PROJECT 7
REPORT 5/1979

Water Resources Branch,
Department of the Northern Territory,
CONTENTS

SUMMARY

CONCLUSIONS

RECOMMENDATIONS

1 INTRODUCTION

2 HYDROGEOLOGY
   2.1 Mode of Recharge
   2.2 Profile and Extent of the Aquifer

3 SAFE YIELD DETERMINATION

4 EFFECTS OF MINING AND REHABILITATION

5 MONITORING


FIGURES A - Correlation of Water-Year Rainfalls for Gove Airport and Yirrkala

B - Correlation of Study Area Groundwater Discharge with Yirrkala Lagoon Surface outflow (late dry season)

C - Map of Gove Peninsula Groundwater Basin
SUMMARY

A mathematical model has been developed to study the water balance and determine a safe yield for the Gove borefield. A safe yield of 12 million kilolitres per year is obtained for the borefield under current hydrogeological conditions but the importance of the effects of mining on future recharge are stressed. The area to the western side of the plateau is identified as a likely future water source.

CONCLUSIONS

1. The Gove aquifer can be adequately represented by a relatively simple model involving evapotranspiration, infiltration and groundwater discharge.

2. The water level in the aquifer has in fact risen by some metres since pumping started. This is directly related to years of above average and favourably temporally distributed rainfall; it must not be overlooked that a period of comparative drought will reverse this situation.

3. Under current recharge conditions and using the criterion that surface flows from Yirrkala Lagoon should be maintained in an "average" year, the annual safe yield of the borefield is about 12 million kilolitres.

4. Extension of the mined area will probably reduce the safe yield owing to the reduced deep infiltration. The methods of rehabilitation require careful consideration and monitoring.

5. A promising area for a new borefield development exists on the western side of the plateau, where the safe yield could approach that of the existing borefield.
RECOMMENDATIONS

1. The procedures used in rehabilitation of the mined area should be examined as soon as possible in conjunction with the Land Conservation Section, in view of the objectives of maximising infiltration and minimising evapotranspiration. A Branch project should be initiated for this purpose. The establishment of Monitoring facilities such as a recorder station on Shady Tree Creek should be considered as part of the project.

2. The water-balance of the aquifer should be re-examined in 1980, with the aid of the four additional years' data. The study should use the present model as a basis, and concentrate on detecting any change in recharge or other conditions. It may be that the permitted extraction rate from the present borefield should be modified in the light of new information.

3. Irrespective of the above study, collation and examination of the hydrologic data must be on a continuing basis. The Basin Management Section of the Branch should be responsible for this.

4. If at some stage Nabalc.o envisage an increased water requirement, or the allowable yield of the present borefield is likely to fall, investigations should proceed on the western side of the plateau with the objective of confirming the suitability of that area for a second borefield.
1 INTRODUCTION

The Gove Peninsula Aquifer has in recent years supplied the entire water requirement of some 10 million kilolitres per annum to the town of Nhulunbuy and the Nabalco Aluminium plant.

Because the borefield is the highest-producing in the Territory, and the demand may further increase, the importance of monitoring and managing the aquifer has been recognised since the original development. Accordingly, a number of reports by consultants and the Water Resources Branch have been prepared, each making use of additional hydrogeological information at the time.

In 1976 a mathematical re-appraisal of the Gove Aquifer was carried out. This study, with a brief amount of the hydrogeology of the aquifer, has been summarised in a paper presented to the 1977 Annual Hydrology Symposium of the Institution of Engineers, Australia. A copy of the paper is given in the Appendix.

Little original field investigation has been carried out since earlier reports (a reference list is given in the paper), and no new geological interpretation has been attempted. However, the unreliability of some earlier interpretations has been revealed.

A new permit (No 234) under the Control of Waters Ordinance was issued to Nabalco Pty Ltd in 1976. This enables the company to withdraw 12 million kilolitres of water annually from the aquifer, which is contained within Gove Water Control District No. 3. At the time of issue of the permit, the re-appraisal had not been completed, but it was judged that in view of the very favourable state of the resource, the increased pumpage could be allowed at least for some years.

