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The design, construction and testing of a horizontal wellpoint in a dune sands aquifer as a water source

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Abstract
A horizontal wellpoint has been constructed to supply irrigation water to a golf course from a coastal dune sands aquifer. The source provides the required quantities with relatively limited drawdown compared with what would be expected from a conventional vertical wellpoint system. Pumping test data have been analysed using a curve fitting method based on parabolic isochrone curves. The resulting values for the aquifer characteristics fall within their anticipated range.

Introduction
The Southport and Ainsdale Golf Club (S&A) has a traditional links golf course located on part of the sand dune belt that runs along the Sefton coast between the Mersey and Ribble Estuaries (Fig. 1). These dune sands form a minor aquifer used by several golf clubs in the area including S&A as a source of irrigation water and it also supports a number of important wildlife habitats.

Habitat conservation considerations
In 1995, English Nature designated the Sefton coastal belt as a candidate Special Area of Conservation (cSAC) in terms of the EC Habitats Directive (Council of European Communities 1992) and the various UK habitat protection regulations (UK Government 1994, 2000) because it hosts species and habitats of European importance. A number of these habitats are wetland areas or water dependent habitats. These features include seasonal ‘wet slacks’ or valleys between the sand dunes where the winter level of the water table is high enough to form pools; and ‘dry slacks’ where the water table never rises above the ground level although the shallow water table plays an important role in habitat support. The wet slacks form suitable breeding

conditions for Natterjack toads and various species of newts, and provide growing conditions for several rare plant species.

The habitat protection regulations (UK Government 1994, 2000) require all permissions that regulate activities including water abstractions, to be reviewed in terms of the potential impact on protected habitats. The Environment Agency (EA) has a policy statement regarding such reviews (Environment Agency 2001) under which the EA carries out investigations to gather sufficient data for the review to be completed. The EA's North West Region carried out such an investigation along the Sefton coast dunes aquifer that involved the construction of a number of boreholes and the construction of a numerical groundwater model as a consultancy project (Entec 1999).

Water supply needs

S&A needed to increase its water supply for a new irrigation system for the tees, greens and fairways to encourage grass growth in areas of high wear. The system is computer-controlled to limit water application to meet measured water needs in each part of the course, thereby minimizing both the use of water and pumping costs. The Club has a Countryside Stewardship agreement with the Department of the Environment, Food and Rural Affairs (DEFRA) for the management of the dune heath habitat and a strategy to conserve the dune environment and minimize environmental impacts that includes avoiding over-irrigation and the selection of appropriate native grass species. The irrigation water abstraction was originally from a lagoon excavated below the water table, but this source had a limited yield and problems of both safety and maintenance. It was also located on the western side of the course, closest to the area of wet slacks. It was decided therefore to apply to the EA for permission to construct a new source that would minimize these problems.

The EA was unable to give permission to construct and test a new source in advance of the completion of its own investigation and asked S&A to complete an investigation of the groundwater conditions in the vicinity of the golf course to support the licence application. A network of observation wells was installed to monitor groundwater levels and these data along with geological information, were used to construct a conceptual model of the local hydrogeology. A steady-state MODFLOW model was used to assess the potential environmental impact, which showed that the proposed increased abstraction was unlikely to affect the water dependent natural features in the area (Longstaff & Brassington 1998).

Options for improved water supply

The anticipated limited thickness and moderate hydraulic conductivity of the dune sand aquifer militated against the use of a conventional borehole water source as the relatively shallow borehole depth was not likely to yield sufficient to meet the S&A's needs. An alternative groundwater source sometimes used in shallow sand aquifers is the wellpoint system, consisting of lines or groups of shallow wells (known as wellpoints), which are pumped by a suction pump via a common header pipe (Driscoll 1986).

It was initially proposed to replace the lagoon with such a conventional wellpoint system, which was later changed to a horizontal wellpoint during the course of project for the reasons discussed below. This paper describes the design considerations for the horizontal wellpoint and both the pumping test carried out and its interpretation (Brassington 2000).

Hydrogeological background

The coastal dunes extend from south of Formby Point for some 15 km to the north of Southport and vary in width from about 4 km near Formby to about 2.5 km near Ainsdale (Fig. 1). They consist of a series of ridges and intervening valleys (or slacks) that run parallel to the coast with the highest point being about 25 m above Ordnance Datum (AOD). On the Southport and Ainsdale golf course the highest point is about 15 m AOD.

The dunes are of recent origin and were formed by sand wind-blown from the west. Consequently, the sand deposit both thins and becomes progressively more fine-grained to the east. In the Ainsdale area, the eastern limit of the sand deposit approximates to the Sandy Brook, which also forms the eastern limit of the urban development and runs along the boundary between the sands and the peat moss to the east.

The dune sand sequence includes peat layers as the remnants of vegetation in former wet slacks since filled by blown sand. The lenses are expected to be a few metres wide and to extend over several hundred metres in a direction parallel to the dune ridges. Such peat layers range in thickness from a few centimetres to more than a metre. An EA observation borehole (used as a monitoring point during the pumping test) was drilled at a recreation ground close to the eastern boundary with the S&A golf course. A thin peat layer was encountered at a depth of about 9 m in this borehole that penetrated mainly fine-grained sand to its full depth of 17.5 m. A very thin layer of peat was also encountered in the hole excavated during the construction of the horizontal wellpoint.

A geophysical survey using ground probing radar methods carried out by Neal (1999) demonstrates that the western half of the dune deposits overlie older beach deposits and the eastern half is on top of an extensive peat deposit that is an extension of mosses further inland that overlie marine and freshwater silts and clays with peat layers. These post-glacial materials in turn overlie glacial till at depth.

The water table across the dune sands is shallow, ranging in depth from 700 mm to 2.2 m. The elevation of the water table across the golf course has been defined by measurements in the observation wells network (Fig. 2). Each observation well comprises 19mm diameter screw jointed steel pipe fitted with a permeable piezometer tip. They were installed by dynamic driving methods to depths of 4–9 m. Groundwater levels collected at the Ainsdale Sand Dunes National Nature Reserve and in the EA observation boreholes show that there is a groundwater divide in the dune sands aquifer running parallel to the coast about 1.5 km inland. Consequently, the groundwater flow on the western side of the divide is seaward and that on the eastern side discharges into the local watercourses. In the Ainsdale area the groundwater divide lies to the seaward side of the Liverpool–Southport railway that forms the western boundary of the S&A golf course. Significantly, the wet slack areas that are important to nature conservation lie in the western area and the S&A abstraction point lies in the area that drains to the east.

