Prediction of Flow Rates for Potable Water Supply from Directionally Drilled Horizontal Wells in River Sediments

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ABSTRACT
Horizontal wells installed by directional drilling in the highly permeable river bottom sediments can improve the quality of water delivered to water treatments plants by filtration of suspended solids and dilution with groundwater. Predicting the flow rates available from horizontal wells is an important step in evaluating the technology, so a series of three-dimensional finite-element models were developed to evaluate this. Initially, the model was calibrated to match measured flow rates from a pilot-scale horizontal well test cell. The calibrated model was then used to simulate a horizontal well located beneath a river and a parametric analysis of predicted flow as a function of the design parameters pipe length, pipe diameter, depth below river bottom and sediment hydraulic conductivity was conducted to determine optimum horizontal well configurations. The effects of well screen hydraulics were also included in the model. The results of the numerical models indicated that the frictional head losses in the well screen have a significant impact on predicted flow rates. The analysis of well length and pipe diameter indicates that for each specific well configuration there exists an optimum length, beyond which no increase in flow occurs. The modelling results indicated that maximum flows occur when horizontal wells are placed as deep as possible until it is within 0.5 to 2.5 m of an impermeable lower boundary. The results of the study indicate that horizontal wells may be a viable alternative to obtain water from river bottom sediments for a water treatment plant.

RESUME
Les puits horizontaux installés par entraîner directionnel dans les extrêmement sédiments de lit de rivière de perméabilité peuvent améliorer la qualité d'eau livrée pour arroser des plantes de traitements par le filtrage de solides et la dilution suspendus avec l'eau souterraine. Prédire les débits disponibles des puits horizontaux sont une étape importante dans évaluer la technologie, donc un feuilleton de modèles de fini-élément à trois dimensions a été développé pour évaluer ceci. Au début, le modèle a été calibré pour égaler des débits mesurés d'une cellule de test de puits horizontale pilote-à l'échelle. Le modèle calibré a été alors utilisé pour simuler un puits horizontal localisé en dessous d'une rivière et une analyse paramétrique de flux prédit comme une fonction des paramètres de conception, la longueur de tuyau, le diamètre de tuyau, la profondeur au dessous du lit de rivière et au dessous du sédiment conductivité hydraulique a été dirigée pour déterminer les configurations de puits horizontales optimum. Les effets de bien hydraulique d'écran a été aussi incluse dans le modèle. Les résultats des modèles de rivière numériques ont indiqué que les pertes de tête de friction dans l'écran de puits ont un impact significatif sur les débits prédits. L'analyse de bien diamètre de longueur et tuyau indique que pour chaque configuration de puits spécifique existe là-bas une longueur optimum, au delà de qui aucune augmentation dans le flux arrive. Les résultats de modelage ont indiqué que les fluxs maximums arrivent quand les puits horizontaux sont placés le plus comme possible jusqu'à ce que c'est dans 0,5 à 2,5 m d'une frontière plus basse imperméable. Les résultats de l'étude indiquent que les puits horizontaux peuvent être une alternative viable pour obtenir de l'eau des sédiments de lit de rivière pour une plante de traitement d'eau.

1. INTRODUCTION

Horizontal wells placed in the high-permeability sand and gravel sediments beneath rivers (Figure 1) should possess some advantages over the intake structures commonly used by water treatment plants. The quality and variability of the water pumped from a conventional intake structure is identical to river water; it contains the same concentration of suspended solids and pathogens, and fluctuates between the same extremes of quality. Horizontal wells installed by directional drilling could improve some of the characteristics (e.g., turbidity) of the water supplied to treatment plants. Water would flow from the river to the horizontal well through the sand and gravel in the riverbed, where the concentration of suspended solids and pathogens would be reduced by filtration (particle straining, adsorption and biological degradation) and dilution with groundwater (Ray *et al.*, 2002). In addition, the volume of the riverbed sediment should buffer changes in river water quality, leading to a more uniform raw water supply. Because significant amounts of chemicals, such as alum, are used to remove suspended solids from the raw water supply (EPCOR Water Services Inc., 2002), a cleaner water supply should reduce required dosages and cost to treat. Predicting the flow rates available from horizontal wells is an important step in evaluating the technology.

