

Pumping from unconfined aquifers of limited saturated thickness with reference to wellpoints and horizontal wells

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Abstract Groundwater in unconfined aquifers of limited saturated thickness can be a valuable resource but frequently it is not developed because conventional boreholes are unsuitable. However, successful exploitation of shallow unconfined aquifers has been achieved using either a line of wellpoints or horizontal wells extending for more than 100 m. The flow processes by which wellpoints and horizontal wells collect water from unconfined aquifers are explored by developing conceptual and computational models. Several representative examples are considered and it is found that similar discharges occur if the wellpoints are closely spaced. The sensitivity of the yield to physical dimensions of the wells and aquifers is explored; the impact of alternative aquifer parameters is also examined. Results from these computational models are used to identify the causes of air entry into wellpoint systems; the prevention of air entry into horizontal wells is also considered. This evaluation demonstrates that wellpoint systems and horizontal wells can efficiently abstract water from unconfined aquifers of limited saturated thickness provided that precautions are taken to prevent air entry.

Keywords Horizontal wells · Wellpoints · Shallow aquifers · Conceptual models · Numerical models

Introduction

Unconfined aquifers of limited saturated thickness receive only limited attention in the literature, yet these aquifers often receive substantial recharge and can therefore deliver a valuable resource of water provided that appropriate techniques are selected for groundwater abstraction. Furthermore, these aquifers may provide the only source of water in some areas. Standard texts include comments such as Fetter (2001) “An unconsolidated deposit must extend more than 10 m deep to be useful for water supply”. Todd and Mays (2005) explain that “Subsurface conditions often preclude groundwater development by normal vertical wells. Such conditions may involve aquifers that are thin, poorly permeable, or underlain by permafrost or saline water.” They also suggest that “in developing areas of the world, the cost of constructing a horizontal well may be far less costly than drilling a vertical well.” An informative report by Barry et al. (2010) illustrates different methods of exploiting aquifers of limited saturated thickness in Ghana.

For normal vertical wells with a submersible pump, the inlet screen (perforated casing) is usually located below the pump; the length of the pump plus the screen is generally 5 m or more (Price 1996; Todd and Mays 2005). Since the pumped water level should be above the submersible pump, pumped drawdowns are severely restricted in unconfined aquifers of limited saturated thickness. Even if a suction pump is used with the inlet pipe extending below the well water level, the presence of a seepage face means that the pumped water level is a substantial distance below the aquifer water table, resulting in a restricted discharge (Rushton 2003).

Although “normal vertical wells” may not be suitable for groundwater development, Raghunath (1987) explains how wellpoints can be driven up to 10 m into unconsolidated aquifers with four or more wellpoints spaced 8–16 m apart connected to a single pump and used for irrigation. A further

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practical example of the successful exploitation of a shallow aquifer is described by Mailvaganam et al. (1993). Two alternative methods were considered for abstracting water from this coastal aquifer with a saturated thickness of 5 m. The conventional approach involves clusters of low-yielding vertical wells each cluster having its own suction pump; however, the alternative approach of a horizontal well proved to be effective. Additional examples of the successful exploitation of aquifers of limited saturated thickness are summarised by the Central Ground Water Board (2004); for example in Kerala State, India the weathered zone of crystalline aquifers, shallow tertiary sediments, laterite aquifer in valleys and shallow alluvial aquifers provide yields of 2–35 m³/d using dug wells and shallow borewells.

During a detailed investigation of a horizontal well in a dune sand aquifer in northwest England (UK) (Rushton and Brassington 2013a, b) the question was posed about the use of wellpoints as an alternative to horizontal wells. A preliminary comparison reported in Rushton and Brassington (2013a) concluded that further field and modelling investigations were required to explore this question; these investigations are described in this study.

This paper explores how groundwater can be abstracted from unconfined aquifers of limited saturated thickness. Initially four field examples are reviewed

briefly including vertical wells, large diameter wells, wellpoints and horizontal wells. It is apparent that lines of vertical wellpoints or horizontal wells are viable alternatives to dug wells or conventional boreholes. The merits of these alternatives of vertical wellpoints and horizontal wells are investigated by developing both conceptual and computational models. Representative examples are investigated in detail and the influence of conditions such as anisotropy and well loss are assessed. Certain of the practical difficulties of using wellpoint and horizontal well systems are explored with reference to the Sefton Coast sand dune aquifer of northwest England (Brassington and Preene 2003). A critical issue is the existence of hydraulic heads which are below atmospheric pressure in both wellpoint and horizontal well systems.

Field examples

Four field examples illustrating a range of approaches to the exploitation of unconfined aquifers of limited saturated thickness are reviewed. These particular examples are selected because information about their operation is available (see Fig. 1 and Table 1). The first example (Fig. 1a) refers to the high

Fig. 1 Field examples of exploitation of an unconfined aquifer of limited saturated thickness: **a** vertical well with submersible pump in gravel aquifer, **b** large diameter well in weathered zone, **c** wellpoints in sand dune aquifer, **d** horizontal well in sand dune aquifer

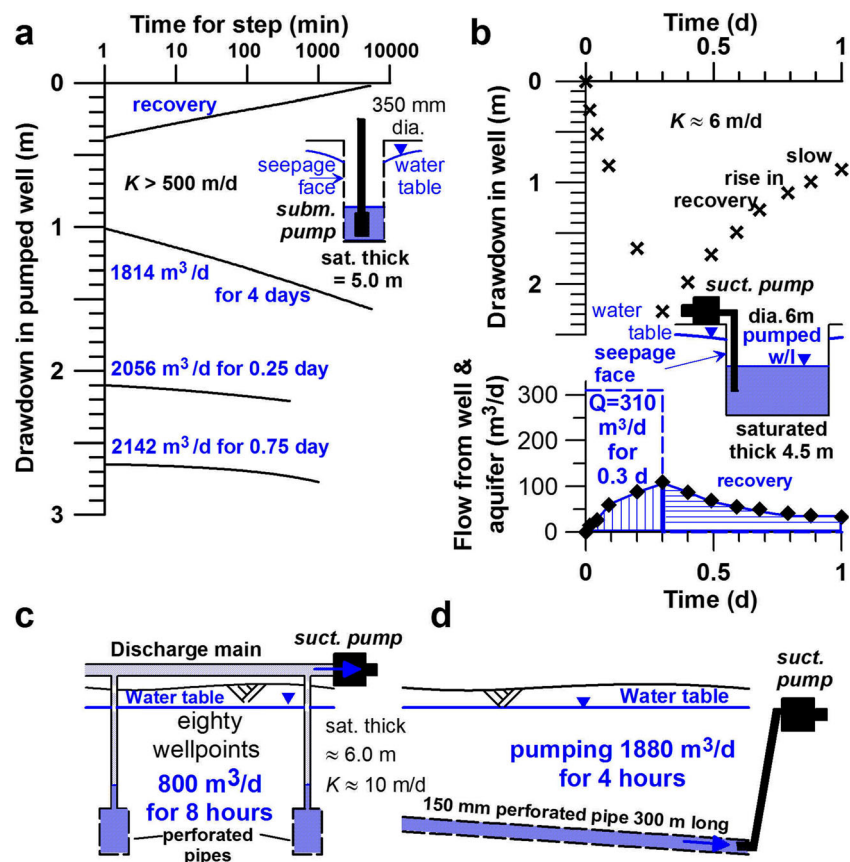


Table 1 Details of important features of field examples of abstracting water from shallow aquifers of limited saturated thickness

