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The prediction of minewater inflows*

by K.L. MORTON†, P.C. BOUW‡, and R.J. CONNELLY†

SYNOPSIS

Uncertainties in the forecasting of the volume of groundwater likely to enter underground workings present difficulties for mine management in planning and costing the water-related activities of mining. This paper describes a technique that was developed to assess future inflows into a gold mine in the Orange Free State. The approach employed was based on the interactive operation of two separate computer models: a regional-flow model and an inflow model.

As a first stage, a regional finite-element model of groundwater flow was set up and calibrated. Predictive runs were made to establish the influence of mining on the water levels from base-line conditions. This step was necessary since observations of the regional water levels were sparse. The predicted water levels were transferred to the inflow model, and the future flowrates were calculated.

Both models were calibrated by trial and error until a satisfactory match was obtained between historical records and the values predicted by modelling. In this way, an improved monitoring system to record regional water levels and pressure heads within a mine was established. By the use of information, the initial model predictions can be refined as mining progresses. The models used are based on a non-linear relationship between the area mined and the inflows. A phased behaviour in the rates of inflow increase was noted.

In conclusion, the modelling approach can provide mine management with guidelines for dewatering requirements. The confidence levels depend upon the records that have been collected during the mine's history.

SAMEVATTING

Onsekerheid wat betref die voorspelling van die volume grondwater wat waarskynlik in ondergrondse delfplekke sal beland, skep probleme vir die mynbestuur wat betref die beplanning en kosteberekening van die waterverwante bedrywighede in mynbou. Hierdie referaat beskryf 'n tegniek wat ontwikkel is om die toekomstige invloei in 'n goudmyn in die Oranje-Vrystaat te raam. Die benadering wat gebruik is, is gebaseer op die interaktiewe werking van twee afsonderlike rekenaarmodelle: 'n streeksvloeimodel en 'n invloeimodel.

As 'n eerste stap is daar 'n streeksmodel met 'n eindige element van die grondwaterinvloei opgestel en gekalibreer. Daar is voorspellingslope uitgevoer om die invloed van mynbou op die grondwatervlakke aan die hand van basislyntoestande te bepaal. Hierdie stap was nodig omdat waarnemings van die streekgrondwatervlak skaars was. Die voorspelde grondwatervlakke is na die invloeimodel oorgedra en die toekomstige vloeitempo's is bereken.

Albei modelle is lukraak gekalibreer totdat 'n bevredigende passing verkry is tussen die historiese rekords en die waardes wat met behulp van modelle bepaal is. Op hierdie manier is daar 'n beter moniteerstelsel verkry om streekswatervlakke en -drukhoogtes in 'n myn te registreer. Met gebruik van hierdie inligting kan die aanvanklike modelvoorspellings verfyn word namate die mynbou vorder. Die modelle wat gebruik is, is gebaseer op 'n nie-lineêre verhouding tussen die oppervlakte wat gemyn is en die invloei. Daar is 'n fasegedrag in die toename in die invloeitempo's waargeneem.

Hierdie modelleerbenadering kan ten slotte die mynbestuur voorsien van riglyne wat die ontwateringsvereistes betref. Die betroubaarheidspeile hang af van die rekords wat in die loop van die myn se geskiedenis gehou is.

Introduction

The gold mines in South Africa are known to vary widely in the inflow of groundwater during the course of their life. The magnitude of inflows varies from 'dry' to more than 100 Ml per day. The uncertainty in the forecasting of inflow rates results in difficulties in the planning and costing of dewatering systems, water-treatment plants, and minewater supply. This paper presents a procedure for the rational assessment of potential groundwater inflows into mines, with particular reference to geological conditions in the Orange Free State goldfields.

The magnitude and duration of groundwater flow into underground mines depend, not only on the position of the water level with respect to the mine workings, but also on the degree of fracturing and fracture interconnection within the rock mass.

Two major types of inflow can be distinguished:

- a background, fairly steady drainage from fractures and joints penetrating the rock mass, and
- sudden inflows of high magnitude resulting from intersecting mining operations and major water storing and/or transmitting structural features, such as fault zones.

Predictions on the groundwater hazard presented by major structural zones can be made from an analysis of the structural geology[1] and are not covered in this paper. This paper is concerned with the use of computer-modelling techniques to predict 'background' drainage into workings based on the assumption that the aquifer is essentially homogeneous on a regional scale. Model calibration is achieved by the use of the historical hydrogeological data.

Geology and Hydrogeological Units

The geological succession in the Orange Free State

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† Steffen, Robertson & Kirsten Inc., P.O. Box 8856, Johannesburg 2000.

‡ Formerly of Steffen, Robertson & Kirsten Inc.

goldfields consists of up to 800 m of sub-horizontal Karoo sediments overlying rocks of the Witwatersrand Supergroup. In some areas, lavas of the Ventersdorp Supergroup are present beneath the Karoo sediments. The pre-Karoo rocks have been extensively folded and faulted, and the geological succession has been intruded by dykes and sills, mainly of doleritic composition.

The Karoo sediments have a low permeability and are regarded as confining the underlying pre-Karoo sequence. Dewatering of the latter is regarded as the principal source of inflow to mine workings. Some minor additional flow may be derived from leakage through the Karoo rocks.