The re-appraisal has now indicated that the permit figure of 12 million kilolitres is appropriate. Nevertheless, future changes in hydrogeological conditions, such as extension of the mined area, and the possibility of Nabalco requesting a further increase in pumpage, will necessitate further reviews.
2. HYDROGEOLOGY

This subject is summarised in the paper. However, some aspects are worthy of further discussion.

2.1 Mode of Recharge

The argument as to whether recharge is by direct infiltration or by groundwater flow from other areas has continued for some years. However, the remote recharge theory can be completely discounted by the following arguments.

(a) Response of the water levels to wet season rainfalls is very apparent when the hydrographs are examined. After a rational allowance for the satisfaction of soil moisture deficiency, recharge commences immediately and to a degree very consistent with the water balance theory developed in the paper.

(b) Furthermore, the response of water level in all the observation bores is virtually simultaneous. OB 16 (RN 4984) which is to the south of the borefield and in the path of supposed recharge, responds no earlier and to no greater magnitude than (say) OB 15 (RN 4925) which is on the north-west side.

(c) The topography does not rise significantly to the south of the basin. To obtain the volume of recharge concerned, any remote recharge would have to emanate from extensive areas of the Latram and Giddy River catchments. It can be seen on 1:100,000 map sheet 6273 that these areas are generally topographically lower not only than the Airstrip Plateau topography but also (to some extent) than the actual potentiometric surface at the Airstrip Plateau.

(d) In the argument against direct infiltration it has been stated that the water, after infiltrating through the bauxite, does not percolate through the pallid clay zone, but moves laterally to the edge of the plateau and is found to be "fairly pouring out" at all the creeks on the plateau fringe during and after the wet season. In fact, the flows concerned have not been quantified but are certainly very minor compared with the discharges which would be expected if the phenomenon accounted for most of the infiltration. For instance, if these flows continued for 6 months of the year, the average discharge in the upper reaches of Shady Tree and Rocky Bay Creeks should be of the order of a kilolitre per second each.

(e) The concept of the pallid clay zone being impermeable is untenable, for the bauxite itself has only come into existence by precipitation of minerals from water which has, under past hydrologic conditions, permeated upwards through the clay. Furthermore, it is relevant to note that in groundwater studies of bauxite environments in the Perth area, the aquifer being examined is in fact the pallid clay zone itself, as there is apparently no more permeable aquifer beneath. (Ref: D.H. Hurle, C.S.I.R.O. Perth, W.A.)
Hydrogeology Cont'd.

In common with most hydrologic models, it cannot be proved that the mathematical model now developed faithfully describes the recharge mechanism, for although the calibrated model appears to work quite accurately, in-built and compensating errors and "fudge factors" in model parameters sometimes provide a distorted picture of the time process.

However, there is a dearth of data on the seasonal rate of evapotranspiration from tropical eucalypts and any meaningful examination of groundwater flow in the unsaturated zone at Gove would be necessarily expensive and time-consuming. It is difficult to see how this aspect of the model could further be developed without for instance, an intensive program of neutron logging.

For practical purposes, the model appears to be rational to "work". There is probably little justification for attempting to improve it unless new data casts doubt on its validity.

2.2 Profile and Extent of the Aquifer

Australian Groundwater Consultants (1970) conducted extensive surface geophysical surveys and presented a detailed interpretation of the "Bedrock" profile. Figure 5 of their report shows this profile, but is misleading because the contours shown are actually according to depth below ground level and not depth below some datum. When a correction for topographic variation is applied, the shape of the contours is changed considerably.

A new bore OB 18 (RN 9026) was drilled at the request of Water Resources Branch in 1974 (see Figure C). This was partly for stratigraphic investigation and partly to provide a new observation bore. The bore was located on A.G.C. Traverse Line "D" near the south-western end, where the interpretation indicated a bedrock depth of about 150 metres. However, when the bore was completed at 250 metres the strata being encountered was still of sand and clay. A gamma-ray log of the hole indicates the strata is of a similar nature to that at the borefield.

No other work has been performed which could test the validity of the A.G.C. bedrock profile, but this one case casts considerable doubt on its usefulness.

Bore OB 18 has proven that a significant depth of aquifer material exists on the western side of the plateau, although the permeability has not been tested. The groundwater flow in the area is westward and currently not utilised. Furthermore, the Yirrkala Lagoon complication does not exist on that side. The area is, then, very promising for future borefield development.

