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8550 Exploration, evaluation and development of large-scale groundwater supplies in the Botswana Kalahari

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Unlike some other major semi-arid regions, the Kalahari is not blessed with an extensive prolific aquifer. Large areas are underlain by thick Karoo and Kalahari strata, however, and either sequence may include some consolidated sedimentary formations which form sub-regional aquifers, possessing sufficient transmissivity for production boreholes to yield 5–15 l/s of acceptable quality groundwater. While such aquifers appear capable of making a significant contribution to the large water supplies required for the region's development, hydrogeological complexity increases the cost of, and reduces confidence in, groundwater resources evaluation. Five main problems are commonly encountered and these are discussed in relation to the case of a 20 Ml/d water-supply for a new mine and associated infrastructure. The interim solution utilizing groundwater was achieved inside 3 years at a total capital cost of about US$ 11 million, some 15% of which represented exploration costs, compared with the surface water alternative priced at more than US$ 40 million. The effect which groundwater resource uncertainties have on the approach to technical development and capital investment for mine water-supply is also highlighted.

Introduction

Background to water supply demand

The existence of a major diamond prospect at Jwaneng in southern Botswana was discovered in 1976. By mid-1977 the need for a water-supply of 15–20 Ml/d for 300 d/a, over at least 20 years, for mine process water and mining infrastructure, had been defined. Only the latter needed to be of potable quality. The economics of such a mining venture are highly dependent upon establishing an adequate water-supply, since the cost and effectiveness of diamond recovery methods vary widely with water-supply availability. The Jwaneng project represented an increase of more than 10% in Botswana's water demand. Groundwater had previously been developed to a short-term capacity of some 10 Ml/d, from the Cave Sandstone for the Orapa–Letlhakane mining complex, but only as a standby supply.

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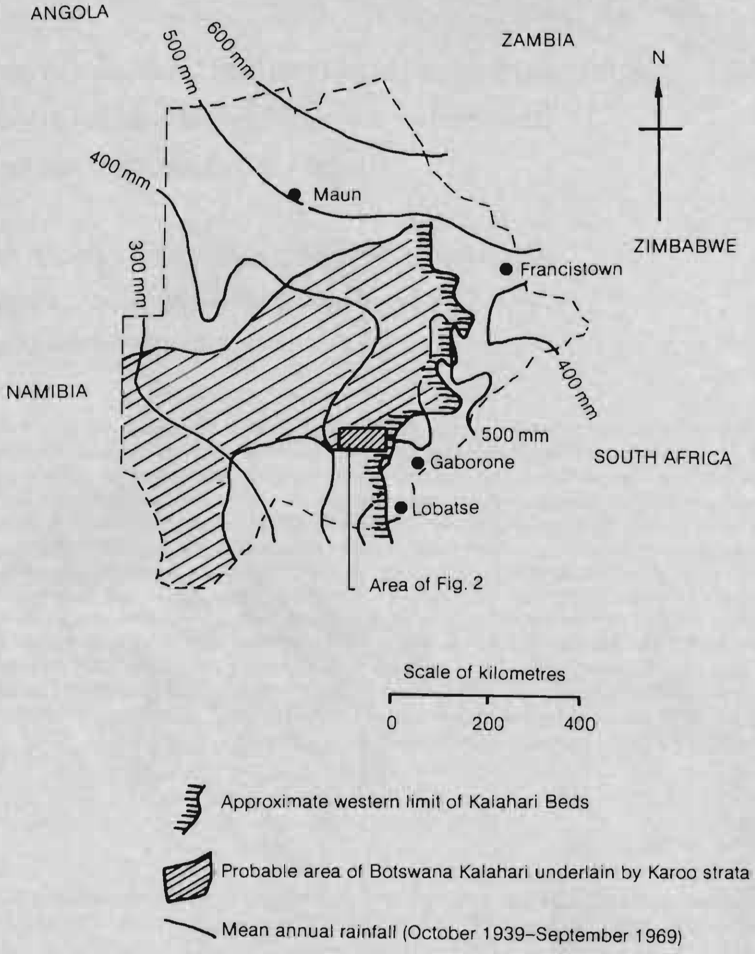

Fig. 1. Botswana: location of investigations

2. During 1977 preliminary evaluation of the possibilities of developing surface water resources revealed that:

(*a*) The only realistic option involved a pipeline from the Gaborone Dam, over 120 km west, at a capital cost of about US$ 36 million;* the dam would also have to be modified to increase available storage at a further cost of some US$ 10 million, and its use would prejudice future expansion of Gaborone's water-supply.

(*b*) The reliability of a surface water storage scheme could not be assessed

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* All costs are in US$ on dates implied in text, when the Botswana Pula was valued at about US$ 1·25 and UK£ 0·55.

with any confidence until 1981, at the very earliest, because of meagre hydrological records.

3. Thus groundwater appeared the only means feasible to satisfy the mine's water demand of 1–3 Ml/d for construction and pilot operation during 1978–81, building up to 15 Ml/d in the early years of full-scale operation from 1982 onwards. It was possible that, if necessary, a conjunctive use of surface and groundwater resources could be implemented some 3 years after the reliability of a surface water scheme had been adequately evaluated.

Geohydrological setting of southern Botswana

4. Across much of southern Botswana (Fig. 1) the Kalahari is underlain by the Karoo system (of Carboniferous–Jurassic age), within which useful subregional aquifers may be present in the Ecca and Cave (Stormberg) sandstones. The geology of the Karoo system is very complicated and has only been elucidated locally during mineral exploration. The complex stratigraphy, sedimentology and structure of the Ecca Series reflect a continental basin environment of deposition. Later, during the Stormberg, more uniform conditions of sedimentation prevailed and, in consequence, the stratigraphy of the Cave Sandstone is less complex. Unfortunately, however, this formation does not appear to be characterized by as high transmissivity and storativity as some Ecca sandstones and completion of efficient production boreholes is also more difficult. The overall geohydrological picture is further complicated by late-Karoo volcanism and by the surficial blanket of Kalahari Beds (Fig. 1). No thick Middle Kalahari aquifers, like those in parts of Namibia[1] appear to be present.

5. In southern Botswana, the Kalahari Beds (of Cretaceous to Recent age) rarely exceed 40 m thickness except in occasional pre-Kalahari buried channels, and comprise a sequence of essentially aeolian sands, calcretes and related deposits. The remarkably flat sand-covered plain has very variable, high intensity rainfall, averaging 250–550 mm/a (Fig. 1) and occurring mainly in the hot wet season (December–March) when potential evaporation reaches 8 mm/d. For the most part, the region is sufficiently vegetated to stabilize the sand cover and only in the extreme south-west do true desert conditions prevail. Despite high rainfall intensities, surface run-off is localized and rare, although some water stands quite regularly in pans. The existence of 'fossil' valleys must be a relic of historic wetter periods.

Scope of groundwater investigations

6. In 1977 a groundwater feasibility study was initiated over 100 km radius from the projected mine to assess the prospects of obtaining the required water-supply for a minimum of 7 years, with priority on an area of about 3200 km^2 of the Karoo margin some 20–70 km north (Fig. 2). This area is fairly remote, being 85 km from the nearest all-weather road and 140 km from an airport or railhead. Although its broad stratigraphy was known from some 20 cored boreholes for coal exploration, very little hydrogeological data were available.