Basic Concept in Inflow Calculations

In preliminary assessments, problems of mine dewatering can be simulated by the assumption that the mine shafts and workings are equivalent to a large-diameter well and a series of linear underground roadways. The mine geometry consists of an excavation about 2 m high, roughly circular at the bottom of a grouted vertical shaft. This geometry is similar to a large borehole, with a radius equal to the approximate mine radius, over the length of the cased shaft but only open over the last 2 m of the bottom (Fig. 1).

A modelling approach to the prediction of dewatering is the calculation of inflow from an aquifer at a flowrate that will lower the piezometric surface below the bottom level of the excavation at the assumed mine radius. The pumping rate of the well is taken as equivalent to the potential inflow quantities.

Drawdown caused by the pumping of water from a borehole has two components:

- a laminar-flow component proportional to the pumping rate, and
- a turbulent-flow component proportional to a certain power of the pumping rate; this component varies with the geometry and the size of the intake area of the borehole.

The dewatering process of a mine in a confined aquifer can be divided into 4 successive phases, as illustrated in Fig. 2 (a to d):

- *Initial development of the excavation.* There is a turbulent-flow component caused by the small intake area. Pumping rates are relatively low, with high drawdowns caused by a large 'well loss' component.
- *Enlargement of the excavation.* The turbulent flow decreases and, as a consequence, the inflow increases. This is the phase of a rapid increase in inflows.
- *Aquifer dewatering.* The piezometric surface drops below the confining layer, resulting in a change from confined to unconfined conditions. In this case, the value for storage coefficient is replaced by a value for specific yield. Additionally, the transmissivity decreases with the saturated thickness of the aquifer. Inflows continue to increase but at a slower rate.
- *Interactive effect of several pumping shafts.* When several mines are operating at close range, each of

