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The role of hydrogeological research in the realization of a combined pumping and deep infiltration system at the excavation 'Duinenabdij'

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Abstract

Hydrogeological interventions in ecologically valuable areas must be well studied beforehand. Modelling of these interventions based on field observations and field studies is herein a valuable step. This is illustrated with an example in the western Belgian coastal plain. A new drainage system had to be designed for the preservation of the archaeological excavation site 'OLV Ten Duinen'. This site is situated in a valuable and protected dune area. A system of pumping and deep infiltration of water was studied to optimise the draining of the site but to minimise the effects in the nearby dunes. A double pumping test was used to derive the relevant parameters. These were then used to simulate and find the optimal configuration of the extraction and deep infiltration wells.

Keywords: Hydrogeology; Parameter identification; Double pumping test; Modelling; Deep infiltration.

Introduction

The archaeological site of the medieval abbey 'OLV Ten Duinen' is situated in the dunes of Koksijde, Belgium (Fig. 1). Because of its low topographic level and the occurrence of a shallow semi-permeable layer, the excavation suffered from high water levels during the winter periods. Since the former draining was ineffective, a new drainage system was needed to preserve the archaeological relics. Furthermore, the conservation of the ecologically valuable dunes surrounding the site was a second objective in the realisation of the system. A profound knowledge about the hydrogeological characteristics of the concerning aquifer was indispensable to plan this system. A study of relevant literature (Lebbe, 1973, 1978; Lebbe *et al.*, 1984; Baeteman, 1985; Van Houtte *et al.*, 1992; Lebbe *et al.*, 1996; Van Houtte, 1998) provided a first insight in the hydrogeological constitution of the groundwater reservoir. The aquifer is composed of Quaternary sediments existing of three sandy, permeable layers, which are separated by

Fig. 1. Situation of the study area (white rectangle) and preserved dune areas.

two silty, semi-permeable layers (Fig. 2). Underneath, the aquifer is bounded by a Palaeogene clay layer considered impermeable in the scope of this study. The occurrence of the two semi-permeable layers was confirmed by the interpretation of borehole descriptions and geophysical borehole measurements, viz. electromagnetic conductivity measurements, in wells at different locations on the site (Louwyck, 2001; Lust, 2002). Because the entire groundwater reservoir contains fresh water (De Breuck *et al.*, 1974), the fluctuations of these conductivity measurements give a qualitative insight in the lithological constitution of the aquifer.

The former drainage system extracted only water above the shallow semi-permeable layer which caused a smaller infiltration through this layer. This explained largely its ineffectiveness to drain most of the recharge water away. A solution is to pump below the shallow semi-permeable layer so that a large part of the recharge water would flow through this layer deeper in the groundwater reservoir. However, this pumping would not only cause a descent of the water table at the excavation, but would also affect the surrounding dunes. Therefore, it would be necessary to deep infiltrate the pumped water in the two undermost permeable layers at the borders of the site. Modelling this system of combined pumping and deep infiltration, given the specific hydrogeological constitution, revealed the importance of an accurate knowledge of the hydraulic parameters of the concerning hydrogeological layers, particularly the hydraulic resistance of the two semi-permeable layers (Louwyck, 2001). Estimations of the parameters based on the interpretation of pumping tests executed in the vicinity of the study area were not reliable, because of the heterogeneous nature of Quaternary deposits in the Belgian coastal plain (Baeteman, 1999). The performance of a pumping test at the excavation was therefore inevitable. Moreover, in order to achieve a reliable deduction of the hydraulic resistance of both semi-permeable layers, it was necessary to execute a double pumping test affecting the two undermost permeable layers. The drawdowns recorded during these two tests were simultaneously interpreted by means of an inverse numerical model and this interpretation resulted in reliable parameter values. The model simulating the system of combined pumping and deep infiltration based on the deduced parameter values gave a profound insight in the system's effectiveness: not only the excavation would be drained properly, also the surrounding valuable dunes would be protected (Lebbe *et al.*, 2002; Lust, 2002).

