conductivity of the upper layer by the inversed-auger-hole method was 0.94 m/d with an $s_{\bar{x}} = 0.76$ m/d. Repeat tests carried out on 4 test holes showed that there was no significant difference between the first and repeat readings with an F ratio of 0.57. A value of 1.0 m/d was taken as the hydraulic conductivity of the upper layer.

Hydraulic conductivity in the laboratory

The hydraulic conductivity of the sandy loam subsoil was 0.2 m/d but this sample was found to have one stone of 53 cm^3 occupying 6.4% of the volume. The hydraulic conductivity of the remoulded samples averaged 0.92 m/d for 3 samples with an $s_{\bar{x}} = 0.38$ m/d. Values of 3.10^{-3} m/d for a well compacted sample and 9.5 m/d for a loosely packed sample were also recorded.

Hydraulic conductivity by permeameter

The hydraulic conductivity of the sandy gravel sample varied because of turbulent flow from 1825 m/d at 0.1% gradient through 1800 m/d at 0.2%, 1500 m/d at 0.5%, 1200 m/d at 1%, 700 m/d at 5%, 550 m/d at 10% and 365 m/d at 30% gradient. This is about the hydraulic conductivity of a 2-5 mm washed gravel or broken stone aggregate. However, this value could not be taken as representative of the second layer because of the great variation in composition and the difficulty of simulating field conditions in the permeameter as well as sampling problems. Only the pit bailing and aquifer pumping tests are capable of sampling enough area to give a weighted average value for hydraulic conductivity. In fact, using laboratory methods such as the permeameter to measure hydraulic conductivity can give rise to erroneous results.

Hydraulic conductivity by pit-bailing and pumping tests

The hydraulic conductivity of the saturated soil layer determined by the pit bailing method in the 2-m pit was 12 m/d and in the 5-m pit 18 m/d. The mean value was 15 m/d.

Drawdown in the water-table and piezometric tubes in the aquifer pumping test is shown in Fig. 4. Drawdown in piezometers P_1 and P_2 and water-table tubes W_1 and W_2 indicate unconfined aquifer conditions while drawdown in piezometer P_3 indicates an unconfined aquifer with delayed yield or a semi-unconfined aquifer condition. Overall, the curves in Fig. 4

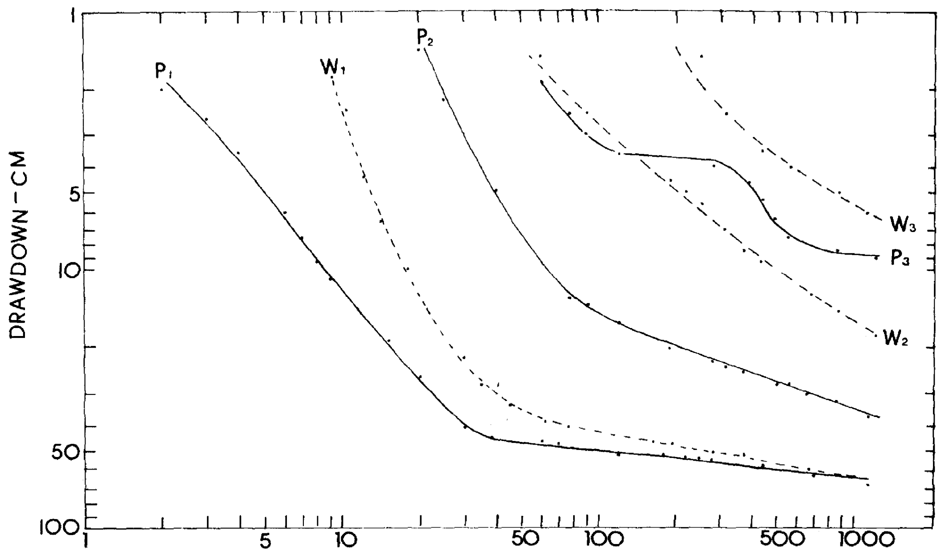

Fig. 4: Drawdown in the water-table and piezometer tubes with time; the subscripts 1, 2, and 3 refer to distances 7.5, 15 and 30 m from well

indicate a nearly unconfined aquifer which is layered and inhomogeneous with depth and area. The data were analysed by the unsteady-state-flow methods of Chow, Hurr and Hantush II (Kruseman and de Ridder, 1970). The Hantush II method is applicable to semi-confined aquifers and hence the KD of the gravel layer is obtained by this method. The Chow and Hurr methods gave similar values.

The data obtained by the different methods are shown in Table 3. Since the dominant flow was the horizontal flow through the sandy gravel, the hydraulic conductivity of this layer can be computed from the data derived from the inversed-auger-hole and the pit-bailing and aquifer-pumping tests by the formula:

$$K_t D_t = K_1 D_1 + K_2 D_2$$

where K_t is the hydraulic conductivity of the saturated thickness of the soil above the impervious layer (= 15 m/d).