Example ID	Example	Well diameter or length/ saturated thickness	Hydraulic conductivity (m/d)	Typical discharge	References	Comments
a	High-permeability aquifer	350 mm/5 m	>500 m/d	1,800 m ³ /d	Rushton and Booth (1976)	Single well not suitable for high permeability
b	Large diameter well	6.0 m/5 m	6 m/d	310 m ³ /d for 7.2 h	De Silva and Rushton (1996)	Ideal for irrigation
c	Wellpoints	0.15 mm, 80 wellpoints at 2.0 m/≈ 6 m	≈10 m/d	800 m ³ /d for 8 h		Each wellpoint needs careful adjustment
d	Horizontal well	300 m long/≈ 6 m	≈10 m/d	1,880 m ³ /d for 4 h	Rushton and Brassington (2013a, b)	Reliable yield in shallow aquifers

permeability Yazor Gravels aquifer in Herefordshire, UK; the hydraulic conductivity is estimated to be more than 500 m/d (Rushton and Booth 1976; Rushton and Redshaw 1979). With a saturated thickness of only 5 m, drawdowns in the pumped well are limited due to the need to have a sufficient depth of water over a submersible pump. Test pumping provided a discharge of 1,814 m³/d for 4 days (Fig. 1a). Recovery, with a rise in well water level from 2.75 to 0.3 m in the first minute, indicates that there are significant well losses mainly due to the seepage face. This example indicates the shortcomings of a single well with a submersible pump in highly permeable unconfined aquifers of limited saturated thickness.

The second example is concerned with a large diameter well in the weathered zone of an aquifer in Sri Lanka which provides water for irrigation (De Silva and Rushton 1996). The well has a diameter of 6 m and an initial saturated thickness of 4.5 m (Fig. 1b). Following test pumping, the water level in the well was 2.4 m below the original water-table elevation. After the pump was switched off, the water level in the well rose slowly due to groundwater continuing to enter the well after pumping ceased to refill well storage, with more groundwater drawn into the well during recovery than during the pumping period. Consequently, large diameter wells provide a reliable method of abstracting limited volumes of water from shallow aquifers (see chapter 6 of Rushton 2003; Limaye 2010).

The final two examples relate to alternative techniques for abstracting groundwater from the Sefton Coast sand dune aquifer in NW England (UK) where the water is used for golf course irrigation. One approach involves a line of wellpoints; two of the well points are illustrated schematically in Fig. 1c. A wellpoint consists of a perforated well screen, typically 1.0 m in length and up to 150 mm in diameter, with water drawn up a riser pipe to a discharge main by means of a suction pump. In part of the riser pipe and in the discharge main, pressures are below atmospheric as indicated by the light stipple in Fig. 1c. An air vessel and vacuum pump are provided to remove any air entering the system.

An alternative approach is to use a horizontal well to abstract water from the Sefton Coast sand dune aquifer (Fig. 1d). The horizontal well, 300 m long, uses a 150-mm slotted-agricultural-drainage pipe which was laid using a trenching machine at depths of 4–6.5 m (Brassington and Preene 2003). A suction pump is located at one end of the horizontal well. Groundwater heads in the aquifer and hydraulic heads in the well have been monitored—conceptual and computational models have been developed to study the interaction between the horizontal well and the aquifer (Rushton and Brassington 2013a, b). Both vertical wellpoints and horizontal wells are viable methods for abstracting water from unconfined aquifers of limited saturated thickness; this paper focuses on these alternative approaches.

Conceptual models for wellpoints and horizontal wells

Flows from water table to wells

Conceptual models of groundwater flow into wellpoints and into horizontal wells are presented in Fig. 2. Figure 2a refers to a line of vertical wellpoints, each wellpoint consists of a slotted cylinder about 1.0 m long with a riser pipe which connects to a discharge main. The suction pump, which is attached to the discharge main, draws water from each of the wellpoints; two adjacent wellpoints are shown in the right hand diagram of Fig. 2a. Due to the suction in the discharge main, in each wellpoint there is a column of water with pressures above atmospheric which extends from the bottom of the wellpoint at an elevation of z_{wp} above the impermeable base (which is taken as datum), to a height of H_{wp} above the base. Above this elevation, the water in the riser pipe is at a pressure below atmospheric (shown speckled), while the water pressure in the discharge main is also below atmospheric. The difference between the hydraulic head in the wellpoint H_{wp} and the water-table elevation z_{wt} causes water to be drawn into the wellpoint. Flowpaths from the water table to the wellpoints are sketched in the right hand diagram of Fig. 2a, which is a vertical (y - z) cross-section through the wellpoints, parallel to the discharge main. The flowpaths are highly curved due to the combined vertical-radial flow from the water table to the partially penetrating well and due to interference between

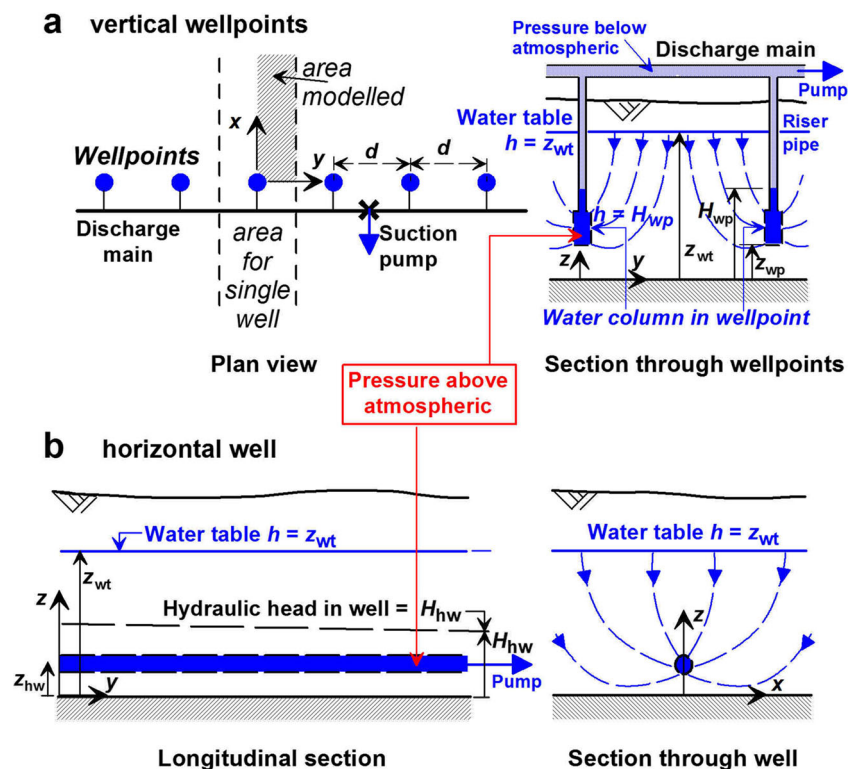
adjacent wellpoints. For a vertical cross-section perpendicular to a wellpoint, flowpaths are not so highly curved since they are not constrained by interference from adjacent wells. Accordingly, when studying flow to an individual wellpoint, account must be taken of the three-dimensional (3D) nature of the groundwater flow. For a representative wellpoint which is not at the end of the line, it is sufficient to consider the area shown shaded in the left hand diagram of Fig. 2a.

