PERIODICA POLYTECHNICA SER. CIV. ENG. VOL. 45, NO. 1, PP. 63–84 (2001)

THE APPLICATION OF THE ANALYTIC ELEMENT METHOD FOR REGIONAL GROUNDWATER PROBLEMS

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Received: Sept. 5, 2000

Abstract

The analytic element method for groundwater flow modelling is presented earlier in this volume. This paper introduces its application for regional groundwater flow problems. Three examples are discussed, each of them describes the effects of different interventions in surface waters. The first one examines how the modified operation of a river barrage influences the groundwater regime around a village. The second example shows how different versions of a planned canal can be evaluated from the point of view of groundwater. Finally, the third case study examines the enlargement of gravel pits. Though in each case a short solution for the technical questions is also given, the paper rather focuses on the applicability of the method.

Keywords: groundwater modelling, regional effects of surface waters on the groundwater, applicability and effectiveness of the model.

1. Introduction

There are several numerical ways to model the quasi-horizontal groundwater flow. One of them is the deterministic, semi-analytic *analytic element method* developed about 20 years ago. The aim of this paper is to introduce its application for regional groundwater problems. After a short summary of the main features, case studies will be given to demonstrate its efficiency.

The method is based on the well known potential theory, but instead of the usual velocity potential, it uses its integral over the saturated aquifer, the so-called discharge potential. With the help of this potential the simplified basic equation of groundwater flow turns to be the *Laplace* equation with the same form for both phreatic and confined aquifers.

The aquifer examined is subdivided to such elements, that represent one individual feature of it, like a surface water course, the variation of an aquifer parameter, infiltration, etc. Such an individual feature is taken as one element of the aquifer. The effects of each element may be described by well founded potential functions. Based on the linearity of the *Laplace* equation, these potentials can be superimposed to gain the full description of the aquifer. As several of the potentials contain such parameters that are not known in advance, boundary conditions at control points are needed to determine them.

A given problem is always connected to a well defined region, though there are also several effects coming from outside. Most of the numerical models include these effects as boundary conditions. But the application of the potential approach considers an infinite plane without any boundaries. To limit this infinite plain and to take the outer effects also into consideration, around the area of interest an outer area has to be defined. This outer area provides a transition between the area of interest and the area left out of consideration. Its size, the elements to include in or to cancel and also the formulation of the included elements may be determined by calibration. The full description of the method is given in an earlier paper of this volume.

The main part of this paper covers three case studies. Each of them describes interventions in surface water courses and examines their effects on the groundwater. They are the following:

1. The operation of the river barrage at Bőcs on the River Hernád is planned to be modified. The higher headwater level may increase groundwater level in the nearby village. The task was to determine how the effects of higher headwater spread over the village, and also to determine the amount of seepage around the structure and its contribution to obligatory release.

2. There were several versions for the extension of the Jászsági Main Irrigation Canal to reach the Rivers Tarna and Zagyva. Each of these versions influences the groundwater regime of the region in different ways. The task was in this case to find the version which seems to be the most advantageous from the point of view of regional groundwater regime and to give hints for the leakage control of the canals.

3. There is a large scale gravel dredging over the region south-east to Budapest. Due to the high groundwater level these gravel pits form a series of lakes. The evaporation over the large free water surface of the lakes is recharged by the groundwater. That is why each new pit further decreases the groundwater level. The task was to predict the effects of the enlargement of some gravel pits with special respect to inhabited and recreational areas.

Only the first case study is going to be discussed in details, giving the most important data and an evaluation of the results, as this is the simplest and shortest one. In case of the other two due to their complexity such a detailed description is beyond the scope of this paper. Therefore after a short drawing up of the problems themselves, modelling considerations, applicability and effectiveness of the method will be emphasised. A detailed evaluation of the technical problems may be found in some references (BME Vízépítési Tanszék, 1993, VARGA–CSOMA, 1997).

2. The Effects of the River Barrage at Bőcs on the Groundwater Regime

2.1. The Problem

The River Hernád is one of the major rivers of the northern, mountainous part of Hungary. Its origin is in the Carpathians, and its recipient is the River Sajó, a right tributary of the River Tisza. Due to the reasonable difference in height along the river, there are several hydroelectric power plants in operation. The lowest one is a diversion canal plant with a river barrage near the village Bőcs, at the distance of about 13 km from the mouth. The barrage consists of a fix weir, movable gates, fish pass and an inlet to the diversion canal. The full establishment (barrage, canal and power house) was built more than 50 years ago, and its reconstruction was planned in 1993. (BME Vízépítési Tanszék, 1993.) This reconstruction also covered the following:

- the modification of operation to increase energy production with a 30 cm rising of its headwater level;
- a control how the requirements of obligatory release could be fulfilled.

The region around the river barrage is over the common talus of the River Hernád and its recipient, the River Sajó. It is of gravel and sandy gravel with clay laminae. The gravel layer has a high hydraulic conductivity. Therefore any intervention in the operation of the river barrage may modify groundwater conditions.

Village Bőcs itself is lying on the right side of the river, in a sharp curve, it is bordered by the river from three sides. If there is any modification in the groundwater regime, it will directly appear at the inhabited area. Therefore the increasing of the headwater level cannot have any adverse effects even under the most unfavourable conditions.

West to the village Bőcs, at the distance of 5–6 km, over the talus a well field of the regional water works is in operation with the daily capacity of around 55000 m^3/d. It is proven, that the groundwater regime of the region is determined by this well field. So if the well field is in operation, the slight increasing of the headwater level vanishes due to the drawdown. But if the well field is closed down for a longer time for any reason, then the river Hernád is the dominating effect around Bőcs again. So as the most unfavourable case the situation without well field was chosen to determine the undisturbed effects of the modified operation of the river barrage.

