Mine Water Environ (2011) 30:90–104
DOI 10.1007/s10230-011-0149-1

TECHNICAL ARTICLE

Dewatering of Multi-aquifer Unconsolidated Rock Opencast Mines: Alternative Solutions with Horizontal Wells

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Received: 2 December 2010 / Accepted: 28 March 2011 / Published online: 13 April 2011

Abstract Horizontal directional drilling (HDD) can be a cost-effective way to dewater excavations and surface mines. Laboratory and field experiments provided insight into the important processes involved and allow us to reproduce them through modelling. A new algorithm based on the flow equation by Manning–Strickler was developed and introduced into the groundwater model, PCGEOFIM®, which allows one to calculate open channel flow within HDD wells. The experimental and numerical results clearly showed that HDD wells have certain advantages over vertical wells, such as more cost effective dewatering in thin aquifers. Additionally, free flowing HDD wells dewatering technology allow mining to proceed without requiring the removal of the wells.

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Keywords Mine dewatering · Horizontal directional drilling · Modeling of groundwater flow with horizontal wells · PCGEOFIM · Dewatering experiments · Central Germany

Introduction

Many mining and engineering projects require dewatering of underground aquifers to ensure safe and efficient excavation, transportation, and dumping of excavated material. Generally, vertical wells are used to dewater open pit mines and building excavations. Vertical wells have a short screened section, particularly in thin aquifers. In addition, the effective screened section is continuously being reduced by the dewatering process. On average, vertical wells have a maximum pumping rate of 1–2 m^3/min. As a result, in thin aquifers, many closely spaced vertical wells are needed to effectively dewater an area. All these vertical wells require pumps of lower capacity that are less efficient than one large pump with the same total capacity. In addition, each well needs its own electrical equipment and piping systems as well as control and feedback systems.

Horizontal well technology, based on horizontal directional drilling (HDD) (Fengler 1998; Kleiser and Bayer 1996) (see Fig. 1), is the subject of ongoing investigations. It can (partially) dewater thin-seam aquifers by gravity flow. The recovered water is directed into sumps located in the pit, from where it can be removed with large and efficient pumps. Because horizontal wells have long screened sections, recovery rates are typically significantly higher than those of vertical wells. Consequently, fewer wells are needed for the same dewatering effort, requiring less pumping energy and materials.

Fig. 1 Installing an HDD well with a 12 tonne drill rig in a lignite mine

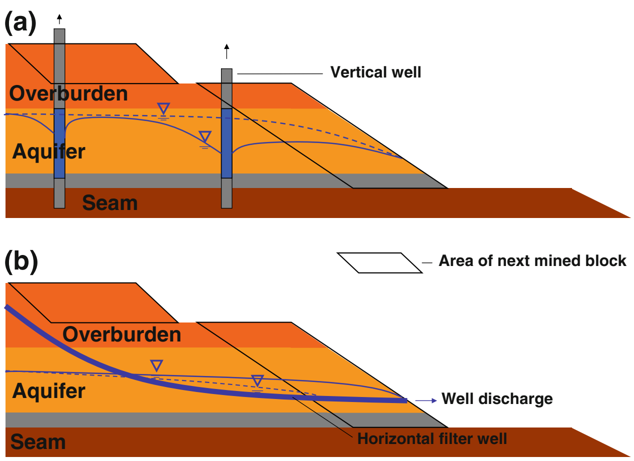


Fig. 2 **a** Interruption of dewatering with vertical field wells before excavation. The pumping has to stop days or weeks before the moving face reaches the wells. **b** Stable dewatering with horizontal well with free discharge even during excavation. The pumping can continue throughout the whole excavation period

In addition to these hydrological, energetic, and material advantages of HDD wells, there can be operational and technological benefits as well. As an example, Fig. 2 compares the effects mining would have on a group of vertical wells and on a HDD well. When the cutting face reaches a vertical well field (Fig. 2a), the dewatering operations have to be interrupted before the excavation reaches them. This results in a rising water level near the slope. In contrast, horizontal wells with gravity discharge (Fig. 2b) can work without interruption because the well itself can be excavated. This allows for continuous dewatering and prevents rebound of groundwater levels (Struzina and Drebenstedt 2008).

Even if site conditions prevent gravity flow from HDD wells, the well head can be positioned outside the drainage area. This allows operating wells below actively mined pits. This setup is not possible with vertical wells.

Well Equations

The flow of groundwater and dewatering processes in open pit mines are usually represented with numerical groundwater models. One-phase flow is generally adequate to model field scale groundwater flow in two and three dimensions. The mathematical formulation of the process is based on Darcy's Law (Eq. 1)

$$v_f = -k_f \cdot \text{grad}\ h \tag{1}$$

where v_f is the filter velocity, k_f is the permeability coefficient, and h is the hydraulic head. The specific storage is calculated by Eq. 2 (David 1998);

$$S_0 = n_e \cdot \rho g \beta_f, \tag{2}$$

In Eq. 2 S_0 represents the specific storage, ρ the fluid density, n_e effective porosity, and β_f the fluid compressibility coefficient. Rock compressibility is assumed to be negligible. For unconfined conditions the liquid is assumed to be incompressible, i.e. $S_0 = n_e$. Considering mass continuity, sources and sinks, and specific storage, the integrations of the flow equation can be written as Eqs. 3 and 4.

$$\frac{\partial}{\partial t}\int_{z}^{h}\iint_{\Delta A_{ijk}} n_e \,\mathrm{d}A\,\mathrm{d}z = \iint_{\Delta O_{ijk}} k_f \text{ grad } h \,\mathrm{d}o + V_{q\,ijk}$$
(unconfined case)

$$(3)$$

$$\frac{\partial}{\partial t}\iiint_{\Delta V_{ijk}} S_o h \,\mathrm{d}V = \iint_{\Delta O_{ijk}} k_f \text{ grad } h \,\mathrm{d}o + V_{q\,ijk} \tag{4}$$
(confined case)

with V_q = volume of sources and sinks, A = area, o = area of element surface, t = time. This formulation is used in the finite-volume-method-based numerical software, PCGEOFIM® (Müller 2007). Aquifer anisotropy in PCGEOFIM® is determined by the conductivity tensor $\underline{K}$

$$k_f = \underline{K} = \begin{Bmatrix} k_x \\ k_y \\ k_z \end{Bmatrix} = \begin{Bmatrix} k_{xy} \\ k_{yx} \\ k_z \end{Bmatrix} \tag{5}$$

with $k_z = \beta \cdot k_{xy} = \beta \cdot k_{yx}$ and β as global anisotropy factor.

Many authors have analyzed the flow to horizontal wells and found analytical or empirical solutions that are generally suitable for the conditions shown above. Several methods that describe the processes around horizontal wells are designed for classical horizontal wells with one vertical central collection well with radial filter screens. Analytic analysis of this well type can, according to Busch et al. (1993), be based on that for the fully penetrating vertical well using a virtual surrogate radius. Examples of investigations for this well type are provided by Lass (1975), Offerhaus (1961), and Rueckert (1977).

Lass (1975) looked for analytic solutions based on potential theory by treating the radial filter screens as fully penetrating vertical wells with surrogate radii. Similarly, Rueckert (1977) developed analytical solutions based on potential theory, applying surrogate radii for $\geq$4 filter screens. Offerhaus (1961), on the other hand, used an empirical approach to analyze pumping data.

In contrast to classical horizontal wells, where screen sections are radially arranged and connected to a central vertical shaft, HDD wells have one screen section that is typically longer. Instead of the aerial withdrawal of classical horizontal wells, they cause line withdrawals. Therefore, the methods described above may not apply. Although Aguilera et al. (1991) suggested that the surrogate radii approach can be used for line elements under ideal conditions, Sass (1994) disagreed and pointed out that this approach introduces unacceptable inaccuracies. Busch et al. (1993) also advised against the surrogate radii approach for horizontal elements or long galleries of vertical wells.

Wildenhahn (1972) used potential theory to calculate the yield from horizontal wells by integrating point sinks into a line sink. Zhan and Park (2003), Zhan and Zlotnik (2002), and Zhan et al. (2001), built on this approach and used Laplace and Fourier transformations, eliminating space and time to solve the differential equation in closed form. However, they did not provide a closed solution that can be transformed back, so this approach has no practical applications (Müller et al. 2009). Park (2002) presents a solution based on Laplace transformation and back transformation into the dimensionless original space. He investigated the systematic behavior of horizontal wells around the screen, taking into account skin effects, anisotropy, reservoir outflow, and inflow from the aquifer above. He did not consider the effect of the flow in the well itself. Park (2002) provided the following relation, which is valid under the condition that the reservoir inflow is zero and the whole inflow into the horizontal well comes from the aquifer outflow:

$$Q = 2 \cdot \pi \cdot r_w \cdot L_w \cdot \frac{k_{fS}}{D_S} \cdot (s_w - f) \tag{6}$$

Q is the well outflow, r_w is the well radius, L_w the length of filter section, k_{fs} is the conductivity of the skin layer, D_s is the thickness of the skin layer, s_w is the drawdown in the well, and f is the drawdown at the skin layer.