Groundwater flowpaths to a horizontal well are indicated in Fig. 2b; the perforated pipe of the horizontal well is at an elevation z_{hw} above the impermeable base. The groundwater table is at a height z_{wt} above the base. Since the hydraulic head inside the horizontal well H_{hw} is lower than the water-table elevation z_{wt} , water is drawn from the water table into the well as indicated in the right hand diagram of Fig. 2b. Groundwater flow associated with a horizontal well can be examined by considering a vertical (x - z) plane perpendicular to the well pipe because, apart from close to the ends of the well, flow occurs predominantly in this vertical plane.

Formulation and idealisations

Idealisations are often required so that the processes identified in conceptual models can be represented by computational models. These idealisations depend on the purpose of the investigation. The present investigation is concerned with the pumped discharge of wellpoints and horizontal wells. Groundwater problems are 3D in space and also time-variant.

Fig. 2 Features of vertical wellpoints and horizontal wells



For the time-variant aspect, it is convenient to use a “time-instant” approach in which conditions at a specific time are represented (Rushton 2003). The time-instant method is introduced by considering the field results in Fig. 3a for pumping from a horizontal well (Rushton and Brassington 2013a). Small fluctuations occur at the water table with small declines during periods of pumping but during periods of recharge, the water table partially recovers. The chain-dotted blue line indicates an average water-table elevation. Hydraulic heads resulting from pumping in the horizontal well are indicated by the red symbol ‘x’; all these values lie between 3.5 and 4.0 m below datum and therefore an average hydraulic head can be identified as shown in Fig. 3a.

To summarise, the hydraulic heads in the well pipe fall rapidly due to pumping, but water-table fluctuations are small due to the combined effect of recharge and water released from storage at the water table (specific yield effect). Consequently, as indicated in Fig. 3b, pumping conditions can be approximated by a time-instant analysis with a specified head in the well and a constant water-table elevation. Although in practice there will be small differences in the water-table fluctuations for wellpoints and horizontal wells, the selection of a constant head water table allows comparisons to be made. An example of the modelling of actual water-

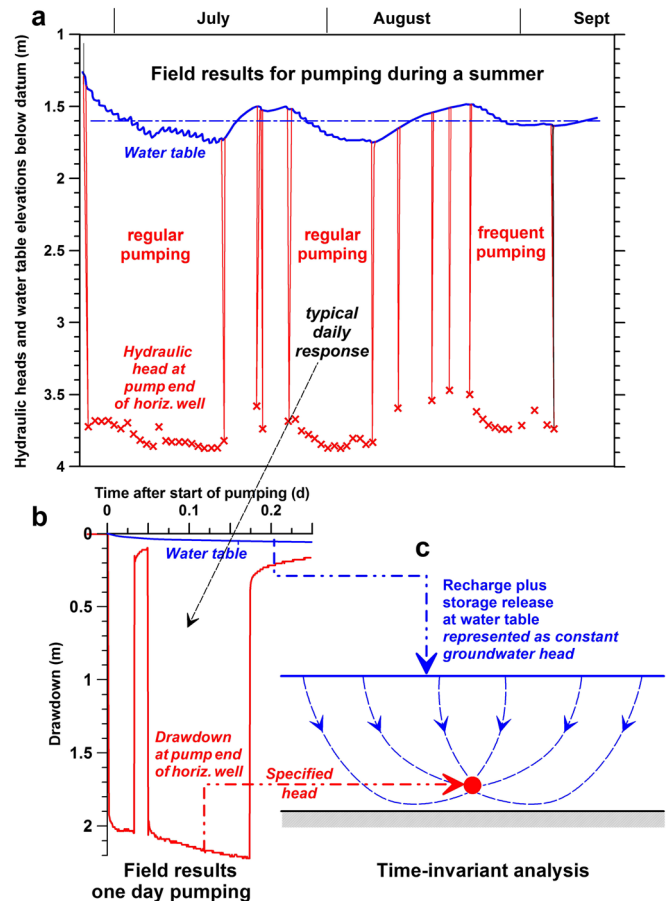
table fluctuations for a horizontal well can be found in Rushton and Brassington (2013a). This approach is discussed in Rushton and Howard (1982), Cooley et al. (1987) and the “Anisotropy” section of Rushton (2003). Similar responses of a water table and a pumped well are also apparent in pumping test field results quoted by Moench (2004).

Decisions also need to be made about the spatial dimensions of the analyses. As indicated in Fig. 2a, for vertical wellpoints, it is essential to consider the 3D nature of the groundwater flow including the small diameter of the well and the extent of the aquifer from which water is drawn. For a long horizontal well, groundwater flows into the well can be approximated using a two-dimensional (2D) vertical section (Fig. 2b).

Computational models

Computational models are used to explore groundwater flow patterns associated with vertical wellpoints and horizontal wells. Representative examples are selected in which the aquifer is assumed to have a saturated thickness of 5.0 m above an impermeable base which, for this analysis, is assumed to be horizontal. Horizontal and vertical hydraulic conductivities

Fig. 3 Field results for pumping from a horizontal well: **a** pumping during the summer (*red x*'s indicate hydraulic heads resulting from pumping), **b** time-instant conceptual model with a specified head in the well and the water table at a constant groundwater head (*chain-dotted blue line* indicates average water-table elevation)



both equal K m/d. For each example, the same hydraulic heads within the wells are specified and the resultant groundwater discharges are calculated. The base of the aquifer is defined as datum for elevations and groundwater heads. Anisotropic conditions, well losses, alternative hydraulic heads in the wells, different water-table elevations and depths to the underlying low permeability zone are considered in subsequent sections.

The numerical models discussed in the following use the finite difference approach in which the study area is divided into a rectangular grid of variable spacing, with smaller mesh subdivisions closer to the wells and increasing mesh spacing to represent regions distant from the wells. Both the wellpoint and the horizontal well are represented by octagonal shapes with cross-sectional areas the same as the circular wells. The finite difference equations are solved using the technique described in Rushton and Redshaw (1979); MODFLOW (McDonald and Harbaugh 1988) can also be used. Finite difference numerical models have been used successfully for problems involving vertical wells (for instance Bliss and Rushton 1984) and horizontal pipes in aquifers (for example Khan and Rushton 1996); further examples can be found in Rushton (2003).

Vertical wellpoints

For an individual vertical well point, a 3D analysis is necessary, while for the representative example, the saturated thickness of the aquifer is 5.0 m. Each wellpoint is 1.0 m in length and 150 mm in diameter, it extends to $z_{wp}=1.0$ m above the base of the aquifer (Fig. 2a). For a line of well points with a single suction pump, it is assumed that the hydraulic heads on the perforated screens of the line of wellpoint all equal $H_{wp}=2.5$ m relative to the base of the aquifer. Consequently, in the numerical model, the groundwater heads at the nodes on the circumference of the wellpoint are $h=2.5$ m. The unperforated riser pipe extends from $z=2.0$ to 5.0 m. Wellpoints lie on a straight line at a spacing of $d=2.0$ m; all the wellpoints are at the same elevation.