The objective of the study was to estimate the flow rates produced by a horizontal well located in the sand and gravel sediments beneath a river, and evaluate the influence of several factors on the yield. The work took place in three stages: pilot-scale tests conducted on sample well screens, numerical modelling of the flow rates from the pilot-scale test equipment, and numerical modelling of the flow rates from a full-scale horizontal well installation. In the pilot-scale tests, the flow rate of filtrate and filtering performance from several soil-well screen combinations was measured. A three-dimensional finite-element model of the test equipment was developed, using measured material properties to match the measured flow rates. The objective of this study is the prediction of the potential yield from a full scale installation beneath a river using a three-dimensional finite-element model which includes the effects of well bore hydraulics. The study also includes a sensitivity analysis of the results to several design parameters and material properties.

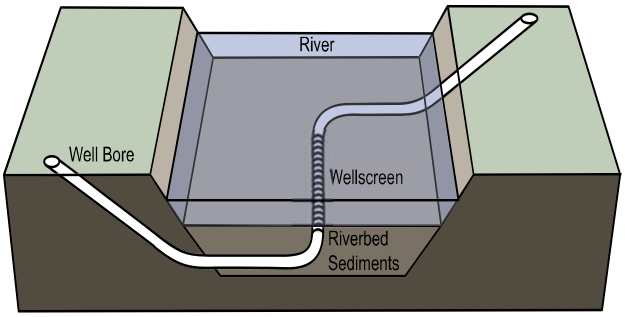

Figure 1 – Potential HDD drill path for potable water production (not to scale)

2. NUMERICAL MODEL SETUP

2.1 Software

Numerical modelling for this study was performed with two commercially available software packages: FlexPDE™ (PDE Solutions, 2002) and SVFlux™ (SoilVision Systems Ltd., 2002). SVFlux is a pre-processor that produced the text input files (which were then modified) for use by FlexPDE. FlexPDE, a solver and post-processor, uses the finite-element method (FEM) to solve partial differential equations. The program automatically generates and refines the mesh, with user control over mesh density and solution accuracy. The three-dimensional numerical models were constructed by extruding two-dimensional regions into multiple layers with variable material properties and boundary conditions in each layer.

2.2 Riverbed Model Geometry

In the hypothetical riverbed under consideration, the horizontal well was located directly below the center of the river. Because this simple conceptual model was symmetric, the domain of the numerical model (Figure 2) used to represent it consisted of one-half of the aquifer, river and well screen. The half-width riverbed model measured 12m high, 65m wide and from 250m to 700m long, depending on the length of the well screen (the model domain always extended 100m beyond the ends of the proposed well screen). A 25m wide river was incised 2m into the top of the aquifer. The well screen varied from 50 to 500m in length (L), from 100 to 300mm in diameter (Ø), and was located between 2.5 and 9.5m below the base of the river (D).

2.3 Riverbed Model Boundary Conditions and Material Properties

The model of the horizontal well and riverbed was constructed to generalize riverbed geometry and minimize computation time. The river channel surfaces (the side and bottom of the river) and the upstream and downstream faces of the model domain were represented by constant-head boundaries (using head values of 12m on these faces). The open end of the well screen was also modelled as a constant-head surface, using a head value equal to the elevation of the well screen (i.e., zero pressure and zero velocity head). All other exterior surfaces of the model domain were represented by zero-flux boundaries.

Horizontal hydraulic conductivity (k_h) in the riverbed model was varied from 10^{-3} m/s to 10^{-6} m/s to cover the range of values reported in the literature (e.g., Karanth, 1997, Mikels, 1992 and Ray *et al.* 2002). Anisotropy (k_h/k_v) was set at 10 for all cases.

2.4 Incorporation of Well Hydraulics

Two methods were used to simulate the well hydraulics in the riverbed numerical simulations. The first method which is described below uses a uniform conductivity based on an average velocity of water in the well screen. The second more rigorous approach assumed that velocity in the well, rather than being constant, was a function of the location along the well screen (z). The rigorous approach also included the effect of radial inflow on the calculation of friction factor. Both methods provided similar results and details of the rigorous methods and it comparison to the uniform conductivity methods are presented in Birch, (2003).