The other part of the problem concerned the obligatory release. To ensure the normal regime of flow downstream the river barrage a certain amount of water is needed. But this obligatory release may reduce the discharge diverted to the hydroelectric power plant, so it reduces the energy production. Obligatory release may be ensured by several ways. The safest way is to let this amount through the gates of the barrage, though the outlet through the fish pass, together with the seepage around and below the structure will also be added to it. A well founded estimation of the latter three items may reduce the amount of water let through the structure, and increase energy production.

The seepage below and around the structure is actually a three dimensional flow. But it may be assumed, that the seepage below is a flow in vertical plain, and the one around is a horizontal groundwater flow, a local element of the regional flow mentioned earlier.

To solve these problems an analytic element model was developed with two versions. The first one is the regional one, while the second is more refined around the river barrage.

2.2. The Description of the Area and Applied Data

The talus between the rivers Hernád and Sajó consists of gravel of about 40–45 m. This thick gravel layer is subdivided by some smaller or larger clay laminae. One of the thickest ones is at the depth of 13–15 m, its average thickness around 2 m, and it is almost horizontal. This clay layer is considered as the base of the model aquifer. The negligence of the deeper gravel layers means a thinner aquifer which is more sensitive for any changes. Based on soil mechanical and hydrogeological investigations, the average permeability of this upper gravel layer can be taken as $k = 10^{-3}$ m/s. Though on the ground surface there is a thin cover layer of low permeability, the groundwater can be considered as phreatic. The left side of the river Hernád is mainly of loess with a rather low permeability. So this region is left out of the examinations.

The groundwater regime of the area may be examined by the recordings of four observation wells of the national hydrographic network. Two of them have a time series of almost 40 years, while the two others were used only for twelve years, about 35 years ago. The two wells of longer observation show a decreasing groundwater level from about 1980. This may be explained by two reasons:

1. a relatively dry period, which is also proven by the time series of precipitation,
2. the increasing water production of the well field mentioned before.

Though the two other observation wells of shorter recordings are nearer to the well field, they show a more stable regime, as they reflect the situation before the operation of the well field.

For the calibration of the model all the four wells were applied with average groundwater levels. This average covered the full period of the wells with the earlier recordings, but in case of the other two only the same, earlier period was taken into consideration. This was in accordance with the assumptions mentioned before, and this is how a homogeneous data series could be obtained, that described the situation without the operation of the well field.

In the first problem the water levels of the river were calculated with a one-dimensional steady state open surface flow model, both for the original normal headwater level and both for the planned operation. The downstream level was the minimum permissible water level of the prescribed obligatory release.

In case of the second problem to determine the seepage around the structure three different modes of operation were assumed. This meant three water level differences at the river barrage. One of them is the same, as in the first problem.

Though the area of interest was mainly the surroundings of the village Bőcs, the area examined covers a much larger region. The area of interest is given in *Fig. 1*.

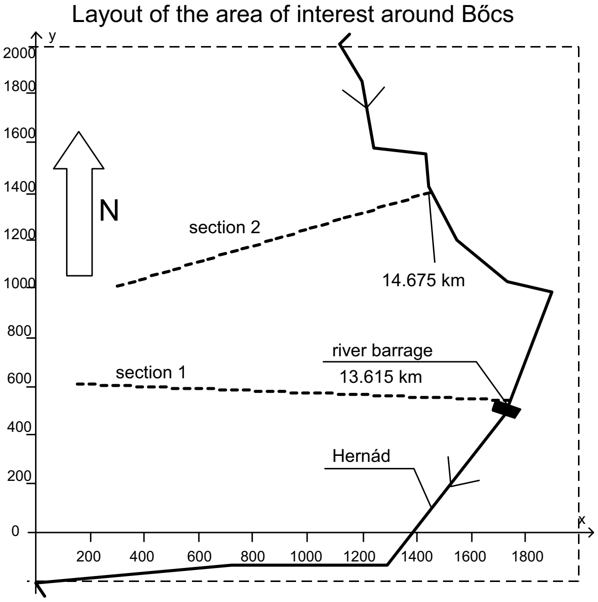

Fig. 1. Layout of the area of interest around Bőcs

2.3. *Modelling Considerations*

The area of interest is actually the village Bőcs itself in the first problem, and the surroundings of the river barrage in the second one. As it is mentioned earlier, the well field is left out of consideration, so the only feature influencing the groundwater regime is the River Hernád with its river barrage.

The River Hernád is modelled with the string of second order line sinks. A more than ten kilometres part of the river was modelled, though around the village there is only a few kilometre stretch. This modelled length was found by trial and error. This part in the upstream coincides the distance that the effects of higher headwater level vanishes in the river. This length in the river was determined by the earlier mentioned open surface flow model.

The elements of the line sink are usually shorter around the village, while further they are longer. Their layout follows the river as much as possible. While identifying the cross-sections for the computation of the backwater curves a special care was taken to this layout, as well.

The river barrage was modelled as an inhomogeneity with a string of line doublet. This inhomogeneity involved

- a reduced permeability due to the sheet piles of the structure,
- a reduced thickness of the aquifer bordered by the impermeable fundament of the structure from above,

and also a transition from unconfined to confined layer, with the fundament plate acting as a confining cover. This sharp inhomogeneity required the second order line doublet.

This model was suitable for both problems mentioned in point 2.1 in such a way, that

- the groundwater regime was examined with the full model
- the seepage around the structure was modelled with
  - more refined string of line sinks around the barrage,
  - more refined string of line doublets for the barrage itself,
  - cancelling some far away lying string elements of the river.

This is how the area of interest of the regional problem turned to be the full model area of the second, local problem.

2.4. Evaluation and Conclusions

Based on the data of point 2.2 and the modelling considerations of point 2.3 the AEM model provided the groundwater levels for both the problems given in point 2.1.