7. The positive results of this study in respect of an area of central Kweneng some 30–50 km distant, where Ecca sandstones occur at relatively shallow depth, led to an intensive staged investigation of a smaller area of some 1250 km^2 (Fig. 2), to evaluate the groundwater resources and to plan groundwater development.

Table 1. Timetable, scope and cost of groundwater investigations

Stage	Duration	Area, km^2	Surface geophysics, line km	Drilling sites	Pumping tests			Costs, US$ million*		
					Step only	Steady rate		Supervision	Drilling	Total
						With observation boreholes	Without observation boreholes			
Feasibility study	Apr. 1977 to Oct. 1977	3200	140	18	11	5	0	0·28	0·26	0·54
Government research (part of parallel programmes)	1977–78	1200	0	5 + 8	0	2	0	0·13	0·18	0·31
Stage I investigation	May 1978 to Dec. 1978		450	15	12	5	6	0·51	0·31	0·82
Stage II investigation	Feb. 1979 to July 1979		120	6	5	0	5	0·12	0·06	0·18
			710	39	28	12	11	1·04	0·81	1·85

* All costs refer to dates indicated; the Botswana Pula was valued at about US $1·25 and UK £0·55.

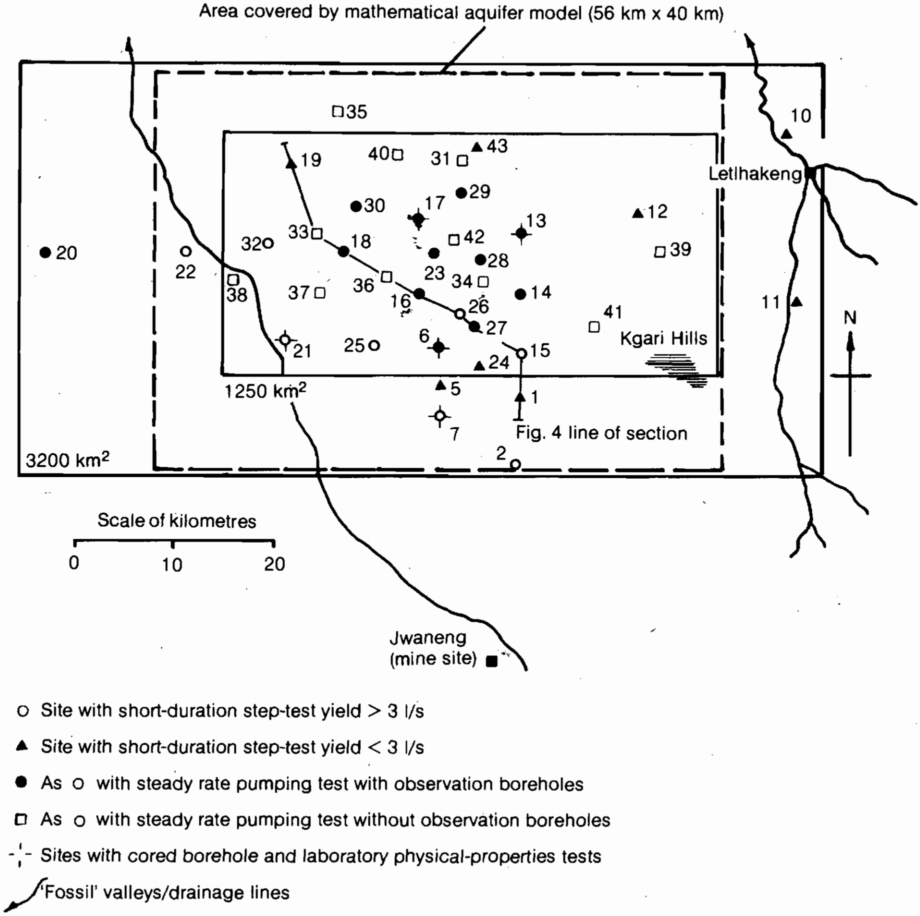


Fig. 2. Central Kweneng: location of investigation area and sites

Existing abstraction totalled only some 0·7 Ml/d for livestock watering and village water-supply. A timetable of the investigations, with a breakdown of costs, is given in Table 1. The principal methods of hydrogeological exploration and groundwater resources evaluation utilized are summarized in the following paragraphs.

8. *Surface geophysical surveys.* Two techniques were employed, gravimetric and magnetic. The gravity results were used in an attempt to delineate the major tectonic features and to define the configuration of the underlying (pre-Cambrian) basement, composed in this area of highly indurated sediments with widespread doleritic intrusions. The magnetic results were complementary where the basement was apparently doleritic, but were also used to search for any late-Karoo intrusions. Some 22 north–south traverses of varying lengths, totalling about 710 km, were surveyed with prismatic compasses. Geophysical stations for gravimeter and

magnetometer readings were established every 200 m along each traverse and accuracies better than 0·1 mgals and 2 gammas respectively achieved. Electric resistivity soundings were not pursued because of the potentially complex and time-consuming data interpretation associated with highly variable Karoo lithologies, but it should be recognized that both geoelectric[1] and seismic techniques might have been employed with some success.

9. *Drilling programme.* The main programme involved drilling at 39 discrete sites (Fig. 2). Combined air-hammer/rotary drilling machines were used throughout, equipped with a compressor/booster system capable of delivering up to 0·4 m^3/s at 3·1 MPa, with a limiting capacity of 260 mm dia. 'completions' to 150 m, and 200 mm 'open-hole' to 350 m. At each site a single exploratory/trial borehole was put down initially and the following data were collected: geological strata record; incremental airlift yield during drilling; and geophysical formation logs by electric self-potential, single-point resistivity, natural gamma and bulk density (gamma–gamma) techniques; with, where justified, (short-duration) step-test pumping. Additionally, government groundwater research work has included parallel drilling programmes with

(*a*) five cored boreholes at certain of the above sites (Fig. 2) to improve stratigraphical correlation and to provide samples for laboratory testing of aquifer properties;

(*b*) power augering and coring of the Kalahari Beds to study their stratigraphy and to generate soil, rock and water samples for physical, chemical or isotopic analyses.

10. *Hydrogeological pumping tests.* At twelve of the above sites (Fig. 2) further boreholes were drilled to produce suitable conditions and proper control for the conduct of steady-rate hydrogeological pumping tests, mainly of 2–5 days' duration. At a further eleven sites (Fig. 2) steady-rate pumping tests without observation boreholes were conducted to permit the estimation of transmissivity. During such testing, geophysical flow logs (micro-conductivity, differential temperature and impellor flowmeter) were run at some sites in an attempt to establish the presence of any major fissure-flow horizons. Systematic water sampling for chemical analyses was also carried out.

11. *Mathematical aquifer modelling.* A mathematical model was used to aid groundwater resources evaluation, to establish the sensitivity of such evaluation to errors in estimation of certain critical parameters and to guide wellfield design. The finite difference method of discretization was used, with alternating-direction, implicit, iterative procedures of solution to an acceptable convergence for the selected time increments. The area selected for modelling (Fig. 2) was 56 km by 40 km; data files on the basic aquifer hydraulic parameters and boundary conditions being established on a 1 km grid and progressively upgraded during the investigation programme.

