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Production of Marron in Western Australian Wheatbelt Farm Dams

BY

N. M. MORRISSY

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WESTERN AUSTRALIAN
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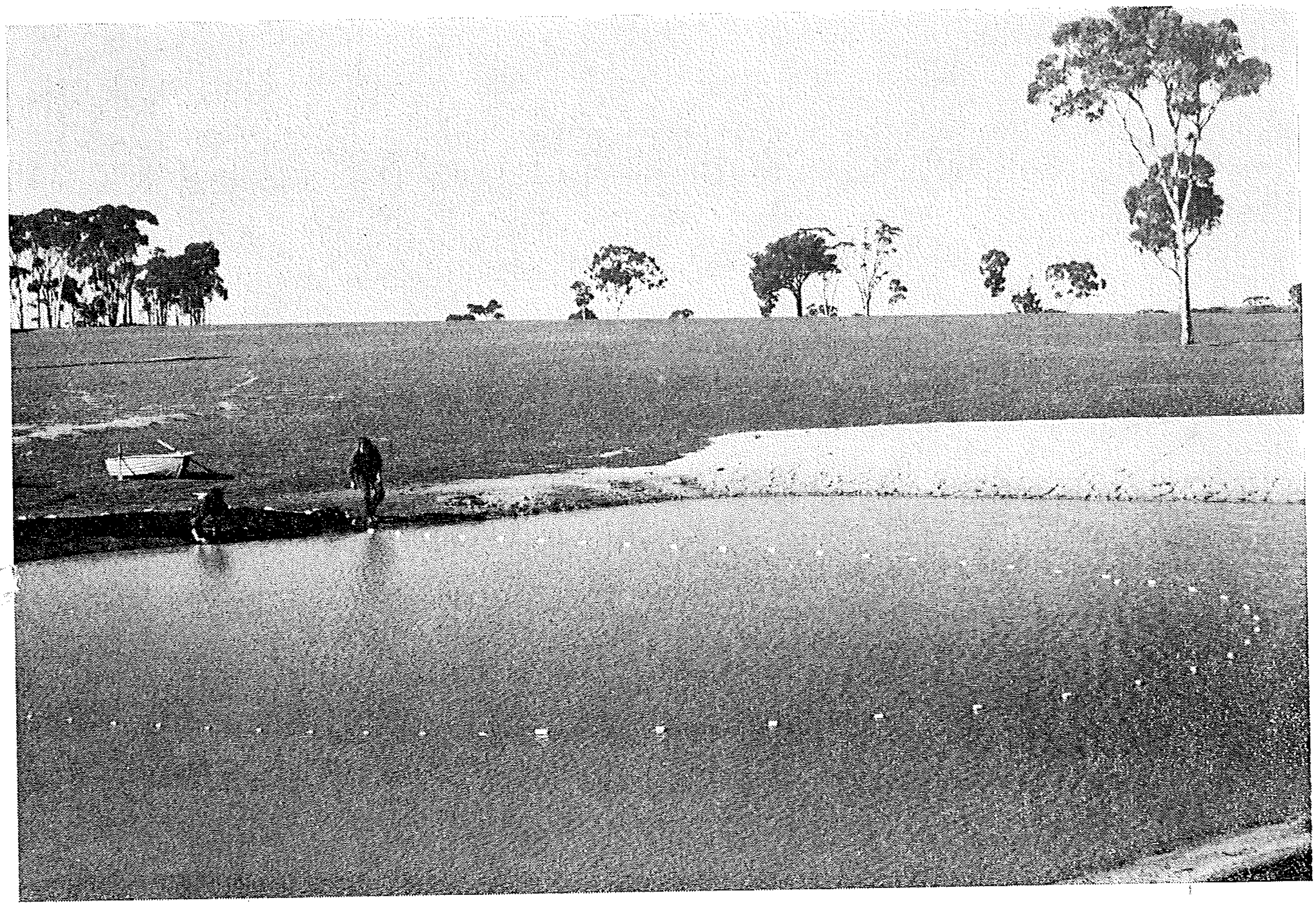
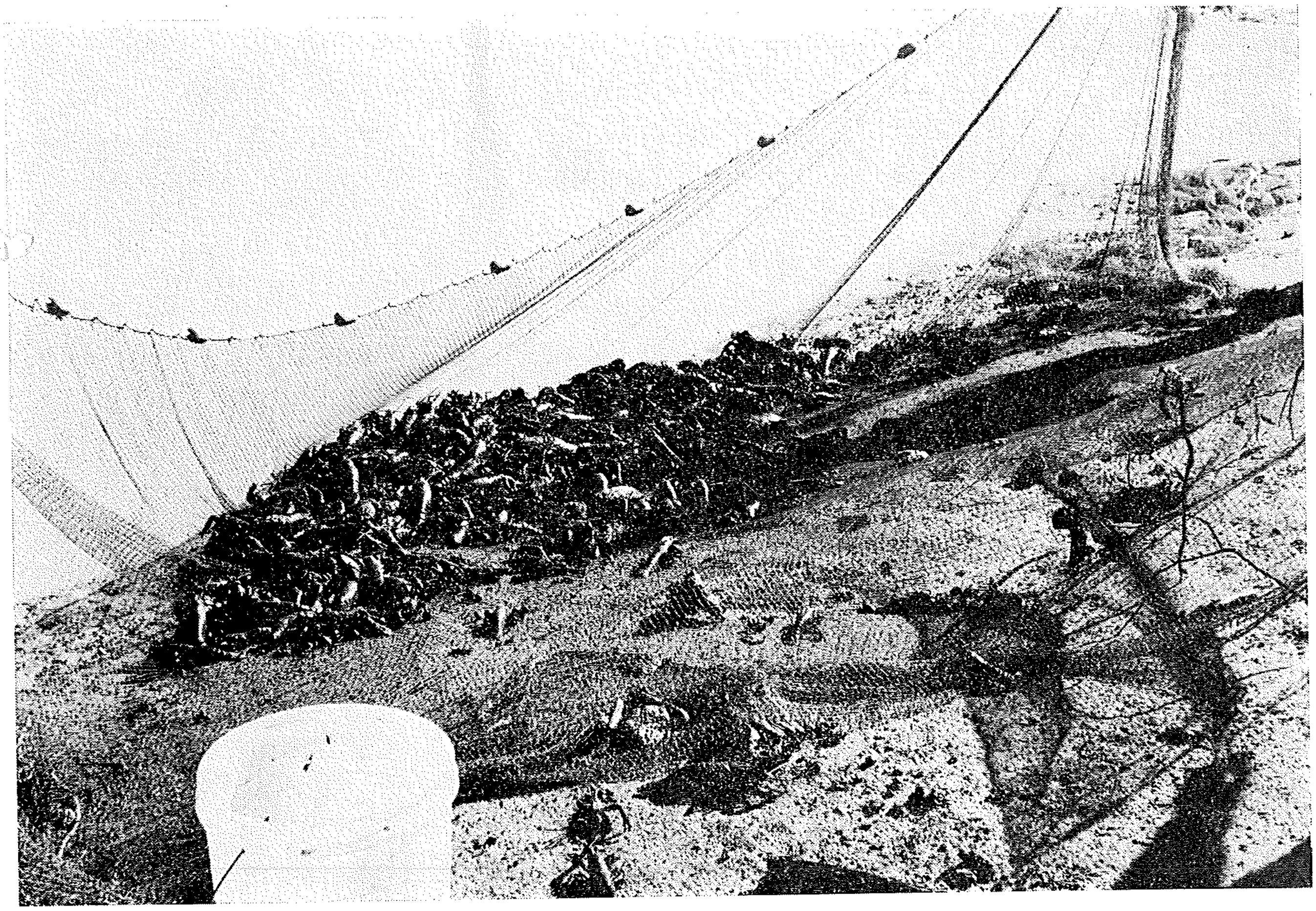
DEPARTMENT OF FISHERIES AND WILDLIFE
PERTH, WESTERN AUSTRALIA

GLOSSARY OF TERMS

Autotrophism	Process by which organisms (green plants, algae) build up organic substances using sunlight as an energy source.
Biomass	Also standing crop, stock. Total weight of organisms, usually of a given species, at one point in time, expressed per unit area e.g. kg/ha.
Cohort	A defined group of animals of the same age, i.e. a year-class.
Density	Total number of animals expressed per unit area e.g. -/m^2.
Endogenesis	A process by which conditions are brought about by internal features of the situation.
Heterotrophism	Process by which organisms (bacteria, fungi, animals) build up organic substances using energy obtained from other trophic levels.
Holomixis	Mixing of a water body between all depth levels.
Insolation	Incidence of sunlight.
Meromixis	Incomplete mixing of a water body with a permanent stagnant bottom layer.
Polymictic	Describes water bodies which frequently mix completely to all depths.
Production	Total weight of organisms, usually of a given species, which is grown over a specified period including individuals which die before the end of the period.
Sodicity	Relative proportions of exchangeable monovalent cations (sodium) to divalent cations (calcium and magnesium).
Stratification	Density layering of a water body with depth, usually due to temperature, resulting in lack of vertical mixing.
Trophism	Organisation of animals at different levels in an ecosystem relating to the transfer of energy through food chains.
Turbidity	Organic (algae) or inorganic (clay) material suspended in water influencing light penetration and apparent water colour.
Turnover ratio	Production of animals over a period relative to the mean biomass.





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FRONTISPIECE

Upper—Recovery of over 90% of marron in each dam was made by dragging a seine net across the bottom of the entire dam.
Lower—A catch of marron recovered from the net.

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PRODUCTION OF MARRON IN WESTERN AUSTRALIAN WHEATBELT FARM DAMS

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ABSTRACT

Fifteen 0·1 ha farm dams in the southern wheatbelt of south-western Australia were stocked with hatchery bred three-month-old marron in the density range 0·5–2·5/m². Three dams suffered mass mortalities in the first spring or summer. In the other dams survival over 2–2·5 years was 12·7–87·4%, final mean size was 23–89 g, final biomass was 206–1 106 kg/ha (including cropped marron) and total production was 437–1 425 kg/ha.

Seasonal variation in monthly production was positively related to water temperature except during summer when oxygen depletion occurred intermittently in deeper water due to periods of persistent thermal stratification. Using Bayly and Williams (1973) modification of the Hutchinson-Löffler thermal classification of still waters, the farm dams fall into the polymictic category, with some qualifications because of high inorganic turbidity and short periods of summer meromixis. With an average relative depth, Z_r, of 8·5 the dams lie in the type IV category for meromixis caused by endogenesis (Walker and Likens 1975). Variation in turbidity (clay-silt) was related to salinity, sodicity, clay type and particle size. Montmorillimite clay, a feature of eastern Australian dams, occurred in the most turbid dam (Z_{SD} 2·5–6·0 m) with the more characteristic kaolin clay.

The annual cycle of drawdown and filling of the dams was described in relation to salinity and nutrients. Three consecutive years of decreasing winter rainfall reduced the flushing of the dams by overflow (August–September).

The considerable variation in production between dams was negatively correlated with clay-silt turbidity. Lowest production occurred in dams with high and seasonally constant turbidity, highest production occurred in dams which tended to clear in summer and show algal blooms, and failed dams were more extreme in the latter characteristics. Turbidity and apparent water colour in mid-summer were a useful trophic index for marron production. Suspended clay-silt suppressed the deleterious effects of high organic and nutrient loadings, from the agricultural catchments, usually expressed in dense algal blooms and excessive oxygen depletion. However, phytoplankton occurred at high clay turbidities, as noted by Weatherley (1958). Algal buoyancy and aphotic viability and nutrient absorption on clay particles were implicated.

Because of varying degrees of inorganic turbidity, farm dams appear to bridge the extremes from the common algal (autotrophic) expression of high nutrient loadings to the other rarer extreme of almost solely microbial decomposition (heterotrophism), categorized by Hutchinson's "argillotrophic" lake system.

Australian parastacid growth rate, biomass production and cohort turnover ratio data, almost all for marron, were reviewed. Growth rate and density (0·1–25/m²) for marron were inversely related by a hyperbolic model which is more representative than previous negative linear models applied to crayfish. Extensive aquaculture of marron in farm dams is confined to densities of <2/m² at two years of age given by stocking rates of 0·5–2·5/m². Legal-sized marron (>125 g) are obtained at densities <0·2/m², and possible export sizes (40–60 g) at <1·0/m², with a biomass of 300–450 kg/ha.

Cohort turnover ratios (P/B) for cultured marron were about 2·5, i.e. half those predicted by Waters (1969, 1977) and found by Momot and Gowing (1975) for wild crayfish. The lower value is to be expected under aquaculture conditions where the high production rate is not accompanied by high mortality experienced by wild year-classes.

The economics of commercially rearing marron in farm dams are a low return per farm, relative to agricultural pursuits, but a high return per dam relative to low capital and labour inputs. Therefore, the only likely avenue for viable commercial marron farming is a venture operating over many farms.

I INTRODUCTION

Wild stocks of a large south-western Australian freshwater crayfish, the marron (*Cherax tenuimanus* (Smith)) are protected from commercial exploitation for sport fishing (Morrissy 1978a). Previous research on intensive aquaculture of domestic marron in specially constructed drainable ponds was reported by Morrissy (1976a, b: 1979). Further research reported here, on a less intensive form of aquaculture in existing private farm dams (Morrissy 1970a, 1974a) was conducted near Kojonup (Fig. 1) over the period 1974–76 following stocking of selected dams with juvenile marron bred at the Pemberton Fish Hatchery (Morrissy 1976b). A prime obstacle to the reliability and intensification of aquaculture of marron, and other species, is food pollution and consequent oxygen depletion (Morrissy 1979). This topic can be related, conceptually, to the earlier ecological discovery of successional stages of trophism in farm dams due to increasing degrees of adventitious loading with allochthonous organic material (Morrissy 1974a).

