THE RELIABILITY OF A GROUNDWATER MODEL: THE HISTORY OF MODELLING THE JWANENG NORTHERN WELLFIELD IN BOTSWANA

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ABSTRACT The Jwaneng Northern Wellfield covers, within its present perimeter, an area of some 200 km$^2$ and is situated 55 km north-west of the Jwaneng Diamond Mine, on the fringes of the Kalahari Desert in the Kweneng District of south-eastern Botswana. At the time of the wellfield’s inception, a two-dimensional finite difference model was developed to aid long term groundwater resources management. This model has overestimated maximum regional drawdowns in the wellfield centre by a factor of five and as a consequence, the model was restructured and recalibrated in 1984. The recalibrated model has overestimated the same drawdowns by 80%. Estimates based on a new hydrogeological model which incorporates isotope data, indicate significant local recharge to the wellfield. A simple analytical model of wellfield behaviour shows that this calculated recharge rate brings the modelled drawdowns into the range of actually observed values. With the current expansion of the wellfield now completed to allow for a maximum monthly abstraction of over 100,000 m$^3$, a more detailed, three-dimensional finite difference model is now available and has replaced all previous models as a long term groundwater management tool.

INTRODUCTION

By the end of 1990, the daily abstraction of good potable water from the Jwaneng Northern Wellfield (Fig. 1) will have increased from 15,000 to 30,000 m$^3$, supplied by twenty six, 203 to 330 mm diameter, 230 m deep production boreholes. Since 1981, Jwaneng Mine has submitted to the Botswana Geological Survey and Department of Water Affairs biannual monitoring reports on the Jwaneng Northern Wellfield’s performance (not referenced). This wellfield is, to date, the largest and most productive in Botswana and represents a very important groundwater resource in this semi-arid country where reliable surface water supplies are very scarce.

This paper briefly describes the history of the separate phases of groundwater modelling at Jwaneng and illustrates the point that as hydrogeological knowledge of the area has improved, so has the calibration and reliability of the groundwater models used.
WELLFIELD HYDROGEOLOGY

The geology of the Jwaneng Wellfield delta was analysed by Buckley (1984) and is schematically shown in the section of Fig. 2.

Groundwater is encountered in the Ecca sandstone (Carboniferous to Jurassic) of a coarse, highly transmissive facies deposited in a fluviatile delta environment. The aquifer dips shallowly to the north west under increasing thicknesses of mudstones and siltstones and fans out in this direction. The massive storage characteristics of the aquifer have generally been underestimated.

The chemistry of the wellfield water is of the calcium-magnesium bicarbonate type, reflecting a recharged groundwater system, quite distinct from the water found in wells penetrating the Ecca sandstone (Bath, 1980) in the rest of the surrounding area.
THE FIRST MODELLING PHASE, 1980-1984

At the time of the wellfield's inception, a two dimensional finite difference model (WCS, 1980) developed from the computer program package by Prickett & Lonquist (1971) was used to model an area of 3900 km². The overall shape and size of the model was constrained by increasingly uncertain aquifer characteristics outward from the wellfield centre.

It was imperative that a conservative approach to the modelling exercise be taken and, although it was established that the aquifer extends beyond the model boundaries in other directions, all boundaries were assumed to be impervious to any flow, recharge or vertical leakage. Aquifer parameter inputs were obtained from field tests and matrices of transmissivity (T) and storage coefficient (S) generated. Values of T range from 10 to 1700 m² day⁻¹ and the confined and unconfined S used are 3x10⁻⁴ and 1x10⁻² respectively. The model's predicted regional drawdown is shown in Fig. 3. The large discrepancy between observed and modelled drawdowns is obvious. It should be noted, however, that in the absence of historical data, predictions had to be made without any assistance from model calibration. The model was recalibrated in 1982 (WCS, 1982) to adjust for actual abstraction rates and well loss coefficients at boreholes A1 and A2, but aquifer parameters remained the same, with the exception that for one model run, the effect of substantially reducing the aquifer limits were tested. Figure 4 shows the recalibrated model predictions.
FIG. 3 Jwaneng aquifer models various maximum regional drawdown predictions.