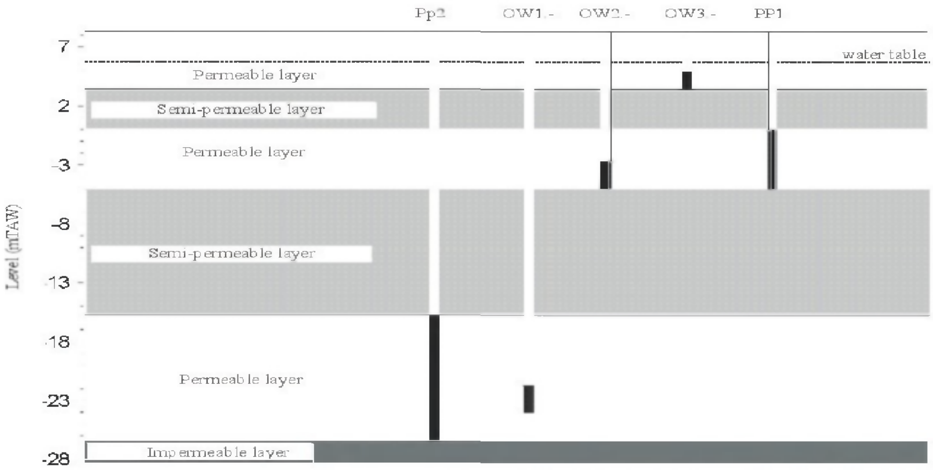

Fig. 2. Schematic constitution of the groundwater reservoir and position of screens (black) of pumping (PP-) and observation (OW--) wells. The mTAW is the Belgian ordnance datum, referring to mean low low seawater level, about 2.3m below mean sea level.

Methodology

Fig. 3 shows schematically the groundwater flow during a pumping test in an aquifer with permeable (B,D_1,D_2) and semi-permeable (A,C) layers (Vandenbohede and Lebbe, 2003). An amount of water is extracted from the permeable layer B, which causes a horizontal movement of water in this layer towards the pumping well. This groundwater flow is mainly characterised by layer B's horizontal conductivity K_h (m.d^{-1}) and specific elastic storage S_s (m^{-1}). The effect of pumping can be observed by the lowering of hydraulic head or drawdown s (m) in observation wells with screen in this layer. The pumping also causes a vertical movement of water from the adjacent semi-permeable layers to the permeable layer. This is called hydraulic leakage and is principally determined by the vertical conductivity K_v (m.d^{-1}) and specific elastic storage S_s of layers A and C. The drawdown in observation wells with screen in D_1 or D_2 is caused by this leakage. The resulting groundwater flow towards the pumping well is treated by the following radial flow equation:

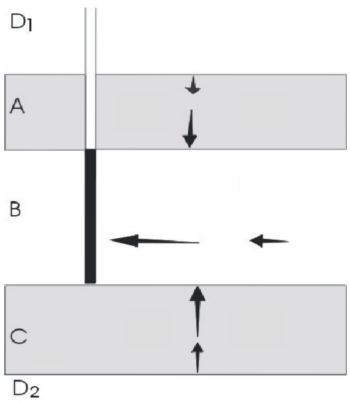

Fig. 3. Schematised flow towards a pumping well in a layered aquifer.

$$K_h\left(\frac{\partial^2 s}{\partial r^2}+\frac{1}{r}\frac{\partial s}{\partial r}\right)+K_v\frac{\partial^2 s}{\partial z^2}=S_s\frac{\partial s}{\partial t} \qquad (1)$$