By comparison of the areas available for infiltration, the total annual yield potential of this western area should approach that of the existing borefield. To confirm suitability for a new borefield, groundwater investigations should commence in the area as far in advance as possible of any foreseen increase in requirement or shortcoming of the existing borefield.

A possible location for a new borefield is shown on Figure C.
3. **SAFE YIELD DETERMINATION**

The method of derivation of a safe yield, based on the Yirrkala Lagoon outflow criterion, is outlined in the paper. The derived figure is 12 million kilolitres per year.

It should be noted that the calculated yield of the borefield based on average recharge conditions and without consideration of the above criterion is 14.7 million kilolitres per year.

The outflow criterion, which states that in an "average" year surface flows from Yirrkala Lagoon to the sea should be maintained throughout the dry season, may seem rather arbitrary particularly if a supply for Yirrkala other than from the lagoon is established. However, in the natural condition the surface discharge appears to represent a much greater amount of outflow from the Lagoon than does sub-surface flow. Ecologically, it can be argued that the cessation of surface outflow may have significant impact on the fauna and flora of the Lagoon and on the water quality as it effects the local human inhabitants, and in the absence of better information this criterion was adopted. Nevertheless it should be noted that due to the paucity of outflow data, the dependence on the truthfulness of the model, and the method itself, the method of application of this criterion can hardly be described as rigorous.

Some data and other aspects of the model study and safe yield determination are presented below, to enlarge on the summary provided in the paper.

With regard to input data, Table A lists the water levels in the various observation bores at the end of October each year. The changes from year to year, in conjunction with Theissen Heights (also shown) were used to drive the increase in water level (L) for each water year, which are given in Table 1 of the paper.

Table B gives the figures used to derive the "Q" column (groundwater discharge) in Table 1 of the paper. As stated in the paper, the discharge was defined as being directly proportional to the difference in level between Yirrkala Lagoon and the mean of the levels on OB 11 and OB 13, with the discharge in 1967/68 being defined as the unknown (Q1).
4. EFFECTS OF MINING & REHABILITATION

Although there has been no observed effect on aquifer recharge as yet, the bauxite mining must reduce the infiltration capacity of the upper strata due to the removal of the most permeable agent and exposure of less permeable layers beneath it. Available information does not indicate whether this reduction is sufficient to show infiltration to the point where significant run-off occurs.

Rehabilitation of the mined area is undertaken progressively and in consultation with the Soil Conservation Section of the Department of N.T. While this program may be effective according to soil conservation criteria, it is unlikely that the natural infiltration conditions are being approached.

As mining progresses across the plateau, the effect on the aquifer hydrology should become noticeable, possibly to the extent of seriously reducing the available yield.

The method of rehabilitation should be examined with this in mind. Two objectives are apparent: surface runoff should be minimised and total evapotranspiration should also be minimised.

There may be considerable scope for the reduction of surface runoff as the mined area spreads further away from the escarpment, allowing the introduction of internal drainage systems. These have been mentioned in Soil Conservation Section reports, but further consideration is warranted.

Where the construction of internal drainage is not possible, other soil conservation measures must be given careful thought. Unfortunately no data currently exists on the amount of runoff from the areas already rehabilitated, nor on how much this runoff may increase as the plants in the rehabilitated area mature. However, this situation could be remedied by the installation of a recorder station at one of the silt traps at the top of Shady Tree Creek, to allow an examination of the rainfall-runoff relationship from the area already mined.

In respect of evapotranspiration reduction, it appears from the model study that some 60% of the annual rainfall, although infiltrating, is subsequently lost to the system by evapotranspiration before percolating to the saturated zone.

Considering that this evapotranspiration appears to be perennial, and that the soil moisture store from which it draws in the dry season must be of some depth (say 20 metres), it is clear that in the natural condition the Eucalyptus Tetrodenta must be responsible for the majority of the evapotranspiration.