12. While the above methods represent a 'relatively advanced package' in the field of groundwater resource exploration and evaluation, they are all accepted techniques. This Paper, therefore, does not describe them in any detail nor does it report their results systematically. The main objective is to appraise how far such methods were successful in quantifying the groundwater resources of a previously little-explored area with complex geohydrological conditions, given the prevalent time constraints and budget controls. Five principal hydrogeological problems were encountered and each is examined in subsequent sections.

Principal hydrogeological problems

Exploration for major aquifers

13. Since the various formations within the Ecca Series were known to have been deposited in basin and basin-margin environments, it was believed from the outset that basement configuration, together with major tectonic structures, could be highly significant in the exploration for important aquifers.

14. On completion of the surface geophysical surveys, conducted largely during the feasibility study and at the first stage of the main investigation, Bouger gravity (Fig. 3) and total magnetic intensity maps were produced. These data were digitized and subjected to spatial wavelength filtering by computerized techniques to produce upward continuation and second derivative maps, thus enhancing the study of the larger basement features and of the shallow smaller geophysical anomalies respectively. Specific traverses and anomalies of interest were also subjected to two- and three-dimensional modelling to aid interpretation; a density contrast of 0·5 g/cm^3 being assumed between the Karoo sediments and the basement. Two main southern basins, separated by a NNE–SSW basement ridge, were defined (Fig. 3), bounded to the north by a major regional WSW–ENE fault system with a variable net downward throw to the north in excess of 150 m. All fault systems are likely to be reactivated basement features; a frequent direction of faulting in the area being WNW. In general Karoo strata are wedged and faulted out southwards against the rising basement complex.

15. The drilling programme for the feasibility study (over 3200 km^2) included 18 sites to explore the geohydrological conditions in areas of differing geophysical signature. This led to the following main conclusions:

(*a*) The widespread occurrence on the basement ridge, and in much of the south-eastern basin, of a sandstone sequence possessing transmissivity (T) frequently in excess of 400 m^2/d; the major aquifer apparently being a coarse arkosic sandstone within the Upper Ecca, containing remarkably fresh Ca-HCO$_3$ groundwater.

(*b*) The existence of useful sandstone aquifers, also containing low salinity groundwater but with lower T (up to 200 m^2/d, but frequently less than 100 m^2/d) over wider areas.

(*c*) The presence of Ecca sandstones regionally downdip and to the north of the regional fault system, containing fresh Na-HCO$_3$ groundwater under high confining heads beneath thick Beaufort Shale (Fig. 4).

16. In subsequent drilling programmes, attention was focussed on the aquifers of the two southern basins and their boundaries. The density of drilling sites over the central part of the exploration area was increased from one per 50 km^2, at the end of the feasibility study, to more than one per 20 km^2. The results can be summarized as follows:

(*a*) The groundwater contained by the Ecca sandstones is encountered at depths of 60–140 m and extends to depths of up to about 300 m, with the piezometric surface generally at about 40–60 m below ground level.

(*b*) Over much of the basement ridge and the relatively shallow south-eastern basin, the main water strikes are in the Upper Ecca (Masope) Formation, with additional aquifers in the underlying Middle Ecca Group (Fig. 4). The lowermost 20 m or so of the former are generally by far the most permeable and the groundwater in this (Lower Masope) aquifer is,