Considerable literature exists on agricultural and engineering aspects of the ubiquitous Australian farm dam (Burton 1965; Fietz 1969). However, the limnological characteristics and fisheries potential of these stillwaters have been little studied so far (Weatherley 1958, 1967; Bayly and Williams 1973; Morrissy 1974a; Walker 1974; Timms in press).

II METHODS

1. Marron

Fifteen dams (Fig. 1), mean surface area approximately 0·1 ha, were stocked with 22 500 two to three month old marron at rates of 500 1 000 1 500, 2 000 or 2 500 per dam (approximately 0·5–2·5/m²). Mortality during transport from Pemberton to Kojonup (150 km), in sealed plastic bags using oxygenated water in the cooler post summer month of March, ranged from 0·4 to 1·2% in 1974. Seven dams (A group) were stocked during March 1974 and studied until July 1976 (marron, 30 months old) and eight dams (B group) were stocked in March 1975 and studied until November 1976 (23 months old).

Following stocking, 0+group marron were sampled monthly from May until January of the following year using two synthetic weed samplers (Morrissy 1974a, 1976b) and ten scoop net (opening 30 x 48 cm) passes over the bottom out from the shoreline. Drop net sampling (Morrissy 1973), using five nets set from the bank, was introduced in November when the catchability of the 0+ group marron by the other methods commenced to decrease with rapid growth in size.

In the following February a full monthly drop net sampling programme was commenced with fifteen nets set in a standard saturation pattern (Morrissy 1974b) from a dinghy and hauled at half hourly intervals up to four times.

In anticipation of summer mortality, absolute estimates of surviving numbers were obtained for the end of November (1974) by a special mark-recapture exercise using Bailey's (1951) method. A full capture-mark-release-and-recapture (C.M.R.R.) programme commenced in February on the newly 1+ group marron employing pleopod removals and tail-fan punch marks for subsequent identification either of individuals or for month of previous capture. All the data (43 899 observations) were filed by computer for estimation of absolute numbers by the Jolly-Seber method (Jolly 1965; Seber 1965) and mean monthly size. Final inventory was carried out using a very large seine net ("wings" each 57·5 m in length, "bunt" 31 m, "drop" 200 meshes, mesh size 2·5 cm). Usually over 90% of the surviving marron were removed in four seine hauls, the declining catch rate of successive hauls allowing a "DeLury type" estimate of absolute numbers (Leslie and Davis 1939; DeLury 1947) and, hence, a check on the Jolly-Seber estimates.

Individual size was measured as eye orbit carapace length (O.C.L. cm). Live body weight (W, gm) was calculated from $W = 0{\cdot}926\,80\ \mathrm{O.C.L.}^{2{\cdot}867\,1}$ (Morrissy 1970-b).

Production was calculated by the method of LeBlond and Parsons (1977).

2. Morphometry of farm dams

Dam morphometrics were estimated in full dams during the winter of 1974 from soundings at 5 m intervals on the X-Y co-ordinate grid system proposed by Morrissy (1974a). Surface area of water, substrate or bed area underwater, and volume of water were then computed for 50 cm intervals of maximum depth up to the full level (see appendix) and graphed against depth. Monthly relative water level (gauging post) was calibrated to soundings of maximum depth. For dams retaining an approximately square surface area of water up to the full stage, agreement between predicted area (P.A. m^2) and that observed (O.A.), calculated from monthly dam width and length, was satisfactory; for example for D_1,

$$\mathrm{P.A.} = -67 + 1{\cdot}14\ \mathrm{O.A.}$$

$$n = 26,\ \text{correlation co-efficient } (r) = 0{\cdot}967$$

Soundings for predicted areas included deviations from a square shape, corner curvature and shallow backwaters at full stage.

3. Temperature and oxygen

The annual cycle of heating and cooling of the dam waters was described using monthly maximum and minimum readings from max-min thermometers (Zeal, London) set at the surface and bottom of each dam over the position of maximum depth. Vertical oxygen and temperature profiles were measured during the monthly marron samplings over summer with a DO/TEMP meter (Titron, Melbourne). Water temperature at the surface, 1, 2 and 3 m depth from the surface and oxygen at 3 m depth were recorded continuously in one dam, D1—the farthest to the warmer north-east (Fig. 1), during the summer of 1974–75. Thermister probes and the oxygen probe registered on mini-strip chart recorders (Grant, Cambridge, U.K.; Rustrak, Manchester, New Hampshire, U.S.A.); air temperature was recorded by a shaded thermograph (Thies, Göttingen). Recorders were situated on a raft loosely moored at the centre of the dam to give oxygen probe movement.

Independent checks of water profiles were carried out with an electronic thermometer (Thermophil, Adelaide) and a temperature-compensated DO/TEMP meter (E.I.L., Cambridge, U.K.

4. Rainfall

The possible occurrence of sporadic but brief, heavy cyclonic summer downpours was anticipated by siting metal rain gauges, with a large capacity (5 l), a large orifice (35 mm), but a normal collecting area (322 cm^2; standard Bureau of Meteorology rain gauge, 324 cm^2) near each dam. A project rain gauge was placed alongside a standard (Australian Bureau of Meteorology) rain gauge in the town of Kojonup, allowing calibration.

5. Other invertebrates

A sample of other macro-invertebrates was obtained by drawing a scoop net (0·8 mm mesh opening), triangular frame 55 x 30 x 30 cm, handle 1·5 m) across about 2m. of the bed of the dam to the shoreline. All the dams were sampled in February 1974 (initial survey), February 1975, August 1975, and March 1976. One dam, D13, was sampled monthly until June 1976.

6. Water analyses

Water samples were taken at mid summer in February 1974, 1975 and 1976 and at mid winter in July, or August, 1974, 1975 and 1976 and analysed for the following properties, by the Government Chemical Laboratories (G.C.L.), Western Australia, using current standard American Public Health Association (APHA) methods: pH; conductivity; total dissolved solids (by evaporation); sodium, calcium, magnesium, and potassium cations and carbonate, bicarbonate, chloride, sulphate, and nitrate anions; ammonia nitrogen, nitrate nitrogen, and organic nitrogen; and total phosphorous in solution. Samples were preserved with 0·1% of chloroform and the above laboratories performed the chemical analyses after filtration (0·45 μm) to remove suspended matter Monthly water samples were analysed at the Western Australian Marine Research Laboratories as follows:—

Conductivity (K_{20}) was measured with a Radiometer (Copenhagen) Type CDM2e meter calibrated with 0·1N KCl (11 670 μScm^{-1} at 20°C). Total solids were measured by evaporation of a 300 ml sample to dryness at 110°C (2 days). Total dissolved salts were calculated from conductivity using a co-efficient (0·67–0·69) derived from the G.C.L. data. Total suspended matter was calculated by subtraction using the above values. Total suspended clay-silt was calculated by further subtraction ("subtraction method") of total organic matter (particulate and dissolved) which was measured by ignition of the dried total solids at 550°C for three hours in a muffle furnace. All weighings were carried out on a Mettler balance (Model H10T) to the nearest 0·1 mgm.

7. Suspended clay-silt particle sizes and concentration

Estimates for a yearly series of monthly samples from D3 and one or two samples from each of the other dams during the same year were obtained by a "filtration method". Known volumes of subsamples from the well-shaken sample of dam water were passed through a range of filter sizes (47 mm dia.), viz 12 μm (Sartorius), 8, 3, 1·2, 0·45, 0·1 and 0·025 μm (MF-Millipore). Pore size limitations of these filters are given by Paerl and Shimp (1973). Weight of filtrate, and hence concentration in the original sample, was determined after ignition of the filter paper at 550°C, and redrying at 110°C following cooling in the muffle furnace, using small crucibles (Halden-Wanger, Berlin, type 9MF). Filtration was performed at a negative pressure of 250 mm Hg. Great care was taken to prevent clogging which yielded over-estimates due to retention of finer particles; volumes filtered were adjusted proportionally to filter size by monitoring the rate flow of the filtrant and, if necessary, replication was carried out after graphical examination of the first series of data for a sample. Residual filter ash (of non-grid paper) was negligible (12 μm—0·025 mg, 0·025 μm—0·056 mg) in relation to the smallest volumes filtered (5 ml) and sub-sample weights (4 mg), i.e. about a maximum of 1·4% by weight of the estimate.

Although this "filtration" method also gave satisfactory estimates of total suspended clay concentrations it was too time-consuming, and developed too late in the programme, to allow its use on the routine monthly water samples taken from fifteen dams.

Possible errors in water analyses associated with the estimation and presence of characteristically high concentrations of suspended clay-silt (up to 2 600 mg/l), and often of considerable magnitude in the fine clay fraction ($<0\cdot2$ μm), were discussed by Morrissy (1977).

8. Optical turbidity

Turbidity, as well being estimated as total suspended clay-silt by the two independent gravimetric methods ("subtraction" and "filtration", above) was also estimated optically in the field using the Secchi disk (20 cm dia.—all white) read to the nearest 0·5 cm and in the laboratory by nephelometry (Hach Model 2100A), using formazin standards (APHA 1971). Further study of light penetration in the turbid dams was also carried out using a LI-185 meter (Lambda Instrumention Corporation, Lincoln, Nebraska) and a LI-192S underwater PAR quantum sensor coupled with a LI-190S aerial sensor for concomitant surface reference; submerged light readings were multiplied by 1·34, as recommended by the manufacturer, and adjusted to the initial surface air value for each dam; the vertical attenuation coefficient and reflectance were calculated following Kirk (1977).

9. Sources of allochthonous organic material

The seasonal abundance of pasture on the catchments was monitored as a measure of the primary allochthonous source of sediment detritus constituting the marron's food, following the model proposed by Morrissy (1974a). Samples were taken monthly from May 1974 to August 1975 and again in August 1976. Two samples of pasture to a soil depth of 2·5 cm were removed from quadrats of 500 cm^2 area located in a random fashion on each catchment (within throwing distance of the dam bank). From April to August 1975 five adjacent quadrats on a homogeneous area of each catchment were successively sampled in a systematic manner each month. Each sample was sorted into "coarse" and "fine" fractions using prolonged waterborne seiving (500 μm, Endecott's, London), with the residual sand being discarded.

The incidence of stock, especially cattle, in the dam paddock was noted monthly.

10. Sediments

The sediments in each dam were sampled quarterly at the centre of each dam using a corer (Fig. 2) based upon principles of construction in the Kajak-Brinkhurst corer (Brinkhurst *et al* 1969). Duplicate samples, using the top 1 cm layer of each core, were frozen and stored in stainless steel containers. Special surveys of the distribution of sediments in some dams were also undertaken. During January, February and March 1976 three cores were taken from each dam and pooled for protein analysis (see below).

Depth of sediment over the hard-packed clay bed of the dams was underestimated by the depth observed in the corer tube. The relationship between the true and apparent depths of the sediments was established with a special depth sounding plate and tape normally used for measuring maximum depth, giving depth of water over the sediment, and the corer rod, giving depth to the hard clay bed from the water surface.

Organic content of the sediment was estimated by loss on ignition at 550°C. Stomach contents of marron were analysed by the same method to test whether selective feeding occurred. Water of hydration of clay-silt material lost upon ignition was estimated as 1·1% by adding distilled water after ignition and redrying at 110°C.

The method given by Gornall *et al* (1949) for total protein in blood was modified for sediments as follows. A sediment sample was dried in the collecting container, thoroughly pulversied using a mortar and pestle, and a subsample of from 0·5 to 1·0 g was weighed in the reaction test tube. Volumes of distilled water and Biuret re-agent added to these subsamples were unchanged. Before measuring optical density (O.D.) at 540 nm on a colorimeter (Cecil, Cambridge, U.K.) the solutions were filtered (1·2 μm M.F.—Millipore). O.D. was read against a Biuret blank, also filtered. Bovine crystalline albumin (Calbiochem) was used as the standard (1 O.D. unit = 35·4 mg protein). The original method for blood recommended a standard solution but greater accuracy was attained by weighing out the albumin standards as dry solids, in the same way as the sediments, directly into reaction test tubes. Tests of standards over the range 4 to 50 mg showed that digestion and reaction, by the volume of Biuret re-agent used, was adequate only up to 30 mg albumin (Fig. 3). Replicate tests of sediment samples showed that subsamples over 1·0 g gave consistently slightly lower protein values than smaller subsamples. Protein content of the sediments was expressed as mg protein per gm of dry weight of the total sediment or per gm of dry weight of the organic content.

11. Algal blooms

Monthly estimates of chlorophyll 'a' and pheo-pigments were obtained from July 1975 to November 1976 as surrogates for algal biomass. Water samples were frozen upon collection and thawed just prior to preparation. The solids collected by vacuum filtration at 300 mm Hg on a 1·2 μm filter (MF—Millipore) from a known volume of sample, usually 10–100 ml depending upon turbitidy, were placed, with the filter paper, in 10 ml plastic centrifuge tubes and treated with 10 ml of cold 90% acetone (Analar R) overnight in a domestic refrigerator. Most of the samples were centrifuged at 2 000 rev./min. for 10 minutes to remove turbidity;

later, when the centrifuge was no longer available, the optical density (O.D.) reading at 750 nm was used to correct for turbidity.

