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ORIGINAL ARTICLE

Evaluation of alternatives for lowering the groundwater table in a village in upper Egypt affected by the construction of the New Naga Hammadi barrage

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Abstract The Egyptian government is replacing the existing Naga Hammadi barrage, located across the Nile River some 450 km south of Cairo, with the New Naga Hammadi barrage (NNHB) to incorporate a hydropower plant and to improve conditions for river traffic. The new structure will lead to an increase in river water levels, both locally near the new barrage and upstream. The rise in river water levels will in turn result in changes in groundwater levels in the aquifer system up and downstream of the barrages. In this paper, an area is chosen, which is expected to suffer from a high groundwater table after the construction of the NNHB, to investigate the problem and propose alternatives for lowering the groundwater levels. The study area is a village called Bakhaness, with an area of 588 ha. It is located some 1.5 km upstream of the NNHB. A computer model (MicroFEM) has been used to simulate the groundwater conditions before and after construction of the NNHB. Alternatives for lowering the groundwater table are proposed, simulated and evaluated. The systems, which are assessed are a municipal sewer system, a system of perforated pipes in urban areas, and tile drainage with different values of efficiency in agricultural areas.

Keywords Groundwater lowering · MicroFEM · Subsurface drainage · Egypt · New Naga Hammadi barrage

Introduction

The rise of groundwater levels may result in some adverse effects. Papadopoulos et al. (2005) studied the effects on structures and construction activities. Drablos and Melvin (1991) investigated the effects of elevated groundwater levels on plants. They concluded that drainage is an important and profitable practice for sustainable farming activities, leading to the improvement of crop production and allowing the use of more intensive farming practices on level land. The removal of excess water from the saturated soil mass is termed drainage or dewatering. Several studies have discussed the hydrogeological aspects of the following dewatering methods: well point systems (Mansur and Durrett 2002), pumping well system (Tokgoz et al. 2002), vacuum method (Wynn et al. 2004), cut off covered dam (Mansur and Durrett 2002), and subsurface drainage (Drablos and Melvin 1991; Skehan and Christen 2001).

Description of the study region

The NNHB and hydropower plant is planned as a replacement for the existing Naga Hammadi barrage located near the town of Naga Hammadi, some 360 km downstream from Aswan on the Nile River in Egypt. The old barrage was completed in 1930 to regulate water for irrigation in Sohag and Assiut Governorates. The new barrage at Naga Hammadi will be operated with a static head pond level of 65.9 m asl for most of the year. This

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level is some 0.5 m above the current maximum operating level in summer, and 0.8 m above the corresponding level in winter. Backwater effects will be detectable at least as far upstream as Qena (50 km upstream). In addition, the new barrage will be located 3.5 km downstream of the existing barrage, resulting in an increase of between 4 and 7 m in Nile River water levels in the intervening reach. This increase in river water levels, both locally near the new barrage and upstream, will result in changes in groundwater levels in the aquifer system upstream and downstream of the two barrages. Figure 1 shows a general location map of the study area.

In this paper, an area is chosen, which is expected to suffer from a high groundwater table after the construction of the new barrage, to investigate the problem and propose alternatives for lowering the groundwater levels. The study area is a village called Bakhaness, with an area of about 588 ha (5.88 km^2). It is located some 1.5 km upstream of the NNHB. The Bakhaness area consists mainly of two different types of surface cover. The first type is the main city, covered with residential and public buildings, streets, etc. The second type of cover is agricultural land with scattered residential and public buildings. Figure 2 shows a map of the Bakhaness area. In the agricultural area of this village, a tile drainage system already exists (constructed in 1982) for lowering the high groundwater level. In this research, the efficiency of this tile drainage system will be assessed. In the urban area of the village, there is no dewatering system. A perforated pipes network at different places and a sewer system will be assessed for lowering the high groundwater levels.

Geomorphology and geology

The alluvium underlying Bakhaness village may be subdivided into two units, a top clay-silt layer, underlain by a graded sand layer. The graded sand layer ranges in thickness from a minimum of 105 m to a maximum of 120 m. The clay layer thickness is about 9.0 m (Abdel Ghaffar 1997).

Permeability values were determined during earlier hydrogeological studies in the Nile valley by the Research Institute for Groundwater (RIGW 1994). On the basis of these data and the geological profiles of the existing boreholes in the study area, the overall permeability for the aquifer system can be summarized as follows:

- The upper Holocene layer in Bakhaness consists of varying portions of fine to medium sand intercalated with silty clay. The horizontal permeability is in the range of 0.018–2.0 m/d. The vertical permeability is estimated to be one-tenth of the horizontal permeability.
- The lower Pleistocene layer in Bakhaness is mainly composed of medium to coarse sand intercalated with fine sand and gravel. The permeability is in the range of 40–120 m/d.