FIG. 4 1982 Recalibrated model East West section along model row 24.

THE SECOND MODELLING PHASE, 1984-1988

By 1983, it was deemed necessary to re-examine and recalibrate the existing groundwater model in order to realistically simulate existing conditions. The modelled area remained the same. Initial work centred around the established T and S matrices from the 1980 model, with sensitivity analyses being undertaken in order to examine the influence on regional drawdown of changes in these parameters. Simultaneously, much of the geological, structural and hydrogeological data pertaining to the wellfield was re-examined in order to investigate the nature of any leakage into the aquifer from overlying formations and to assess any possible redistribution of regional transmissivity which may be necessary in order to simulate aquifer through-flow. However, the most fundamental changes to the 1980 model were in areal storage conditions, as summarized below:
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a) North/North east zone: Aquifers are totally confined by a significant thickness of sandstone with $S$ of $1 \times 10^{-4}$.

b) Central wellfield zone: Early aquifer pump tests were probably of too short a duration to fully determine the magnitude of a leakage contribution to abstraction, a semi-confined $S$ of $5 \times 10^{-3}$ was adopted in order to incorporate leakage effects.

c) South/South east zone: Confining head data in this aquifer margin area indicates that a virtually unconfined situation exists and a $S$ of $1 \times 10^{-2}$ was chosen.

The major variation in "starting surface" between this and the 1980 model is that an actual measured prepumping piezometric surface (September 1978) was utilised instead of the basic flat surface previously used. Following model sensitivity evaluation incorporating a variety of boundary conditions from 'no-flow' to 'fixed heads' to 'inflow-outflow', the final model was established using 'fixed head' boundaries. The most realistic alternative, that of 'inflow-outflow' boundaries, was not considered representative since excessive groundwater buildup or groundwater drawdown occurred adjacent to the model margins. In order to compare this model with previous models, the revised model was operated under an identical abstraction regime to that used in previous model runs. Results, as shown in Fig. 3, indicate a 70% reduction in the maximum regional drawdown predicted by the 1980 model, yet drawdowns still differ by 80% from those observed.

THE LATEST MODELLING EXERCISE 1989-1990

The 1984 recalibrated model ceased to be used as a management tool shortly after its release since it was apparent from an increasing discrepancy between observed and predicted drawdowns that aquifer mechanisms had still not properly been understood. Further exploration and production wells were drilled in 1988 and 1989 (AAC, 1988, 1989a) and results of isotope sampling conducted show that an extensive body of relatively young i.e. less than 3000 years old, groundwater exists in the wellfield and that therefore earlier theories of remote recharge to the wellfield are now untenable. Figure 5 shows the isotopic data upon which the flow lines in Fig. 2 are based.

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**FIG. 5** Radiocarbon values in pmc for pumped water from existing private and wellfield production boreholes as well as for first strike water in exploration boreholes.
The anomaly of the more confined water having the higher radiocarbon concentrations and thus appearing younger is explained elsewhere (Verhagen & Brook, 1989). All the evidence points towards the aquifer being a 'normally' recharged, dynamic groundwater basin. This allows for the estimation of a recharge rate as follows:

\[ R = \frac{H \cdot n}{8270 \ln \frac{A_o}{A}} \]  

(Verhagen & Brook, 1989)

where:
- \( R \) = recharge (mm year\(^{-1}\))
- \( A \) = observed radiocarbon concentration (pmc)
- \( A_o \) = initial radiocarbon concentration (pmc)
- \( H \) = Depth of aquifer well penetration (m)
- \( n \) = aquifer porosity (%)

For \( A = 55 \) to \( 75 \) pmc we obtain \( R = 3 \) to \( 8 \) mm year\(^{-1}\), some 1 to 2\% of the mean annual rainfall (M.A.R.) for the area i.e. 7000 m\(^3\) day\(^{-1}\). Results of a simple analytical model (Clarke, 1987) of wellfield behaviour, (Brook, 1989) incorporating a vertical recharge of 2\% of M.A.R. over the unconfined and semi-confined aquifers, are shown in Fig. 6.