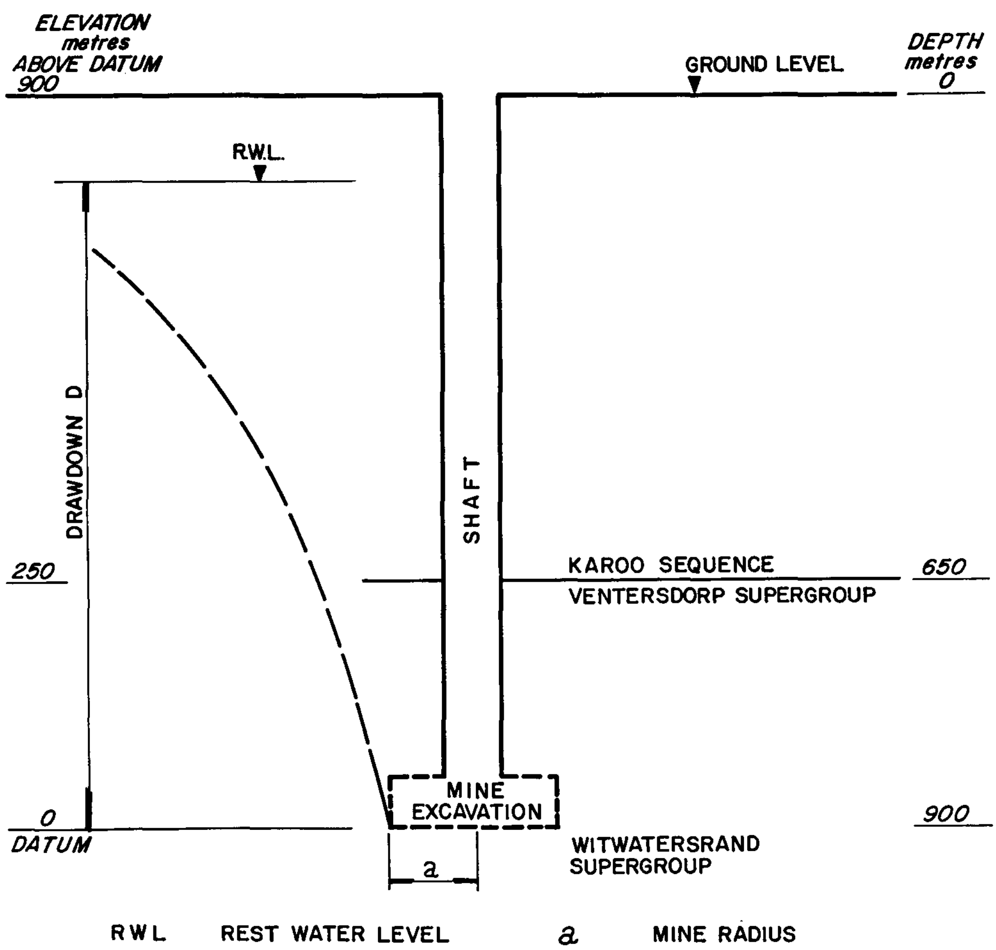

Fig. 1—Configuration of a mine and its aquifer

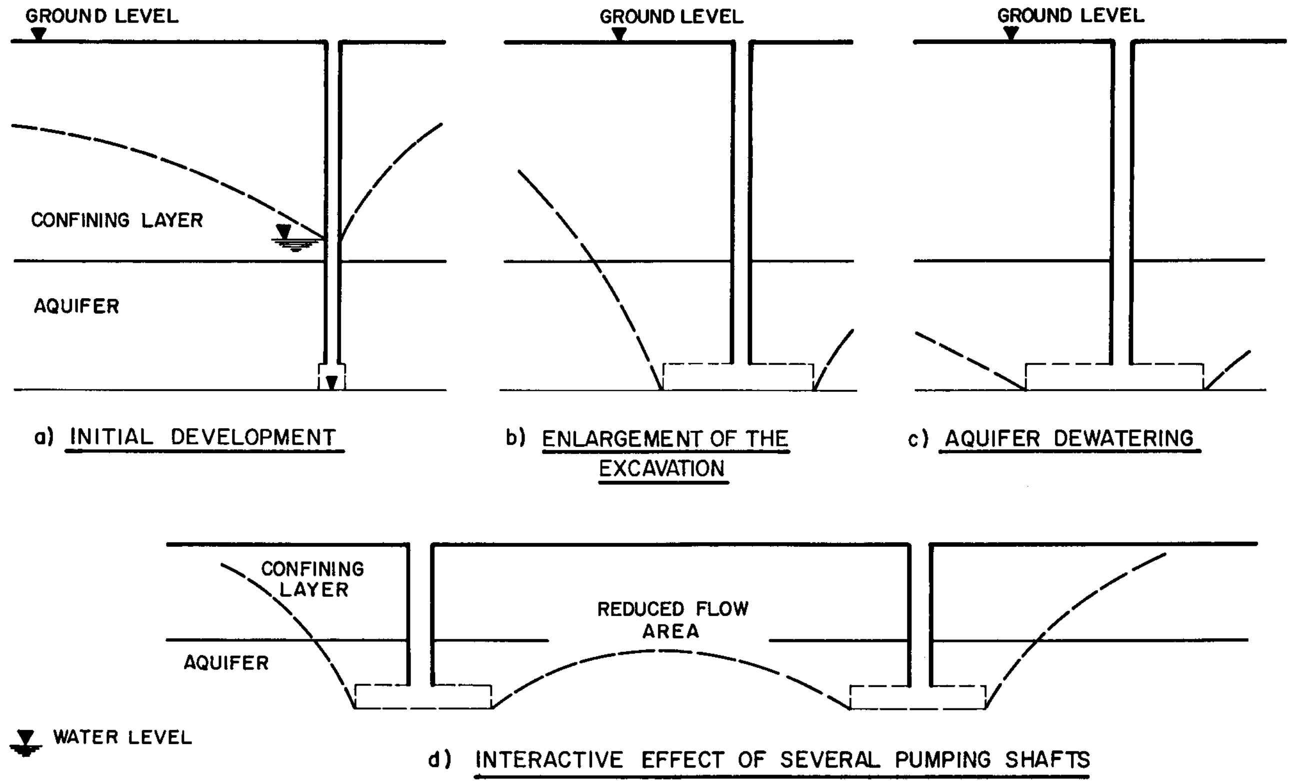

Fig. 2—The dewatering process

them diverts some part of the flow that would otherwise reach the other mines, resulting in a reduction of the inflow.

Fig. 3 shows a typical inflow record from an underground gold mine in the Orange Free State, in which the first three phases can be identified. Phase 4 is described by Venter[2].

In general, the rate of inflow to a mine is seen to behave in a non-linear fashion. Inflows are noted to decrease after reaching a certain peak. This seems to occur approximately 8 to 12 years after the start of mining.

Inflow Equation

Several analytically-derived inflow models are available. Here, use is made of a non-linear radial-flow model developed by Schmieder[3–5] and Perez-Franco[6], and summarized in Singh and Atkins[7]. The analytical solution based on unsteady-flow condition requires the following information.

- *Aquifer Characteristics*
  Transmissivity and storage coefficient are the most important aquifer characteristics. Values for transmissivity can be derived from either pump-in testing or pump-out testing, or a combination. Pump-out testing obtains values for a large area of aquifer, the size depending on the number of observation boreholes. Pump-in testing obtains values for sections of individual borehole profiles using inflatable packers. The storage coefficient can also be obtained from test pumping. A check on the regional values of the aquifer characteristics can be made by the back-analysis of historical piezometric data.
- *Water Level*
  The drawdown to be obtained is the difference between the lower level of the mine and the initial static water level. Historical piezometric fluctuation records can be useful in the calibration of aquifer characteristics.
- *Aquifer Geometry*
  The drawdown created by the pumping in a mine depends on the aquifer geometry, i.e. the presence of lateral boundaries, as well as the presence of a confining or semi-confining layer over the aquifer.
- *Mine Geometry*
  The inflow equation requires that the water level should be lowered beneath the level of workings on the mine periphery. Some simplification of the mine geometry is required for the conversion of the actual geometry into a circular geometry centred on the bottom of the shaft.

Method of Inflow Prediction

When the required data listed above are available, it is theoretically possible to predict the inflow rate during the life of a mine. But, if historical pumping and piezometric data also exist, the validity of the inflow prediction can be tested. Without this calibration, the confidence levels will be fairly low. Two computer models run in tandem can be used for this purpose.

- *An Aquifer Model.* By use of the historical piezometric data, the aquifer model will calibrate the regional aquifer characteristics and the aquifer geometry. In the second stage, it can be used to predict the long-term piezometric fluctuation under certain pumping conditions.