There are several model approaches in oil field exploration that characterize steady-state flow to horizontal wells (Borisov 1964; Giger 1983; Joshi 1988, 1991).

$$Q = 2 \cdot \pi \cdot k_{f_h} \cdot (H - h) \cdot \frac{1}{\{S_{R.-D}, S_{B.}, S_{G.}, S_{J.}\}} \tag{7}$$

S stands for solution and the indices *R.-D.*, *B.*, *G.* and *J.* stand for Renard-Dupuit (Joshi 1991), Borisov (Borisov 1964), Giger (Giger 1983), and Joshi (Joshi 1988), respectively. The detailed solutions can be written as follows:

$$S_{R.-D.} = \operatorname{arccos}\frac{2 \cdot a}{L_w} + \frac{h}{L_w} \cdot \ln\left(\frac{h}{2 \cdot \pi \cdot r_w}\right) \tag{8}$$

$$S_{B.} = \ln\left(\frac{4 \cdot R}{L_w}\right) + \frac{h}{L_w} \cdot \ln\left(\frac{h}{2 \cdot \pi \cdot r_w}\right) \tag{9}$$

$$S_{G.} = \ln\left(\frac{1 + \sqrt{1 - (L_w/(2 \cdot R))^2}}{L_w/(2 \cdot R)}\right) + \frac{h}{L_w} \cdot \ln\left(\frac{h}{2 \cdot \pi \cdot r_w}\right) \tag{10}$$

$$S_{J.} = \ln\left(\frac{1 + \sqrt{1 - (L_w/(2 \cdot a))^2}}{L_w/(2 \cdot a)}\right) + \frac{h}{L_w} \cdot \ln\left(\frac{h}{2 \cdot r_w}\right) \tag{11}$$

a at Eqs. 8 and 11 describes the length of the main axes of the ellipsoidal zone of the drainage area of the well (Eq. 12):

$$a = \frac{L_w}{2} \cdot \left[0.5 + \sqrt{0.25 + (2 \cdot R/L_w)^4} \right]^{0.5} \tag{12}$$

If anisotropy and skin effect must be considered, r_w at Eqs. 8–11 can be replaced by r_{eff} on the basis of Joshi (1991) and Sass (1994);

$$r_{\mathrm{eff}} = \left(\frac{(1+\beta) \cdot r_w}{2 \cdot \beta} \right) \cdot \exp\left(\left[\left(\frac{k_f}{k_{fS}} \right) - 1 \cdot \ln\left(\frac{r_S}{r_w} \right) \right] \right) \tag{13}$$

Aquifer anisotropy coefficient β can be written as follows (Joshi 1991; Sass 1994):

$$\beta = \sqrt{k_{f_h}} / \sqrt{k_{f_v}} \tag{14}$$

In Eqs. 7–14, H = hydraulic head at R, R = drainage radius, r_S = skin radius, k_{f_h} = horizontal conductivity, k_{f_v} = vertical conductivity.

Poweleit (1988) intensively investigated the flow to horizontal drainage structures in screens at the base of dams for unconfined, homogenous conditions. The flow in the well pipe is calculated by the conservation of momentum after Press and Schroeder (1966), and the Bernoulli equation with the resistance of flow according to Colebrook/White (cited in Zierep and Bühler 1996). The filter entry resistance is based on results of experiments for several combinations of screens and soil types.

The effect of horizontal wells in large-area groundwater models in PCGEOFIM had been calculated so far with an analytical solution for fully penetrating vertical wells adapted to horizontal conditions (Eq. 15).

$$Q = \frac{2 \cdot \pi \cdot k_f \cdot L_w}{\ln(r_a/r_w)} \cdot (h_w - h_{we}) \tag{15}$$

There, r_a stands for the half of the aquifer thickness, h_w for the water level in the well, and h_{we} for the water level in the finite volume element containing the well. Due to its origin from the steady-state analytical solution for the radial flow to a well, Eq. 15 is valid only for fully submerged filter screens and when the filter screen is in the center of the aquifer. Furthermore, no skin effects or impact of pipe flow are accounted for.

The methods presented above are designed for classical horizontal wells with several radial filter screens (Lass 1975; Offerhaus 1961; Rueckert 1977). Since the HDD wells used here have a significantly different design, these solutions cannot be used. The complex, closed, analytical solutions by Wildenhahn (1972), Zhan and Park (2003), Zhan and Zlotnik (2002) and Zhan et al. (2001) support investigations on well yield, influenced by different parameters especially for the space close to the filter screen. The solutions from oil field exploration by Borisov (1964), Giger (1983), Joshi (1988), and Renard-Dupuit (in Joshi 1991) are generally very suitable as solutions in large-area flow models. The different solutions provide very similar results (Joshi 1991). The problem is that the range of drawdown is needed for the calculations. This would require either reasonable approximations or an iterative solution of a numerical application.

Model Assumptions

There are problems modeling HDD wells using Eq. 15, as reported by Struzina (2005). Therefore, extensive research was planned to better describe HDD wells using numerical modeling. A different algorithm, based on Eq. 6, as described below, was developed to improve the accuracy of the representation of HDD wells in numerical models. The steady-state formulation of the flow in the aquifer calculated in this manner has significant advantages for the numerical, time-discrete calculation, compared to using Eqs. 7–12 and 15. There is no dependence on the range of drawdown or any aquifer properties. However, solving horizontal well problems using Eq. 6 requires the well parameters as asked by this formula and the groundwater flow through the aquifer (see Eqs. 1–4). Therefore, only numerical solutions that intrinsically account for aquifer properties may be used. PCGEOFIM calculates the conductance between well and aquifer based on a rearranged version of Eqs. 6, 16:

$$L_{B_i} = 2 \cdot \pi \cdot r_{w_i} \cdot L_{w_i} \cdot \frac{k_{fS_i}}{D_{S_i}} \tag{16}$$

where L_{B_i} represents the conductance between well and aquifer segment i. The drawdown at the skin layer may be neglected as a reasonable approximation, resulting in an inflow to a well element i, which can be calculated using Eq. 17:

$$q_{B_i} = L_{B_i} \cdot (h_{w_i} - h_{we_i}) \tag{17}$$

The flow in one well segment i, is Q_{B_i}:

$$Q_{B_i} = \sum_{1}^{i} q_{B_i} \tag{18}$$

Figure 3 shows schematics for these relationships for channel as well as pressure flows. The calculation of the flow in the well is shown below.

In practice, it is often difficult to avoid a skin layer around HDD-wells (Struzina 2005). Such skin layers may result from drilling fluid leftovers (difficult cutting removals from horizontal drill holes) and from difficulties in adjustment of opening width of filter pipe to the grain size distribution of heterogeneous aquifers. The skin effect can be parameterized using two different methods:

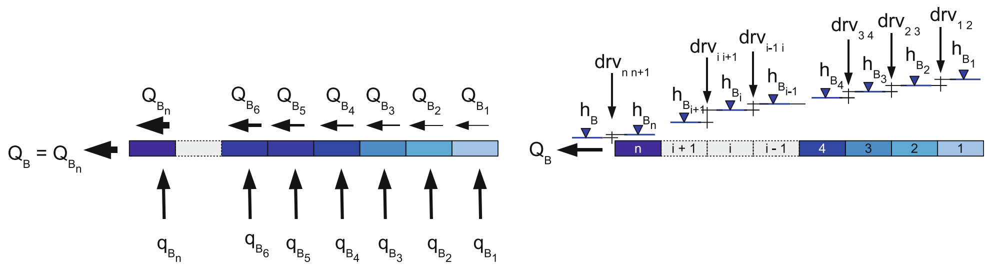


Fig. 3 Schematics of channel flow (*left*) and pressure flow (*right*) in the horizontal well screen as used in PCGEOFIM

(1) If sufficient data is available, k_{fs_i} and D_{S_i} can be chosen according to the actual well properties.
(2) Alternatively, the k_f–values from the containing finite volume element may be used for k_{fs_i}. Then the numerical value for D_{S_i} must be close to the numerical value of k_{fs_i}, so that $k_{fs_i}/D_{S_i} \approx 1$ and the skin resistance in Eq. 6 has no effect. Furthermore the well radius in PCGEOFIM (in Eq. 16) must be parameterized by $r_{w_i} = r_{\mathrm{eff}_i}$ using Eq. 13, considering well resistance within $r_{w_i} = r_{\mathrm{eff}_i}$. Since the anisotropy can be accounted for in PCGEOFIM, a value of $\beta = 1$ can be used.