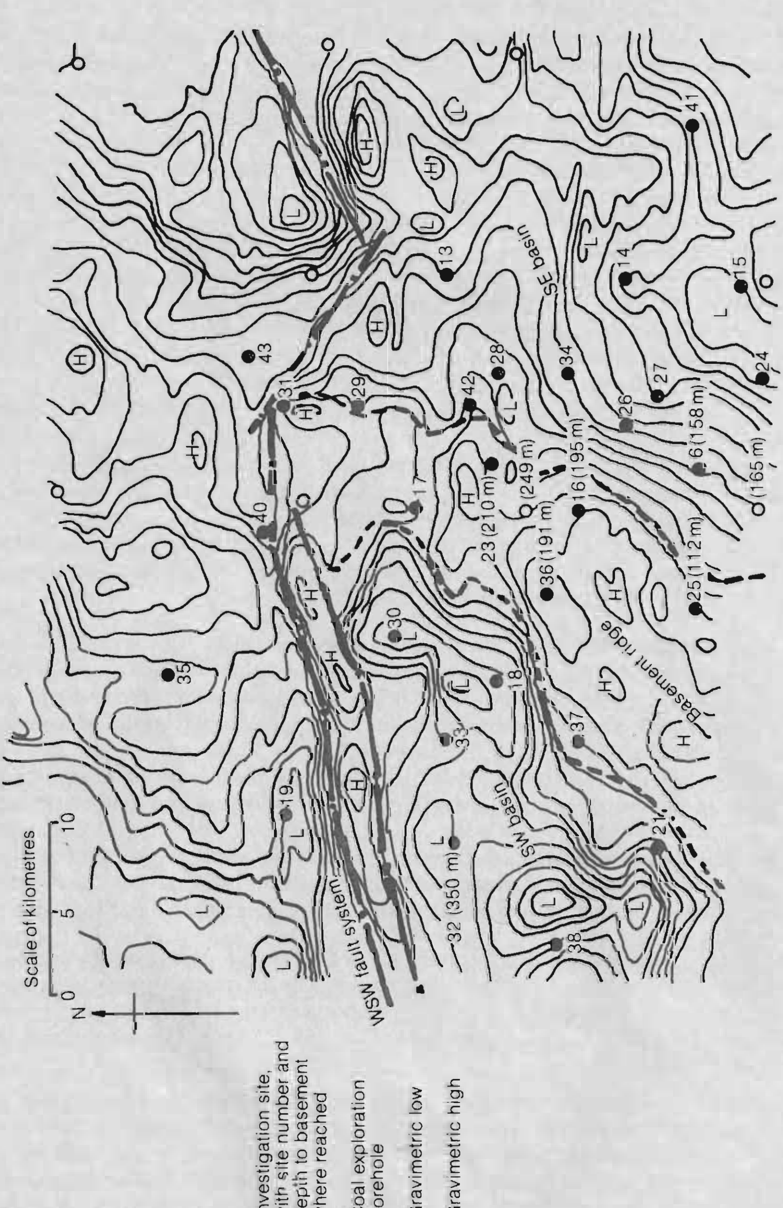


Fig. 3. Bouger gravity map for central part of investigation area

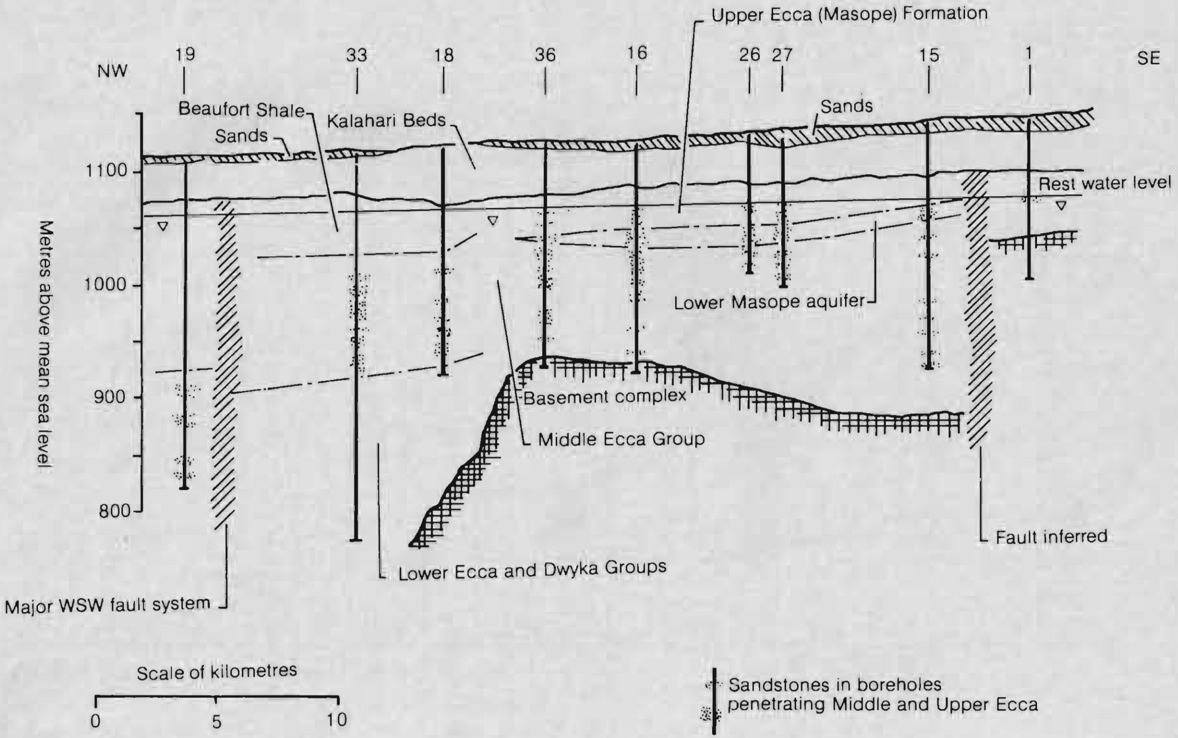


Fig. 4. Hydrogeological cross-section with tentative correlation (vertical exaggeration approx. ×50; see Fig. 2 for line of section)

Table 2. Summary of hydrogeological pumping tests

Site	General location*	Number of observation boreholes	Pumping rate, l/s	Total test duration, d	Terminal drawdown,† m	*T*, m^2/d	(S) Sy	Response/ boundary‡
6	SEB	3	9	13·0	4	500	$1 \cdot 10^{-2}$	DY
13	SEB	2	11	2·0	20	680	$(3 \cdot 10^{-4})$	LC¶
14	SEB	1	5	2·0	8	320	$(3 \cdot 10^{-3})$	LC
16	BR	1	8	4·5	7	190	$2 \cdot 10^{-2}$	DY
17	BR	3	19	6·8	1	1000+	$(2 \cdot 10^{-4})$	LC
18	SWB	1	11	2·4	11	440	$(1 \cdot 10^{-4})$	C
20	OUT	1	11	5·0	8	140	$(1 \cdot 10^{-3})$	LC
23	BR	1	14	2·0	14	400	$(3 \cdot 10^{-4})$	LC¶
27	SEB	1§	10	4·7	17	600	$(1 \cdot 10^{-3})$	LC¶
28	SEB	1	11	3·3	2	1000+	$3 \cdot 10^{-2}$	DY
29	BR	1§	15	5·4	14	1000+	$2 \cdot 10^{-2}$	DY
30	SWB	1	15	2·6	6	580	$(3 \cdot 10^{-4})$	C

* SEB In south-eastern basin; SWB In south-western basin; BR On basement ridge; OUT Outside central area of investigation.

†. Of trial production borehole, including variable well-loss component.

‡ C Confined response; DY With delayed yield (indication of gravity drainage); LC With indication of induced leakage.

§ Shallow observation borehole also installed.

¶ Analysis much complicated by 'dead' head.

in practice, frequently confined (at 15–30 m head), by immediately overlying finer-grained, less permeable strata.

(*c*) In the deeper south-western basin, the Masope Formation is absent (Fig. 4); the main aquifer is a thick (30–150 m) sequence of Middle Ecca sandstones, which, as in the north, is overlain by a confining bed of Beaufort Shale.

(*d*) At only one site, No. 32 in the south-western basin (Fig. 3), was groundwater of significantly high salinity encountered at depth in the Middle Ecca sandstones.

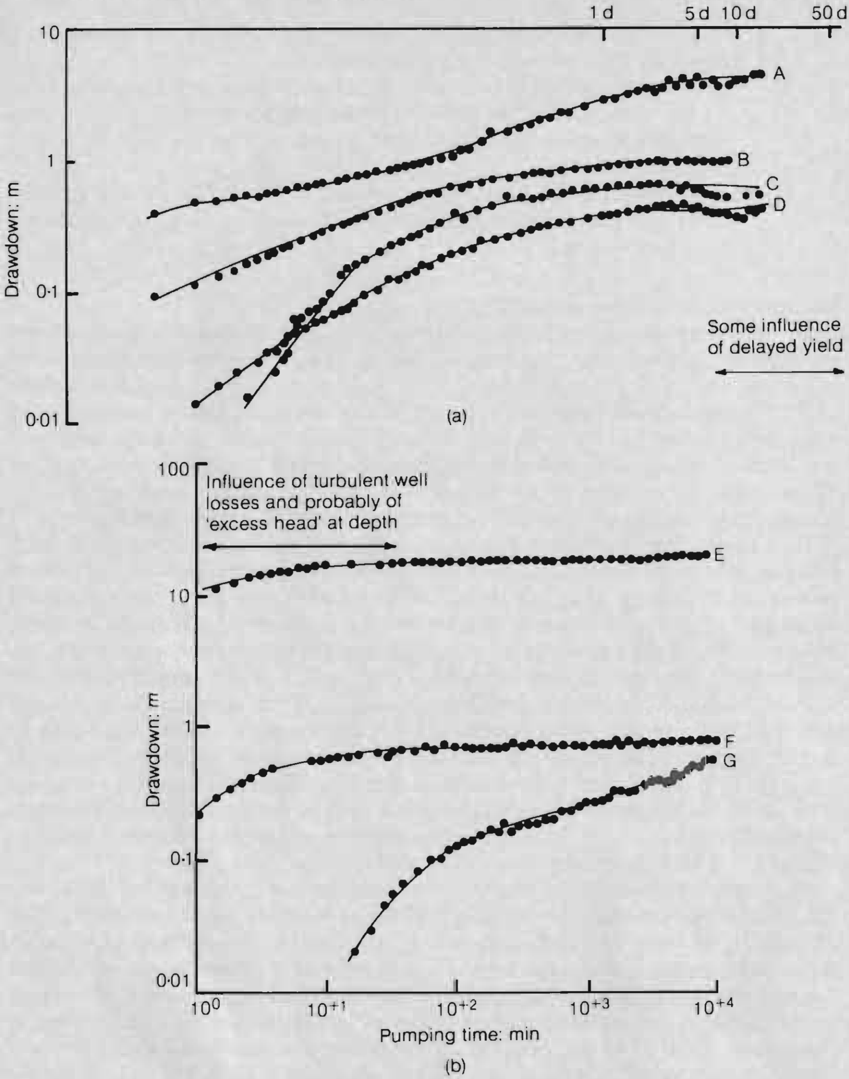
Evaluation of aquifer characteristics

17. Hydrogeological pumping test data (Table 2) from the south-western basin showed fully confined responses but over the rest of the main investigation area the behaviour was much more complex (Fig. 5). Most sites exhibited responses similar to the 'leaky confined' type, perhaps artificially enhanced by the penetration of solid lining tubes, with subsequent signs of 'delayed yield' at some sites and pronounced directional anisotropy in certain instances. The responses were compatible with the concept of a major Lower Masope aquifer receiving induced leakage from overlying less permeable strata, and possibly also from below.