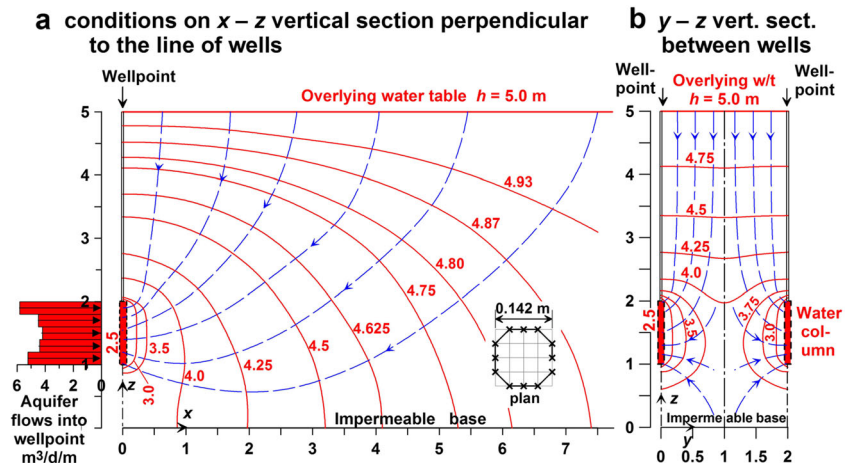
Brief details of the numerical model are as follows. Due to symmetry about both the line through the wellpoints and the centre-line between wellpoints, only one quarter of the area associated with an individual wellpoint is modelled (see Fig. 2a). The 5.0-m saturated thickness of the aquifer is represented by 16 mesh intervals with the maximum vertical spacing of 0.5 m reducing to 0.2 m in the vicinity of the well. From the well to the mid point between wells there are 12 mesh intervals varying from 0.0355 to 0.15 m. Perpendicular to the line of well points there are 21 mesh intervals varying from 0.0355 to 13 m; the outer no-flow boundary is 40 m from the well.

In the numerical model the circumference of the well is represented by 12 nodes as shown in the inset of Fig. 4a; although, due to double symmetry, only one quarter of the well is included in the computational model. The plan area within the wellpoint nodes of 0.0176 m² is equivalent to a radius of 0.075 m. Groundwater heads on the boundary of the wellpoint and the upper surface represents the overlying water table are 2.5 and 5.0 m respectively.

Two diagrams are used to illustrate the complex flow patterns from the overlying water table to the wellpoint. Figure 4a shows equipotentials and flowpaths on a vertical $x-z$ section through a wellpoint and on a line perpendicular to the wellpoints. This diagram extends to 7.5 m from the well although the outer boundary of the overlying water table extends to 40 m; the flow from 20 m or more from the wellpoint is negligible. Conditions on a second vertical section between two adjacent wellpoints in the $y-z$ plane are shown in Fig. 4b; the flowpaths exhibit substantial changes in curvature due to the interaction between the wellpoints. There is an additional diagram on the left in Fig. 4a which indicates the distribution of water entering the well. Along the water column, higher inflows occur at the top and bottom of the water column (Cookey et al. 1987; Simpson et al. 2003).

The inflow into a single wellpoint is $Q_{wp}/K=4.84$ m². For comparison with the horizontal well, this inflow is expressed per unit length of the line of wellpoints. Since in this reference

Fig. 4 Equipotentials and estimated flow paths for regularly spaced wellpoints: **a** vertical section perpendicular to wellpoints with inset showing finite difference grid for the well in plan; **b** vertical section between wellpoints



example, the wellpoints are 2.0 m apart, the inflow per unit length $Q_{wu}/K=2.42 \text{ m}^2/\text{m}$.

Effect of spacing between wellpoints

For the reference problem the wellpoint spacing is 2.0 m; the effect of decreasing or increasing the well spacing is shown in Fig. 5. Moving wellpoints further apart leads to an increase in the discharge from an individual wellpoint Q_{wp}/K but a decrease in the discharge per unit length Q_{wu}/K of the line of wellpoints. The limiting case is that of a single wellpoint where the $Q_{wp}/K=6.54 \text{ m}^2$. Closely spaced well points lead to an increase in the total discharge but also increase the cost of constructing and operating the system.

The numerical model has also been used to explore the effect of different wellpoint diameters on the discharge. For a wellpoint diameter of 100 mm, the discharge is calculated to be 90 % of the reference example with a diameter of 150 mm. For an increase in diameter to 200 mm, the discharge increases to 107 % of the reference discharge. This finding is consistent with Cashman and Preene (2013) who suggest that the discharge increases only marginally by increasing wellpoint diameters.

As an alternative to wellpoints in which there is only a limited length of screen open to the aquifer, wells can be constructed with slotted screens extending over the full saturated depth of the aquifer. Inside the well casing there is suction pipe which draws water into a discharge main. Inflow of groundwater occurs over the entire saturated thickness with a seepage face forming above the well water level. Groundwater inflows along the seepage face pass through the well screen and fall by gravity on the inside face of the well (Rushton 2006; Chenaf and Chapuis 2007). A numerical model solution for fully penetrating wells, with the same spacing as the reference example, predicts well discharges of $Q_{wp}/K=4.94 \text{ m}^2/\text{m}$. This is roughly double the discharge for the reference wellpoint; however, the

disadvantage of lower discharges from wellpoints is compensated by their simpler construction and ease of installation and operation (Cashman and Preene 2013).

Horizontal well

The conceptual flow processes of water moving from an overlying water table to a horizontal well are illustrated in Fig. 2b. The computational model refers to the x - z plane; due to symmetry, it is sufficient to consider only one-half of the vertical section. The hydraulic head in the well pipe is below the elevation of the water table so that water is drawn from the water table into the well. However, it is essential that the hydraulic head H_{hw} is higher than the top of the pipe so that the pipe remains full of water.

For the reference example, a horizontal well of 0.17-m diameter is located with its centre at $z_{hw} = 1.0 \text{ m}$ above the base of an isotropic aquifer; the hydraulic head within the well is $H_{hw}=2.5 \text{ m}$. The water table is located 5.0 m above the impermeable base. There are slots in the horizontal well through which water can pass; well losses are not included in this reference example.

Details of the numerical model are as follows. A rectangular finite difference mesh is used with 37 mesh intervals in the vertical z direction having a maximum mesh spacing of 0.20 m, reducing to 0.04 m in vicinity of the horizontal well. The 0.17-m diameter well is represented as specified heads at nodes as indicated on the inset diagram of Fig. 6. The cross sectional area of the well in the model is 0.0224 m^2 (diameter 0.169 m). There are 36 mesh intervals in the horizontal x direction from the well to an outer no-flow boundary at 40 m; the smallest mesh interval is 0.04 m and the largest 5.0 m.