Groundwater level monitoring

Measuring groundwater levels is essential for model calibration (adjusting the model's key parameters so that observed and calculated groundwater levels coincide within reasonable limits) before any reliable simulation

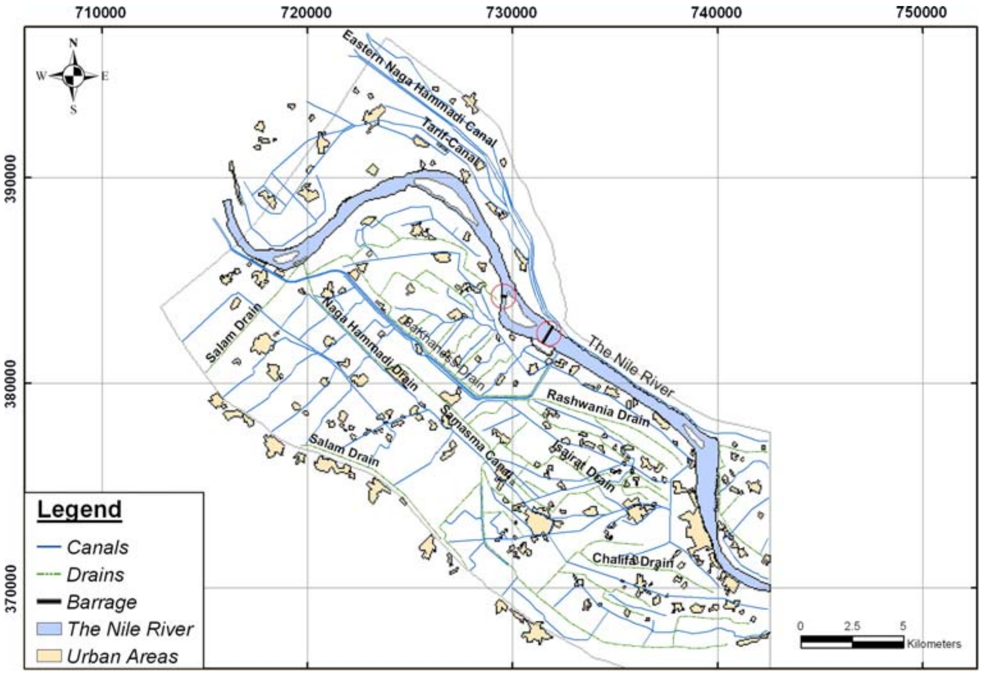


Fig. 1 General location map of the study area

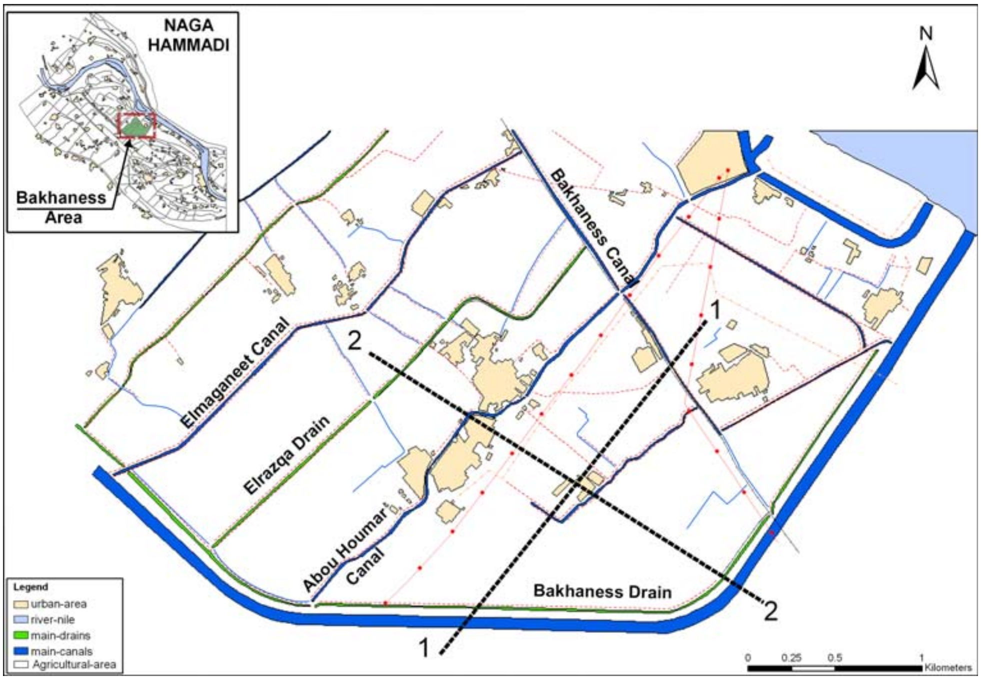


Fig. 2 Map of the Bakhaness area

runs can be undertaken. Some observation wells were installed by the Ministry of Water Resources and Irrigation (MWRI) in three installation campaigns (Lahmayer 2002). The piezometers were installed at shallow depths (5–10 m) in the upper Holocene layer. Figure 3 represents average observed depth to water in the upper layer during summer, which represents the season of highest groundwater levels. The hatched areas represent the critical areas within the area of study (critical area is defined as an area in which the depth to groundwater is less than 1.0 m, as this affects plant growth and human life). The critical area represents about 35% of the total area. It is noted that the water table levels in the top layer are higher than the adjacent Bakhaness drain and lower than the Bakhaness canal and Elmaganeet canal for the whole study region, so it is obvious that the Bakhaness drain acts as the main drain to the adjacent top layer at the present situation and Bakhaness canal acts as the main water source.

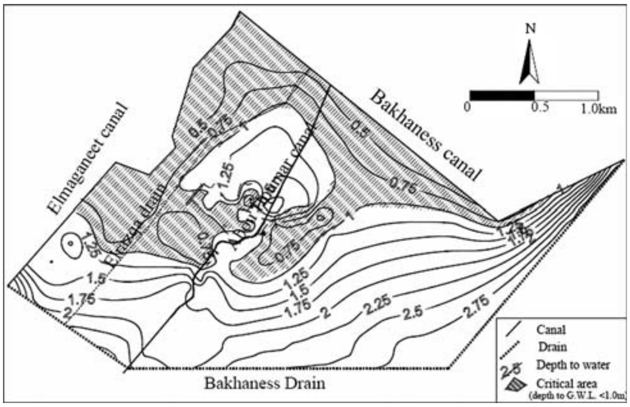


Fig. 3 Observed depth to water in summer 2002

The subsurface drainage system

The agricultural area is equipped with subsurface drains (535 ha, 5.35 km^2) representing 91% of the total area under study. The tile drains consist of a subsurface collector with attached lateral pipes (laterals). Each collector and its laterals cover an area of about 42 ha. The distance between collectors is around 500 m. The laterals have a diameter of 10 cm and are wrapped in filter cloth. They are designed to begin about 1.2–1.4 m below the ground surface, and have a maximum length of about 200 m. Depending on soil characteristics, the laterals are installed every 30–40 m, perpendicular to collectors. The slope of each lateral is 0.1%. Each lateral discharges into a collector drain, a PVC pipe of diameter 15–45 cm. Collectors can extend over 1 km in length, with a slope of 0.03–0.04%. In order to gain access to the collectors for cleaning and maintenance, manholes are installed at least every 200 m along the collector pipe. Figure 4 shows the layout of the collectors of the tile drainage system in the region.

The sewer system and the perforated pipes network

A sewer system and a perforated pipes network are presently under construction in the urban areas of Bakhaness. The sewer system consists of pipes of 20–25 cm diameter and 0.4% slope. They are designed to start about 1.5–1.7 m below the ground surface. Manholes are installed at least

