EVALUATION OF THE GROUNDWATER DISCHARGE FROM THE YARRAGADEE FORMATION INTO THE BLACKWOOD RIVER, BLACKWOOD PLATEAU, WESTERN AUSTRALIA USING WATER BALANCE ANALYSIS

(Evaluasi Aliran Air Tanah Dari Akifer Yarragedee ke Sungai Blackwood, Dataran Tinggi Blackwood, Australia Tenggara Menggunakan Analisis Kesetimbangan Air)

Baina Afkril
Jurusan Fisika FMIPA Universitas Negeri Papua
Jl, Gunung Salju Amban Manokwari Papua Barat
Email: bainaafkril@yahoo.com

ABSTRAK

Area studi terletak di bagian tenggara Dataran Tinggi Blackwood, Australia Barat mencakup 71 km^2. Akifer Yarragadee di daerah studi utamanya tersusun oleh batu pasir yang mengandung lapisan-lapisan batu lempung dan liat. Akifer ini merupakan akifer tak-tertekan karena muncul dipermukaan sepanjang alur Sungai Blackwood pada daerah hilir di Nannup dan merupakan sumber airtanah yang keluar ke sungai. Sungai Blackwood mengalir melintasi Dataran Tinggi Blackwood. Selama musim kering, aliran permukaan ke dalam Sungai Blackwood dapat diabaikan, namun aliran dasar dari airtanah menjadi sumber utama bagi aliran sungai. Neraca air pada daerah studi dilakukan dengan menggunakan analisa jaring-aliran dan kesetimbangan air guna mengevaluasi masukan airtanah dari akifer Yarragadee ke dalam Sungai Blackwood. Mayoritas sel-sel jaring-aliran adalah sel-sel keluaran dan kebanyakan aliran airtanah masuk ke dalam Sungai Blackwood di daerah studi. Curah hujan rata-rata tahunan area studi sekitar 6.7 x 10^7 m^3 a^{-1}. Sekitar 9 % dari total curah hujan rata-rata tahunan ini masuk ke dalam tanah sebagai sumber bagi air tanah dan 91 % hilang melalui proses evapotranspirasi. Volume total airtanah yang masuk ke dalam Sungai Blackwood antara stasiun Darradup dan Layman Flat yang dihitung menggunakan analisis jarring-aliran dan kesetimbangan air sekitar 8.1 GL a^{-1}.

Kata kunci: *Sungai Blackwood, Keluaran Airtanah, analisis jaring-aliran, kesetimbangan air.*

INTRODUCTION

Identification of groundwater discharge from the underlying aquifers into a river is of particular interest for evaluating the hydrogeology and groundwater resources of the study area as well as the ecological functions that this discharge plays in order to sustain stream baseflow; to maintain specific habitats for aquatic ecosystems; and to provide nutrients to these ecosystems (Woessner, 2000; Hinton, et al, 2003). In order to maintain the stream health and floodplain ecological functions, conceptual models of water exchange between the aquifer and stream are required to ensure that the resource is managed in a sustainable way (Woessner, 2000).

The Blackwood River flows across the Blackwood Plateau in the Southern Perth Basin. River flows are mainly contributed by tributary streams and groundwater discharge from the underlying aquifers. During summer, the surface flows into the Blackwood River are negligible, but groundwater flow is the main source of the river flow. In the study area, downstream from Nannup, the Yarragadee aquifer is exposed in the river channel and is a source of groundwater discharge into the Blackwood River (Baddock, 1995).

Different methods have been applied by researches to study the interactions between groundwater and the Blackwood River. Thorpe and Baddock (1994) estimated the discharge using gauging in the river channel between the Darradup gauging station and Layman Flat in this area was about 10 GLa^{-1}. Jeevaraj (2003) applied a baseflow separation method to estimate the groundwater discharge from the Yarragdee aquifer into the Blackwood River between Darradup and Nannup, which was about 8 GL a^{-1}.

This study is aimed to evaluate the groundwater discharge from the Yarragadee aquifer into the Blackwood River using water budget and flownet system analysis. The particular river stretch to be evaluate is between Darradup gauging station and Layman Flat (Fig. 1).