Hence, to reduce losses from the system and promote groundwater recharge, it is logical for the purpose of rehabilitation that the emphasis should be on grasses and shrubs and the cultivation of trees should be avoided.
5. MONITORING

Experience has shown that temporal fluctuations in the water table are consistent and relatively smooth, and for this reason the required frequency of measurement of standing water levels was reduced in Permit 234 from weekly to monthly. However, no reduction in the number of bores in this program (18) was considered owing to the likelihood of changes to the aquifer hydrology (as a result of mining) and the need to examine these on an areal basis.

Official rainfall measurements are now made at Nhulunbuy post office instead of at the airport. The new location is unsatisfactory in respect of the groundwater reservoir, and it is important that the practice of Nabalco of taking measurements at the borefield be continued. This requirement should be written explicitly into future permits, although it can presently be specified under Condition 16 (h) applying to Permit 234.

As mentioned in Section 4, it is important that a gauging station be established on the upper part of Shady Tree Creek to monitor the rainfall-runoff relationship for the mined and rehabilitated area. This should be undertaken by the Water Resources Branch with the possible assistance of Nabalco.
Water Balance of the Gove Peninsula Groundwater Aquifer

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SUMMARY A mathematical model has been developed to study the water balance and determine a safe yield for the semi-confined aquifer which provides ten million kilolitres per year for the Gove water supply. An unusual feature of the site is the negligible surface-runoff which is attributable to the high permeability of the surface bauxite deposits. This facilitates an examination of the infiltration - evapotranspiration balance. The model indicates that the annual evapotranspiration from the tropical woodland savannah forest over the aquifer is about 1000 millimetres, or half the open-forest evaporation. Also indicated is a storage coefficient for the aquifer of 0.04. An annual safe yield of 12 million kilolitres is obtained for the borefield.

1 INTRODUCTION

Water consumption of the Gove Peninsula mining town Nhulunbuy and the Navalco Aluminium plant has rapidly increased in recent years to about 10 million kilolitres per annum. This requirement is satisfied by seventeen production bores located in an aquifer of sands and clays. It is the highest-producing borefield in the Northern Territory, and the Company plans to increase the consumption.

While earlier assessments of the aquifer's potential were based mainly on hydraulic approaches, increased abstraction and extreme rainfalls have permitted the derivation of a useful water-balance model.

2 GEOLOGY

2.1 Geology

The aquifer at Gove consists of partially consolidated Cretaceous sand and intermittent clays, and underlies some fifty square kilometres of the Airtris Plateau. The upper strata (about 10 metres thick) consist of highly permeable bauxite and laterite of Tertiary age. Basement is Arensian granite and is at a depth of up to 300 metres.

2.2 Topography

The Airtris Plateau has an elevation of some sixty metres and is bounded by escarpments which drop to the sea or to narrow coastal plains. Plateau vegetation consists of tropical woodland savannah forest, the predominant species being Eucalyptus Tetrodonta.

2.3 Runoff and Infiltration

Except on the margins, there is no effective runoff from the plateau despite the high intensity monsoonal rainfall which averages about 1600 millimetres. This has been evidenced by a runoff plot and by direct observation. The bauxite is a very permeable deposit which provides a retention storage while slower infiltration takes place through a zone of less permeable shales and sandy clay underneath. On the margins of the plateau some of this infiltration water moves laterally to feed springs which discharge for a short duration after rainfall.

The potentiometric surface is located some 30 metres below the plateau. This is too deep to allow evapotranspiration from the saturated zone. However, evapotranspiration from the unsaturated zone is believed to play a major part in the recharge mechanism.

2.4 Inflow to the Aquifer

Some previous workers partly or wholly discounted infiltration as a recharge source and claimed that recharge flowed into the aquifer from the south. While the exact shape and extent of the basement profile is uncertain, significant recharge from the south can be discounted by several arguments, including the physical lack of topography to contain the necessary potentiometric surface. Some of the earlier studies were carried out during low-rainfall years when little or no infiltration recharged the aquifer. More recent trends display a marked response to the wet season.

A steeper portion of the potentiometric surface to the south of the borefield is attributable to shallower basement and hence lower transmissivity, and a small component of recharge from the upper part of the Lettin River.

2.5 Aquifer Discharge

The potentiometric surface stands up to about 30 metres above sea level. This results in groundwater movement eastward to the sea and westward to Melville Bay. In both directions this causes perennial baseflow in some coastal streams and, in the case of the east side, maintains a discharge from the Yirrkala Lagoon. Some groundwater discharges directly into the sea via aquifers but data on this aspect is scant. During the dry season groundwater discharge causes a gradual fall in the potentiometric surface.