2.4.1. The Effects of the Modified Headwater Level

The effects of higher headwater level are examined from three different aspects.

a./ Regional Groundwater Regime
The contours of groundwater levels for both headwaters at the river are given in *Fig. 2*. It shows the same region as *Fig. 1*. The contours are given with the step of 0.5 m.

Comparing the two sets of contours it can be seen, that on the southern part of the village, downstream the river barrage there are no changes. On the northern – north-western part the differences are more significant. The contour of 107.0 m A.f. follows the layout of the river in both cases, but with the higher headwater level it is pushed to the south – south-west. This displacement is around 150–200 m. Similar effects can be observed in case of the contour of 106.5 m A.f., though in smaller extent. The displacement of these contours is less than 50 m.

b./ Leakage from the River

The flow around the river barrage seems to be rather high. But this amount of water will return into the downstream bed. Based on the obtained intensities of the first string members of the line sinks up- and downstream the barrage, this amount is 1.7 l/s/m in case of the lower headwater level, and 2.0 l/s/m in case of the higher one.

After the distance of some 100–150 m this higher flow rate sharply decreases. Further, by the section at 14.675 km there is already an almost constant infiltration along the river. This is the main part, where the leakage may change the groundwater level in the village. Along a 1 km part the average leakage is 0.03 l/s/m in case of the lower, and 0.04 l/s/m at the higher headwater level. This leakage takes 2600 m^3/d and 3500 m^3/d recharge respectively, which gives a 900 m^3/d surplus. Due to our basic assumptions, this amount was calculated under extreme conditions. Comparing this extreme value to the 55000 m^3/d production of the well field, it is negligible. Further upstream the leakage turns to be negligible.

c./ The Rising of the Groundwater Level

To examine the rising of the groundwater level two characteristic sections were taken. Section 1 is between the river barrage and the centre of the village, while section 2 starts 1 km upstream the river barrage and also reaches the village. Both sections have the origin of longitudinal co-ordinate at the river. The sections are also indicated in *Fig. 1*. *Fig. 3* shows the groundwater levels obtained by the two headwaters in both sections.

As section 1 is right at the headwater of the river barrage, it shows a rather intensive infiltration near the structure at both headwater levels. But within 100 m the effect of higher headwater decreases to its half, i.e. 15 cm and it remains almost constant for a larger length. By 1.2 km it is less than 10 cm, and further the difference gradually vanishes.

At section 2 the rising of the water level in the river is still the same, as at the barrage. As this section is further to the headwater, the intensity of infiltration is much smaller. The effect of the higher headwater decreases in this section much slower, the increment of 15 cm appears at the distance of 900 m, and the difference of 10 cm appears by 1.3 km.

Based on the above evaluation, it can be stated, that the higher headwater level has practically no adverse effects on the groundwater regime in the village of Bőcs. The rising of the groundwater level in the most part of the village is less than 10–15 cm even in the most unfavourable case.

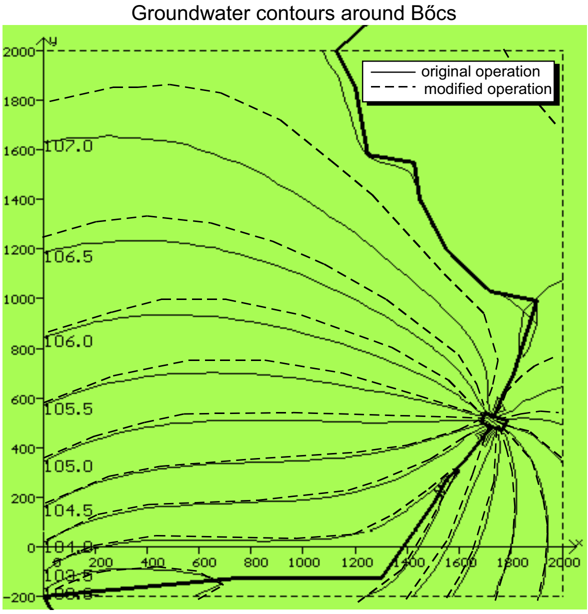

Fig. 2. Groundwater contours around Bőcs

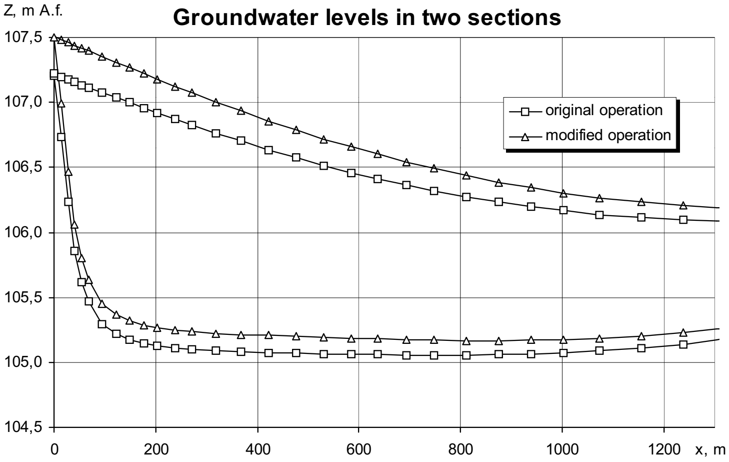

Fig. 3. Groundwater levels in two sections in Bőcs

2.4.2. *The Contribution of Seepage Around the Structure to Obligatory Release*

The second part of the investigations was to determine the seepage around the structure and its contribution to obligatory release. In this case three different heads of the structure were taken into consideration. This covered the range of normal operation, short time extreme situations were not examined. The model applied was the refined one mentioned earlier.

In this case the string members of the line sink around the structure were half as long as in the regional investigations. This refined approach proved that the leakage along the 100–150 m length of the upstream will return to the downstream bed, which is in accordance with the former results, though the discharges turned to be a little higher. This is due to the shorter line sink members, as they can follow sharper changes more accurate, while the longer ones refer more to average conditions. Finally, in the obligatory release these higher discharges with a length of 100 m were taken into consideration.