The groundwater ridge has been modified into a series of mounds by the effects of urban development over part of the aquifer that occurs in two ways. Firstly, paved areas and drains divert water to local streams thereby reducing recharge. Secondly, groundwater flow rates will be enhanced by the backfill material in service trenches (water, gas and sewer pipes, and electricity and telephone cables), which is both less compact and coarser than the natural sand making it more porous and permeable than the natural ground. The groundwater modelling by Longstaff & Brassington (1998) showed that these artificial influences are important factors affecting the present groundwater flow system.

The groundwater hydrographs (Fig. 3) show an annual fluctuation in the range 75–50 cm and are similar to those measured by the 25 year long record at the Ainsdale Sand Dune National Nature Reserve (Longstaff & Brassington 1998).

Horizontal wellpoint system

A horizontal wellpoint consists of a perforated drainage pipe installed horizontally below the water table and connected to a suction pump (Fig. 4). These systems are used in dewatering schemes for civil engineering construction as an alternative to vertical wellpoint installations (Cashman & Preene 2001; Preene *et al*. 2000). The use of a horizontal wellpoint as a permanent water source is unusual and no other UK examples are known. Pyne (1994) reports that horizontal well technology for water supplies is relatively new with some examples in the USA having been in successful operation over five-year period.

Horizontal wellpoints are commonly installed using crawler-mounted trenching machines equipped with a continuous digging chain. As the machine tracks forward, a vertical sided trench about 225 mm wide is cut to depths between 2 and 6 m. A reel of flexible perforated drainage pipe feeds through the boom supporting the digging chain and is laid in the base of the trench. One end of the pipe is unperforated and is brought to the surface to be connected to a suction pump. For basic installations the spoil from the trench is allowed to fall back into the excavation and cover the drainage pipe. However, in many cases the hydraulic performance of the pipe can be improved by placing a more permeable filter material as a gravel pack around the pipe. This can be achieved by deflecting the spoil away from the trench, and placing the filter media into the excavation from a special hopper mounted on the trenching machine.

A horizontal wellpoint is hydraulically efficient because it has a very large screen area, and horizontal flow will be planar to the sides of the perforated pipe. This contrasts with flow local to a vertical wellpoint system, where flow lines converge radially to each wellpoint, resulting in greater drawdowns. The reduced drawdown with horizontal wellpoints will result in minimal environmental impacts to groundwater dependent habitats as well as lower pumping costs. Small flow velocities mean that the fine particles in an aquifer are less likely to be mobilized and drawn to the screen, thereby reducing the risk of clogging and significantly extending the life of the system.

Design of horizontal wellpoint system

The horizontal wellpoint option was chosen to take advantage of these operational and limited impact benefits. A further important advantage is the limited visual impact of the source works. In a conventional wellpoint system, the top of each wellpoint extends above ground level and is attached to a header main that runs along the ground surface. This contrasts with a horizontal wellpoint, which has no above-ground works other than the pump and therefore can be located below landscape features.

Horizontal wellpoints are usually employed to control groundwater in construction work where only a limited operating life is required and the long-term efficiency of the system is not important. In this case however, the system is used as a water source and an operating life of several decades is required, demanding a much greater level of design consideration. Fine-grained and well-sorted aquifers such as the dune sands at the S&A site pose practical difficulties in conventional well design as the optimum gravel pack has a limited range of grain size. This requires careful specification of both the grain size of the gravel pack and the slot size for the screen perforations to avoid sand pumping or the screen becoming clogged. In the absence of a generally accepted method to determine the need for, and the design of, a gravel pack round a horizontal well point, it was decided to adopt the method for conventional tubewells originally proposed by Backiewicz *et al*. (1985) and further developed by Clark (1988). The method uses the particle size distribution curve for the aquifer material to construct an envelope defined by four- and six-times the aquifer grain size to delineate that for an ideal gravel pack. This method is a practical approach that provides latitude in the pack specification allowing flexibility in the choice of a suitable commercially available sand.

Particle size distribution curves were obtained for three sand samples obtained from the EA borehole close to the S&A course (Fig. 5). These all showed a similar well-sorted fine grained sand with 90% of the material falling in the range 150–300 µm. The uniformity coefficient (or coefficient of sorting) defined as D_{60}/D_{10} (Clark 1988) is about 0.22/0.15 = 1.47 demonstrating a very high degree of sorting. Values less than 2.5 indicate well-sorted materials and normally require an artificial gravel pack round the screen in a conventional well design.

An envelope for the gravel pack specification was constructed following the method described by Clark (1988) and used to select a commercially available well-sorted, coarse silica filter sand. It is important only to use silica sands for a gravel pack as other materials may cause the pack to deteriorate and significantly change the hydraulic design of the well. The extremely well-sorted nature of the aquifer sand imposed severe difficulty in locating a similarly well-sorted commercially available filter sand. It was necessary to compromise and use the closest available sand that was slightly finer than the design envelope in the coarsest 50% of the material. It was judged that these differences are small and would not cause disadvantages to the effectiveness of the pack material.

For practical and cost reasons it was decided to construct the horizontal wellpoint using standard land drainage pipe. The pipe used is made of corrugated plastic with a diameter of a 160 mm, a slot size of 2 mm and was factory-wrapped in Terram 1000 geotextile with a pore size of 150 µm. This pore size equates to the D_{10} size of the aquifer material and is smaller than the recommended slot size for the gravel pack (Clark 1988). However, in view of the difficulty in placing a layer of filter sand completely around the pipe, it was decided that a cautious design should be adopted and the smaller pore size used.

Installation of horizontal wellpoint system

The location of the horizontal wellpoint is shown in Figure 6. The pipe was installed with the deep trenching machine seen in Figure 7 being positioned to start the construction with its cutting head positioned in a 1.9 m deep temporary excavation and the digging boom extended for the initial trench depth of 6.5 m. The horizontal wellpoint then runs sub-horizontally for some 150 m to the S–SE where it turns through some 65o to the north and runs in a northeasterly direction for a further 130 m. The depth of burial gradually decreases along the length of the horizontal well point and is some 4.5 m at the change point and some 4 m depth at the furthest end. This installation was completed in less than two hours. The installation of the drainage pipe caused a significant disruption along the line of the trench as can be seen in the second photograph (Fig. 8). The sides of the trench collapsed resulting in lateral tension cracks running parallel to the trench and the mounding of the excavated spoil. The effects of the resulting increased porosity can be seen in the pumping test analysis (see below).