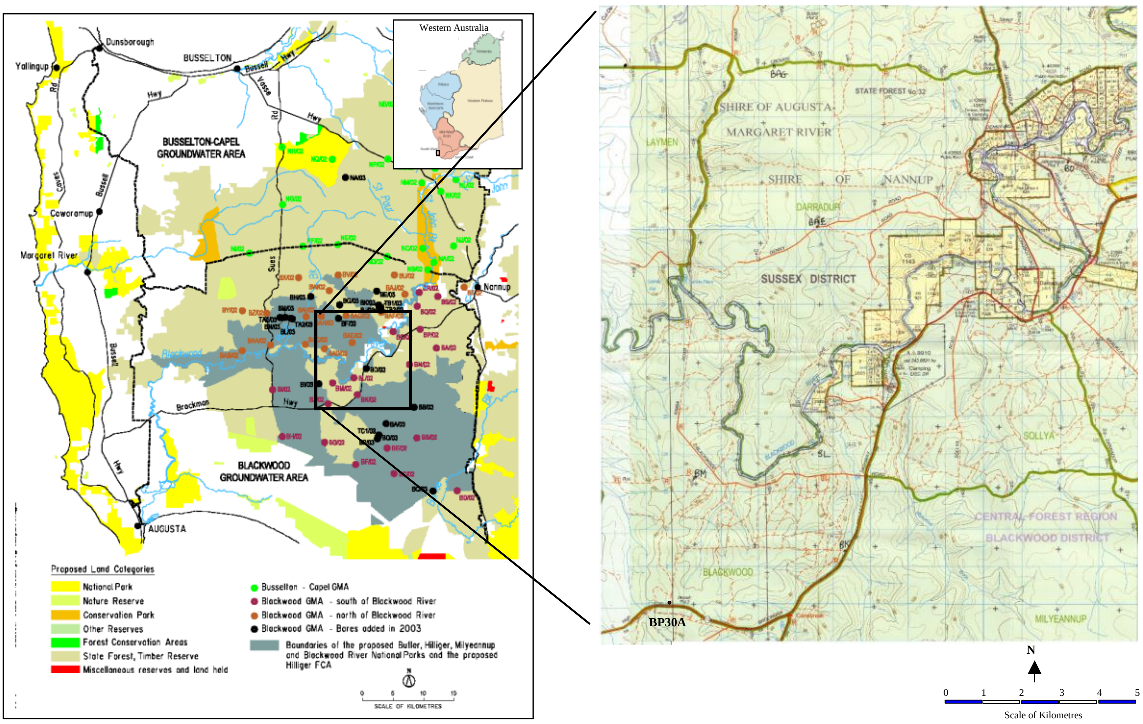


Figure 1. Location of study area (Water Corporation, 2003; Conservation and Land Management, 1996)

WATER BALANCE AND FLOWNET ANALYSIS

1. Water Balance

The water balance is a useful technique to evaluate the overall groundwater-flow system within an aquifer if the water budget equation can be made equal (Brassington, 1998). This method is basically a mathematical approach involving all components of the hydrological cycle. In applying the water balance method it is assumed that all the amounts of water entering an aquifer are equal to the amounts of water leaving it, with any changes in groundwater storage, or it can be written as follows:

$$I = O \pm \Delta S \qquad (1)$$

Where, I = inputs
O = outputs
ΔS = changes in storage

The components involved in the water balance equation on a particular catchment depend upon identified and measured variables of the water balance. For this research work, the water balance equation is expressed as follows:

$$R + G_{wi} = G_{wo} + d + E + E' \pm \Delta S \qquad (2)$$

where,

R = rainfall over the study area,
G_{wi} = groundwater inflow,
G_{wo} = groundwater outflow,
d = groundwater discharge to drains or streams,
E = apparent evapotranspiration,
E' = unaccounted evapotranspiration due to inherent inaccuracies of flownet analysis method, and
E_t = $E + E'$ = total evapotranspiration
ΔS = changes in aquifer storage.