The flow in the well can occur as free channel flow or as pressure flow. The free channel flow is calculated based on Manning–Strickler. The flow-water-level relationship is divided into three sections, following the findings of Bollrich and Melhem (1990) (Eqs. 19–21). The last section was modified and turned into a linear relationship to avoid numerical instabilities (Müller et al. 2009)

$$Q_{B_i} = M\,F\,R_{hy}^{2/3}\,I^{1/2} \quad \text{for } h_w/d \le 0.3 \tag{19}$$

$$Q_{B_i} = Q_{\mathrm{full}_i} \cdot (1.46 \cdot h_w/d - 0.24) \quad \text{for } 0.3 < h_w/d < 0.8 \tag{20}$$

$$Q_{B_i} = 0.928 \cdot Q_{\mathrm{full}_i} + \left(\frac{0.072 \cdot Q_{\mathrm{full}_i}}{0.2 \cdot d}\right) \cdot (h_w - 0.8 \cdot d) \quad \text{for } h_w/d \ge 0.8 \tag{21}$$

where Q_{B_i} represents the flow in the well segment, M the Manning–Strickler coefficient, F the flow cross section, R_{hy} the hydraulic radius, I the bottom slope, h_w the water level at the well, and d the well diameter. The maximum flow Q_{full_i} in a pipe is defined as $Q_{\mathrm{full}_i} = Q_{B_i}/0,928$ for Q_{B_i} according to the Manning–Strickler (Eq. 19) at $h_w/d = 0.8$. Figure 4 shows the three segments graphically.

The pressure flow is calculated with the flow equation from Chezy (Müller et al. 2009).

$$Q_B = \frac{\pi}{4} \cdot d^2 \cdot \sqrt{\frac{8 \cdot g}{\lambda}} \cdot \sqrt{R_{hy} \cdot I} \tag{22}$$

In Eq. 22, λ represents the pipe friction factor. The hydraulic radius of round pipes for pressure flow is $R_{hy} = d/$4. The experiments and the modeling described below were conducted to verify the assumptions concerning open channel flow for practical purposes.

Methods and Experimental Scales

To verify the model assumptions stated above, investigations were conducted at different scales or are planned. These include: micro-scale laboratory experiments (completed), meso-scale field tests (completed), and macro-scale field tests (planned).

The laboratory tests were conducted with screen lengths between 1 and 4 m and diameters between 32 and 100 mm. These dimensions were chosen to avoid significantly different physical effects from the field tests.

The test station shown in Fig. 5 has a base area of 6 × 6 m and a height of 2.5 m. It is partially filled with aquifer material with a volume of approximately 75 m^3. Three sides of the test station are equipped with devices to keep a specified water level and therefore define constant head boundary conditions. A horizontal filter screen dewaters the container through the fourth side. The outflow rate and the flow towards the boundary condition cells were measured with two electromagnetic flow meters.

Experiments were set up varying the type of filter screen and filter screen diameter, the annular space fillings, the inclination of the filter well, the water level of the boundary condition cells, and effective filter length, in different combinations.

The main purpose of the meso-scale field tests was to verify that the results obtained in the laboratory tests applied at the field scale. Furthermore, these field tests are providing information about technological potential and allow quantification of economic and environmental aspects. The ratio between laboratory and meso-scale field test is about 1:10, based on the screen length.

In the next step, a full-size macro-scale field test is planned. The ratio between meso- and macro-scale will again be about 1:10.

Both laboratory and field experiments were designed based on numerical modeling of flow in porous media using the finite volume groundwater flow and transport

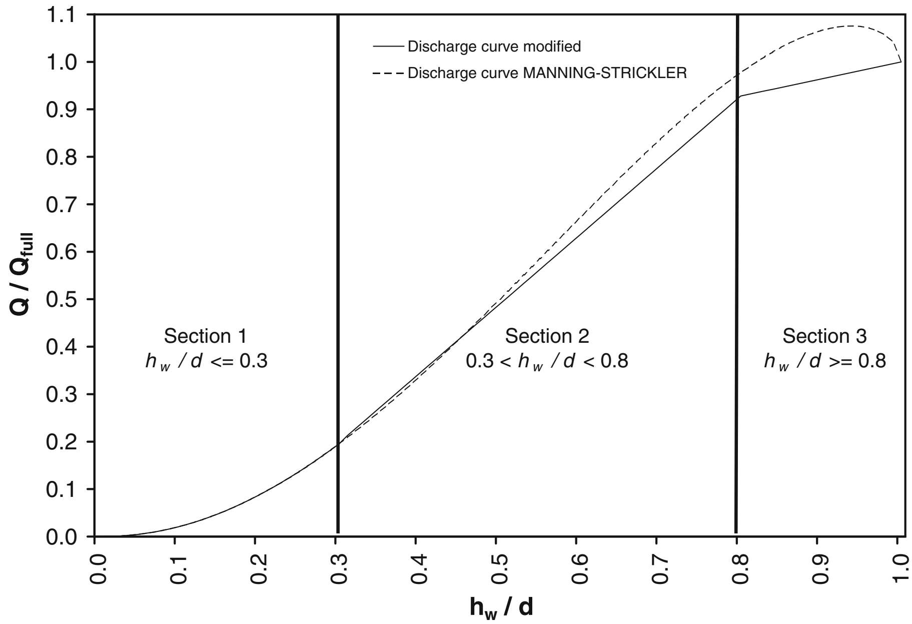


Fig. 4 Modified discharge curve after Manning -Strickler for open channel flow

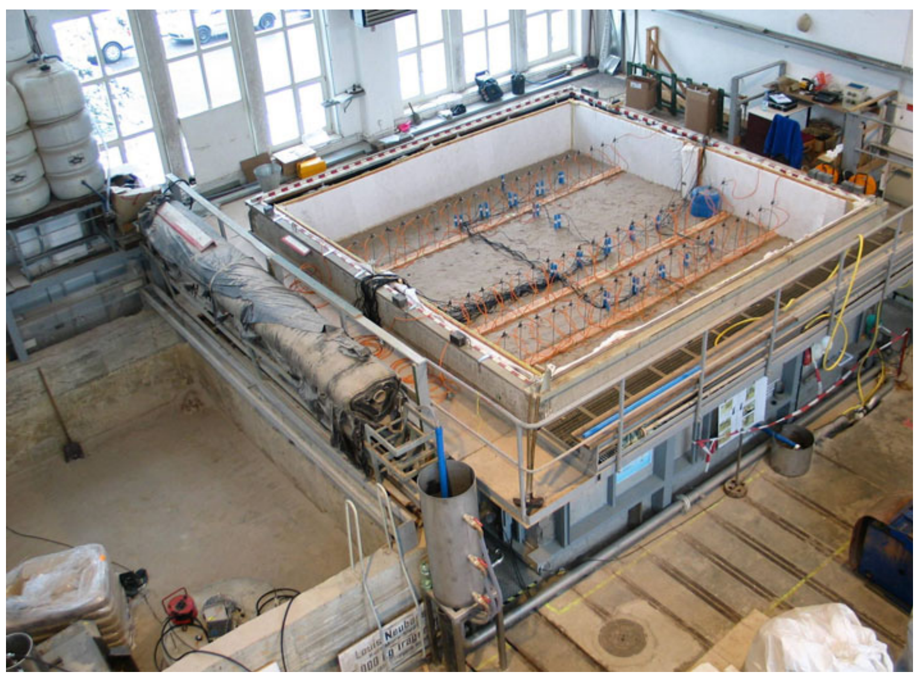


Fig. 5 A bird's eye view of the laboratory test station

model, PCGEOFIM. PCGEOFIM is a sophisticated model specifically designed for modeling groundwater flow in open pit mining areas.

The results of the laboratory tests corresponded with those of the field test. Therefore, the next sections concentrate on the field test results and present approaches for technological strategies of HDD wells in surface mining sites. The results of the laboratory experiments can be found in Müller et al. (2009).