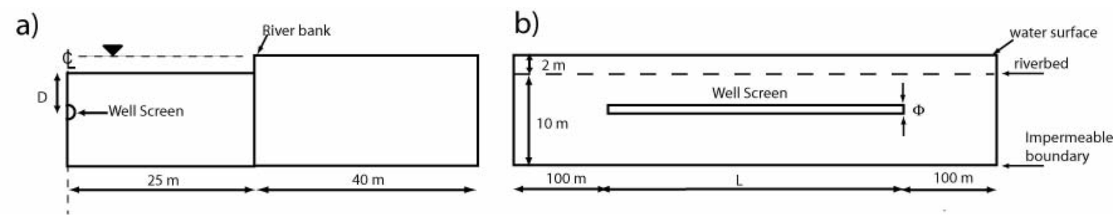

Figure 2 – Riverbed model dimensions (not to scale) :a) transverse section b) longitudinal section

To model the connecting pipe correctly, the pipe walls had to be considered perfectly impermeable. Rather than using a very low hydraulic conductivity, which caused numerical instability with the software, the pipe walls were treated as a void. Voids are regions of the model where the mesh is not created, so no flow can occur through them, and are therefore treated as perfectly impermeable materials. Examination of the model results confirms that the void region functioned as intended.

Assigning the properties of the well screen and the inside of the connecting pipe to accurately simulate frictional head losses was more complicated. From Darcy's equation,

$$k = \frac{V}{i} \quad [1]$$

where V is velocity (m/s), i is gradient, and the hydraulic conductivity k (m/s), is a constant for a homogeneous and isotropic porous medium. In pipe flow, however, the gradient ($\Delta hf/L$) is proportional to the square of the velocity, as seen after rearranging the Darcy-Weisbach equation:

$$\frac{\Delta h_f}{L} = \frac{fV^2}{2gØ} \quad [2]$$

where Δh_f is head loss due to friction (m), L is pipe length (m), f is friction factor, g is gravitational acceleration (9.81 m/s^2), and Ø is the pipe diameter (m). Adding to the differences between pipe flow and flow through porous media, the friction factor, f, is usually calculated as a function of the Reynold's number, R_e: as seen in Haaland's equation (Haaland, 1983):

$$f = \left[1.8\log_{10}\left(\frac{6.9}{R_e} + \left(\frac{\varepsilon}{3.7Ø}\right)^{1.11}\right)\right]^{-2} \quad [3]$$

$$R_e = \frac{VØ}{\nu} \quad [4]$$

where ν is kinematic viscosity (m^2/s), Combining Equations [1] through [4] yields

$$k = \frac{2gØ}{V}\left[1.8\log_{10}\left(\frac{6.9\nu}{VØ} + \left(\frac{\varepsilon}{3.7Ø}\right)^{1.11}\right)\right]^{2} \quad [5]$$

where ε is pipe roughness (m). The kinematic viscosity of water, ν, was set at 10^{-6} m^2/s for all model runs. Pipe roughness, ε, was set differently for the two materials subject to pipe flow: 10^{-3} m for the well screen, and 10^{-5} m for the connecting pipe.

Because FlexPDE does not solve different constitutive equations in different regions of the model domain (i.e., one equation governing flow through porous media and another equation governing flow through pipes), modelling head losses due to friction in the well screen required assigning values of hydraulic conductivity to the well screen that would simulate the head losses caused by pipe flow. From Equation [5], the hydraulic conductivity at any point in the well screen was a function of several constants (diameter, Ø, roughness, ε, and viscosity, ν) and one unknown variable (velocity, V). Two ways of approximating the hydraulic conductivity along the well screen were considered: first by using the average velocity of water in the well screen to calculate the hydraulic conductivity in Equation [5], and secondly by using a simple function, V(z), in Equation [5] to calculate a function describing the hydraulic conductivity along the well screen. The first method was used in the all simulations presented in this paper The second method was used in a few simulations to compare to results from the uniform hydraulic simulations. Details of the simulations and how they compare are presented in Birch (2003).

Using a uniform hydraulic conductivity applied to the well screen was a simple and efficient approximate solution to the problem of modelling pipe hydraulics with porous media. The average velocity of water in the well screen, as computed by the numerical model, was used in Equation [5] to calculate the hydraulic conductivity of the well screen. A simple iterative procedure where the well screen pipe conductivity and exit head were adjusted until the well conductivity changed by less than 1% between iterations. Details of the iterative approach are present in Birch (2003).