Spectrophotometric readings (Shimadzu, Japan) of O.D. at 665 nm (using a 1 cm light path), before and after acidifiation with HCl, allowed calculation of chlorophyll "a" and pheo-pigment concentrations, using the equations given by Lorenzen (1967). O.D. was also measured at 430 nm.

A superficial record of the monthly appearance of each dam was kept photographically (Kodak Instamatic Model 233—Kodacolor II film) for later confirmation of algal blooms, and changes in turbidity.

Methods Appendix

Calculations of surface area, ground area, and volume of water of dams (N. Caputi, Statistician, Department of Fisheries and Wildlife, Western Australia).

The data used in the calculation of the volume of water, water surface area and ground area below water at different depths consisted of measurements of the depth of water on a 5 m x 5 m grid over the dam.

In the calculations of the above quantities, each 5 m x 5 m square was divided into two triangles and each of the quantities was estimated for every triangle and then combined to provide an estimate for the dam. In estimating the ground area it was assumed that the triangle formed at the bottom of the dam was a plane since no information was available regarding the degree of curvature between points.

These quantities were calculated at the depth measurements were carried out and also at each successive 50 cm interval down to a maximum depth of 50 cm. When calculating the quantities for each successive 50 cm interval a check was carried out to see if any of the three points of the triangle were above the water level. If one or two of the points were above the water level and the rest were below the water level then linear interpolation was used to find the positions on the sides of the triangle reached by the water level and the above three quantities were calculated using the resultant smaller triangle (or trapezium).

III RESULTS

A. GROWTH, SURVIVING NUMBERS, BIOMASS AND PRODUCTION OF MARRON

1. Dam morphometry

Density, biomass and production of marron were calculated on the basis of mean surface area of water over the period of residence. Monthly bottom area was employed to calculate density, biomass and production per unit area in specific instances to illustrate summer crowding of marron. Monthly volumes were used in conjunction with salinity to show seasonal and longer term patterns of dilution, concentration and flushing of dam waters.

The selected dams were typical in morphometry of the excavated ("2 000 cubic yard", $\backsim$1 500 m^3 capacity) tank type of dam found over the Western Australian wheatbelt (Morrissy 1970a, 1974a; Laing 1977). These dams are prismoidal in shape with a rectangular plan, holding most of the water below the original ground level. At full-to-overflowing water level, mean statistics (Bayly and Williams 1973) for the dams were:— maximum depth (Z_m), 3·72 m; mean depth ($\bar{Z}$), 1·33 m; surface area, 1 499 m^2; volume 1 890 m^3; (Table 1) and a high volume development ($3\bar{Z}:Z_m$) of 1·07. Over the period of study the mean and minimum surface areas of the dams were 63% and 41% on the average, respectively, of the full values.

2. Marron statistics

Initial mean size of the stocked 0+ year old marron, 0·48 g (range 0·27–0·73 g), was stunted by previous rearing at very high densities at the Pemberton Fish Hatchery. Introduction to the dams was unavoidably delayed until late March when the marron were three months of age, because of physical and climatic obstacles to collection and transport earlier in the summer. Therefore since appreciable increase in mean size did not commence until springtime, growth rates were retarded by this unfavourable start to the dam growth schedule, i.e. by exclusion of the first summer growing season.

The marron in three of the fifteen dams suffered mass mortalities during the first year or so of life. In the other dams final survival, 12·7–87·4%, mean size, 23–89 g, biomass, 206–1 106 kg/ha (including cropped marron) and cumulative monthly production, 437–1 425 kg/ha varied widely between dams (Table 2). The large variability in individual size of members of each year-class cohort of marron in the dams is characteristic of marron (Fig. 4). The percentages of the final biomass for marron larger than certain sizes are shown in Table 3.

Mean survival in the A-group over 28 months and two summers in the dams was 25·4% (35·6% excluding three failed dams), range 0– (20·0–) 56·4%, and in the B-group over 21 months and one summer 49·6% (56·7%), range 0– (12·7–) 87·4%, (Table 2). In the A-group over 21 months (to compare with the B-group) mean survival was 39·6% (55·5% excluding failed dams), range 0– (38·5–) 69·0%. After one summer in the dams and 16 months residence (age 18 months) before cropping commenced, mean survival was 64·1%, range 39·6–88·0%. These survival rates compare favourably with those from intensive marron trials at higher densities at the Pemberton Fish Hatchery where survival of about 50% over one year was considered to be acceptable (Morrissy 1979).

Final statistics were dependent upon the different time and cropping schedules of A and B group dams and whether, or not, failed dams were included. Dependence of mean size, density, biomass and production on initial stocked density was therefore best examined at a marron age of 18 months, i.e. after 16 months and one summer in the dams.

Correlations with initial density were found for biomass ($r = 0{\cdot}75$, $P<0{\cdot}01$), cumulative production ($r = 0{\cdot}77$, $P<0{\cdot}001$) and density ($r = 0{\cdot}83$, $P<0{\cdot}001$), but not mean size ($P>0{\cdot}05$), at eighteen months of age; correlation co-efficients were slightly less if failed dams were excluded. There was no negative correlation between mean size and density at eighteen months ($P > 0{\cdot}05$). The subject of density-dependent growth of marron is considered in detail in the DISCUSSION by employing the present and previous results spanning an extended density range.

3. Spawning

The frequency of spawning amongst 1+ year old females showed unusual variability, 0–37·5% (Table 4). Previously, pond spawning at this age had been observed to be negligible with a significant spawning frequency (75%) first occurring in the following year of life, i.e. at 2+ –3 years old (Morrissy 1974c). Since ovarian development commences in the summer prior to the springtime spawning period, and requires considerable energy reserves (females become anecdysial from at least April), a correlation with growth was sought. Spawning frequency was most highly positively correlated with mean size in September (0+ years old) at the start of the first spring-summer period of high growth rate ($r = 0{\cdot}86$, $P < 0{\cdot}001$).

4. Cropping

Cropping of larger sized marron (A group dams > 90 g for 8 months; B-group dams > 60 g for 5 months) noticeably reduced the skewness of the final size distributions relative to uncropped dams (Fig. 4, Table 3). The total crop weight (Table 5) was positively correlated with the final mean size of marron surviving in the dams ($P < 0{\cdot}001$) but not to the mean size at the start of cropping ($P = 0{\cdot}15$). Therefore, the crop weight was less dependent upon prior growth rate, and, hence, the weight of croppable marron available at the start of cropping, than on subsequent production. Dam 14B with a much larger initial croppable weight than dam 13A gave a lower total crop weight because of the shorter growth period for B group dams (Table 5). Within A-group dams the production yielding crop-sized marron after cropping commenced was probably dependent upon food supply, the relative reduction in numbers due to cropping being similar in these dams. Cropping did not appear to promote a greater final biomass (including cropped marron) than would have been expected without it. Relative to the biomass at the commencement of cropping, cropped dams did not yield a higher biomass than uncropped dams (Fig. 5). All of the cropped B-group dams and one A-group dam (D7) yielded less biomass finally than was present at the commencement of the cropping or was given by uncropped dams.

5. Seasonal growth and survival

Changes in mean size, surviving number, biomass and production with time within each dam are shown in Figs. 6 and 7.

Seasonal changes in growth rate of the farm dam marron can be expected to be correlated with the annual water temperature cycle, while abrupt decreases in survival rate during summer could be associated with temperature stratification and consequent oxygen depletion in deeper water (Morrissy 1974a).

6. Annual water temperature cycle

Long term mean monthly air temperatures and the general relationship between predicted monthly water temperatures at Kojonup and more climatically equable coastal localities have been presented previously (Morrissy 1974a, 1976a).

Annual variation in surface maximum and minimum and bottom minimum water temperatures at maximum depth over the period of this study are shown as mean monthly values for all dams in Fig. 8. The bottom minimum monthly temperature corresponded closely to the predicted water temperature during the colder months (Fig. 9(a)); however, the almost daily incidence of marked temperature stratification during the warmer months (Fig. 8) was reflected in a marked departure from it. A simple stratification model (Fig. 10) was employed to derive a single monthly water temperature for the average dam water mass (Fig. 8) using the three temperatures recorded monthly on the max-min thermometers. The temperature calculated using the expression (1/4 maximum surface temperature + 3/4 minimum surface temperature + minimum bottom temperature) /2, corresponded most closely to predicted temperature (Fig. 9(b)). For validation, hourly recordings of temperature at surface, 1 m, 2 m and 3 m depths in D1 over the summer of 1974–5 were examined for five days, chosen in a random manner. The mean daily temperature based upon hourly values did not differ significantly from that derived by the above expression ($P = 0{\cdot}40$, mean difference $= 0{\cdot}084$°C). Analysis of daily max-min thermometer recordings from a very shallow pond (< 0·5 m) at the Pemberton Fish Hatchery showed that a calculated mean monthly water temperature varied little whether based upon daily, weekly, or, as in the case of farm dams, a single monthly reading of the thermometer (Morrissy, 1976a).

However, one prominent feature of the monthly temperature incorporating a bottom minimum reading from deeper (> 1 m) ponds or dams was a difference between spring and autumn periods of rising and falling temperatures (Fig. 9(a), (b)). This feature was not an artefact of measurement but is a characteristic of the seasonal heating and cooling of deeper water masses subject to stratification (Szumiec 1978). It has been shown also for a shallow, turbid marron pond (maximum depth 1 m, 800 m^2), subject to stratification, when the monthly water temperature over two years was derived from either single monthly max-min thermometer readings or daily values taken from a continuous strip chart recording (Morrissy unpublished data).

7. Temperature correlated growth

A preliminary summary of the growth of the 0+ and early 1+ year-old farm dam marron showed a seasonal correlation between specific growth rate and water temperature (Fig. 2 in Morrissy 1976a). Two periods of slowed growth could be identified from the growth curves for individual dams (Fig. 6). A marked, virtual cessation of growth occurred during the "winter" period, May-September, corresponding to temperatures below about 12–13°C (Fig. 8), a growth threshold described for laboratory marron by Morrissy (1976a). However, while all 0+ year-old marron were affected, this feature was not always present for 1+ year-old marron particularly in dams otherwise showing a higher growth rate, e.g. D11. Marked slowing of growth also occurred in some dams during the "summer" period, December-April, when bottom water temperatures were most favourable for growth (16–20°C). In most of these dams the event was also associated with a marked decrease in survival rate, e.g. D3, D6, D7. In dams where a mass mortality occurred over summer, there was a decrease in mean size, presumably due to a higher mortality rate for larger marron, e.g. D2, D5. Therefore, an association was indicated between poor summer growth and oxygen depletion, encouraged by temperature stratification, an event explored further in Section 8 below.

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As a consequence in most dams growth over the December-April period fell well below that found in intensive pond culture trials at the Pemberton Fish Hatchery employing higher densities of marron (2–15/m²) (Fig. 11). By contrast, growth of 1+ year-old marron during the "spring" period, August-December, compared favourably with the Pemberton values while 0+ year-old marron greatly exceeded these values (Fig. 12).

8. Limiting summer conditions

During summer, variation in the catch rate of marron from drop nets set over the range of depths in the dams was correlated with the degree of increasing oxygen depletion with depth (Fig. 13). Catch rate was highest in the nets set in shallow water (< 1 m) near the shoreline (nets 1–7, Fig. 13) and was negatively correlated with the relative depth of the 50% oxygen level ($\simeq$ oxycline depth) from the surface i.e. when oxygen levels were lower in deeper water, a higher proportion of the total catch was caught near the shoreline. By contrast, catch rate was lowest in nets set close to maximum depth (nets 13–15, Fig. 13) and was positively correlated with the depth of the 50% oxygen level from the surface. Nets (8–11) set at intermediate depths (< 1 m) on the dam batters (Fig. 13) which have a slope of 1 in 3, showed somewhat higher catch rates than those in the deepest water but the same unfavourable influence of stratified oxygen depletion on marron distribution in the dams was evident.

Some degree of stratified oxygen depletion was a general condition in all the farm dams during summer. One important implication was the effect on growth and survival over summer of enforced crowding of the marron in shallower areas. This crowding effect was of course additional to that due to the decreasing bottom area of the dam under water through the dry season (due to evaporation, etc.). Monthly production per unit bottom area was a sensitive indicator of the less favourable summer dam conditions and significantly decreased over summer in all the dams except D15 and D9 (Fig. 14). The mean fraction of the total bottom areas of the dams which was under less than 1 m of water in February was about 46% (36·0–58·3%) (Table 1). Additionally mid-afternoon water temperatures in shallow water close to the shoreline may have transiently exceeded the incipient lethal high temperature level for marron, 31·5°C at 20°C acclimation (Morrissy 1967a). As well as increased physical crowding, the food supply was sparser in shallower water. The microbially enriched sediments, constituting the marron's food as well as the major source of stratified oxygen depletion, tended to accumulate towards deeper water because of the steep batters (Morrissy 1974a); see Section E,3. The degree of oxygen depletion with depth may vary widely through summer depending on the frequency and intensity of climatic conditions favouring circulation of the water mass (Morrissy 1974a, 1976a); see Section C,2. Apart from these varying factors, a more precise estimate of the degree of physical crowding would also depend upon the, as yet, unknown tolerances of marron to low oxygen levels with respect to avoidance of oxygen depleted regions, feeding activity, ecdysial success and survival. Twelve of the fifteen farm dams showed a continuum of varying degrees of decreased growth during summer, sometimes more extremely accompanied by decreased survival. Even more extremely, mass mortality occurred in the three other dams, in D2 and D5 after the onset of summer and in D4 even earlier, in the spring.

