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Ground Water Model for the Island of Anholt, Denmark

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The development and application of a digital computer model of the ground water reservoir of the island of Anholt is described.

The model is based on a finite difference, two-dimensional approach. It was successfully used to investigate if the ground water at a planned well field might be polluted by sewage from nearby cesspools. Although the model is an approximation of the real aquifer conditions, the authors found the model very useful and suggest that modelling techniques be more widely used in ground water resource investigations.

Introduction

In 1973 a hydrogeological survey was performed on the Danish island of Anholt in Kattegat, (56° 45'N, 11° 30'E).

The aims of the survey were to find the best location of ground water wells necessary for a future development of a summer house area on the island and to investigate the possibility of salt water intrusion.

The survey consisted of approximately 60 geoelectrical soundings and series of systematic ground water level observations during the year. As the maximum future ground water withdrawal is expected to be 200,000 m^3/year and the recharge approx. 6 mill. m^3 the problems of salt water intrusion should only be expected as a response to the fact that the withdrawal would go on mainly during the summer period and the recharge during the winter months.

However, the survey showed directly (1973 had a very dry summer) that the yearly fluctuation was negligible compared to the thickness of the freshwater lense.

When the survey was completed, the municipality of Grenå (to which Anholt belongs) wanted to evaluate the feasibility of establishing a sewerage system for the development areas based on cesspools instead of an expensive piped sewage system including a treatment plant etc.

In order to make sure that no sewage would flow from the cesspools to the wells, even under extreme conditions (for instance several years of drought), a ground water model was developed. A model which made it possible to appraise quantitatively the response of the aquifer to pumping, drought and seeping sewage.

Geology

The geology of Anholt is relatively well documented. A geological map of Anholt is shown in Fig. 1.

The surface geology has early been mapped by the Geological Survey of Denmark (Jessen, 1897). In recent years Swedish investigations of raised beaches, isostasy and eustasy in the Kattegat area (N. A. Mörner 1969) have made a detailed understanding of the late and postglacial history of the island possible.

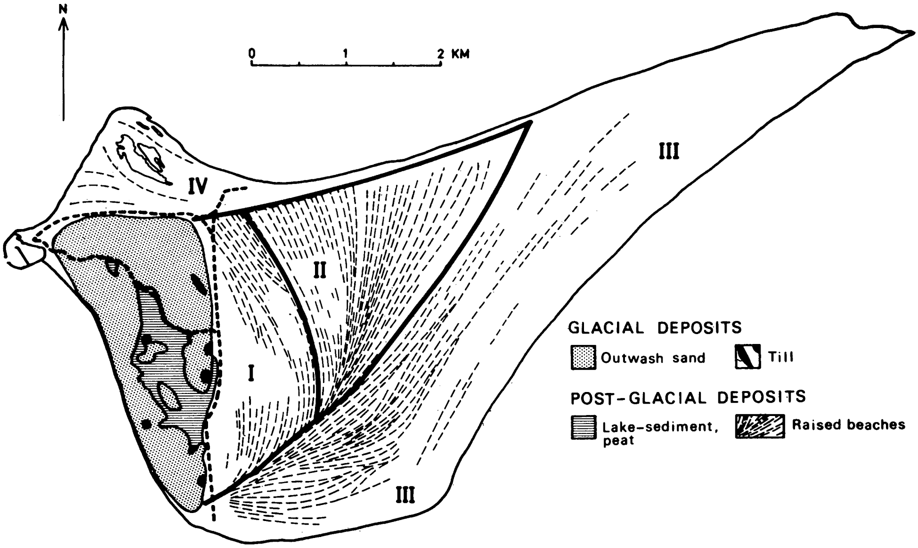

Fig. 1. Geological map of Anholt, showing the formations at the base of aeolian sands. The postglacial raised beaches are divided in four groups (I-IV) according to age. The dotted lines indicate roads.

