Journal of Hydrology (2006) **329**, 98–109

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Horizontal wells in shallow aquifers: Field experiment and numerical model

Azuhan Mohamed [1], Ken Rushton *

School of Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK

Received 10 October 2005; received in revised form 30 January 2006; accepted 3 February 2006

KEYWORDS
Horizontal well;
Pipe flow;
Shallow aquifer;
Conceptual models;
Computational models;
Finite differences

Summary This paper is concerned with horizontal wells in shallow aquifers; information about a field test is presented and the development of appropriate conceptual and computational models is discussed. Particular attention is paid to the processes of flow from the aquifer into the horizontal well and the hydraulic conditions within the well. A combined computational model representing the aquifer and the horizontal well is developed. This methodology is used to study a horizontal well in a shallow coastal aquifer; a detailed pumping test is analysed using the combined model. The combined model is then used to predict the consequences of increasing the abstraction, lengthening the well or using the horizontal well for an extended period when there is no recharge. The results from the combined model indicate that the commonly adopted assumptions of either a uniform flux into the well or a constant head along the well are not suitable for this field problem.

Introduction

Horizontal wells can have significant advantages over vertical wells in shallow aquifers because they can be positioned towards the bottom of the aquifer. Furthermore, the provision of one long horizontal well rather than a number of vertical well clusters reduces the number of pumps required.

For horizontal wells, any analysis of their time-variant response should include the following three component, the flow processes within the aquifer, flow from the aquifer into the horizontal well and thirdly the hydraulic conditions within the horizontal well pipe. A number of analytical solutions have been developed for horizontal wells but they do not include all of these components. For most analytical solutions the horizontal well is represented either as a constant head boundary or as a uniform flux boundary; no account is taken of hydraulic conditions within the well. For example Kawecki (2000), using approaches developed for the oil industry, considers a number of alternative approaches and presents approximate analytical expressions for drawdowns due to both constant head and uniform flux

* Corresponding author. Address: 106 Moreton Road, MK18 1PW Buckingham, UK. Tel.: +44 1280 824 942.
E-mail addresses: azuhan@epu.jpm.my (A. Mohamed), k.r.rushton@cranfield.ac.uk (K. Rushton).
[1] Present address: Economic Planning Unit, Prime Minister's Department, Level 5, Block B6, 62502 Putrajaya, Malaysia.

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2006.02.006

conditions at the well face; the influence of a skin factor around the well is also considered. Analytical solutions have also been developed by Zhan et al. (2001), Zhan and Zlotnik (2002) and Zhan and Park (2003); the horizontal well is treated as a line sink and the flux distribution along the well is assumed uniform. A variety of aquifer conditions are represented including leaky aquifers with and without aquitard storage; conditions on the upper boundary of the flow field include confining strata, water table conditions including delayed yield and an overlying reservoir.

The issue of the distribution of flux on the well bore is considered by Cassiani and Kabala (1998) and by Zhan and Zlotnik (2002). Cassiani and Kabala (1998) present analytical solutions for vertical wells and explain that, although drawdowns are not sensitive to flux non-uniformity, the flux distribution along the well screen is non-uniform. Zhan and Zlotnik (2002) present analytical solutions for horizontal and slanted wells. They also refer to a numerical simulation of a hypothetical example with the length of the well 1.7 times the unconfined aquifer thickness with either uniform head or uniform flux well bore conditions. Differences in drawdowns from the two solutions are less than 10% at distances greater than five times the well diameter from the end of the well.

The importance of hydraulic conditions in the horizontal well was recognised by Tarshish (1992) who considers steady-state conditions in a horizontal well in an aquifer underlain by an impermeable base and overlain by a water reservoir; boundaries are represented using image wells. The well is simulated as a linear sink with a non-uniform inflow. Flow within the well is represented taking into account energy losses and the momentum flux change along the well. To simulate losses due to the high approach velocities into the well, a well loss coefficient can be introduced (Kruseman and de Ridder, 1990).

Chen et al. (2003) present a new treatment of in-well hydraulics for horizontal wells which avoids the assumption that the well is a constant head or a uniform inflow internal boundary. The horizontal well is represented as an equivalent hydraulic conductivity with head losses along the well. Five alternative flow regimes in the well bore are identified, a laminar regime with the head loss proportional to the velocity u, smooth turbulent flow with the head loss proportional to $u^{1.75}$ and a rough turbulent regime with the loss proportional to $u^{2.0}$; transitions between these regimes are also included. Finite difference solutions are developed; comparisons are made with a physical laboratory model which represents pumping from beneath a river. Chen et al. (2003) recognise that additional well losses occur due to radial flow through the slots of the well screen. Furthermore the radial flow direction into the well changes to axial at the inside wall of the pipe reducing the cross-section occupied by pure axial flow within the pipe. No corrections are made for these processes.

A field test of a horizontal well in a shallow aquifer in Sarawak, Malaysia provides a focus for this study. Features which must be incorporated in the analysis of this problem include significant variations in the pumping rate from the well, the occurrence of recharge during the test, substantial falls in the water table elevation leading to a reduction in the saturated thickness, also the specification of maximum water table elevations equal to the ground surface elevation. The resistance to flow as the water enters the well (well loss) is an important consideration as is the estimation of hydraulic head losses in the horizontal well pipes. These complex features can be represented by three interconnected numerical models. The three components mechanisms of time-variant flow in a shallow aquifer to a horizontal well, flow from the aquifer into the horizontal well and flow within the horizontal well pipe are examined. For each component both conceptual and computational models are proposed; detailed information is presented about the computational models. Due to uncertainties about flow processes close to the well including the flows through the slots in the wall of the pipe and the resultant reduction in the area of axial flow within the horizontal pipe, coefficients are introduced to represent these features. These coefficients are adjusted during the model refinement to obtain an adequate match with field observations. In this paper the methodologies refer specifically to horizontal wells in shallow aquifers and to the analysis of a field pumping tests. However, they can be adapted for horizontal wells in deeper aquifers and horizontal wells beneath water bodies.

Field example of horizontal well

The development of conceptual and computational models is strongly influenced by the intended application. Therefore a representative field problem of a horizontal well in a shallow aquifer is summarised in this section, conceptual and computational models are introduced in ''Conceptual and computational models'' section with a detailed study of the field problem in ''Application to horizontal well at Loba'' section.

A horizontal well system has been installed and tested at Loba, Sarawak, Malaysia. Loba is a small coastal village, not far from Kuching, on the South China Sea. The site is suitable for tourist development since a shallow sand aquifer can provide good quality water. The sand aquifer extends about 700 m from the coast, Fig. 1(a); the base of the sand aquifer is about 4 m below mean sea level with a maximum

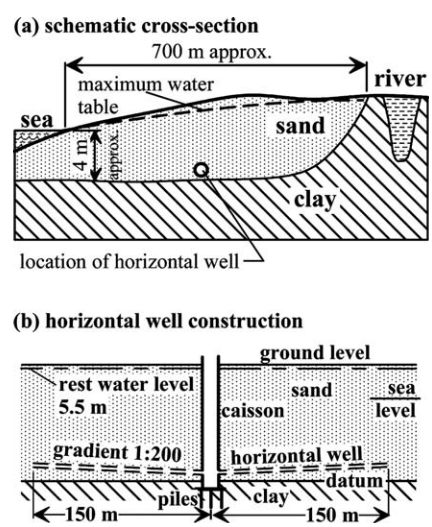

Figure 1 Representative cross-section and construction of horizontal well at Loba.