Water is abstracted from the horizontal wellpoint by means of a top delivery, centrifugal self-priming suction pump driven by an electric motor installed in a chamber constructed at the starting point seen in Figures 6 and 7. The control panel and switches are housed in the nearby Greenkeeper's shed along with the control gear for the irrigation system. During operation water will be delivered to the adjacent water tank by the pump that is controlled on float-switches as part of the computer-controlled irrigation system.

Pumping test

A programme of test pumping (Table 1) was carried out on the horizontal wellpoint to establish the yield and to provide data to support the abstraction licence application.

The effect on groundwater levels was monitored in the observation well network across the course and a series of specially constructed observation wells close to the horizontal wellpoint. Three rows were installed at right angles to the horizontal wellpoint, one at each end and the third near the centre, in line with the EA's observation borehole. The depths and spacings are summarized in Table 2 and the locations are shown on Figure 6. During the test, the water was discharged into the former abstraction lagoon some 200 m to the SE that allowed it to soak back into the aquifer without influencing the test results. Groundwater level measurements in observation wells near the lagoon demonstrated that there was no recirculation effect.

A four-hour pumping trial was carried out one week before the test to check the equipment and observation well responses. Some 303 m^3 was abstracted with an average pumping rate over the last three-hours of 79.8 m^3/hour. The water was discharged over scrubland some 30 m from the wellpoint. The water initially contained small amounts of silt/clay and cleared after a few minutes. Subsequent operational experience shows that the water is coloured when pumping recommences after a long period of rest. The colouration is due to small quantities of ochre derived from iron oxides in the dune sands.

The average pumping rate for the main 72-hour pumping test was 46.25m^3/hour although for the majority of this period some 46.75m^3/hour was achieved, indicating that there was some development of the source during the early part of the test period. The pumping rate was less than that in the earlier pumping trial due to head losses in the 300 m delivery pipe to the lagoon. The recovery in water levels was measured for some 18 days following the cessation of pumping.

Pumping test data

The data collected during the test are principally the water level measurements from the observation well network and the EA's observation borehole. They have been scrutinized to evaluate the aquifer behaviour and assess the hydraulic conductivity and storativity.

Non-pumping conditions

Groundwater levels measured in the observation wells close to the horizontal wellpoint conform to the general pattern across the course (Fig. 2) with a hydraulic gradient to the SE. At Row C however, there is a reversal of the gradient on the southern side of the horizontal wellpoint indicating that the buried pipe is acting as a drain in this vicinity. Measurements show a head difference of 0.46 m between Row A and Row B with the gradient towards Row B and a head difference between Row C and Row B of 0.045 m, again with the gradient towards Row B. The horizontal wellpoint is sub-parallel to the groundwater contours and extends a short distance in the down-gradient direction. As a result, the horizontal wellpoint has the potential to act as a drain under non-pumping conditions with the flow towards the central area near Row B. Flow rates are expected to be small, as they will be controlled by the hydraulic conductivity of the sand.

Time-drawdown data

The drawdown in the close proximity observation wells varied generally in accordance with the distance from the horizontal wellpoint pipe and also with their proximity to the pump (Fig. 9). The greatest drawdown was 1.10m in C3, which lies above the horizontal wellpoint on the line closest to the pump. The least drawdown was observed in the observation wells furthest from the horizontal wellpoint.

Examination of the EA observation borehole record (Fig. 10) shows that pumping from the horizontal wellpoint is detected almost as soon as it commences. The data do not allow the precise time to be determined although it appears to be immediate. Such a rapid response is anomalous as it indicates that the aquifer is behaving in a confined manner despite the absence of any confining stratum. It is considered likely that the effects of dune bedding will result in an extreme anisotropy, with a significant contrast in the hydraulic conductivity in the vertical and horizontal directions. This effect is amplified by the fact that the borehole fully penetrates the aquifer and encounters all the layers that have low vertical permeability values. Subsequent methods of analysis assumed confined behaviour under the influence of pumping

The maximum drawdown from the proposed new abstraction can be estimated by the extrapolation of the semi-log plot of the drawdown data. The daily pumping rate during the test was equivalent to 2.6 times the rate proposed in the licence application and if this were to be continued for some 24.3 days (c. 3.5×10^4 minutes) the total volume removed would be equivalent to the proposed annual quantity. By extending the drawdown plot for C3 the drawdown after 3.5×10^4 minutes is estimated to be less than 1.5 m. The observation borehole data (Fig. 10) shows a drawdown of some 0.435 m during the test. When the data are plotted on a semi-log scale the drawdown after 3.5×10^4 minutes is estimated to be about 0.8 m.

Recovery data
The later part of the recovery phase coincided with the commencement of an unusually wet period that caused the groundwater levels to rise to elevations much higher than those at the start of the test as can be seen from the latter part of the observation borehole hydrograph (Fig. 10).

Pumping test analysis
The standard methods for analysing pumping test data from conventional wells are described in textbooks (e.g. Kruseman & de Ridder 1990) and include the steady-state equations of Thiem and Dupuit, and the non-steady state methods such as Theis and Cooper-Jacob. A basic assumption for all these analytical methods is that the flow to the vertical well is radial. On the other hand, a horizontal wellpoint is effectively a long, pumped drain and therefore groundwater flowing towards it will be planar and perpendicular to the line of the pipe. Flow lines will generally be parallel, and will not exhibit the radially converging flow pattern that occurs around wells. Consequently, the conventional methods of analysis are not applicable to the data set collected during this pumping test.

Water flow models for planar flow, analogous to the flow towards the horizontal wellpoint, exist in soil mechanics practice. The use of these models originated in the analysis of soil mechanics laboratory tests to determine consolidation parameters of soil samples. When a soil sample is compressed in an oedometer, the time dependent pore water pressure distribution in the sample can be modelled very closely if it is assumed that the pore water pressure profile at any time is parabolic in shape. This method, known as parabolic isochrone method, has been used in laboratory testing since the 1960s. More recently, Powrie & Preene (1994) applied the method to the estimation of drawdown around long lines of wellpoints, by assuming that the drawdown curve under planar flow conditions is a parabola, and obtained good correlations between field data and predicted drawdowns.

The application of the parabolic isochrone model to determine aquifer properties from wellpoint test data is an iterative process where a storativity (S) is assumed and the hydraulic conductivity (k) is adjusted to give a match between the theoretical curve and the field data. In this manner, the field data are compared to a succession of type-curves representing different values of k and S to establish the likely range for these parameters.