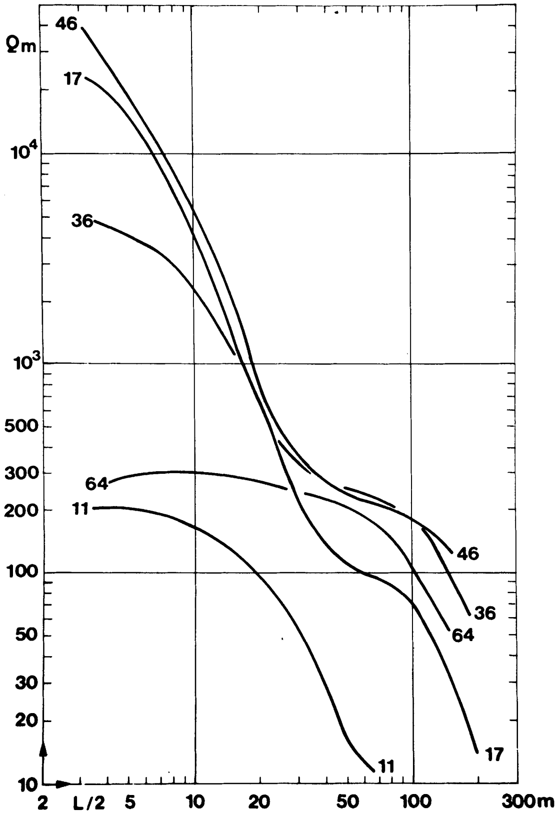

Fig. 2. Geoelectrical soundings on which the profile of Fig. 5 is based.

Prequarternary rocks are not known from Anholt, a 229 m deep boring east of the harbour has penetrated only quarternary deposits mainly outwash sands, but with minor clay layers. The existence of thick quarternary series also appears from a seismic section from the sea south of Anholt, this section also indicates that the prequarternary rocks in the area consist of mainly sandy Jurassic and lower Cretaceous rocks.

However, the nature of the deposits must be sandy as the dense net of electrical soundings shows no specific resistivities less than 100 ohm-m for deposits in the fresh water zone (Fig. 2).

Concerning the greater part of the island consisting of raised beach sand, wells and eustatic-isostatic considerations show that this postglacial formation is 30 m thick and homogeneous.

Hydrology

The average precipitation of Anholt is about 550 mm/year. Due to the extreme large permeability of the soil nearly all the precipitation infiltrates the soil and is used either by the vegetation or recharges the ground water reservoir. Consequently the surface runoff is negligible.

Based on measurements of evapotranspiration from lysimeters in the Neatherlands (Wind 1958) it has been estimated that the evapotranspiration of Anholt amounts to about 250 mm/year in the eastern, sparsely vegetated part of the island and to about 350 mm/year in the western part, where the vegetation is more dense. The average recharge of the ground water reservoir has therefore been estimated to 300 mm/year in the eastern part and 200 mm/year in the western part.

The recharge is balanced by ground water flow to the sea, as evidenced by the water level map, Fig. 3. As the recharge occurs with irregular intervals, the ground water level fluctuates a little (Fig. 4).

The position of the boundary between fresh and salt water (defined as the level where the concentration of cloride is 300 mg/l) has been determined by geoelectrical soundings (Schrøder 1970). The result is shown in Fig. 5, which indicates that the thickness of the freshwater body below sea level is approximately 35 times that above sea level.

In order to detect possible fluctuations of the boundary between fresh and salt water, geoelectrical soundings were repeatedly carried out in selected locations, but it was not possible to identify any fluctuation. This may be due to the presence of thin impermeable or semipermeable layers which effectively reduces short-term movements of the boundary, but this explanation is tentative only.