B. ENVIRONMENTAL VARIABILITY BETWEEN DAMS

The RESULTS presented in Section A showed considerable variability in the growth and survival of the marron between dams. Although there is an inverse relationship for marron between growth and density (taken, for example, as mean size and density at two years of age) over the large density range 0·1–25/m² the rate of change of growth per unit density is only appreciable below 1/m² because of the hyperbolic nature of the inverse relationship (see Discussion). Therefore, it is not unexpected that the present variability in growth was not correlated with density in the restricted range given by the five-fold variation in the initial stocking densities (0·5–2·5/m²). Similarly, intensive aquaculture trials at the Pemberton Hatchery within a higher range of densities (2–15/m²) showed only a slight negative influence of density on growth rate (Morrissy 1979) relative to other factors; a major correlation was found at Pemberton between growth rates, biomass change or production and seasonal water temperatures similar to that described in Section A, for the farm dams. But the most important limitation in these trials was the necessity of curtailing feeding during summer and employing mechanical circulation and aeration devices, with continuous pond flushing, so as to reduce oxygen depletion due to organic pollution.

The factors contributing to this serious limitation of intensive aquaculture can also be found in retrospect in an earlier ecological investigation of the marked variability in success of marron between superficially similar farm dams (Morrissy 1974a). The variability between dams was associated with trophic level (taken as the degree of organic sediment loading) and consequent favourability of oxygen levels; in one dam the favourability of the environment for marron survival deteriorated markedly during the investigation due to organic pollution following a heavy summer rain.

The natural seasonal cycle of a farm dam and the daily manual operation of an intensive aquaculture pond are compared in Table 6. Obviously there are important limitations to aquaculture in farm dams in the environmental aspects of vertical water circulation and flushing of accumulated organic loadings; these aspects are examined in the following sections.

C. WATER CIRCULATION AND AERATION

1. Thermal classification of farm dams

In the modification of the Hutchinson-Löffler thermal classification of lakes proposed by Bayly and Williams (1973), these farm dams fall, with some qualifications, into the polymictic category. Polymictic water bodies show no persistent thermal stratification; heating and temporary stratification may occur during the day but at night much of the heat is lost and holomixis takes place. The farm dams are a further example of this category of still waters in temperate regions to those already pointed out by Bayly and Williams (1973). However, the high turbidity is a divergent feature, resulting in steeper, more stable, stratification than in clear water and a very shallow thermocline (usually 0·25–1·5 m). Absorption of most of the daytime insolation close to the surface increases heat loss during the daily overnight cooling cycle. A further qualification is neccessary for the summer period of high insolation and less windy conditions, particularly the lack of storms, when holomixis is infrequent, and meromixis, i.e. vertical circulation to less than maximum depth, is the usual daily event.

Calculation of the average relative depth of the farm dams, using the expression $Z_r = 50\ Z_m\ \sqrt{(¶/A)}\ \%$ gave a value of 8·52. Using the classification of causes of meromixis proposed by Walker and Likens (1975) this value of Z_r falls into the type IV category for endogenesis. That is, meromixis originates by virtue of shelter afforded from wind by the small surface area to maximum depth ratio and by the dam banks. Density stratification is thermal; there is no density stratification contributed chemically by deep water anaerobiosis although oxygen stratification is developed rapidly by sediment respiration.

2. Characteristics of summer stratification

Descriptions of the temperature and oxygen profiles and their diurnal cycles, with and without holomixis, have been given by Morrissy (1974a). The present study was more concerned with the summer frequency of holomixis and the climatic and dam characteristics influencing vertical mixing.

Mean temperatures calculated from continuous recordings in D1 over summer at different depths showed that the mean mid a.m., or minimum, daily temperature decreased with depth (Fig. 15). This feature indicated that equilibration of surface water with deeper water was less than daily and became less frequent with increased depth. An interesting feature shown by Fig. 15, was the fall in temperature at 3 m as the daily stratification developed to a maximum intensity at mid p.m., and conversely, the rise in temperature at 3 m as mid a.m. equilibration was approached.

The water at 3 m in D1 was anoxic when recording commenced on 18 December, 1974, the thermocline being at about 50 cm and the 50% oxygen level at 1·55 m depth from the surface at 15 30–16 00 hrs; re-aeration at 3 m to 50–100% from very low levels occurred over three subsequent periods of 4 days, 10 days and 18 days, the latter terminating in the advent of storms and cooler weather at the start of autumn in mid March (Fig. 9 in Morrissy 1976a). Over these three periods, equilibration of surface with 3 m water occurred on 3, 8, and 12 days, respectively. Re-aeration at the commencement of each period was abrupt due to the advent of a summer "cool change" and windy conditions. Over the whole period of 81 days of recording, equilibration of surface and subsurface water, usually at mid a.m. except during the "cool changes", occurred on 25 days at 3 m, 29 days at 2 m and 50 days at 1 m. However, both the duration of equilibration at 3 m by mid a.m., before heating recommenced (Fig. 16), and the prevailing wind conditions were important variables influencing the degree of re-aeration. The degree of cooling of the surface and subsurface waters overnight necessary to achieve equilibration with the deepest bottom water was dependent upon the temperature of the latter as well as the prevailing air temperatures. Appreciable variability between dams in temperature at maximum depth (18·25–22·0°C), T.M.D., during the February 1975 monthly samplings was significantly related to the Secchi disk depth, Z_{SD} cm. and maximum depth, Z_m cm, ($P < 0{\cdot}001$, $R^2 = 77{\cdot}0\%$) T.M.D. $= 20{\cdot}41 + 2{\cdot}697 \log_{10} (Z_{SD}) - 0{\cdot}01239 (Z_m)$. Turbidity accounted for 53·1% and maximum depth 23·9% of the variability in bottom temperature.

The summer range of daily mixing and re-aeration patterns to 3 m in D1 are illustrated in Fig. 17 and 18. Fig. 17 shows the onset of vigorous long term circulation induced by strong winds from the S.E. with the advent of a typical summer "cool change". Fig. 18 shows the effect of lower than usual overnight temperatures on 25 January, during a period of moderately high daytime temperatures, in producing mid-morning circulation and partial re-aeration over a brief period of two hours. Of particular significance in comparison to the previous day, was the slight but cooler, easterly wind from farther inland passing over the waters surface through the open "front" of the dam.

Under continuously stratified conditions between such brief periods of vertical mixing the 3 m depth oxygen concentration declined steeply (shown in Morrissy 1976a as Fig. 9) due to the respiration of aerobic heterotrophic bacteria in the surface layers of the bottom sediment. Respiration decreased with fall in oxygen tension as shown by the values for oxygen decline, from high newly aerated levels, of 1·4 mg/l for 1 day, 4·4 mg/l for 3 days, 5·5 mg/l for 5 days and 7·8 mg/l for 11 days or 0·7 mg/l per day. Oxygen depletion in a column of water 1 metre deep over one square metre of freshwater sediment is usually about 0·7 mg/l per day (Brewer *et al* 1977).

3. Statistical analysis of factors influencing holomixis and re-aeration in D1

Shaded air temperatures recorded by thermograph located on the instrument raft were highly correlated with standard Bureau of Meteorology readings at Kojonup:

Dam site maximum $= 1{\cdot}13 + 0{\cdot}968$ Kojonup maximum, $n = 23$, $r = 0{\cdot}99$

Dam site minimum $= -1{\cdot}05 + 1{\cdot}05$ Kojonup minimum, $n = 26$, $r = 0{\cdot}97$

On an absolute basis daily minimums and maximums at the dam site tended to be increasingly lower and higher, respectively, towards lower values in each range (minimum, 5–18°C; maximum, 24–39°C) than at Kojonup. However, the incompleteness of the thermograph (7-day) record necessitated use of the Kojonup values in the following analysis.

Results of multiple regression analysis of the recorder data are summarized in Table 7. Daily air and surface water temperatures were highly positively correlated. The number of hours of temperature equilibration of water at 1, 2 or 3 m depth with the surface was less at higher maximum air temperatures and greater at higher wind speeds and when the wind direction was from the sector N.E.–S.E. through the open front of the dam The % O_2 value at 09 00 hours and 3 m depth was less when maximum air temperatures were higher and increased with number of hours of holomixis to 3 m. Increase in the % O_2 value over the previous day was associated with lower minimum air temperatures and more hours of holomoxis to 3 m.

D. FLUSHING

1. Rainfall

Mean annual rainfall at Kojonup is 551 mm and annual pan evaporation is 1 270 mm (Climatic Survey undated). Annual rainfall for 1974, 1975 and 1976 was 600, 540, and 486 mm, respectively. Seasonal variation in rainfall is large; mean monthly rainfall in the driest month, January, is 11·7 mm and in the wettest month, June, 93·7 mm. This normal annual pattern of heavy winter rainfall and infrequent light summer showers occurred in 1974, of above average total rainfall, and in 1975, of average total rainfall (Fig. 19). But in 1976, which had below average total rainfall due to reduced falls in June, July and September, there were several brief but heavy downpours in the period January to April with the passing of thunderstorms.

2. Dilution and overflow

Monthly measurements of salinity and volume provided a useful description of the annual cycle of concentration and dilution of dam waters. While salinity *per se* was concerned in the control of turbidity (Section D5) it could also be taken as a readily measured surrogate for other dissolved substances of trophic significance, i.e. phosphate and nitrate, which were only analysed for bi-annually (Section E7).

The empirical salinity-volume curves departed from the classical dilution-concentration (hyperbolic) curve for a constant total salt content because of greater-than-zero salinity of the wet season inflow and loss of salts due to seepage and stock drinking, sometimes partially offset by seepage gain, during the dry season. When overflow occurred dam salinity could either decrease (usual feature), increase, or remain approximately constant, with constant volume depending on the relative salinity of the inflow at that stage (Fig. 20). Representative curves illustrating these features are shown in Fig. 21. Given adequate annual flushing, i.e. overflow, dam salinity should tend to remain constant from year to year at a given volume, a feature noticed by Morrissy (1974a). Dam salinity at the full volume should approach the salinity of the inflow to a degree dependent on the extent of overflow.

During the annual period of drawdown, September-April, marked increase in salinity occurred due to the high evaporation rate (mean standard pan evaporation at Kojonup $\backsim$ 200 mm/month during summer); but appreciable decrease occurred in total salt due to seepage and stock watering (Table 8). Inflow during most of the wet season only served to reduce salinity while increasing the total salt content. Actual flushing of the dams, i.e. reduction in the total salt (and nutrient) content occurred, if at all, towards the end of the wet season with overflow in August or September. Volume of inflow/month (m^3) was significantly positively related to monthly rainfall (ml) but also to number of months from April (April = 0, May = 1, etc.) ($P < 0{\cdot}001$), viz (inflow) = —170 + 0·066 (rainfall) + 196 (month). Extensive priming of the catchments by considerable initial rainfall is neccessary before major flood runoff occurs in the region (Clarke 1970).

The mean total salt content of the dams increased over the three years of study because of decreasing rainfall (Table 8). All the dams overflowed in 1974, 60% overflowed in 1975—a year of average rainfall, but only 8% overflowed in 1976 (Fig. 22). Rainfall salinity averaged 21·5 mg/l from May to November 1975 (range 11·0–37·1 mg/l). Although corrected for evaporation in the rain gauge, this value was considerably higher than that of about 8 mg/l estimated by Hingston (1958) for Kojonup. Inflow salinity varied from month to month with a tendency, not statistically significant, to be negatively correlated to volume of inflow; mean inflow salinity for the dams over three years was 207 mg/l (range 89–573 mg/l) (Table 8). For the successive years of decreasing incidence of overflow, dam salinity at maximum winter volume was decreasingly correlated with mean inflow salinity over the months of inflow as follows:

1974, correlation coefficient $r = 0{\cdot}81$ ($P < 0{\cdot}001$);

1975, $r = 0{\cdot}61$ ($P < 0{\cdot}05$);

1976, $r = 0{\cdot}40$ (n.s.)

Examples of salinity conditions during early filling and later overflow in a dam are shown in Fig. 23.

3. Turbidity

Suspended clay-silt was a primary constituent of the water supply, sometimes exceeding salinity in concentration, and flocculated with organic matter to form the dam sediments (90% clay-silt) upon which the marron fed selectively (Section E,2). Concentrations of clay-silt ranged up to 2 600 mg/l (Z_{SD} 2·5 cm) in D6, the sole montmorillinite clay dam or 1 280 mg/l (Z_{SD} 4·0 cm) in the other, kaolin clay, dams, while salinity was in the range 178–1 126 mg/l. Clay-silt was usually in the range 150–600 mg/l corresponding to a Z_{SD} range of 6–20 cm (Fig. 24). The greatly reduced light intensity experienced by the marron gave high daytime catch rates; feeding activity is normally restricted to night-time in clear water (Morrissy, 1974a). High turbidity also prevented bird predation, a major cause of mortality in clear water dams or uncovered commercial aquaculture ponds with little or no refuge cover for marron (Morrissy 1974a, 1976a). High turbidity, also confined daytime heating to the near surface layers (Section C 2) and reduced heating by enhancing albedo or reflection of solar radiation (Schiebe *et al* 1975). The light transmission characteristics of farm dam water appeared to be radically different from those of transparent freshwater (or distilled water) in the red to infra-red wave length range (Fig. 25). However, values of 3·5 times the Secchi disk depth were usually close to the measured depth of 1% transmission of surface P.A.R. irradiance which is taken as the compensation depth, or lower limit to the euphotic zone (Holmes 1970) (Fig. 26). The light intensity at the Secchi depth has also been taken as about 5% of that of the surface and approximately the lower limit of the major photosynthetic zone (Odum 1971).