with r (m) the distance from the pumping well, z (m) the depth, and t (d) the time after starting of the test. Groundwater flow towards a pumping well can be considered in a layered heterogeneous groundwater reservoir with constant parameter values in each layer. Using drawdowns observed on different distances and times during a pumping test, one can deduce the mentioned hydraulic parameters by solving (1). HYPARIDEN (HYdraulic PARameter IDENtification) (Lebbe, 1999) is a set of computer codes developed as a generalised interpretation method for single and multiple pumping tests in layered heterogeneous aquifers. It is based on an axial symmetric, numerical model AS2D, specifically designed for the simulation of pumping tests. In that sense, the model has several advantages over frequently used numerical groundwater flow models in the analysis of pumping tests. HYPARIDEN also includes an inverse numerical model allowing the derivation of optimal values of hydraulic parameters or groups of hydraulic parameters from the observed drawdowns. All observations from different wells and on different times are involved together in the parameter identification process and in the case of a multiple pumping test, all observations from all tests are simultaneously interpreted. The algorithm of the inverse model is obtained by the combination of the forward numerical model and a non-linear regression algorithm. In the first step the forward model calculates the drawdowns on the concerning observation places and times. The second step involves a number of sensitivity analyses. Based on these sensitivities and the differences between calculated and observed data, the calculation of adjustment factors for the derivable hydraulic parameters is finally performed. By successive execution of these three steps the optimal values of the hydraulic parameters are derived iteratively along with their joint confidence region. In this study, the double pumping test was executed in the north eastern corner of the site. The relative position of pumping and observation wells is pictured in Fig. 4. The location of the well screens is shown in Fig. 2. During the first pumping test, a discharge of $178 m^3.d^{-1}$ was pumped on pumping well PP1 with screen situated over the entire depth interval of the middle permeable layer. Drawdown measurements were performed in this pumping well and in the observation wells on different times during the duration of the test, which is two days. In the second test PP2 with screen in the deepest permeable layer was used as pumping well. The discharge amounted to $599 m^3.d^{-1}$ and the duration of the test was three days. Again, the drawdown was measured in the pumping and observation wells on different times. Between the

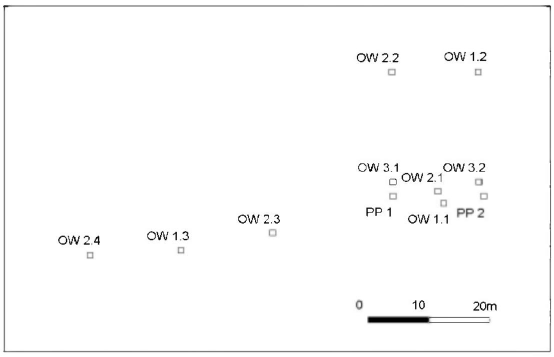

Fig. 4. Position of pumping and observation wells.

two tests a 'period of recovery' of two days was needed to ensure the observations of the second test were not influenced by the first test.

After interpretation of the observed drawdowns by means of HYPARIDEN, which has resulted in reliable parameter values, it was possible to simulate the system of combined pumping and deep infiltration. In fact, an estimate of the drawdown due to simultaneously pumping and deep infiltrating in the different wells of the system was simulated. Knowing the hydraulic parameters of the groundwater reservoir and the discharges for the individual wells, this drawdown can be calculated by application of the rule of superposition (Lebbe, 1999):

$$s_l(x_m, y_n, t) = \sum_{p=1}^{nw} \frac{Q_p \, s_{AS2D}(l, r_p, t)}{Q_{max}} \quad \text{with} \quad r_p = \sqrt{(x_p - x_m)^2 + (y_p - y_n)^2} \qquad (2)$$

where $s_l(x_m,y_n,t)$ is the drawdown (m) in layer l at x-coordinate x_m (m) of the m^{th} row of a mesh-centred grid, and y-coordinate y_n (m) of the n^{th} row of the grid, and at time t (d) after starting of the pumping system; x_p and y_p are respectively the x- and y-coordinates (m) of the p^{th} pumping well; Q_p is the discharge rate ($m^3.d^{-1}$) of the p^{th} pumping well; nw is the number of pumping wells; $s_{AS2D}(l,r_p,t)$ is the drawdown in layer l at distance r_p (m) from the p^{th} pumping well at time t calculated with discharge rate Q_{max} ($m^3.d^{-1}$) by means of the AS2D model. Note that the discharge rate Q_p is less than zero when the p^{th} well is a deep infiltration well. Thus, this rule states that the drawdown due to pumping on a multiple well field is equal to the sum of drawdowns due to pumping on each individual well and the drawdown due to pumping on an individual well is proportional to the discharge rate. The MULTPU-code in HYPARIDEN is designed to simulate drawdown due to a multiple well field by application of (2). Remark that (2) is only valid if the groundwater flow is linear, meaning that in case of considerable interaction between the pumped aquifer and the surface waters, this model is not appropriate. In this study the assumption of linearity is justified and thus the estimated drawdown calculated by means of MULTPU is similar to the one calculated by means of MODFLOW, a groundwater flow model which can deal with interaction between groundwater reservoir and surface waters. In this particular case one could even state the requirement of boundary conditions makes the MODFLOW model less realistic and the estimated drawdown less accurate (Lust, 2002). To