Figure 6, which refers to a vertical section in the x - z plane, includes equipotentials constructed from the nodal groundwater heads; however, this diagram only extends to $x=7.5 \text{ m}$ from the well, although the numerical model continues to

Fig. 5 Effect of spacing on flow to an individual wellpoint and flow per unit length of the wellpoint system

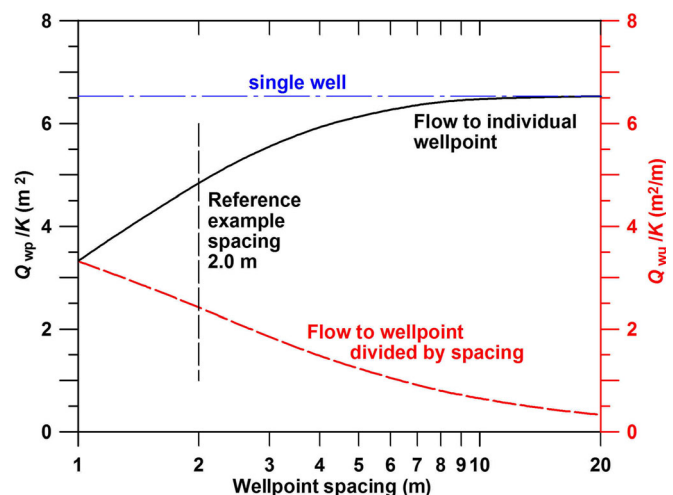
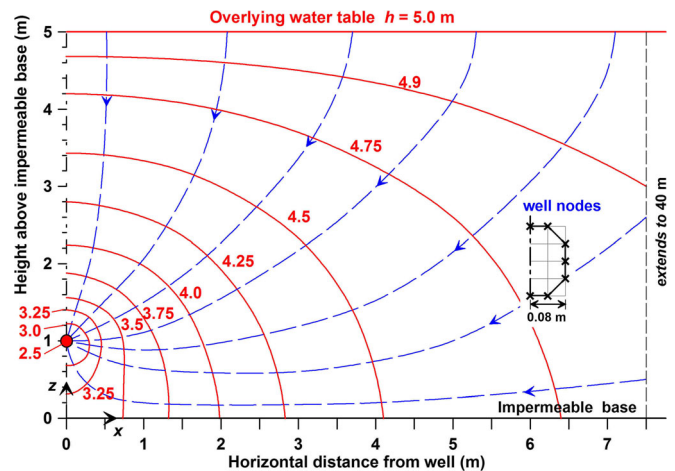


Fig. 6 Equipotentials (red solid lines) and flow paths (blue broken lines) for the reference example of a horizontal well. The inset diagram shows the nodes representing the periphery of the well



40.0 m from the well. Flowpaths are also included in the diagram. The total inflow per metre length of the horizontal well is $Q_{hw}/K=2.92 \text{ m}^2/\text{m}$. Doubling the distance to the outer boundary has no effect on the flow into the well.

The numerical model has also been used to explore the effect of different well diameters on the horizontal well discharge. For a horizontal well of 100-mm diameter with a hydraulic head of 2.5 m, the discharge is estimated to be 91 % of the reference example; for an increase in diameter to 240 mm, the increased discharge is 107 % of the reference discharge. Even if the diameter is increased to 350 mm, the discharge is estimated to be 118 % of that for the 170-mm diameter well. Although the well diameter has only a small effect on the quantity of groundwater drawn into the well, smaller diameters have a considerable impact on the hydraulic head losses in the pipe, possibly drawing the head below the top of the pipe (Rushton and Brassington 2013b).

Comparing inflow rates from wellpoints and horizontal wells

For these representative examples, inflows to the line of wellpoints per metre length is $2.42/K\text{m}^2/\text{m}$, inflow to the

Fig. 7 Decrease in yield from wells due to anisotropy in the aquifer

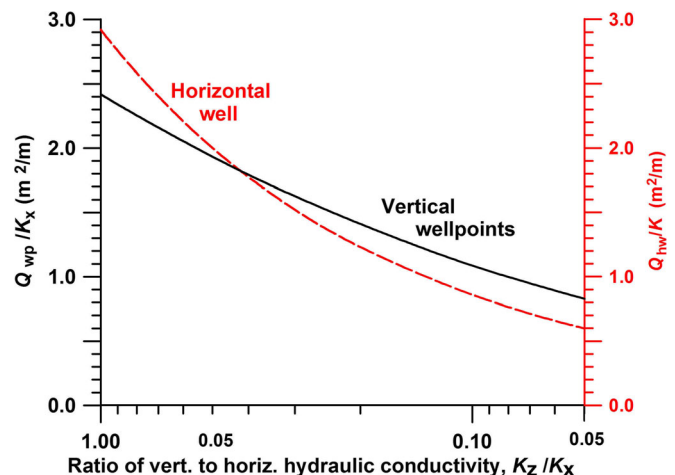
horizontal well is $2.92/K\text{m}^2/\text{m}$. Although the horizontal well has a slightly higher discharge, the differences are not significant because a wellpoint spacing of 1.37 m results in identical well discharges. This indicates that wellpoints, at a sufficiently close spacing, and horizontal wells can be equally successful at drawing water from an aquifer of limited saturated thickness.

Alternative conditions in the aquifer and the wells

The two reference examples described in the preceding are selected as representative of typical conditions in wellpoints and horizontal wells. However, further characteristics which can influence the yields of wellpoints and horizontal wells are considered in the following; this information is required for specific case studies which are considered later in the paper.

Anisotropy

For the reference examples, isotropic conditions are assumed to apply; however, anisotropic conditions frequently occur in



practice, resulting, for example, from sedimentary features of the aquifer material so that the vertical hydraulic conductivity K_z is lower than the horizontal hydraulic conductivity K_x (Price 1996; Domenico and Schwartz 1998; Todd and Mays 2005). Using the computational models described in the previous section, estimates are made of well discharges for decreasing vertical hydraulic conductivities; the lowest vertical hydraulic conductivity is 0.05 of the horizontal. Apart from an increase in the distance to the outer boundary in the x direction, all other conditions are the same as for the reference examples.

The results in Fig. 7, in which a logarithmic scale is used for K_z/K_x , show that the discharge from wellpoints is affected less by lower vertical hydraulic conductivities. This occurs because the wellpoints extends from 3.0–4.0 m below the water table, whereas for a horizontal well, the depth is constant at 4.0 m.

Well loss represented as a reduction in hydraulic conductivity

At a wellpoint or horizontal well, there is usually an additional head loss as water passes through the apertures in the casing. In addition, the hydraulic conductivity in the vicinity of the well may be reduced due to clogging. These well losses (or skin effects) can be represented by reducing the hydraulic conductivity around the well (Price 1996; Rushton 2003, section 8.2). For this study, the hydraulic conductivities between the nodes on the outer casing of the wellpoint and nodes one mesh spacing into the aquifer, are adjusted by a coefficient which varies between 1.0 and 0.05. A similar approach is adopted for the horizontal well although modified factors are used due to the slightly larger mesh spacing around the horizontal well.

Results are included in Fig. 8 for modified discharges due to well losses in both wellpoints and horizontal wells; the reduced hydraulic conductivity is plotted to a logarithmic

Fig. 8 Decrease in groundwater inflows due to reduced hydraulic conductivities (K) around the wells (with adjustments for different mesh spacing of the horizontal well model)

scale. The effect of well losses is more significant for wellpoints. With a hydraulic conductivity coefficient of 0.1 the wellpoint discharge is 56 % of the case with no well losses. For a horizontal well with the equivalent hydraulic conductivity coefficient, the discharge is 69 % of the zero well loss condition. The surface area of the horizontal well in contact with the aquifer is 2.5 times the surface area of the wellpoints when account is taken of the well spacing. With the lower contact area for wellpoints, the inflow velocities are higher resulting in larger groundwater head losses around the wellpoint and a reduced inflow of groundwater.