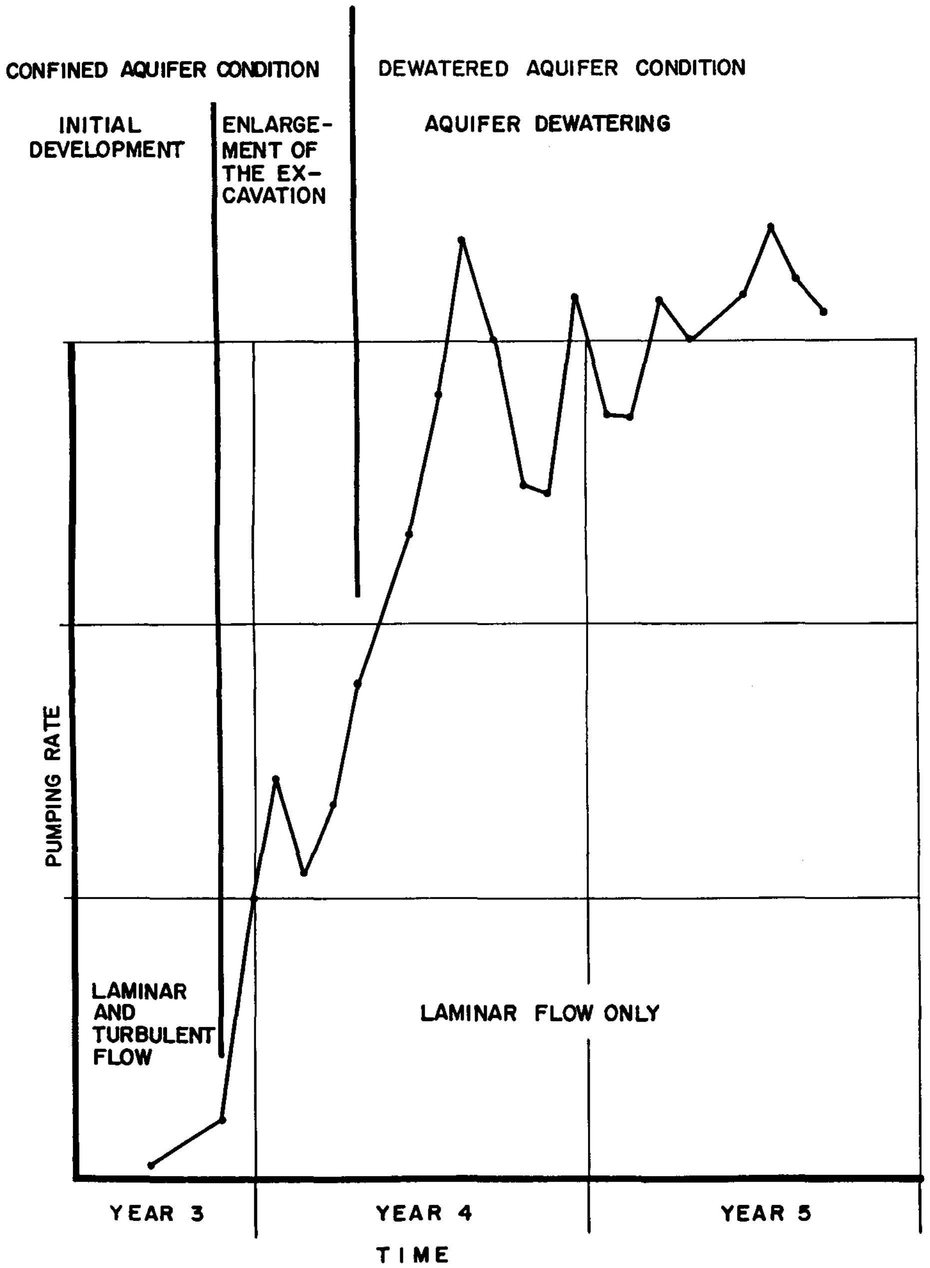

Fig. 3—Dewatering phases in a typical gold mine

- *An Inflow Model.* By use of the regional aquifer characteristics calibrated by the aquifer model, the inflow model is calibrated by back-calculation of the historical pumping rates. In the second stage, it can be used to predict future inflow rates to the mine for specific water-level conditions.

The interactive process is presented schematically in the flow chart of Fig. 4.

Application

The method described above was used in the prediction of groundwater inflow rates to a new gold mine in the Orange Free State. In this particular case, an adjacent mine had been operating for the past few years with the consequence that

- historical pumping and piezometric data were available; and
- the pumping from two shafts of the existing mine had influenced the water level in the area of the new mine. This had to be taken into account in the estimation of the drawdown required to dewater the new mine.

The aquifer consists of faulted and folded Ventersdorp and Witwatersrand Supergroup rocks, confined by sediments of the Karoo Sequence. The average permeability obtained from packer testing was 0,016 m per day. The initial static water level was about 100 m below ground level in 1980. Owing to the dewatering in the operating mine and possibly in other mines further away, the water level dropped considerably. This fall had been monitored by an observation borehole. Historical pumping records were also available for the existing mine.