3. NUMERICAL MODEL RESULTS AND DISCUSSION

The numerical model of the riverbed was solved using a range of values for several design variables. From a base case of aquifer horizontal hydraulic conductivity (k_h) = 10^{-3} m/s, well screen diameter (Ø) = 300mm, length (L) = 250m and depth (D) = 5.0m, the following variations were made:

Horizontal Hydraulic Conductivity – 10^{-3}, 10^{-4}, 10^{-5}, and 10^{-6} m/s

Diameter – 100, 200 and 300mm

Length – 50, 100, 175, 250 and 500m

Depth – 2.5, 5.0, 7.5 and 9.5m

Hydraulic conductivities were chosen to cover the range of values reported in the literature from horizontal collector well and infiltration gallery installations. The ranges of diameters and lengths are based on the limitations of HDD installation techniques. The range of depths proceeds from an estimated minimum depth of 2.5m (considering factors such as riverbed scour and hydraulic fracture) to a depth of 9.5m, or 0.5m above the base of the model domain. Using the uniform conductivity solution to calculate frictional head loss along the well screen described above, the computed rates of flow at the open end of the well from these combinations are plotted against well screen length in Figure 3 to 6 The model results provide the rate of flow out of the open end of the well under the condition of atmospheric pressure and zero velocity head at the opening. This would simulate, for example, the well draining into a sump from which water was pumped at a rate sufficient to maintain the water level in the sump at the elevation of the well.

The curves of flow rate vs. length are easily interpreted in the context of wellbore hydraulics. The rate of inflow (m^3/s per metre length) at a given point in the well depends (in part) on the total head in the well at that point – lower head in the well produces more inflow, and higher head produces less inflow. Because water flows toward the open end of the well (and head decreases in the direction of flow due to friction), the head in the well is lowest at the well's open end (the heel) and highest at the well's closed end (the toe). Longer well lengths and smaller well diameters increase the frictional head losses in the well, accentuating the head difference between the heel and toe and reducing the rate of inflow at the toe. Figures 3 through 6 clearly show this trend: the curves of flow rate vs. length have smaller slopes ($\partial Q/\partial L$, or the rate of inflow at the toe of the well) at longer lengths and smaller diameters. This effect is more pronounced with high aquifer hydraulic conductivity because the peak flow velocities (and thus the total head losses due to friction) are larger.

The plots of flow rate vs. length also comment strongly on the optimization of well design, both in terms of length and diameter. From Figures 3 through 6 it can be seen that frictional head losses act to diminish the additional flow delivered by increasing well lengths. At some optimum length (which can only be accurately determined by analyzing the economics of horizontal well installation, a topic beyond the scope of this work but covered adequately by Cho and Shah, (2002) the additional flow produced by extending the well would not justify the cost of extending the well. In Figure 3, where the horizontal hydraulic conductivity in the aquifer is 10^{-3} m/s, one can see from the slopes of the curves that the optimum length of a 300mm-diameter well (250m to 300m) is significantly longer than the optimum length of either a 200mm- or 100mm-diameter well (approximately 125m and 75m respectively). At an aquifer hydraulic conductivity of 10^{-6} m/s (in figure 6) however, the optimum lengths for the three well diameters are all greater than 500m because even at this length, inflow rates and frictional head losses are too small to be significant. It also appears that horizontal wells should be designed with the largest feasible diameter. In cases where head losses are significant (for example, when aquifer hydraulic conductivity is 10^{-3} m/s and length is 500m) it appears that increasing diameter from 100mm to 300mm more than a triples flow from the well. While bigger is better, the best well diameter will be a function of economics and HDD installation techniques as well as flow rates.

Figure 7 shows the response of the model to the depth of the well beneath the river. The increasing head difference with increasing depth results in increased flow rates. As the well location nears the base of the aquifer, simulated by an impermeable boundary, the flow rate levels off. Between 7.5m and 9.5m below the river (i.e., between 2.5m and 0.5m above the base of the aquifer), the effects of the impermeable boundary become significant, as the flow of water into the well from below becomes restricted. The results indicate that the maximum flow rate is achieved from wells placed as far below the river bottom as possible. In reality though, it is likely that this determination will require an analysis of the construction and operation costs associated with horizontal wells, the limitations of the HDD installation technique, the distribution of hydraulic conductivity in the aquifer, and a better understanding of the boundary conditions acting on the riverbed aquifer.