Satisfactory measurement of high turbidity was difficult (Morrissy 1977). At concentrations of clay-silt above about 600 mg/l both the Secchi disk and nephelometry gave lower values for turbidity than expected and the latter method could not be standardized because of varying bias dependent upon the degree of dilution (Fig. 24). Calculated values of clay-silt concentration (mg/l) by the routine monthly subtraction method (S) were lower than those given by the filtration method (F) developed later during the study, due to loss of volatile salts in drying and ignition of water samples:

$$F = 133 + 1{\cdot}20S,\ n = 27,\ r = 0{\cdot}87,\ P < 0{\cdot}001.$$

There was no significant difference in the total suspended solids (T.S.S.) between water samples from the surface and 200 cm depth in D3, showing a seasonal cycle in turbidity, nor in D6, showing a stable turbidity.

4. Variation in turbidity

Some dams maintained a high and relatively constant turbidity over the period of study, i.e. D1, D6, D7, D9, D11, D13 (Table 9). Other dams showed a seasonal decrease in turbidity during summer, suggesting a (negative) correlation with increasing salinity, i.e. D3, D12, D14, D15. Dams D17 and D18, which maintained stocks of marron over the study, showed longer term trends of decreasing and increasing turbidity, respectively. Finally dams D2, D4 and D5 showed decreasing turbidity until a spring or summer period of mass mortalities associated with intense green algal blooms.

Clay type, particle size and water salinity were examined as probable causes of this variability. Soils from the wheatbelt are fairly uniform over wide areas, with clay contents less than 35%, silt contents less than 12% and with kaolinite (white china clay) as the predominant clay material (Turton *et al* 1961). These contrast with the red piping soils in eastern Australia which tend to have clay contents in excess of 40% and have either montmorillinite (bentonite type clay) or illite as the chief clay constituent (Wood *et al* 1964). Montmorillinite clay particles are smaller (specific surface, 475 $m^2 g^{-1}$) and lighter s.g. 1·8–1·9) than those of kaolinite (8 $m^2 g^{-1}$, s.g., 2·65), they disperse more readily in water as very fine particles (high plasticity) and form more stable suspensions less likely to aggregate and flocculate (Fietz 1969; Edzwald and O'Melia 1975; Walker and Hutka 1976).

The total cation concentration and the proportion of sodium cations to the total exchangeable cations adsorbable on clay are known to be determinants of clay suspension kinetics in relation to "piping" or failure of farm dam walls (Wood *et al* 1964; McKenry 1966; Fietz 1969).

5. Salinity and turbidity

Sodium and chloride dominated the ionic composition of the salinity; bicarbonate was also a major ion, no carbonate being present at the neutral to alkaline pHs encountered (Table 10). Chloride was closely related to conductivity, K_{20}, over the range 55–315 mg/l,

$$Cl^- = -50 + 0{\cdot}30\ K_{20}$$
$$n = 68,\ r = 0{\cdot}93,\ P < 0{\cdot}001$$

The bicarbonate /K_{20} relationship for dams D1, 4, 5, 6, 11, 14, 15, 17, 18 over a range of 60–280 mg/l was:

$$HCO^-_3 = -46 + 0{\cdot}37\ K_{20}$$
$$n = 42,\ r = 0{\cdot}88,\ P < 0{\cdot}001$$

and for dams D2, 3, 7, 9, 12 ,13 over a range of 55–210 mg/l was:

$$HCO^-_3 = -75 + 0{\cdot}25\ K_{20}$$
$$n = 26,\ r = 0{\cdot}83,\ P < 0{\cdot}001$$

More than 50% of the variability in turbidity between farm dams could be explained by the following ionic factors (Table 11). Conductivity was taken as a relative measure of cation concentration and the sodium adsorption ratio, S.A.R. $= Na^+/\{(Ca^{2+} + Mg^{2+})/2\}^{\frac{1}{2}}$ in me/l, as a measure of the sodicity or exchangeable sodium percentage of the water.

Total suspended solids, T.S.S. (mg/l), was significantly related to salinity, as K_{20} ($\mu S\ cm^{-1}$), and S.A.R. by multiple regression analysis;

July 1974: T.S.S. $= -256 - 1{\cdot}93\ K_{20} + 576$ S.A.R.
$n = 13$; $R^2 = 58{\cdot}7\%$; K_{20} ($P < 0{\cdot}01$); S.A.R. ($P < 0{\cdot}01$); overall ($P < 0{\cdot}01$).

February 1975: T.S.S. $= 113 - 1{\cdot}19\ K_{20} + 268$ S.A.R
$n = 15$; $R^2 = 72{\cdot}1\%$; K_{20} ($P < 0{\cdot}01$); S.A.R. ($P < 0{\cdot}001$); overall ($P < 0{\cdot}001$).

July 1975: T.S.S. $= 259 - 1{\cdot}39\ K_{20} + 333$ S.A.R.
$n = 15$; $R^2 = 79{\cdot}2\%$; K_{20} ($P < 0{\cdot}001$); S.A.R. ($P < 0{\cdot}001$); overall ($P < 0{\cdot}001$).

February 1976: T.S.S. $= 505 - 2{\cdot}15\ K_{20} + 422$ S.A.R.
$n = 13$; $R^2 = 51{\cdot}1\%$; K_{20} ($P < 0{\cdot}05$); S.A.R. ($P < 0{\cdot}05$); overall ($P < 0{\cdot}05$).

August 1976: T.S.S. $= 905 - 2{\cdot}67\ K_{20} + 511$ S.A.R.
$n = 7$; $R^2 = 97{\cdot}1\%$; K_{20} ($P < 0{\cdot}001$); S.A.R. ($P = 0{\cdot}001$); overall ($P = 0{\cdot}001$).

Total Suspended Clay (T.S.C.) values gave similar results, e.g.;

July 1975: T.S.C. $= 96 - 1{\cdot}20\ K_{20} + 295$ S.A.R.
$n = 15$; $R^2 = 75{\cdot}9\%$; K_{20} ($P < 0{\cdot}01$); S.A.R. ($P < 0{\cdot}001$); overall ($P < 0{\cdot}001$).

February 1976: T.S.C. $= 479 - 2{\cdot}14\ K_{20} + 393$ S.A.R.
$n = 13$; $R^2 = 59{\cdot}3\%$; K_{20} ($P < 0{\cdot}05$); S.A.R. ($P < 0{\cdot}01$); overall ($P < 0{\cdot}05$).

August 1976: T.S.C. $= 843 - 2{\cdot}54\ K_{20} + 453$ S.A.R.
$n = 7$; R^2 $98{\cdot}0\%$; K_{20} ($P < 0{\cdot}001$); S.A.R. ($P < 0{\cdot}001$); overall ($P < 0{\cdot}001$).

The constant term (TSS mg/l) in the multiple regressions increased with time as did the regression coefficients for K_{20} and S.A.R. (TSS mg/l per unit of K_{20} or S.A.R.) and the amount of variability (i.e. R^2) in TSS which was statistically correlated with variation in K_{20} and S.A.R. These changes with time can be interpreted as an increasing reliance of turbidity control on K_{20} and S.A.R. associated with the decreasing incidence of annual flushing of the dams and its variability between dams after 1974.

The interesting feature of this control of turbidity by the opposing effects of increasing salinity and S.A.R. was that S.A.R. tends to increase significantly with increasing salinity (Fig. 27) balancing the negative effect of the latter over a wide range of salinity than would otherwise be the case:

S.A.R. $= 1{\cdot}54 + 0{\cdot}310 \times 10^{-2}\ (K_{20}) - 0{\cdot}147 \times 10^{-6}\ (K_{20})^2$, $n = 32$, $R^2 = 0{\cdot}966$, $P < 00{\cdot}001$. Although divalent cations, the denominator in S.A.R., increase in absolute amount with increasing salinity, relative to monovalent sodium, calcium (or magnesium) is a lower proportion of the total salinity in more saline than in fresher water (Fig. 27). $Ca^{2+} = 10{\cdot}5 + 0{\cdot}103 \times 10^{-1}(K_{20}) - 0{\cdot}891 \times 10^{-6}(K_{20})^2$ $n = 70$, $R^2 = 0{\cdot}841$, $P < 0{\cdot}001$.

The study dams were not representative of the Kojonup area with respect to salinity. Other dams may show higher salinities because of the widespread salinizaton of flat land soils and surface water (Morrissy 1974a, 1974d, 1978b), e.g. D16 with $K_{20} = 2\,350\ \mu Scm^{-1}$ in February 1974.

6. Particle size

Suspended clay in the highly turbid dam D6 (appearing red-brown at high turbidities) was analysed by X-ray diffraction (Government Chemical Laboratories, Perth) as kaolin (20–60%) and montmorillinite (20–60%) with no illite or calcite detectable. Dam D3 was taken as representative of the other dams the clay being kaolinite (> 60%) with illite (< 10%) in the > 3 μm fraction and calcite only detectable in a < 3 μm subsample (< 10%).

The changes in the particle size distribution and total suspended clay concentration in D3 over a year were probably influenced by four factors (Fig. 28). In June (1976) and July (1975) higher turbidity and a higher proportion of larger particles were probably due to inflow of material as the dam filled. The following fall in turbidity in August and September occurred with flushing by overflow. High turbidity and more larger particles occurred again during January and March, probably due to the activity of the dense population of marron crowded into shallower water because of oxygen depletion in deeper water (Section A.8). Subsequently, turbidity fell with increase in salinity until the end of the dry season. Excluding the August and September data during overflow there was a positive correlation between the percentage of particles > 5 μm and K_{20} (r = 0·88, P < 0·001) indicating partial aggregation at higher salinities (see Kranck 1973). About 80% of the suspended material in the montmorillinite dam D6 was of coarse clay (0·2–2 μm) and fine clay (< 0–2 μm) sizes, while silt sizes predominated in the other dams except for D9 and the clear dam D18 (Fig. 29).

E. TROPHIC FACTORS

1. Other Fauna

Species of other invertebrates sampled belonged to the Gammaridae, Corixidae, Ostracoda, Dytiscidae, Trichoptera, Notonectidae, Chironomidae, Gastropoda, Copepoda and Daphnidae. Previous investigation of farm dams showed a strong negative correlation between abundance of marron and relative numbers of other invertebrates in different dams during summer (Morrissy 1974a). Dams with high numbers of marron and favourable oxygen levels were characterized by high relative densities of aquatic respirers such as Gammaridae; less favourable dams were characterized by very high (relatively or absolutely) densities of aerial respirers, notably Corixidae. The Gammaridae predominated in D13 during the winter of 1974 and again during the following spring after the August-September overflow ceased (Fig. 30). However, Corixidae, with Ostracoda, dominated the autumn peak in invertebrate numbers in both 1975 and 1976, but the peak was less pronounced in 1976 and there were no intervening peaks involving Gammaridae in 1975. The effect over all the dams on total invertebrate numbers of introducing marron was one of drastic reduction (Fig. 31). In general, higher total numbers of invertebrates (I) were associated with a higher Corixidae/Gammaridae ratio (C/G) (range 0·06–850), I = 350 + 1·39 C/G n = 40, r = 0·45, P < 0·001, as found previously by Morrissy (1974a).

2. Stomach contents and sediments

Microscopic examination of stomach contents indicated that the marron appeared to feed on the dam sediment detritus. Organic content of stomach contents (n = 40) was 81·1% ± 12·2 while that of the sediments at maximum depth and organic content (n = 144) was 11·3% ± 2·38, implying selective feeding. Stomach contents (S_{g}) increased in quantity with increase in size (O.C.L. 2·0–7·3 cm) S = 0·36 + 0·14 O.C.L., n = 40, r = 0·61, P < 0·001, averaging 210 mg ± 213; S = 0 when O.C.L. = 2·5 cm. Percentage organic level of the stomach contents (SO) decreased with increase in size, SO = 100–4·82 O.C.L. n = 40, r = 0·35 P < 0·05, implying that larger marron were less adept at selecting finer particles, which have a higher microbial content (Hargrave 1972).

In terms of total dry weight of surface (1 cm deep) sediment sub-samples, protein was 2·2% ± 1·4 (0·67–6·6), obviously constituting an inadequate diet; but in terms of organic dry weight the protein content was 19·6% ± 12·8 (5·5–57·4) (n = 35, mean organic content = 11·6% ± 2·7 (5·2–15·5)). Based upon the organic content of the stomach contents, the latter would contain 15·4% protein by dry weight.

3. Sediments

Mean % organic matter at maximum depth varied little between dams (but see Section 5) except for the highly turbid dam D6 which gave consistently lower values (Table 12). There was no significant variation with time over the three years covered by eleven samplings. Values were similar to those found previously in farm dams (about 11% organic matter) except for a grossly polluted dam showing 43% organic matter (Morrissy 1974a). They represent a considerable degree of organic enrichment over levels of 2–4% organic matter found in surface soils (Satchell *et al* 1975). Similar values have been found in Tasmanian farm dams (Walker 1974).

Mean sediment depth (D) at the centre showed more variation between dams and increased over the three years (t, months) by about 11 cm (16·7 cm, true depth). D = 26·7 + 0·305 6 t, n = 11, r = 0·91, P < 0·001.

