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Significance of hydraulic head gradients within horizontal wells in unconfined aquifers of limited saturated thickness

K.R. Rushton [a,*], F.C. Brassington [b]

[a] Emeritus Professor, University of Birmingham,106 Moreton Road, Buckingham MK18 1PW, UK
[b] Newcastle University, School of Civil Engineering & Geosciences, Cassie Building, Newcastle upon Tyne NE1 7RU, UK

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SUMMARY

Horizontal wells can be used to withdraw water from shallow aquifers. Frequently there is a substantial hydraulic gradient within the horizontal well. This paper considers the significance of the hydraulic head distribution for horizontal wells in shallow aquifers and estimates the inflows of groundwater along the length of the well. Conceptual and computational models are developed to represent time-variant regional groundwater flow. Convergent flows towards and into the horizontal well and hydraulic conditions within the well are also included. A case study of a 300 m long horizontal well, curved in plan, in an aquifer of limited saturated thickness is used to illustrate the approach. Field monitoring indicates significant drawdowns in groundwater heads in the vicinity of the well. Substantial difference in hydraulic head between the pump end and the far end of the well are also identified. Successful comparisons are made between field and model results. From the numerical models, groundwater inflows along the well are estimated; inflows at the pump end are about four times the inflows towards the far end. The effect of reducing the length of the well is explored.

1. Introduction

Horizontal wells provide an efficient means of collecting groundwater in aquifers of limited saturated thickness. A common form of horizontal well is a collector well which is usually located beneath or adjacent to a river bed. Radial collector wells consist of a number of horizontal perforated pipes (often termed laterals) connected to a shaft or caisson; their performance can be assessed either using an approximate formulation (McWhorter and Sunada, 1977) or an advanced technique such as the analytical element method (Bakker et al., 2005; Patel et al., 2010). However, horizontal wells can also be installed in shallow unconfined aquifers where water is withdrawn using a suction pump located towards the centre or at one end of the horizontal well (Mailvaganam et al., 1993; Preene et al., 2000; Brassington and Preene, 2003).

A limited number of laboratory investigations have been carried on horizontal wells. The sand tank experiments of Kim et al. (2008) provide valuable insights into conditions in a horizontal well positioned under a riverbed. Results show that, for wells with a limited cross-sectional area, the hydraulic head loss in the half of the well at the discharge end is about 80% of the total head loss. The experimental results also indicate that the inflow through the pipe walls increases substantially towards the discharge end. Chen et al. (2003) describe an experiment in a sandbox, 4.63 m long, in which a horizontal well collects water from a ponded reservoir above the upper surface of the sand. Piezometric heads and discharges were measured. Their paper also introduces a finite difference numerical model in which the horizontal well is simulated as equivalent hydraulic conductivities representing five alternative flow regimes within the wellbore, ranging from a laminar regime to a rough turbulent regime. Satisfactory agreement was achieved between experimental and numerical model results. The numerical model results demonstrate that the well is neither a constant head nor a uniform inflow internal boundary. Birch et al. (2007) describe a numerical model study using parameters deduced from experiments in a sandbox in which water lies above the upper surface of the sand. Parameters deduced from the sandbox experiment were incorporated in a finite element model with the frictional effects in the pipe simulated as an equivalent hydraulic conductivity. Simulations indicate significant falls in hydraulic head inside the well. Finally, although not a physical experiment, numerical modelling experiments by Tarshish (1992) demonstrated the importance of hydraulic conditions in a horizontal well. Flow within the well was represented taking account of energy losses and momentum flux changes. From representative calculations, Tarshish identified substantial differences between the hydraulic head in the pipe and the groundwater head on the external surface of

* Corresponding author. Tel.: +44 1280 824 942.
E-mail address: kenrrushton@btinternet.com (K.R. Rushton).

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the pipe; neither the calculated hydraulic heads nor the fluxes through the walls of the well exhibit uniform values.

Field evidence concerning the interaction of horizontal wells and aquifers is limited. Mohamad and Rushton (2006) present monitoring data collected for a horizontal well consisting of two arms, each extending 150 m from a central caisson, which was constructed in a shallow coastal aquifer in Sarawak. During 6 days of test pumping, drawdowns were measured both in the caisson and in observation piezometers in the aquifer; hydraulic heads were also monitored in the horizontal well. The difference in hydraulic head inside one of the arms was 0.042 m for the relatively low total discharge rate of 230 $m^3\ d^{-1}$; if the discharge rate doubled, the difference in hydraulic head was estimated to be 0.24 m. Another investigation concerning a 300 m long horizontal well is described by Brassington and Preene (2003); detailed monitoring included piezometric heads in the vicinity of the horizontal well and in the surrounding area. No data were collected for hydraulic heads in the well. Apart from the coastal aquifer in Sarawak mentioned above, the authors are not aware on any published information of field measurements of hydraulic heads within a horizontal well.