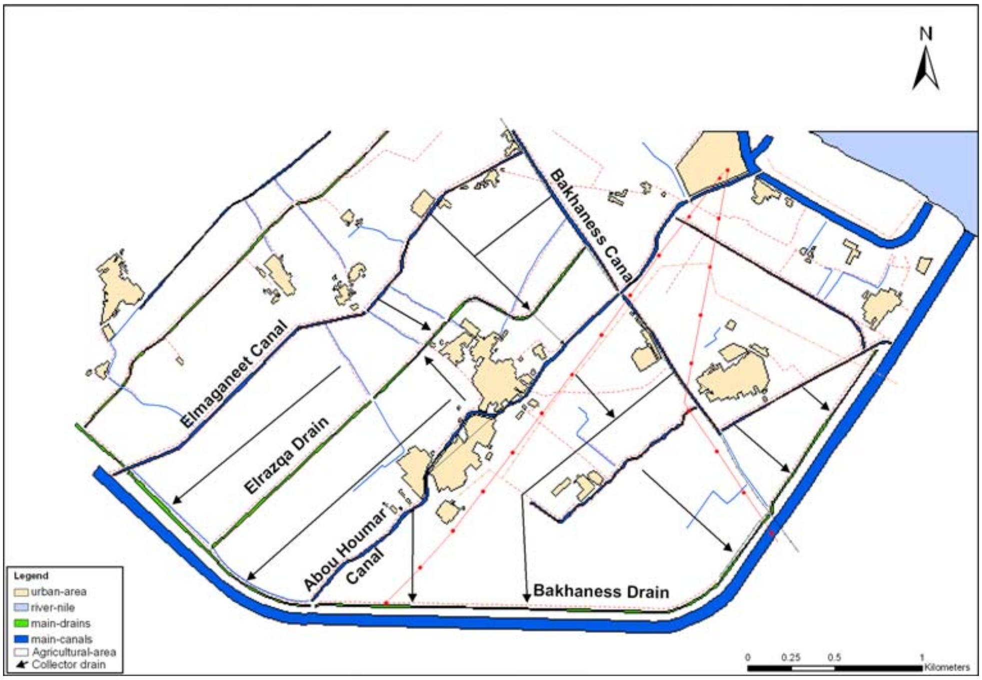


Fig. 4 Layout of collectors of the tile drainage system

every 30 m along the pipes. The discharge of the sewer system is collected in a water treatment plant located at the south of the village.

The perforated pipes network consists of pipes of 20–25 cm in diameter overlying the sewer system and collected at different manholes. The pipes are surrounded by a graded gravel filter. The total length of pipes is 2.6 km. The pipes are laid about 0.2 m above the sewer pipe and at the same slope. Figure 5 shows the layout of the perforated pipes only.

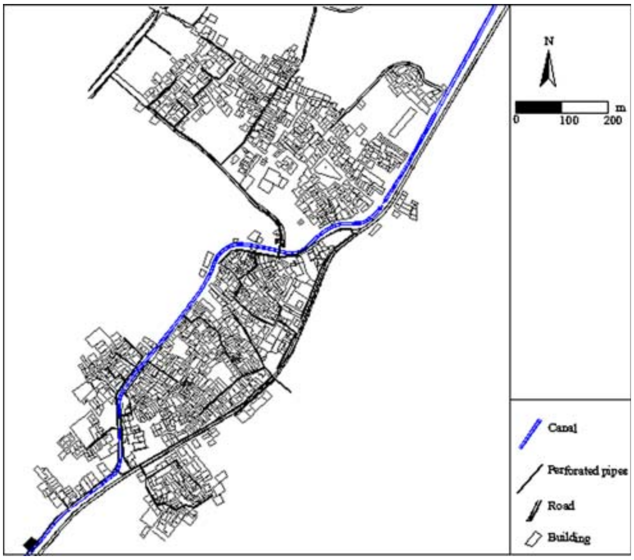


Fig. 5 The layout of the perforated pipes system

Groundwater model development

The approach adopted for simulation of groundwater conditions within Bakhaness is a quasi thee-dimensional approach, which simulates horizontal flow in each layer as two-dimensional flow, in addition to vertical flow between the layers. To achieve this, a multi-layer finite element model has been utilized for the study area. The computational model selected for this study is MicroFEM version 3.6 (Hemker and Smits 2004; Diodato 2000). Confined, semi-confined, phreatic, stratified and leaky multi-aquifer systems can be simulated with a maximum of 20 aquifers. Heterogeneous aquifers, aquitards and spatially varying anisotropic aquifers can be simulated under steady-state and transient flow conditions. The model can simulate spatially and temporally varying wells and boundary conditions, precipitation, evaporation, drains, rivers and wadi top systems.

Model construction

In order to numerically model any aquifer, it is necessary to define its physical extent and to describe its boundaries and interior points in such a way that the computer model adequately represents the aquifer. The model domain was divided in plane view into 4,519 elements and 2,321 nodes. The hydrogeological conditions underlying Bakhaness were simulated as two layers. The upper layer is represented by the silty-clay cap, while the lower layer is represented by the sand aquifer. Interchange between the two layers was simulated through the specification of a leaky layer in between the two layers, having a vertical permeability of one-tenth the horizontal permeability of the upper layer. Field data obtained from shallow piezometers as well as from pumping tests have been entered to the model at well locations.