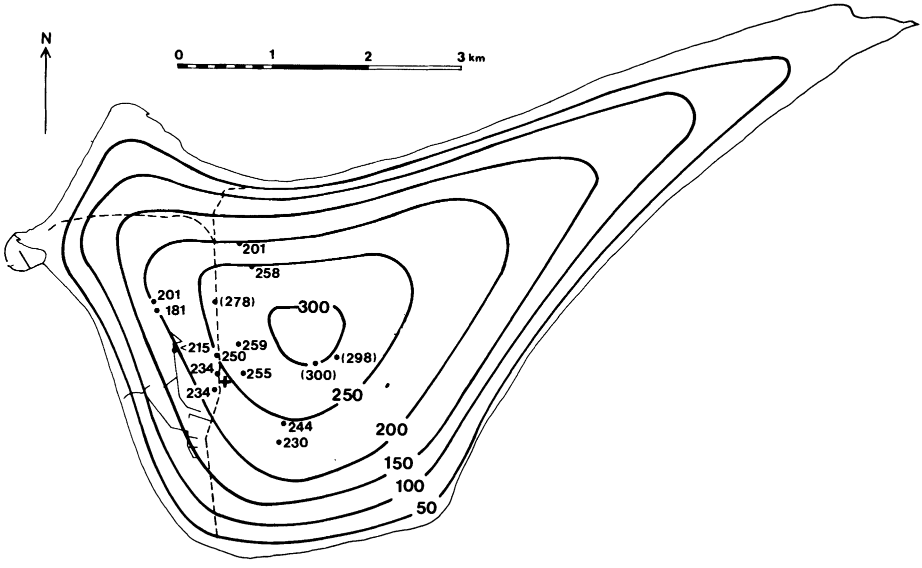

Fig. 3. Observed ground water level in cm above mean sea level.

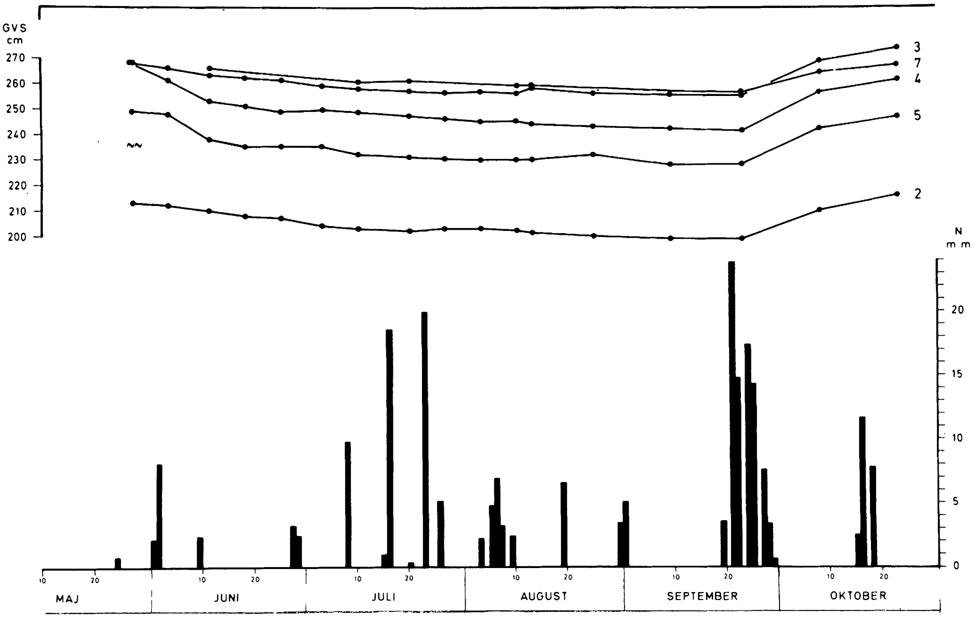

Fig. 4. Rainfall and observed water level for 5 wells on Anholt for the summer 1973.