Time-drawdown data
Examination of the time-drawdown data in the observation points close to the horizontal wellpoint suggests that the disturbance caused by the construction of the horizontal wellpoint enhanced the permeability of the sand and these data have not been used to calculate the hydraulic properties. Several observation wells also appear to have been affected by clogging and give anomalously low results (see Fig. 9). The observation wells comprise driven tube-wells. They are relatively crude monitoring points as they do not have specific aquifer response zones delineated by bentonite seals, and were installed into the area affected by the installation of the horizontal wellpoint. They are adequate for

estimation of long-term or steady-state drawdowns, but are considered unreliable for assessment of time-drawdown behaviour. The EA observation borehole was previously installed to Agency standards, fully penetrates the aquifer and, at some 28.9 m from the horizontal wellpoint, is unlikely to be affected by the installation of the horizontal wellpoint. For the purposes of analysing time series drawdown data, the most reliable estimates of hydraulic properties are likely to be obtained from the EA borehole.

Using a hydraulic conductivity value of 7.3 m/d a good match was obtained with the late time data from the EA observation borehole (Fig. 11). This value of hydraulic conductivity, applied to the parabolic isochrone type curve, implies a distance of influence of around 70 m (either side of the horizontal wellpoint) at the end of the test.

Distance data

Distance drawdown values for Rows B and C were subjected to the same analysis. Data from Row A appears to be anomalous and has not been used. A hydraulic conductivity value of 9 m/d gave a reasonable match with the deepest observed drawdowns in monitoring Row B in the later part of the test. Some of the observation wells showed much smaller drawdowns, but it is assumed the slow response is most likely due to clogging. The drawdown values along Row C in the later part of the test imply a lower hydraulic conductivity of around 3 m/d.

Discharge rate

Back analysis of the flow implies a higher value for the hydraulic conductivity than is inferred from the drawdown data. A hydraulic conductivity of perhaps as high as 20–25 m/d is needed to be able to maintain a discharge rate of 46 m^3/hour at the end of the test. It is thought likely that the high discharge rate is strongly influenced by the hydraulic gradient that generates the regional groundwater flow caused by the horizontal wellpoint being normal to the southeasterly regional flow direction.

Discussion

The system yielded some 79.8 m^3/hour when pumped against no head and 46.75 m^3/hour during the constant rate test when pumped against an increased head during the pumping test. The wellpoint construction used commercially available materials with the selection of the filter sand around the drainpipe and the filter size of the geofabric wrap ensuring that the water system did not draw fines into the pumped water.

The yield proved to be greater than would be expected from an aquifer with the hydraulic properties assessed from the pumping test. This is attributed to the horizontal wellpoint running sub-parallel to the water table contours and the enhanced aquifer characteristics along the horizontal wellpoint caused by the disruption during construction. When the system was not being pumped, groundwater level measurements along the line of the pipe showed that there is a continuous flow along it.

The groundwater level measurements obtained during the pumping test were used to assess the hydraulic properties of the dune sands aquifer using a method based on a parabolic isochrone type-curve. The range of values obtained for the hydraulic conductivity is 3–9 m/d with the value of storativity as 15%.

Many hydrogeological textbooks provide values for these parameters based on the lithology and grain size of the aquifer materials based on the US published data (Bureau of Reclamation 1977). The dune sands at the S&A site are fine-grained and well sorted. The expected hydraulic conductivity values for fine-grained sands are in the range 5 x 10^{-1} to 10 m/d and a specific yield (storativity) value of 20–30%. The well-sorted nature of this dune sands aquifer means that the hydraulic conductivity is likely to fall at or above the upper end of the quoted range. This is consistent with values of hydraulic conductivity assessed from empirical correlations (Hazen 1892) with particle size distributions of samples of the dune sand; samples from the observation well installations imply a hydraulic conductivity of 15–20 m/d.

It is understood that another pumping test in a more westerly part of the dune sand aquifer produced hydraulic conductivity values of about 10 m/d and a storativity value of 18% (J.E. Campbell, pers. comm. 2000). These values were used to construct a parabolic isochrone curve to compare with the observed drawdown data from the EA observation borehole. Although the curves have a similar form, the fit is poor compared with the curve in Figure 11 where a hydraulic conductivity value of 7.3 m/d was assumed. The poor fit may be related to the value of storativity used. The value of 18% quoted above implies unconfined behaviour, which does not appear to be consistent with the very rapid response observed in the borehole. The lower Storativity values found at the S&A site are attributed to the fine-grained nature of the sand resulting from the generally fining-eastwards nature of the dune system.

These results are consistent with the assumed values used in the steady-state MODFLOW simulation undertaken as part of the initial appraisal covering the dune sand aquifer around the S&A site (Longstaff & Brassington 1998). A two-layered aquifer was used with the upper layer given different values of hydraulic conductivity to reflect the increased permeability caused by service trenches in built up areas. The values used were 12 m/d for the undisturbed sand and 20 m/d for the built up areas. The deeper aquifer was given a value of 3 m/d. The model generated a pattern of water table levels that matched the field data both in terms of their distribution and fluctuations.

Conclusions

The construction of the horizontal wellpoint as a source for irrigation water in a well sorted, fine-grained sand aquifer was successful. Field test show that drawdowns are low and therefore the environmental impact can be considered to be at the achievable minimum. The pumping test data have been analysed to provide values for the aquifer hydraulic conductivity and storativity using a curve-fitting technique. The resulting range of values have been compared to other data and fall within an expected range confirming that the parabolic isochrone method of analysis is suitable for the examination of data from such pumping tests.

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Table 1. *Construction and testing programme for the horizontal wellpoint (HWP)*

Date	Activity
13/9/00	Construction of HWP system
22/9/00	Completion of installation of HWP observation well array
5/10/00	Main pre-test pumping trial - about four hours pumping at 79.8 m^3/hour
13/10/00	Second pre-test pumping trial – about one hour pumping at 46.25 m^3/hour
16/10/00	Commencement of 72-hour constant rate pumping test
19/10/00	End of 72-hour constant rate pumping test – start of recovery period
6/11/00	Completion of recovery monitoring

Table 2. *Summary details of observation well array along the HWP*

Observation Well Row	Observation Wells	Spacing* (m)
Row A – depth 3.5 m – A1 over HWP	A1 – A2	4.9
Row B – depth 4 m – B3 over HWP	B1 – B2	7.25
	B2 – B3	3.0
	B3 – B4	3.1
	B4 – EA Obh	25.8
Row C – depth 6 m – C3 is over HWP	C1 – C2	12.3
	C2 – C3	2.8
	C3 – C4	2.9
	C4 – C5	12.1