Model calibration

Calibration refers to the process of adjusting the model's key parameters so that the observed and calculated water table levels coincide within reasonable limits. Calibration is carried out at the beginning of modeling as part of setting up of the model, and is necessary before any reliable simulation runs can be undertaken after the grid. One of the reasons for the rise of groundwater levels is due to septic tanks in the areas, which have no sewer system. This effect was entered into the model by adding a precipitation of 1.8 mm per day. This value was calculated knowing that the number of population of this region was 9,341 capita as given by the Information Center of Qena (2002) and assuming a water consumption per capita of 100 l per day. This value is distributed over the urban area of about 0.5 km^2. The permeability of the upper layer is adjusted to simulate the field environment. Figure 6 represents the comparison between the model results and field measurements at five representative piezometer locations distributed over the study area. The figure reveals that the difference between measured and simulated values is acceptable, and hence the model can be used for predicting the future groundwater conditions.

Simulation of future conditions with existing groundwater lowering systems

Following calibration of the groundwater model, a simulation run was carried out considering construction of the NNHB. According to regional hydrogeological studies and predictions by NNHBHP (2002) and Gad El-Rab (2006), the water surface elevation of the water bodies prescribing the boundary conditions of the study domain will rise due to the construction of the NNHB by a value of about 40 cm. This value has been used to adjust the boundary conditions for the prediction of local conditions in the study region.

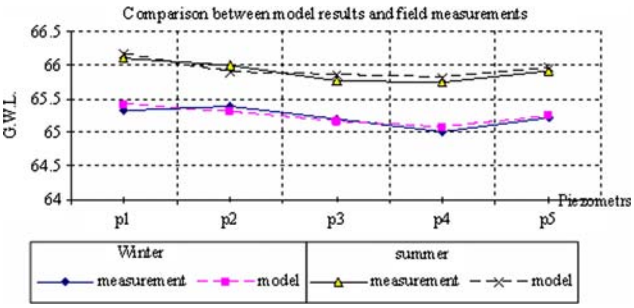
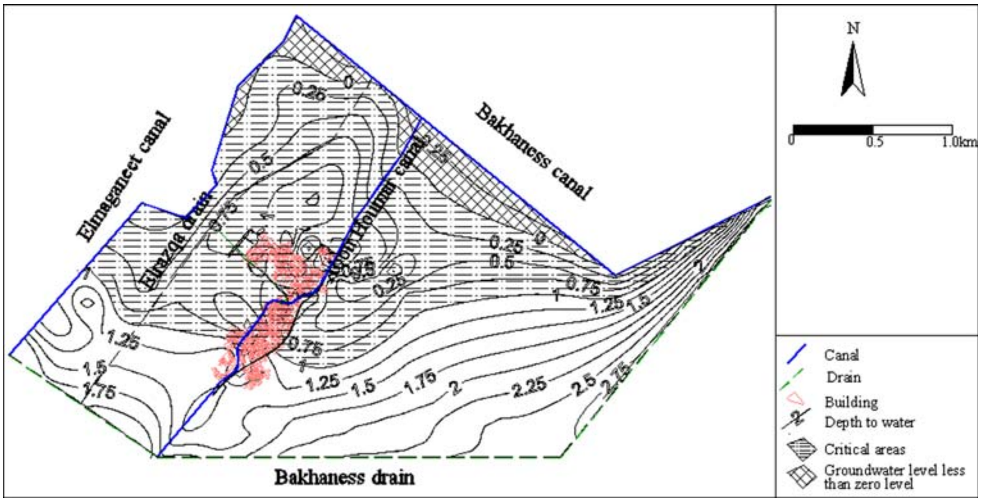


Fig. 6 Comparison between measured and simulated water levels at five piezometers

Figures 7 and 8 show contours of depth to water in the upper layer in summer. The simulation shows that in future, 55% of the study area will be affected for this scenario compared to 35% at present. It can be seen that the area mostly affected by elevated groundwater is in the northern and western region of the city bordering the Bakhaness canal and Elmaganeet canal, extending to more than half the city's width to the west. It is seen that in some areas, the level of groundwater will be above the ground surface level. The total amount of water drained into the Bakhaness drain would be about 290 m^3/day compared to 240 m^3/day at present. Comparing the present and future water table contour maps, no significant changes to the overall groundwater flow pattern can be identified. The change occurs in water table level values.