2. Flownet Analysis

The flownet analysis is an analysis of groundwater inflows and outflows of the study area by constructing flownet cells. The groundwater inflows and outflows are calculated using Darcy's law as follows:

$$Q_{Do} = TiL = kbiL \qquad (3)$$

where,

Q_{Do} = volume of groundwater passing through section ($m^3 d^{-1}$),
T = transmissivity of the aquifer ($m^2 d^{-1}$),
i = hydraulic gradient (dimensionless),
k = horizontal hydraulic conductivity (md^{-1})
b = saturated aquifer thickness (m),
L = section width of flownet cell (m).

In applying the Darcy's equation assumptions have been made as follows: (Todd, 1980),
(1) the flow is laminar within porous medium,
(2) the flow velocities are very low,
(3) the Reynolds number (N_R) is less than one.

Davidson (1995) derived 13 types of flow cells combinations generated using hydraulics and chloride mass balance, as shown in Fig. 2. These are grouped into three main classes;
(1) neutral cells occur when the groundwater flow gains are equivalent to its losses (gains = losses),
(2) recharge cells occur when the groundwater flow gains are greater than that for its losses (gains > losses) , and
(3) discharge cells occur when the groundwater flow gains are less than that for its losses (gains < losses).

A reduction in inflow and a gain to throughflow by chloride mass balance ($Q_{Clo} > Q_{Di}$) suggests recharge has occurred from rainfall (*R'*). On the other hand, an increase in inflow and a reduction in chloride concentration outflow ($Q_{Clo} < Q_{Di}$) suggests that there has been a net loss due to evapotranspiration (*E*).

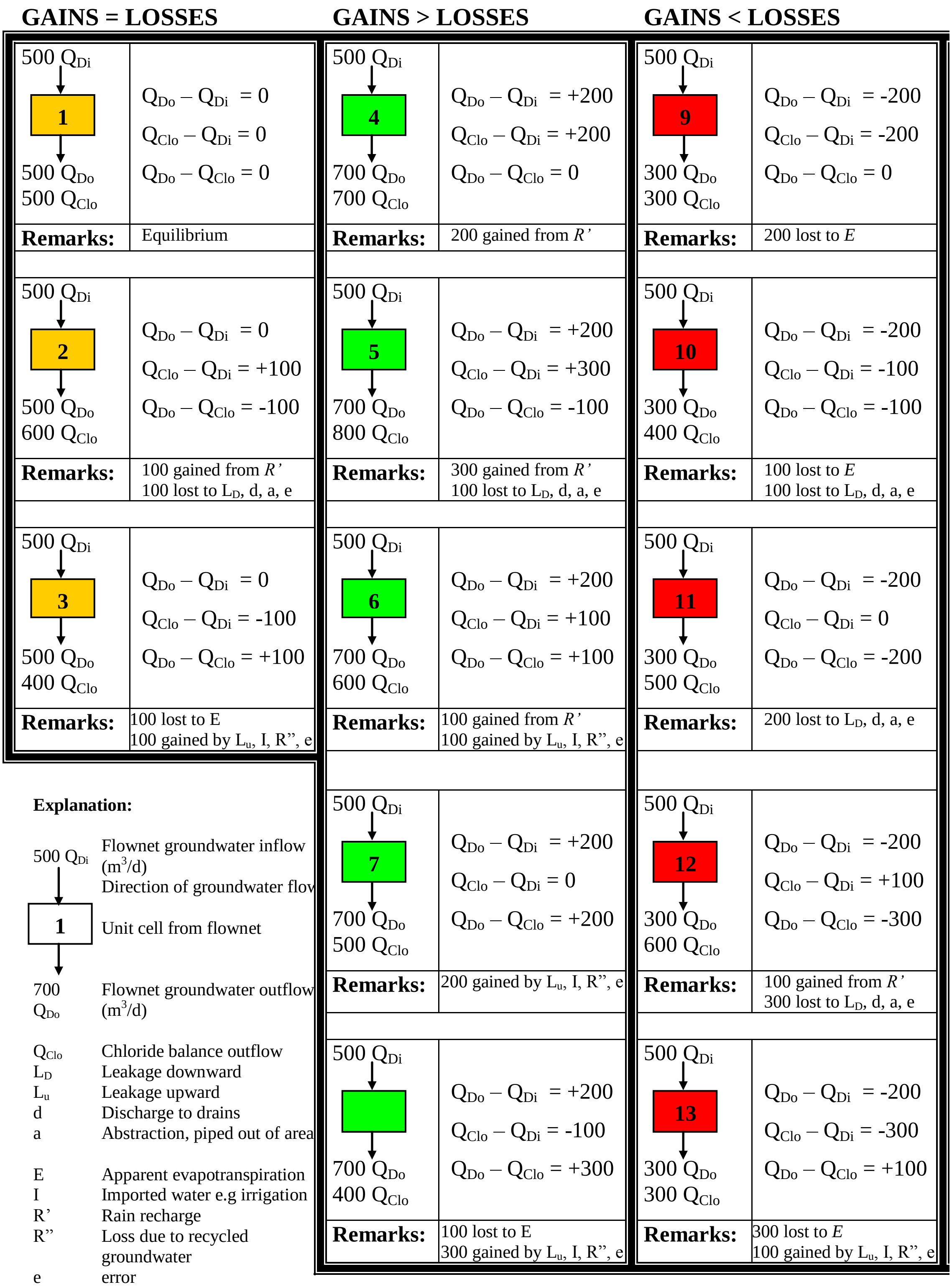
When the chloride concentration outflow is less than the groundwater flownet outflow ($Q_{Clo} < Q_{Do}$) a gain to the groundwater flow has occurred without changing