The calculations showed that even in case of the smallest water level difference there is a leakage of 100 l/s. This amount may be a reasonable part of the obligatory release, which is presently 0.5 m^3/s. Experiences showed that this value is rather small, sometimes even insufficient. Therefore the rising of this prescribed value may be expected. But even if it turns to be the double, the contribution of leakage to the obligatory release remains reasonable.

3. The Extension of the Jászsági Main Irrigation Canal

3.1. The Problem

Parallel with the construction of the river barrage at Kisköre on the River Tisza at both sides irrigation canal networks were set. The right side one is the Jászsági Main Irrigation Canal (JFCS) with its distribution system. The original plans contained a system of two branches until the Rivers Zagyva (tributary of the River Tisza) and Tarna (tributary of the River Zagyva), but their construction was postponed. The dry period of the recent decade turned the attention for the extension again with the aim of irrigation water supply and recharging the Rivers Zagyva and Tarna so that the water use on the upper catchment may increase.

The main branch of the extension is between the present JFCS and the River Zagyva (branch Z) in south-west direction. It is fully gravitational. By the middle of it the branch starts to the River Tarna (branch T) in west – north-west direction. As this branch crosses higher lying areas, near the branch Z a pumping station and a pressure conduit are also needed. For the horizontal layout of the canals three versions of branch Z and two versions of branch T were planned. As all the combinations of the versions are feasible, this means all together six versions.

Each version of branch Z start with a common part of 5.5 km, then there are three possibilities:

- Z1 is northern one with the length of 34.2 km. Along most parts of the branch the normal water level is below the ground surface, so almost no levees are needed;

- Z2 is the middle version with the length of 36.3 km. The normal water level is mainly below the ground level, but some levees, especially above the branch T are needed;
- Z3 is the southern one with the length of 33.9 km. The normal water level is above the ground surface, along the full length levees are needed.

For the capacity three versions are prepared. The maximum capacity of the canals above the branch T is 30 m^3/s, and below it 19 m^3/s.

The two versions of branch T have three parts, a lower canal, the conduit with the pumping station and the higher canal. The versions are as follows:

- T1 is the northern one, the lower part is 2.5–7.1 km long depending on the version of branch Z, the conduit is 2.1 km long, the pumping station has the head of about 7 m, and the upper path is 15.6 km. The normal water level is around the ground surface with levees at both sides;
- T2 is the southern branch, the lower part is 2.1–6.7 km, the conduit is 0.7 km long, the pumping station has the head of about 5 m, and the upper part is 14.8 km long. The normal water level is mainly below the ground surface, but some levee is needed.

The maximum capacity of the canals is planned as 7.2 m^3/s.

Both the Z and T branches have a rather small bottom slope, 11 cm/km. This small bottom slope with the relatively big capacity requires a reasonable size of canal that may influence the groundwater regime of the region.

All the layout versions are prepared so that they take land use (location of inhabited areas, roads, other canals, etc.), technical and environmental questions, nature protection, etc. into consideration, so each of them is feasible. The investigations aimed to determine, which one is the most advantageous from the point of view of the regional groundwater regime (VARGA–CSOMA, 1997). This means two aspects:

- from the point of view of the region to determine which version modifies the present groundwater regime the less,
- and from the point of view of the canal design to find those parts, where special care must be taken for leakage control.

3.2. Description of the Area and Applied Data

The area of interest is lying between three rivers, the Tisza, Zagyva and Tarna. The region is formed by the fine sediment of the rivers, mainly the Zagyva, modified by some sinking in the south-eastern part. The area consists of fine and clayey sand with the thickness of around 8 m over a clayey base. It is covered by a not fully permeable layer, which may be locally missing. The base is sloping to the south-east. On the north there is a rather sandy part reaching the ground surface, and

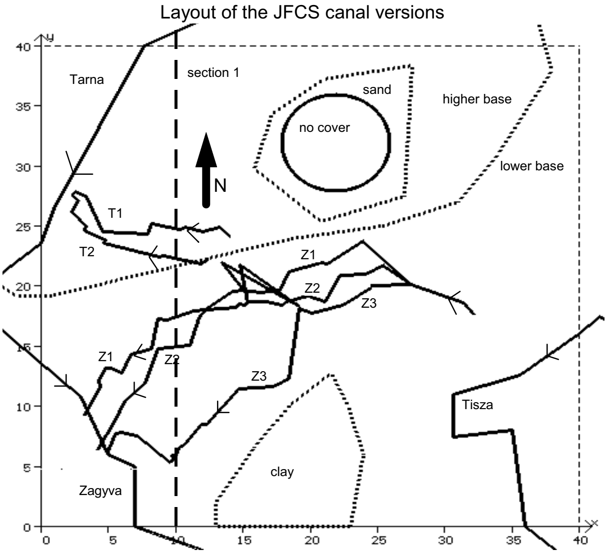

Fig. 4. Layout of the JFCS canal versions

on the south, at the lower part of the River Zagyva there are larger parts with finer material, mainly clay. Most part of the aquifer could be considered as confined, with an exception at the northern part, where the sand reaches the ground surface. Based on grain-size distributions of several boreholes over the region the average permeability may be taken as $k \cong 10^{-5}$ m/s, while over the sandy part at the north $k \cong 10^{-3}$ m/s, and in the clayey part at the south $k \cong 10^{-5}$ m/s.

The Rivers Tisza, Zagyva and Tarna were taken into consideration with their mean water level. The planned canals were modelled by two different water levels. The one was the dynamic level in case of water delivery. This is a steady state flow, the water levels are parallel with the bottom. The other is the static level, still standing water in the full system. Along each of the new canals no structure of leakage control was taken into consideration, as it was one of the aims to give hints for it. The presently existing JFCS has a full leakage control so it cannot influence groundwater flow in such an extent, that it should be taken into consideration.