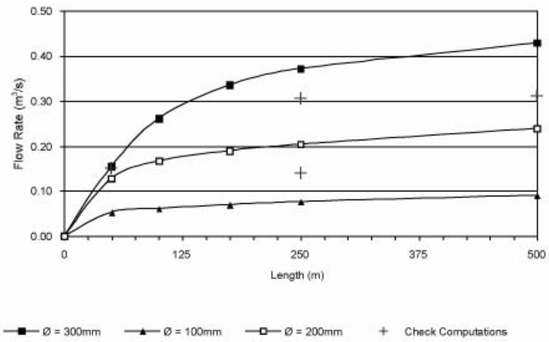

Figure 3 – Flow rate vs. length: hydraulic conductivity (k_h) = 10^{-3} m/s, depth = 5m

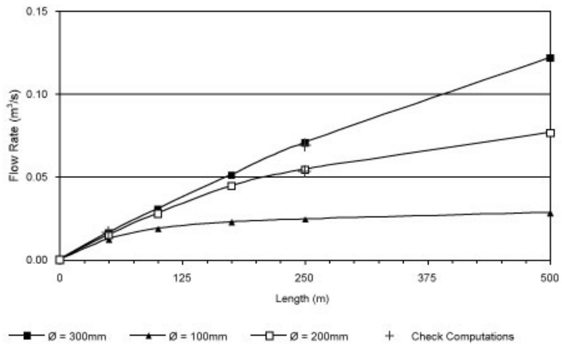

Figure 4 – Flow rate vs. length: hydraulic conductivity (kh) = 10-4 m/s, depth = 5m

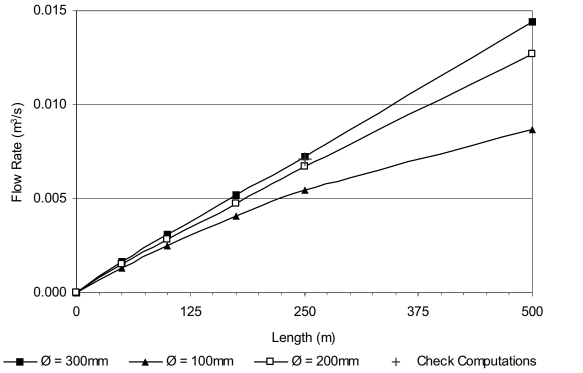

Figure 5 – Flow rate vs. length: hydraulic conductivity (kh) = 10-5 m/s, depth = 5m

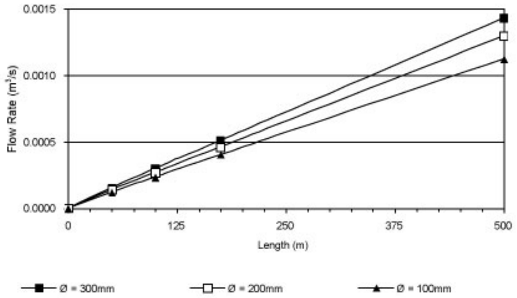

Figure 6 – Flow rate vs. length: hydraulic conductivity (k_h) = 10^{-6} m/s, depth = 5m

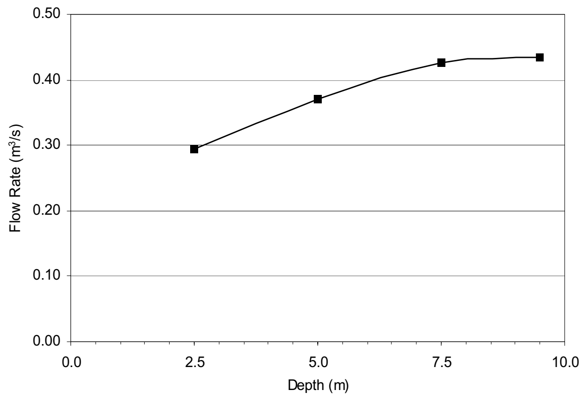

Figure 7 – Flow rate vs. depth: hydraulic conductivity (k_h) = 10^{-3}

The check computations presented in Table 1 and shown in Figures 3 to 6 represent instances where variable velocities were used in the calculation of frictional head losses along the well screens. They show good agreement with the uniform conductivity predictions in most cases. The two solution methods are closest in cases where frictional head losses are small (i.e. where *V(z)* varies linearly over the length of the well because the rate of inflow along the length of the well screen is relatively uniform). In these cases, the rigorous solution tends to predict flow rates within 3% of the uniform conductivity results. Where the head losses in the well screen are larger (i.e. where *V(z)* is non-linear because more inflow occurs near the heel of the well than near the toe), the difference between the uniform conductivity and rigorous solutions increases to as much as 32%. At most points, the two solution techniques predict flow rates close enough to each other to be confident in the results of either. The ease of use and time savings associated with the uniform conductivity solution method seem to be worth the potential error.