Note: * spacing is distance between observation well pairs shown in column 2

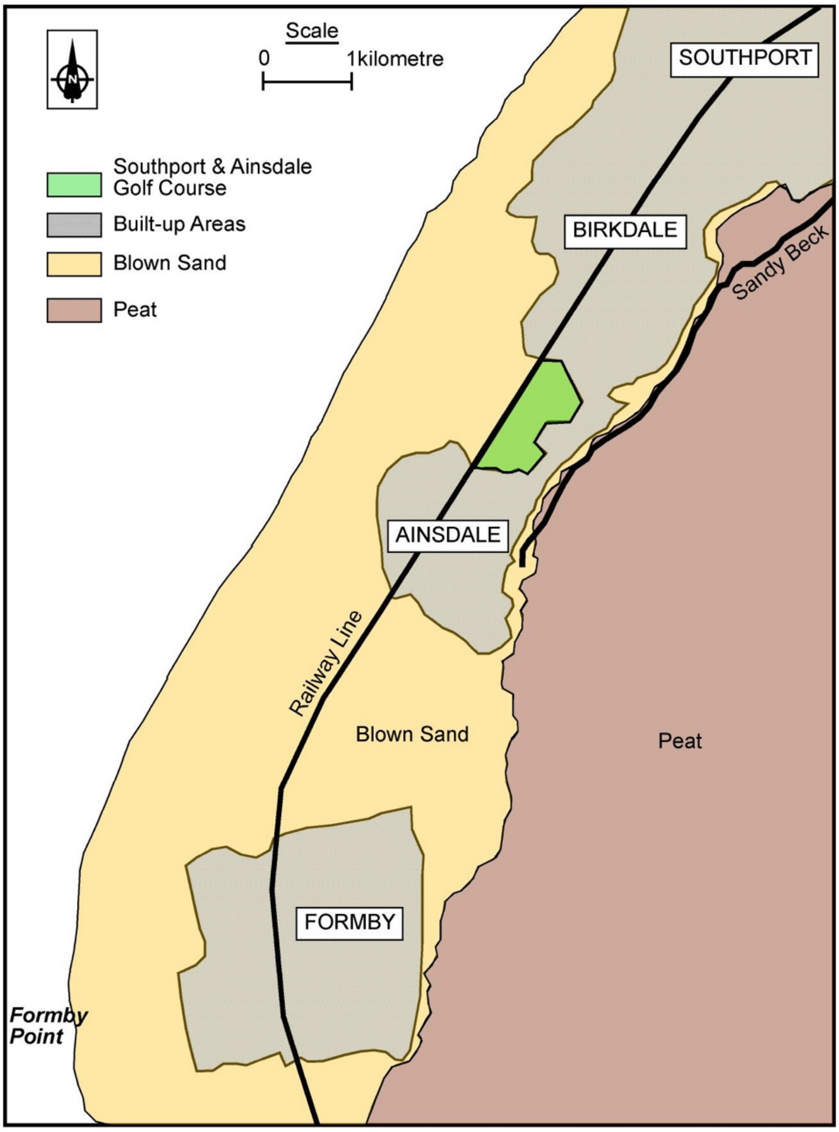

Fig. 1. Location and surface geology.

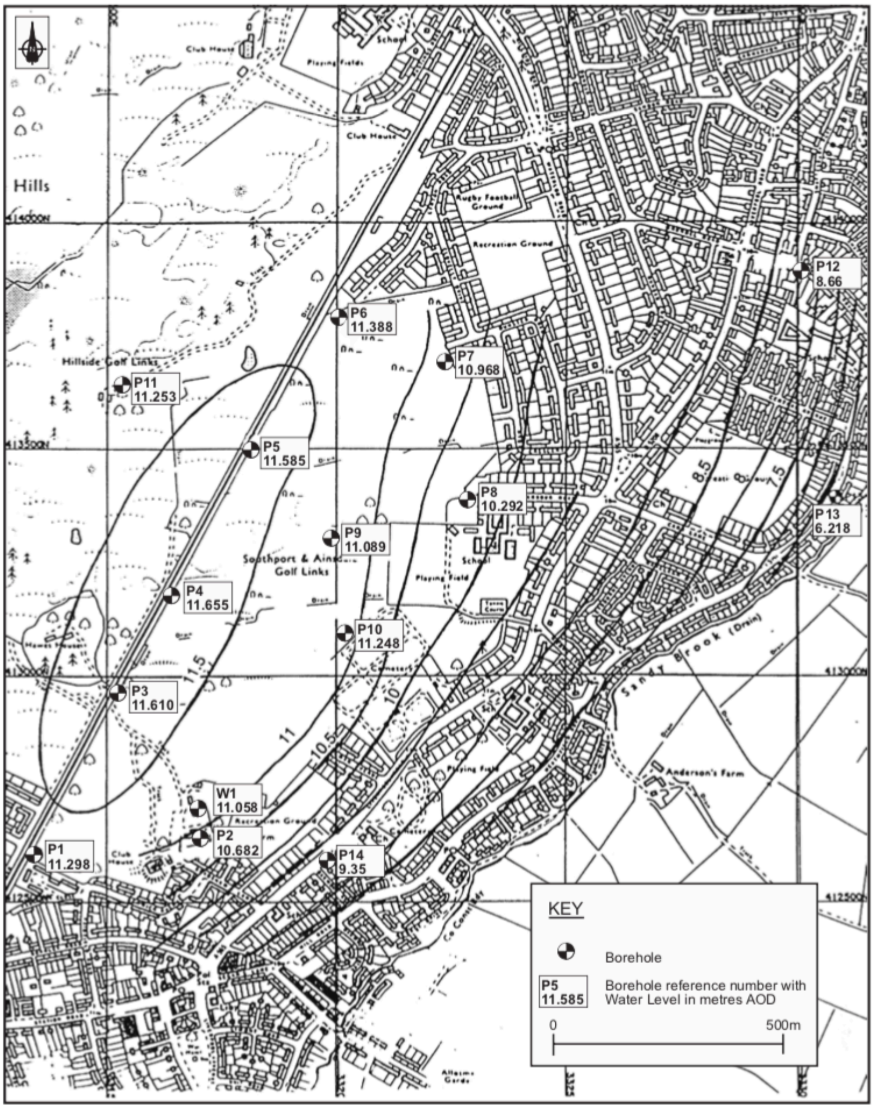

Fig. 2. Groundwater levels across the S&A golf course showing the location of observation wells. Note four wells were constructed off the golf course. (Base map © Crown copyright Ordnance Survey. All rights reserved)

