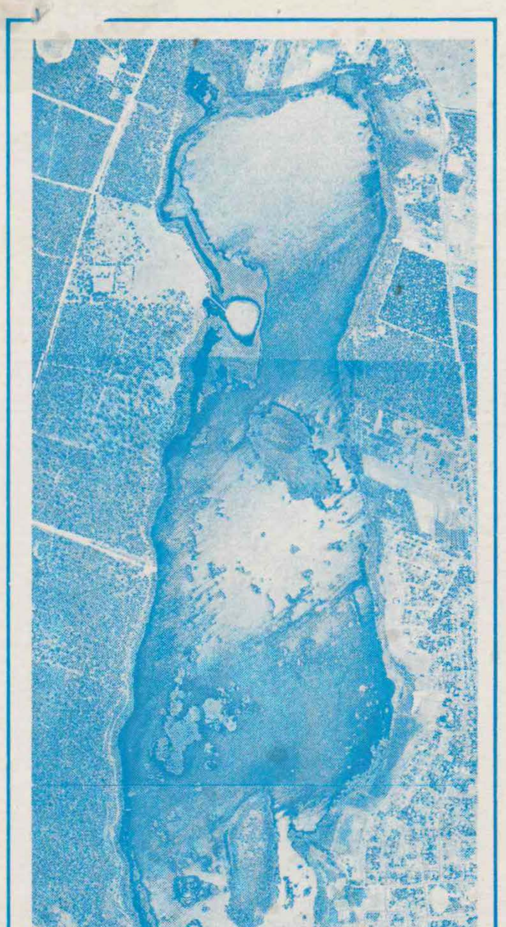
The Water Balance of Lake Joondalup



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THE WATER BALANCE OF LAKE JOONDALUP

by

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1. INTRODUCTION

The aim of the following study was to document the relative importance of rainfall, groundwater and evaporation in determining the volume of water in Lake Joondalup.

The water balance of a lake is given by:

$S_i + P + GW_i = S_o + E + GW_o + \Delta S$

where — S_i = surface water inflow,
P = precipitation,
GW_i = groundwater inflow,
S_o = surface water outflow,
E = evaporation,
GW_o = groundwater outflow, and
ΔS = change in surface water storage

Since there is no significant surface water outflow from Lake Joondalup (Congdon 1979), the balance may be re-expressed as:

$\Delta S = S_i + P \pm GW - E$, or
$\pm GW = \Delta S - P - S_i + E$,

where — $\pm GW$ = net groundwater exchange.

Groundwater inflow and outflow are very difficult and expensive parameters to measure directly, as such measurements entail the construction of piezometer networks (e.g. Allen 1980). In the following work, net groundwater exchange was estimated as the residual in the water balance equation.

2. MATERIALS AND METHODS

2.1 Sampling Sites and Data Base

Most of the water quality data collected during this study have been stored on computer tape and punched cards to form a data base for future analysis and reference. Site numbers recorded in the computer data are based on the order of sampling of the sites, with distinctive numbers used for sites other than those in the lake (Appendix 1). For simplicity, in this report sites have been renumbered consecutively from north to south (Fig. 1).

2.2 Changes in Water-level and Lake Volume

Graduated staffs were located in the lake on the western shore near Hawkins Park (site 19) and at the southern end, off Mullaloo Drive (site 45) (Fig. 2). Depths were recorded at site 19 weekly and site 45 twice weekly.

Staffs were also installed at site 36 (in the storm-water sump at the end of Ariti Avenue), site 54 (in the southern-most basin of the lake), site 57 (in the channel connecting Beenyup Swamp with the lake) and site 59 in Beenyup Swamp (Fig. 2). Depths were measured at these sites twice weekly.

Hypsographic and direct volume curves were constructed from the Metropolitan Water Board's bathymetry map of Lake Joondalup (Congdon 1979). The direct volume curve was later revised and the new curve is shown in Figure 3. In the construction of the bathymetry map, no further separation of contours was made between 16.50 and 17.00 mAHD (Australian Height Datum) and 17.00 and 17.50 mAHD at the edge of the lake, where contour gradients are steep. The areas between these contours were divided evenly into 5 and apportioned at 0.10 m intervals so that the direct volume curve could be drawn with 0.10 m water level intervals. Surface water storage was read from this curve for the depth recorded at site 19 at the end of each sampling period used in the water balance.

Twenty-eight day periods, rather than calendar months, were used for budgeting purposes since field trips were made on a regular basis (Mondays and Thursdays).

2.3 Rainfall

Rainfall and evaporation were measured at Edgewater on the south-western shore of the lake (Fig. 2). As the main prevailing winds are from the south-west they pass over the evaporation pan before picking up moisture over the lake. The equipment was located on a well-exposed site within a locked compound fencing a stormwater sump. Measurements were taken on the Monday and Thursday of each week from August 1979 to December 1980.

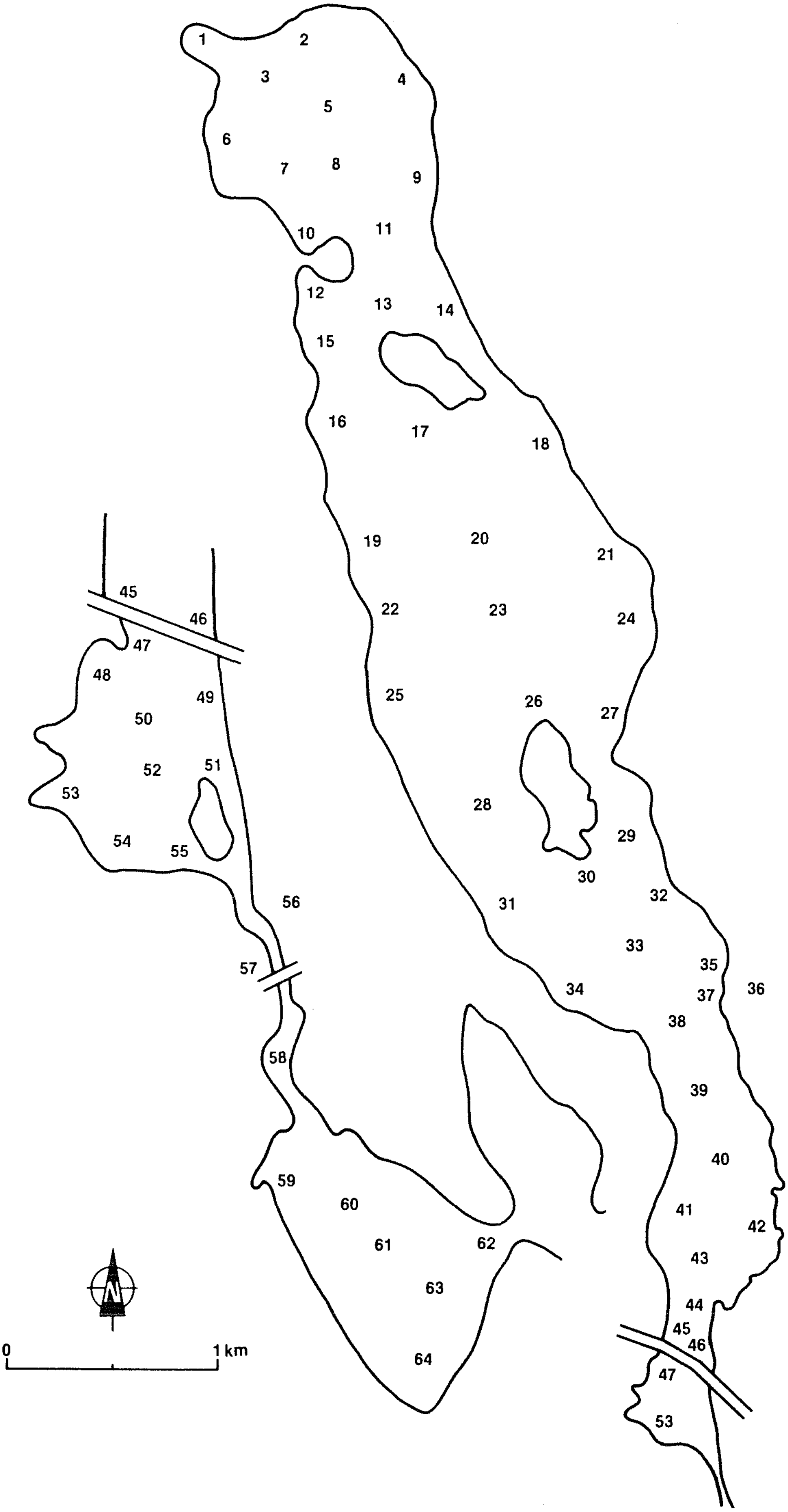


Figure 1 Lake Joondalup and Beenyup Swamp showing sampling sites.

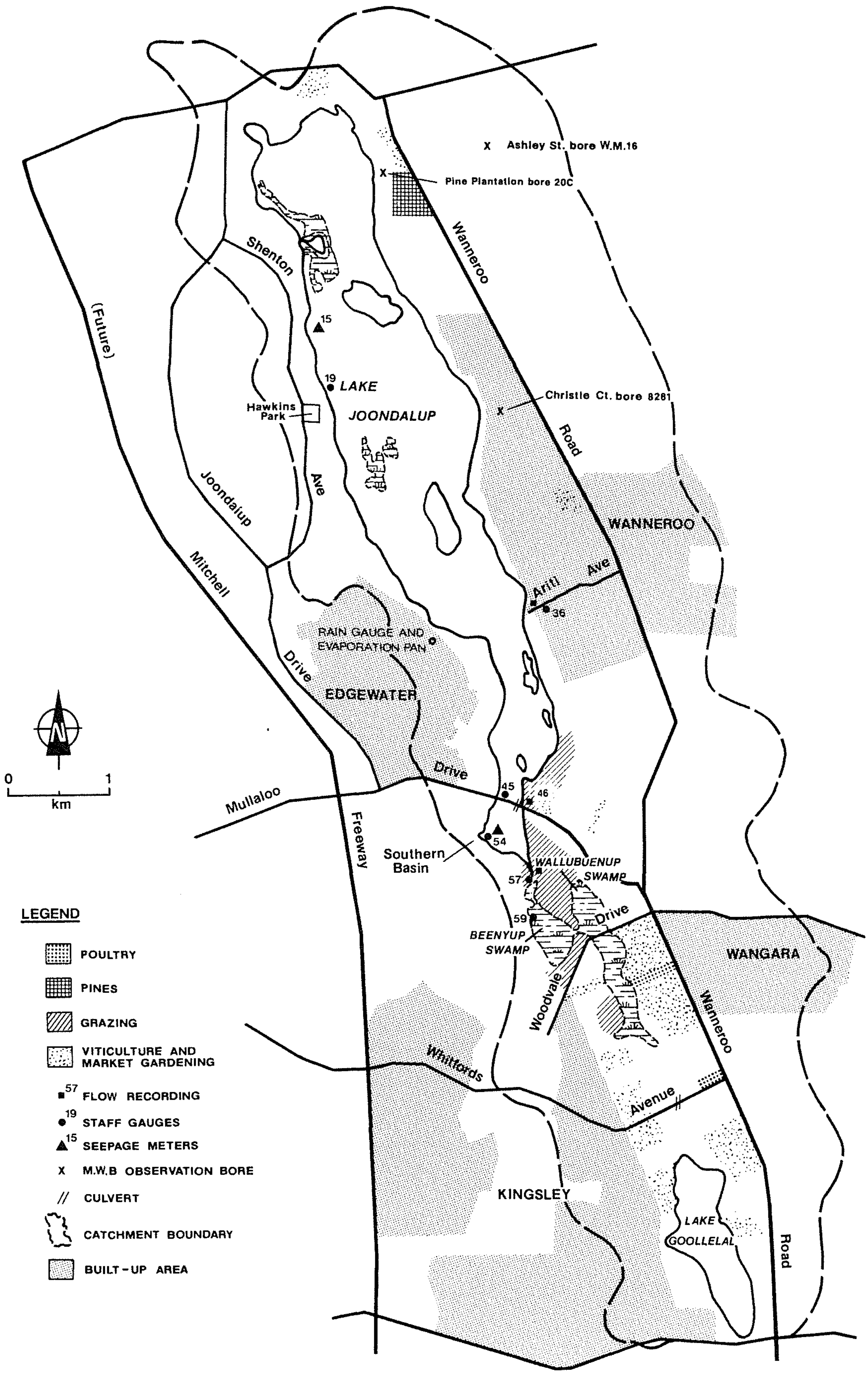


Figure 2 Lake Joondalup catchment, showing land-use and measurement sites for the hydrological study. The broken line is the catchment boundary as supplied by the Town Planning Department.

Rainfall was measured with a simple collecting gauge mounted 40 cm above ground-level. Rainfall is also recorded at Wanneroo by the Bureau of Meteorology. Rainfall input was calculated by multiplying the rainfall recorded for each 28-day water balance period by the average area of the lake for that period. The lake areas at the beginning and end of each sampling period were determined from the hypsographic curve (Fig. 3) using the recorded depth at site 19.

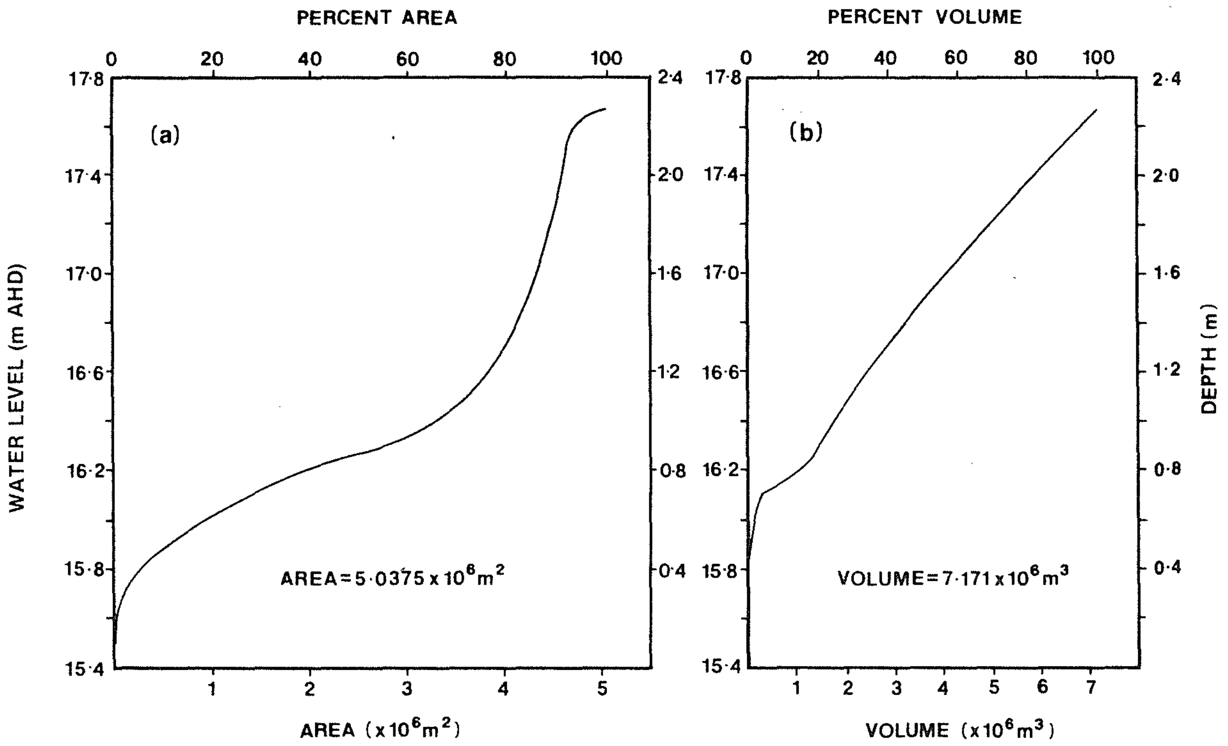


Figure 3 The (a) hypsographic and (b) direct volume curves for Lake Joondalup.

2.4 Evaporation

For shallow lakes the simplest and cheapest reliable technique for measuring evaporation is the pan-lake evaporation method (Cheng Wan-Li 1978, Hoy and Stephens 1979, Black and Rosher 1980). Lake evaporation is determined by multiplying pan evaporation by a pan factor (lake-to-pan coefficient) for each sampling period, and then multiplying by the average area of the lake for that period.

Pan evaporation was measured with a Class A Evaporation Pan mounted on a slatted wooden platform and covered by a bird-guard (World Meteorological Organization 1968, 1969). Evaporation estimates from a Class A pan with bird-guard may be converted to equivalent Class A evaporation by multiplying by 1.07 (van Dijk 1975). The pan was initially filled with lake-water and subsequently the level was maintained with tapwater using a fixed-point gauge mounted in a stilling well. Perth is the nearest station where the Bureau of Meteorology records evaporation.

Pan factors can vary significantly in space and time (Hounam 1973, Hoy and Stephens 1979), and it is important to use those which have been derived under similar climatic conditions for similar water bodies. Two sets of pan factors have been determined for Class A pans in the Perth area. Hoy and Stephens (1979) derived a set for Mundaring Reservoir in the Darling Scarp and Black and Rosher (1980) have determined a set for a study of the hydrology of Peel Inlet (Table 1). Both sets of pan factors were used in calculations of lake evaporation for comparison.

Table 1: Monthly lake-to-pan factors determined by Black & Rosher (1980) for Peel Inlet and Harvey Estuary, and Hoy & Stephens (1979) for Mundaring Reservoir, using Class A evaporation pans with bird guards.