Apparent sediment depth (AD), i.e. as measured on the core tube, was related to true depth (TD) by TD = 1·52 AD, n = 7, r = 0·99, P < 0·001.

Sediment depth, over the base clay bed, significantly increased from shoreline to centre i.e. from shallow to deeper water (Fig. 32), a process termed "focussing" by Likens and Davis (1975), as found previously (Morrissy 1974a). Percentage organic matter increased significantly as sediment depth increased in dams showing appreciable depth of sediment at the centre (Fig. 32).

4. Pasture

Attempts to sample the runoff load from pastures quantitatively were unsuccessful due to the infrequency of visitation and hence flooding of catchment tanks set in runoff channels leading to a dam. Quadrat sampling of pastured or cropped catchment showed that fine plant debris (< 500 μm), observed to be carried into dams, was twice as plentiful on the catchments in 1975 and 1976 (1·5 kg m^{-2} dry weight) as in 1974 (0·77 kg m^{-2}) after less winter rainfall to August in 1975 and 1976; coarser material, including germinated pasture or crop, was at about the same level (1·1 kg m^{-2}) in August in all years (Fig. 33). Most of the active plant growth occurred from September to November, providing the source of the following year's fine debris.

5. Organic content of sediment and water

The organic content of the sediments showed only small apparent variation between dams despite the wide variability in total suspended clay and in the total organic concentration (Table 12). Neither season of the year nor presence or absence of marron had any obvious effect on organic content of the sediments. However, the organic content of the sediments was positively correlated with the higher and more widely varying organic content of the total suspended solids (plus D.O.M.) complex, supplying the sediments, % organic sediments = 10·6 + 0·022 5% organic T.S.S. n = 16, r = 0·55, ($P < 0{\cdot}05$).

Total organic concentration (T.O.) in the dam water was highly positively correlated with total suspended clay concentration (T.S.C.) between dams, T.O. = 77·6 + 0·126 T.S.C. n = 16, r = 0·83 ($P < 0{\cdot}001$). Since addition of clay to leachates (D.O.M.) of organic material results in rapid flocculation of both organic and inorganic components this positive correlation indicates that most of the total organic material was of a particulate form.

In summary, dam waters with a higher clay turbidity had a higher total organic content but a lower % organic content contributing to a lower sediment % organic content. The organic fraction of the suspended solids in the water, contributing to the organic fraction of the sediments, appeared to be much smaller in less turbid dams, suggesting that most of the organic fraction in the latter was unicellular algae and zooplankton, settling at a much lower rate than clay-silt. In the more turbid dams (see next Section) there appeared to be, besides algae, a greater proportion of the organic material in a form which settled out at a rate closer to that of the clay-silt or in association with the latter.

There was no significant difference in concentration of clay-silt or organic material between the usual surface water samples and ones taken at 200 cm in D3 and D6 ($P > 0{\cdot}05$).

Despite the very high clay-silt turbidity of D6, this dam was subject to intense algal blooms in the last year of study as phosphate built up in the dam due to lack of flushing. However, the sediments were not enriched organically and marron growth remained poor; the organic contents of water and sediment relative to clay remained low.

6. Algal blooms

No attempt was made to investigate the algae further than by using photosynthetic pigment concentration as a surrogate for algal biomass. Since chlorophyll is only a very small fraction of the total biomass of algal cells, changes in pigment concentration are not necessarily correlated with biomass change; the chlorophyll/biomass ratio may change as a result of change in turbidity or with nutrient limitation (Fraleigh 1978) and where the euphotic zone is thermally stratified through summer (Paerl *et al* 1976).

Taking the chlorophyll "a" concentrations (ug/l) analysed monthly over a year, there was only a weak but significant positive correlation with the reciprocal of the Secchi disk depth (Z_{SD}):

$$\text{Chlor "a"} = 0{\cdot}039 + 0{\cdot}000\,27\ (1/Z_{SD})$$
$$n = 193,\ r = 0{\cdot}145\ (P < 0{\cdot}05);$$

mean chlor "a" = 68·5 ± 116·3 ug/l, mean Z_{SD} = 9·1 ± 16 cm. The correlation was more pronounced with the inclusion of pheopigments:

$$\text{Chlor "a"} + \text{pheopigment} = 0{\cdot}085 + 0{\cdot}0016\ (1/Z_{SD})$$

r = 0·629 ($P < 0{\cdot}001$), mean pigments = 89·5 ± 159 ug/l.

Algal blooms contributed to turbidity so the correlation was less, but only to a minor extent, when total suspended clay concentration (T.S.C. mg/l) was substituted,

$$\text{Chlor "a"} + \text{pheopigment} = 6{\cdot}2 + 0{\cdot}23\ \text{T.S.C.}$$

r = 0·527 ($P < 0{\cdot}001$), mean T.S.C. = 373 ± 516 mg/l.

Pigment concentrations at the surface and at 2 m depth from the surface in the highly turbid dam D6 (Table 13) reflected wind-induced water circulation and the buoyancy behaviour of algae in turbid farm dams. On one occasion an extremely dense algal bloom was observed in a dam with high clay turbidity as a dark (green) surface mat at first light; the mat rapidly dispersed to subsurface layers as the sunrise advanced. Buoyancy mechanisms (Fogg and Walsby 1971) probably play a very important role in algal production in the highly turbid farm dams; algal species which have the ability to float into the very limited illuminated surface water layer no doubt have an enormous selective advantage. Retention of viability under aphotic conditions may also be an important factor in phytoplankton production (Vincent 1978).

Algal production usually shows strong seasonal cycles depending upon the availability of light and nutrient phosphate; four consistent peaks could be identified over a year in the farm dams (Fig. 34). Peak A was probably promoted by nutrient washed into the dams in the early part of winter; similarly peak C during summer was probably encouraged by increased release of phosphorous and nitrogen in soluble inorganic forms from anaerobic bottom sediments (Mortimer 1942). Peaks A and C were shown by chlorophyll "a" and its degraded (pheo-) pigments at 665 nm, and by the optical density at 430 nm. Peak B, following the August-September period of minimum concentration of salts in the dams and dilution by overflow, was shown only by pheopigments and probably resulted from the breakdown of filamentous algae observable annually along the dam shorelines. Peak D in winter was shown only by pheopigments probably derived from allochthonous organic matter washed into the dams by runoff. Laboratory tests on three year old dried clover confirmed the persistence of pigments (Yentsch 1967) (Table 14).

Examining each of the dams separately, there was no correlation between monthly total organic material (T.O.) in the water and pigments except for D6. In D6, showing the highest total organic levels (302 ± 363 mg/l and developing an intense algal bloom towards the end of the study (430 ± 78 ug/l), there was a positive correlation:

$$\text{Chlor "a"} + \text{pheopigment} = -327 + 2{\cdot}51\ \text{T.O.}$$
$$n = 17,\ r = 0{\cdot}538\ (P < 0{\cdot}05)$$

Examining the same relationship for each month over all the dams there were weak positive correlations for October (peak B) and June and July (peak D) and strong ones for January and March (peak C) (Table 15). Rooted emergent higher plants were not present at any time in the dams.

The estimation of pigment concentrations did not include that of bacteriochlorophyll which has a maximum peak for optical density at 772 nm, which may be more significant than that of chlorophyll at 665 nm; Hussainy (1973) has discussed this usually neglected feature of photosynthetic pigment estimation.

7. Nutrient phosphorous

Measurement of phosphorous in various forms and its dynamics in aquatic ecosystems and, in particular, in the phosphate form immediately limiting algal production is extremely complex and fraught with difficulties of interpretation.

Platell and Jack (1974) concluded from an analytical viewpoint that for water samples total phosphorous is the only "definite measurable phosphorous form".

Using the biannual estimates of total phosphorous in solution (Table 16), pigment concentration (chlorophyll "a" plus pheopigment ug/l) was significantly positively correlated with phosphorous, P mg/l, in February 1976 (P = 0·22 ± 0·12 mg/l; pigments = 55 ± 36 ug/l) but not in July 1975 (0·04 ± 0·03 mg/l; 73 ± 46 ug/l) or, discounting D6, in August 1976 (0·30 ± 0·28 mg/l; 64 ± 50 ug/l).

For February 1976, pigments = —3·20 + 271P, n = 13, r = 0·85, ($P < 0·001$). When pigments = O, P = 0·012 mg/l which is close to the threshold usually observed for nuisance blooms of algae (0·015 mg/l, Sawyer 1966) or eutrophication (Vollenweider 1968). However, the positive relationship implies that most of the phosphorous in solution may not have been in an available nutrient form and/or that shading by clay turbidity suppressed algal utilization of phosphate.

Dams with the highest turbidities also showed the highest phosphorous levels, e.g. D6, D7, total phosphorous in solution being significantly positively correlated with both the reciprocal of the Secchi disk depth or total suspended solids ($P < 0·01$).

Mean phosphorous level in the dams was related to the incidence of overflow and flushing each winter, reaching a minimum value (0·04 mg/l) after the above average rainfall winter of 1974 and rising to a maximum (0·30 mg/l) in 1976 with lack of runoff (Fig. 35). The N/P ratio showed the opposite trend: March 1974, 23·5; July 1974, 12·8; February 1975, 58·3; July 1975, 72·0; February 1976, 14·7; August 1976, 12·7.

Total particulate phosphorous exceeded total phosphorous in solution, e.g. in October 1976 for D14, 0·15 and 0·06 mg/l, respectively, and for D6, 0·82 and 0·53 mg/l, respectively. Total phosphorous in solution included phosphorous absorbed on clay particles passed by a 0·45 μm filter. Since D6 showed a much higher proportion of these smaller particles than other dams, values for phosphorous in solution were likely to be correspondingly inflated.

8. Nutrient and organic pollution

Organic pollution is the most common cause of deterioration in the quality of farm water supplies (Victorian Irrigation Research and Advisory Services Committee 1969). Nuisance algal blooms are common (Aplin 1967; Potter 1971). The noxious effect of collapsed algal blooms can be disastrous for aquatic life (Barica 1975).

Sudden nutrient and organic overloading of farm dams by high inputs of fertilizer, stock manure and pasture or crop debris due to summer thunderstorms, experienced in a previous study (Morrissy 1974a), was prevented in the present study by diversion banks.

Information on the effects of flooding prior to the commencement of this project was provided from chemical analyses of dam waters sampled just before and after such pollution. These were undertaken by Government Chemical Laboratories, Perth, using samples provided by the Department of Agriculture, Perth (I.A.F. Laing pers. comm.). This thunderstorm (10 February, 1973) was the fourth highest daily downpour (40 mm) recorded at Kojonup over summer in 22 years Many of the dams offered for the present marron study by farmers were polluted at this time. The immediate effect of the inflow was a dramatic decrease in salinity (Table 17). However, both pH and oxygen levels (at the surface) fell and there were very large increases in phosphorous and D.O.M. (colour). Taking into account the dilution factor, organic nitrogen and ammonia, found under reduced (anaerobic) conditions, also increased to very high levels.

A stock inspector, P. A. Brett, of the Department of Agriculture described such pollution in an unsolicited letter to the Department of Fisheries and Wildlife dated 29 April, 1970. "Due to the cyclone 'Ingrid' in February many dam waters were contaminated due to the washing in of large quantities of sheep manure and debris from paddocks. In a number of cases marron were found either dead on the dam edges or very dopey and sick." Long term effects of such severe pollution on any surviving marron were concisely expressed in another such communication from a farmer (L. Woods, Brookton, undated). "Please find enclosed a bottle of some type of tick (eggs of Corixidae) which is stuck to our marron in a dam." "The whole of the body is just covered with them." "The water has gone rather green in colour." "The marron came to the edge of the water and died." "We did have sheep in the paddock but the water made them very wormie and thin."

During the present study, a number of thunderstorms passed over the Kojonup area during the summers of 1975 and 1976 but not in 1974. Neither of the only two storms in 1975, both during March, yielded more than 10 mm of rainfall; but very strong swirling winds during the second storm on March 20, 1975 deposited large quantities of debris in D3, D5 and D12. Eucalypt leaf leachate coloured the clay turbidity of D12 yellow for several subsequent months, crop debris darkly coloured D3 briefly, and pasture debris darkly coloured D5 severely for many months. These inputs were of no apparent trophic significance to D3 and D12. But in D5 the already unfavourable oxygen levels were intensified and the few surviving marron were taken by bird predators at the shoreline. These events suggest that the various types of allochthonous organic material differed in nutrient enrichment because of the degree to which they were refractory to decomposition, i.e. pasture > crop > bush (Moore 1974). Widespread heavy rain occurred on January 7, 1976 with falls of 40–50 mm at Kojonup townsite and all dam sites. However, D11, the only dam not provided with a summer flood diversion bank was not polluted by this early summer downpour of 51 mm.

The next thunderstorm on February 22, 1976, gave about 10 mm of rainfall at all the dam sites except D13, where a brief downpour of 47 mm was recorded. Due to a substandard flood bank of sand rather than clay, some inflow of crop debris occurred. The amount of organic material did not appear to be excessive, as growth of the marron increased greatly in March having been very poor during the previous spring.

The sporadic nature of downpours and the catastrophic effect on farm dam water quality for humans, sheep and marron from this storm was reported in the popular press (Bunny 1976). A further brief downpour of 34 mm at Kojonup townsite on March 13–14, 1976, did not extend to the dam sites.