Fig. 7 Predicted depth to water in the future after construction of NNHB (2012) without any dewatering system



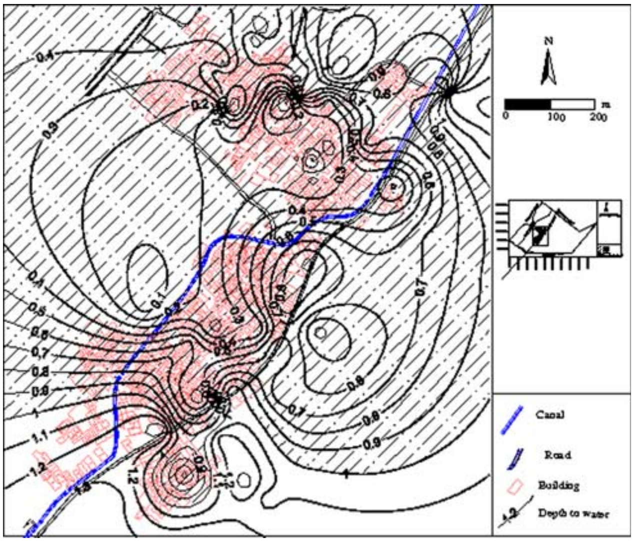


Fig. 8 Predicted depth to water in future inside urban areas after construction of the NNHB (2012) without any dewatering system

Description and evaluation of groundwater lowering alternatives

Effect of sewer system

The sewer system has been described in the section "The sewer system and the perfortated pipes network". The effect of sewer system has been simulated through modeling the study area without the adding of precipitation (section "Model calibration"). Figure 9 depicts contours of depth to water with the sewer system in operation before and after the NNHB implementation. The figure reveals that in the present situation (left map), there would be no affected area inside the village after the construction of the sewer system, while after the NNHB implementation (right map), some areas will be affected. The hatched areas are the critical areas within the urban areas. The affected area in urban areas will be 0.23 km^2, which represents 46% of the areas. This means that the sewer system alone will not be sufficient in the future.

Effect of the perforated pipes network

The average depth below the ground surface is 1.5 m, which was entered into the model as a fixed head boundary (i.e., assuming 100% drainage efficiency of the perforated pipes). The water collected by the perforated pipes and the sewer system is drained into the same pumping station. After placing the perforated pipes, the affected areas decreased and there were no critical areas inside the village. The collected discharge by the perforated pipes was calculated to be 1,400 m^3/day (16.2 l/s). The capacity of the pumping station of the sewer system has to be increased by about 60% due to the quantity of water collected by the perforated pipes. The above-described systems have been under construction in the field. However, the following analysis is conducted to investigate the effect of decreasing the number of installed perforated pipes on the groundwater conditions in the village. A second scenario with decreased pipes (total length of 2.0 km) has been simulated by the model. The perforated pipes remain with the same diameter. The collected discharge by the perforated pipes was calculated to