	Black & Rosher	Hoy & Stephens
January	0.6	1.02
February	0.6	1.06
March	0.7	1.12
April	0.8	1.18
May	0.9	1.15
June	1.0	1.18
July	1.0	1.01
August	1.0	0.91
September	0.8	0.81
October	0.8	0.78
November	0.7	0.79
December	0.7	0.94
Annual Average	0.8	1.00

2.5 Surface Water Inflow

Only two surface flows of any magnitude were found. Water flows into the lake from a stormwater sump (site 36) at the end of Ariti Avenue by a narrow channel for most of the year (Fig. 2). However, the most significant input is through the culvert under Mullaloo Drive (site 46), at the southern end of the lake. This water flows from the Wallubuenup-Beenyup Swamp system and flow can be traced as far south as a culvert under Whitfords Avenue. This water movement follows the groundwater contours, which show a gradient from Lake Goollelal to Lake Joondalup (Fig. 4).

Water flow (or discharge) was determined by the area-velocity method (Rosher and van den Berghe 1977), which is based on the hydraulic equation

$$Q = V \times A$$

where Q = discharge,
V = velocity, and
A = cross-sectional area, given by width $\times$ depth

To increase the accuracy of the method, the channels were divided into smaller cross-sectional areas (panels) and velocity, depth and width were determined for each. Total discharge was then obtained by summing the discharge for all the panels. At site 57 as many as 11 measurements were taken when the channel was 5.25 m wide. Three panels were used at site 46 and at site 36, where the channel width varied from 28 to 120 cm, 3 to 8 panels were measured.

The discharge was plotted against water depth (stage) to obtain discharge rating curves (Bruce and Clark 1966) (Figs. 5 — 7). These plots were used to estimate discharge from the recorded depths by interpolation, at times when the current meter was not available, such as from September 29 to October 20 1980.

Water velocity was measured twice weekly at sites 36, 46 and 57 (Fig. 2), with an electromagnetic water current meter (Model 201 M, Marsh-McBirney Inc., Gaithersburg, Maryland).

Readings at site 46 were taken just inside a culvert under Mullaloo Drive. (Subsequent to this work the road has been realigned, and a new culvert constructed).The culvert consisted of concrete box sections, rectangular in cross-section and 120 cm in width. Water depth was measured at the centre of the first box section at the northern end of the culvert from September 1978, but it became apparent by June 1979 that this section was tilting and that the water flow was irregular and uneven across the cross-section. From July 4 1979, water depth was measured at the centre of the second last box section at the northern end of the culvert. When the water current meter became available, water velocity was measured at this site. As flow was declining in September 1980, it became too shallow to use the current meter there, and so velocity measurements were taken at the southern end of the culvert where the water depth was greater.

Bricks and concrete slabs were used to modify the channels at sites 36 and 57 to produce a uniform bottom and thus give more accurate readings. At times of low discharge the cross- sectional areas of the channels were decreased, so as to increase flow and obtain optimum instrument sensitivity.

The discharge values obtained from the area-velocity method and the discharge rating curves were used to calculate daily discharges, assuming that the flow would not vary significantly within one day. Monthly discharge was then calculated by interpolating values for the days when discharges were not determined, assuming a linear change in discharge between sampling days.

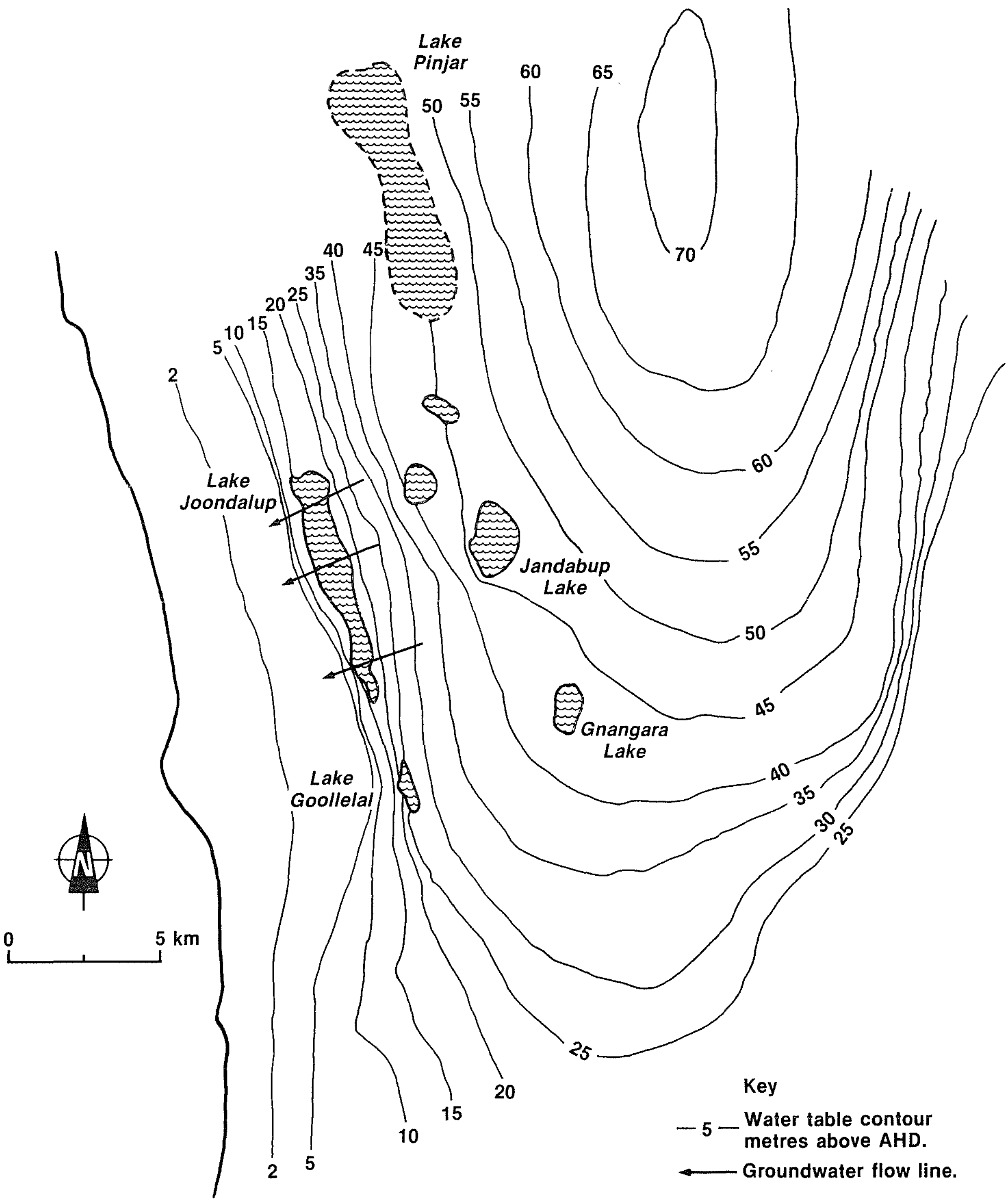
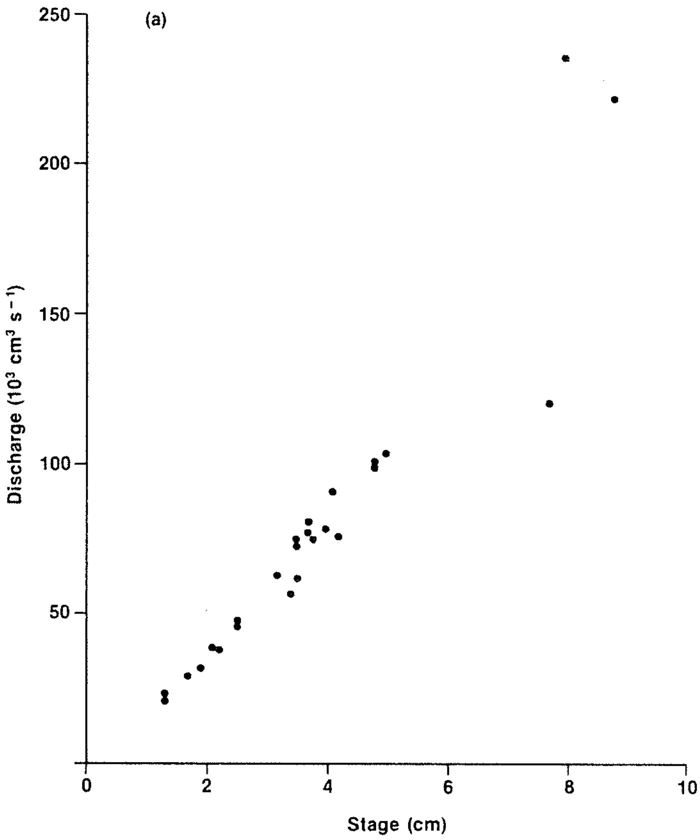


Figure 4 Water table contours in the Wanneroo area (adapted from Havel 1975).



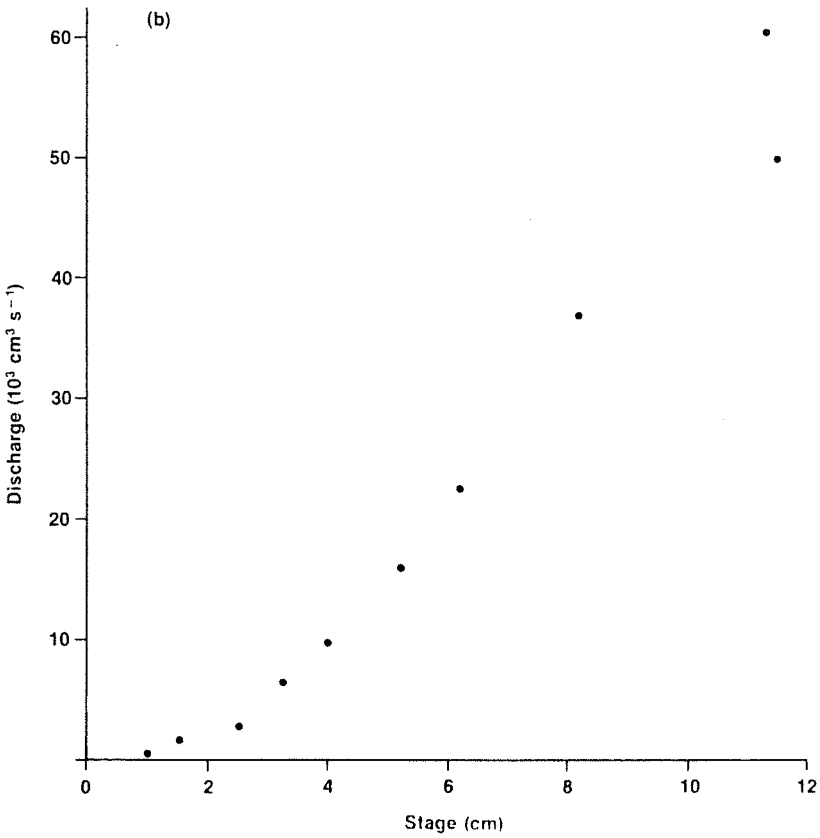


Figure 5 Discharge measurements for site 46 — the culvert under the Mullaloo Drive causeway, (a) gives readings for the north end of the culvert (30.6.1980 to 22.9.1980) and (b) for the south end (23.10.1980 to 24.11.1980).

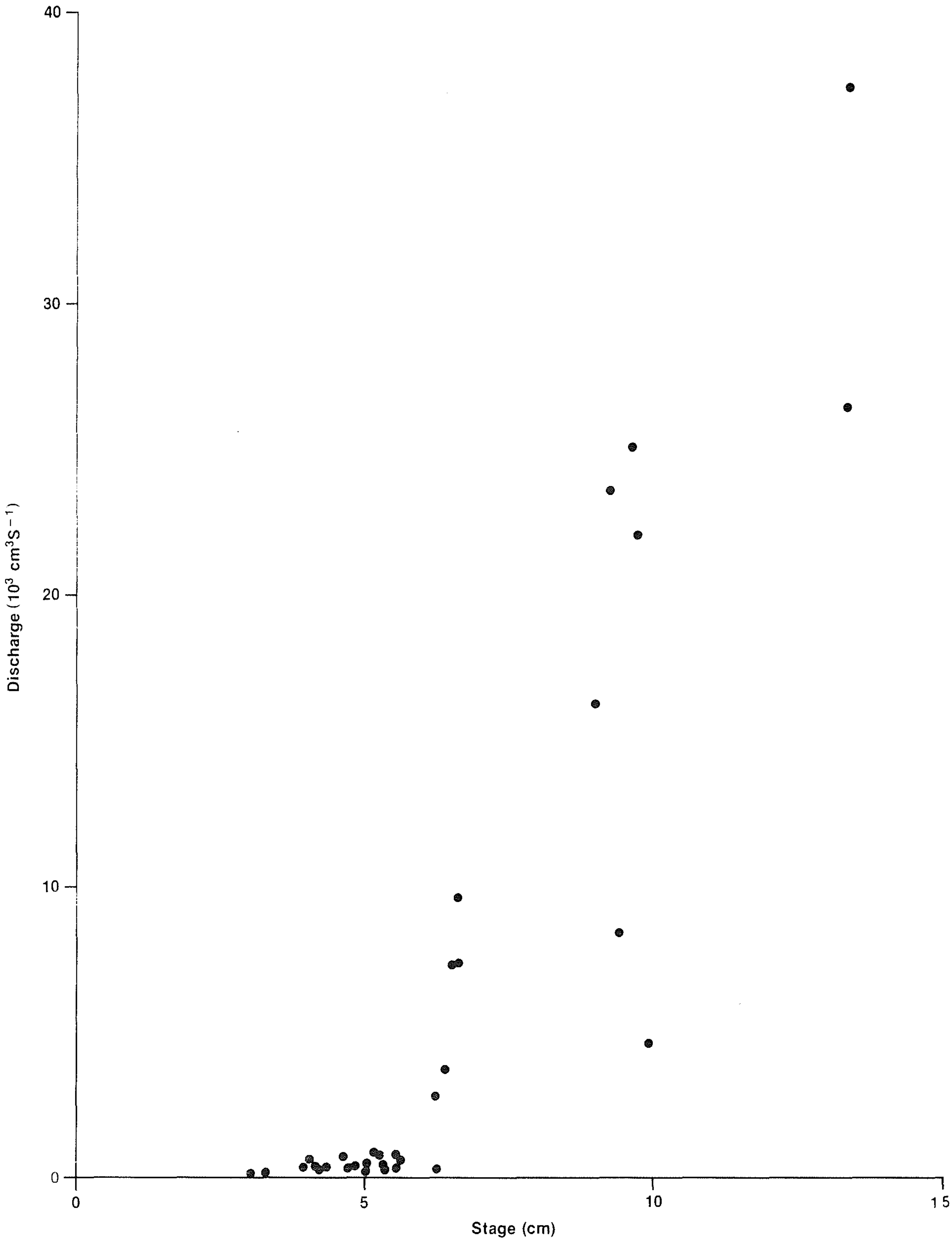


Figure 6. Discharge measurements for site 36, the stormwater sump on the eastern shore of Lake Joondalup.

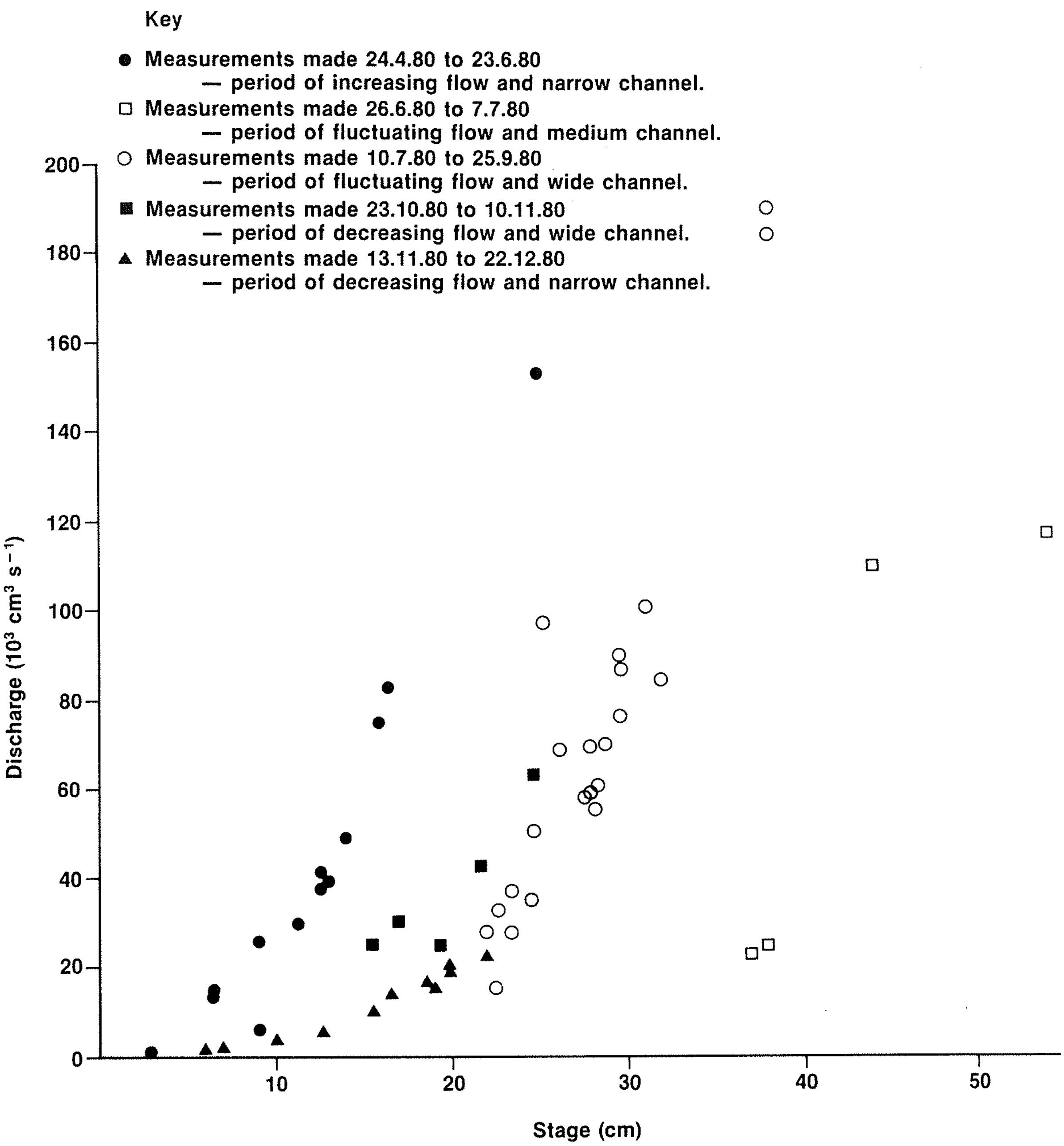


Figure 7 Discharge measurements for site 57, in the channel between Beenyup Swamp and the southern basin of Lake Joondalup.