Table 1– Riverbed model flow rate computations for select cases

Length (m)	Diameter (mm)	Aquifer Permeability (m/s)	Flow Rate (m^3/s) Uniform Permeability	Rigorous Solution (Linear or Exponential)	Difference (%)
50	300	10^{-3}	0.155	0.151 (L)	-2.0
50	300	10^{-4}	0.017	0.016 (L)	-2.3
250	300	10^{-3}	0.371	0.305 (E)	-17.9
250	300	10^{-4}	0.071	0.069 (L)	-2.2
250	300	10^{-5}	0.007	0.007 (L)	-2.4
250	200	10^{-3}	0.204	0.139 (E)	-31.7
250	200	10^{-4}	0.055	0.053 (L)	-2.8
500	300	10^{-3}	0.428	0.311 (E)	-27.3

Model output also included the solution mesh generated by FlexPDE, the calculated flow velocity and total head in the aquifer and well screen, as seen in Figures 8 to 12, and the equivalent hydraulic conductivity assigned to the well screen (Figure 13) These figures reveal some useful information not apparent from an examination of the flow rates alone. For example, the contours of total head (also known as equipotentials, or lines perpendicular to the direction of flow) seen in Figure 8 indicate that water flows from the river to the well screen through the region of the aquifer not directly beneath the river, and suggest the importance of including this region in future site investigations. The equipotentials in Figures 9 and 10 show that water flows into the well screen from the regions beyond the ends of the well screen, and that groundwater in the riverbed flows preferentially towards the heel end of the well. The profile of total head in the well screen in Figure 11 shows frictional head losses of approximately 5m between the toe and heel of the well. The slope of the profile of axial velocity in the well screen (Figure 12) increases towards the heel end of the well screen (at z = 250m), indicating the greater rate of inflow at that end, where the total head is lowest. Finally, the hydraulic conductivity assigned to the well screen, seen in Figure 13, decreases from a maximum of approximately 1200 m/s at z = 0m (where velocity is lowest) to a minimum of approximately 40 m/s at z = 250m (where velocity is highest).

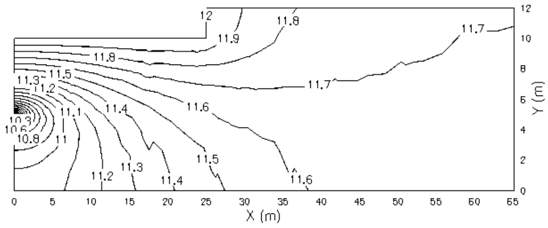

Figure 8 – Riverbed model output: transverse section view of contours of total head at z = 125m: L = 250m, Ø = 300mm, $k_h = 10^{-3}$ m/s

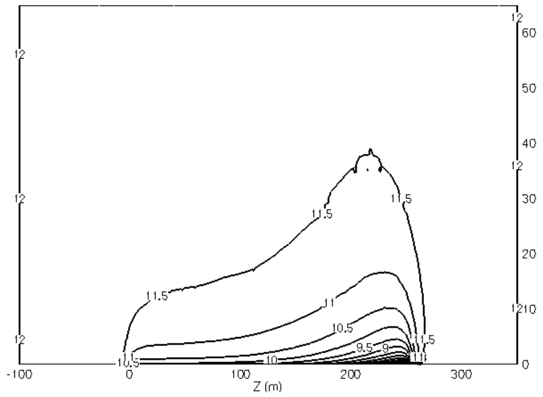

Figure 9 – Riverbed model output: plan view of contours of total head at y = 5m: L = 250m, Ø = 300mm, $k_h = 10^{-3}$ m/s