2.6 Aquifer Hydraulics

The main portion of the aquifer, which is best described as semi-confined, has a transmissivity of the order of 1000 ft²/day. Pumping tests indicate an initial storage coefficient of the order of 0.05, but more general considerations suggest a much higher value corresponding to the longer term (unconfined) situation.
2.7 Water Quality

The groundwater quality is quite uniform both horizontally and vertically. Most of the TDS concentration of 30 milligrams per litre is probably contained in the original rainfall or dissolved from the unsaturated zone during infiltration.

3 AVAILABLE DATA

Pumping from the basin commenced in 1969 and the rate increased steadily to the current level in 1974/75. Statistics are available from Nabalco Pty Ltd; Fig. 2 shows the annual abstractions.

Standing water levels in between 8 and 18 observation bores have been monitored by Nabalco on a weekly basis since late 1967. There are some breaks in the record but there are short enough to permit reasonable interpolation. The hydrographs for all bores exhibit a similar pattern. Four examples are shown in Fig. 2. There has been only a minor distortion in the shape of the potentiometric surface since pumping commenced but, paradoxically, water levels have risen dramatically.

Daily rainfall figures are available for Goose Airport, which is centrally located over the basin, and raingages at two production bores. A nine-year rainfall record for the basin has been compiled using the arithmetic average of the available figures for any given time. Long-term rainfalls are available for Yirrkala, where readings are generally lower than corresponding readings for the plateau.

The rainfalls in each of the five water-years up to 1975/76 were above average, while the rainfalls for the previous six were below. The 1975/76 rainfall (over 2300 millimetres) is a record maximum for the area and, by correlation with thirty-six years of Yirrkala figures, probably corresponds to a return period of the order of 25 years.

Baseflows in the Latram River (to the west) and at Yirrkala Lagoon have been monitored for some ten years.

4 THE MODEL

A mathematical model has been developed to describe the hydrology of the aquifer. The model is based on an annual water balance in which each "year" is a water-year commencing in November. An area of 36 square kilometres (Fig. 1) was defined for the model on the basis of the shape of the potentiometric surface and the extent of the aquifer. The following assumptions were then made in respect of the study area:

[a] There is no surface runoff from rainfall.
[b] In view of the high rainfall intensity, interception losses are a negligible component.
[c] The only water input to the aquifer is by direct infiltration from rainfall. Infiltration from the upper part of the Latram River is ignored, in view of the no-runoff assumption.
[d] Mining activity, which currently occupies some 10% of the area, and which will eventually change the infiltration characteristics of the plateau, is ignored.
Groundwater discharge towards Yirrkala Lagoon and pumping abstractions are the only outputs. The general equation describing the water balance was then:

\[ C + Q + S \cdot A - A' = 0 \]  

where
- \( C \) = Pumping abstraction (\( \times 10^6 \) m\(^3\))
- \( Q \) = Groundwater discharge
- \( S \) = Storage coefficient
- \( h \) = Increase in height of the potentiometric surface (m)
- \( A \) = Area under study (\( \approx 35 \times 10^6 \) m\(^2\))
- \( I \) = Depth of rainfall resulting in deep infiltration (m)

Some of these parameters are discussed in more detail below:

(a) Groundwater discharge

Because this takes place towards and partly into Yirrkala Lagoon, the level of which is well controlled at its mouth, the discharge was defined as being directly proportional to the difference in level between Yirrkala Lagoon and the mean of the levels in two of the observation bores (11 and 13) near the outflow "boundary" of the study area. The discharge in 1967/68 was defined as the unknown \( Q \) and the discharges for other years were related to this by proportion.

(b) Storage coefficient

This refers to the average storage coefficient for the whole study area, and corresponds to the long-term value for which the potentiometric surface is at equilibrium with any recharging or discharging processes.

(c) Increase in height of the potentiometric surface

For each water-year the change in water level in all available bores was computed. The change in water level applicable to the whole study area was then derived using Thiessen weights.