2.6 Chloride and the Major Metallic Cations as Tracers of Water Movement

2.6.1 Spatial and Temporal Changes in Concentration

Biologically-conservative elements can be used to trace the flow of water (Allison and Hughes 1978; Allison and Leaney 1980), and chloride in particular has been used to check water budgets by the mass-balance method (e.g. Balleau 1973; Allen 1980).

Chloride was determined routinely to (i) compare with biologically-active elements in this study, (ii) use as an indicator of water volume (the concentration of chloride increases as lake volume decreases), (iii) indicate water origin, and (iv) to compute a mass-balance model to compare with the water budget model. On one occasion, June 19 1980, the major metallic cations (sodium, potassium, calcium and magnesium) were determined for 21 sites to see if they indicated different water masses within the lake.

Chloride was determined potentiometrically with a Clinical Chloride Titrator (Model 4-4415, American Instrument Co., Silver Spring, Maryland). Cations were determined by atomic absorption spectrophotometry (Model AA6, Varian Techtron Pty Ltd, Springvale, Victoria), after the addition of caesium and strontium chlorides to minimise ionization interference (Parker 1972).

The distributions of chloride and cation concentrations were mapped using the SYMAP computer mapping technique (Dougenik and Seehan 1977).

2.6.2 Chloride Mass Balance

Computer maps were also used to estimate the amount of chloride in the lake for the mass-balance computation. Chloride loadings, per square metre, were calculated for each site by multiplying the concentration in g m^{-3} by the depth of each site in metres, and mapped. The areas of map in each loading size class were then determined with a digitizer (Model ID-RS232, Summagraphics Corp., Fairfield, Connecticut) and the total amount of chloride in the lake calculated, and corrected for lake area by a factor derived from the hypsographic curve. The concentration of chloride in rainfall from Edgewater was found to be below the sensitivity of the chloride analysis used (<20 mg Cl l^{-1}). Teakle (1937) recorded an average of 16.5 mg Cl l^{-1} for Perth for 1926, while Hingston (1958) found rainfall 16 km from the south-western Australian coast to contain 11.5 mg Cl l^{-1}. Hingston and Gailitis (1976) recorded annual chloride accessions in rainfall at Perth and Floreat, ranging from 10.7 to 13.0 mg l^{-1} over the years 1973 to 1974. Chloride accessions in rainfall at Lake Joondalup were calculated using their mean value of 12.0 mg Cl l^{-1}.

The chloride input to the lake from surface flow was found by multiplying the discharges at sites 36 and 46 by the chloride concentrations, interpolating between sampling times, and then summing the daily inputs to find the total.

The chloride budget for the lake was then determined using the equation:

$$\pm GW_{Cl} = \Delta S_{Cl} - P_{Cl} - SI_{Cl}$$

where —

$\pm GW_{Cl}$ is the mass of chloride contributed by the groundwater,

ΔS_{Cl} is the change in mass of chloride in the lake,

P_{Cl} is the mass of chloride in the precipitation, and

SI_{Cl} is the mass of chloride in the surface inflow,

(Mass was calculated as the product of volume and concentration in all cases).

2.7 The Use of Seepage Meters to Examine Groundwater Seepage

Seepage meters (Lee 1977, Downing and Peterka 1978) were used in an attempt to gain some estimate of the groundwater flux into the lake. One meter was installed at site 15 on the western shore of the lake during August 1979 (Fig. 2), where it could be visited by boat at fortnightly intervals. Another was installed at site 54 in the southern-most basin in August 1980. This site has a coarse sandy bottom and ground-water contours suggest that significant seepage could occur in this area.

Several problems were encountered with the use of the seepage meters. Few samples were taken during summer and autumn since the shallowness of the lake and the softness of the lake bed precluded sampling at these times. Rapid increases in depth during winter and spring made it difficult to retrieve some samples and occasionally the plastic bag became detached and lost between sampling periods. At one sampling location (site 54) the coarse sandy sediment made it difficult to push the seepage meter into place, and by the time the meter had been left to equilibrate, few samples could be taken as the water level fell rapidly and exposed much of the meter. Sampling was impractical in the area of site 37, where seepage seems to be very significant in late summer. At this time beds of algal material accumulate at this site making it difficult to install a conventional seepage meter because of the deep, soft bed of decomposing material, and also making it difficult to gain access to the water in the vicinity.

3. RESULTS AND DISCUSSION

3.1 Changes in Lake Water-level and Lake Volume

The water levels in the lake during 1979/1980 showed a regular pattern of low levels in April-May and high levels in September-October (Fig. 8). The minimum water level recorded in 1980 was the lowest for at least 12 years, showing the cumulative effect of previous dry years depleting the water-table (Fig. 9). Except for 1978 and 1980, Perth's annual rainfall was well below average for all years since 1974. Previous low minimum water levels were recorded in the summers following the dry years 1969, 1972 and 1977.

The maximum water levels recorded for 1979 and 1980 were similar to that of 1977, these three years having the lowest maximum water levels for the twelve years since records commenced in 1968, being some 75 cm lower than the highest recorded water level, in 1970 (Fig. 9).

Lake water levels have probably been much lower, or at least more erratic, in the past as indicated by the presence of submerged fence posts in the southern end of the lake and on the western side of Malap Island, and by the greater extent of swamp vegetation near the Mullaloo Drive causeway as shown in aerial photographs taken in October 1963 and December 1953. Also there is no apparent

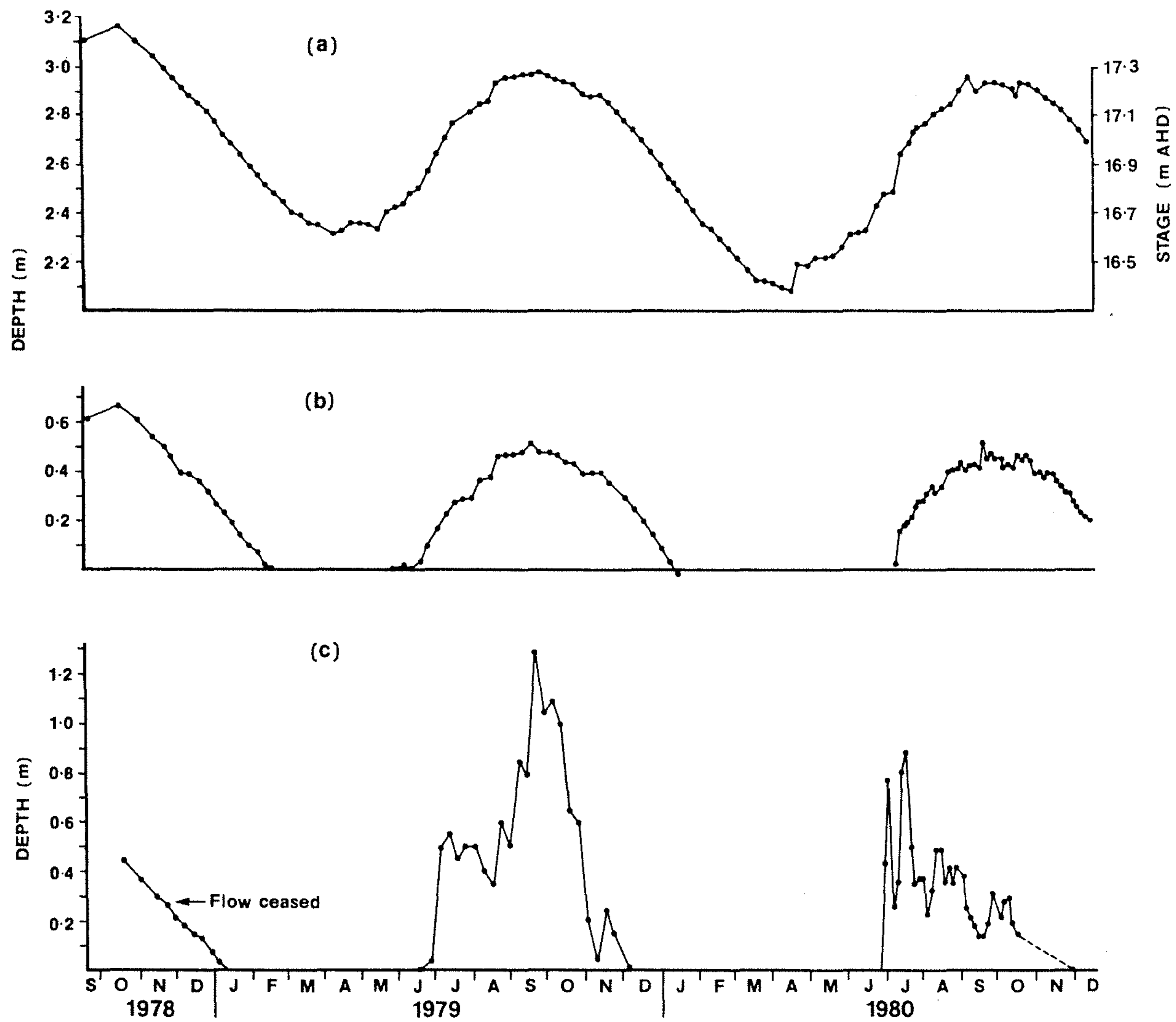


Figure 8 Water levels at (a) site 19, in the main water body of Lake Joondalup, (b) site 45 in the south of the main waterbody and (c) site 46, the culvert under Mullaloo Drive.

open water in Beenyup Swamp in the 1963 photograph, after a winter of high rainfall. It is interesting to note that the patches of swamp vegetation in the central portion of the lake do not appear to have changed noticeably since 1953 as evidenced from photographs.

The clearing of native vegetation allows the water-table to rise, through decreased evapotranspiration and interception, and with the construction of shedding surfaces such as roads and roof-tops, which concentrate rainfall. Consequently clearing and urbanization can result in increased water levels in local lakes (Evans and Sherlock 1950). Over the last 20 years the water level in Star Swamp, North Beach, has risen 1 m due to these two factors (Burton 1976). The addition of imported MWB water from septic tanks and irrigation can also raise the water-table (McFarlane 1981).

Water level changes at site 45 showed some small fluctuations which were not apparent at site 19 (Fig. 8). These may be due to effects of wind over the lake and observer problems in taking an accurate reading at site 19 when the water surface was disturbed by waves.

Rapidly increasing water levels in the lake during July coincided with the increase in depth of water in the Mullaloo Drive culvert (Fig. 8). However, the increasing lake level is not due completely to flow from the south, but also to direct rainfall, runoff and gradually increasing groundwater seepage.

The water level in the sump at the end of Ariti Avenue (site 36) was measured from May 22, 1980 (Fig. 10). It fell by 35 cm between July 10-17 when the channel draining the sump into the lake was cleared of earth and vegetation. The water level remained relatively constant except for short-term increases of 5 to 10 cm which occurred when rainfall recorded at Edgewater exceeded 10 mm (Fig. 12b). This close correlation between water level and rainfall shows the rapid drainage of stormwater from rain events into the sump and lake (for rainfall vs water level at site 36, $r = 0.602$, $n = 45$, $P < 0.001$).

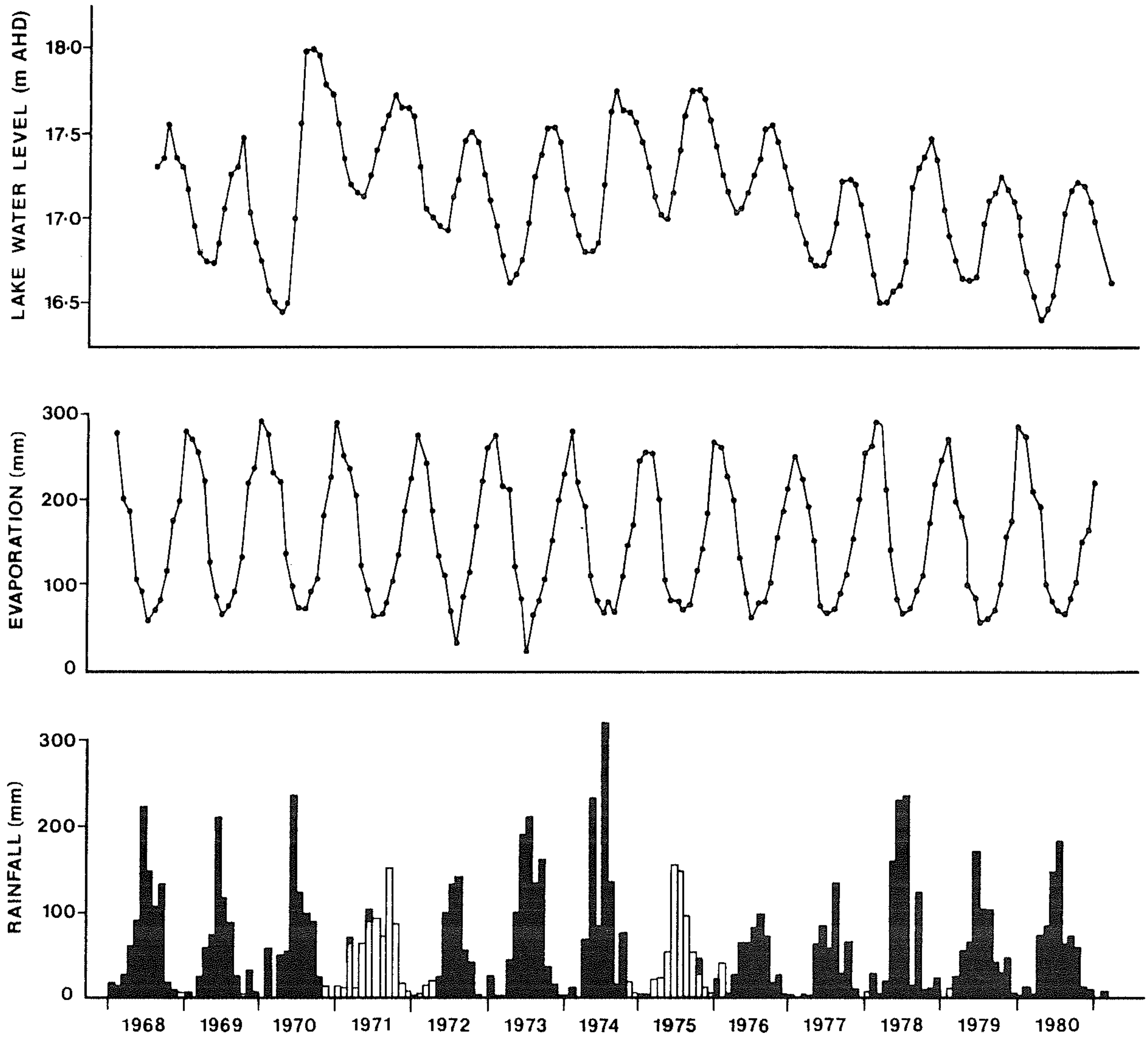


Figure 9 Lake Joondalup water levels, evaporation at Perth and rainfall at Wanneroo.

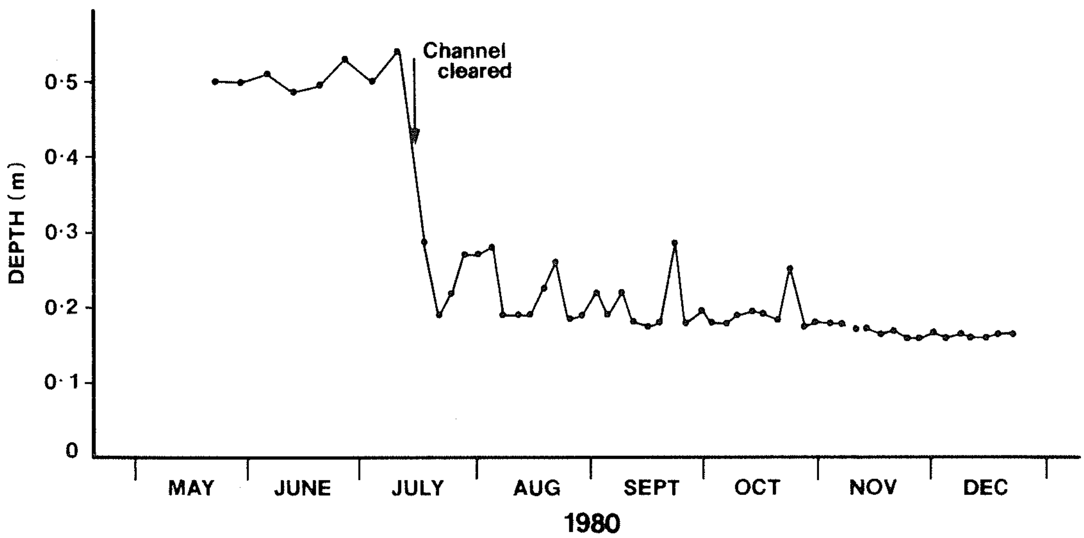


Figure 10 Water level at site 36, the stormwater sump on the eastern shore of Lake Joondalup.

Changes in water level at site 59 in Beenyup Swamp, at site 54 in the southern basin of Lake Joondalup (Fig. 11) and at site 57, in the channel between the two (Fig. 12) are very close, showing the direct water continuity between the three sites (for the water level of Beenyup Swamp vs that at site 57, $r = 0.520$, $n = 66$, $P < 0.001$; for site 57 vs site 54, $r = 0.986$, $n = 52$, $P < 0.001$).