the chloride concentration. This gain can be from upward leakage from an underlying aquifer (L_u), importation from irrigation water, or from rainfall recharge carrying accumulated salt (*R"*) from swampy areas. In addition, it can result from the loss due to evapotranspiration of recycled groundwater used for irrigation.

When the throughflow by chloride mass balance is greater than that for groundwater outflow ($Q_{Clo} > Q_{Do}$), groundwater has been lost from the flow system without any change in chloride concentration. This can result through downward leakage to an underlying aquifer, (L_D), discharge into drainage (*d*), or through abstraction or piping of groundwater out of the area (*a*).

METHODS

Flow net analysis and the water balance equation are used in order to evaluate groundwater discharge from the Yarragadee aquifer into the Blackwood River in the study area. Groundwater hydraulics and chloride mass balance equation are used in the groundwater flow net analysis. This analysis is based on the work of Davidson (1995) who studied the water balance of the Perth Region in detail. Additional data are incorporated to evaluate the water balance and to construct the flownet cells. Data needed are:
(1) Borehole logs are used to calculate the transmissivity of each bore; Seven bores were chosen from both sides of the river based on the Water and Rivers Commission and Water Corporation research sites in the Blackwood Plateau. They are BP16B(D), BP17A(D), BP21A(S), BP23A(S), BP25A(S), BP30A(S), and BP38A(S), where D and S indicate deep and shallow bores respectively. Bores BP16B, BP17A and BP25A are located on the northern side of the Blackwood River and bores BP21A, BP23A, BP30A and BP40A are located on the southern side of the river.
(2) Surface elevations of the Blackwood River and water levels in well bores within the study area are needed to construct the groundwater level contours.
(3) Chloride Mass Balance to construct the isochlor map of the Yarragadee aquifer in the study area.
(4) Rainfall and apparent evapotranspiration data to calculate the net inflows and outflows in the constructed flownet cells.
(5) Other available data, which contribute to the analysis of water budget in the study area.



Q_{Do}-Q_{Di} = +ve Rain recharge
Q_{Do}-Q_{Di} = -ve Apparent E
Q_{Do}-Q_{Clo} = +ve L_u, I, R'', e
Q_{Do}-Q_{Clo} = -ve L_D, d, a, e

Figure 2 Flow combination using aquifer hydraulics and chloride balance (modified from Davidson, 1995)

RESULT AND DISCUSSION

1. Water Balance Components

In the study area, the water balance was carried out using equation 2. The water balance was calculated using data collected in autumn, from February to May, 2003. The main natural inputs and outputs of the water balance are precipitation and evapotranspiration.