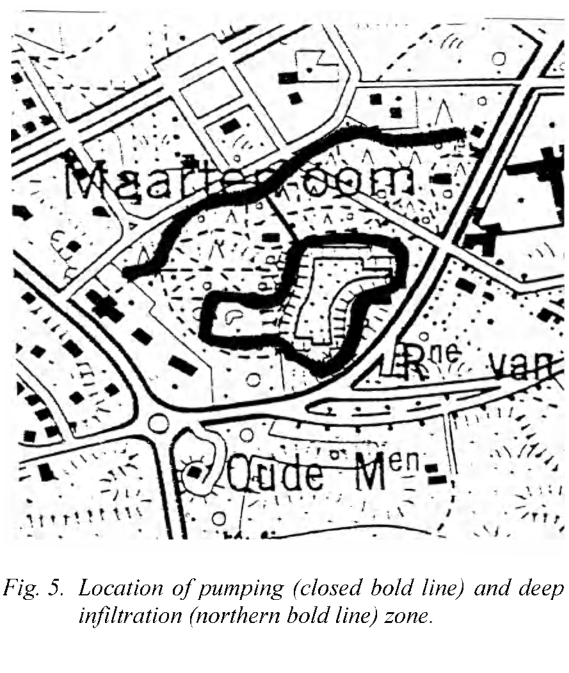

Fig. 5. Location of pumping (closed bold line) and deep infiltration (northern bold line) zone.

simulate the combined pumping and deep infiltration system by application of (2), knowledge about its technical design is required, viz. the exact location of the different wells, the position of their screen, and their individual discharge rate. Fig. 5 shows the exact location of the pumping and deep infiltration zone. The 26 pumping wells with screen in the middle permeable layer are located around the relics of the excavation; the 24 deep infiltration wells with screen in the middle permeable layer are located at the northern boundary of the site. In between the latter wells, 12 deep infiltration wells with screen in the deepest permeable layer were constructed. The simulation of the system was performed with a discharge rate equal to $60m^3.d^{-1}$ for each pumping well, a discharge rate equal to $-49,33m^3.d^{-1}$ for each deep infiltration well with screen in the middle permeable layer, and a discharge rate equal to $-40m^3.d^{-1}$ for each deep infiltration well with screen in the deepest permeable layer.

Results

The sensitivity analyses indicate that the optimal value of seven relevant hydraulic parameters or parameter groups could be deduced from the observations of the double pumping test (Lebbe *et al.*, 2002; Lust, 2002). Table I gives an overview of these parameters and their optimal value calculated by means of the inverse numerical model. The number between parentheses refers to the layer number, taking into account the layers are counted starting with the deepest permeable layer, the deepest semi-permeable layer, etc. C_v (d) is the hydraulic resistance of a semi-permeable layer, which is the thickness of the layer (m) divided by its vertical conductivity ($m.d^{-1}$). Figs 6 and 7 show the time-drawdown and distance-drawdown graphs for respectively the first and second pumping test. The crosses indicate the observed drawdowns, the solid lines are calculated with the forward numerical model by using the optimal values of the hydraulic parameters. At first sight one can observe a good agreement between the observed and calculated drawdowns. Analysing the 424 residuals we inferred their distribution as normal with zero mean and total sum of squared residuals equal to 1.919. Remark the absence of observations in the uppermost permeable layer because of their insignificancy: the high hydraulic resistance of the uppermost semi-permeable layer caused a drawdown with the same magnitude of observed natural head fluctuations. This high resistance is also the reason why the hydraulic parameters of the uppermost permeable layer are not identifiable, which means these parameters have little influence on the drawdown in the other layers. A rough estimate of their values is thus sufficient in the interpretation of the double pumping test and the simulation of the combined pumping and deep infiltration system. It's already been mentioned HYPARIDEN enables to deduce the optimal values along with their joint confidence region. The analysis of this confidence region gives an idea about the accuracy of the deduced values and their mutual dependency (Lebbe, 1999). For the double pumping test in this study, all parameter values show a moderate mutual