Beenyup Swamp dried out completely during April 1980, exposing a black peaty bottom. The swamp filled very rapidly from April 24, the water level increasing 45 cm in two weeks. This increase in water level was earlier, and greater, than that in Lake Joondalup (Fig. 8). The fall in water level began in late October, at the same time as in Lake Joondalup, and fell at a similar rate (29 cm at Beenyup Swamp compared to 24 cm in the lake over 56 days).

The water level at site 54 showed a dramatic increase of 2.3 m over 7 weeks, from May 8 to June 26 1980, as the southern basin of Lake Joondalup filled with water (Fig. 11b). After reaching its peak on June 26, flow through the culvert under Mullaloo Drive began and the level thereafter fluctuated in sympathy with the water level of Beenyup Swamp and site 57. The surface water flow from Beenyup Swamp is therefore very important in maintaining the water level of the southern basin of Lake Joondalup, and ultimately of Lake Joondalup itself.

Water level changes at site 57 were monitored from June 1979 (Fig. 12) and surface water was always present. From December to May the water level did not fluctuate more than 5 cm, and there was no surface flow from Beenyup Swamp, so this level is maintained by groundwater seepage. This is supported by analyses of chloride concentration. On February 14, 1980, samples taken near Beenyup Swamp (sites 58 and 59) contained 220 to 425 mg Cl l^{-1}, samples from sites 57 and 56 contained 108 mg Cl l^{-1} and samples from the southern basin of Lake Joondalup contained 320 to 344 mg Cl l^{-1}. The water level at site 57 did not increase greatly until late May, when surface flow began. Subsequently the water level fluctuated in phase with the water level of Beenyup Swamp. Peaks in water level generally occurred 3 to 4 days after peaks in rainfall of more than 30 mm (Fig. 12).

Lake volume decreased from October 1979 to May 1980 and then increased until October 1980 (Fig. 8). Based on the direct volume curve this decrease represents a fall in volume of 45%, and represents an exposure of 25% of the lake bed. This exposure can affect the growth of benthic vegetation. The increase in volume from May 1980 to October 1980 was the fourth largest since 1970 (Fig. 9 and Table 2), despite the lowest minimum volume, since records commenced in 1968, being recorded in April 1980. This suggests the possibility of a high input of groundwater at low lake levels, and the recovery of the watertable following a higher rainfall in 1980 compared with 1979.

3.2 Rainfall and Evaporation

The rainfall and evaporation recorded at Edgewater during the study are shown in Fig. 13, together with the monthly changes in the water level of the lake. Rainfall and evaporation are inversely related ($r = -0.826$, $P<0.001$), while both show a relation with the change in water level that is displaced in time. Lake water level peaked some 10 weeks after rainfall due to continuing runoff and baseflow. The lowest level was recorded some 14 weeks after the peak evaporation reading was obtained, just before rainfall became significant enough to raise the water-table.

The total rainfall recorded at Edgewater for 1980 was 830 mm, compared with Bureau of Meteorology readings of 709 mm for Wanneroo and 844 mm for Perth. The Edgewater rainfall shows a very close correlation with the records for Wanneroo ($r = 0.96$, $P<0.001$) and Perth ($r = 0.96$, $P<0.001$) on a four-weekly basis (Table 3). Paired t-tests show that there are no significant differences ($P<0.05$) between any of the three sets of rainfall data. The lowest probability that any two records are significantly different is 0.062 for Edgewater and Wanneroo data. The 1980 rainfall was a little below average but much higher than that for 1979 (Fig. 9).

The total evaporation recorded at Edgewater for 1980 was 1705 mm which was very close to the reading for Perth of 1702 mm, which was slightly lower than the Perth average of 1713 mm. The evaporation readings for Edgewater and Perth show a very close correlation on a four-weekly basis ($r = 0.98$, $P<0.001$, Table 3). A paired t-test shows that there is no significant difference between the two sets of data ($P = 0.415$).

The close relationship between the two sites for rainfall and evaporation indicates that Perth data may be used with some confidence for examining the approximate water balance of the lake for times when data from a site near the lake are not available.

Lake evaporation was estimated with two different sets of pan factors (Table 1). Monthly pan factors can vary significantly and thus be unreliable for estimating monthly lake evaporation, but most of this variation is due to heat storage and advection in deep lakes (Hounam 1973). The pan factors of Hoy and Stephens (1979) were determined for Mundaring Reservoir, a deep, artificial, freshwater lake located in the Darling Scarp some 40 km from the ocean. Pan factors have also been calculated

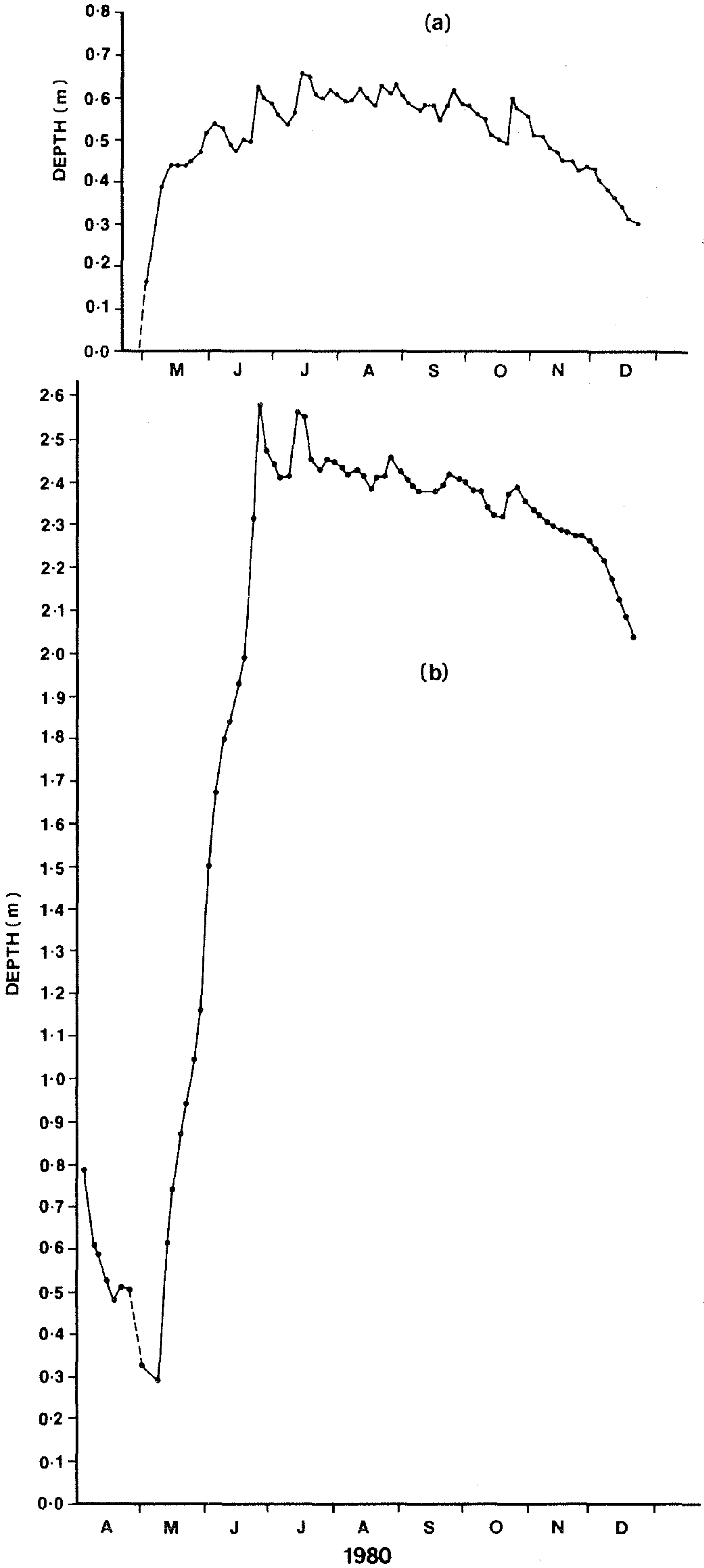


Figure 11 Water levels at (a) site 59 in Beenyup Swamp, and (b) site 54 in the southern basin of Lake Joondalup.

for Peel Inlet, a shallow estuary situated some 5 km from the ocean (Black and Rosher 1980). Although Peel Inlet is seasonally saline, Lake Joondalup has a high total dissolved salts content compared to Mundaring Reservoir, and Walker (1973) has found that saline water (up to 56 °/oo salinity) evaporation was only about 8% less than evaporation from fresh water. Since Lake Joondalup is shallow and lies 5 km from the ocean, Black and Rosher's pan factors are most appropriately applied for the lake. Also since heat storage and advection are not liable to be as significant in the lake, monthly pan factors can be applied more reliably than to the much deeper lakes generally considered in the literature. It is encouraging to note that the monthly pan factors obtained by Black & Rosher (1980) are substantiated by Cheng (1978) who studied a comparable waterbody (Lake Albert in South Australia) using more extensive and complex continuous recording instrumentation.

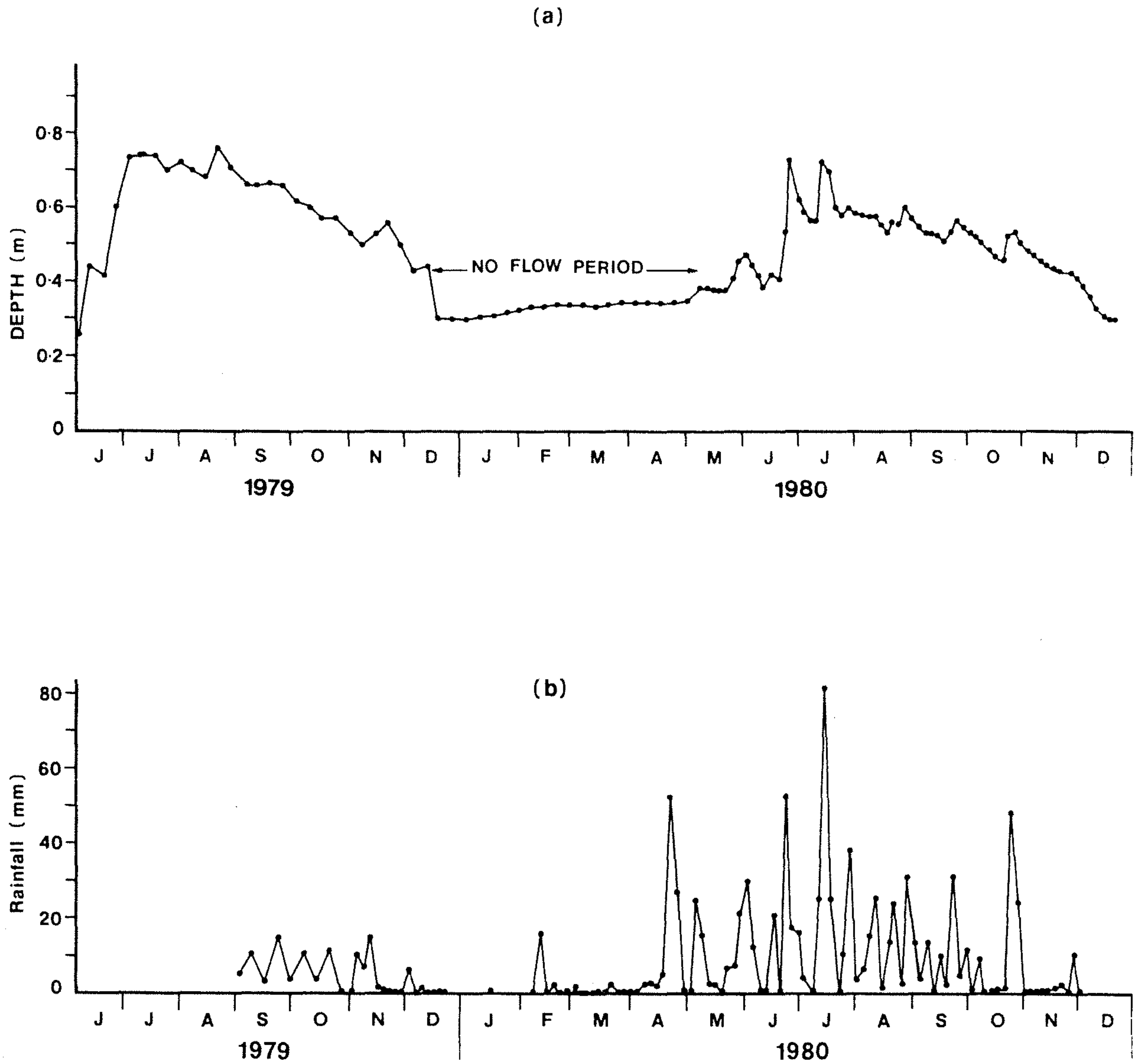


Figure 12 (a) Water level at site 57, in the channel between Beenyup Swamp and the southern basin of Lake Joondalup, and (b) rainfall recorded at Edgewater between sampling days.

Table 2: Changes in volume of Lake Joondalup from 1968 to 1980.

Year	Perth rainfall (mm)	Maximum water level (m AHD)	Maximum volume ($m^3 \times 10^6$)	Minimum water level (m AHD)	Minimum volume ($m^3 \times 10^6$)	ΔS ($m^3 \times 10^6$)	Month of maximum	Month of minimum
1968	930	17.55	6.596	—	—	—	Sept.	—
1969	574	17.47	6.223	16.73	2.969	3.254	Sept.	April
1970	908	17.98	8.825[1]	16.46	1.948[1]	6.877	Aug.	March
1971	799	17.72	7.460[1]	17.13	4.675	2.785	Sept.	April
1972	611	17.50	6.362	16.93	3.803	2.559	Sept.	May
1973	973	17.53	6.502	16.62	2.535	3.967	Oct.	March
1974	939	17.74	7.565[1]	16.78	3.173	4.392	Aug.	March
1975	682	17.76	7.670[1]	16.99	4.060	3.610	Sept.	April
1976	711	17.55	6.596	17.03	4.234	2.362	Sept.	March
1977	608	17.23	5.123	16.72	2.928	2.195	Sept.	April
1978	924	17.47	6.223	16.51	2.123	4.100	Oct.	Feb.
1979	560	17.26	5.258	16.63	2.574	2.684	Sept.	April
1980	844	17.22	5.077	16.38	1.682	3.395	Sept.	April
Mean Volume			6.575 ($\pm$0.304)[2]		3.059 ($\pm$0.277)	3.515 ($\pm$0.368)	Mode Sept.	Mode April

[1]For years when the maximum water level exceeded 17.60 m AHD (the depth at the time when the bathymetric map was prepared, and on which the direct volume curve is based), volume was estimated by adding the volume at 17.60 m AHD to the volume given by the depth of water above 17.60 m AHD multiplied by the maximum lake area ($5.25 \times 10^6 m^2$).

[2]Standard error of the mean given in parentheses.

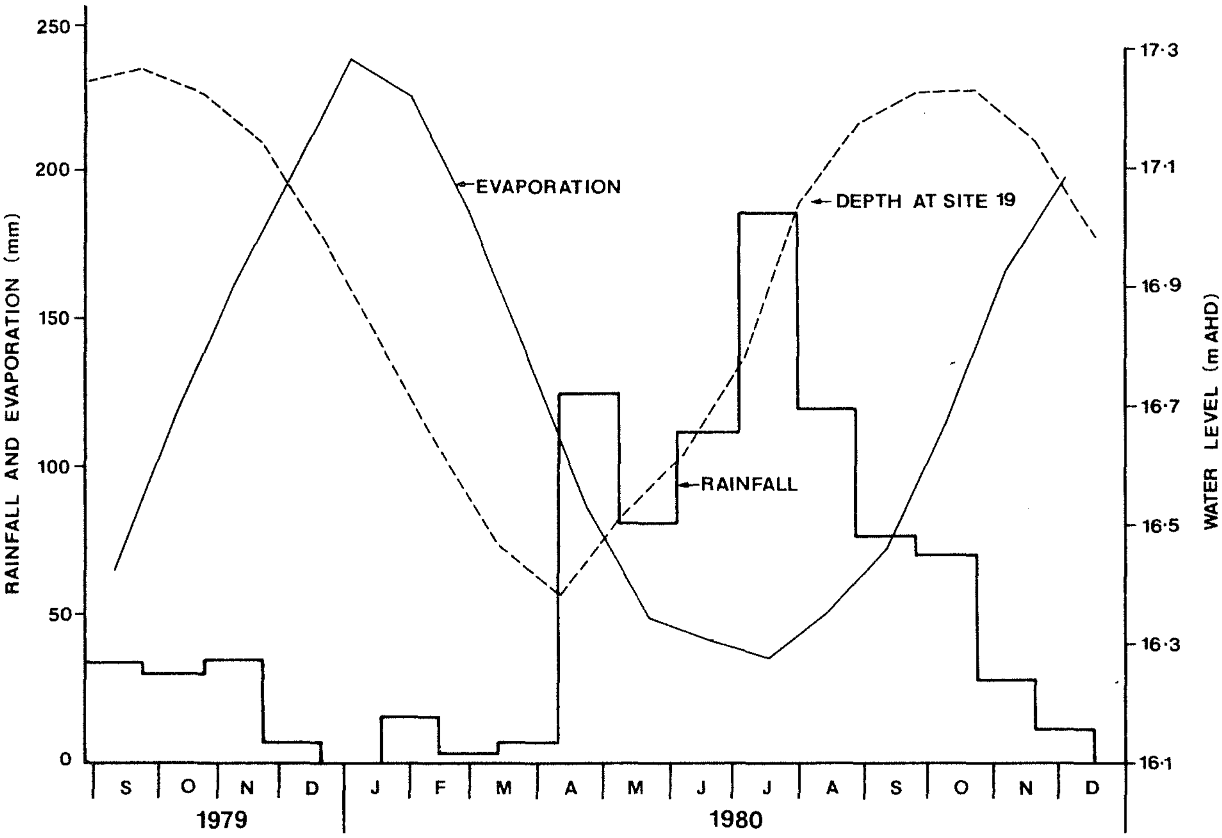


Figure 13 Lake water level, evaporation and rainfall for each 28 day period of the hydrological study.