TABLE 3: Hydraulic conductivity values for the gravel layer

Test		Piezometer	$K_t D_t$ (m^2/d)	K_t (m/d)	$K_2 D_2$ (m^2/d)	K_2 (m/d)
Pit bailing			19.5	15	18.6	62.0
Pumping	Chow	P_1	21.5	16.5	20.6	68.7
		P_2	16.3	12.5	15.4	51.3
	Hantush II				16.9	56.3
Mean						59.6

D_t is the thickness of the saturated soil layer (= 1.3 m).
K_1 is the hydraulic conductivity of the upper slow layer (= 1.0 m/d).
D_1 is the saturated thickness of the upper slow layer (= 1.0 m).
K_2 is the hydraulic conductivity of the sandy gravel.
D_2 is the thickness of the sandy gravel (=0.3 m).

The average hydraulic conductivity of the sandy gravel is 60 m/d (Table 3).

Drain spacing by Ernst's solution
The drain spacing can be computed once the geometry and hydraulic conductivity are known and a drain discharge value and depth to ground water are chosen taking the rainfall frequency and system of farming into account. The following values for the parameters are chosen: hydraulic conductivity of the upper layer (K_v) = 1 m/d; hydraulic conductivity of the sandy gravel layer (K_h) = 60 m/d; discharge value (q) = 12 mm/d; depth to groundwater below ground level = 0.45 m. Two depths of drain are chosen, 1.9 m and 1.6 m (Fig. 5). In the case of the 1.9-m depth, the drain is resting on the sandy gravel while in the case of the 1.6-m depth the drain trench is excavated to 1.9 m and backfilled to 1.6 m with a cheap pit-run connector gravel on which the pipe is placed (Fig. 5). The hydraulic conductivity of the connector gravel equals or exceeds 60 m/d.

The drain spacing is computed from Ernst's equation with the symbols as defined by Wesseling (1973) and where in addition to the symbols already defined above the following are defined overleaf.

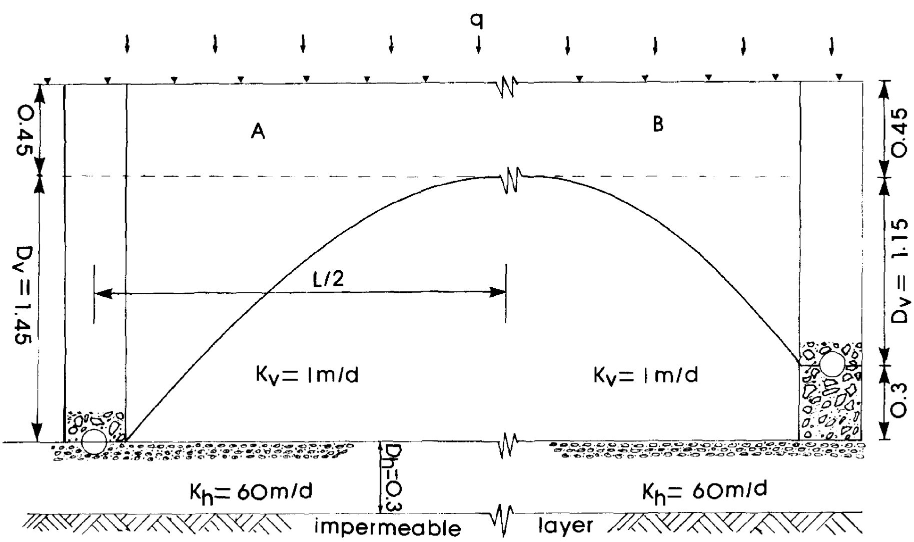

Fig. 5: Diagrammatic sketch showing geometry for the Ernst equation; Case A — drains at 1.9 m deep; Case B — drains at 1.6 m deep underlain by a connector gravel; all linear dimensions are in m

$$h = \frac{q\,D_v}{K_v} + \frac{q\,L^2}{8K_hD_h} + \frac{q\,L}{K_r}\ \ln \frac{aD_r}{U}$$

h = Total hydraulic head loss or height of water-table above the mid point of the drain.
L = Drain spacing.
K_r = Hydraulic conductivity for radial flow (= K_h).
a = Geometry factor for radial flow; a = 4 for $K_h/K_v > 50$.
D_r = Thickness of layer over which radial flow is considered ($D_r = D_h$).
U = Wet perimeter of drain.

In the case of the 1.9 m drain, h = 1.45 m; q = 0.012 m/d; D_v = 1.45 m; K_v = 1 m/d; D_h = 0.3 m; K_h = 60 m/d; U = 0.25 m; a = 4; D_r = 0.3 m; K_r = 60 m/d.

Neglecting the last term of the equation, which is extremely small, the drain spacing works out at 131 m. Where the drains are at 1.6 m, only the head loss (h) changes to 1.15 m and the drain spacing becomes 117 m (Table 4). Sensitivity analyses show that the drain spacing is insensitive to variation in the value of K_v (the hydraulic conductivity of the upper layer) provided that this exceeds about 60 mm/day. The drain spacing is very sensitive to variation in the hydraulic conductivity of the lower more permeable layer. This shows that it is not necessary to have an accurate value for the hydraulic conductivity of the upper layer provided it exceeds a threshold value of 60 mm/d.