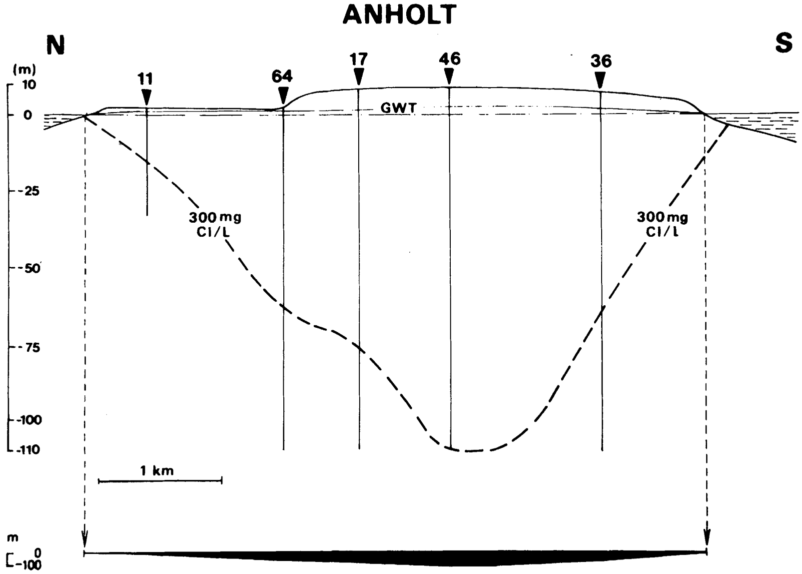

Fig. 5. Cross-section through the island (NNV-SSE), showing the position of the boundary of salt and fresh ground water (defined as the boundary level where the concentration of cloride is 300 mg/ 1).

Ground water model

Based on the available hydrogeological data and forecasts of the future water demand, it was estimated that safe yield of the ground water reservoir, considering the risk of sea water intrusion, is at least 10-15 times the future demand. However, as it was decided to investigate the feasibility of solving the sewerage problems of the future development areas by using cesspools instead of a complicated and expensive sewerage system and treatment plant, a detailed hydrogeological study including development of a ground water model was carried out in order to evaluate the risk of pollution of the ground water resources being reserved for water supply purposes.

As may be seen from the water level map, Fig. 3, the direction of the natural ground water flow is from the future production wells towards the development areas, the location of which is shown in Fig. 6. Withdrawal of ground water will lower the water table around the production wells, while the percolation from the cesspools will rise the water table in the developed areas. The question was if the combined effect of these two opposite directed influences would be a reversal of the ground water flow direction so that sewage would flow towards the production wells and eventually cause a pollution of the wells. The purpose of the ground water modelling was to provide an answer to this question.

The ground water reservoir was modelled using a finite difference approach. The

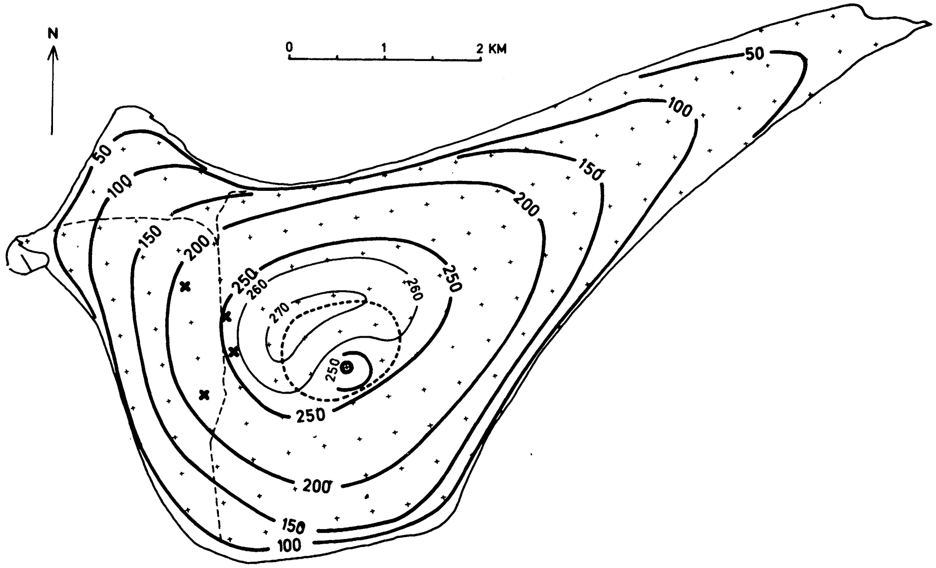

Fig. 6. Computed steady-state water level in cm above m.s.l. under the assumption of withdrawal of 200,000 m^3/year from wells located in the central part of the island (indicated by a circle), while 175,000 m^3/year is assumed to seep to the ground water from cesspools in the development areas (indicated by crosses). The dotted line around the wells indicates the ground water divide.