Table 3: Comparison of meteorological data collected at Edgewater with that supplied by the Bureau of Meteorology for Wanneroo and Perth.

28 Day Period			Rainfall (mm)			Pan evaporation (mm) (with birdguard)	
			Edgewater	Wanneroo	Perth	Edgewater	Perth
29.8.79	—	26.9.79	33.9	39.0	44.6	79.8	93.6
26.9.79	—	24.10.79	29.8	28.0	29.0	123.7	121.5
24.10.79	—	22.11.79	34.7	44.8	27.0	171.7	170.2
22.11.79	—	20.12.79	7.0	4.0	2.8	212.3	233.4
20.12.79	—	17.1.80	0.2	0.8	0.0	253.5	251.0
17.1.80	—	14.2.80	15.8	12.0	16.2	240.5	236.8
14.2.80	—	13.3.80	3.3	1.0	3.4	198.5	184.8
13.3.80	—	10.4.80	6.7	5.6	3.8	146.6	142.0
10.4.80	—	8.5.80	124.2	93.8	102.4	91.1	84.4
8.5.80	—	5.6.80	80.3	84.4	127.0	52.4	68.3
5.6.80	—	3.7.80	111.2	111.6	131.0	44.5	59.4
3.7.80	—	31.7.80	184.3	178.0	180.2	38.1	62.0
31.7.80	—	28.8.80	118.8	65.8	124.0	53.6	73.6
28.8.80	—	25.9.80	76.4	61.0	61.4	77.4	93.6
25.9.80	—	23.10.80	69.9	59.6	57.6	120.9	120.6
23.10.80	—	20.11.80	27.8	10.0	9.8	176.7	145.1
20.11.80	—	18.12.80	11.5	10.6	13.6	210.3	202.5

3.2.1 The Effect of Transpiration on the Evaporation Estimate

Early studies suggested that evapotranspiration exceeds evaporation in swamp vegetation. Clayton (1949, cited in Shih 1980) found an evapotranspiration: pan coefficient of 1.2 for sawgrass (*Cladium jamaicense*) based on seven years data. Shih developed a model to include marsh zone evapotranspiration in a water budget for a large shallow lake in Florida using Clayton's figure. He found that over a year the inclusion of the evapotranspiration estimate gave a difference of only some 2% in the surface water storage of the lake.

However, evapotranspiration from Ugandan papyrus swamp is about 60% of evaporation from the open water (Gaudet 1979), whilst studies of four helophytes, including two *Typha* species, in Poland gave transpiration coefficients (water used for production of above-ground dry weight) varying from 11 to 66% (Bernatowicz *et al.* 1976). In calculating evaporation losses from four lakes, Bernatowicz *et al.* used coefficients of 0.97 to 1.27 to correct transpiration, depending on the proportion of each helophyte species present.

Linacre *et al.* (1970) did a short study of evaporation from a *Typha orientalis* swamp in New South Wales. They found that during dry periods the *Typha* swamp lost less water than an open water surface, whilst following heavy rainfall evaporation and evapotranspiration losses were similar.

Swamp vegetation, principally containing *Baumea articulata, Typha orientalis* and *Melaleuca rhaphiophylla* covers about 84 ha of Lake Joondalup which is about 16% of the lake surface — not including the terrestrial vegetation on the islands. During dry periods the low water level means that some exposed areas carry swamp vegetation which is transpiring. Such transpiration has not been corrected for, but would probably be quite small in view of the area involved. The summer-autumn evaporation may also be underestimated somewhat because evaporation from exposed sediment was also not included. For example, evaporation from a water-table at 1 m depth may be 50% of the evaporation from the surface (Pollett *et al.* 1979).

3.3 Surface Water Inflow

The discharge-rating curves for sites 36, 46 and 57 all gave very significant correlations between discharge and depth ($P < 0.001$) (Figs. 5 to 7). Discharge and depth were least well-correlated for site 36 where the channel cross-section varied most and flows were generally low, although the linear correlation was still highly significant and correlation coefficient high ($r = 0.833$, $n = 37$, $P < 0.001$).

In general, depth and discharge were least well-correlated at high discharge levels and this may have introduced some error into the discharge estimates, although these high discharges were least frequent.

At site 57 the best correlations between depth and discharge were obtained for extended periods of increasing or decreasing depth (Fig. 7), and so it was useful to treat site 57 data in segments. This probably reflects the greater accuracy of measurement at low flow when a smaller cross-section was used, and the better correlation of depth and discharge at low discharge levels. The concrete pipe which crosses the channel to the south of this site probably also acts as a reservoir at high water levels which may affect the depth-discharge relationship through a hysteresis effect. Since water flows under this pipe, at low water levels, discharge is direct, but as the water level increases the pipe increasingly influences discharge.

Significant flow did not commence until May 1980 at site 57 and it fell considerably in December. Highest discharges were recorded in July (Fig. 14c), when rainfall was greatest (Fig. 13). Discharge varied with rainfall (discharge vs rainfall at site 57 from May 15, 1980 to December 22, 1980: $r = 0.789$, $n = 64$, $P < 0.001$). The response of discharge to rainfall was very rapid; on occasions it increased more than 300% within 3 to 4 days (i.e. between sampling occasions), and fell more than 100% within the same period. If more accurate information were needed in future, continuous records would be needed.

Discharge through the culvert under Mullaloo Drive (site 46) commenced late in June (Fig. 14a), when the water level in the southern section of the lake reached the level of the culvert (Fig. 11b) and changes in discharge reflected changes in discharge at site 57. 81% of water flowing from Beenyup Swamp passed under Mullaloo Drive (Table 4). Discharge through the culvert ceased in November, 1980.

Discharge at site 36 fluctuated more rapidly than at site 57, increasing as much as 69-fold and decreasing as much as 90- fold within 3 to 4 days. This indicates that the catchment for site 36 drains very quickly after a rainfall event, and this is expected since the stormwater sump's catchment includes road surfaces (for discharge at site 36 vs rainfall recorded on that sampling day: $r = 0.477$, $n = 48$, $P < 0.001$).

Table 4: Discharges at sites 57, 46, and 36 for each 28-day sampling period.

Period			Discharge (m^3)					
			Site 57	n[1]	Site 46	n	Site 36	n
20.12.79	—	17.1.80	0		0		0	
17.1.80	—	14.2.80	0		0		0	
14.2.80	—	13.3.80	0		0		0	
13.3.80	—	10.4.80	0		0		0	
10.4.80	—	8.5.80	3,890	2	0		0	
8.5.80	—	5.6.80	70,970	8	0		0	
5.6.80	—	3.7.80	177,240	8	44,220	2	10.050	2
3.7.80	—	31.7.80	224,130	8	279,960	8	36,370	5
31.7.80	—	28.8.80	158,850	8	179,470	8	17,020	8
28.8.80	—	25.9.80	113,320	8	106,910	8	11,900	8
25.9.80	—	23.10.80	107,160	1[2]	124,620	1[2]	21,860	1[2]
23.10.80	—	20.11.80	98,840	8	56,890	8	6,420	6[2]
20.11.80	—	18.12.80	24,580	8	510	8	780	8
		Total	978,980		792,580 88.4%		104,400 11.6%	

[1]n = number of occasions on which discharge was measured with the current meter during each 28 day period.

[2]On sampling dates when the current meter was unavailable, flows were interpolated, using the recorded depth at the site and the discharge rating curves.

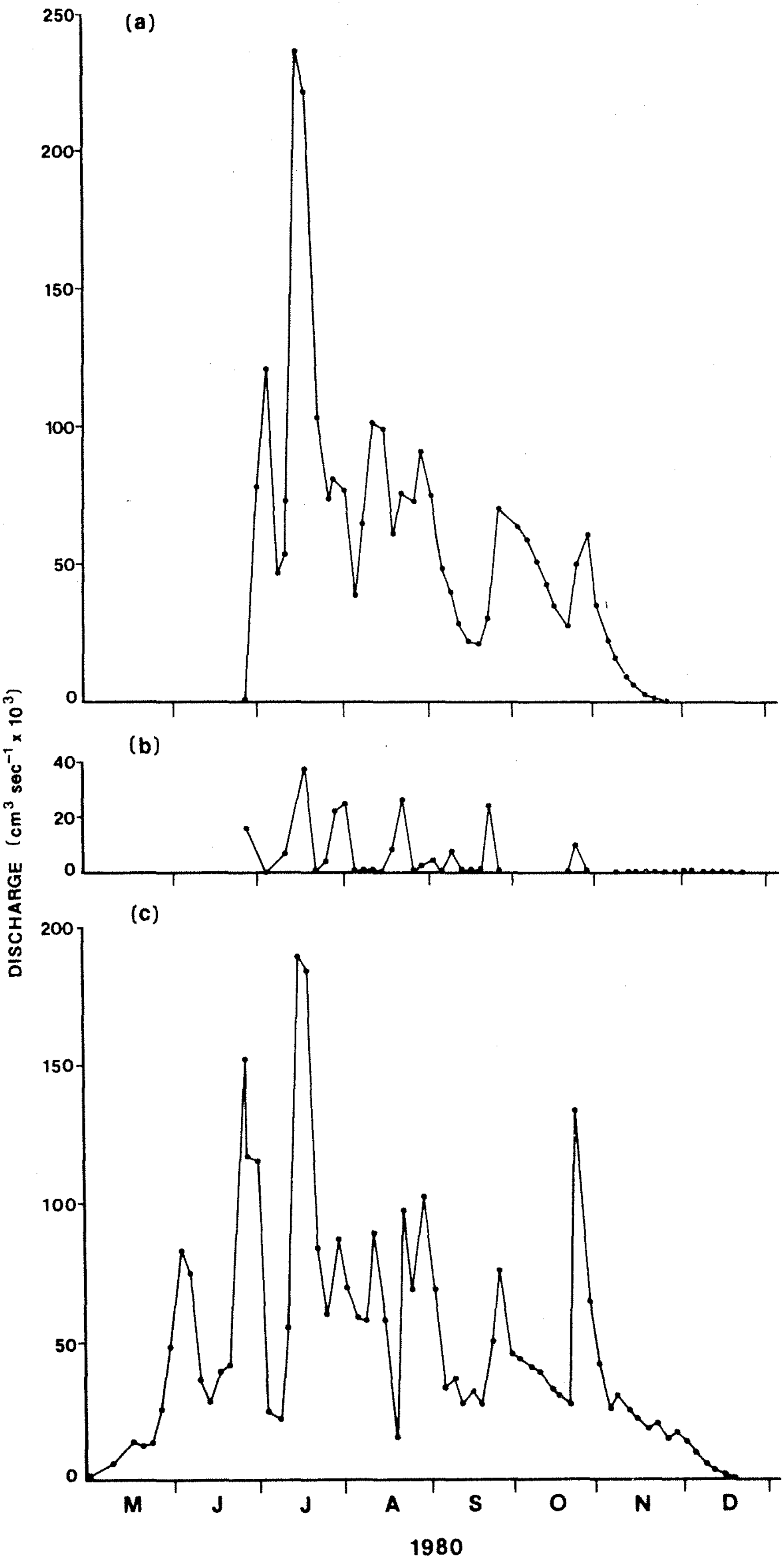


Figure 14 Water discharge recorded for (a) site 46, the culvert under the Mullaloo Drive causeway, (b) site 36, the stormwater sump on the lake's eastern shore, and (c) site 57, the channel between Beenyup Swamp and the southern basin of Lake Joondalup.

The culvert under Mullaloo Drive was the most important source of surface flow, providing 88% of the measured input (Table 4). Discharge at site 36 only accounted for 12% of the volume discharged by surface flow into the lake during 1980.

3.4 The Water Balance for Lake Joondalup

3.4.1 The Seasonal Water Balance (December 1979 to December 1980)

The components of the water balance, calculated for 28-day periods, are given in Table 5. The change in lake volume during the period of detailed monitoring (20 December 1979 to 18 December 1980) was zero.

The lake evaporation calculated using the pan factors of Hoy and Stephens (1979) was significantly higher than that calculated from Black and Rosher's (1980) pan factors — a difference of $1.26 \times 10^6 m^3$. Hoy and Stephen's pan factors are higher for the summer and autumn months and result in a higher estimate of groundwater input (a net exchange of $2.03 \times 10^6 m^3$ compared with $0.72 \times 10^6 m^3$ for Black and Rosher's pan factors) and lower estimate of precipitation input (as a percentage) than Black and Rosher's pan factors.

Direct rainfall contributed $3.37 \times 10^6 m^3$ during 1980 (Fig. 15). Lake evaporation exceeded the input due to rainfall; rainfall was equivalent to 70% of evaporation (using the pan factors of Black and Rosher; 54% by Hoy and Stephens).

The channelized surface inflows contributed $0.90 \times 10^6 m^3$ for 1980, which was only 27% of the input due to rain falling directly on the lake. As noted earlier, 88% of the surface inflow to the main water body of Lake Joondalup came from the culvert under Mullaloo Drive.

Table 5: Water balance for Lake Joondalup (north of Mullaloo Drive) — August 1979 to December 1980 (x $10^6 m^3$)

	Period	Change in lake volume	Precipitation	Evaporation (Black & Rosher)	Surface inflow	Net Groundwater input (Black & Rosher)
	29.8.79-26.9.79	+0.09	0.15	0.32		
	26.9.79-24.10.79	−0.18	0.13	0.45		
	24.10.79-22.11.79	−0.36	0.16	0.61		
	22.11.79-20.12.79	−0.70	0.03	0.65		
	20.12.79-17.1.80	−0.80	0.00	0.70	0.00	−0.10
SUMMER	17.1.80-14.2.80	−0.68	0.06	0.58	0.00	−0.16
	14.2.80-13.3.80	−0.59	0.01	0.47	0.00	−0.13
	13.3.80-10.4.80	−0.27	0.02	0.39	0.00	+0.10
AUTUMN	10.4.80-8.5.80	+0.40	0.42	0.26	0.00	+0.24
	8.5.80-5.6.80	+0.37	0.30	0.19	0.00	+0.26
	5.6.80-3.7.80	+0.64	0.44	0.17	0.05	+0.32
WINTER	3.7.80-31.7.80	+1.15	0.78	0.16	0.32	+0.21
	31.7.80-28.8.80	+0.57	0.52	0.21	0.20	+0.06
	28.8.80-25.9.80	+0.25	0.34	0.28	0.12	+0.07
SPRING	25.9.80-23.10.80	+0.02	0.31	0.44	0.15	0.00
	23.10.80-20.11.80	−0.36	0.12	0.55	0.06	+0.01
	20.11.80-18.12.80	−0.70	0.05	0.64	0.00	−0.11
ANNUAL BALANCE	(20.12.79-18.12.80)	0.00	3.37	5.04	0.90	+0.77

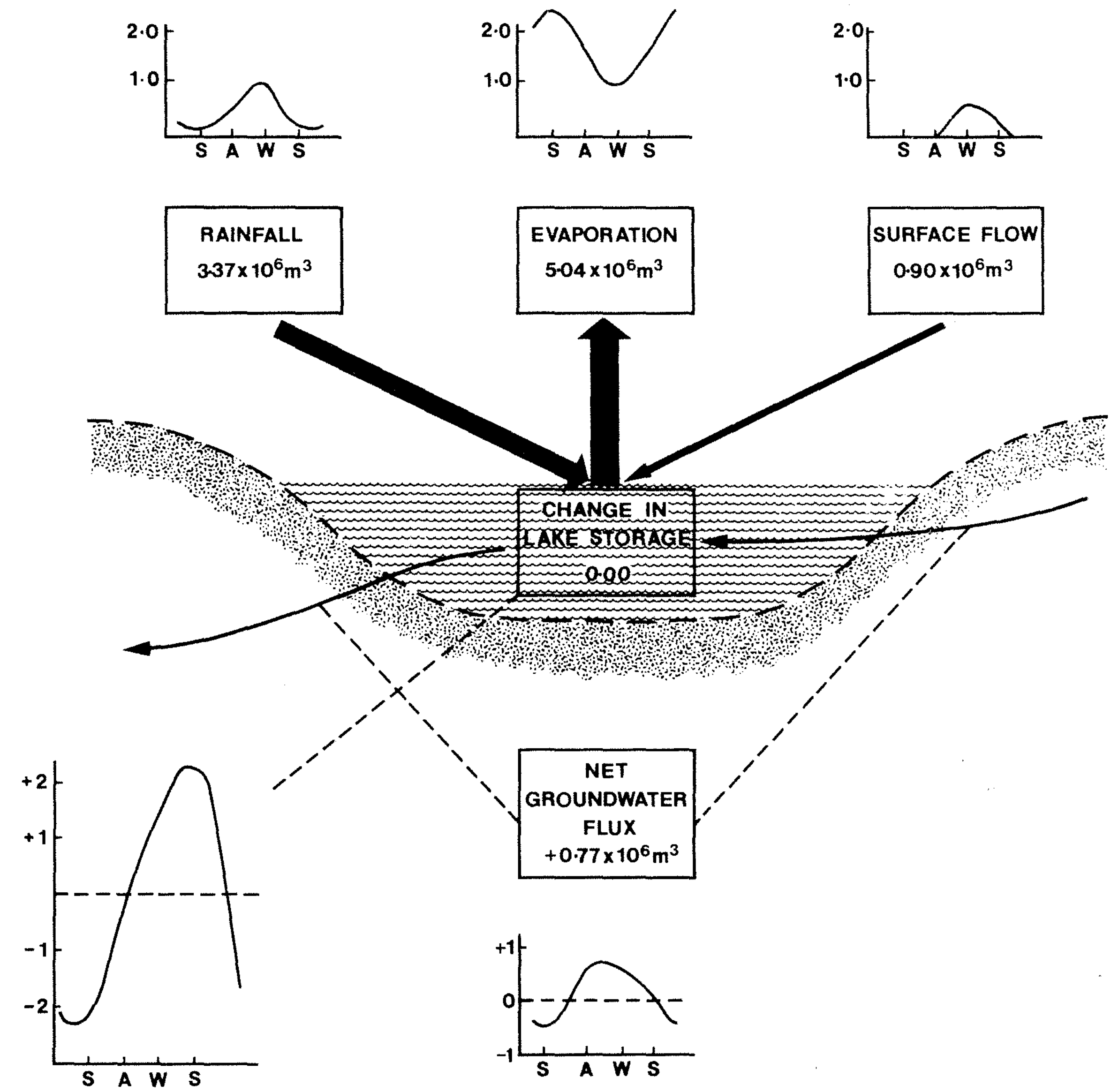


Figure 15 Annual water balance model for Lake Joondalup for the period 20.12.1979 to 18.12.1980.