Hydraulic heads

For both vertical wellpoints and horizontal wells, a suction pump is used to draw water through the well screens. The operation of the suction pump results in hydraulic heads in the wellpoints H_{wp} or the horizontal well H_{hw} which are lower than the overlying water-table elevation. Consequently, it is instructive to determine how the discharges per unit length, Q_{wu} , and Q_{hw} , vary with hydraulic heads.

Numerical model results have been obtained for problems with the same geometry as the reference examples but with different magnitudes of hydraulic head in the wellpoints or in the horizontal well. Results for the inflow flow per unit length are presented in Fig. 9. Limiting conditions are that the hydraulic head in the wellpoint must not fall below the top of the wellpoint at 2.0 m (indicated by a vertical chain-dotted line); the maximum discharge is $Q_{wu}/K=2.90$ m²/m. When the hydraulic head in the wellpoint is 5.0 m the discharge is zero. A linear relationship holds between these two limits because the geometry does not vary with changing hydraulic heads.

For the horizontal well, the lowest hydraulic head is determined by the top of the well pipe at 1.085 m; the discharge is $Q_{hw}/K=4.54$ m²/m. Again, a linear relationship applies. The advantage of the horizontal well is that the hydraulic head can be lower than for the wellpoint, hence the higher discharge.

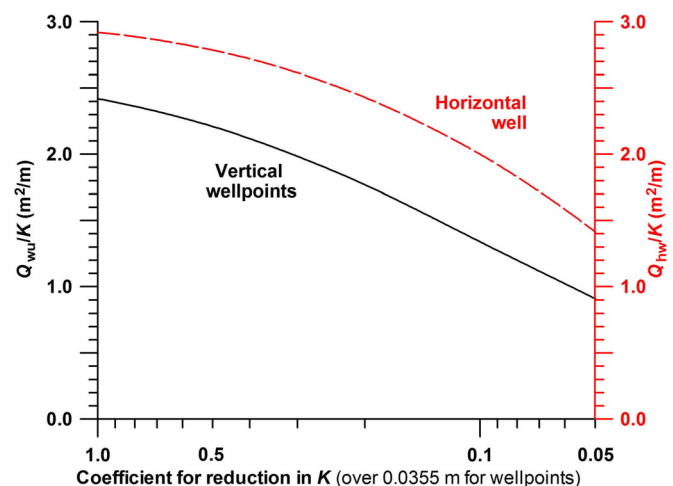
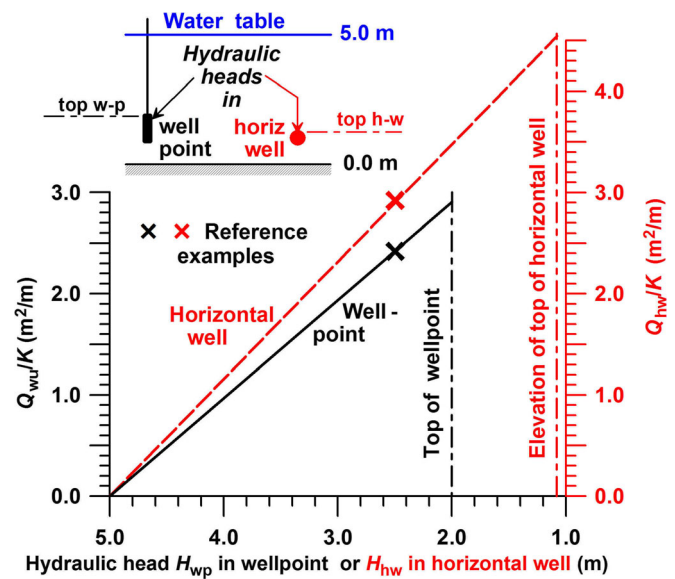


Fig. 9 Discharge per unit length due to changes in hydraulic head in the wells. The top of the well point is indicated by a vertical chain-dotted line. Locations of the wellpoint and horizontal well relative to the base are the same as for the reference examples



Water-table elevations

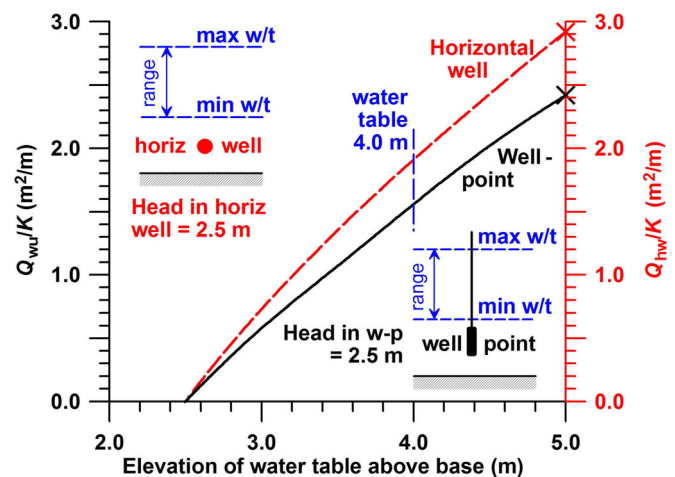
Across a line of wellpoints, or for a horizontal well, the elevation of the overlying water table changes due to seasonal fluctuations. When different water-table elevations are represented in numerical models, the relationships between inflow to the wells and the water-table elevations are no longer linear, see Fig. 10. In this analysis, water-table elevations vary between 5.0 m above the base (the reference examples) and 2.5 m above the base (the magnitude of the hydraulic head in the wells). When the water-table elevation is 4.0 m above the base (water table 4.0 m on Fig. 10) the discharge of a wellpoint is $Q_{wu}/K=1.56$ m²/m, or 64 % of the reference example; for the horizontal well $Q_{hw}/K=1.91$ m²/m, 65 % of the reference discharge. In Fig. 10, the slight curvatures of the lines occurs because changes in the water-table elevations alters the saturated thickness, resulting in a change in the geometry of the flowpaths.

Elevation of wells relative to base of aquifer

The effect of setting a well at a different elevation relative to the base of the aquifer has also been explored. If the bottom of the wellpoint is lowered by 0.8 m so that it is only 0.2 m above the impermeably base, the discharge is 89 % of the reference example. Raising the wellpoint to 0.5 m above that for the reference example leads to an estimated discharge of 1.05 times the reference value. Note that the hydraulic head remains the same for these simulations. For the horizontal well, the changes are greater; with the pipe lowered 0.8 to 0.2 m above the base, the discharge is estimated to be 77 % of the reference value; if the horizontal well is raised by 0.5 m, the estimated discharge is increased to 1.09 of the reference value.