(d) Depth of rainfall resulting in deep infiltration (recharge)

The nature and rate of evapotranspiration was largely unknown, and thus the model was constructed to cater for a variety of assumptions. The basic premise was that deep infiltration was assumed to occur only as a result of any rainfall in excess of the...
Case (iii)

That is, for each of the above cases, and for a variety of maximum evapotranspiration rates \( e_i \), weekly values of evapotranspiration rate, soil moisture deficiency and deep infiltration were generated using weekly rainfall records. Annual total infiltration (\( I \)) figures were thus obtained for a variety of assumptions.

For each of cases (i), (ii) and (iii) and for each water year, an equation was fitted relating the infiltration to the assumed maximum evapotranspiration rate. The general equation was derived from

\[
e = e_i + b + c/I
\]

which gives a curve asymptotic to the straight lines \( e_i \), \( aI + b \) and \( I = 0 \). The form of the equation used was

\[
I = (e_i - b - (b^2 + 4ae_i - 4ae_i^2))/2a
\]

This equation was found to provide a good fit to the data points and allowed a continuous function approximation to the fact that, for each year in each case, \( I = 0 \) for values of \( e \) over some particular value. Values of \( a, b, c \) and \( I \) were shown on Table I. Note that the units of \( a, b, c \) are \( \text{mm}^{-1} \), while the units of \( I \) are \( \text{mm} \).

Hence for each water year and for each of cases (i), (ii) and (iii), the values of \( b \) and \( c \) and the relationship between \( I \) and \( e \) were known. In Equation (1) then, the unknowns were \( a, b \) and \( c \).

For each of cases (i), (ii) and (iii), nine equations in the three unknowns were compiled from the nine water-years of record. Each set of equations was then optimised to give the solution of best fit. A "least-squares" criterion was used to obtain this solution, as follows:

(a) The nine expressions corresponding to the left-hand side of Equation (1) were squared and summed.

(b) The objective function thus obtained was minimised by calculating the partial derivatives with respect to \( a, b \) and \( c \) equating these to zero, and obtaining the simultaneous solution.

The partial derivatives were too complex to permit direct solution, and an iterative process was used. This involved combining two of the equations to eliminate \( b \), and choosing an \( e \) value which then gave a corresponding \( a \) value, with both \( a/b, a \) and \( a/b^2 \) equal to zero; then the corresponding values of \( S \) and \( I/S \) were determined. This process was continued iteratively until \( I/S \) was found to equal zero, at which point the solution had been found.

RESULTS

The results provided by the above process are shown in Table II, with the corresponding values of the objective function \( F \).

It can be seen that the optimum solution might apply to a situation somewhere between cases (ii) and (iii), but a finer tuning of the model was not considered practical. Instead, the three solutions were used to simulate, on a monthly basis, the water level record for the nine years. The results are shown graphically in Fig. 2, from which it is apparent that the case (i) solution is much infer-
I

6 APPLICATION OF RESULTS

From the derived evapotranspiration rate and with the aid of an additional 27 years of record for Yirrkala, correlated to provide rainfall data for the plateau, the average annual recharge to the aquifer was found to be 430 millimetres. This gives an average recharge over the 25 square kilometre study area of 14.7 million kilolitres per year, which corresponds to the average aquifer discharge rate under natural conditions. It is also an estimate of the maximum possible long-term yield of the existing basin. The high storage coefficient and large available drawdown provide a storage of some 100 million kilolitres to allow for consecutive years of low recharge.

For comparison with the above figures, the aquifer "underflow" figures (roughly equivalent to the aquifer discharge in the model) derived by previous workers are, in million kilolitres per year, 28 (Morton), 14 (Egginton), 9.2 (Birch) and 14.5 (Australian Groundwater Consultants).

A safe yield for the study area was determined using Yirrkala Lagoon as a criterion. The lagoon normally overflows continuously to the sea near the Yirrkala community, due to groundwater flow into the lagoon. For aesthetic and public health reasons it is desirable that this flow be maintained. Gaugings of the flow during the late months of each dry season were studied and correlated with the corresponding aquifer discharge figures as determined by the model. It was thereby deduced that to maintain the surface discharge, the aquifer discharge had to exceed 2.7 million kilolitres annually, and hence, to maintain the surface discharge in an "average" year, pumping from the aquifer should not exceed 12 million kilolitres. This is a safe yield for the study area.