Field Tests

The field tests were conducted at the Vereinigtes Schleenhain lignite open pit mine, which is owned by the company MIBRAG mbH. The experimental site was located in an area with fluvial sediments in a local depression with a thickness of 3–6 m. The aquifer is characterized by alternating layers of fine sands and fine gravel sediments with a trend of increasing grain size at

Fig. 6 Investigation site at the surface mine Vereinigtes Schleenhain with wellhead in foreground

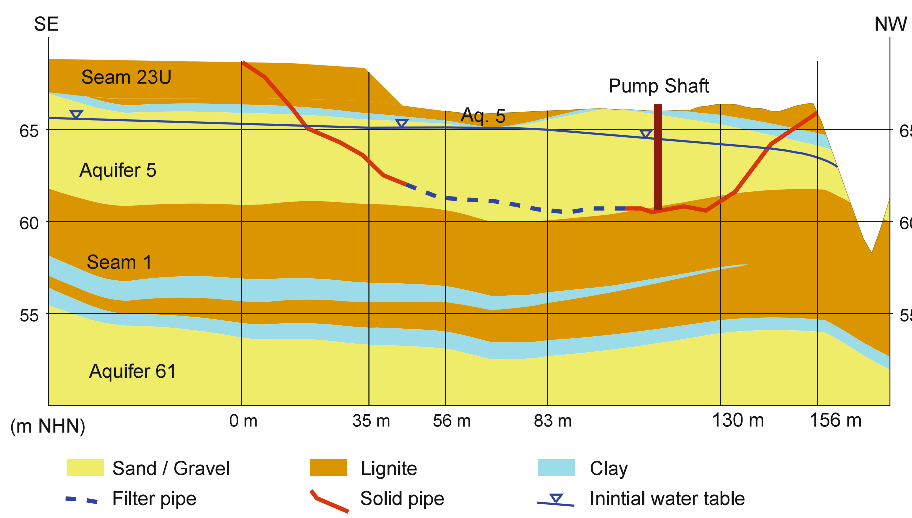


Fig. 7 Cross section through field test location showing geology, initial water table, and HDD well

greater depth. At the beginning of the experiments, the aquifer was saturated, with some parts being slightly confined.

The north border of the local depression is a mine slope. Its east–west extension is about 200–300 m. The south of the experimental area consists of a 2 × 2 km aquifer that borders in the south and west to old dumps. The main flow direction is north. The aquifer was dewatered through the local depression in the experimental area. No other dewatering measures were present. Figure 6 shows the experimental site.

In total, 21 groundwater observation wells with automatic data loggers were implemented in the area. Hydraulic conductivities were determined from grain size distributions of 56 disturbed soil samples that were taken from the bore holes for these observation wells. The average value for hydraulic conductivity, k_f, was between 1×10^{-5} and 5×10^{-4} m/s, excluding some outliers. These values were basically confirmed by slug-and-bail tests and correspond with those determined by Linke et al. (1987).

A 150 m long bore hole was created throughout the deepest portion of the local depression using HDD technology with a Vermeer D24/40 device. A 60 m long continuous-slot (wire wrap) PVC screen with a diameter of 100 mm and a slot size of 0.75 mm was placed into this bore hole at a predefined position. At the deepest point, the screen is about 6 m below the terrain surface. Clay-free polysaccharide drilling fluid was used. The screen had a slight tilt from southeast towards northwest and delivered the water by gravitational flow. The general cross-section through the field test area is shown in Fig. 7.

A 90-day continuous pumping test with free outflow was carried out. This caused an extended drawdown. Outflow rates ranged from over 800 L/min in the very beginning to about 250 L/min for the quasi steady-state conditions. The observed drawdown and well yield were compared the modeling results.

Field Test Results

To predict the groundwater flow process in the test area, a PCGEOFIM model was established. The model for the field experiments was set up as a 3D-model with several nested telescopic mesh refinements. This allows detailed representation of the near-well regions with high spatial resolution, and a lower spatial resolution over the rest of the area. This keeps model runtimes within practical limits. The model discretization for the area close to the HDD-well is shown in Fig. 8 (200 × 140 m detail) along with the calculated water table for steady-state conditions. The

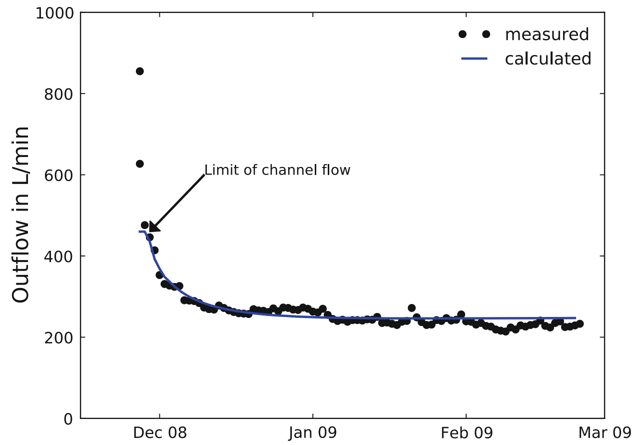


Fig. 9 Measured and calculated outflow rates over time for the field experiments

whole model covers an area of ca. 2000 × 2000 m. Model parameterization for aquifer geometry and k_f has been made dependent on the element position, and based on the spatial distribution of hydrogeological data collected from drillings, grain size distributions, and slug-and-bail tests, as outlined above. Effective porosity, n_e, was parameterized as a function of k_f following Henning (cited by Strzodka

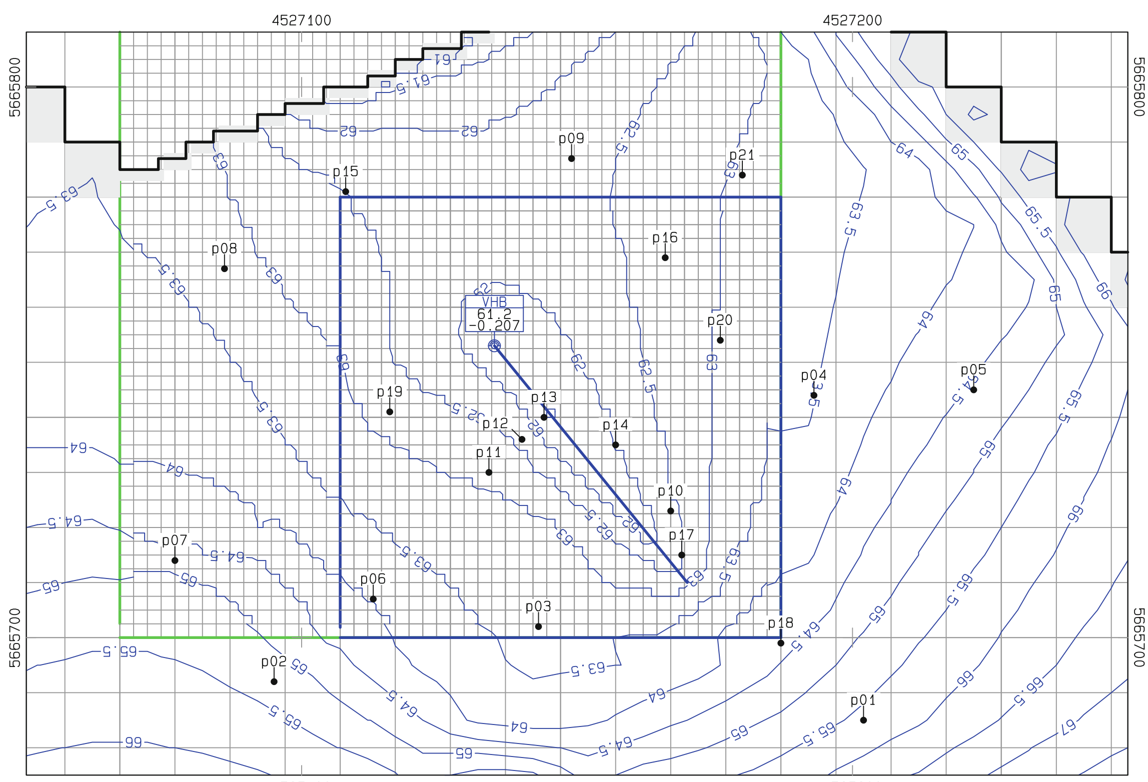


Fig. 8 Steady-state contour lines of groundwater levels for the field test; the model discretization with telescopic mesh refinement is shown in the background

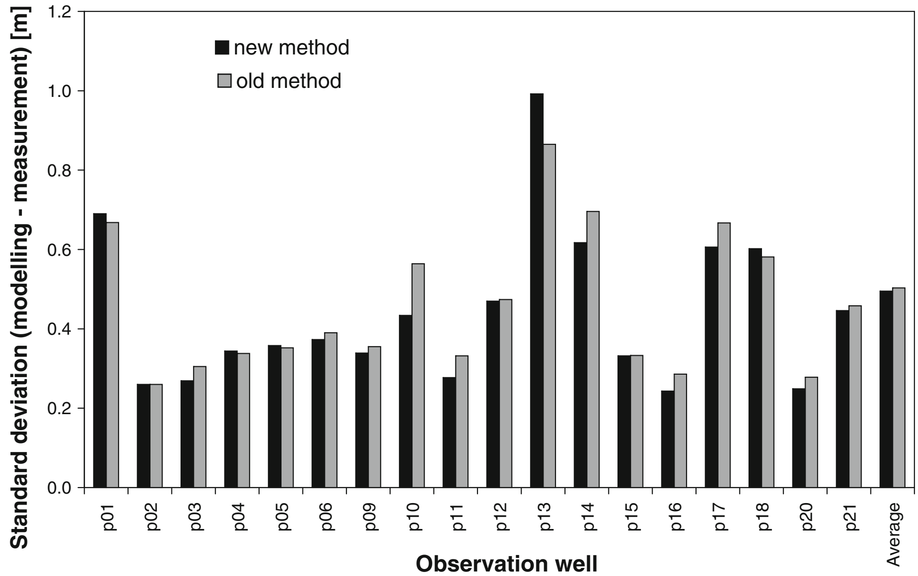


Fig. 10 Standard deviation between modeled and measured well heads (observation wells)

Table 1 Comparison of modeling results for pumping rate and hydraulic heads

Statistical value	Old method	New method
s_h [m]	0.503	0.495
s_q [l/min]	12.19	12.34
v_q [%]	1.16	1.09

s_h standard deviation (hydraulic head observation wells), s_q standard deviation (well pumping rate), v_q coefficient of variation of well pumping rate

1975). Boundary conditions were set to account for external inflow from mine dumps, the outflow from mine slopes, the time dependent movement of the mine face, groundwater recharge, and the effect of the horizontal well. There was no coupling to other aquifers at this site. Using the improved model, the measured and calculated outflow rates corresponded well (Fig. 9).