These are significant results because they demonstrate that locating either a well point or a horizontal well at a lower elevation with an unchanged hydraulic head leads to a reduction in the discharge, which occurs because the flowpaths

Fig. 10 Discharge per unit length due to different water table (w/t) elevations. Locations of the wellpoint and horizontal well relative to the base are the same as for the reference examples



from the water table are longer. Nevertheless, there is an advantage in having wells at a lower elevation because hydraulic heads can be lower, leading to a greater head difference relative to the water table. If, in addition to locating the wells closer to the base, the hydraulic heads are at 1.7 m rather than 2.5 m as in the reference example, the discharge from a wellpoint is estimated to 117 % of the reference example, whereas for a horizontal well, the discharge is 102 % of the reference example. These results illustrate the sensitive balance between the elevation of the wells, hydraulic heads and the resultant discharge.

Elevation of the impermeable base

Another factor which can influence the discharge is the elevation of the impermeable base relative to the water table. If the impermeable base is 2.0 m lower than the reference example with the wells at the same elevation relative to the overlying water table, there are small increases in discharge. For the wellpoint, the discharge is estimated to be 106 % of the reference value, while for the horizontal well the discharge is 112 % of the reference value.

Comment on alternative conditions

Computational models have been used to explore situations with alternative aquifer properties or with different geometries. Two conditions which frequently arise in practice are aquifer anisotropy and well losses. For each situation there is a reduction in well discharge (Figs. 7 and 8) which, with typical field parameters, can result in a discharge of about 50 % of the idealised conditions of the reference examples. Higher hydraulic heads lead to a proportionate decrease in discharge (Fig. 9). Water-table fluctuations are another feature of field conditions—as the water table falls, but with the same hydraulic heads in the wells, there is a corresponding decrease in discharge (Fig. 10).

Application of results to the operation of wellpoints and horizontal wells

The numerical results from the computational models are used to explore the operation of wellpoints and horizontal wells. Both wellpoints and horizontal wells use suction pumps to abstract water. This can lead to difficulties in operating the systems efficiently. For wellpoints, pressures are below atmospheric for most of the riser pipe and the whole of the discharge main (Fig. 2a). The discharge main and wellpoints should be approximately level (Roberts and Preene 1994), but this may be difficult to achieve when the line of wellpoints used for groundwater abstraction extends for more than 100 m. The hydraulic efficiency of the total wellpoint

installation is crucial—air leaks can drastically reduce the effectiveness of the suction that is available to withdraw water from the aquifer (Cashman and Preene 2013). For horizontal wells, the hydraulic head in the well pipe must always be higher than the top of the pipe, otherwise air can enter the system (Rushton and Brassington 2013b).

Risk of air entry for wellpoint schemes

Detailed field investigations of wellpoint schemes are difficult because they are sealed systems. Cashman and Preene (2013) discuss the operation of wellpoints for the dewatering of excavations. “As the water level at each wellpoint is drawn down to near the level of the top of the screen, there will be a risk of entraining air with water and thereby reducing the amount of available vacuum. The trim valves at each individual wellpoint connection to the discharge main enable the experienced operator to adjust the amount of suction such that the intake is predominantly water and the amount of air intake is minimised.” These comments refer to systems of wellpoints surrounding an excavation; however, when a line of wellpoints is used for water supply, maintaining a vacuum for the whole system can be even more challenging. The necessity of ensuring that the water level in the wellpoint remains above the top of the screen is emphasised in many texts including Driscoll (1986).

In order to discover more about the operation of a line of wellpoints for water supply, the arrangement of Fig. 11 is examined. It refers to a line of wellpoints at 2.0-m centres extending for 150 m. A full 3D analysis of the 76 wellpoints is very demanding; thus, as an alternative, the numerical results from the previous section are used to study conditions at three specific locations. This analysis focuses on wellpoints A and C, which are towards either end of the line, and wellpoint B, which is near the centre of the line where the pump is located. Ground level and the base of the aquifer fall by 1.0 m over the line of wellpoints; since each wellpoint assembly is of the same length, wellpoint C is 1.0 m lower than wellpoint A. Each wellpoint has a screen 1.0 m long. The water table falls along the line of wellpoints by 0.8 m. A suction pump draws water from the discharge main; an air vessel and a vacuum pump are provided to remove any air that enters the system.

Two alternative suction conditions are explored with the second suction 0.3 m less than the first. For condition I (Fig. 11a), a suction of 4.4 m is recorded by a pressure gauge located at an elevation of 9.8 m. Assuming that hydraulic head losses in the riser pipe and wellpoints total 0.04 m with head losses of 0.06 m in the discharge main between the distant wellpoints and the pump, the elevations can be determined where the pressure is zero. For wellpoints A and C, the pressure is zero at an elevation of 5.5 m ($9.8 - 4.4 + 0.04 + 0.06$). This zero pressure line is above the top of wellpoint C but

0.1 m below the top of wellpoint A which is at an elevation of 5.6 m (Fig. 11a); consequently, air can enter wellpoint A. For condition II of Fig. 11b, where the suction at an elevation of 9.8 m is 4.1 m, the zero pressure line for wellpoints A and C at 5.8 m, is above the top of both wellpoints, avoiding the risk of air entrainment.

The discharge from these three wellpoints is estimated using the numerical results for individual wellpoints from Figs. 9 and 10. The difference between the water-table elevation and the hydraulic head in the well (which corresponds to the elevation of the zero pressure line) determines the discharge for each wellpoint. These differences are shown adjacent to the vertical broken lines with arrows in Fig. 11. Adjustments are made for the difference between the hydraulic head and the water-table elevation (Fig. 9) and the elevation of the water table above the base (Fig. 10). The discharge for wellpoint C under condition I is $Q_{wu}/K=1.87 \text{ m}^2/\text{m}$. For wellpoint C in condition II, the head difference is 1.60 m compared to 1.90 m for condition I, consequently the discharge for wellpoint C is $Q_{wu}/K=(1.60/1.90) \times 1.87=1.57 \text{ m}^2/\text{m}$. Discharges for wellpoints A and B in Fig. 11 are obtained using the same procedure. For wellpoint A under

condition I, the discharge is effectively zero since the hydraulic head is below the top of the wellpoint.

This analysis illustrates the need to adjust the pump suction carefully—a suction which is too high can result in air entrainment at some wellpoints, yet as the suction is decreased, the yield of all the wellpoints is reduced.

Maintaining positive hydraulic pressures in horizontal wells

Horizontal wells are also at risk of air entry. This discussion is based on the case study of Fig. 1d, the horizontal well in the Sefton Coast sand aquifer. Field measurements were made of both water-table elevations and hydraulic heads inside the 300-m-long well; time-variant conditions in the aquifer were monitored for more than 4 years (Rushton and Brassington 2013a, b). Figure 12 shows the elevation of the horizontal well which was constructed with a slope of approximately 1:200 towards the pump; this slope was introduced to be consistent with conventional drainage practice. The full lines in Fig. 12 indicate the water-table elevation and hydraulic head distribution in the well when pumping at a rate of 1,880 m³/d during

Fig. 11 Three wellpoints from a line of wellpoints; exploring the effect of different suctions (vacuums) on the yield of the wellpoints: **a** condition I, **b** condition II. This diagram summarises the analysis of conditions in wellpoints towards the ends and at the centre of a line of wellpoints