Precipitation is the main component of recharge to groundwater consisting mostly of rainfall that percolates into the aquifer (Brassington, 1998). The amount of precipitation over the study area (R) is a product of average rainfall (R_v) and the area of the study (A). The average rainfall of the study area is 2.58 x 10^{-3} m d^{-1} (or 0.943 m a^{-1}) and the study area is 70.96 x 10^6 m^2. Therefore, the average daily rainfall over the study area is 1.85 x 10^5 m^3 d^{-1} (or 6.69 x 10^7 m^3 a^{-1}).

Evapotranspiration is the sum of evaporation from the land surface and transpiration through vegetation and trees over the study area. The total evapotranspiration is obtained by rearranging equation 2 as follows

$$E_t = (R + G_{wi}) - (G_{wo} + d) \qquad (4)$$

The value of each parameter in equation 4 is obtained from flownet analysis. By substituting values of each component of the water balance E_t is found to be about 1.67 x 10^5 $m^3 d^{-1}$. Therefore, about 91 % of this total rainfall is lost to evapotranspiration and approximately 9 % of the annual rainfall enters the groundwater system over the study area.

2. Constructed Flownet Cells

The Constructed flownet cells in the study area are shown in Fig. 3. The study area is divided into eight flow channels. Six flow channels are in the south of the Blackwood River and the two are in north side of the river. Water table contours are drawn between 42 m and 22 m at a 2 m contour interval.

In this study, the groundwater gain from and loss to an underlying aquifer is assumed to be negligible because it has been assumed that only the upper 100 m of the full thickness of the Yarragadee aquifer contribute to groundwater discharge to the Blackwood River in the study area.

Imported water (I) and abstraction (a) are also negligible as there is no water scheme for irrigation, agriculture or water supply in the study area.

The constructed flownet cells (Fig. 3) shows that the study area is mostly covered by recharge cells and most of the groundwater gain is discharging into the Blackwood River in the study area.

3. Net Discharge

The study area is mostly covered by the Yarragadee aquifer, which has been assumed to be unconfined in the area. Therefore, the flow to the river is largely contributed by the groundwater movement from this aquifer (Thorpe and Baddock, 1994). The Bunbury Basalt, which occurs to the east of the study area, acts as a barrier to groundwater movement (Baddock, 1995). The presence of the Leederville Formation in the northern part of the river in the study area suggests that there is no direct recharge from rainfall to the Yarragadee aquifer at this place. Furthermore, recharge from the Leederville aquifer to the underlying Yarragadee aquifer is assumed to be negligible because the Leederville Formation in this area mainly consists of a thick clay layer. Therefore, only groundwater from the Yarragadee aquifer discharges to the Blackwood River.

Within the study area, the groundwater movement, from both sides of the river, is to the river because the hydraulic head at the river channel interface is greater than the stream level (Fig. 3). In the study area, the net groundwater discharge from the Yarragadee aquifer into the Blackwood River can be obtained by adding the total groundwater outflow from the last cell of each channel of the flownet cells as given in Table 1.

Table 1 Groundwater outflows from last cells of each channel of the constructed flownet cells.

Channel	Position about the River	Outflows (m^3 d^{-1})
1	South	4,735
2	South	4,350
3	South	4,185
4	South	4,743
5	South	1,269
6	South	508
7	North	1,425
8	North	979
Total		22,194