governing differential equation (Prickett and Lonnquist 1971) was assumed to be

$$\frac{\partial}{\partial x}\left(T\,\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\,\frac{\partial h}{\partial y}\right) = S\,\frac{\partial h}{\partial t}+Q$$

where

T = aquifer transmissivity
h = head
t = time
S = aquifer storage coefficient
Q = net ground water withdrawal rate per unit area
x, y = rectangular coordinates

The differential equation was written in finite difference form and the resulting linear equations was solved using the method devised by Prickett and Lonnquist (1971).

The transmissivity of the aquifer was assumed to be constant in time because the water level changes were very small compared to the saturated thickness of the aquifer.

In order to limit the amount of computer work the ground water flow of the island was assumed to be two-dimensional, although it was fully recognized that this is only an approximation to the real three-dimensional flow.

In order to provide data on aquifer characteristics a test pumping of 3 weeks duration and capacity 26 m^3/hour was carried out. The location of the pumped well is shown in Fig. 6. It is anticipated that this well together with another well, which was drilled 61 m to the west, will be the future production wells.

During and after the pumping test the water level was measured in the pumped well and in 4 observation wells located on a line from the pumped well towards the west. The distance from the pumped well to the observation wells was 36 m, 61 m, 121 m and 302 m, respectively. The radius of the area influenced by the pumping test was approx. 270 m.

On basis of the water level measurements the transmissivity and storage coefficients of the aquifer were computed to 1025 m^2/day and 5% respectively.

However, the computed storage coefficient seemed to be too low, considering that the aquifer consists of medium to coarse grained pure quartz sand, which indicated a storage coefficient of 20-30%. The reason for this is probably that delayed gravity drainage took place during the pumping test. Another explanation could be an upward flow from the fresh water body, but this is not likely (at least not in the relatively short pumping test period), because of the presence of a thin layer of clay about 25 m below sea level. A storage coefficient of 30% was assumed in the following computer runs. As the geological survey indicated that the aquifer is homogeneous throughout the island, it was assumed as a first approximation that these values of transmissivity and storage coefficient were representative for the whole of the island.

The natural recharge of the aquifer was assumed to be 200 mm/year in the western part and 300 mm/year in the eastern part of the island.

The finite difference grid of the model appears from Fig. 7. The model was calibrated by comparing computed and observed water level data for august 1973, where the ground water flow could be assumed to be approximately steady.

At all nodes outside the island the water level was fixed at sea water level by setting the storage coefficient to an extremely large value.

The result of the first computer run is shown in Fig. 8. The shape of the computed water surface is in general agreement with the measurements, but the computed heads are much too low indicating serious errors in the model. A review of the geological and hydrological data suggested the explanation that the sea water acts as a barrier to the fresh water flow (Glover 1959). This effect was accounted for by diminishing the models transmissity outside the central part of the island. The resulting computed water level is shown in Fig. 9. The agreement with the actual water level was now judged to be sufficiently good. A closer match could of course be obtained by further adjustments of the hydrogeological parameters, but is was felt that the available data did not justify such refinement.