While the new algorithm for representing the HDD well in the model resulted in improved results for the laboratory experiments (Müller et al. 2009), the modeling results for the field experiments using the old and the new approach were not significantly different. Table 1 compares the methods for coefficient of variation of pumping rate v_q, standard deviation for pumping rate s_q and hydraulic head at observation wells s_h. Fig. 10 shows the standard deviation s_h for each of the observation wells. Most problems in computing dewatering process still occur very close to the filter pipe (p01, p13, p14, p17, p18), but this is also the area of highest geological uncertainty at field test locations. Some observation wells are missing in Fig. 7 because they became dry during the field test.

The good agreement of the results between both methods may be attributed to the exceptionally large amount of water level measurements, which allowed an intensive calibration. For the old method, all effects could be lumped into the parameters in Eq. 16. The new method allows a better representation of processes such as pipe flow and near-field inflow into the well. Furthermore, there is no more dependence on the spatial resolution of the model. Therefore, the new method is expected to give better results if less calibration data is available and if the spatial resolution is less favourable. The insignificant differences of the results of both modeling methods in the field test may indicate the small influence of channel flow compared to other effects and compared to pipe flow, as demonstrated by Voigt and Häfner (2007).

Although the model can be considered well fitted, certain differences between measured and calculated values remain. But obviously, at a field scale, other effects dominate. Struzina and Benndorf (2011) looked at geological uncertainty as one cause for these discrepancies. They used the model presented here to carry out a Monte-Carlo-based uncertainty study. They performed geostatistical simulations, varying aquifer geometry as described by the parameters aquifer bottom level and thickness with the generalized sequential Gaussian simulation algorithm (GSGS) (Benndorf 2009). These simulation results were used to create a number of different parameter sets for the PCGEOFIM-model. The model was used as a transfer function. It produced outputs for each model run that were statically analyzed to quantify model uncertainty due to lack of knowledge in an exact spatial distribution of subsurface properties. The predictions based on these different realizations for the steady-state differ up to 18.5% of the expected value of well output. In conclusion, the residual error of the calculation methods is small compared to the influence of geologic uncertainty in this case.

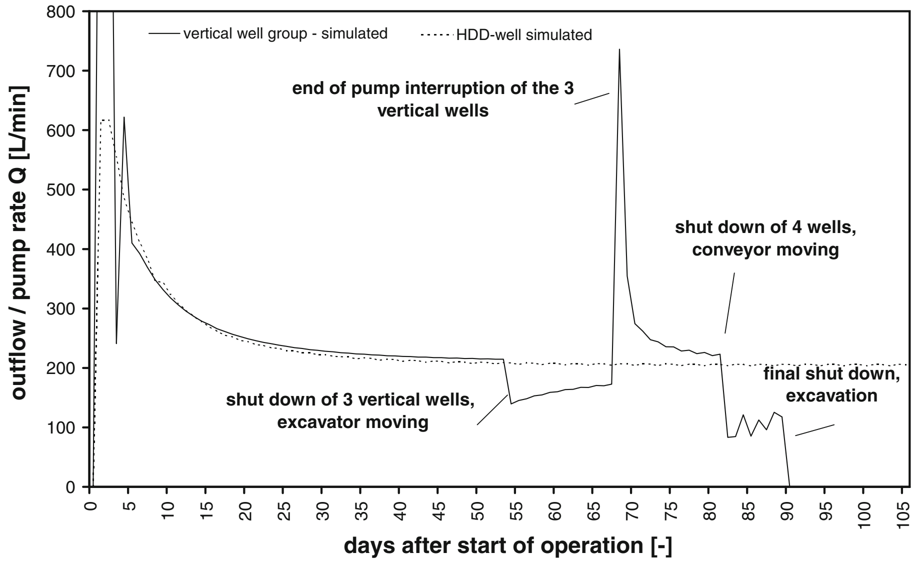


Fig. 11 Comparison between HDD-well and vertical dewatering considering mine technology

The improved model was used to compare the dewatering effects of the installed HDD well in the field experiment with the effect of vertical wells. The model results suggest that seven vertical wells are necessary to achieve the dewatering effect of a single HDD well (Müller et al. 2009). Therefore, the use of HDD wells yields significant savings in energy and material consumption. Furthermore, there is no need to remove the HDD well before excavation. This allows continuous operation, as opposed to vertical wells that have to be removed some time before excavation, which allows ground water to rebound (Fig. 11).

The modeling results show that water levels would be nearly back to original levels after 2 weeks without dewatering. As this is the typical time required to remove vertical wells before excavation, there would essentially be no net benefit for dewatering.

Technological Variants of HDD Wells in Open Pit Mines

Filter well systems require a number of dewatering elements working together to obtain the desired level of dewatering. In thin aquifers, the screened section in a single HDD well is significantly larger than the filter length that a single vertical well can have. In order to decide whether an HDD well or a group of vertical wells would be the best solution for a given hydrological problem, one needs a quantitative indicator to compare the technological variants due to their dewatering efficiency. Therefore, Sass and Treskatis (2000) suggest the productivity index, φ, which is defined as the geometrical ratio between effective filter length, $L_{w_{\text{eff}}}$, and total drill length, L_t. The following discussion assumes that $L_{w_{\text{eff}}} = L_w$.

$$\varphi = \frac{L_w}{L_t}; \quad \varphi_H = \frac{L_{w_H}}{L_{t_H}}; \quad \varphi_V = \frac{L_{F_V}}{L_{t_V}} \tag{23}$$

The indices H and V refer to the HDD well (H) and the vertical well (V). It is assumed that there is a decision-depth, t_v, that represents the depth of the filter section of a well if the productivity index for a horizontal and a vertical well are the same ($\varphi_H = \varphi_V$). In other words, t_v is the border depth at which HDD wells or vertical wells are equally well suited. If one of the productivity indices is larger, one type of well would be better.

There are different possibilities to combine either a number of HDD wells with each other or one or more HDD wells with a number of vertical wells as an alternative to vertical-well-only systems.

Figures 12 and 13 show the most common configurations for dewatering problems with either 1 or n aquifers. The cases a to f describe the oppositional horizontal and vertical well systems. For case g, no t_v exists, because vertical and horizontal wells will be combined in one well system. In case g, vertical infiltration wells dewater the upper aquifers and infiltrate the drained water into the lowest aquifer. The lowest aquifer is then dewatered by an HDD well, which also drains the infiltrated water.