Table I. Optimal values for relevant parameters

Parameter group	Optimal value	Unit
$K_h(1)$	42.00	$m.d^{-1}$
$K_h(3)$	13.80	$m.d^{-1}$
$C_v(2)$	49.70	d
$S_s(1)$	$7.120x10^{-5}$	m^{-1}
$S_s(3\text{-}4)$	$7.800x10^{-5}$	m^{-1}
$S_s(2)$	$2.090x10^{-5}$	m^{-1}
$C_v(4)$	735.0	d

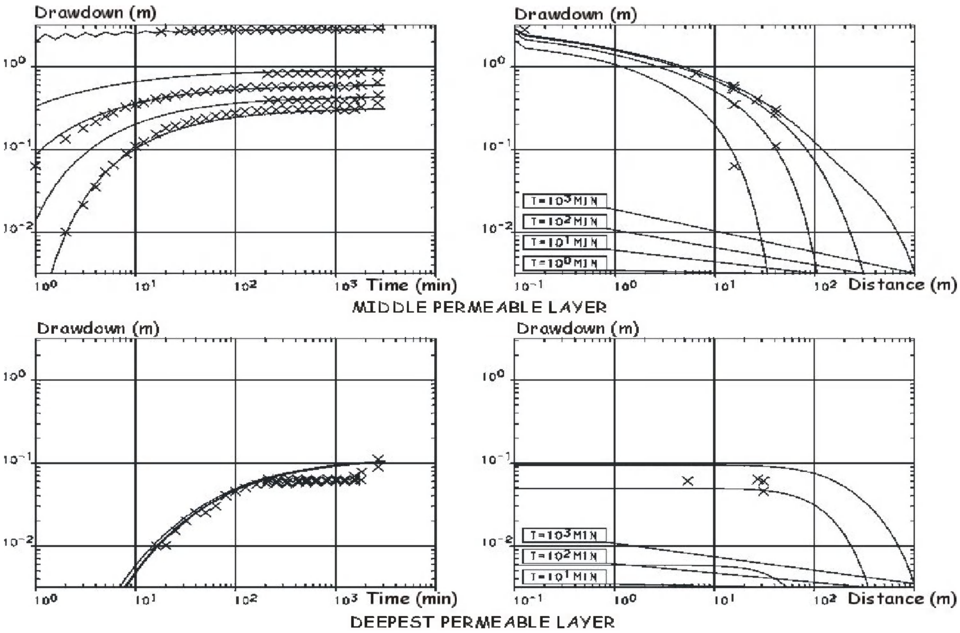

Fig. 6. Observed (crosses) and calculated (solid lines) drawdowns for the first pumping test.