18. There were also indications that, in some cases, the situation is yet more complex. Excess, or increasing, groundwater heads at depth, of up to a few metres, were quite frequently observed in the Middle Ecca Group, and static borehole water-levels must often be composite. In such instances, the initial rate of pumping test drawdown will be governed by well storage alone and the transmissivity of the aquifer horizon possessing the excess head (Fig. 5). If, as will be the case, the latter is small in relation to that of the Lower Masope aquifer, then the excess component of the composite static water-level will behave as a 'dead' head and be rapidly depleted until drawdown has reached the piezometric surface of the Lower Masope. Estimation of its magnitude was attempted by analysis of step pumping tests. Some of the observed (minor) changes in groundwater chemistry of discharge samples during pumping tests probably reflect the existence of excess heads at depth (and others the development of induced leakage).

19. Laboratory testing of borehole core samples from five sites (Fig. 2) showed the interstitial horizontal permeability of the sandstones to be generally in the range 0·01–1·0 m/d. The wide variation in lithology makes selection of representative samples from unit core intervals difficult and although some sandstones (notably the Lower Masope) do appear to possess sufficient permeability to permit major intergranular movement of groundwater, an important and perhaps major component of the total *T* (in the high *T* areas) must be associated with fissures of some nature. Since high *T* is areally widespread, these fissures are not necessarily of tectonic origin, and many are likely to be bedding-plane joints enlarged by water movement. Detailed descriptive logging of borehole cores showed coarse friable arkosic sandstones at the base of the cyclic units of sedimentation, with many cavities resulting from the decomposition and removal of part of the feldspathic matrix probably being responsible for the relatively high formation *T*. The SiO_2 concentrations of the groundwater (30–60 mg/l) are higher than those generated by quartz dissolution alone and suggest that silicate alteration is taking place. Fissures were ubiquitous throughout the profiles and in the coarser zones included cavities up to 50 mm dia., aligned parallel to the bedding.

20. In heterogeneous and fissured aquifers it is not sufficient to know only the



A Pumping borehole; screen 85–145 m (160 m)
B Observation borehole; 010°; $r = 30$ m; open-hole 160 m
C Observation borehole; 275°; $r = 30$ m; screen 70–155 m
D Observation borehole; 190°; $r = 15$ m; open-hole 160 m
E Pumping borehole; screen 80–115 m (135 m)
F Observation borehole; $r = 10$ m; screen 85–95 m (Lower Masope)
G Observation borehole; $r = 10$ m; screen 65–75 m (leakage beds)

Fig. 5. Selected data from hydrogeological pumping tests: (a) site 6; rest water level 66 m below ground level, pumping rate 9 l/s, Lower Masope Aquifer 78–102 m below ground level; (b) site 27; rest water level 65 m below ground level, pumping rate 10 l/s, Lower Masope Aquifer 84–98 m below ground level

magnitude of transmissivity. The depth and thickness of the main permeability developments are more important than the overall saturated thickness, since they directly relate to the heads that can be utilized in groundwater abstraction and therefore to the behaviour of individual production boreholes. Major groundwater inflows into pumping boreholes are normally associated with minor variations of electrical conductivity and/or temperature of the borehole fluid column, which can be logged using sufficiently sensitive equipment, and estimates of vertical flow rates below the pump can be made by flowmeters, giving a semi-quantitative indication of productive zones. However, the maximum completion diameter for trial production boreholes resulting from the drilling technique used (170 mm and latterly 210 mm) imposed a serious constraint on the application of the above methods, since it was insufficient to allow access for the borehole flow logging probes, when pumping plant of appropriate capacity was installed. From the important evidence of the incremental airlift yield during drilling, it is tentatively concluded that highest permeability is associated with the Lower Masope, where this is present, but this could not be confirmed.

Establishment of lateral aquifer continuity

21. Stratigraphic and lithologic correlation between boreholes in the Ecca Series is extremely difficult, because of repeated cycles from coarse to fine sandstones, siltstones and carbonaceous shales, marked facies variation and frequent tectonic disturbance. The question of the extent of lateral continuity of aquifer horizons arises.

22. Areas of shallow gravimetric (Fig. 3) and magnetic gradients appear to reflect general continuity in broad geological terms, but not necessarily of aquifer horizons themselves. While numerous faults, probably of small throw, are postulated from the surface geophysics, it is not clear whether these will enhance or diminish local formation transmissivity on a consistent basis. A few prominent, but small, magnetic and gravimetric anomalies, which might have represented localized post-Karoo intrusions, were carefully analysed to determine most likely geometry. In each case their depth appeared too great to represent an intrusion into the aquifer system and at one site this was confirmed by drilling.

23. Perhaps the most important indication of hydraulic continuity is the fact that in twelve hydrogeological pumping tests no indication of lateral 'barrier' (impermeable or low permeability) boundaries was recorded, but the complex hydrogeological conditions at many sites somewhat reduces confidence in their interpretation. The prominent basal arkosic sandstones of the Masope Formation were positively identified over a fairly wide area (Fig. 4); correlation being aided considerably by geophysical formation logging, especially natural gamma. However, doubts remain about the continuity of the main aquifer units, and the hydraulic relation between the Lower Masope of the south-eastern basin and the thick Middle Ecca of the south-western basin can only be speculated upon.

Likelihood of current groundwater replenishment

24. Although some groundwater replenishment associated with surface run-off may occasionally occur east of the area under consideration, the magnitude of any diffuse recharge from modern rainfall is regarded as a more critical question. Basic meteorological statistics for central Kweneng are sparse, but suggest that infiltration to depths of more than 2 m could occur occasionally during wet seasons, possibly at a mean rate of 25–35 mm/a during 1961–77. However, in areas where

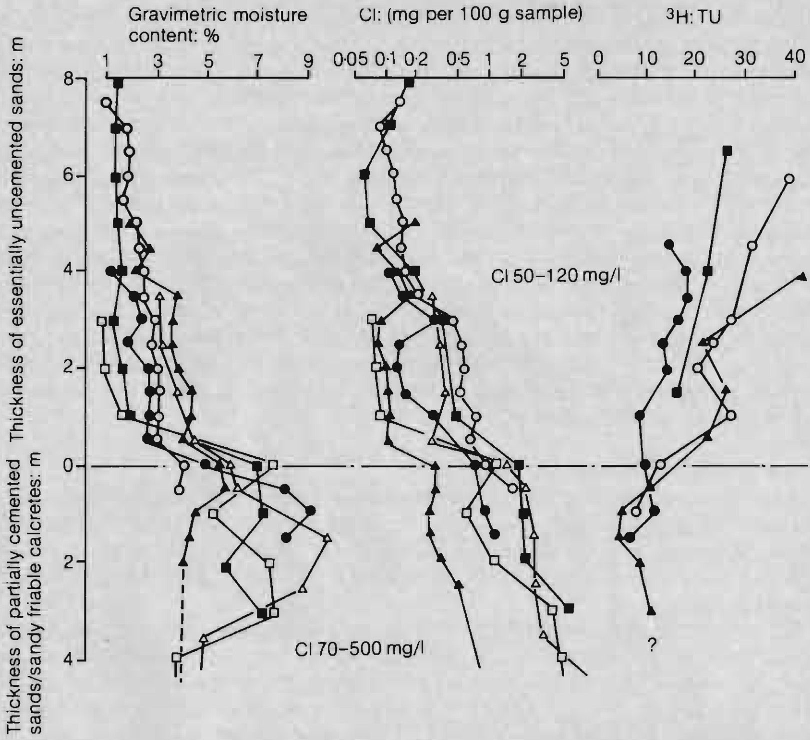


Fig. 6. Moisture content, pore-water chloride and tritium profiles for Kalahari sand-cover (October–December 1977)

the sand cover is deep, this moisture will be retained and, during subsequent dry seasons, may be largely or totally lost by evapotranspiration.