The groundwater regime of the area can be examined by long term average contours. It may be characterised by a flow from the northern hilly area to the south, in the direction of the Rivers Tisza and Zagyva. This is modified by the drawdown of the rivers. The groundwater contours also reflect the geological formations mentioned before.

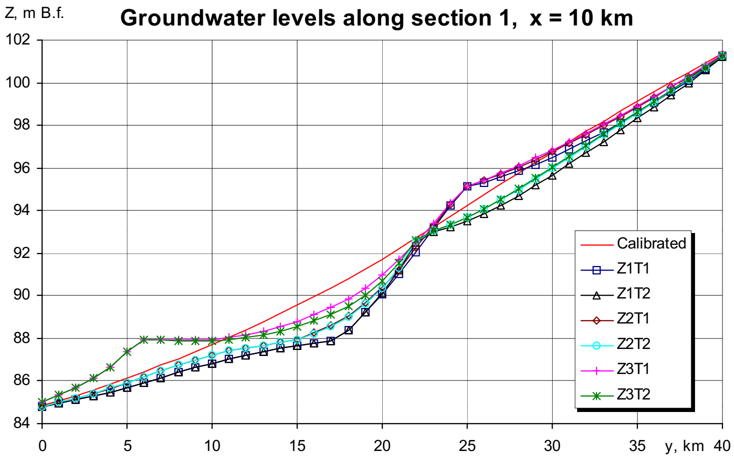

Fig. 5. Groundwater levels along section 1, $x = 10$ km

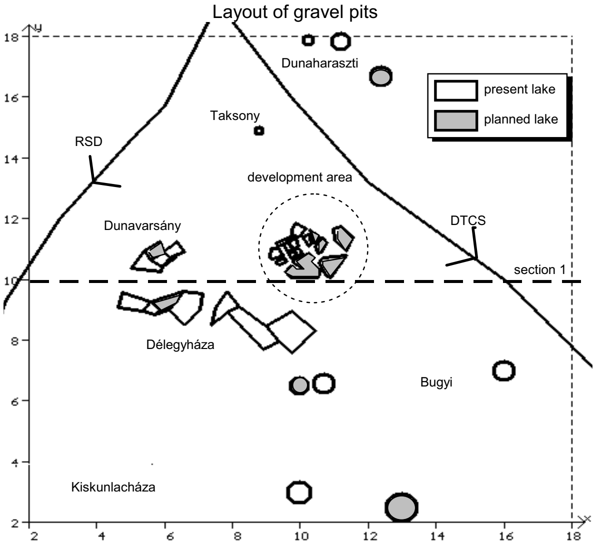

Fig. 6. Layout of gravel pits

3.3. *Modelling Considerations and Calibration*

The area of interest is between the three rivers, it covers an area of about 1500 km^2, though a much larger region was modelled. In this region several geological formations were taken into consideration. The area of interest is given in *Fig.*5. Instead of the natural formations the figure contains the elements applied for their description. While identifying these elements several considerations were made. In this point they are introduced.

The sloping base was modelled with two different elevations. It was considered as an inhomogeneity of base elevation. Its south-eastern part is indicated in *Fig. 6*, while the rest of it is out of the area of interest. This inhomogeneity was modelled by a string of second order line doublets. The distribution of string members is dense within the area of interest, while it is sparser out of it. Its size and location was verified by the calibration.

Within this higher base part there is the sandy region with no cover. It is once again an inhomogeneity, but now of permeability and also of the thickness of the aquifer. In this region the otherwise confined aquifer turns to be unconfined. This was also modelled with a string of second order line doublets. Its size and location were determined by the geological map, it was not the subject to calibration. This second inhomogeneity is imbedded in the other one of base elevation.

Imbedded inhomogeneities are possible to model, if the borders of the two ones do not cross each other. In case if the geological conditions require such inhomogeneities whose borders are crossing each other, then one of them must be split into two parts in such a way, that within each single inhomogeneity the permeability, aquifer thickness and base elevation are constant.

Usually sharper inhomogeneities of permeability are modelled with second order line doublets, while for the base elevation the simpler, first order one is also sufficient. But in this case, as the border of the imbedded other inhomogeneity is rather near to the changing of the base elevation, the more reliable second order one was required.

Finally the third inhomogeneity is the clayey part at the south. This is a simple inhomogeneity of permeability, modelled also by second order line doublets. Its size and location were also determined by the geological map.

The permeability values were the subject of calibration in a limited way. Their order of magnitude was the one given in the former point, but their best suited value was identified during the calibration. This process was followed both in case of the aquifer permeability and both for the inhomogeneities.

The rivers and the planned canals were modelled by strings of second order line sinks. Though it cannot be seen in *Fig. 5*, each river was taken into consideration with the length of 30–40 km. This length was also verified by calibration. The string members of the canals were as dense as their layout required it, while the rivers especially further to the canals and out of the area of interest were approximated with sparser strings.

The calibration was made without the planned canals. During the full calibration the emphasis was on the sufficient description of the regional groundwater movement, while smaller, local features were left out of consideration.

The dominant groundwater flow from the north to the south was taken into consideration as cross flow. The groundwater contours helped in the estimation of its direction and magnitude, though it was also the subject of calibration.

First the calibrations showed reasonably lower groundwater levels than indicated by the long term average contours, which referred to water deficit. This turned the attention to the cover layer, that is not fully permeable and locally missing. Therefore a low infiltration from the ground surface was applied to take this into consideration. At the sandy part where the cover layer is missing, a circle shaped area sink was also added with a higher infiltration. As the infiltration rate was rather small, it did not require the more accurate polygon shaped area sink. These two extra elements provided a groundwater regime that follows the given contours the best.

In case of water deficit the increasing of the cross flow could have also been a solution. But some test computations showed, that with this approach the shape and layout of the contours are adversely deformed.