Cattle and sheep manure were obvious sources of nutrient and organic pollution. Cattle unlike sheep defaecate and urinate directly into dam waters while wading to drink. However, flocks of sheep provide large amounts of persistent faecal pellets often washed into dams. Dams which supported both cattle and sheep were D3, D11 and D17 and the failed dams D4 and D5. D14 and D18 supported cattle only, while the remainder of the dams carried sheep only.

Most of the dam catchments had mixed pasture including clover; D3 and D17 were cropped and D6 and D13 were pastured at first and later cropped; native trees (Table 18) were sparse except on D7. Catchment paddocks were fertilized annually with approximately 120 kg/ha of superphoshate. Size of dam catchments were:—10–12 ha, D6, D15; 12–30 ha, D2, D7, D9, D11, D12, D14, D17; 30–50 ha, D1, D3, D4, D13, D18. Another source of organic pollution was shallow flooding of catchment pasture (which decomposed swiftly in solution) by dam waters at full stage during winter. (By the nature of the construction of excavated farm dams, the site is cleared of any nutrient-rich plant material before inundation c.f. "gully dams".) This event only occurred in two dams D4 and D5 both of which suffered subsequent mass mortality of marron. D2, the other failed dam, had to be filled (from a polluted saline creek) in 1970 due to lack of run-off after construction in 1969 and did not fill again until 1974.

All the failed dams, D2, D4 and D5, and the dam showing the highest level of marron growth (D3), were located on the same property.

There was no clear relationship between chronological age of the dams and trophic level measured as either sediment depth, level of marron production, or water quality parameters. Eleven of the dams were constructed between 1964 and 1969; D18 (1953) and D13 (1959) had sediment depths at maximum water depth of 53 and 35 cm, respectively, while D5 and D1 (both 1972) had depths of 38 and 19 cm respectively. Walker (1974) also concluded for Tasmanian farm dams, that beyond a certain initial stage the age of farm dams had little apparent effect upon limnological properties compared with other factors, notably stock usage.

9. Trophic index for marron production

Dams showing the lowest marron production, taken as the cumulative production to 18 months of age, were characterized by a high and seasonally stable (particularly during summer) clay turbidity i.e. D6, D7, D9 and D11; dams with the highest production tended to clear of clay turbidity during summer and showed green algal blooms during the height of summer, i.e. D3, D15, D17 and D18; dams in which marron failed, cleared of clay turbidity rapidly during the spring and showed intense green algal blooms, i.e. D2, D4, and D5. Mean Secchi disk depth over the production period, or just for February during the first summer of residence of the marron in the dams (14 months of age), and the apparent water colour were sufficient to establish a trophic index (Fig. 36).

Cumulative production of marron to (or biomass at) 18 months of age was also broadly positively correlated with calcium ion concentration (7–33 mg/l), viz $P_{18} = 263 + 12 \cdot 2\ (Ca^{2+})$, $r = 0 \cdot 57$, $P < 0 \cdot 05$, a similar finding to Morrissy (1970a). Dependence of freshwater crustacean physiology on calcium levels in the environment, for example, for ecdysis, have, however, long been discounted (Bayly and Williams 1973). Associations between bacterial activity, rate of detrital formation and calcium appear to be important (Egglishaw 1968, Ordal 1977). Increasing calcium level was also associated with decreasing turbidity ($r = 0 \cdot 66$, $P < 0 \cdot 01$) due to the ionic mechanisms controlling flocculation of clay, through either increasing salinity or decreasing S.A.R., described earlier.

Turbidity due to suspended clay, to which water quality factors such as total organic matter, photosynthetic pigments, and phosphorous levels were positively correlated, obviously played a unique role in suppressing unfavourable effects of eutrophication. Clay turbidity appeared to suppress incorporation of high levels of phosphorous in solution into noxious algal blooms to a considerable degree permitting marron production and survival under conditions usually judged, on the basis of nutrient concentration, as highly eutrophic (compare Figs, 36 and 37). The combination of respiring bottom sediments and algal blooms in producing severe oxygen deficits in the water column, notably before sunrise, also appeared to be radically suppressed in turbid dams; for example turbid dams had much lower oxycline gradients than clearer dams (Fig. 38).

IV. DISCUSSION

1. Trophism

A numerical classification of trophism is preferable to a nomenclatural one (oligo-, meso-, eutrophic). At present the trophic status of water bodies is difficult to measure objectively, particularly in Australia and more so with the turbid farm dam. In Australia high nutrient levels, usually taken as indicating eutrophy, are prevalent but are often unaccompanied by the nuisance algal blooms which result overseas; possibly this is due to the suppressing influence of inorganic turbidity, water colour, or salinity (Williams and Wan 1972; Moore 1974; Wood 1975).

Use of turbidity as a trophic index for stillwaters has been confined to organic turbidity where positive correlations can be established with algal pigments or biomass, phosphorous concentrations or loadings, and oxygen deficits; the presence of suspended inorganic matter (clay-silt) and colour (D.O.M.) invalidate this autotrophic model (Eberly 1975; Carlson 1977; Brezonick 1978).

While the autotrophic model is most commonly applicable it appears to describe only one trophic outcome of increasing phosphorous (and nitrogen) loading of water bodies. The other, much more rarely expressed, extreme, the heterotrophic model, is Hutchinson's "argillo trophic" lake system which has the following characteristics (Daborn 1975): extreme shallowness (< 1m) relative to a large wind-swept surface area resulting in extreme turbidity (4–5mm), either temporary or perennially astatic water levels, relatively high levels of dissolved phosphorous and nitrogen (eutrophic), virtually no phytoplankton, a very limited but abundant zooplankton (phyllopods, daphnids, copepods) heterotrophically dependent upon suspended allochthonous

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detritus, and a very sparse bottom fauna (chironomids, corixids, notonectids). The farm dams described in this study appear to be intermediate between these two model extremes. The action of suspended clay-silt in suppressing autotrophic expression of high phosphorous loadings is of interest in bridging the models.

Obviously a greater phytoplankton biomass is often sustained in turbid farm dams than might be expected from the degree of shading (Weatherley 1958; Ericksen 1966). Differences in the types of algae between less and more turbid dams should be investigated particularly with regard to buoyancy and aphotic viability.

Suspended clay also undoubtedly has an important influence on reducing amounts of inorganic and organic nutrients in solution through adsorption (Rae and Bader, 1960). Availability to heterotrophs may not be affected (Button 1969). Release in a soluble form available to planktonic algae may require sedimentation of the clay particles and anaerobic conditions (McColl 1975). Farm dams showing a range of clay turbidities present an excellent opportunity for assessing the relative importance of biological and physical uptake of phosphorous in solution. However, one of a number of analytical difficulties is the assessment of phosphorous adsorbed on 'filterable' clay particles.

Further research on the interesting trophic complexity of farm dams may be more rewarding if the water body and catchment are viewed as the ecosystem rather than just the former (Odum and Prentki 1978). And the dynamics, rather than the static biomass, of microbial and algal populations should be estimated in terms of phosphorous and organic, 'loadings' of the water mass (Vollenweider 1976). In terms of crayfish production in the carbon cycle, the relative contributions of algal and allochthonous organic material to the bottom detritus should be estimated. The possibly more important role of dissolved, rather than the more obvious particulate, allochthonous organic input for microbial production should also be assessed.

2. Biomass (Standing crop)

Momot *et al* (1978) has reviewed the estimates in the literature for, mostly, biomass, and, rarely, production for the Astacidae. All available data for the Australian Parastacidae are summarised in Table 19. Although the data on mean size for marron contain variability due to age and cropping, a density dependent relationship, first documented by Morrissy (1974c) is apparent (Fig. 39). A theoretical model for this density dependence can be proposed based upon the following assumptions which will afterwards be examined for their relevance to crayfish.

(i) The total amount of food eaten (= available), F g, by a year-class cohort over the period of growth to an individual mean size $\bar{w}$, g, is the same at all densities, D-/m², i.e. food supply is always limiting.

(ii) The food supply is shared equally amongst all individuals at all densities, i.e. individuals are uniform in size and growth rate ($w = \bar{w}$).

(iii) The proportion, k, of the food eaten which is converted to production is the same for all individuals at all densities.

(iv) Mortality is the same at all densities so that the proportion, k′, of the total food eaten by the cohort which is converted to surviving production, i.e. biomass B, is constant.

It follows that: $w = k'. F/_D$.

i.e. $w \propto 1/_D$, a hyperbolic relationship between growth rate and density reviewed for fish by Backiel and LeCren (1969), and W.D. = B (gm/m²) = k′.F

i.e. B is a constant or independent of density.

Although all these assumptions are either unrealistic empirically or invalid for crayfish and fish (Backiel and LeCren 1969) a hyperbolic model is superior to previous simplistic linear ones for either $\bar{w}$ and D (Morrissy 1974c) or for the non-independently ascertained variables of growth rate and B (Momot and Jones 1977). Some obvious comments on the assumptions are as follows:—

(i) The rate of production of detrital food supply is probably independent of marron production because the main sources are dead allochthonous (plant) and autochthonous (zoo- and phytoplankton) material. There is some possibility of a density-dependent effect if, as is likely, mortality of marron increases with density and there is a reduction in live food (benthic flora and invertebrates) production by proportionally higher interim densities of marron. If the food supply per individual is not limiting for growth at lower densities $\bar{w}$ will attain the species potential (i.e. asymptote). The model also predicts, unrealistically that $\bar{w}$, or rather $\bar{w} - \bar{w}_0$ where $\bar{w}_0$ is the insignificant (0·06g) initial size at release, asymptotes to zero towards higher densities. Obviously when the average food supply per individual approaches insufficiency for growth and maintenance requirements adjustment to lower densities will be accelerated by greatly enhanced mortality.

(ii) Food is not shared equally amongst all individuals because of varying sizes and degrees of feeding subordination in a cohort's dominance hierarchy. Possible changes in the strength of size dominance with density, i.e. the extent of skewness of size-frequency distributions and the effect on $\bar{w}$, require investigation.

(iii) Gross food conversion to growth will be influenced by varying maintenance requirements (per unit size) with size and any dependence of spawning frequency amongst females (gonad production) on density.

(iv) If mortality increases with density (Momot and Gowing 1977) due to feeding competition, k′ will decrease, i.e. the surviving biomass will reflect an apparently smaller food supply. Alternatively the model also assumes that environmental factors controlling feeding and growth (temperature and oxygen levels) are not a source of variability in field data. In practice this is unrealistic since these factors also effect density through mortality; dams or ponds with better growth conditions will tend to have higher final densities for a given stocking rate because of lower mortality.

For the present data, a trial and error fit was (Fig. 39), $\bar{w} = 15 + 28 \cdot 5/_D$, i.e. a hyperbolic curve but not one asymptoting to zero at higher densities (e.g. $\bar{w} = 30/_D$) as predicted by the model. The effect of this seemingly small departure from the model, of about 15g at high densities, is a ten-fold increase in B, i.e. in the food supply—a violation of the first assumption of the model.

Data for densities $> 3/m^2$ were from preliminary intensive feeding aquaculture trials at Pemberton. Later and more efficient intensive aquaculture trials at Pemberton predicted, for the most favourable south-west temperature conditions, much larger values of $\bar{w}$ and B (at $2\cdot5/m^2$) than those in Table 19 given by farm dams or earlier trials.

However, extensive aquaculture of marron in farm dams appears to be confined to densities at two years of age of $< 2/m^2$ given by stocking rates of $0\cdot5$–$2\cdot5/m^2$. Legal-sized marron (> 125 g) are obtained at densities $< 0\cdot2/m^2$ and possible export sizes (40–60 g) at $< 1\cdot0/m^2$. As pointed out by Morrissy (1976b) these densities can be provided by levels of stocking requiring very few mature females. The biomass at $< 1\cdot0/m^2$ can be expected to be between 300 and 450 kg/ha (or 30–45 kg per 0·1 ha dam).

3. Turnover ratios (P/$\bar{B}$)

Definition of the turnover ratio (TR) for a particular species is of considerable interest for resource management as a means of prediction of production (P) from the more easily obtained estimate of biomass (B), i.e. P = TR x $\bar{B}$. Estimates of TR are of two types (Waters 1969, 1977). The annual TR of a population of year-class cohorts is dependent upon voltinism (generation frequency) and lies between 0·7 and 2 for the Astacidae and other crustaceans with life spans of several years (Momot *et al* 1978). Of more basic significance is the TR for a single cohort over a life span. For stable populations with growth and mortality identical for successive cohorts, the cohort or life cycle TR is, numerically, equal to the annual population TR multiplied by the life span in years (Allen 1971). Momot and Gowing (1975) estimated the TR of several year-class cohorts of the small crayfish *Orconectes virilis*, life span 3–5 years, as 5·1 to 6·0. These values agree with Water's (1969, 1977) reviews that cohort TR appears reasonably constant and for almost all aquatic species in the wild ranges from 4 to 6.

Cohort TRs calculated from the present farm dam data of monthly estimates of B and P over the period 3 to 24 or 30 months of age were consistently about half those found by Momot and Gowing (1975); The mean TR for 12 dams was 2·65, range 2·27–3·20. Exceptions were values for D2 and D5 of 5·53 and 5·00, respectively, associated with reduced life spans caused by high natural mortality.

Most of the marron production occurred from 6 to 18 months of age and the cumulative TR declined after this period (Table 20a). By contrast values for *Orconectes virilis* increased (Table 20b). Based upon the predicted TR values given by Waters (1969, Table 4), the lower cohort TR values obtained for marron in farm dams could be due to the artificial termination of the life span at high numbers relative to stocked numbers (12·7–87·4%), c.f. 0·1–1·0% (Momot and Gowing 1975). This could be interpreted as meaning that the TRs were low because B was too high due to a high biomass at the end of the "life span". However, simulation of a further period of decline of the cohort to zero, with little additional production, showed no significant change in TR.