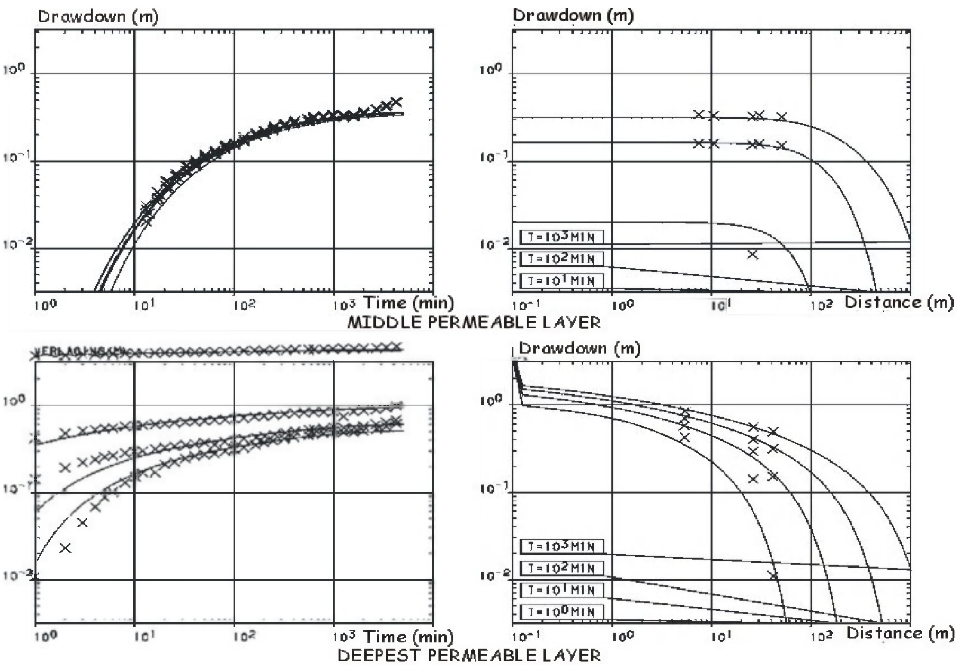

Fig. 7. Observed (crosses) and calculated (solid lines) drawdowns for the second pumping test.

dependency (Lebbe *et al.*, 2002; Lust, 2002). Moreover, the first five parameter groups in Table I are accurately inferred. The optimal value for $S_s(2)$, the specific elastic storage in the deepest semi-permeable layer, is less reliable. Finally, the deduction of the hydraulic resistance of the shallow semi-permeable layer is not accurate due to the lack of significant drawdown measurements in the uppermost permeable layer. However, by calculating the difference between the hydraulic head in the two uppermost permeable layers and estimating the infiltration rate of groundwater through the shallow semi-permeable layer, we can assign this parameter a more reliable value by application of Darcy's Law (Louwyck, 2001; Lust, 2002). When assuming the infiltration rate is twice the annual average infiltration rate and thus equal to $1.53 mm.d^{-1}$ (Lebbe, 1978), the estimated hydraulic resistance of the uppermost semi-permeable layer equals to 1300d (Lebbe *et al.*, 2002).

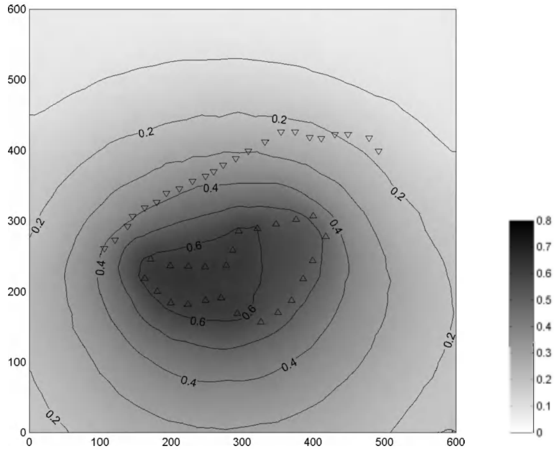

Fig. 8. Calculated drawdown (m) due to drainage system after 10^5min in upper permeable layer. Triangles indicate position of pumping (triangle up) and deep infiltration (triangle down) wells.