3.4. Evaluation and Conclusions

Based on the data of point 3.2 and the modelling considerations of point 3.3 an AEM model was built to examine the effects of all the layout versions. The problem covers a wide range of questions, so a full evaluation like in the former case could be excessive in this paper. That is why only a short summary is going to be given here. For the illustration the groundwater levels along the section at $x = 10$ km are given in *Fig. 5*. It contains the groundwater levels gained by the calibration to describe the situation without the new canals and also all the six combinations of the planned versions.

General remarks to describe the common effects of the planned canals can be summarised as follows:

- The north – north-eastern part is the furthest from the intervention, it can be considered as being out of the influence area.
- Without any seepage control the static water level of the canals will determine the groundwater regime of the area instead of the rivers.
- The upper part of the branch Z and also branch T after the conduit is almost parallel with the groundwater contours, so the original direction of flow is not reasonably modified.
- The lower part of branch Z near the river Zagyva is almost perpendicular to the original contours, so the flow direction will be modified. The character and magnitude of this modification depends on the version discussed.
- Along the pressure conduit there is a strong seepage, so it needs a serious protection.
- On the south – south-east the canals will provide an almost horizontal groundwater table. Its extension and level depends on the version discussed.

Examining the versions of branch Z, together with the lower parts of branch T before the pumping station the following may be found:

- The common part of each Z version will not change the direction of regional groundwater flow, but due to its relatively high level it will raise the groundwater table, so leakage control is needed.
- Versions Z1 and Z2 cause a sinking of the groundwater table at the southern south-eastern part of the region, while version Z3 causes a rising of the groundwater table.
- The long lower part of branch T connected to branch Z3 causes a greater modification of flow direction over the region between the Rivers Zagyva and Tarna.

Examining the upper parts of the different versions of branch T, the following may be concluded:

- The versions of branch T are almost parallel with the original groundwater contours, though their static levels are different.
- The version T1 has the higher static level, it is above the original groundwater level, so it needs a leakage control.
- The version T2 has almost the same static level as the original groundwater level, so it causes almost no changing in the groundwater table.

Based on the above considerations, and taking the dynamic water levels and winter operation also into consideration the combination of version Z1 with T2 seems to be the most advantageous solution from the point of view of regional groundwater regime. Although it has to be mentioned, that it was only one aspect in the later process of decision making, and finally based on other advantages, the combination of Z1 and T1 was chosen for further investigations.

4. The Effects of Gravel Pits on the Regional Groundwater Regime

4.1. The Problem

South-east to Budapest there is an extensive gravel terrace which provides good quality material for construction works. Due to the large scale gravel dredging in the region there are several gravel pits in operation, while some of them are already abandoned. As the groundwater table is relatively high over the region these gravel pits form a series of lakes. The region may be characterised by a deficit in the water balance, as the yearly precipitation is usually lower than the evapotransspiration, especially in the last, dry decade. Therefore, any new free water surface – like a new gravel pit – will increase this deficit and lower the groundwater level.

Gravel dredging over such an area is a serious load on the groundwater. During the operation there is a loss of groundwater due to the following reasons:

- some water is taken away together with the gravel;
- in the pits themselves the place of the removed gravel is filled by the groundwater;

- the growing area of the cultivated pits will increase the evaporation,

while in case of abandoned pits only the evaporation loads the groundwater resources.

The region examined cannot be considered as a natural environment, as there are already several operating and abandoned gravel pits over there. On the shores of some abandoned ones already recreational areas developed, while the region itself is an agricultural area as well, with several villages. Therefore any further development of the dredging activity needs a special care.

The aim of the present chapter is the examination and prediction of the effects due to the enlargement of an existing gravel pit. Based on technological and other considerations both the present plant and also the planned development consist of several pits. As not all the dredged material can be utilised, some of the new pits may be filled with it. So the examination has to cover the following fields:

- the control of the sequence of pits to be cultivated to determine which ones may be open simultaneously, and which ones have to be filled by dead material as soon as possible;
- the effects of the increased gravel dredging over the full region;
- the expected drawdown at inhabited and recreational areas;
- combination with the planned and/or assumed development of other establishments in the surroundings.

4.2. Description of the Area and Applied Data

The area to be examined is around 200 km^2. From the west it is bordered by the Ráckeve (Soroksár)- Danube Branch (abbreviated as RSD). It is a regulated, almost still standing branch of the Danube. From the north – north-east the area is bordered by the Danube – Tisza Canal (abbr. DTCS), while further from the east there is the Danube Valley Main Canal (abbr. DVCS). Both of them are regional canals of the land drainage network. On the south there is no such natural boundary. Within this area a special attention has to be paid to the region between the RSD – DTCS and the villages Bugyi, Délegyháza, Dunavarsány and Taksony. Most of the gravel dredging and also the abandoned lakes with the recreational areas are concentrated here, especially at Délegyháza.

The subsoil of the area is mainly of gravel originated from the earlier meandering of the Danube during the geological ages. The average thickness of this gravel layer is around 10 m. It is covered by a thin layer of fine sediment and bordered by a clayey base gently sloping to the south. This base was described with an average height given by an interval. At the development area a dense network of boreholes were set, so detailed grain size distributions were provided. The permeability was estimated with the help of the characteristic grain diameter. Several methods were used and compared. Though locally rather high values also appeared (e.g. 300 m/d), finally also an interval was defined as an average. The average meant both a vertical average coming from different levels of a given borehole along the aquifer and both a regional average. This interval was set as 30–50 m/d. More refined value was gained later, by the calibration.

The main groundwater resource is the RSD, though there is also a reasonable recharge from the northern, hilly regions. Based on the long term average groundwater levels of round ten observation wells of the national hydrographic network and also on the recordings of the boreholes, the aquifer is phreatic.