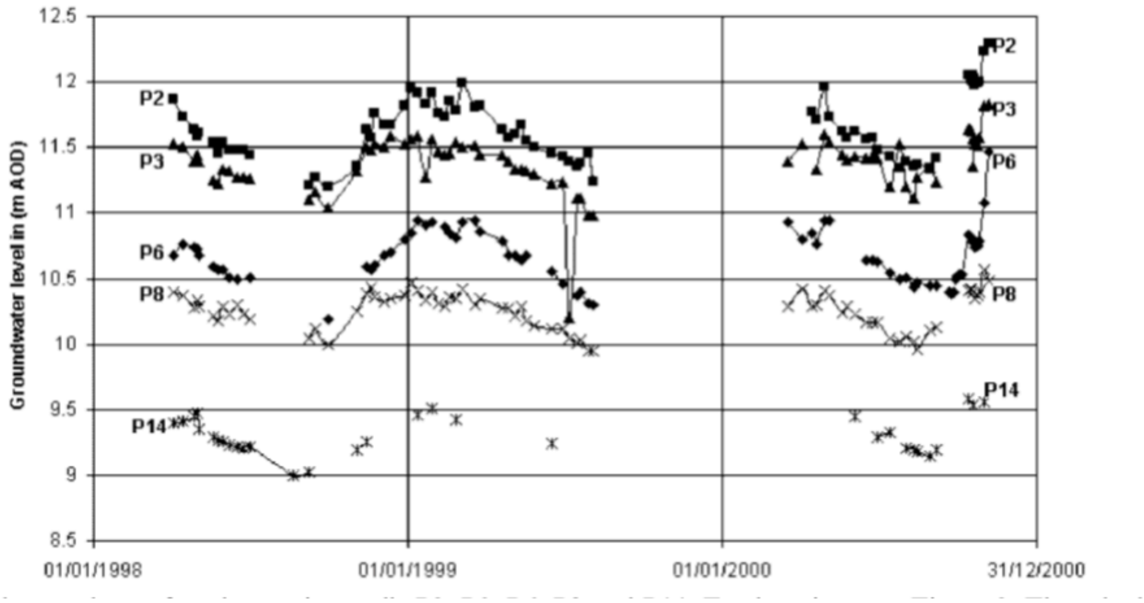

Fig. 3. Hydrographs are shown for observation wells P2, P3, P6, P8 and P14. For locations see Fig. 2. These hydrographs give an indication of the seasonal fluctuations and the changes in elevation across the area.

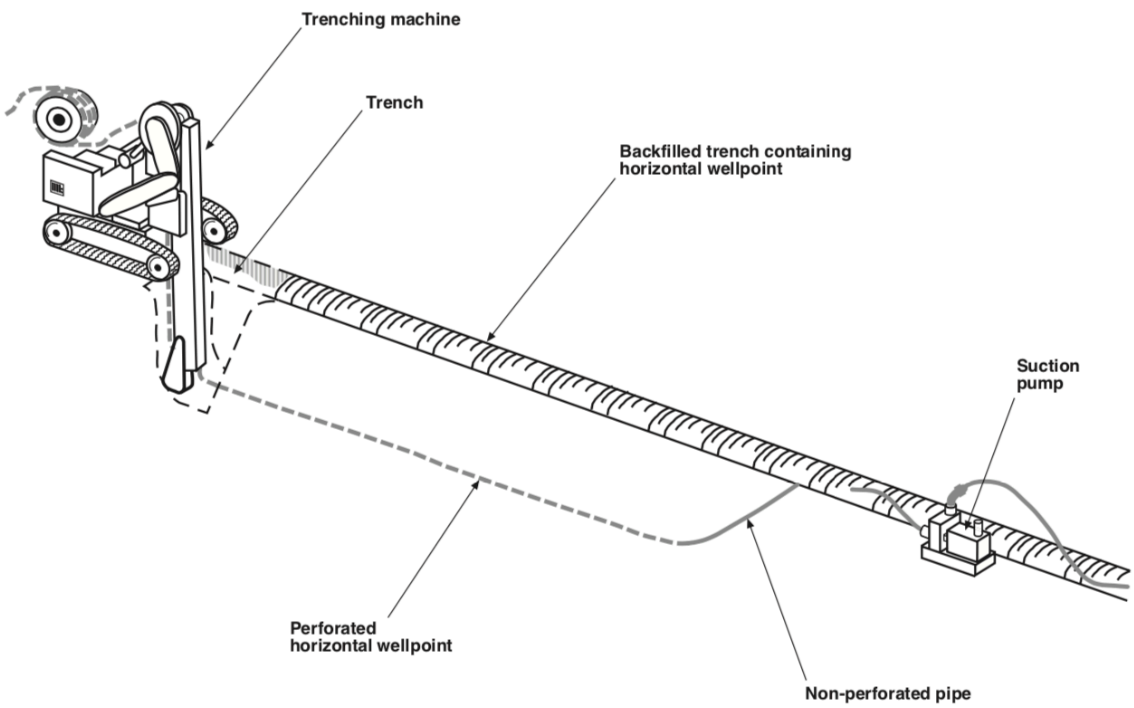

Fig. 4. Basic features of the installation of a horizontal wellpoint system (after Preene *et al.*, 2000).