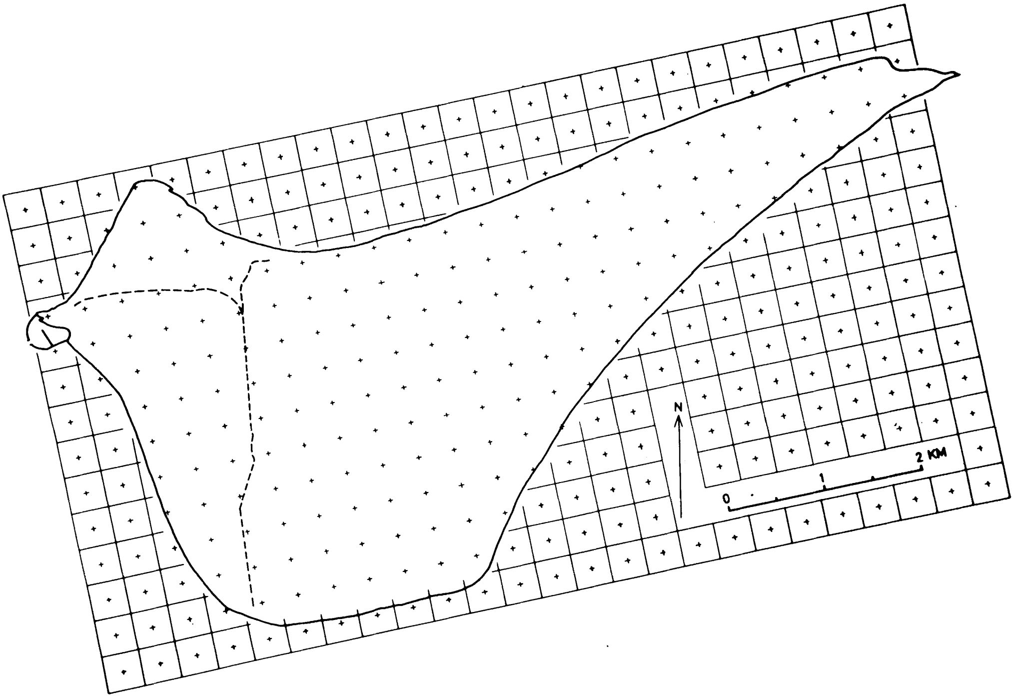

Fig. 7. Finite difference grid of the digital computer model.

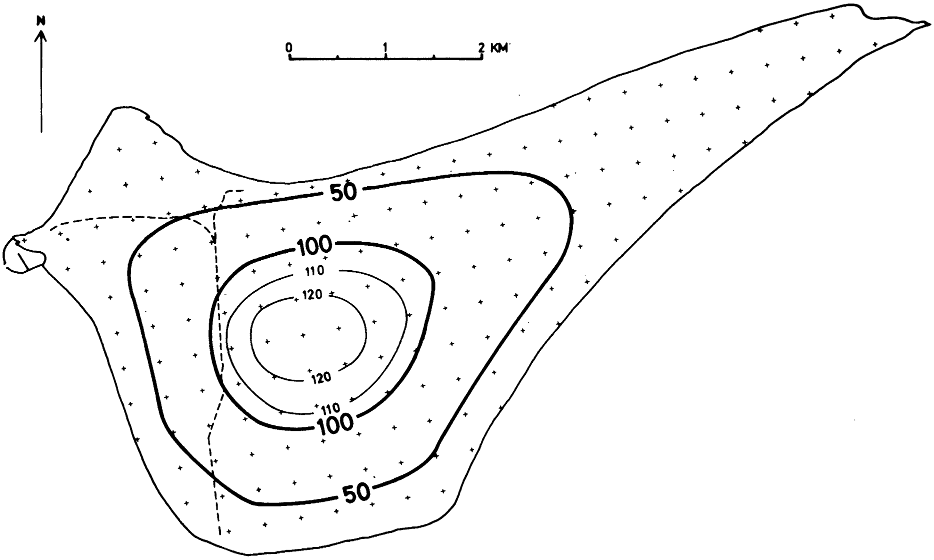

Fig. 8. Computed steady-state water level in cm above m.s.l., from the first computer run.