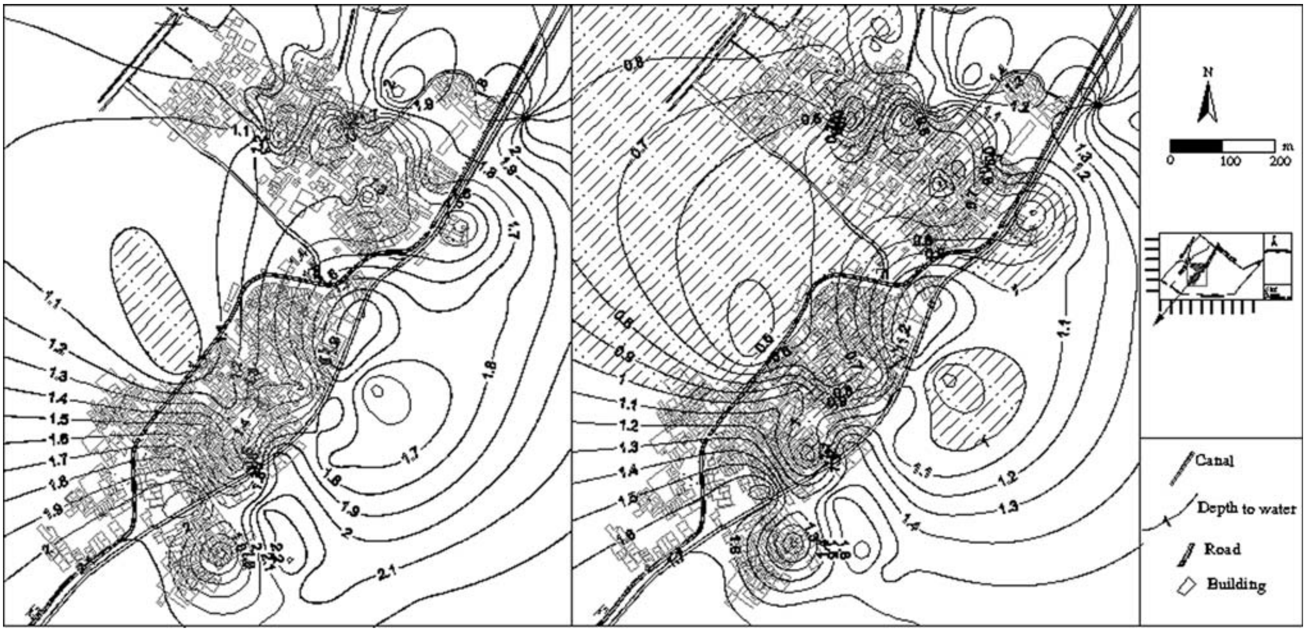


Fig. 9 Depth to water inside village before and after construction of NNHB (2002) with the sewer system in operation inside village

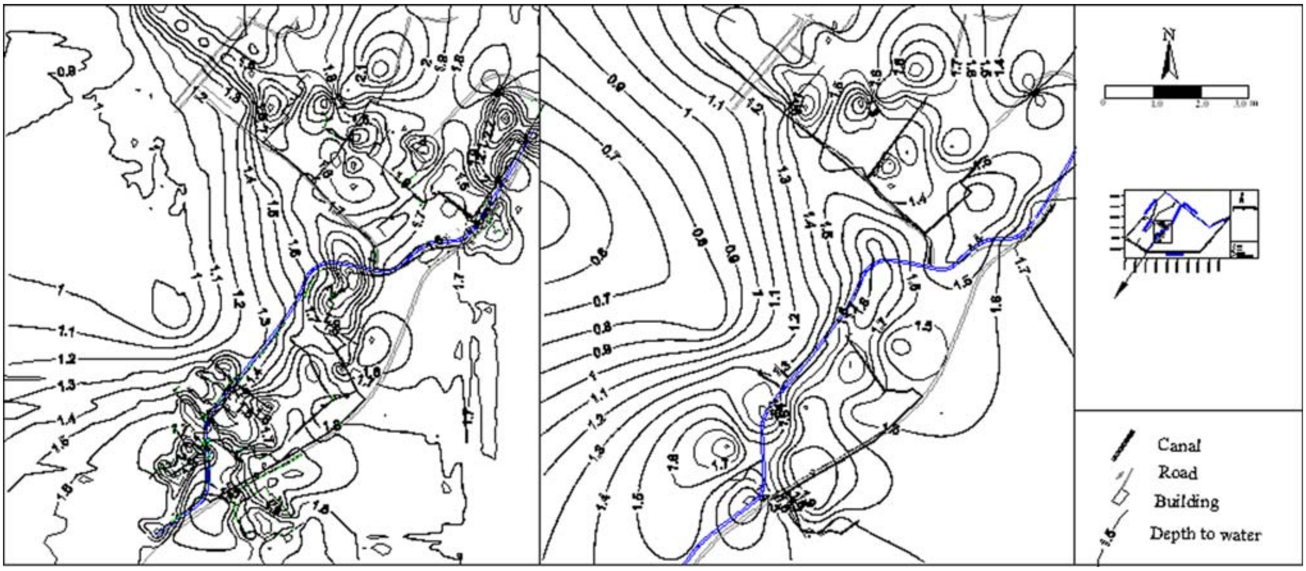


Fig. 10 Predicted depth to water in future after construction of NNHB (2012) with sewer system and perforated pipe (scenarios 1 and 2)

be 1,069 m^3/day (12 l/s) for this scenario. Figure 10 depicts the layout of perforated pipes and contours of depth to water in the shallow aquifer with perforated pipes in the village after NNHB implementation for the two above scenarios. In the second scenario, the depth to water is less than the first scenario by about 20 cm, but the study region will still have no critical areas. Thus, in the second scenario the capacity of the pumping station of the sewer system has to be increased by only about 45% due to the quantity of water collected by the perforated pipes.