Calculating groundwater flux as the residual in the water balance indicates a net input of groundwater through 1980. This agrees with Balleau's (1973) findings that there is a net groundwater loss near lakes. Allen (1980) also found a net inflow of groundwater into Lake Jandabup (some 5 km east of Lake Joondalup), where groundwater outflow amounted to only 24% of the groundwater flowing into the lake. A net groundwater outflow from Lake Joondalup was recorded from December to March, whilst net groundwater inflow occurred during the other months.

It is of interest to compare Allen's (1980) data for Lake Jandabup with the results for Lake Joondalup, and this can be done with the following equation:

	$\pm GW$	$= \Delta S$	$- P$	$- S_i$	$+ E$	
Lake Joondalup:						
(Black & Rosher)	0.77	0.00	3.37	0.90	5.04	(x10^{6}m^3)
(Hoy & Stephens)	2.03	0.00	3.37	0.90	6.30	
Lake Jandabup:						
	3.43	0.12	2.04	0.00	5.87	

Allen's (1980) Lake Jandabup study covered the period April 1977 to March 1978. The year of 1977 was particularly dry, only 436 mm being recorded at Wanneroo, so the rainfall was lower and evaporation higher than for the period of the Lake Joondalup study. However, Allen (1980) records a much greater net groundwater input. This may be a real difference caused by seasonal climatic differences and differences in the hydrogeology of the two lakes. It should be noted, however, that there must be some uncertainties with the estimation of groundwater contribution as the residual in a water balance, as the residual includes all those errors in measurement and interpretation of the other hydrologic parameters (Winter 1981).

A conceptual model of the seasonal water balance of Lake Joondalup can now be arrived at. During summer, rainfall and surface water inflow are very low (Fig. 16). Water loss by evaporation is very high and there is a net loss of groundwater to the falling water table. The lake reaches its lowest level in autumn but there is an increase in lake volume towards the end of the season when rainfall begins to become significant. No surface inflow occurs so that groundwater inflow becomes significant as a net input, presumably due to the lake water level falling faster than the groundwater table (Fig. 17). Evaporation still accounts for a large water loss.

The lake water-level increases from May onwards as rainfall increases and the greatest increase in lake volume occurs in winter. There is a net groundwater input as the water table rises due to increased rainfall and decreased evaporation. During spring the lake reaches its maximum volume. Rainfall and surface inflow are still significant inputs but the net input of groundwater declines as rainfall declines and evaporation increases.

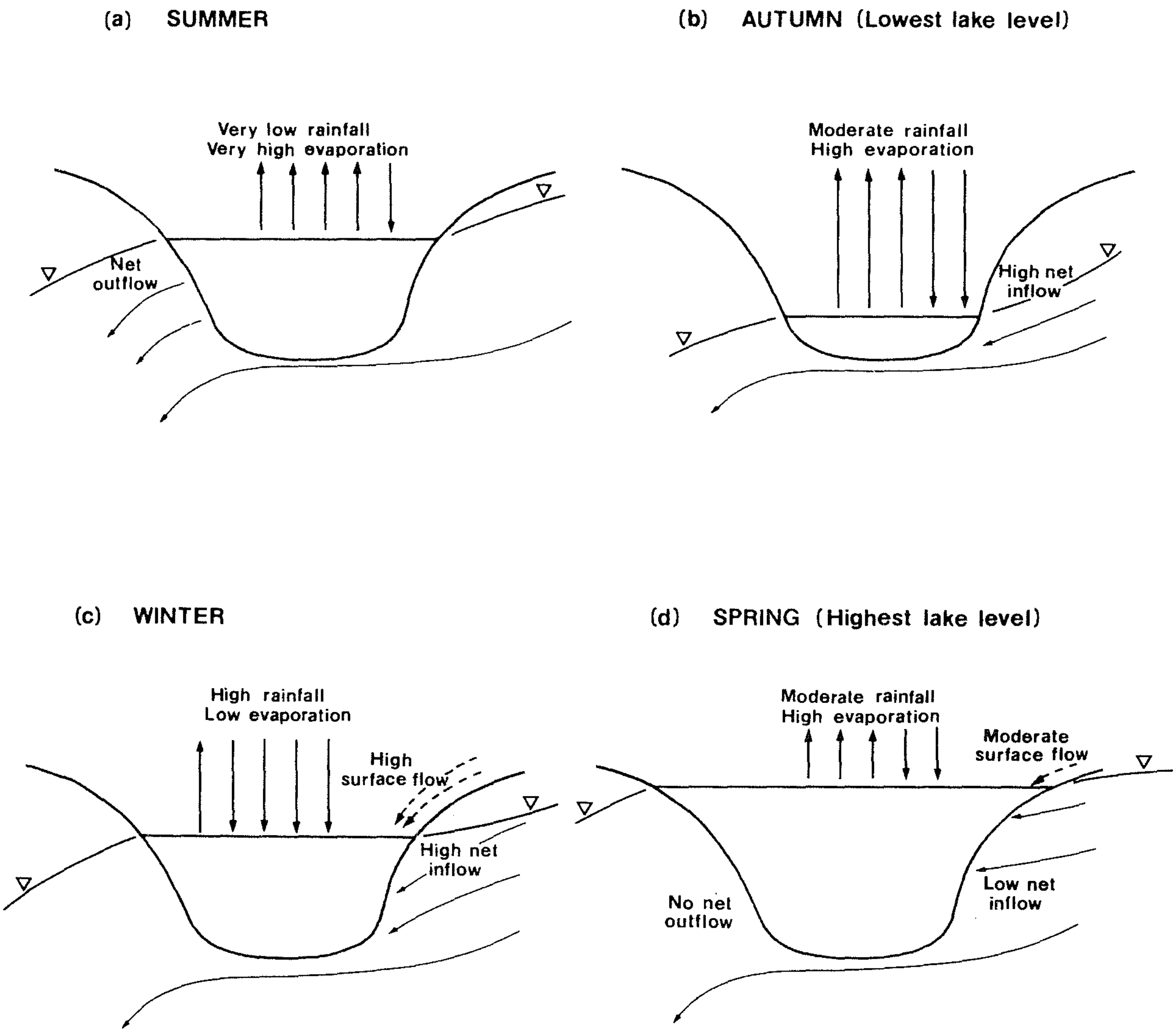


Figure 16 Model of seasonal changes in contributions to the water balance of Lake Joondalup.

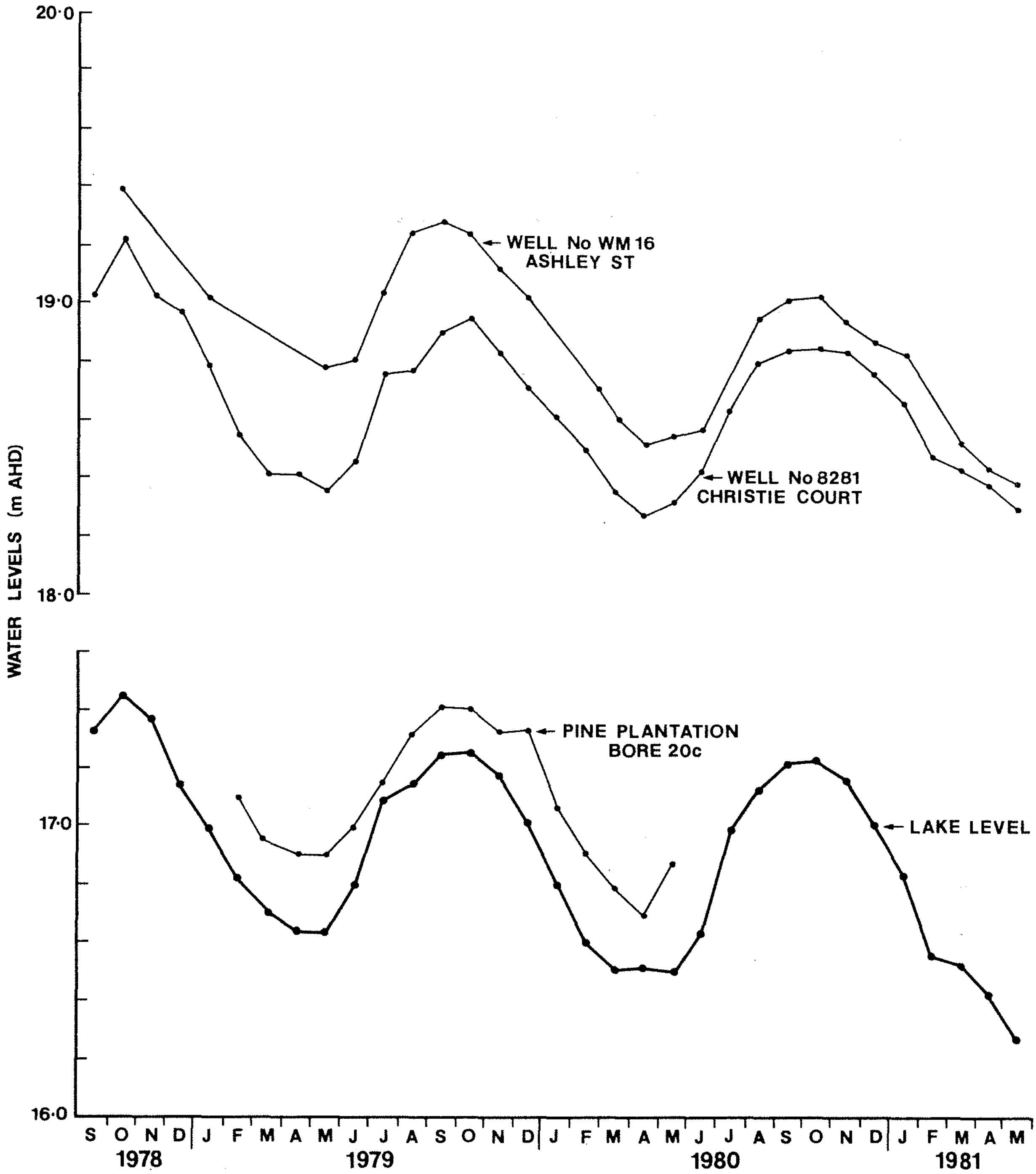


Figure 17 Water levels of Lake Joondalup and three bores located east of the lake.

3.4.2 Annual Water Balances

The annual water balances for Lake Joondalup have been calculated for the years 1969 to 1980, using monthly rainfall and evaporation records for Perth, the pan factors of Black and Rosher (1980), and the volume and hypsographic curves (Fig. 3). Net groundwater exchange and surface water inflow are given by the residual. However, surface flow and net groundwater flux are probably of the same order judging from the year of data obtained here.

Net decreases in lake storage volume occurred in years of below average rainfall, and the highest 'residual' inputs (groundwater plus surface flow) generally occurred after these years (Table 6). The greatest increase in lake storage occurred in 1970, a wet year following a year of below average rainfall (by 34%) and the estimated net residual input was very large ($6.11 \times 10^6 m^3$).

When this budgeting approach was applied to the period from December 1979 to December 1980, the net inflow of 'groundwater' was estimated as $1.86 \times 10^6 m^3$. The detailed water balance considered in the previous section gave an estimated net groundwater input of $0.77 \times 10^6 m^3$, but when the surface water input of 0.90 × $10^6 m^3$ is added to this it approaches the estimate based on the Perth data. The surface water input may therefore be a large proportion of the net 'groundwater' input calculated from the annual budget method.

Table 6: Direction of monthly net groundwater exchange and water balance data for August 1968 to December 1980.

	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	Mode
January		–	+[1]	–	–	+	–[1]	+[1]	–	–[1]	–	+	–	–
February		+	+	+[1]	–[1]	–	+[1]	–	0	0	–	–	–	–
March		+	+	+	+	–	+	+	+[1]	–	+	+	–	+
April		+	+	+	+	+	+	+	+	+	+	+	+	+
May		+	+	+	+	+	–	+	+	–	–	+	+	+
June		+	+	–	+	–[1]	+	+	+	+	–	+	+	+
July		+	+	+	–	+	+	+	+	+	+	+	+	+
August	+	+	+	+	+	+	+	+	+	+	+	+	+	+
September	+	+	–	+	+	+	–	+	+	+	+	+	+	+
October	–	–	–	–	+	+	+	–	–	+[1]	+	+	+	0
November	+	–	+	+	–	+	+	–	–	+	+	+	–	+
December	+	+	+	+	+	–	+	+	+	–[1]	–	–[1]	+	+

	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	$\bar{x}$	s.d.	Coeff of variation
ΔS[2]		-1.89	+3.64	+0.18	–2.24	+0.40	+1.19	–0.14	–1.14	–1.18	+0.65	–0.65	+0.26			
Rainfall input		2.45	4.13	3.79	2.74	4.24	4.25	3.19	3.23	2.17	3.85	2.38	3.44	3.22	0.75	22.6%
Evaporation output		6.54	6.60	6.10	6.02	5.45	5.86	6.26	5.92	5.85	6.08	5.43	5.14	5.94	0.44	7.4%
Groundwater flux		+2.20	+6.11	+2.49	+1.04	+1.61	+2.80	+2.94	+1.55	+2.50	+2.88	+2.40	+1.96	+2.54	1.27	50.0%
Rainfall[3]	930	574	908	788	611	973	939	682	711	608	924	560	844	774	155	20.0%
Evaporation[4]	1817	2056	1986	1771	1938	1735	1761	1827	1764	1831	1968	1728	1702	1837	133	7.2%

[1]Groundwater flux on these occasions was < 0.02 x $10^6 m^3$.

[2]Change in storage, rainfall input, evaporation output and groundwater flux as $10^6 m^3$.

[3]Average annual rainfall for Perth is 875mm.

[4]Average annual pan evaporation for Perth is 1713mm.

The data show that changes in lake storage volume and 'groundwater' input depend to a large degree on previous years' rainfall and lake storage. Net 'groundwater' inflow remains high for the first year of a drought period (e.g. 1975) if the water table is high due to preceding wet years, but gradually falls if the dry years persist. While rainfall additions are very variable, evaporative loss is relatively constant between years. The large variability of rainfall makes it difficult to generalize about the lake's water balance on a quantitative basis. However, it appears that, over a period of average annual rainfall, the net groundwater and surface water input may be about 1.5 × $10^6 m^3$.

During the period August 1968 to December 1980, net monthly groundwater inflow was found on all occasions in April and August (Table 6). Net estimated groundwater outflow, however, was only predominant in January (8 out of the 12 cases) and February (6 years out, 2 years zero). The direction of net monthly groundwater flux is very dependent on monthly rainfall and evaporation. For example, net outflow occurred in July 1972 and June 1973 when the monthly pan evaporation was 3 mm and 2 mm respectively.

3.5 Chloride and the Major Metallic Cations as Tracers of Water Movement

3.5.1 Spatial and Temporal Changes in Concentration

Changes in chloride concentration are inversely related to changes in volume. Sites within the lake showed a rapid increase in chloride concentration during February, with a peak in March/April, followed by a rapid decrease in April and lowest concentrations in July/August/September (Fig. 18). Sites 19 and 34 showed similar trends. Minimum concentrations in winter were similar for 1979 and 1980 (250 — 400 mg Cl l^{-1}), whilst maximum concentrations achieved in autumn were much higher in 1980 (1600 — 1750 mg l^{-1}) than in 1979 (1050 mg l^{-1}), reflecting the lower water level in the lake in 1980.

Sites in the southern basin of the lake had a smaller mean (and range) of chloride concentrations indicating a supply of fresher water from the south. As indicated earlier, the surface flow reflects the groundwater contours in the Beenyup- Wallubuenup Swamp area. Concentrations at site 57 varied from 75 mg l^{-1} in March and April 1980 to 325 mg l^{-1} in May 1980 (Fig. 19a). The lowest concentrations occurred when there was no surface flow from Beenyup Swamp and when concentrations were highest in the lake, indicating a fresh groundwater input. The large increase in concentration during May occurred when surface flow from Beenyup Swamp resumed (Fig. 11a), and the concentration decreased through June to levels similar to those found when there was no flow. This suggests that salts are flushed from the Beenyup-Wallubuenup area by fresh water during May/June. This fresher water may be from both run-off and rain falling directly onto the swamps, and increased groundwater flow as the water-table rises with recharge from rainfall.

Site 47 reflected the changes at sites 34 and 19 although chloride concentrations were lower due to the input of fresh water from the south (Fig. 19b). Concentrations varied from 80 to 150 mg Cl l^{-1} between July and September to 800 mg l^{-1} (at site 54) when the southern basin of the lake was drying out in April.

Chloride concentrations at site 46, the culvert under Mullaloo Drive, also followed the trends shown at sites 19 and 34 (Fig. 19c). Lowest concentrations (80 — 150 mg Cl l^{-1}) occurred soon after water began flowing through the culvert from the south.