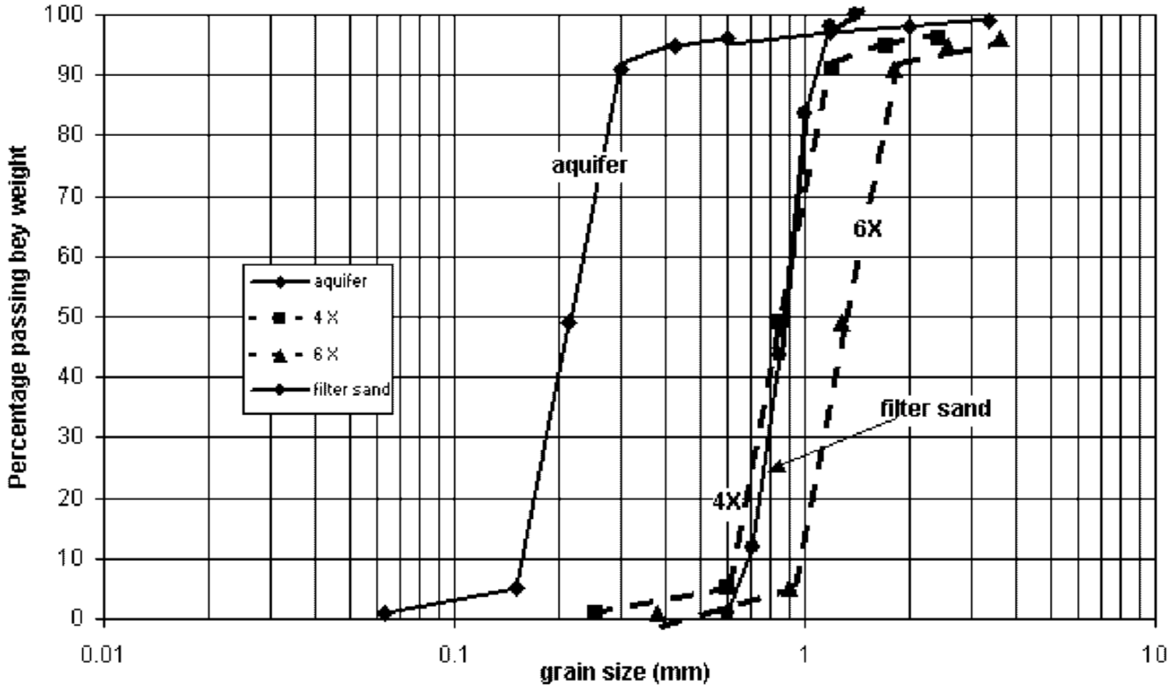

Fig. 5. Particle size distribution curve for the aquifer sand together with the envelope defining the suitable gravel pack material. The filter sand used is slightly finer than this ideal range in its coarsest part.

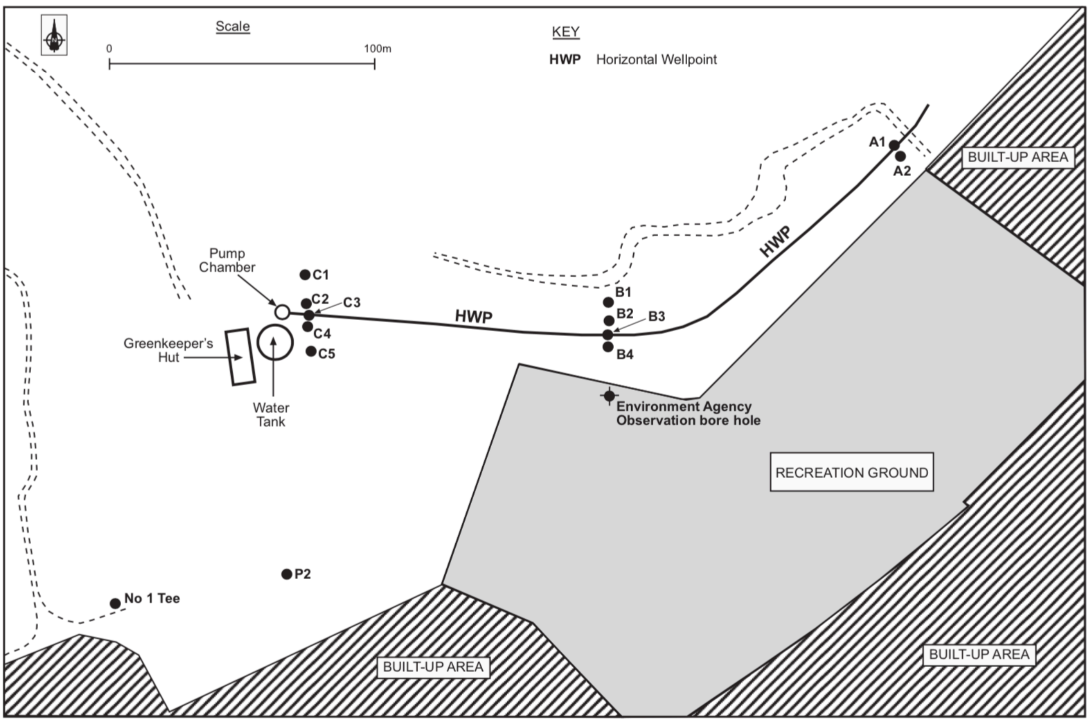

Fig. 6. The location of the horizontal wellpoint is shown with respect to the Greenkeeper's hut and the site boundary. The three rows of observation wells are shown with details of their depths and spacing given in Table 2.

Fig. 7. The trenching machine is seen as the cutting head is being positioned to commence the installation of the horizontal wellpoint with the digging boom fully extended. The continuous chain of buckets runs along the bottom of the boom with the square-section pipe feed-tube immediately above the buckets. Operators can be seen feeding the drainpipe into the funnel on the top of this feed-tube. A second, larger guide-tube lies on top of the assembly to feed filter sand on top of the pipe as it is guided into the bottom of the trench. The filter sand is stored in the large hopper at the top of this feed-tube. The initial length of unperforated drainpipe can be seen extending out of the bottom of the digging boom assembly and has been secured to a stake (out of shot) so that it remains at the surface at the pump end of the horizontal wellpoint. The suction pump was installed at this end of the pipe with water pumped into the adjacent storage tank on the right of the picture.

Fig. 8. The trench is being excavated to 6m depth. The wet sand spoil forms a lateral mound along the centre line of the trench and the original ground surface sags with lateral tension cracks running along each side about 1.5 m from the centre of the trench. Once the pipe installation had been completed, the mound was flattened filling the collapse feature.