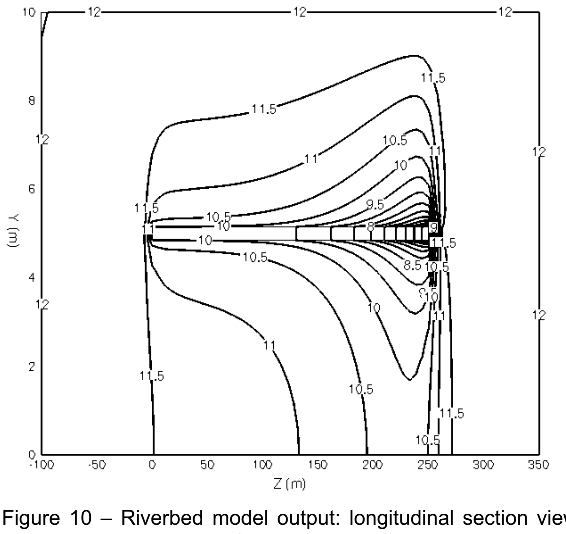

Figure 10 – Riverbed model output: longitudinal section view of contours of total head at x = 0m: L = 250m, Ø = 300mm, $k_h = 10^{-3}$ m/s

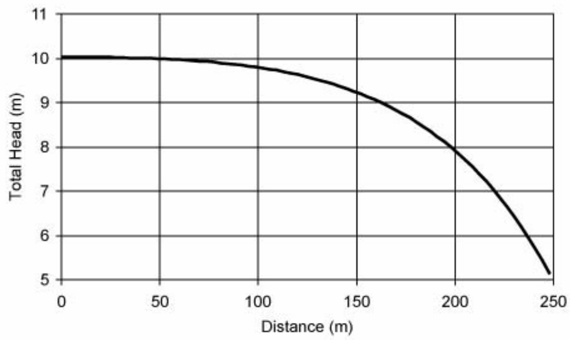

Figure 11 – Example riverbed model output: profile of total head along axis of well screen: L = 250m, Ø = 300mm, $k_h = 10^{-3}$ m/s

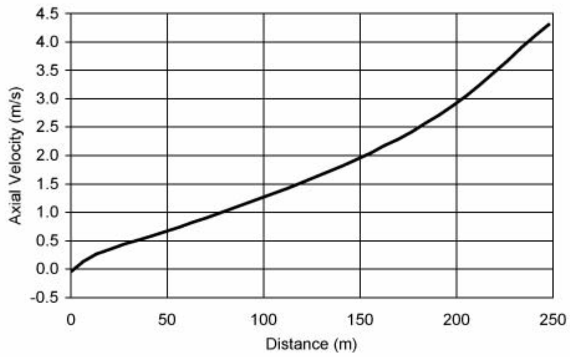

Figure 12 – Example riverbed model output: profile of axial velocity along axis of well screen: L = 250m, Ø = 300mm, $k_h = 10^{-3}$ m/s

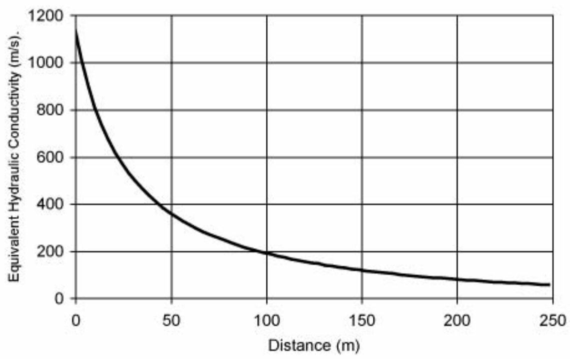

Figure 13 – Example riverbed model output: profile of equivalent hydraulic conductivity along axis of well screen: L = 250m, Ø = 300mm, $k_h = 10^{-3}$ m/s

The results of these numerical models were compared with the reported performance of horizontal collector wells and infiltration galleries in Table 2. While none of the cases reported in the literature exactly match the design parameters used in the riverbed model, the ranges of well lengths, depths, diameters and aquifer hydraulic conductivities are approximately the same. The rates of inflow per metre length are very similar between each of the cases reported in the literature and the results of the riverbed numerical model. The maximum rate of inflow per metre length calculated by the numerical model ($3.1x10^{-3}$ $m^3/s/m$) is larger than the largest of the reported inflow rates ($1.9x10^{-3}$ $m^3/s/m$), but the difference is small and is not considered to be significant. The close agreement suggests both that the numerical model is relatively accurate, and that horizontal wells could be economically used for the provision of potable water.