The results obtained by the model are also useful to predict the potential of a portion of the aquifer which is currently unused, on the western side of the plateau. It is possible that future water requirements will be drawn from this area.

7 CONCLUSIONS

7.1 The Gove groundwater aquifer can be adequately represented by a relatively simple model involving evapotranspiration, infiltration and groundwater discharge.

7.2 The storage coefficient of the aquifer is about 0.25.

7.3 Evapotranspiration from the tropical woodland savannah forest of the plateau is approximately 23 millimetres per week, or 1000 millimetres per year, which is half the open-can evaporation.

7.4 For the area modelled a safe yield is 12 million kilolitres per year.

8 REFERENCES

1. AUSTRALIAN GROUNDWATER CONSULTANTS PTY LTD. Water Supply Exploration Program Results, Gove N.T., Report 2 1970

2. BIRCH, I. Gove Peninsula Groundwater Assessment, NTIA, Water Resources Branch, Report 1987/1


Section 6 of the paper mentions that the average recharge was determined with the aid of an additional 27 years of record for Yirrkala, correlated to provide rainfalls over the plateau. The correlation is shown on Figure A, using water-years 1967/68 to 1975/76.

Returning to the subject of the Yirrkala outflow criterion, Table C lists the late dry season groundwater discharges from the study areas as obtained from the model, and the corresponding lagoon surface outflow. Note that the OB 11 and OB 13 figures are those for the end of the dry season of each year and not the mean water-year figures as in Table B. The surface outflows were estimated by interpolation of dry season recession gauging figures.

The correlation used to derive the groundwater discharge from the study area corresponding to zero surface outflow is shown on Figure B. Some explanation of the rationale used to derive the correlation is required.

In the steady-state condition the study area discharge should equal the surface plus subsurface discharge from the lagoon. (Note that Rocky Bay Creek does not flow in the dry season and geological evidence suggests no significant subsurface discharge either.) In practice, this relationship does not apply completely due to the storage in the lagoon of wet-season runoff from the escarpment and rainfall directly into the lagoon. This phenomenon explains why the surface discharge actually exceeds the study area discharge at the end of "wetter" dry seasons. However, if surface discharge is just zero then these storage effects do not exist; an increment of extra basin outflow should increase the surface flow by the same amount, bearing in mind that the rate of subsurface outflow would be very insensitive to minor lagoon water-level changes. Hence, the line of correlation should intersect the X-axis at 45°. This assumption was of great assistance in determining the value of study area discharge corresponding to zero surface lagoon outflow.
### TABLE A

**REDUCED OBSERVATION BORE WATER LEVELS AT 31 OCTOBER FOR CALCULATION OF h**

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<td>15.6</td>
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<td>0.07</td>
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<td>8.2</td>
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<td>7.6</td>
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<td>12.9</td>
<td>12.2</td>
<td>12.1</td>
<td>11.5</td>
<td>10.9*</td>
<td>10.8</td>
<td>11.5</td>
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<td>13.1</td>
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<td>0.23</td>
</tr>
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<td>17.4</td>
<td>17.4</td>
<td>16.6</td>
<td>15.9*</td>
<td>16.2</td>
<td>17.2</td>
<td>18.3</td>
<td>19.2</td>
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<td>0.13</td>
</tr>
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<td>18.5</td>
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</table>

* Interpolated using correlation from OB's 1 - 9

### TABLE B

**COMPUTATION OF GROUNDWATER DISCHARGE (Q) (WATER LEVELS IN METRES)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Sea Level Datum (mean)</th>
<th>Lagoon Datum (mean)</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>OB 1</td>
<td>OB 11</td>
<td>OB 13</td>
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</tr>
<tr>
<td>1967-68</td>
<td>8.4</td>
<td>12.5</td>
<td>10.45</td>
</tr>
<tr>
<td>68-69</td>
<td>8.3</td>
<td>12.2</td>
<td>10.25</td>
</tr>
<tr>
<td>69-70</td>
<td>8.0</td>
<td>11.9</td>
<td>9.95</td>
</tr>
<tr>
<td>70-71</td>
<td>7.6</td>
<td>11.2</td>
<td>9.40</td>
</tr>
<tr>
<td>71-72</td>
<td>7.6</td>
<td>10.9</td>
<td>9.25</td>
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<td>72-73</td>
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<td>11.1</td>
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<td>73-74</td>
<td>8.5</td>
<td>11.9</td>
<td>10.20</td>
</tr>
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<td>74-75</td>
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<td>12.6</td>
<td>10.80</td>
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<td>75-76</td>
<td>10.0</td>
<td>14.6</td>
<td>12.30</td>
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TABLE C

Study Area Groundwater Discharge and Corresponding Lagoon Surface Outflow in Late Dry-Season.