Site 37 is located on the eastern shore of the lake where there is some evidence of seepage through the coarse sand found there. Site 35 was sampled when site 37 was not accessible due to build-up of algae and falling water levels. Chloride concentrations varied from 150 mg l^{-1} in May 1979 to 810 mg l^{-1} in January 1980 (Fig. 18c). Concentrations decreased through March 1979 and February 1980 — earlier than at sites 19 and 34, and before significant rain had fallen. This early decrease, and the slightly lower minimum concentrations than elsewhere in the lake, suggest that groundwater seepage into the lake is significant at this site when the water level drops below about 16.65 m AHD. Concentrations increased in June of both years when the water level had risen above 16.65 m AHD.

Chloride concentrations at site 36, in the sump at the end of Ariti Avenue, were lower than in the lake, varying from 15 to 80 mg Cl l^{-1} in March/August to 200 to 240 mg l^{-1} in January/April (Fig. 19d). Since the sump collects stormwater it is affected more rapidly by changes in rainfall than the other sites. Chloride concentrations increased during dry periods and fell rapidly after significant rainfall.

Computer-drawn maps of chloride distribution in the lake after winter rains show a north-south gradient with lower chloride concentration in the southern basin (Fig. 20). This shows that there is an input of fresher water from the Wallubuenup/Beenyup Swamp system. The cation distributions for June 1980 conform with this pattern (Fig. 21). Sodium, potassium and magnesium concentrations increased from south to north, but calcium showed the opposite trend with higher concentrations in the south. The water from the south may be higher in calcium due to its initially having a lower pH, which would give greater dissolution of calcite, or due to it containing a higher proportion of groundwater (higher in $CaCO_3$ relative to stormwater). Consequently the water from the south has a different cationic composition to that in the north of the lake. Based on %-equivalents, the proportions of calcium, potassium and magnesium were higher for the southern sites, and that of sodium lower (Table 7). Stormwater, sampled at site 36 in the sump at the end of Ariti Avenue, contained a higher proportion of sodium and lower calcium, magnesium and potassium than the other sites.

Chloride distributions suggest seepage of groundwater into the lake in certain months. In December 1978 there was a gradient of increasing chloride concentration from west to east across the central portion of the lake (Fig. 20a, Table 8). Since the groundwater gradient is from east to west (Fig. 4), this suggests fresher surface seepage from the west, which is very surprising unless the bottom sediments are thinnest here (allowing better contact with the groundwater). The fact that this same area has the highest concentrations in July 1980 (Fig. 20c) perhaps supports this hypothesis as saline waters would be flushed from the lake at this time.

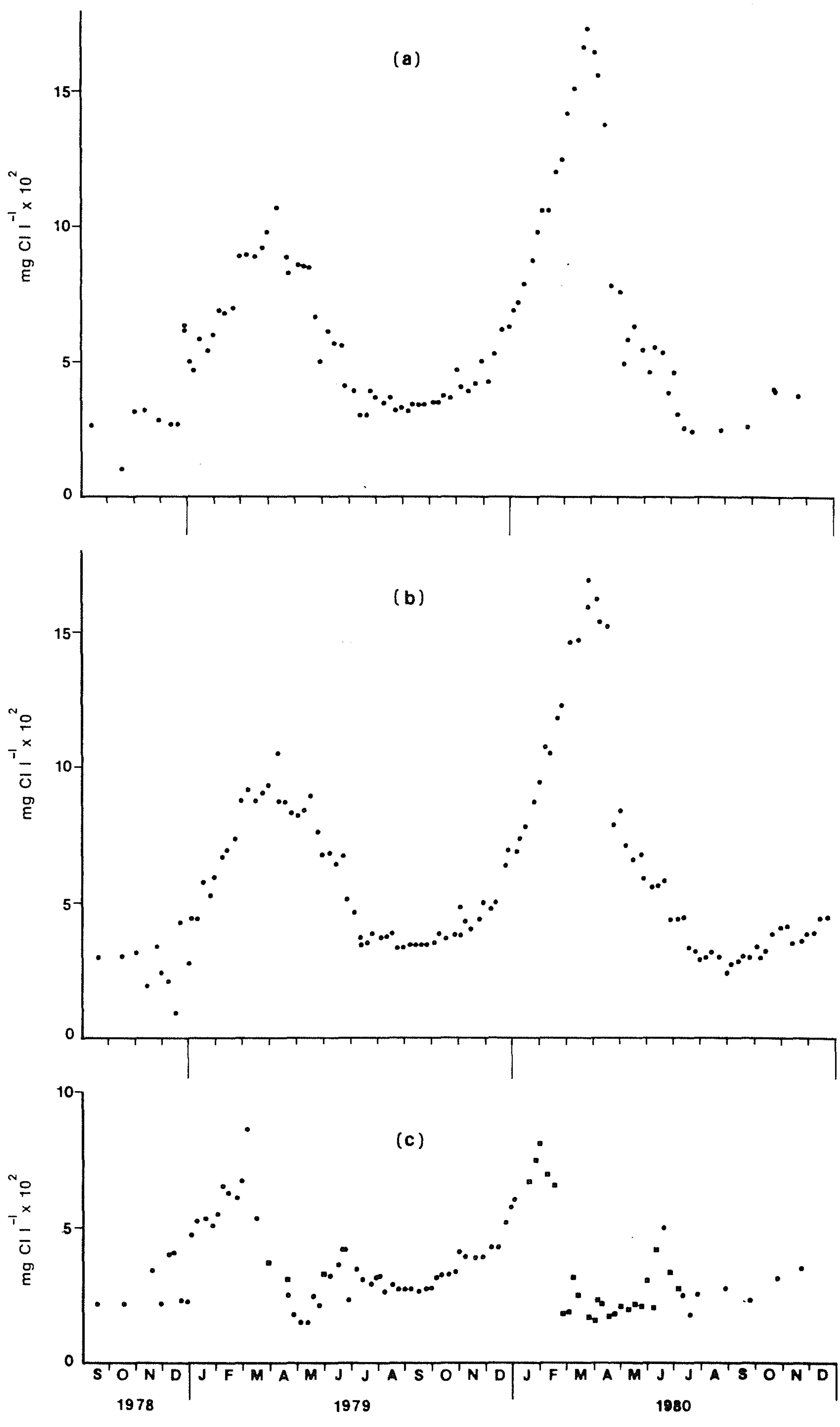


Figure 18 Chloride concentrations at sites in the main waterbody of Lake Joondalup; (a) site 34, (b) site 19, (c) sites 37 and 35 (■).

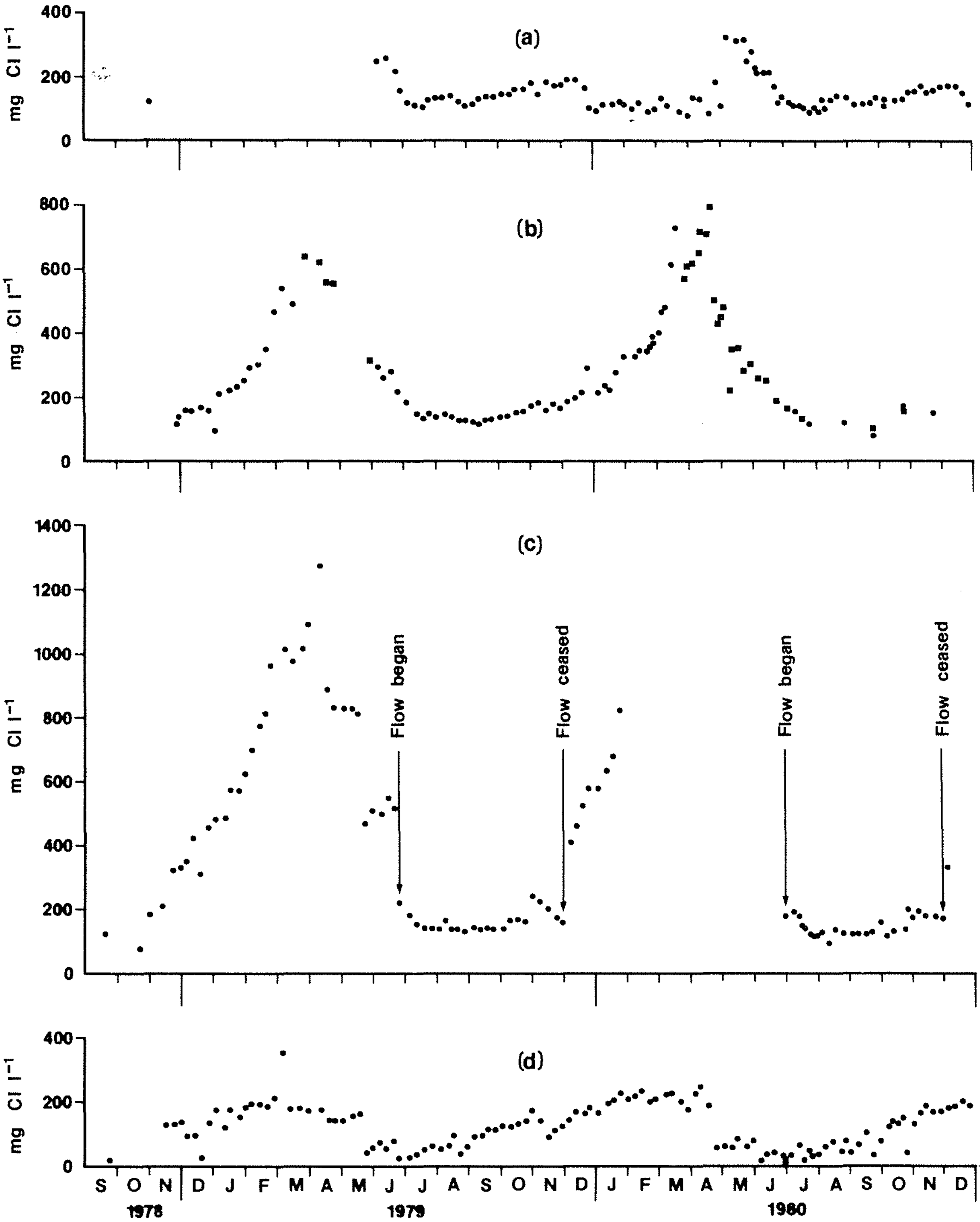


Figure 19 Chloride concentrations at (a) site 57, in the channel between Beenyup Swamp and Lake Joondalup, (b) sites 47 and 54 (■), in the southernmost beasin of the lake, (c) site 46, the culvert under Mullaloo Drive, and (d) site 36 the stormwater sump on the eastern shore of the lake.

As discussed earlier, site 37 appears to be an area where groundwater seeps into the lake. Further evidence is given by some grid studies. The grid study conducted in January 1979 suggested that there was seepage at this site when the chloride concentration was 548 mg l^{-1} compared to 683 mg l^{-1} at site 29.

A relatively low chloride concentration was found in the northern-most part of the lake in March 1979 (site 1 — 784 mg l^{-1}). During the July 1979 grid study, 3 groups of sites had relatively low chloride levels; namely sites 35, 37, 38, 39, sites 16, 17, 18 and sites 22-27. Slightly lower chloride concentrations were also found at site 21 in July 1980 and site 19 in August 1980.

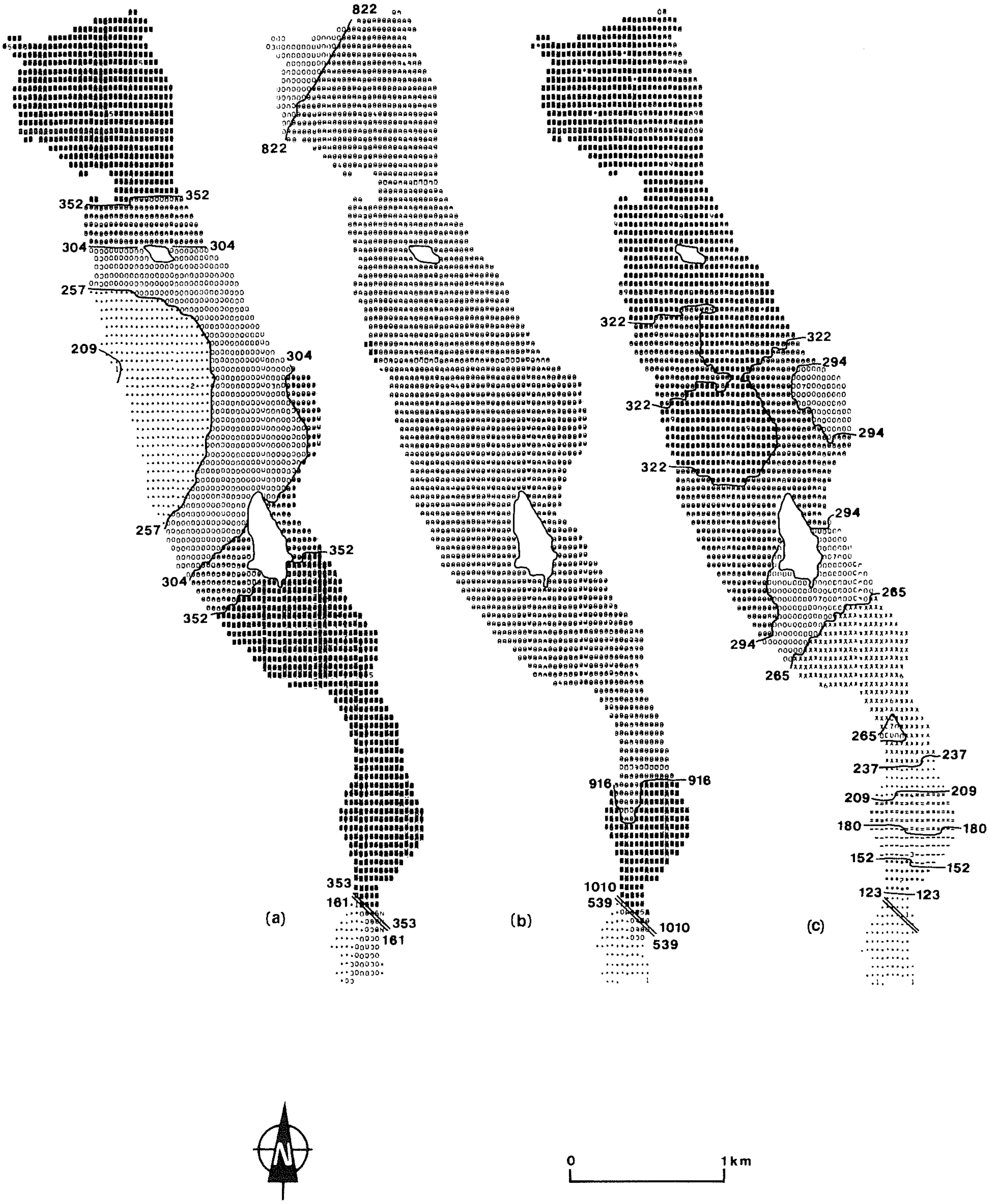


Figure 20 Computer-drawn contour maps of chloride (mg Cl l^{-1}) distributions recorded during grid studies of Lake Joondalup: (a) December 1978, (b) March 1979, and (c) July 1980.

Table 7: The cation composition (% meq l^{-1}) of water samples collected during the June 1980 grid study (Sites are shown in Fig. 1).

Site	Na	K	Ca	Mg
Southern Sites				
57	70.3	6.6	17.9	5.2
54	67.2	6.7	21.0	5.1
Lake Joondalup				
34	86.1	5.3	4.9	3.7
37	84.0	4.8	6.8	4.4
19	85.9	5.8	4.5	3.8
8	86.2	5.8	4.3	3.7
20	86.1	5.7	4.5	3.7
43	83.1	4.5	8.1	4.3
38	83.1	5.3	7.1	4.4
29	84.3	5.5	6.1	4.1
5	87.4	5.5	3.8	3.3
7	86.9	5.8	3.8	3.5
13	87.0	5.0	4.4	3.7
16	86.4	5.6	4.4	3.7
17	86.6	5.5	4.4	3.5
31	85.1	5.2	5.8	4.0
30	85.8	5.5	4.8	3.9
32	86.2	5.4	4.6	3.8
33	85.7	5.3	5.3	3.8
39	83.9	4.7	7.2	4.2
40	83.7	4.4	7.8	4.1
$\bar{x}$	85.4	5.3	5.4	3.9
S.E.	0.3	0.1	0.3	0.1
Stormwater Sump				
36	94.6	0.8	3.8	0.8
Seawater[1]	77.4	1.6	3.3	17.7

[1]Values for seawater taken from Parker (1972).

Table 8: Chloride concentrations across the central portion of Lake Joondalup in December 1978 (mg Cl l^{-1}).