Table 2 – Inflow rates from published studies and select numerical model results

Source	Well Length (m)	Well Diameter (mm)	Well Depth (m)	Aquifer Hydraulic Conductivity (m/s)	Rate of Inflow ($m^3/s/m$)
Ray *et al.* (2002)	41 to 72	200 to 300	15 to 25	N/A	$1.1x10^{-3}$ to $1.9x10^{-3}$
Karanth (1997)	76 to 762	310 to 1000	6	$5.0x10^{-5}$ to $8.0x10^{-3}$	$1.2x10^{-4}$ to $1.1x10^{-3}$
Mikels (1992)	6 to 21	N/A	6	$1.3x10^{-3}$ to $3.1x10^{-3}$	$1.4x10^{-3}$ to $1.9x10^{-3}$
Obst (1974)	36	200	N/A	$1.4x10^{-3}$	$4.5x10^{-4}$
this study (selected data points only)	50 to 100	200 to 300	5	$1.0x10^{-4}$ to $1.0x10^{-3}$	$2.8x10^{-4}$ to $3.1x10^{-3}$

3.1 Limitations of Numerical Modelling

The numerical riverbed model examined the sensitivity of flow rates to the most important design variables (well screen length, diameter and depth), but several other parameters were not given the same treatment. One would expect the flow rate from a horizontal well to be sensitive to total aquifer thickness, river stage (the elevation of water in the river channel), well placement (distance from the center of the river), well inclination (deviation from horizontal), well orientation (parallel, perpendicular or angled to the direction of flow in the river), and numerous other site-specific details (e.g., material heterogeneity and anisotropy). At present it is unclear how these factors will affect results, but the importance of each should be examined before the installation of a full-scale directionally drilled horizontal well.

3.1.1 The Hyporheic Zone

The proposed horizontal directionally drilled wells considered in this study will be placed in a region of soil known as the hyporheic zone – the volume of saturated sediment beneath a river or stream containing a mixture of surface water and ground water (Woessner, 2000; White, 1993). Because the quantity of water produced by the horizontal wells will be affected by the properties of the hyporheic zone (e.g., the extent of the region and the hydraulic conductivity of the sediments) a complete understanding of the hyporheic zone allow better predictions of well performance. Based on the results shown in Figure 7, neglecting groundwater inflow would likely underestimate well production.

In the numerical models presented above, the riverbed aquifer was considered to be recharged by river water alone. In reality, the alluvial sediment in the riverbed is impacted jointly by river water and the local hydrogeologic regime. Horizontal collector wells described by Ray *et al.* (2002) have been shown to draw approximately 30% of their total supply from groundwater. A proper appreciation (and representation in numerical models) of the hyporheic zone will be needed in any complete understanding of flow into a horizontal well. This is a complicated system, and one that is beyond the scope of this study.

4. CONCLUSIONS

Evaluating the potential for horizontal wells to be used as an alternative intake structure for water treatment plants involved measuring the performance of pilot-scale test equipment, and using numerical modelling to simulate the experimental results and to predict the performance of full-scale horizontal well installations.

A three-dimensional finite-element model of a field pilot scaled test was constructed using SVFlux™ and FlexPDE™ to try to match the measured flow rates. Using the best estimates of the hydraulic conductivity of the sand from the test boxes, the numerical model predicted flow rates above median measured values, but below experimental maximums. The numerical model results matched the measured flow rates when hydraulic conductivities were lowered to reasonable lower-bound limits.

A three-dimensional finite-element model of a horizontal well placed in the sediment beneath a river was then constructed. The flow rate from the well, under conditions of zero pressure and zero velocity head at the well opening, was computed. The sensitivity of the model results to several parameters – well length, depth and diameter and aquifer hydraulic conductivity – was examined. Two methods of simulating pipe hydraulics in the well screen were considered, with generally close agreement. The results indicate the significant effect of frictional head losses in the well screen on flow rates, and the importance of optimizing well design. At higher aquifer hydraulic conductivities (above 10^{-4} m/s), maximizing well diameter is important, while less difference between computed flow rates is seen at lower hydraulic conductivities. The optimum length for horizontal wells, the length of well above which flow rates increase little, is also seen in the results. Finally, the numerical model results agree well with the rates of inflow per metre length of well reported by several authors.

Only a small number of the many factors affecting the flow rate from a directionally drilled horizontal well were considered in this study. Accurately calculating the flow rates from the installation of a full-scale horizontal well will require a more detailed analysis, including a number of site-specific parameters such as material heterogeneity and aquifer boundary conditions. Assuming the errors in calculating the flow rates in this study are small, this technique of extracting water from a river should be both feasible and practical for water utilities.

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