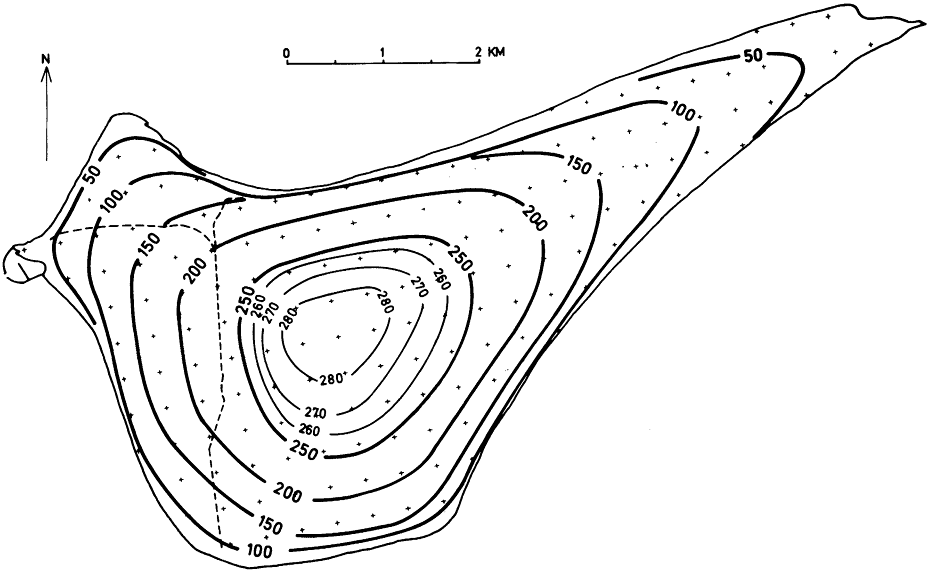

Fig. 9. Computed steady-state water level in cm above m.s.l., after calibration of the model.

The storage coefficient of the model was checked by simulating the unsteady flow during the three-month period June-July-August 1973 assuming no recharge. Comparison with the observed water level showed a reasonably good agreement, indicating that the assumed value of 30% was representative for the real aquifer.

The calibrated model was used to compute the steady-state water level under the following assumptions:

- withdrawal of 200,000 m^3/year from the location indicated in Fig. 6.
- natural recharge of 200 mm/year in the western part and 300 mm/year in the eastern part of the island.
- artificial recharge of 175,000 m^3/year from cesspools in the development areas, the location of which appears from Fig. 6. The remaining 25,000 m^3/year are supposed to evaporate or to be discharged into the harbour.

The computed water level is shown in Fig. 6., which indicates that the sewage would flow towards the coast and not towards the production wells. On this basis it was concluded that use of cesspools in the development areas would not cause pollution of the ground water resources reserved for water supply purposes.

The sensitivity of the conclusion to fluctuations in the natural recharge was evaluated by simulating the ground water flow under the assumption of a sudden termination of natural recharge. The results indicated that not until after about 18 months without natural recharge would the sewage begin to flow towards the production wells (Fig. 10). An analysis of rainfall records showed that the probability of this event is exceedingly small.