Date	Site 19	Site 20	Site 21
December 6	208	245	300
December 13	91	217	
	West	→	East

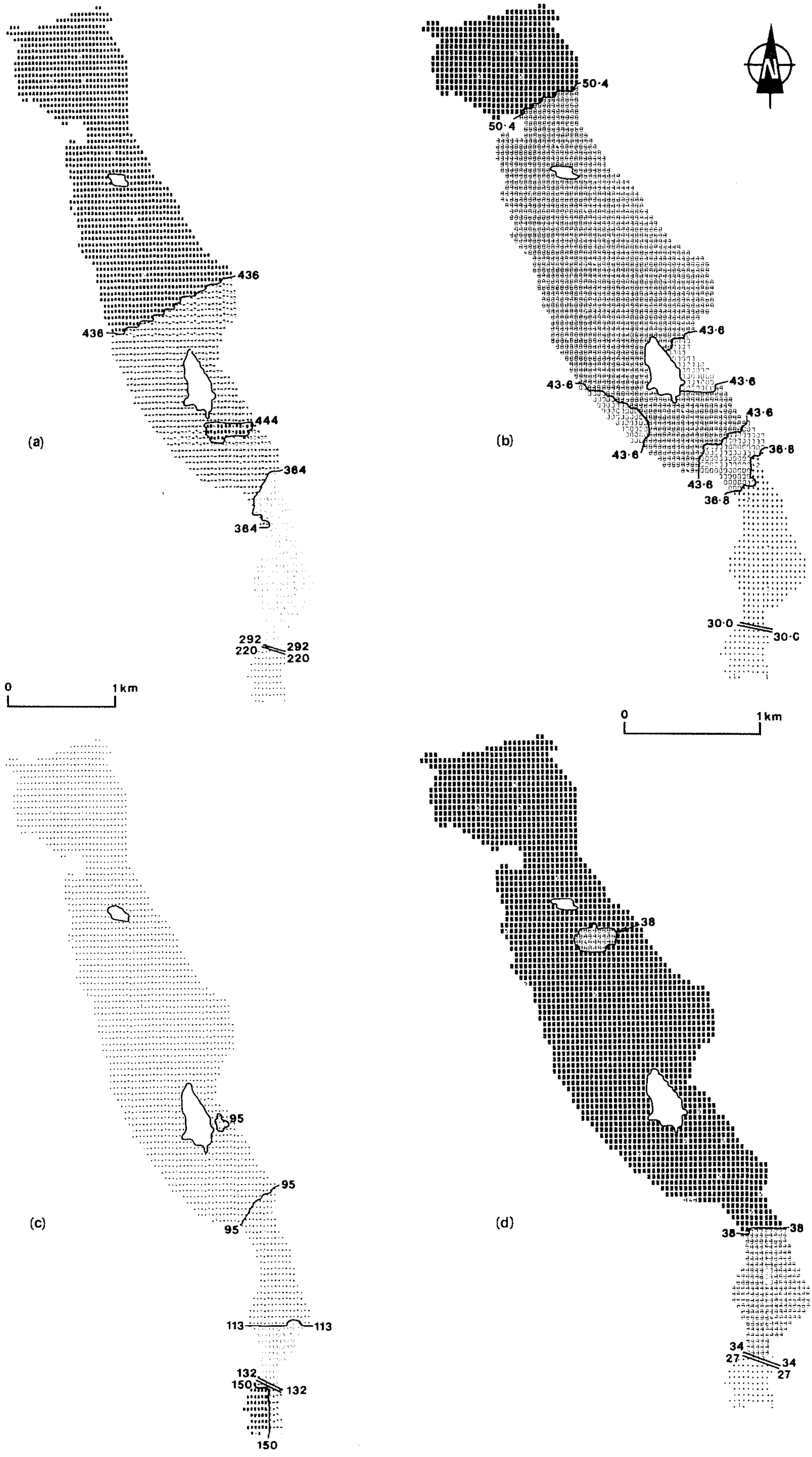


Figure 21 Computer-drawn contour maps of cation (mg l⁻¹) distributions recorded during the June 1980 grid study; (a) sodium, (b) potassium, (c) calcium, and (d) magnesium.

3.5.2 Chloride Mass-Balance

The mass of chloride contributed by rainfall and surface flow was small (Table 9). Chloride inputs in surface inflow were directly related to discharge and rainfall, being highest in July and decreasing through subsequent months. The culvert under Mullaloo Drive contributed 70% of the chloride from surface inputs, compared with 2% from the stormwater sump (site 36) and 28% from rainfall.

Table 9: The chloride mass-balance for Lake Joondalup (Tonnes Cl).

Period	Mass	Net changes	Inputs				Groundwater Exchange
			Site 46	Site 36	Rainfall	Total	
13.12.1978	764						
13.12.78 — 31.1.79	1505	+741	0	0	0	0	+741
31.1.79 — 25.7.79	1326	−179	—	—	21	⩾21	⩽ −200
25.7.79 — 14.1.80	1588	+262	—	—	11	⩾11	⩽ +251
14.1.80 — 19.6.80	791	−797	0	—	12	~12	−809
19.6.80 — 24.7.80	961	+170	38	1	12	51	+119
24.7.80 — 28.8.80	1087	+126	27	1	8	36	+90
28.8.80 — 25.9.80	1157	+ 70	12	1	4	17	+53
25.9.80 —23.10.80	1630	+473	14	0	4	18	+455
23.10.80—20.11.80	1415	−215	10	0	1	11	−226
20.11.80—18.12.80			0	0	1	1	
14.1.80 —20.11.80		−173	101	3	41	145	−318

The mass of chloride in the lake during 1980 decreased from January to June as water levels were falling and increased from June to October as water levels were increasing (Table 9). On the other hand, chloride concentrations were high in January and June, and decreased between June and September, with an increase in October (Fig. 22). Consequently changes in the mass of chloride in the lake cannot be explained by changes in chloride concentration and lake volume alone.

The mass balance indicates that chloride was lost in groundwater at times when its mass in the lake decreased. When chloride mass in the lake increased, groundwater input appeared to make the major contribution. The mass balance shows a net loss of chloride to the groundwater. An increase in groundwater chloride concentration has been found on the western shores of lakes as the groundwater flows from east to west (Allen 1976, Balleau 1973).

The water balance for 1980 indicated a net groundwater output from the lake during December to March, and an input during the remaining months. The chloride budget inferred a net input from June to October and an output of chloride was indicated for November 1980, when the water balance indicates a small net input of groundwater. At this time the lake volume was decreasing (Table 5) although the mean concentration of chloride in the lake also decreased slightly. This suggests that chloride was lost in groundwater outflow.

3.6 The use of seepage meters to examine groundwater seepage

The data collected serve only as approximate indicators of groundwater seepage rates due to few samples being retrieved and few sites being sampled. The chloride concentrations of the groundwater samples collected were often not significantly different from those of the ambient lake water, except for one sample collected at site 15 (17 January 1980) and a sample collected at site 54 (15 September, 1980) (Table 10). This suggests that there was either contamination by the ambient lake water, or that the chloride concentration of the upper groundwater under the western edge of the lake (the area of groundwater discharge) is similar to that of lake water. On occasion other chemical analyses show an increase in ammonium and organic nitrogen in the seepage water compared to the ambient water.

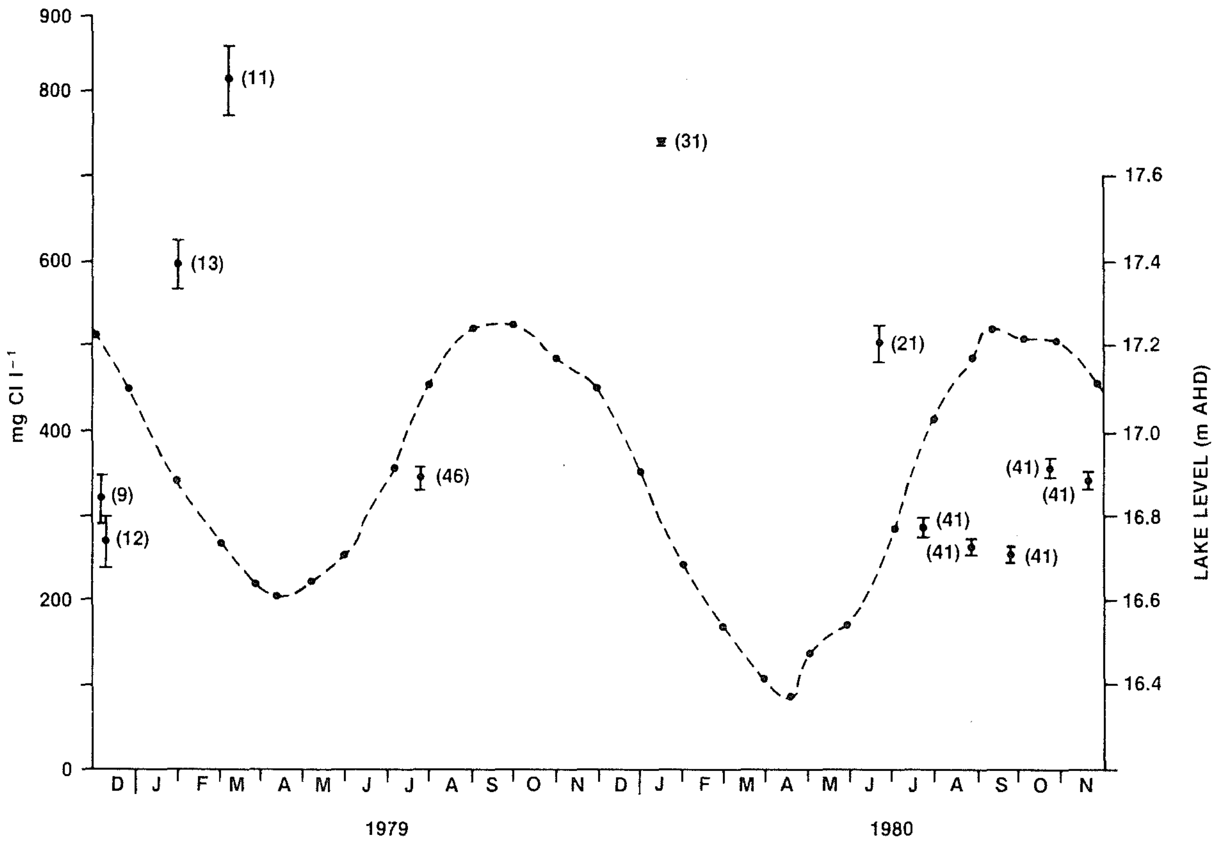


Figure 22 Mean chloride concentrations recorded during grid studies and lake level for Lake Joondalup. The number of samples are given in parentheses.

Table 10: Data from seepage meters — volume collected, chloride, nitrogen and phosphorus concentrations.

Date put in	Date sampled	Duration	Volume (*l*)	Chloride[1]	SRP[2]	Organic P	Nitrate	Ammonium N	Organic N
(a) Site 15									
15. 8.79	29. 8.79	14 days	1.425						
12. 9.79	26. 9.79	14	0.640		59	31	2	147	2720
26. 9.79	10.10.79	14	0.656		68 (76)	22 (15)	1	74 (453)	2628
10.10.79	24.10.79	14	1.220	412 (382)	26 (43)	25 (23)	2 (1)	1418 (33)	3565 (3132)
24.10.79	8.11.79	15	0.955		81 (48)	1 (7)	4 (6)	77 (39)	5748 (3440)
20.12.79	3. 1.80	14	0.72	674 (691)	62 (34)	1 (46)	2 (3)	598 (337)	7801 (2728)
3. 1.80	17. 1.80	14		504 (780)	38		7		
Southern basin									
(b) Site 54									
	28.8.80		0.45	119 (114)	340 (329)			34 (25)	
	15.9.80		0.575	379 (120)					

[1]Values in parentheses are for ambient lake water. Chloride concentrations in mg l^{-1}, others as $\mu g\ l^{-1}$.

[2]SRP = soluble reactive phosphate.

However, rather than this indicating a groundwater input, it might indicate decomposition of metaphyton and release of nutrients from the sediment due to anaerobic conditions created by the seepage meter.

At site 15, lake-water movement may have occurred through the deep layer of metaphyton due to changes in the hydrostatic head with changes in lake water level. Tidal action has been found to have this effect with large enclosures used in marine studies (Smetacek *et al*). 1976) To be effective a seepage meter should penetrate the loose superficial sediment (metaphyton) layer, into the historic sediment so that only groundwater input is likely. Seepage collectors do not always function properly in fine-grained sediments (Cherry 1979, Beauheim 1980 cited in Rinaldo-Lee and Anderson 1980, Winter 1981), and this also appears to be likely for thick metaphyton beds.

The mean rate of seepage from the present study was 11 ml $m^{-2}h^{-1}$ (range 5.3 to 16.6 ml $m^{-2}h^{-1}$). This can be compared with the overall mean inflow rate of 18 ml $m^{-2}h^{-1}$ found by Downing & Peterka (1978) for a lake in North Dakota, and the much higher rates of 360 to 9360 ml $m^{-2}h^{-1}$ recorded by Lee (1977) for lakes in the more temperate states of Minnesota and Wisconsin, and estuaries in Nova Scotia and North Carolina. So the measurements made here for Lake Joondalup agree with what one might expect, from the literature, for an area of comparatively low rainfall.

By extrapolation, the mean rate found for seepage in this study gives a net groundwater inflow of $0.45 \times 10^6 m^3 yr^{-1}$. This is of the same order as the net groundwater input of $0.75 \times 10^6 m^3 yr^{-1}$ estimated from the water mass-balance. Since 4 of the 7 seepage readings obtained were taken in months of estimated net groundwater loss, this estimate is not unreasonable.

4. CONCLUSIONS AND RECOMMENDATIONS

Evaporation was the largest contributor to the water budget of Lake Joondalup, followed by precipitation; both exceeded net groundwater exchange. There are inevitably some uncertainties in the estimate of the groundwater contribution. This is determined as the residual in the water balance, and hence includes all those errors in measurement and interpretation of the other hydrologic parameters.

The inflow of surface water into Lake Joondalup from the Wallubuenup-Beenyup Swamp system, to the south, accounted for 88% of surface discharge into the lake in 1980. This was equivalent to more than 25% of the precipitation falling directly on the lake, and was particularly important in controlling the water level of the southern basin. Beenyup Swamp fills earlier and more rapidly than Lake Joondalup — in mid autumn of 1980. This is presumably due to the swamp's smaller area and the nature of its catchment. Irrigation of market gardens and grazing lands in the Wallubuenup-Beenyup Swamps catchment over summer probably allows run off to begin earlier when rains fall, due to the soil being closer to field capacity than non-irrigated soils elsewhere in the lake's catchment.

Discharge was found to vary considerably, even over periods of 3 to 4 days. If precise measurements of surface water discharging into the lake are required in future, continuous recording equipment should be used, with some protection against possible vandalism.

Development in the lake's catchment should take into account the large variation in water level, due to the natural variability of rainfall and the high loss through evaporation. Low levels may be associated with the release of unpleasant odours (e.g. hydrogen sulphide and methane), blue-green algal blooms and increased populations of chironomids (midge-flies) and mosquitoes.

Lake levels can only be maintained in dry years, and in the face of falling groundwater inputs, by the increase of surface water inflow. At present the surface water flow from the Beenyup-Wallubuenup Swamp system is particularly significant in this regard, and likely to be sensitive to alterations of land-use and land-form in the catchment of this Swamp system. This system is also a most significant source of nutrients causing blue-green algal blooms (to be reported elsewhere), and so its management requires careful consideration.

If the surface water input from the swamps, with the associated nutrient load, were reduced, algal blooms are still likely in dry years with the increasing urbanization of Lake Joondalup's catchment and falling water levels. Allied to urbanization are the competing factors of increased groundwater abstraction and increased urban runoff from stormwater and irrigation of gardens and playing fields. It is necessary that all these factors be considered and appropriate management undertaken, whenever major changes are contemplated for the lake's catchment.

5. SUMMARY

1. The minimum water level of the lake for 1980 (in May) was the lowest recorded for at least 12 years, showing the cumulative effect of previous dry years in depleting the water-table. The maximum water level was recorded in October during 1980.
2. Falling water levels exposed some 25% of the lake bed in 1980, representing a reduction in volume of 45%.
3. The rainfall and evaporation data recorded at Edgewater were closely correlated with, and not significantly different from, records taken for Perth. The input due to rainfall only amounted to 70% of the loss due to evaporation.
4. Evaporation was the largest contributor to the water balance, followed by precipitation.
5. Stormwater from rain events drains very rapidly into stormwater sumps, and thence into the lake on the eastern shore, amounting to 12% of the surface water input for 1980.
6. Surface water flows into Lake Joondalup from the south, from the Wallubuenup-Beenyup Swamp system. This accounted for some 88% of surface discharge into the lake in 1980.
7. Beenyup Swamp fills earlier and more rapidly than Lake Joondalup — in mid autumn of 1980.
8. The southernmost basin of the lake fills very rapidly when water begins flowing from Beenyup Swamp, and this surface flow is very important in maintaining the water level of the basin.
9. Surface discharge into the main basin of the lake, through the Mullaloo Drive culvert, commenced in June and ceased in November 1980. This was equivalent to 27% of the input due to rainfall.
10. There was a net input of groundwater to the lake during 1980. A net inflow of groundwater occurred in autumn, winter and spring, and a net outflow in summer.
11. Seepage meters were used in an attempt to measure groundwater seepage flux but were found to be unreliable due to the nature of the lake bed and the rapid changes in water level at certain times of the year.
12. Lower chloride concentrations indicate seepage of groundwater into the lake on the eastern shore when the lake water level falls below about 16.65 m AHD, and there is also some evidence for seepage near the western shore.
13. Chloride and cation concentrations were used as indicators to trace the flow of water from Beenyup Swamp.

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APPENDIX 1: Site numbers used in this report and corresponding original site numbers used in the computer-based data bank.

Site Numbers Used In This Report	Original Site Numbers	Site Numbers Used In This Report	Original Site Numbers
1	10	33	63
2	25	34	1
3	26	35	21
4	9	36	6
5	27	37	4
6	32	38	14
7	28	39	64
8	8	40	65
9	23	41	66
10	18	42	67
11	29	43	13
12	19	44	68
13	31	45	24
14	30	46	2
15	33	47	3
16	40	48	84
17	41	49	85
18	42	50	81
19	5	51	86
20	12	52	87
21	11	53	83
22	45	54	20
23	44	55	82
24	43	56	88
25	46	57	7
26	17	58	89
27	47	59	99
28	16	60	98
29	15	61	97
30	61	62	94
31	60	63	96
32	62	64	95

APPENDIX 2: Annual rainfall total for Perth and Wanneroo, and evaporation totals for Perth for the period 1968 to 1980 (from Bureau of Meteorology (Australia). Monthly Weather Review — Western Australia, December — 1969 to 1980).

Year	Perth Evaporation	Perth Rainfall	Wanneroo Rainfall	Wanneroo data incomplete for —
1968	1817	930	844	December.
1969	2056	574	633	October.
1970	1986	908	725	November.
1971	1771	799	—	All except March and June.
1972	1938	611	525	February, March, April.
1973	1735	973	908	
1974	1761	939	937	November, December.
1975	1827	682	—	March, April, May, June, November.
1976	1764	711	472	February.
1977	1831	608	436	
1978	1968	924	845	January.
1979	1728	560	671	February.
1980	1702	844	709	
Annual average	1713	875	—	