Geometric parameters cannot be used to meaningfully compare HDD wells with vertical wells. Better criteria are pumping rates obtained from one meter of filter screen because they provide a better estimate of costs per pumped water unit. As mentioned above, it turned out that 7 vertical wells would have the same total outflow Q as a single HDD well. Normalizing the outflow to the underlying effective

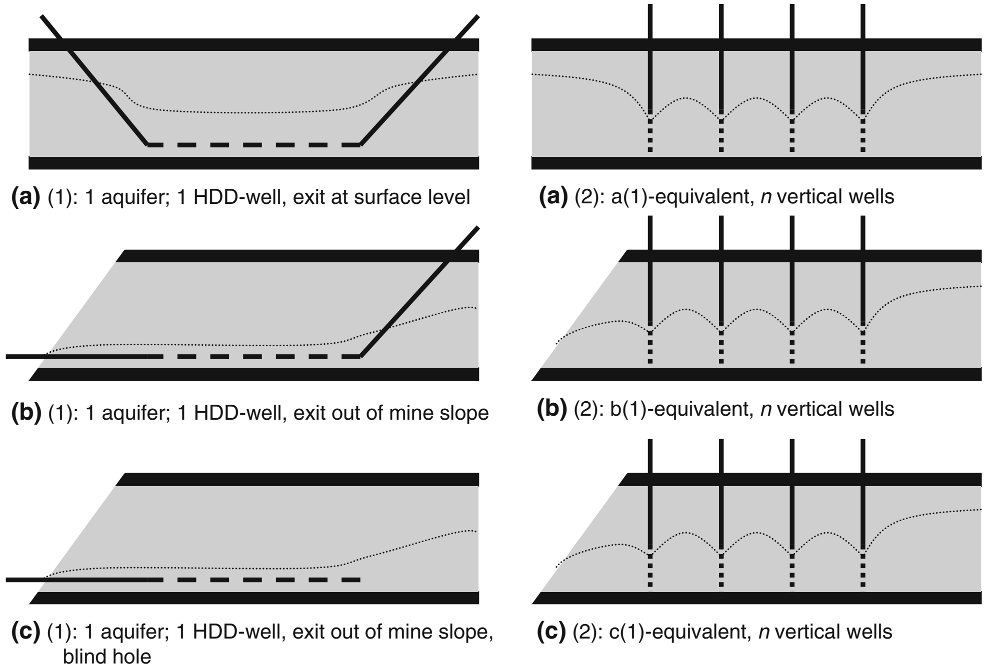


Fig. 12 Well configurations in one-aquifer problems

filter length L_w it was necessary to bring in a productivity factor f_p

$$f_p = \frac{Q_V / L_{w_V}}{Q_H / L_{w_H}} \tag{24}$$

where f_p is approximately 1.61 for the field test. The factor f_p needs to be considered in the calculations for t_v. If the limiting case is defined as $Q_V = Q_H$, then Eq. 24 turns into $L_{w_H} = f_p \cdot L_{w_V}$ and further, into

$$L_{w_H} = f_p \cdot a_V \cdot m \tag{25}$$

where a_V represents the number of vertical wells and m the unaffected water level above bottom of aquifer.

While the one-aquifer problems (as in case *b*) can be easily solved for t_v, iteration becomes necessary to solve the *n*-aquifer problems (as in case *f*). The solutions of t_v for case *b, c*, and the equalized φ ratios for case *f* (Fig. 12 and 13) for example, can be written as shown in Eq. 26 and 27.

Case *b, c*:

$$(b): \quad t_v = \frac{f_p \cdot a_V \cdot m \cdot (L_{w_H} + L_{vA})}{a_V \cdot \left(L_{w_H} - \frac{f_p \cdot m}{\sin \alpha}\right)};$$

$$(c): \quad t_v = \frac{f_p \cdot a_V \cdot m \cdot (L_{w_H} + L_{vA})}{a_V \cdot L_{w_H}} \tag{26}$$

Case *f*:

$$\frac{a_V \cdot f_p \cdot \sum_{i=1}^{n} m_i}{a_V \cdot t_v} = \frac{\sum_{i=1}^{n} L_{w_{H_i}}}{\sum_{i=1}^{n} \left(\frac{t_{L_i}}{\sin \alpha_i}\right) + \sum_{i=1}^{n} L_{vA_i} + \sum_{i=1}^{n} L_{w_{H_i}}} \tag{27}$$

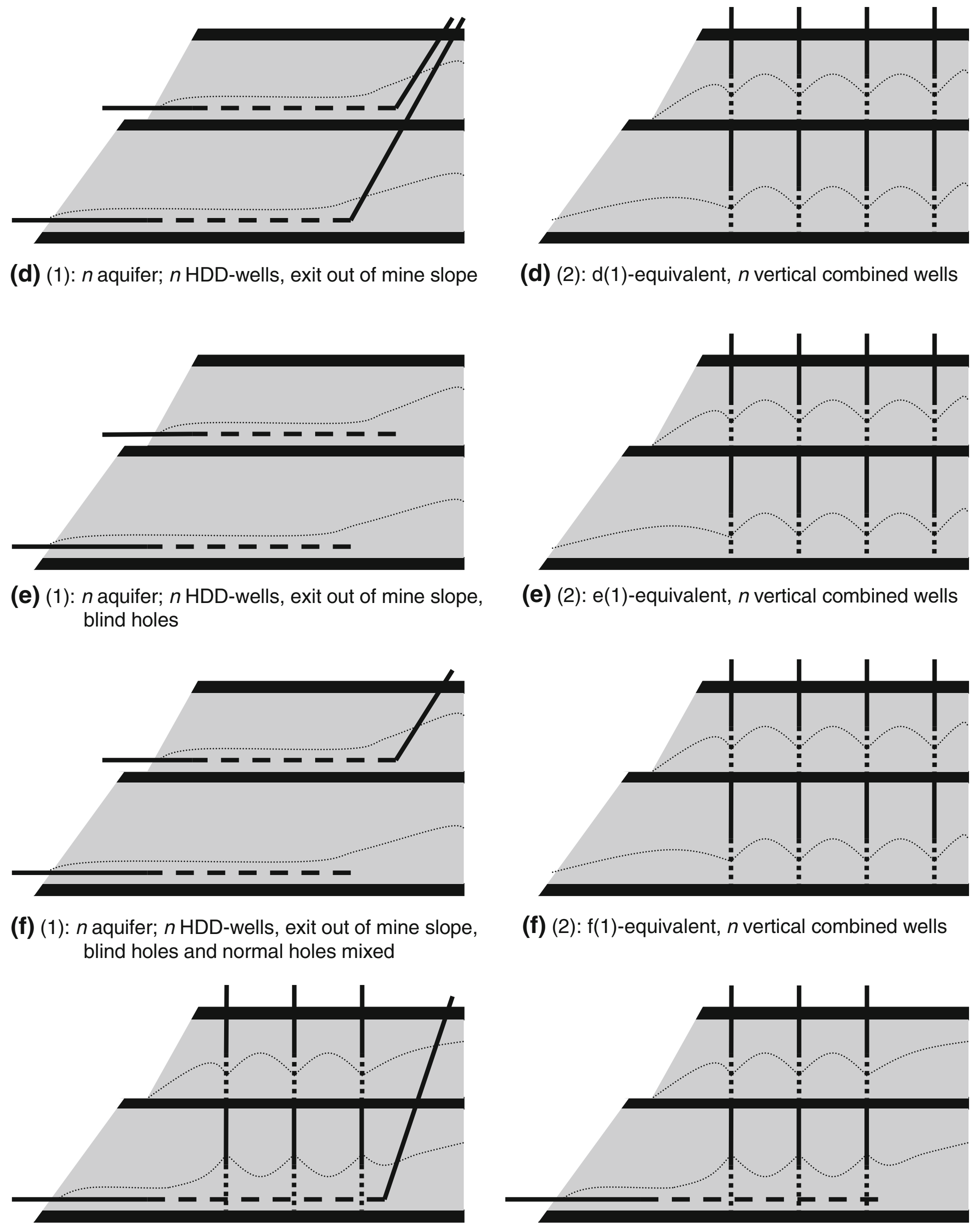
where L_{vA} represents the length of the solid pipe close to the free discharge slope, α the drilling angle of the start section of the HDD well, t_L the depth of the bottom of the aquifer, m is the unaffected water level above the bottom of the aquifer and equals L_w of the vertical wells. Because $\sum_{i=1}^{n} \left(\frac{t_{L_i}}{\sin \alpha_i}\right)$ in Eq. 27 contains $t_{L_{i=n}} = t_v$ it is more suitable to find the solution for case *f* by iteration between the left and the right side of Eq. 27. The geometrical expressions of Eq. 26 and 27 are illustrated in Fig. 14, where $L_{w_H} = f_p \cdot a_V \cdot m$.

For simplification, f_p is assumed to be constant, with a value of 1 (so that a 1 m HDD well is as efficient as a 1 m vertical well). Applied to cases *b* and *c* (single aquifer cases), the typical graphs for t_v (decision depth or depth of filter section) can be generated as shown in Figs. 15 and 16. The area below the graphs is supposed to be more advantageous for vertical wells while the area above is more beneficial for HDD wells.

The results shown in Figs. 15 and 16, illustrate the advantages of HDD wells over vertical wells in thin aquifers even if the horizontal filter lengths are moderate. The parameters used for the calculations are shown in Table 2. The results indicate that t_v does not depend on a_V (in the simplified case, all wells were given the same φ), and α has little influence (case *b*), whereas m has a large influence.