Figs 8, 9 and 10 show the contour lines of the drawdown simulated by means of MULTPU in the three permeable layers due to the combined pumping and deep infiltration of the drainage system after 10^5 minutes. The dimension of the simulated area is 600m x 600m and the y-axis is parallel to the north-south direction. Negative drawdown values are indicating a rising of the hydraulic head. In the middle permeable layer (fig. 9), which is directly influenced by the system, we see the appearance of a large 'depression funnel' and 'infiltration cone' at respectively the pumping and deep infiltration zone. A funnel and cone is also appearing in the deepest permeable layer (fig. 10), although less accentuated and not following the exact shape of the

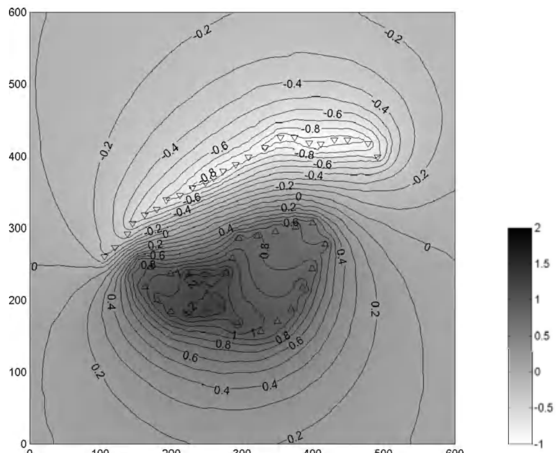

Fig. 9. Calculated drawdown (m) due to drainage system after 10^5min in middle permeable layer. Triangles indicate position of pumping (triangle up) and deep infiltration (triangle down) wells.

well configuration because of the absence of pumping wells in this layer and the occurrence of the deepest semi-permeable layer. The high hydraulic resistance of the shallow semi-permeable layer and the dispersal of deep infiltrated water over the two deepest permeable layers are the reason why an infiltration cone is absent in the uppermost permeable layer (fig. 8). Looking more closely to this graph, the calculated lowering of the water table at the excavation is significant. Note that the lowering at the western part is higher than the lowering at the eastern part. It can also be seen that the drawdown in the surroundings is minimal and especially the northern part of the area is protected because of the location of the deep infiltration zone. In this particular case a configuration with a deep infiltration zone surrounding the entire area could be considered as ideal (Louwyck, 2001). However, not only hydrogeological requirements were playing a role in determining the most suitable configuration.

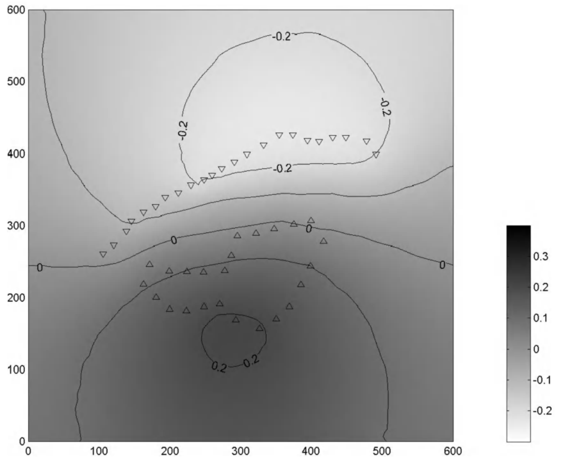

Fig. 10. Calculated drawdown (m) due to drainage system after 10^5min in upper permeable layer. Triangles indicate position of pumping (triangle up) and deep infiltration (triangle down) wells.

Conclusions

Simulating the system of combined pumping and deep infiltration has proved its effectiveness in draining the excavation site without endangering the surrounding valuable dune area. In general, the system of combined pumping and deep infiltration is an outstanding method to create a local lowering of the water table. Moreover, the location of the deep infiltration zone can be chosen in a way the vulnerable area is optimally protected. Furthermore, this study has illustrated the important role of field tests and mathematical modelling in the planning of hydrogeological interventions in ecologically valuable areas. In fact, the different steps in handling a hydrogeological problem in an efficient and scientific justified way could be inferred. Relevant literature was studied to have a first insight in the hydrogeological constitution of the concerning groundwater reservoir. Then supplementary information was gathered by means of borings, geophysical borehole measurements (conductivity measurements) and the performance of a double pumping test. The interpretation of this field data has made it possible to fill the gaps in the hydrogeological knowledge required to model the proposed drainage system accurately. The simulation of the system has showed its effectiveness in taking care of the problem.

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