25. A research programme was carried out to improve knowledge of the Kalahari Beds in central Kweneng[2] and to study the fate of this moisture. The results can be summarized:

(*a*) The Kalahari sand proved generally to be 4–9 m in thickness, highly uniform and fairly well sorted, with a median grain size of 0·18 mm.

(*b*) Field moisture contents at the end of the (1977) dry season were low, and uniform in distribution (Fig. 6); it appearing that the moisture storage capacity of a 4 m deep sand profile would only be exceeded following an exceptional sequence of rainfall events.

(*c*) Tritium (^{3}H) profiles (Fig. 6) were difficult to interpret and could not be reconciled with any simple infiltration model. Many samples exceeded 15 TU,* representing post-1963 rainfall, and the total profile moisture content exhibiting such levels was around 200 mm; the highest ^{3}H

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* Tritium units: 1 TU is 1 tritium atom per 10^{18} atoms of all hydrogen species, and represents a radioactivity of $3{\cdot}2 \times 10^{-3}$ pCi/ml.

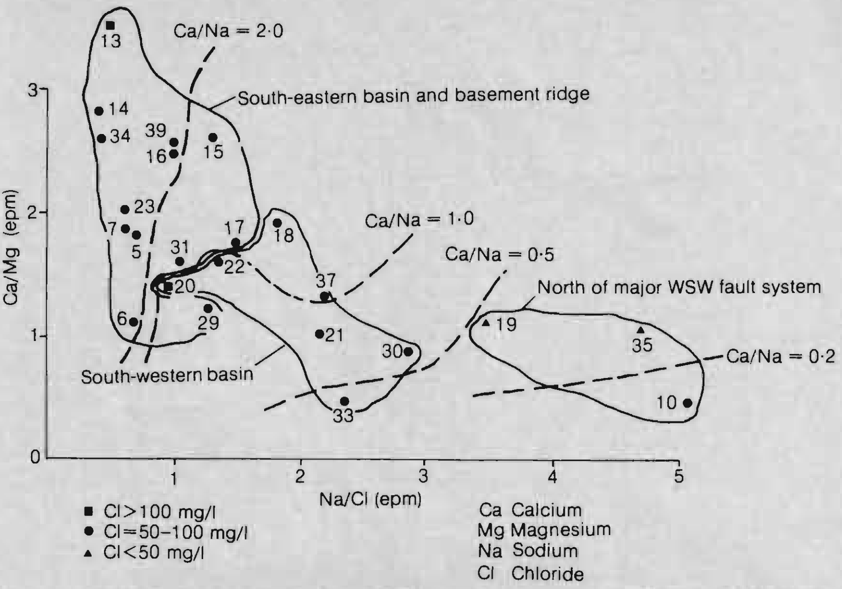

Fig. 7. Summary of chemical characteristics of Ecca groundwaters (bicarbonate (HCO_3) is predominant anion at all sites (generally 250–550 mg/l))

concentrations were in the uppermost 2–3 m and decreased consistently in depth; and the total profile ^3H was less than 5 TU m, small even compared to a single year's fall-out in recent local rain.

(*d*) The dominant feature of chloride (Cl) profiles (Fig. 6) was increasing concentrations with depth, especially towards the base of the Kalahari sands. While the absence of a salt crust implies that some water had been periodically flushing solutes, the profiles were consistent with extremely low net rates of downward movement, certainly much less than 5 mm/a, and the total Cl content of the sands, where more than 4 m thick, represented much more than 50 years' atmospheric input. The fact that concentrations in the lower parts of the sand profiles generally exceeded 100 mg (Cl)/l also suggested little or no recent groundwater recharge, because this value was higher than that of most groundwaters in the underlying aquifers.

26. Most Ecca groundwaters in central Kweneng have remarkably low salinity to surprising depth, with Cl concentrations being mainly in the range 50–100 mg/l. The chemistry of groundwaters appears to relate to the basins from which they derive (Fig. 7), with calcium bicarbonate groundwaters in the south-eastern basin, and increasing sodium, as a result of cation exchange on shale minerals, in the south-western basin and to the north of the major WSW fault system. Pumped groundwater samples from the south-eastern basin mainly recorded very low tritium concentrations (less than 1 TU), suggesting no definite post-1956 water present, and radiocarbon determinations in the range 50–65% modern carbon, indicating groundwater ages of 2000–4000 years before present, or perhaps significantly younger.

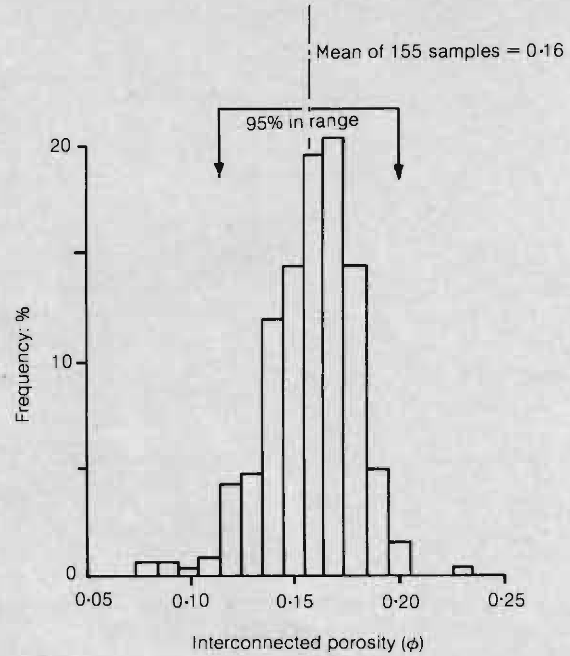

Fig. 8. Porosity histogram for Ecca sandstones (cored boreholes at sites 6, 7, 13, 17 and 21; saturated interval only)

27. Groundwater levels are generally below the base of the Kalahari Beds and the area possesses no identifiable groundwater discharges. Hydraulic gradients are extremely low, generally less than 0·0005 in a westward direction, and unlikely to represent a groundwater flow of more than 2 Ml/d per 10 km flow frontage.

28. In the context of groundwater resource planning, it would thus be imprudent to assume that recharge will occur as a result of present-day rainfall, unless near-sand-free areas can be demonstrated. Such conditions are believed to occur only locally in central Kweneng. Therefore, any large-scale groundwater development must be regarded, for the present, as resource 'mining'. The philosophical question as to whether fresh 'fossil' groundwater in a semi-arid region should be abstracted for use as mine process water is not discussed here. However, since it is only economically practical to 'mine' a proportion of the total groundwater storage, development need not threaten village and cattle-post water-supplies, although remedial action will be required in certain instances.