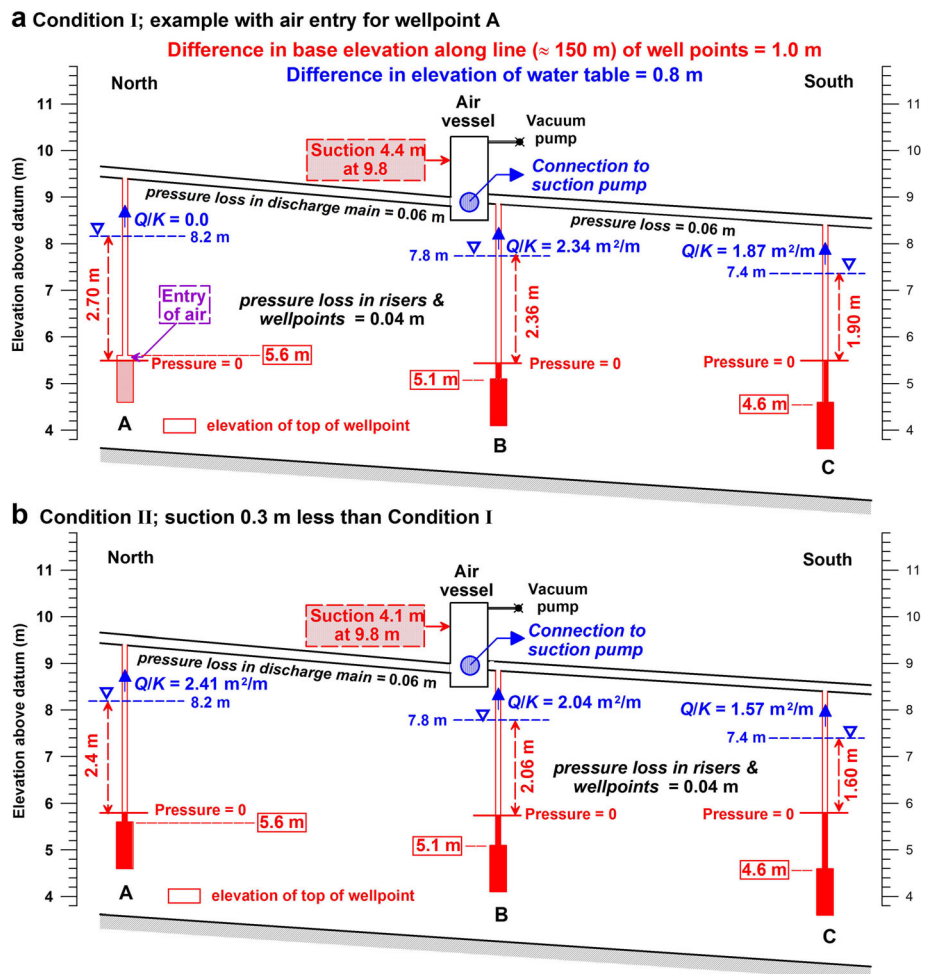
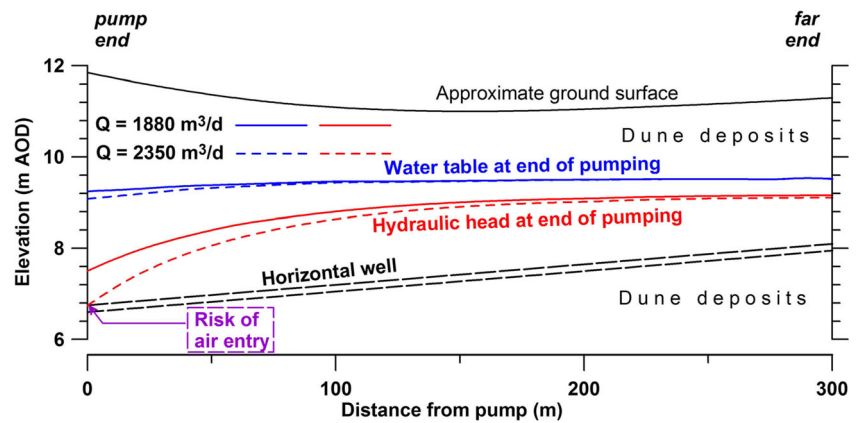


Fig. 12 Water table elevations, hydraulic heads and elevation of the pipe (above ordnance datum) along the 300 m horizontal well. *Unbroken lines* refer to present abstraction rate; *broken lines* represent predictions if the abstraction rate is raised by 25 %



June 2011. Hydraulic heads were only measured at either end of the well; values elsewhere in the pipe are derived from a numerical model of the aquifer system with a horizontal hydraulic conductivity of 8.5 m/d (Rushton and Brassington 2013b). Significant hydraulic gradients occur in the 300-m-long 160-mm-diameter pipe, especially towards the pump end, where the hydraulic head of 7.50 m is 0.75 m above the top of the pipe.

The impact of increasing the pumping rate by 25 % is explored using the numerical model; the results are indicated by the broken lines. There is little difference in the predicted water-table elevations but the hydraulic head at the pumped end is calculated to be 6.74 m compared to the top of the pipe at 6.75 m. This could lead to air entering the horizontal well in the vicinity of the inlet pipe of the centrifugal pump, thereby risking the efficiency of the pump or even damaging it.

Conclusions

Significant quantities of water can be abstracted from unconfined aquifers with a saturated thickness of 5–10 m. The selection of a suitable abstraction system is the key to success. Conventional bore wells with submersible pumps may not be suitable because of the limited saturated thickness. However, large diameter wells, with water abstracted for several hours each day using suction pumps, are widely used. An important feature of their success is that water is drawn from the aquifer into the well even when the pump is not operating. This allows an abstraction rate which initially is taken mainly from well storage and is higher than the rate at which groundwater is drawn into the well. A line of wellpoints and horizontal wells are also valid approaches for drawing water from aquifers of limited saturated thickness.

The flow processes associated with wellpoints and horizontal wells are explored in this paper by developing conceptual models and preparing corresponding computational models. Two reference examples are selected with the same saturated thickness and aquifer properties. For a wellpoint spacing of

1.37 m, similar discharges per unit length of a wellpoint system and horizontal well systems can be achieved. The impact of anisotropic conditions, well losses, well diameters, different hydraulic heads and different water-table elevations are explored; these conditions have broadly similar impacts for wellpoints and horizontal wells.

In terms of collecting water from an aquifer, there is little difference between these two alternative types of wells; however, there are further important considerations, namely the cost of the installation and operational issues. The cost of constructing a horizontal well in an aquifer, such as a coastal sand dune aquifer, is substantially less than for say 80 wellpoints which require a discharge main, air vessel and vacuum pump in addition to the suction pump that is common to each type of well.

Both wellpoint systems and horizontal wells use suction pumps to abstract water. For wellpoints, pressures below atmospheric occur throughout the system including the riser pipes and in the discharge main. Unless each wellpoint is carefully controlled, the zero pressure hydraulic head can be below the top of certain wellpoints so that air entrainment can occur. Due to the possibility of some air entering the system, an air tank and a vacuum pump are usually required (see Fig. 11). In contrast, for horizontal wells, pressures below atmospheric are only likely to occur round the pump inlet pipe which is inserted into the horizontal well pipe. Provided that the discharge rate in the horizontal well is limited so that the hydraulic head within the well pipe is always higher than the top of the well pipe, air will not enter and no ancillary equipment is required. Air entry is less likely to occur if the horizontal well is divided into two parts with abstraction from the central point.

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