Other than the above assumptions, it is very likely that the productivity factor f_p is variable and depends on the water-bearing thickness of the aquifer m, hydraulic conductivity k_f, number of vertical wells a_V and horizontal

Fig. 13 Well configurations in n-aquifer problems



(d) (1): *n* aquifer; *n* HDD-wells, exit out of mine slope

(d) (2): d(1)-equivalent, *n* vertical combined wells

(e) (1): *n* aquifer; *n* HDD-wells, exit out of mine slope, blind holes

(e) (2): e(1)-equivalent, *n* vertical combined wells

(f) (1): *n* aquifer; *n* HDD-wells, exit out of mine slope, blind holes and normal holes mixed

(f) (2): f(1)-equivalent, *n* vertical combined wells

(g) (1): *n* aquifer; 1 HDD-well combined with *n* vertical dry wells, HDD-well with exit out of mine slope

(g) (2): *n* aquifer; 1 HDD-well combined with *n* vertical dry wells, HDD-well with exit out of mine slope, blind hole

filter length L_{w_H}, of HDD well. To be able to predict f_p numerical simulations must be performed using a hydrologic model, which is characterized by:

- Isotropy
- Homogeneity of hydraulic conductivity
- Fully penetrating vertical well
- Validity of Darcy's law by approximation
- Endless range in horizontal plane by approximation and constant thickness
- Saturated soils

These simulations have yet to be performed.

The final decision, whether HDD wells or vertical wells will be used, will be based on economic advantages of the chosen technology for the specific site conditions. There are many factors influencing cost calculations. Well equipment and material and drilling requirements are some of these factors. While HDD wells in single aquifer problems can often be more economic than vertical wells, HDD wells in multiple-aquifer systems may have higher drilling and material costs. Other cost factors are energy and

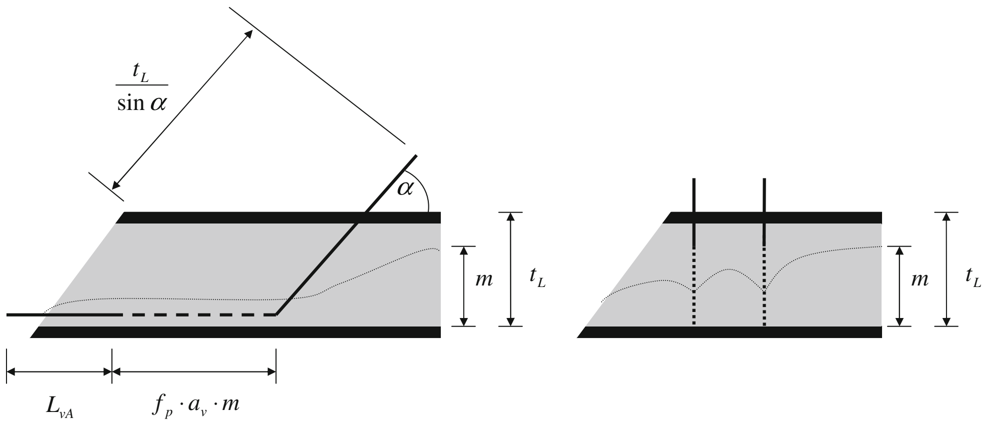
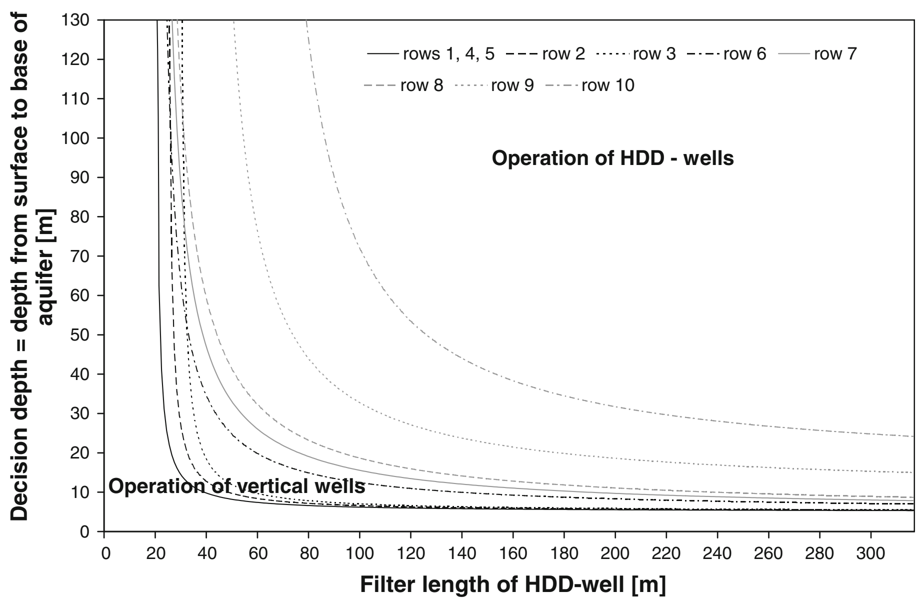


Fig. 14 Geometrical expressions in t_v, solutions, m saturated thickness of aquifer, t_L total aquifer thickness, α angle of well bore, L_{kA} length of well without screen, f_p productivity factor, av number of vertical wells, m unaffected water level above bottom of aquifer

Fig. 15 Decision depth t_v for case b (normal drilling); values in areas *below curves* favor vertical wells, areas *above curves* HDD-wells



operating expenses. It is usually not sufficient to look only at in-well-pumps but also at the whole mine pumping system, costs of pipe systems, and technological effects. For example, HDD wells in many cases can be (partly) mined by mine excavators while the remaining well parts still drain by free outflow as opposed to vertical wells. There is no interruption in dewatering process. That can help reduce the amount of water in the material moved by excavators, which improves excavating efficiency. Depending on the conditions at a specific site, HDD wells can be a cost effective alternative to vertical wells.

Conclusions

In thin aquifers, horizontal dewatering wells installed by horizontal directional drilling (HDD wells) are a better choice than vertical filter wells because one HDD well can have a much longer filtered section than a single vertical well and therefore can replace a number of vertical wells. This decreases material and energy requirements. Also, HDD wells can have a gravity-driven discharge to the mine, allowing interruption-free dewatering.

While this is true for single aquifer problems, this situation is less straight forward at multiple-aquifer sites, which require either the installation of an HDD well per aquifer or a combination of vertical (infiltration) wells with HDD wells. The latter approach is out of the scope of this paper.

The laboratory and field measurements shed new light on processes in freely flowing horizontal wells. The iterations between modeling and modeling with mutual incremental improvements in field test measurements were not significantly different compared to the originally used modeling method. This turned out to be due to the lack of geologic uncertainty in the case of the field study. However, the detailed measured data provided a basis to

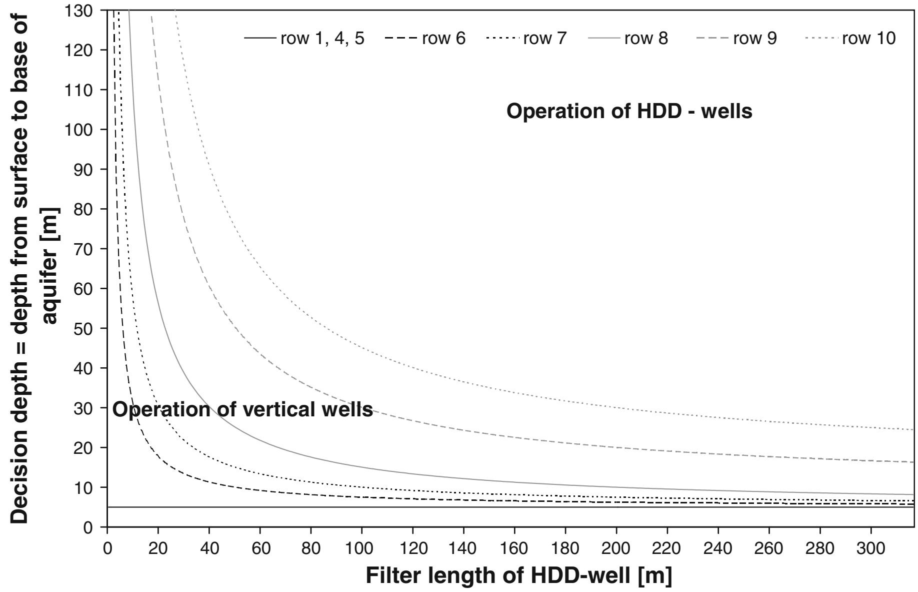


Fig. 16 Decision depth $\underline{t_v}$ for case c (blind hole); values in areas *below curves* favor vertical wells, areas *above curves* HDD wells

Table 2 Parameters for data rows used in Figs. 15 and 16

Row	a_v	$M(m)$	L_{vA} (m)	α (°)
1	1	5	0	15
2	1	5	0	12
3	1	5	0	10
4	2	5	0	15
5	3	5	0	15
6	3	5	50	15
7	3	5	100	15
8	3	5	200	15
9	3	10	200	15
10	3	15	200	15

improve the algorithms for calculating horizontal wells within PCGEOFIM. The resulting model can be used to predict outflow rates of freely flowing horizontal wells and will help improve dewatering planning. Advantages of HDD wells over vertical wells could be quantified for single aquifers.