Estimation of unconfined storage coefficient

29. At eight of the twelve sites for which hydrogeological pumping tests were conducted, 'confined' or 'leaky confined' groundwater level responses were recorded (Table 2), with values of confined storage coefficient (S) mainly in the range 0·001–0·0001. Because of the relatively small confined head in most areas, except for the deepest parts of the south-western basin, the total amount of groundwater in 'confined' storage is estimated to be only about 6300 Ml, compared with a

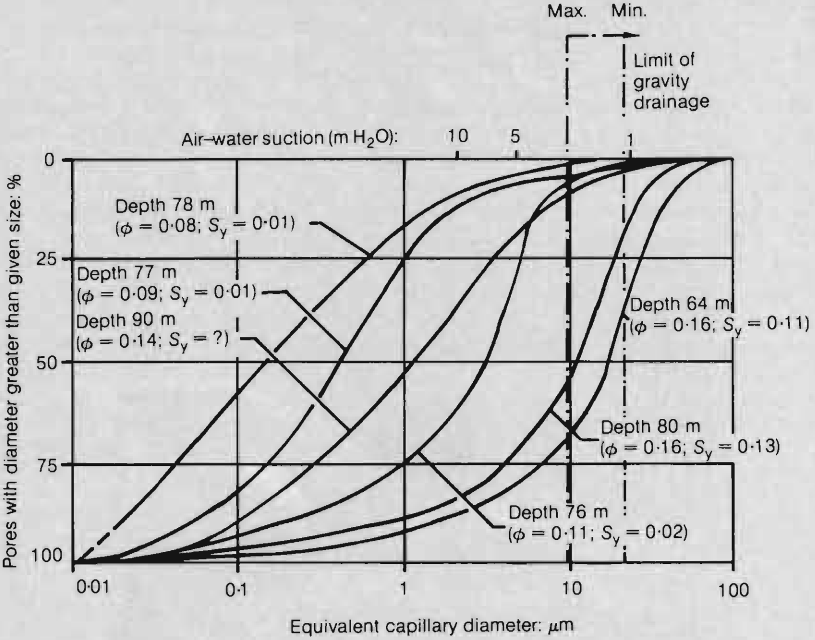

Fig. 9. Selected pore-size distributions for Ecca sandstones (samples from site 13 at depths indicated)

water demand exceeding 4500 Ml/a. In the absence of groundwater recharge, therefore, it is expected that aquifers will become unconfined, and/or drainage of leakage beds will occur, at virtually all production borehole sites within the first few years of pumping. The apparent equilibrium produced by the 'leaky confined' response will, in the absence of groundwater recharge, also be relatively short-lived. The mean unconfined storage coefficient (S_y) of the top 10–20 m of the saturated zone of the main aquifer horizons will, therefore, be critical in determining the groundwater resources and the long term behaviour of a wellfield.

30. At four pumping test sites, suggestions of a 'delayed-yield' unconfined response were recorded (Table 2) and some gravity drainage of the uppermost part of the aquifer appears to have occurred; analyses of these data tentatively suggest an S_y of 0·01–0·03. In order to obtain more representative values it would be necessary to produce larger drawdowns in the unconfined aquifer over wider areas, which at the investigation stage would have required a group of production boreholes continuously pumping at a high steady rate for a number of months, with groundwater being discharged to waste through a relatively long, temporary pipeline to avoid recirculation. This was considered impractical and undesirable.

31. Indirect methods of estimating S_y based on laboratory testing of core samples were, therefore, introduced. Some 155 determinations of interconnected porosity (ϕ) by the liquid resaturation method were made on sandstone samples taken every 1·0–2·5 m from the saturated interval of five cored boreholes; a mean value of 0·16 was obtained (Fig. 8). Only a proportion of ϕ will, in practice, be

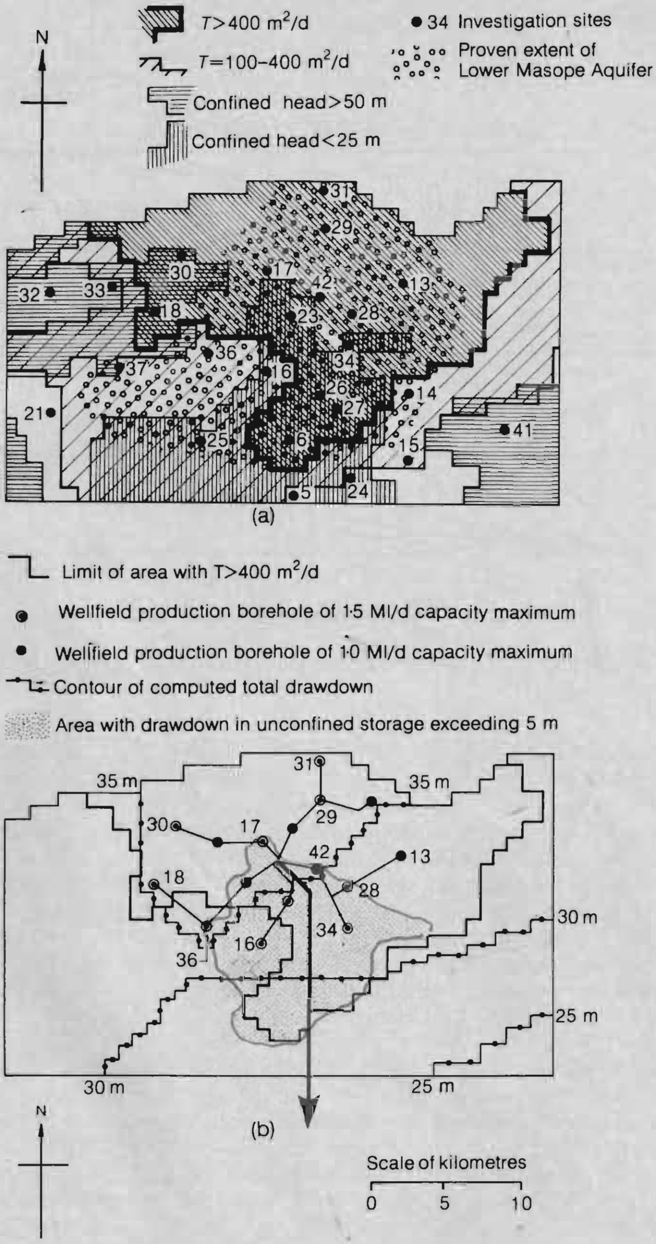

Fig. 10. Mathematical aquifer model: (a) summary of worst-case hydrogeological parameters; $S = 0{\cdot}0003$, $S_y = 0{\cdot}01$; (b) worst-case estimates for drawdowns after about 7 years' abstraction (15 Ml/d for 300 d/a)

drained by gravity and contribute to S_y. This proportion will depend upon the pore sizes and, with certain reservations, can be estimated from measurements of pore-size distribution or from (less time-consuming but more subjective) centrifuge simulation tests. Some ten of the former tests and 25 of the latter were undertaken on samples selected to represent the range of sandstone porosities and lithologies. The results suggest (Fig. 9) that most of the sandstones with $\phi > 0{\cdot}15$ should have an $S_y > 0{\cdot}05$ and occasionally $> 0{\cdot}10$. However, some lower porosity sandstones, with hydraulic conductivities of less than 0·01 m/d, are characterized by much finer grain-size distributions and can be expected to possess an S_y of 0·01–0·05.