Aquifer Model

The aquifer model is a finite-element model with 164 elements and 177 nodes. It covers an area of about 10 km

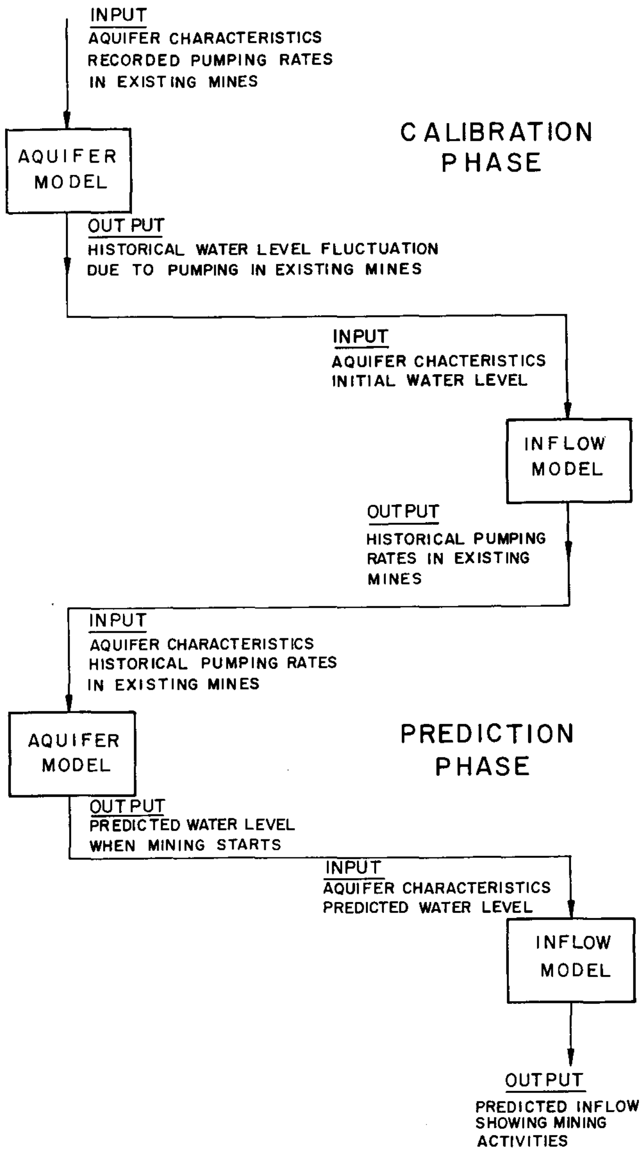

Fig. 4—A modelling flow chart for the prediction of inflow

in radius from the new shaft (Fig. 5).

A no-flow boundary condition was set on the northern boundary of the model to represent the influence of past pumping from distant mines. A constant-head condition was set on the eastern, southern, and western boundaries to represent the extension of the aquifer over a long and unknown distance in those directions.

The mesh of the model was shaped to represent a possible dyke effect between the two mines, although no effect has yet been confirmed.

The aquifer is 250 m thick and confined below 650 m of Karoo Sequence.

The original rest-water level was set everywhere at 110 m below ground level.

The aquifer model was calibrated, and values for the following parameters were assigned to every element:

- permeability
- transmissivity
- storage coefficient
- unconfined storage coefficient
- vertical permeability of the confining layer.

A permeability of 0,016 m per day, obtained from packer testing, was initially entered into the model. This value was then increased up to 0,024 m per day until a good fit was obtained between the calculated and the observed water level in the observation borehole (Fig. 6).

The aquifer model was used to generate the predicted piezometric contours at the time when the new shaft would start operating (Fig. 7).

Inflow Model

The inflow model calculated the inflow rate at a certain time given the drawdown to be obtained at the periphery of the mine, the aquifer characteristics, and the mine radius. The model was developed in such a way as to calculate the inflow under laminar and turbulent flow conditions, and under laminar flow only.

It was calibrated by use of the historical pumping data from the operating shafts of the existing mine (Fig. 8).

(a) initial development: laminar and turbulent flow, confined aquifer;
(b) enlargement of the excavation: laminar flow only, confined aquifer;
(c) aquifer dewatering: laminar flow only, the aquifer becoming unconfined as the water level dropped below the confining Karoo Sequence.

The inflow model was later used to predict the inflow rate for the time when the new shaft starts operating. From the piezometric plan produced by the aquifer model, it was ascertained that the level of groundwater above the lowest level of the mine was about 350 m.

The inflow was therefore calculated on the following assumptions:

- a drawdown of 350 m
- conditions of laminar and turbulent flow during the first 3 months of operation
- laminar flow after 3 months
- pressure flow in a confined aquifer during the first 6 months
- aquifer dewatering and gravity flow after 6 months.

Discussion

It should be stated that the predictive capability of computer groundwater modelling depends upon the quality of the available data. In this particular case, the available information was adequate to develop the models and to test the method, but its weakness should not be underestimated.

- Water levels were observed regularly in only one borehole. If several observation holes had been available, it would have been possible to obtain a better regional estimate of the transmissivity.
- Water levels were measured in the observation borehole only from June of year 3. Previously, water levels had been measured only once—in December of year 0—resulting in the following assumptions for the calibration of the model.
  - The initial rest-water level is believed to have been at 110 m below ground level.
  - It was necessary to assume a certain pumping history during the shaft-sinking period.