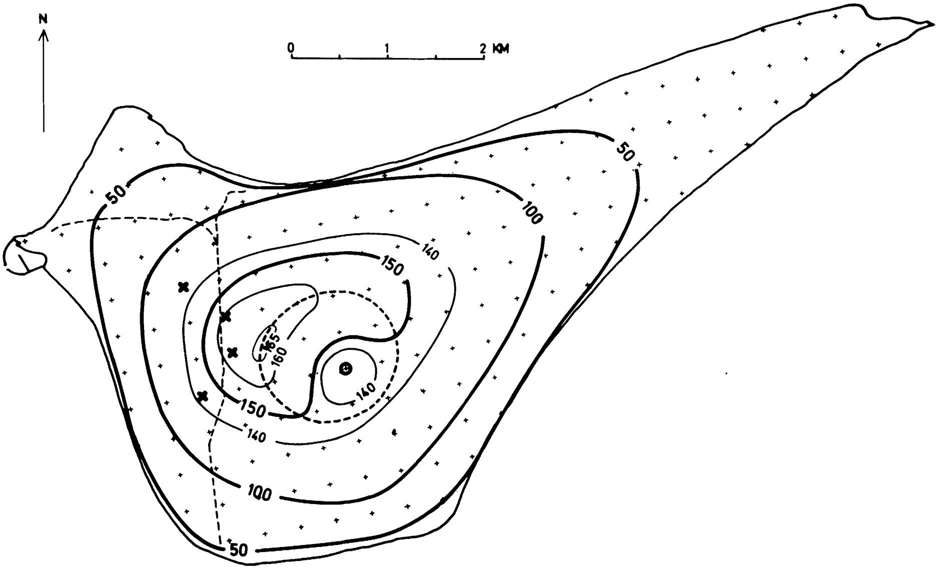

Fig. 10. Computed transient water level in cm above m.s.l., after 475 days without natural recharge. Other assumptions as for Fig. 6.

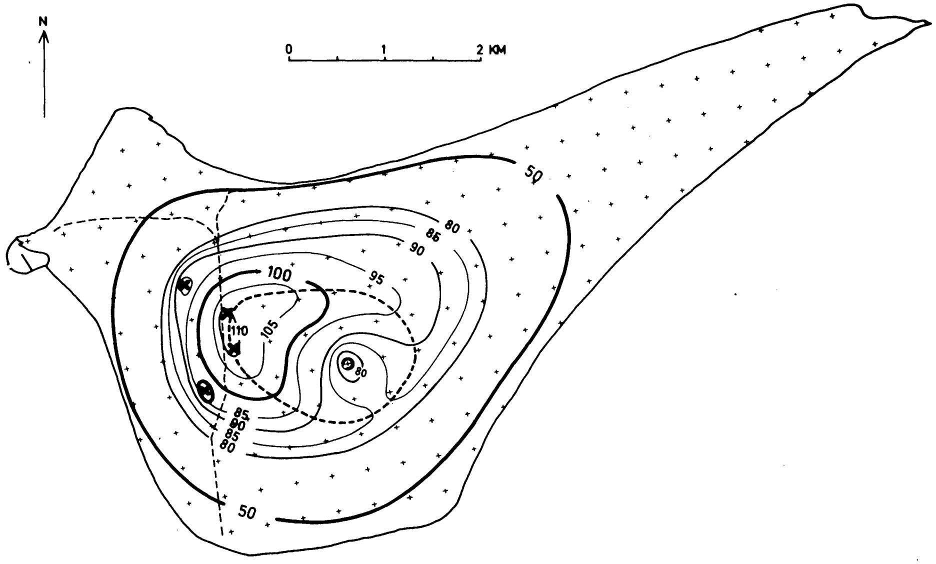

Fig. 11. Computed transient water level in m above m.s.l., after 864 days without natural recharge. Other assumptions as for Fig. 6.

Conclusions

The described ground water model is, admittedly, an approximation to the real hydrogeological conditions of Anholt. Nevertheless, such ground water modelling is very valuable because:

(1) providing input to the model compels the investigator to examine and evaluate all the main aspects of the hydrogeological conditions. During this process possible needs for further field survey may often be revealed.

(2) calibration of the model provides a good knowledge of the mechanisms governing the flow of water in the ground reservoir.

(3) even approximate models may in many cases be useful in evaluating the possibility of adverse effects of a certain withdrawal. If - as in this case - the model shows that the effects even under very pessimistic assumptions will not be serious, it seems safe to conclude that the planned withdrawal is permissible.

A model, of course, is not »better« than the data on the basis of which it was established, but if the model is properly designed and used, maximum benefit is obtained from field data, which often are time consuming and expensive to collect. Thus it can be said that it does not make sense to collect large amounts of hydrogeological data without developing a ground water model, by means of which it can be evaluated if the collected data are sufficient and compatible.

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