32. For the Lower Masope aquifer of the south-eastern basin, ϕ and S_y are expected to be at the higher end of the measured range, but this formation is only about 20 m thick and the possibility that shale horizons could inhibit gravity drainage of the sandstones must not be overlooked. Some 40% of the saturated formation thickness is composed of shales, but considering only the main aquifer horizons the proportion is significantly smaller. A value for S_y of 0·01 was thus selected as a conservative estimate for the sandstones in question. It is hoped that, at least locally and during certain periods of abstraction, values exceeding 0·05 will be experienced.

Approach to groundwater development

State of resources evaluation

33. The uncertainty about the average value of unconfined storage coefficient, and to a lesser degree about continuity of the main aquifer horizons and current groundwater recharge, reduce confidence in the groundwater resources evaluation. The sensitivity of resource estimates to errors in storage coefficient and aquifer boundary conditions was examined using a computerized, finite-difference, mathematical model (Fig. 10(a)). For an assessment of high confidence, the following worst-case assumptions were made:

(*a*) S and S_y to average 0·0003 and 0·01 respectively;
(*b*) neglect any 'leaky' storage from saturated strata overlying the Lower Masope aquifer in the south-eastern basin;
(*c*) treat as impermeable boundaries the main WSW fault system and the limits of the exploration area in all other directions;
(*d*) no active groundwater recharge either within the area modelled or across its lateral boundaries.

34. Operation of this model for various wellfield layouts demonstrated the availability of an absolute minimum of 7 years' supply for the projected mine, with relatively modest drawdowns in the 'unconfined' storage (Fig. 10(b)). Such a supply was considered sufficient to justify the cost of developing the appropriate wellfield, particularly since it would enable the mine to be brought into production at the earliest feasible date. Using more optimistic hydrogeological assumptions, it appeared that the mine could be supplied from groundwater for 20 years and possibly a lot longer.

35. Given the complexity of the hydrogeological conditions, it is not possible to assess groundwater resources with higher precision or greater confidence until the response to some large-scale abstraction has been observed. In particular significant dewatering of the south-eastern basin will be required before estimates

of S_y can be refined. Some 3 years of full-scale operation,* with comprehensive monitoring, would yield much improved data on all hydrogeological parameters, with the possible exception of active groundwater recharge. In unison with this approach, parallel decisions on future water-supply planning and investment, including those related to the possible development of surface water storage and conjunctive use, have been deferred until 1985.

Production wellfield design and construction

36. In addition to the problems limiting confidence in groundwater resources evaluation, two additional factors affect the number of production boreholes, and the wellfield layout, needed to produce the required yield in the long term:

(*a*) The degree of internal continuity of the main aquifer horizons within the areas of groundwater development in the south-eastern and south-western basins.

(*b*) The distribution of permeability with depth and the possibility of rapid non-linear reduction in transmissivity with drawdown in the main aquifer horizons.

The wellfield design must, therefore, be conservative and flexible, so that any loss of yield at individual production boreholes can be compensated by the drilling of additional boreholes at intermediate sites along wellfield pipelines, without necessitating major redesign.

37. A number of wellfield layouts were run on the mathematical aquifer model with printouts of total drawdown and of drawdown in the 'unconfined' storage after operation for approximately 1, 7 and 20 years. The layout selected (Fig. 10(b)) takes into account the above considerations, and that of spreading and minimizing the predicted drawdown in the 'unconfined' storage throughout the proven area of high transmissivity aquifers, together with the need for standardizing production borehole design. It comprises 16 production boreholes of either 1·5 Ml/d or 1·0 Ml/d maximum capacity, and allows for the number of production boreholes to be increased up to 24 without reducing spacing to less than 2 km, should excessive drawdown and concomitant loss of yield occur at any sites.

38. A comparative study of possible pumping plant for the production boreholes suggested that line-shaft turbine pumps (powered by surface motors) have certain disadvantages when compared with electric submersible pumps:

(*a*) Borehole verticality tolerances are more critical, if excessive strain on the line-shaft is to be avoided.

(*b*) They are not as compatible with the range of pumping duties resulting from the continuously falling groundwater levels anticipated; this is likely to lead to higher maintenance costs.

(*c*) They have higher operating costs as a result of line-shaft losses.

Thus electrical submersible pumps were preferred, despite marginally higher capital cost resulting from the need to drill production boreholes of larger diameter. Production boreholes had to be completed at 300 mm dia. to 150 m, the predicted maximum depth for the pump suction, and at 210 mm below that depth, with screens against the main producing horizons. Drilling at diameters sufficient for

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* To the end of 1981 abstraction totalling some 1200 Ml for pilot mining operations has produced no unexpected responses.

these completions is [redacted]ogical limits of the air-hammer method and significant problem[redacted]ere encountered, which necessitated the abandonment of two production boreholes.* Unfortunately no other large-diameter drilling technique appeared practical, given the site conditions and time constraints.

39. The total capital cost of groundwater supply development, including project investigations, production borehole drilling, pumping plant installation, electricity supply, access roads, pipeline laying and monitoring work is about US$ 11·4 million, somewhat over 50% of which is the cost of the external pipeline and associated works. The unit overall (capital plus running) cost of untreated groundwater at the mine is calculated to be nearly US$ 0·5/m^3, assuming a discount rate of 10% and a 20-year wellfield life with some upgrading during the first 10 years. This latter cost is not very sensitive to errors in drawdown estimation because of the comparatively deep static groundwater levels.

Concluding remarks

40. In areas of complex or little understood geology, exploration drilling programmes with a borehole density in the range one per 50–100 km^2, over a broad search area defined by economic and geological criteria, are required if the presence (or absence) of important subregional aquifers is to be confidently established. Surface geophysical surveys should be used to guide site selection but may not allow a significant reduction in the number of boreholes required, at least at the initial exploration stage. Before embarking on major surface geophysical surveys for hydrogeological purposes it is worthwhile evaluating the relative effectiveness and likely cost-benefit of the various techniques available directly, by comparative field tests.

41. The disadvantages of groundwater development from such aquifers, for large-scale water supplies, primarily arise from the difficulty of accurately assessing the size of the two resource components—storage and recharge. A relatively advanced ‘package’ of investigation techniques should allow a preliminary evaluation of the groundwater resources. However, it is well to recognize that, for the refinement of such an evaluation, carefully monitored pilot development schemes are likely to be more effective than continuing investigations, which beyond a given level will arrive at a situation of diminishing returns.

42. The time at which to commence development must depend heavily upon the distance between the demand centre and the groundwater resource, and on the rate of growth of the water demand, since these factors will largely determine the initial capital cost of development and, therefore, the minimum resource required to justify development. Fairly soon after the initiation of groundwater investigations it should be possible to establish a mathematical aquifer model, which can be progressively upgraded as investigation proceeds. If realistic worst-case values for the relevant hydrogeological parameters corresponding to the state of knowledge of the groundwater system are selected, the model can be used to assess the minimum available resource and to steer subsequent investigation.

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43. Much of the work to which this Paper refers was undertaken on behalf of

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* This, in turn, required the upgrading of maximum pumping capacity at certain sites, but the overall development philosophy remained viable.

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