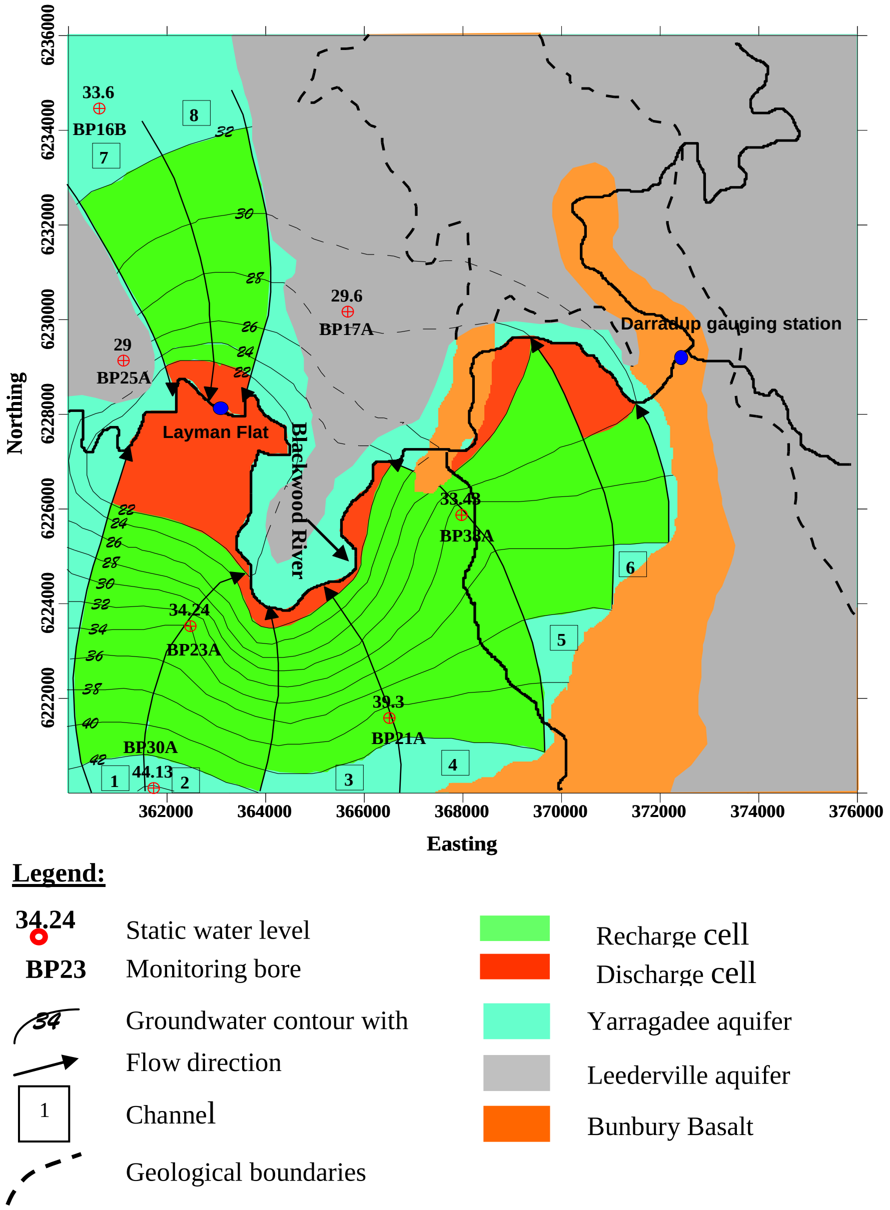


Figure 3 Recharge and discharge relationships of the flownet system in the study area (autumn, 2003)

The estimated total groundwater discharge into the river from all channels is *22,194* $m^3\ d^{-1}$. This amount of daily discharge can be used to estimate for 1 year, which is about $8.1 \times 10^6\ m^3\ a^{-1}$.

Therefore, the net groundwater discharge from the Yarragadee aquifer into the Blackwood River in the study area is about 8.1×10^6 $\mathrm{m^3\ a^{-1}}$ or 8.1 GL $\mathrm{a^{-1}}$.

The amount of groundwater discharge into the Blackwood River in the study area (8.1 GL $\mathrm{a^{-1}}$) is obtained by assuming that all groundwater outflows from last cells of the flow channel construction are discharging into the river. When the last cell of flow channel 5 encounters the Bunbury Basalt (Fig. 3), the groundwater still discharges into the river by a process that the groundwater flows underneath the basalt and discharges into the other side of the river.