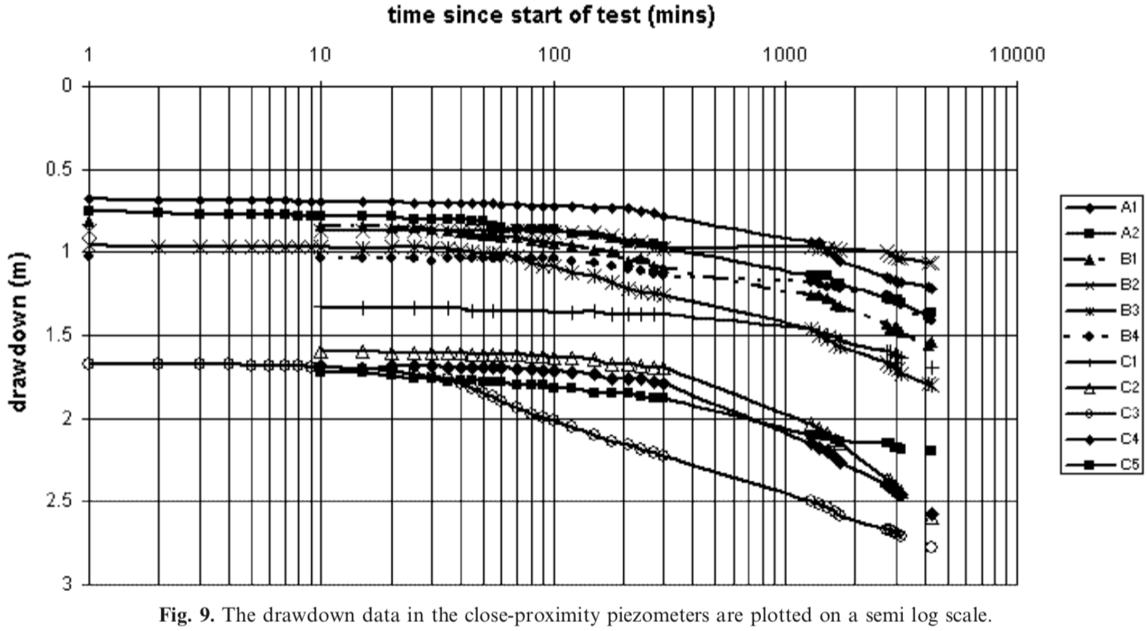

Fig. 9. The drawdown data in the close-proximity piezometers are plotted on a semi-log scale.

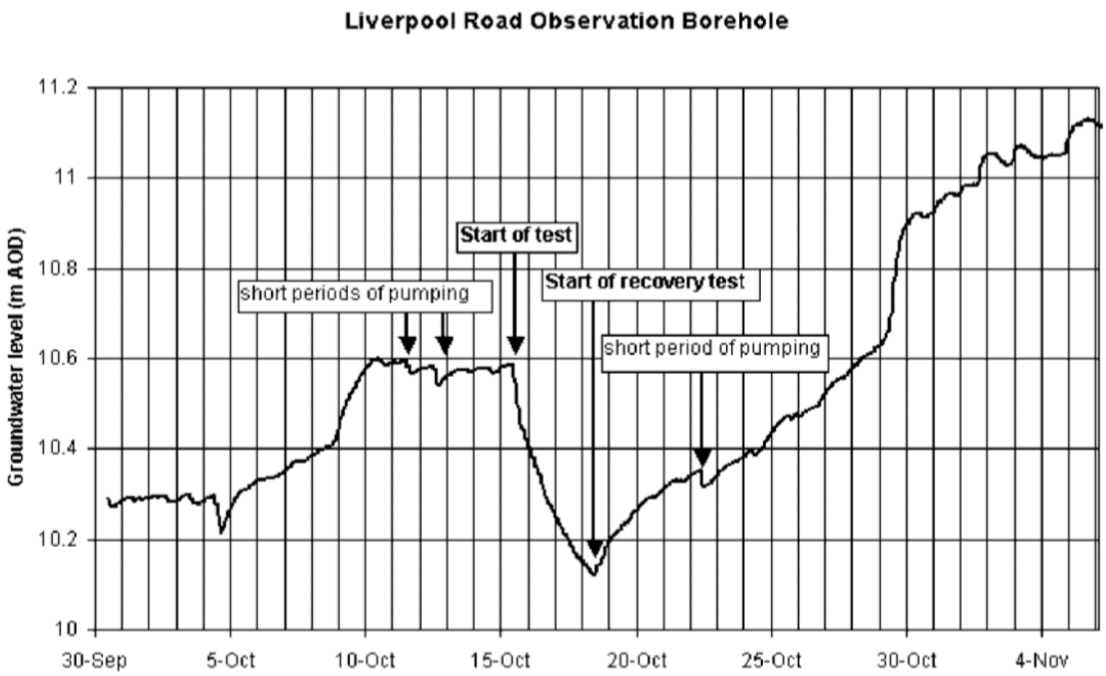

Fig. 9. Groundwater levels recorded in the Environment Agency observation borehole at the recreation ground on Liverpool Road, Ainsdale. The hydrograph shows drawdown caused by the two short pre-test pumping periods as well as the drawdown and recovery from the 72-hour test. The recovery also reflects recharge from heavy rain following the pumping period and a short pumping period on 25 October.

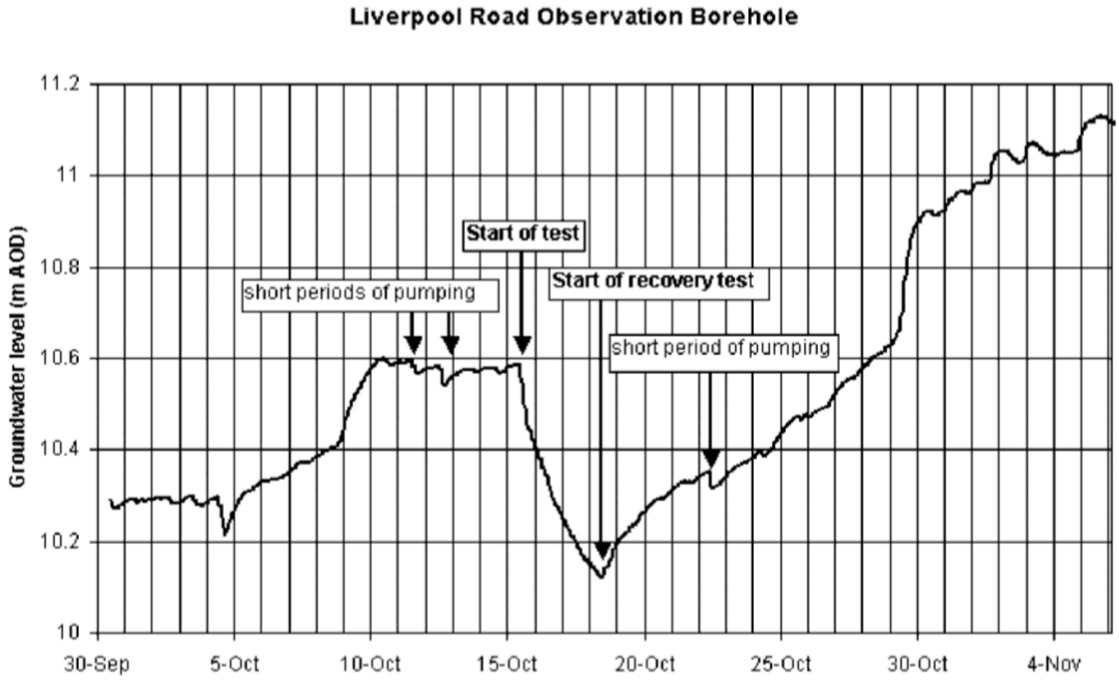

Fig. 10. The drawdown data from the observation borehole are compared with a type-curve for k = 7.3 m/d and S = 0.15. These values gave the closest fit with the observed data.