Analytical solutions have been developed for horizontal wells with the well represented either as a specified constant head or as a uniform flux into the well. For example an analytical solution for a horizontal well with a semi-pervious overlying streambed is presented by Huang et al. (2012); this paper also lists several earlier analytical solutions. In addition, a growing number of numerical models have been developed, usually associated with radial collector wells, which include the hydraulic conditions within the horizontal well. Bakker et al. (2005) utilise a multi-layer analytic element method to represent a horizontal well in steady-state regional flow; skin effects and frictional losses within the well are included. Moore et al. (2012) use the same approach to develop a framework for the design of collector wells. Patel et al. (2010) also used the analytic element method for a radial collector well with a recharge channel distant from the well; this involves upper boundary conditions of a known head at the recharge channel but an unknown water table elevation elsewhere. Their steady state solution assumed that friction losses within a lateral can be ignored. Kelson (2012) uses MODFLOW to estimate steady state collector well yields; converging flows to a lateral are represented using a correction to the conductance suggested by Haitjema et al. (2010).

From the above review, it is apparent that many of the studies of horizontal wells are concerned with collector wells connected to a central caisson. Usually, assessment of the yield of the collector well is the primary purpose; consequently hydraulic conditions in the laterals are of limited importance. Furthermore the laterals are typically tens of metres in length; this, together with diameters of 200–300 mm and possibly a free water surface at the pumping end, minimises the impact of hydraulic head losses. Another feature of many of these investigations is that the well draws water from an overlying water surface; consequently steady-state analyses are adequate since only confined storage properties apply with the result that equilibrium is reached quickly.

There are, however, practical situations where the hydraulic head gradient is of critical importance. This is illustrated by the 300 m long horizontal well situated in a shallow aquifer; the well is curved in plan (Brassington and Preene, 2003). The horizontal well was installed and tested in 2000, although no information was collected about hydraulic heads within the well. As evidence became available in the literature of the significance of hydraulic heads and the risk of operational problems if hydraulic heads fall to the top of the well pipe, transducers were installed in 2011 to monitor hydraulic heads at either end of the horizontal well during normal operation. A substantial hydraulic head gradient was identified.

This paper describes the development of conceptual and computational models for horizontal wells in shallow unconfined aquifers and demonstrates the importance of collecting information about hydraulic heads. The possibility of well failure, due to hydraulic heads falling to the top of the well, is investigated. In addition the significance of the length of a horizontal well is examined. In this discussion of horizontal wells the terms *pump end* and *far end* have been used to distinguish each end of the pipe with the flow inside the pipe being towards the *pump end* during pumping. A companion paper (Rushton and Brassington, 2013) focuses on the regional setting, the effect of abstractions on flows within the aquifer system and a preliminary comparison between vertical and horizontal wells.

2. Conceptual models of flow processes

When formulating conceptual models, the aim is to identify the important features of the processes and describe them in a form which will lead to the development of computational models. Flows from an aquifer to a horizontal well can be described as three processes, which were initially identified by Tarshish (1992) and included in the interpretation of a field study by Mohamad and Rushton (2006). These processes are illustrated in Fig. 1.

(a) *Time-variant regional groundwater flow in the aquifer system*: this depends on aquifer dimensions, aquifer parameters of hydraulic conductivity and storage coefficient, inflows such

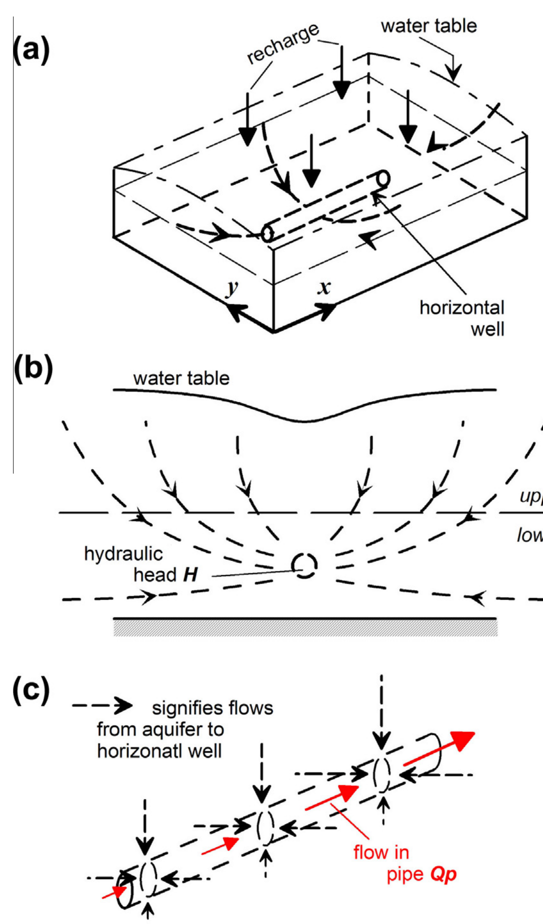

Fig. 1. Conceptual diagram of three flow processes for a horizontal well: (a) flows in the aquifer including recharge, (b) interaction between aquifer and horizontal well, and (c) hydraulic conditions in horizontal well.