CONCLUSION

1. In the study area, the Blackwood River flow is sustained by groundwater inflow from the Yarragaee aquifer as it is exposed in the river channel. The groundwater flows from the northern and

southern parts of the Blackwood River into the river. This confirms that the groundwater from the Yarragdee aquifer is discharging into the Blackwood River.

2. The groundwater flow system of the study area which has been evaluated using flownet analysis and water balance method shows that the area is a recharge area and most of this groundwater gain is discharging into the Blackwood River in the study area. The amount of groundwater discharge from the Yarragadee aquifer into the Blackwood River between the Darradup gauging station and Layman Flat is about 8.1 GL/year.

RECOMENDATION

The use of the water balance and flownet methods depends mainly on the availability of basic data eg, climatic, hydraulic conductivity, pumping tests, etc. Insufficient or lack of data for the water balance parameters may result in inaccuracies in constructing the flownet and estimating the water balance of the study area.

Therefore, the recommendations for more accurate flownet construction and water balance calculation are:

1. Monitoring bores have to be added within the study area to provide more static water level (SWL) data for constructing a reasonably accurate water level contours. In addition, pumping tests program should be carried out in order to more accurately determine the hydraulic parameters of the aquifer in the study area.
2. A more accurate surface geological map of the study area has to be prepared in order to understand the geological controls on groundwater flow within the area.

REFERENCES

BADDOCK, L. J., 1995, Geology and hydrogeology of the Scot Coastal Plain, Perth Basin: Western Australia Geological Survey, Record 1995/7.

BADDOCK, L. J., 1999, Hydrology and numerical modelling of the Yarragadee Aquifer, Southern Perth Basin: Curtin University of Technology, Western Australia, Master Thesis (unpublished).

BADDOCK, L. J., COMMANDER, D. P., GILGALLON, K., MAUGER G. W., SCHOPF, J., SEVERN P., VARMA, S., and XU, C., 2003, Investigation report on the hydrogeology of the South West Yarragadee – Blackwood Groundwater Area. [A draft report for the Water Corporation from the South West Yarragadee - Blackwood Groundwater Area Joint Team, Western Australia]

BRASSINGTON, R., 1998, Field Hydrogeology: John Wiley & Sons, England.

BUREAU OF METEOROLOGY (AUSTRALIA), 2003, Patched Point data for station: 9528 DARRADUP. [Extracted from Silo on 30 May 2003]

CONSERVATION AND LAND MANAGEMENT, 1996, JALBARRAGUP 2029-4. 1:50000 Western Australia Land Management Series, Edition 1.

DAVIDSON, W. A., 1995, Hydrogeology and groundwater resources of the Perth Region, Western Australia; Western Australia Geological Survey, Bulletin 142.

HINTON, M. J., RUSSELL, H. A. J., BOWEN, G. S., and AHAD, J. M. E., 2003, Groundwater discharge in the Humber River watershed [Online],

Available: http://sts.gsc.nrcan.gc.ca/orm/pdf/Hinton_98_1.pdf.

JEEVARAJ, C., 2003, Groundwater discharge to Blackwood River: Water Corporation. [A memo for the Water and Rivers Commission from the Water Corporation, subject: Groundwater discharge to Blackwood River].

MAUGER, G., 2003, Survey of streamflow and salinity in the Blackwood River between Darradup and Hutt Pool. [A report for the Water Corporation from the Geographic Information Analysis Pty Ltd, subject: Survey of streamflow and salinity in the Blackwood River between Darradup and Hutt Pool].

THORPE, P. M., and BADDOCK, L. J., 1994, Groundwater resources of the Busselton – Walpole Region: Western Australia Geological Survey, Hydrogeology Report No. 1994/29.

WATER CORPORATION, 2003, Drilling programme – Proposed land categories map of the South West Yarragadee – Blackwood Groundwater Area

WOESSNER, W. W., 2000, Stream and fluvial plain groundwater interactions: Rescaling hydrogeologic thought: GROUND WATER, Volume 38, no.3, p.423-9.