Although the pumping storage coefficients and transmissivities for individual boreholes modelled vary over wide limits (more than a factor of 4 and 10 respectively), mean values of \( 2.95 \times 10^4 \) and \( 809 \) m\(^2\) day\(^{-1}\) respectively were set for each borehole. Fig. 6b shows the modelled drawdowns at current maximum borehole yields which range from 730 to 2664 m\(^3\) day\(^{-1}\), assuming that pumps operate 50\% of the time. The results overestimate the actual regional drawdown within the wellfield by more than a factor of two and poorly represent the observed drawdown pattern. Fig. 6c shows the model results if vertical leakage equivalent to 2\% of the M.A.R. for the whole area shown in Figure 6(b) is included. The recharge is equally distributed over the two schematic shaded rectangular areas, shown in Figure 6b. The model results show that, despite the complex nature of the hydrogeology of the wellfield, the system behaves essentially as an infinite confined aquifer and ongoing vertical leakage fed by rain recharge can be shown to be responsible for the attenuated drawdowns observed.
The area covered by the latest model, (AAC 1989b) which has used the MODFLOW package (USGS, 1988), is limited to the Ntane Sandstone (Ecca Group) basin which extends 50 km in an east-west direction and 35 km in a north-south direction. A 1 km square grid was used to model this area. This model comprises two layers, the upper unconfined and the lower confined. All water abstraction has been modelled from the lower layer, thus the upper layer contributes by vertical flow only. This assumes a lower, leaky confined layer, although the high value of S finally adopted suggests the aquifer is essentially unconfined. Figure 7 shows the model inputs.

The eastern recharge boundary, with a daily recharge of 6300 m$^3$ day$^{-1}$ (i.e. 2% M.A.R.), was necessary to model a steady state simulation which allowed the 1982 piezometric surface to be matched. The model outflow is shown as a constant head and was controlled by adding a 26 km wide strip of very low T on the western edge. The 16 current production boreholes were then introduced using extraction rates provided by the biannual wellfield monitoring reports. The predicted water levels, after pumping, in the model were compared with the actual groundwater levels measured in observation boreholes and recorded in these reports. The S value was changed until a good correlation of regional drawdown was achieved, the final value being $1 \times 10^{-2}$. It was also necessary to introduce an unconfined S for those boreholes where large drawdown caused a change from confined to an unconfined condition i.e. $2 \times 10^{-2}$. These parameters are therefore realistic and not conservative as in previous modelling exercises.

Fig. 8a shows actual and modelled pumping water levels from a number of production boreholes used in the calibration of the model.

In order to model the actual drawdowns in the production boreholes, it was necessary to adjust the transmissivities in the model grid cells where boreholes are located. The values of T used vary from 5 to $1000 m^2$ day$^{-1}$. The prediction of future wellfield behaviour was carried out by running the model for 25 years and examining the drawdowns every 5 years. (Fig. 8b). The predicted demand was extracted from all 26 wells (see Fig. 1) with individual well extractions determined by assuming a constant extraction rate continuously over 25
years. After preliminary runs, the extraction rates in each well were adjusted so that the drawdown (in each well) after 25 years was acceptable i.e. not excessive. (Fig. 8b).

CONCLUDING REMARKS

Each of the different phases of modelling described have improved on the last in terms of reliability. The adjustment of aquifer parameters, in particular storage and recharge, (modelled as a lateral throughflow) have been based on both improved modelling technique and new hydrogeological information derived from more comprehensive field tests and the isotopic analysis of groundwater.
Accurate calibration of the latest groundwater model, using very comprehensive data sets included in biannual monitoring reports dating back to 1981, has been achieved for a 7 year period and this model is now used by management as a predictive groundwater resources tool. It is proposed that the model performance be reviewed annually and results be reported in the end of year wellfield monitoring reports submitted to the appropriate government departments.

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REFERENCES