<table>
<thead>
<tr>
<th>Year</th>
<th>MSL Datum</th>
<th>Lagoon Datum</th>
<th>Mean of DB 11 and DB 13</th>
<th>Groundwater Discharge Rate</th>
<th>Lagoon Surface Outflow Rate (from extrapolation of gauging figures)</th>
</tr>
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<tbody>
<tr>
<td>1967</td>
<td>10.7</td>
<td>6.7</td>
<td>10.6 m³/yr</td>
<td>7.45 m³/s</td>
<td>0.20 m³/s</td>
</tr>
<tr>
<td>68</td>
<td>10.2</td>
<td>6.2</td>
<td>10.6 m³/yr</td>
<td>6.89 m³/s</td>
<td>0.17 m³/s</td>
</tr>
<tr>
<td>69</td>
<td>10.1</td>
<td>6.1</td>
<td>10.6 m³/yr</td>
<td>6.78 m³/s</td>
<td>0.14 m³/s</td>
</tr>
<tr>
<td>70</td>
<td>9.6</td>
<td>5.6</td>
<td>10.6 m³/yr</td>
<td>6.23 m³/s</td>
<td>0.14 m³/s</td>
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<tr>
<td>71</td>
<td>9.1</td>
<td>5.1</td>
<td>10.6 m³/yr</td>
<td>5.67 m³/s</td>
<td>0.13 m³/s</td>
</tr>
<tr>
<td>72</td>
<td>9.1</td>
<td>5.1</td>
<td>10.6 m³/yr</td>
<td>5.67 m³/s</td>
<td>0.10 m³/s</td>
</tr>
<tr>
<td>73</td>
<td>9.8</td>
<td>5.8</td>
<td>10.6 m³/yr</td>
<td>6.45 m³/s</td>
<td>0.15 m³/s</td>
</tr>
<tr>
<td>74</td>
<td>10.2</td>
<td>6.2</td>
<td>10.6 m³/yr</td>
<td>6.89 m³/s</td>
<td>0.19 m³/s</td>
</tr>
<tr>
<td>75</td>
<td>11.0</td>
<td>7.0</td>
<td>10.6 m³/yr</td>
<td>7.78 m³/s</td>
<td>0.22 m³/s</td>
</tr>
<tr>
<td>76</td>
<td>12.8</td>
<td>8.8</td>
<td>10.6 m³/yr</td>
<td>9.78 m³/s</td>
<td>0.38 m³/s</td>
</tr>
</tbody>
</table>
NOTE: Water year is from November to October.

**Figure A**

Correlation of Water-Year Rainfalls for Gove Airport and Yirrkala

![Graph showing correlation of rainfall between Gove Airport and Yirrkala over the years 1936/37 to 1975/76.](graph.png)

- **Gove Airport Rainfall (mm)**: X-axis
- **Yirrkala Rainfall (mm)**: Y-axis

Key points and notes:
- Airport average (derived)
- Yirrkala average
- Dates and rainfall values for various years
- Equation: \( P_{GA} = P_Y \times 1.10 \) (adopted)

**Technical Report WRD79005**

Viewed at 00:02:41 on 18/02/2010

Page 19 of 21.
LATE DRY SEASON GROUNDWATER DISCHARGE FROM STUDY AREA \((Q (m^3 s^{-1}))\)

- Correlation of Study Area Groundwater Discharge with Yirrkala Lagoon Surface Outflow (Late Dry Season)

**Diagram:**
- Borefield
- Evapotranspiration
- Lagoon
- Subsurface Outflow
- Assumed relationship (for rationale see text)

**Figure B**