Technological variants of HDD wells for one-aquifer and multiple-aquifer-problems were presented. A decision criterion was introduced that helps to identify the advantages of either vertical wells or horizontal wells. Generally, HDD wells have advantages over vertical wells when the aquifer is thin and there is a single aquifer. Often several vertical wells can be replaced by a single HDD well with free outflow. This results in a more effective dewatering process. In addition, the dewatering is independent of mining operations.

The decision-depth method provides a fast yet simple tool to decide between the use of vertical wells or HDD wells. Next, we plan to conduct numerical simulations to determine additional parameters to improve this method and allow more reliable decisions.

Acknowledgments The authors would like to thank the Deutsche Bundesstiftung Umwelt (DBU), Osnabrück, Germany for supporting the presented work that was carried out as part of the research project “Innovatives Entwässerungsverfahren zur Umweltentlastung und Effizienz-steigerung” (Innovative dewatering system for environmental protection and increase in Efficiency), Az. 22473-23.

References

Aquilera R et al (1991) Horizontal wells. Gulf Publ Co, Houston, USA

Benndorf J (2009) Nutzung der geostatistischen Simulation zur Berücksichtigung der geologischen Unsicherheit in der Bewertung von Lagerstätten am Beispiel des Braunkohlenbergbaus (Evaluation of lignite deposits using conditional simulation in geostatistics). PhD dissertation, Clausthal University of Technology, Clausthal, Germany, ISBN 3-938924-12-8

Bollrich G, Melhem G (1990) Neue Füllhöhenkurven für teilgefüllte, kreisförmige Rohrleitungen (New flow-water-level relationship for partly filled circular pipes). Wasserwirtschaft-Wassertechnik 40(6):141–142

Borisov JP (1964) Oil production using horizontal and multiple deviation wells.(trans: Straus J, Soshi SD). Nedra, Moscow

Busch KF, Luckner L, Tiemer K (1993) Lehrbuch der Hydrogeologie (Basics of hydrogeology) Geohydraulik, vol 3, 3rd edn. Gebrüder Bornträger, Berlin

David J (1998) Grundwasserhydraulik: Strömungs- und Transportvorgänge (Hydraulics of ground water: groundwater flow and migration processes). Vieweg, Braunschweig/Wiesbaden

Fengler EG (1998) Grundlagen der Horizontalbohrtechnik (Basics of horizontal directional drilling). In: Lenz J (ed) Schriftenreihe aus dem Institut für Rohrleitungsbau an der Fachhochschule Oldenburg, Bd 13. Vulkan, Essen

Giger F (1983) Reduction du nombre de puits par l’utilisation de forages horizontaux. Oil Gas Sci Technol 38(3):351–360

Joshi SD (1988) Augmantation of well productivity using slant and horizontal wells. J Petrol Technol 40:1426–1433

Joshi SD (1991) Horizontal well technology. PennWell Books, Tulsa

Kleiser K, Bayer HJ (1996) Der grabenlose Leitungsbau (The trenchless technology). Vulkan, Essen

Lass G (1975) Berechnung von Horizontalfilterbrunnen mit beliebig angeordneten Filterrohren (Calculation of horizontal wells with variable arranged filter pipes). PhD dissertation, Technische Hochschule Darmstadt, Germany

Linke L, Hagendorf U, Pohl B (1987) Ergebnisbericht mit Vorratsberechnung des Braunkohlenfeldes Schleenhain (Exploration report and calculation of resources and reserves of lignite field Schleenhain). VEB Braunkohlenbohrungen und Schachtbau Welzow/NL Halle. Halle, Germany exploration report

Müller M (2007) Modellabbildung von Horizontalfilterbrunnen im Programmsystem PCGEOFIM Stand und Ziele (Implementation of HDD-wells in PCGEOFIM state and objectives). In: Drebenstedt C, Struzina M (eds), Grundlagen und Erfahrungen der Übertragbarkeit von Modellversuchen auf großindustrielle Anwendungen (Basics and experiences of transferability of laboratory tests to industrial applications), TU Bergakademie Freiberg, Freiberg, pp 44–58, ISBN 978-9-86012-330-0

Müller M, Drebenstedt C, Struzina M, Mansel H, Preußler F, Bach F, Kretschmer T, Wagner S, Schramm R, Kummer S (2009) Entwicklung eines umweltschonenden und effizienten Verfahrens zur Entwässerung oberflächennaher Lockergesteine im Bergbau und Bauwesen unter Nutzung der verlaufsgesteuerten Horizontalbohrtechnik (Developement of an environmentally friendly and efficient technology for dewatering of loose rock formations in mining and civil engineering using horizontal directional drilling). Project report, Ingenieurbüro für Grundwasser GmbH, Leipzig, Germany

Offerhaus P (1961) Die Horizontalfassungsbrunnen in der Theorie und Praxis (Horizontal wells in theory and praxis). PhD dissertation, Technische Hochschule Karlsruhe, Karlsruhe

Park E (2002) Analytical modeling of contaminant transport and horizontal well hydraulics. PhD dissertation, Texas A&M University, College Station, US

Poweleit A (1988) Verfahren zur Berechnung der dreidimensionalen Zuströmung zu Filterrohren in Drainschichten (Method for calculating 3-dimensional inflow to filter pipes in drainage layers), PhD dissertation, University Karlsruhe, Karlsruhe

Press H, Schroeder RCM (1966) Hydromechanik im Wasserbau (Hydromechanics in water enginieering). Springer, Berlin

Rueckert H (1977) Die Bemessung von Horizontalfilterbrunnen (Dimensioning of horizontal wells). PhD dissertation, Technische Hochschule Leipzig, Leipzig

Sass I (1994) Brunnen und Filter für die Sanierung von Untergrundkontaminationen (Wells and drainages for remediation of contamination in underground). PhD dissertation, University of Karlsruhe, Karlsruhe

Sass I, Treskatis C (2000) Herstellungs- und Bemessungsgrundlagen für einen verlaufsgesteuerten Trinkwasserbrunnen als Pilotversuch an einem Standort in Krefeld (Basics for installation and dimensioning of an HDD-well as a pilot test in Krefeld). Grundwasser 5(1):24–34

Struzina M (2005) Erfahrungen beim Einsatz eines verlaufsgesteuerten Horizontalfilterbrunnens (VHB) zur Beherrschung von Restwasserständen im Tagebau Vereinigtes Schleenhain (Experiences in operating an HDD-well for dewatering at Vereinigtes Schleenhain mine). In: Drebenstedt C, Kudla W (eds) Entwässerungstechnik im Bergbau und Bauwesen (Dewatering technologies in mining and civil engineering), 55-th Berg- und Huettenmaennischer Tag, TU Bergakademie Freiberg, pp 38–48, ISBN 978-3-86012-242-8

Struzina M, Benndorf J (2011) Efficient planning and modelling for modern dewatering concepts in unconsolidated rock under geological uncertainty. World Min 62(2):66–75

Struzina M, Drebenstedt C (2008) Horizontal wells installed by horizontal directional drilling (HDD) as an alternative mine dewatering technology. In: Proceeding ISCSM 9th international symposium, University of Petrosani, Petrosani

Strzodka K (1975) (ed) Hydrotechnik im Bergbau und Bauwesen (Hydro technology in mining and civil engineering). Deutscher Verlag für Grundstoffindustrie dvg, Leipzig, Germany

Voigt HD, Häfner F (2007) Berechnung der Förderleistung horizontaler Bohrungen unter Berücksichtigung von Ähnlichkeitskriterien (Calculation of pumping rate of horizontal wells considering criteria of analogy). In: Drebenstedt C, Struzina M (eds), Grundlagen und Erfahrungen der Übertragbarkeit von Modellversuchen auf großindustrielle Anwendungen (Basics and experiences of transferability of laboratory tests to industrial applications), TU Bergakademie Freiberg, Freiberg, Germany, pp 72–81, ISBN 978-9-86012-330-0

Wildenhahn E (1972) Beitrag zur Berechnung von Horizontalfilterbrunnen (Consideration of calculating horizontal wells). PhD dissertation, University of Stuttgart, Stuttgart

Zhan H, Park E (2003) Horizontal well hydraulics in leaky aquifers. J Hydrol 281(1–2):129–146

Zhan H, Zlotnik VA (2002) Groundwater flow to a horizontal or slanted well in an unconfined aquifer. Water Resour Res 38(7), doi:10.1029/2001/WR000401

Zhan H, Wang LV, Park E (2001) On the horizontal-well pumping tests in anisotropic confined aquifers. J Hydrol 252(1–4):37–50

Zierep J, Bühler G (1996) Strömungsmechanik (Fluid mechanics). In: Czichos H (ed) Hütte, die Grundlagen der Ingenieurwissenschaften (Hütte, Basics of Engineering Sciences). Springer, Berlin, pp E120–E176