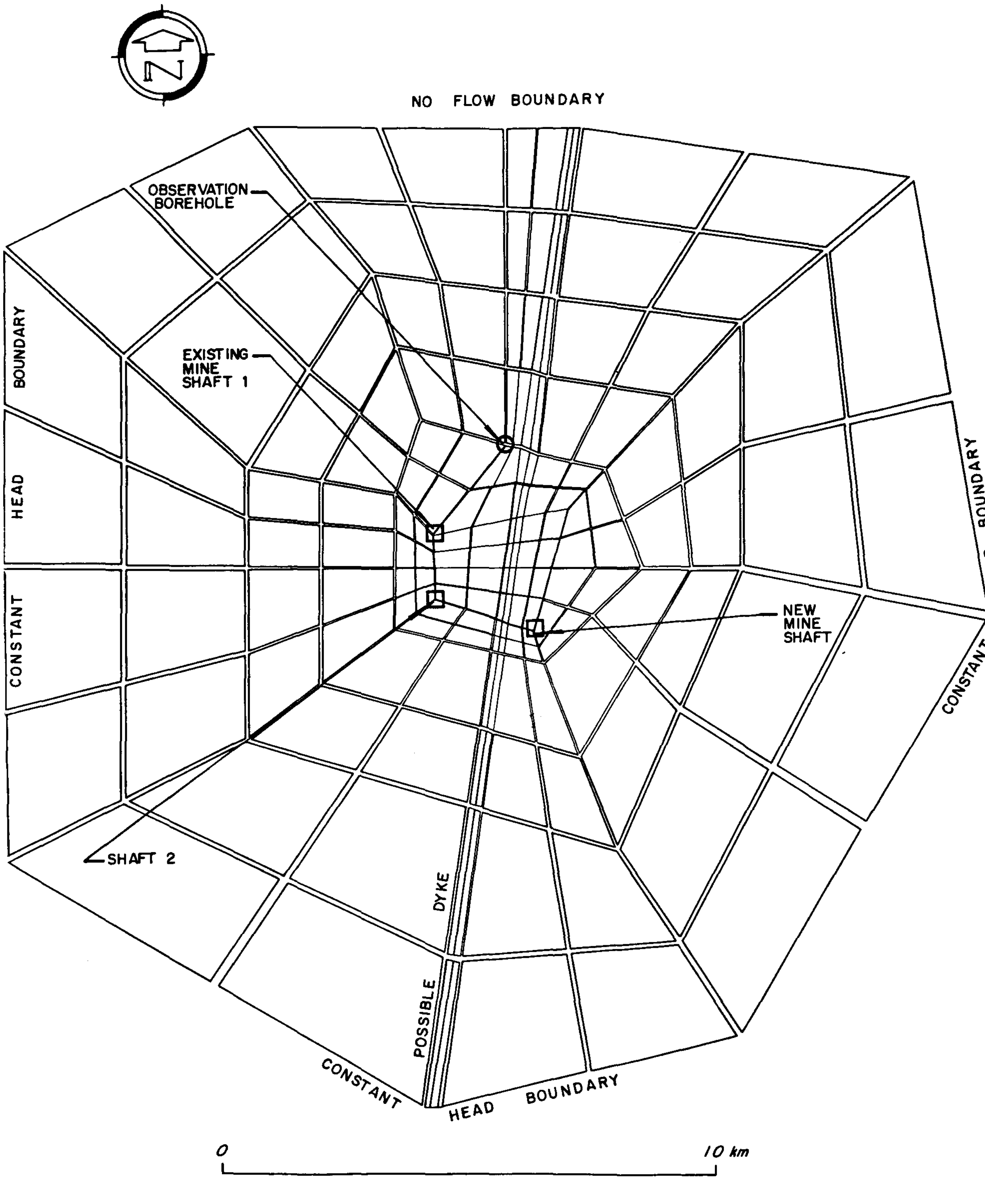

Fig. 5—A finite-element groundwater model

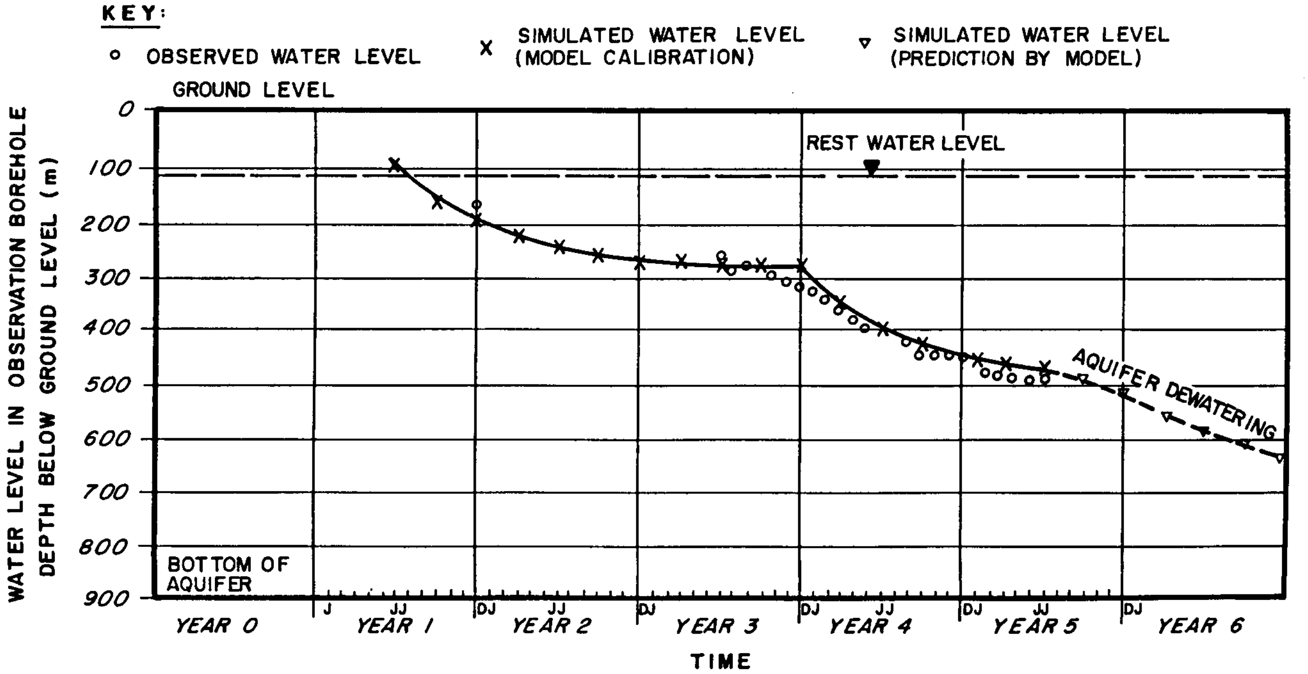

Fig. 6—Calibration of finite-element groundwater modelling

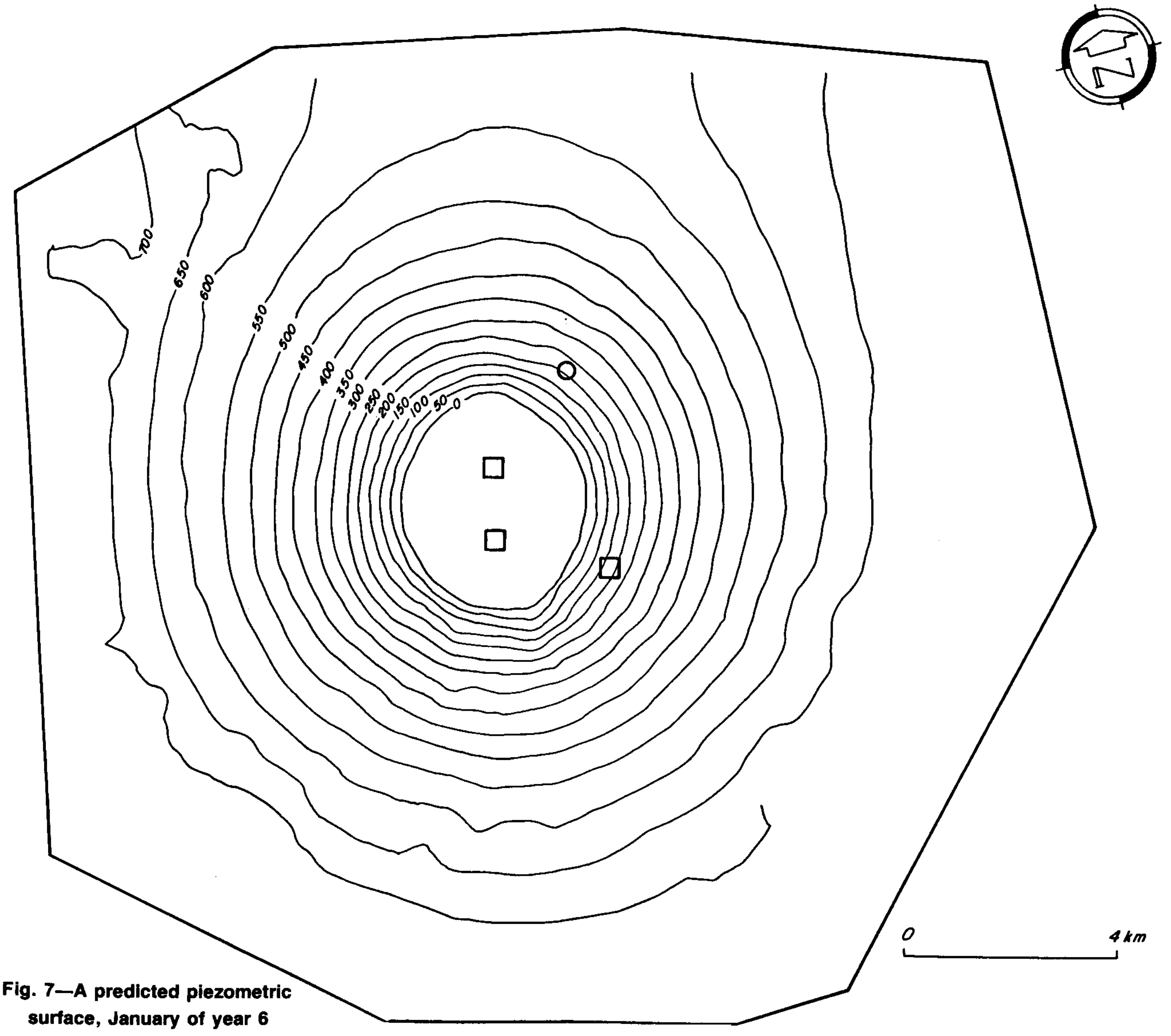

Fig. 7—A predicted piezometric surface, January of year 6

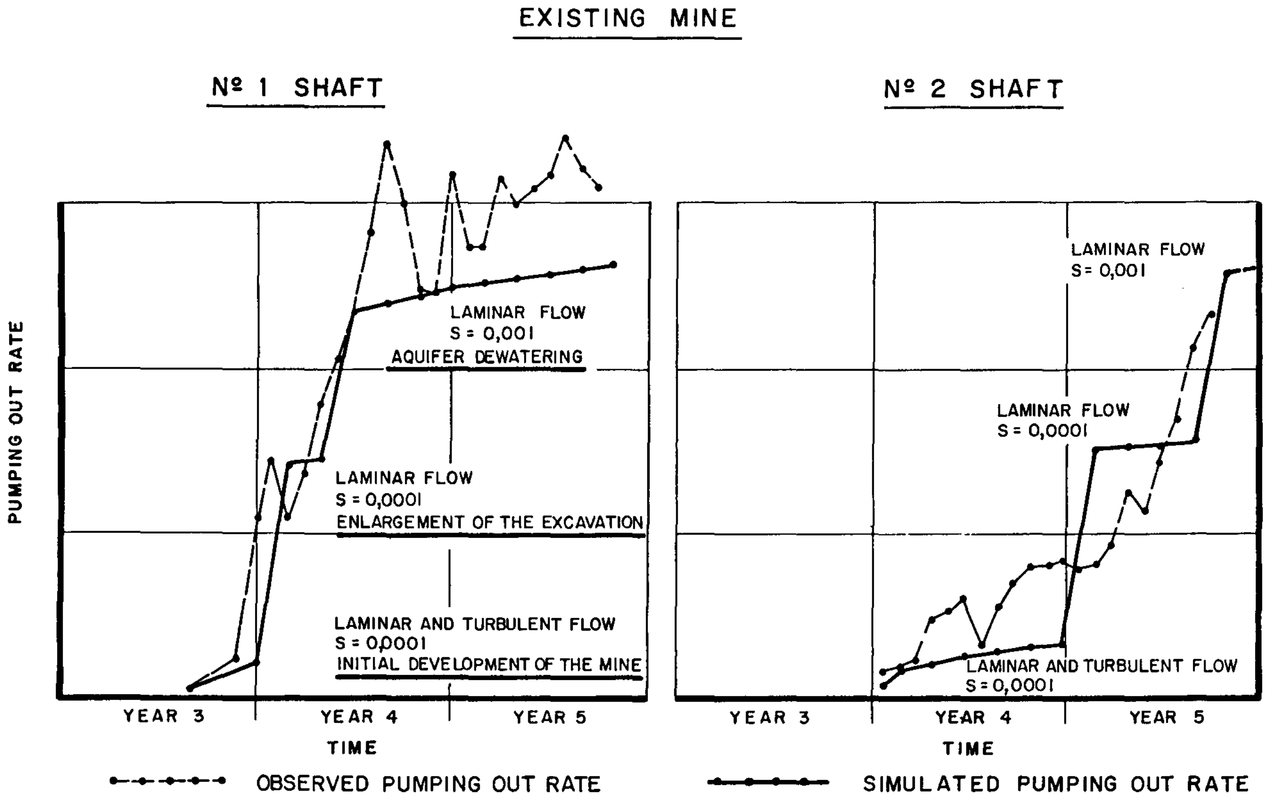

Fig. 8—Calibration of an inflow model (s = storativity coefficient)

- If the water level measured in year 0 is later found to be incorrect, then the model prediction of inflow would change.

The limited data available mean that preliminary conclusions for water inflow should be drawn only on a regional basis. With the information available, the model cannot predict sudden inflows due to the intersection of major faults.

Conclusion

Models are available to simulate the behaviour of aquifers and to predict the impact of mining on water levels and the likely inflow rates into underground workings. These can provide management with guidelines for initial underground pumping requirements, as well as ongoing dewatering requirements, and assist management in designing ways of minimizing the impacts and costs of dewatering.

Higher levels of confidence could be obtained for long-term predictions if the collection of hydrogeological data could be improved on the mines. During the exploratory drilling, much valuable hydrogeological information, such as the intervals of fractured rock, areas of water take, depth to water level, and quality of groundwater intersected, usually goes unrecorded.

Additionally, most exploration holes are left uncased and eventually collapse, and thereby become useless for the monitoring of changes in the water table. For a small additional cost, these holes could be fitted with small-diameter PVC casing and, after being sealed, could be used as observation points to record the effects of mine dewatering on regional water levels in Witwatersrand rocks. The following could also be recorded fairly easily on a regular basis:

- levels of borehole water
- levels of shaft water
- pumping rates
- position of the water recovered from the flows of major individual fissures, and its volume.

The collection of such essential information provides a valuable data base from which the future inflow of water into a mine can be modelled.

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