Effect of the tile (subsurface) drainage system

The tile drainage system is defined in the section "The subsurface drainage system". Although a tile drainage system already exists in the agricultural lands of the study region, a problem of elevated groundwater levels has been observed. This gives an indication that the system is not functioning at 100% efficiency. The subsurface drainage system has been placed by EPADP in 1982. The objective of this section is to compare the observed with the simulated groundwater levels using different values of drainage efficiency for the existing network to obtain the actual efficiency of the network. The average depth to laterals in the study region is about 1.5 m from the ground surface levels. The first assumption is that the system functioned at 100% so the groundwater level would be lowered to the level of the laterals. This assumption has been simulated as a fixed head internal boundary at the top level of the laterals. The collected discharge by the tile drainage system was calculated to be 1,800 m^3/day (0.8 m^3/day/m of the pipes). In this scenario, there is no critical area within the study region.

The second assumption is that the system functions at 75% efficiency. This assumption can be achieved in the model by entering a fixed discharge of 0.6 m^3/day/m of the pipes (0.75 multiplied by 0.8 m^3/day/m of the pipes). Simulation reveals that the affected area will be 0.557 km^2, which represents 11% of the agricultural areas.

The third assumption is that the system functions at 50% efficiency (i.e., a fixed discharge of 0.4 m^3/day/m of the pipes). According to the model, the affected area will be 1.4 km^2, which represents 27% of agricultural areas. Figure 11 gives the comparison between the measured and the simulated groundwater surface profiles with different values of efficiency of subsurface drainage system at section 1–1 (as shown in Fig. 2). This figure shows that the tile drainage system efficiency is only about 50%.

Figure 12 depicts the contour lines of depth to water after construction of the NNHB with 100% efficiency of the subsurface drainage system, sewer system and the perforated pipes network. In this scenario, there is no critical area within the study region.

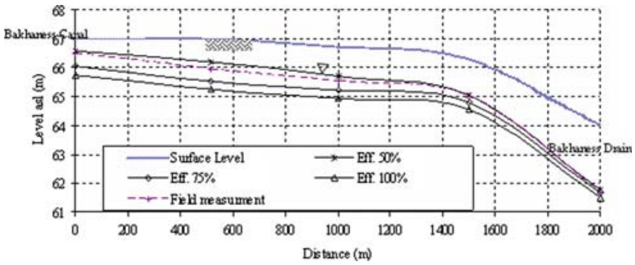


Fig. 11 Comparison between measured and simulated groundwater levels for different drainage efficiency at section 1–1

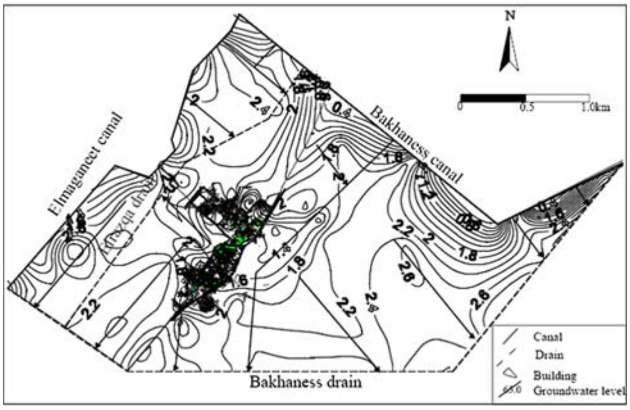


Fig. 12 Predicted depth to water in future after construction of NNHB (2012) with sewer system, perforated pipe, and tile drainage with efficiency 100%

Conclusions and recommendations

The problem of elevated groundwater levels in the study area can be summarized into two main cases. The first concerns the case before constructing the NNHB, while the second concerns the case after constructing the NNHB. For the first case, the management of groundwater can be achieved by employing two dewatering systems. Tile drainage is used for agricultural areas, and a sewer system is used for the urban areas. However, this study revealed that this system would not be sufficient to control the rise in groundwater levels after the construction of the NNHB. Different management scenarios have been proposed, simulated and compared. The recommended scenario for the management of the groundwater conditions in the future consists of employing three lowering systems. Tile drainage is recommended for agricultural areas (i.e., upgrading and maintaining the existing tile drainage system), while for the urban areas both a sewer system and a perforated pipes network (total length of 2.0 km) have been recommended. The collected discharge by the perforated pipes was calculated to be 1,069 m^3/day (12 l/s). The capacity of the pumping station of the sewer system has to be increased by about 45% due to the quantity of water collected by the perforated pipes.

It should be noted that the study revealed that the existing tile drainage system in the agricultural areas of Bakhaness has an efficiency of only about 50%. More care should be exercised in construction and/or maintenance of these drainage systems to achieve better efficiency.

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