In the region there are several gravel pits. The most important ones are as follows:

- Over the development area there are gravel pits with the total area of 40 ha. Some of them are abandoned, while a few of them are under cultivation. In the coming 50 years a development of almost 300 ha is proposed.
- Near Délegyháza lakes of around 220 ha are abandoned, they are utilised for recreation. In this region 78 ha is still under cultivation, and the enlargement of more than 50 ha is planned.
- The lakes at Dunavarsány (cultivated and abandoned) have a total area of 50 ha, and a development of 30 ha seems to be possible.
- At Dunaharaszti there are three lakes with the total area of 40 ha and a further 20 ha of development may be expected.
- At Taksony there is a smaller abandoned lake of 5 ha. Here no more enlargement is planned.
- Finally, in the region of Bugyi – Délegyháza – Kiskunlacháza there are several lakes with the total area of 100 ha and a further 80 ha may appear later.

Several of the above lakes, especially the older, abandoned ones have regular monthly water level recordings, some others have only some data and a few have no recordings.

The main water course of the region is the RSD. Its water level is regulated both at its inlet and outlet by river barrages. The two other regional canals, DTCS and DVCS are also regulated by several structures. Both the Danube Branch and the canals were taken into consideration with their normal water levels given in their licence. Other canals of the land drainage network are of minor importance, so they are left out of consideration.

The evaporation of free water surface was determined by hydrological investigations taking the last, dry decade into consideration. It was also given by an interval.

4.3. Modelling Considerations and Calibration

The area of interest is the region of RSD – DTCS – Bugyi – Délegyháza – Dunavarsány. In this region the following elements were defined:

- *water courses*: RSD and DTCS with second order line sinks of given water level, following their layout as much as possible;

- *gravel pits over the development area*: each lake is described by its exact size, shape and location as polygonal area sinks with given intensity;
- *lakes and pits at Délegyháza and Dunavarsány*: these nearby lying lakes were modelled by area sinks of approximate shape and exact size and location with given sink intensity.

In both cases of area sinks their intensity (which is actually exfiltration) was given by the evaporation of free water surfaces.

The two different ways of the modelling of lakes are based on their importance. The lakes over the development area had to be taken into consideration as exact as possible. That meant that each individual lake – even the smallest ones – was described by such polygons, whose

- corners followed the shape in the best way,
- centroid was located at the co-ordinate given in the licence,
- area was the same as in the licence.

Some lakes of rather irregular shape were even split into smaller parts, keeping still the above consideration in sight. This meant a large number of computations, as the potential function of area sinks is rather compound. At further lying lakes such high level of accuracy could only increase the computation time, but not the reliability of the model. Therefore an approximate shape was applied. This approximation meant that the centroid was exactly at the co-ordinate, where their licence indicated, the size also corresponded the one given in the licence, but the shape was a simplified polygon. This simplification meant the joining of nearby lying lakes, but sometimes also the splitting of some irregular ones, like in the former case. Such considerations required a very careful data preparation, but later these efforts were returned by the efficiency of the model. Most of these elements are indicated in *Fig. 6*.

This first version of the model contained only those elements, that may influence the area of interest the strongest. During the identification of the outer area which was executed parallel with the calibration the following elements had to be modified or added:

- cross flow to describe the recharge from the north – north-east;
- RSD was extended almost for its full length, and DTCS was also extended until DVCS to the south-east with longer members of line sinks to describe their approximate layout;
- the further lying DVCS had to be added with a sparse string of line sinks to describe effects coming from the east;
- lakes and pits at Dunaharaszti and Taksony on the north, and also in the region of Bugyi – Délegyháza – Kiskunlacháza on the south had to be added with exact location of their centroid and area, but with an approximate, circular shape.

This latter item gave the third approximation of lakes. These lakes are over the outer area, their local behaviour is out of interest, but their regional effects could influence the area of interest. Their circular shape with a rather simple potential function saved up a reasonable amount of computation, but the exact size described their real drawdown on a regional scale.

There was a wide range of groundwater levels of different origin provided for the calibration. The most reliable ones of them were the long term recordings of the hydrographic network. So the best fit was required to their average at each observation well. Though several lakes had monthly recordings, these data did not have such a wide range control as the former ones, so some of them had to be left out. And the individual recordings of some other lakes were taken into consideration as approximate values.

Finally the calibration also provided those data that were given by an interval. These are the base elevation, the permeability and the evaporation. Actually it seems to be effective to describe such data with a range to give their magnitude, but the further refinement is left for the calibration.

4.4. *Evaluation and Conclusion*

The calibrated model provided a rather flexible tool to predict the drawdown of gravel dredging. A wide range of versions were modelled with it. These versions covered the different setup of the planned lakes over the development area, their combination with other enlargements, and also the sensitivity test of the evaporation.

Some of the results are summarised in *Fig.* 7. The groundwater levels of four versions along a section at the local co-ordinate of $y = 10$ km are given in it. The version B1 examines the effects of a certain composition of the planned lakes at the development area. This situation may be expected after 20–30 years. The lakes are also indicated in *Fig.* 6. B1B models the simultaneous development of some other further lying lakes also indicated in *Fig.* 6, and its drawdown compared to the calibrated, ‘present’ situation is given in *Fig.* 8. B1C is the same as B1, just the evaporation is increased with 10%. The version B2 gives the effects of a long term, 50 years development. The calibrated, present situation is also indicated in the figure.