TABLE 4: Calculated drain spacing for various drain depths

Formula	Drain depth (m)	Drain spacing (m)
Ernst	1.9	131
	1.6	117
Hooghoudt	1.6	120
Toksöz/Kirkham	0.6	10

Drain spacing by Hooghoudt's solution
The drain spacing can also be computed from Hooghoudt's equation where the drains are at the interface between the upper layer and the underlying sandy gravel layer (Wesseling, 1973) or where the drain is connected with the underlying sandy gravel by a connector backfill yielding similar results to those already obtained (Table 4).

Drain spacing by Toksöz-Kirkham solution
If the drains are placed in the upper layer without a hydraulic connection to the lower more permeable sandy gravel layer, the drain spacing can be computed from equations and nomographs developed by Toksöz and Kirkham (1971 a, b). A common solution up until now to drainage in the valley of the River Maine is to instal drains at shallow depth, such as 0.6 m. Taking the discharge value, depth to ground watertable and hydraulic conductivities already used, the drain spacing for this depth is 10 m (Table 4). In areas of the field where the hydraulic conductivity of the upper layer falls much below 1 m/d, a drain spacing of 10 m will turn out to be too distant with resulting poor control of the water-table and water-logging in wet weather.

Discussion

This investigation shows why less than satisfactory results have been obtained with shallow drains which have been often spaced at 15-30 m in the valley of the River Maine. At these spacings they give poor control of the water-table. However, shallow drains at spacings of 10 m or less are very expensive for grassland farming. Analyses show that distant spacing of deep drains in or in contact with permeable sub-layers gives effective control of the water-table. Deep drains are also recommended by Kirkham, Toksöz and van der Ploeg (1974). While these drains are more difficult to instal, they are often very cost effective because so few are required. They can be easily installed where trenching or trenchless draining machines can be used but the stony nature of Irish soils often preclude the use of these machines

On the experimental site deep drains at 1.6 or 1.9 metres could be installed relatively easily as the top layer of soil is strong and there was little collapse in test pits with tapered sides. Where permeable soil, gravel or rock layers are met at greater depths open drains may be used or a thick layer of connector gravel may be used to connect the permeable layer to the drain pipe where the trench walls are unstable. The latter solution can often be used where cheap gravel is available locally as pit run or can be excavated cheaply from weathered rock quarries. Because of the dangers of sidewall collapse in deep drains, safety codes should always be observed and deep open drains should always be fenced off from livestock.

In an area such as the valley of the River Maine the soil and hydrological conditions are often variable and sometimes complex. Test pits should be excavated to such depth as to explain satisfactorily the groundwater conditions. Where the groundwater conditions cannot be diagnosed in test pits excavated to maximum depth by hydraulic digger, then test bores may be required. However, the costs of test boring are rarely justified for grassland farming and the likely costs of drainage are high as relief wells may have to be employed. The test pits can be used to establish the boundary conditions and to measure hydraulic conductivity.

Test pits dug by hydraulic digger are a quick and fairly inexpensive way to define the boundary conditions of a drainage problem. They are essential in the design of drainage systems in any area at least until sufficient knowledge of the distribution of problems is available to predict the problem type. Wheel-driven diggers, which are widely available in Ireland, can often be used specifically to dig test pits to sufficient depth in summer. Sometimes test pits can be investigated while a site is being cleared for drainage. Where necessary, hydraulic diggers on tracks must be used. The cost of investigating test pits in most drainage jobs is usually less than 10% the cost of carrying out the drainage works.

While no seepage was found on the study site, the geohydrological framework suggests that it may be a significant component in some drainage problems in the valley of the River Maine and indeed is in many similar areas. Additional measurements with piezometers are then required to construct flow nets from which the additional rainfall factor equivalent of the seepage can be derived. In Ireland drainage jobs are small and usually confined to part of a farm; and estimates of the seepage often have to be made taking into account the uphill catchments to minimise costs.

The pit-bailing test is a cheap and rapid means of determining hydraulic conductivity of the soil layer. With care the bailing can be done by using the bucket of an hydraulic digger on tracks while in many areas small pumps are widely available.

Although not employed in the study, the pit-bailing test can be used to determine the hydraulic conductivity of the upper layer as well as of the sandy gravel lower layer. It is recommended as an inexpensive method. Aquifer pumping tests are expensive and time consuming. They can only be justified for experimental use where it may be necessary to classify an aquifer and determine its storage co-efficient. Auger-hole, piezometric and laboratory permeameter methods of measuring hydraulic conductivity cannot be used in most Irish agricultural soils which are stony.

When drainage problems are properly diagnosed and the parameters measured, it is possible to carry out sensitivity analyses on spacing. In this way it may be possible to estimate what the magnitude of the farm management penalties might be by increasing the drain spacing by certain increments to minimise cost. Since, as in the valley of the River Maine, some farmers are in drystock farming, they may be unable to pay the high costs of intensive drainage and may accept a less intensive spacing. Intensive dairy farming requires the best ground conditions that can be provided and should be allocated a high factor of safety.

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