Based on a detailed evaluation of the versions given here and also of those not mentioned, the following conclusions can be made:

- In the present situation there is already an approximately ellipsis shaped depression in the region with its centre at the abandoned lake of Délegyháza.
- The version B1 gives a modified depression of rather triangular shape with the centre pushed in the direction of the development area. In the nearby lying villages and recreational areas (Dunavarsány, Délegyháza) the drawdown is not more than 20 cm. In Bugyi and Taksony the effect is negligible.
- In case of the version B1B the drawdown is 20–25 cm higher, than in case of B1 and also the depression cone is much larger. But due to the uncertainties of

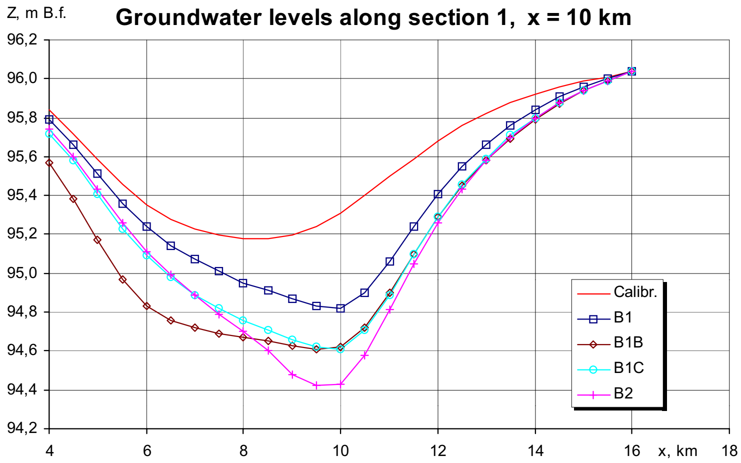

Fig. 7. Groundwater levels along section 1, $y = 10$ km

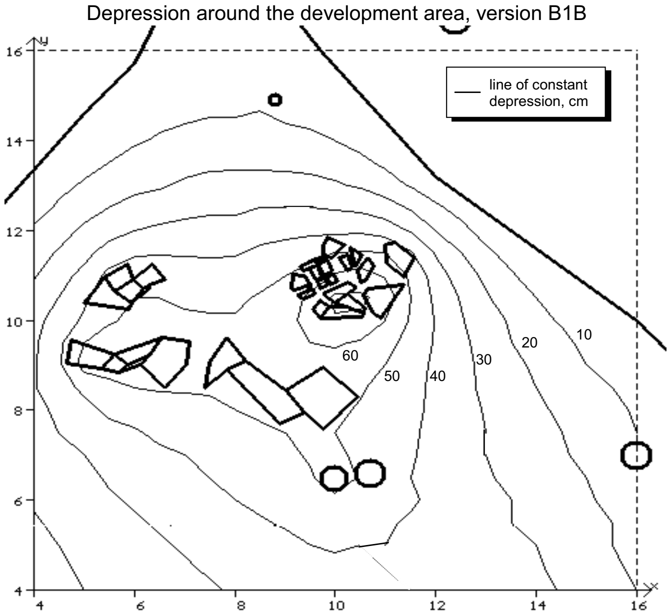

Fig. 8. Depression around the development area, version B1B

the size and location of enlargement of the further establishments this version should be considered as an estimation.

- The version B1C with the higher evaporation gives a deeper depression than B1 around the lakes, but this effect vanishes around the villages.

- Finally B2 gives the greater depression, though it is a rather long term prediction (50 years) with several uncertainties. The effect of this enlargement may also reach the further lying villages, Bugyi and Taksony.

Based on the results such a strategy of dredging could be prepared that was acceptable for all the interested parties.

5. Summary

The present paper introduced the application of the analytical elements method for groundwater flow modelling. Three case studies were given focusing rather on the applicability and effectiveness of the method than on the technical problem itself. They demonstrate several features of the method and its application.

The method itself is based on the potential theory using the discharge potential. Each individual feature of the aquifer, the so-called elements, are given by well chosen potential functions, and the description of the full aquifer is obtained by the superposition of them. Several of the most important elements introduced in a former paper of this volume are applied in the case studies, such as:

- cross flow was almost always used to describe the far field behaviour of the aquifer;
- infiltration was applied in case of phreatic aquifers and also if the cover layer was not fully impermeable;
- rivers and larger canals are usually modelled by strings of line sinks in each case study;
- the river barrage with its impermeable fundament plate and sheet piles is modelled as an inhomogeneity of the aquifer, i.e. the variation of its thickness and permeability, with the help of a string of second order line doublets in the first example;
- also strings of second order line doublets, even imbedded ones, were applied to describe different geological formations of the aquifer in the second problem;
- area sink was applied to describe the locally missing cover layer in the second case study;
- also different types of area sinks were applied to describe lakes of different importance in the third case.

This list of elements and also all the considerations given earlier demonstrate the flexibility of the method in describing different features of an aquifer.

The effectiveness of the model is demonstrated by case studies.

The first study examines the effects of the modified operation of a river barrage. A larger scale and a local problem was solved with almost the same model, that shows its flexibility. Around the barrage itself there is a sharp variation of groundwater levels that the model followed rather reliably. As the effects of modified operation in the river itself were examined by a one dimensional open channel flow model, this problem is a good example to show how surface and groundwater models may work together.

The second case study is the prediction of the effects of a set of planned canals. There were several layout versions to be examined. In this region the geological formations were more complicated, than in the first problem. This case study demonstrates how effective the above elements are in the description of such a compound region. It also showed, how it can be applied in the preliminary design process of a large scale project.

Finally, the third problem examines the effects of gravel dredging. It demonstrates the several possibilities to describe larger open surface waters of different importance. Its simple structure made it possible to examine and evaluate several versions to find such a solution that is acceptable for all the interested parties.

Based on the above experiences, the model may be an effective tool in the design, operation and decision making process connected to groundwater flow problems.

References

[1] BME Vízépítési Tanszék , Bőcsi duzzasztómű rekonstrukciója. Kiviteli terv. (The Reconstruction of the River Barrage at Bőcs, in Hungarian)(1993).

[2] VARGA, I. – CSOMA, R., Jászsági főcsatorna meghosszabbítása. Szivárgáshidraulikai vizsgálatok. Szakvélemény. (The Extension of the Jászsági Main Irrigation Canal. Seepage Hydraulics, in Hungarian) (1997).