In *Orconectes virilis* a high mortality rate occurs throughout the period of greatest production (the first two years of life), whereas in marron high mortality coincides with periods of low production before and after the main period of high production. The pattern of associated high mortality and production for an Australian crayfish (*Cherax albidus*) studied by Woodland (1967) was similar to that of the astacid and calculated TR values were also high (Table 19). For marron the monthly biomass followed cumulative production closely through the year or so of high production; for the astacid the mean annual biomass (< 50 kg/ha) usually changed comparatively little during the first three years. The ratio of total production of marron to maximum biomass (usually attained soon after cumulative production started to level off) approached unity (mean 1·17, range 1·02–1·41).

Thus the lowered TR of the farm dam marron reflects an important difference in the fate of production as a result of aquaculture practice. The mixed cohorts of a wild population of the astacid in a natural aquatic community were subject to heavy natural mortality during production. The production of a single cohort of marron in a man-made farm dam was not subject to any interspecific consumer or inter year-class loss by predation. A very high proportion of the marron production survived for progressive cropping or the final recovery fishing—mean crop/cumulative P = 71·9%, range 36·9–97·6%. A similar low level for TR was also found for other farm dam marron (Morrissy 1974a) and from recent intensive aquaculture trials (Morrissy 1979); however, in earlier pond trials (Morrissy 1974c) high production was accompanied by high mortality at high densities and TR levels were elevated (Table 19).

Production (P) can be calculated as the product of the instantaneous growth rate (G) and the average biomass ($\bar{B}$). It follows that G could be an approximation to the cohort TR (Waters 1969, 1977). Since G is a logarithmic value, the cohort G calculated by adding period values (annual or less) is identical to $\log_e$ (maximum or final size/minimum or initial size). Momot and Gowing's (1975) values for cohort G agreed closely with those for TR for *Orconectes virilis* (maximum size < 20 g at 3·5 years). For farm dam marron of final mean sizes up to 89 g, mean cohort G was 4·87 (4·24–5·58) considerably in excess of the mean TR. Still higher values (6–7) are obtained if the true initial size of 0·06 g at parental release (in Pemberton ponds) are employed. And even higher cohort G values are obtained if other maximum values realised by farm dam marron are used, e.g. 8·8 for 400 g at 2·5 years of age (Morrissy 1974a). Recognizing that the ultimate size of marron approaches 2 000 g, obviously cohort G for marron can be extremely variable over their long life span, particularly because of the dependence of growth rate on density.

The instantaneous mortality rate (Z) appeared to be a closer approximation to cohort TR as predicted by Allen (1971) in the case of exponential mortality and linear growth in weight. Including a mortality rate of 80% for the prestocking period at Pemberton, the mean cohort Z was 2·45 (1·75–3·67), excluding dams showing mass mortalities (D2, 5·73; D5, 6·22).

4. Possible use of farm dams for commercial crayfish farming

Virtually any farmer in the southern wheatbelt can produce sufficient marron on his property for the pleasure of the sport of capture and the ensuing gourmet meal. However, any realisation of worthwhile commercial levels is not possible for the average farmer for the following reasons: The annual agricultural lease value of an improved 800 ha farm in the wheatbelt area is about $20 000 (pers. comm. May 1979. Department of Agriculture, Perth). The average farm has 7–8 dams (in 1970, Laing 1977) of which only some will be favourable for marron (i.e. unpolluted). The current marron growers' price is $7/kg (in 1979), a successful dam yields 35 kg of marron in two years on the average, and, hence, a value of marron per dam per annum of $125. Additionally, farm dam production of marron is more reliable in years of normal or greater winter rainfall when agriculture returns are best. Although little labour is involved annually in managing a marron dam, farmers are fully committed to agricultural pursuits because of present day labour costs. Thus widespread commercial marron farming by many individual wheatbelt farmers is not economically viable because of the projected very low return per farm.

However, a widespread scheme could still be realised by a single entrepreneur operating over many farms, selecting favourable dams. Initially, dam selection, building of summer flood banks, cropping and final netting out may take of the order of two days per dam for a two year cycle. Further cycles would reduce to a labour input of perhaps one day per dam. Minimal capital and operating costs (travelling and nets), with liaison with the farmer over earth-moving equipment for banks, are evident. The return of $250 for 1–2 days labour input per dam over two years appears to be rewarding. Recompense to the farmer could be a guaranteed domestic supply of marron and maintenance of dam water quality for stock, noting that the presence of sheep, but preferably not cattle, is compatible with the project.

The reliability of returns from such an enterprise may rest largely upon two factors:—Firstly, the developed judgement of the entrepreneur in selecting favourable dams because of the wide variability in water quality between dams. Secondly, loss of marron stocks due to poaching. At present theft of marron from dams is a notorious practice in the wheatbelt although marron in farm dams are now classed legally as private domesticated stock (Morrissy, 1978a).

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TABLE 1—SUMMARY OF FARM DAM MORPHOMETRY

Dam	Full (just overflowing): Zm Max. Depth m	Full: $\bar{Z}$ Mean Depth m	Full: Volume m³	Full: Bottom area m²	Full: Surface area m²	Mean and minimum surface area m², and mean max. depth, m, during the marron study	% of the bottom area less than 1 m deep in February: 1975	% of the bottom area less than 1 m deep in February: 1976
1	4·60	1·81	2 105	1 222	1 165	894, 695, 3·99	35·7	36·0
2	3·80	1·47	1 750	1 275	1 190	947, 695, 3·18	49·2	....
3	3·90	1·26	1 500	1 225	1 190	721, 375, 3·19	52·8	52·9
4	3·71	0·64	2 170	3 410	3 380	1 421, 490, 3·33	58·3	57·3
5	3·44	1·29	1 200	975	930	693, 535, 2·97	50·0	....
6	3·10	1·30	1 820	1 435	1 405	1 029, 765, 2·58	50·3	50·1
7	4·20	1·38	2 155	1 615	1 565	935, 495, 3·50	39·5	39·8
8	4·50	1·18	2 150	1 875	1 820	....	37·7	....
9	3·65	1·45	1 820	1 300	1 255	977, 570, 3·22	43·8	44·0
11	3·69	1·36	1 725	1 305	1 270	786, 580, 3·02	43·1	41·2
12	3·12	1·11	1 970	1 800	1 770	1 164, 735, 2·69	52·3	50·6
13	2·92	1·18	1 670	1 440	1 420	918, 515, 2·35	51·5	48·0
14	4·24	1·47	2 410	1 690	1 645	1 064, 850, 3·57	39·8	39·8
15	4·15	1·74	2 520	1 495	1 445	889, 680, 3·05	42·3	40·6
17	3·20	1·43	1 533	1 111	1 072	766, 593, 2·61	37·8	40·0
18	3·31	1·22	1 780	1 490	1 460	1 017, 740, 2·81	50·8	50·3
n = 16	3·72	1·33	1 890	1 541	1 499	948, 620, 3·07	45·9	45·7

TABLE 2—STATISTICS FOR FARM DAM MARRON

	Dam	Initial: No.	Initial: Density —/m²*	Final: No.	Final: Density —/m²*	Final: % Recovered	% Survival	Final mean size g	Final total weight kg and biomass, kg/ha* (biomass including cropped marron)	Maximum monthly biomass* (age-months)	Cumulative production (kg/ha*)	Maximum monthly production* (age-months)
A-group of dams; stocked March 1974; harvested July 1976 after 28 months and two summers in dams (30 months old)	D2	500	0·53	0	....	....	0	....	....	122 (14)	126	60 (12·5)
	D5	1 000	1·44	0	....	....	0	....	....	416 (14)	474	168 (12·5)
	D7	1 000	1·07	259	0·28	94·6	25·9	54	14·0, 150 (270)	371 (25)	478	73 (12·5)
	D9	1 000	1·02	564	0·58	90·6	56·4	45	25·3, 259 (374)	338 (20)	469	60 (14·5)
	D13	1 500	1·63	558	0·61	100·0	37·2	62	34·6, 379 (528)	473 (29)	664	86 (27·5)
	D1	2 000	2·24	400	0·45	91·3	20·0	59	23·7, 265 (433)	389 (25)	521	73 (22·5)
	D3	2 500	3·47	968	1·34	92·9	38·7	82	79·8, 1 106	1 106 (30)	1 425	170 (16·5)
B-Group of dams; stocked March 1975; harvested November 1976 after 21 months and one summer in dams (23 months old)	D4	500	0·35	0	....	....	0	....	....	5 (9)	8	3 (8·5)
	D11	500	0·64	368	0·47	77·2	73·6	89	32·7, 415	415 (23)	437	52 (17·5)
	D15	1 500	1·69	1 311	1·47	92·6	87·4	58	75·3, 847	847 (23)	868	146 (14·5)
	D18	1 500	1·47	613	0·60	97·9	40·9	50	30·4, 300	516 (18)	723	99 (15·5)
	D6	2 000	1·94	1 004	0·98	100·0	50·2	23	23·4, 227 (282)	418 (19)	460	101 (16·5)
	D12	2 000	1·72	1 279	1·10	82·9	64·0	54	69·3, 596	596 (23)	675	162 (12·5)
	D14	2 500	2·35	318	0·30	93·1	12·7	36	11·5, 108 (206)	452 (18)	559	146 (12·5)
	D17	2 500	3·26	1 698	2·22	97·3	67·9	24	40·4, 528 (564)	723 (19)	860	252 (11·5)

* Based upon the mean surface area over the life of the cohort in the dam.

TABLE 3—PERCENTAGE OF THE FINAL BIOMASS FOR MARRON LARGER THAN A GIVEN SIZE

Dams are ordered in sequence of increasing final mean size of marron. Values in parenthesis include previously cropped marron.

Dam	6B²	17B²	14B²	9A¹	18B	12B	7A¹	15B	1A¹	13A¹	3A	11B
>60 g	5·2 (23·8)	2·3 (8·8)	25·7 (62·2)	30·4	41·2	49·6	44·7	60·1	57·4	59·4	75·3	72·5
>90 g	0·0	0·0	0·9	3·5 (36·3)	19·0	25·3	12·8 (52·7)	40·2	22·5 (54·4)	23·9 (43·5)	49·4	54·8
>120 g	0·0	0·0	0·0	0·0	9·1	13·4	1·9	28·5	3·3	8·6	28·9	39·8

Superscripts to dam numbers refer to cropping at >90 g (1) or >60 g (2).

TABLE 4—VARIATION BETWEEN DAMS IN THE FREQUENCY OF SPAWNERS AMONGST LATE 1+ AGE-GROUP FEMALE MARRON

Dam	% frequency of spawning females in drop net catches				harvest
	October	November	December	January	November
D18 B	26·8	32·7	....	....	37·5
D12 B	9·5	12·8	....	....	32·8
D17 B	12·6	16·0	....	....	12·6
D13 A	7·5	7·7	7·7	4·0	(11·1*)
D7 A	2·4	4·0	0·0	0·0	(6·9*)
D15 B	0·0	1·5	....	....	5·4
D14 B	5·8	5·1	....	....	4·1
D3 A	0·0	0·9	0·9	0·4	(3·4*)
D11 B	0·0	0·0	....	....	0·7
D6 B	0·0	0·0	....	....	0·4
D1 A	0·0	0·0	0·0	0·0	(0·0)
D9 A	0·0	0·0	0·0	0·0	(0·0)

* Estimated from the November drop net catch frequency of berried females using the linear relationship between drop net (x) and harvest (y) frequencies for the B group in November ($y = 2{\cdot}35 + 1{\cdot}13x$, $P < 0{\cdot}02$).

TABLE 5—STATISTICS OF CROPPING USING DROP NETS

A-Group dams were cropped for 8 months for sizes >90 g and B-Group dams for 5 months for sizes >60 g.

Dam	17B	6B	14B	9A	7A	1A	13A
Surviving total number at the start of cropping	2 050	1 265	990	630	702	790	990
Number subsequently cropped	39 (1·9%)	76 (6·1%)	156 (15·8%)	91 (14·4%)	97 (13·8%)	136 (17·2%)	121 (12·2%)
Mean size at the start of cropping (g)	27	34	49	40	46	40	38
Crop weight (kg)	2·8	5·7	10·2	11·2	11·2	15·0	13·7
Mean final size (g)	24	23	36	45	54	59	62
Final weight of marron of croppable size remaining uncaptured (kg)	0·91	1·2	0·89	0·88	1·8	5·1	8·2
Crop weight + final weight of crop-sized marron (kg)	3·7	6·9	11·1	12·1	13·0	20·1	21·9

TABLE 6—COMPARISON OF FACTORS INFLUENCING TROPHISM IN AN AQUACULTURE POND AND A FARM DAM

Aquaculture pond	Farm Dam
FOOD: Largely plant substrate forming detritus	Largely plant substrate forming detritus.
FEEDING FREQUENCY: Biweekly; manual addition	Annually; pasture and crop debris washed into dam by earlier winter runoff.
FEEDING LEVEL: Limited in summer to prevent oxygen depletion	Summer debris-laden runoff can be diverted to prevent catastrophic oxygen depletion.
FLUSHING: Continual; at a rate limited by the (summer) water supply relative to volume of ponds	Late winter-early spring; only if dam overflow occurs.
CIRCULATION OF BOTTOM WATER—RE-AERATION: Daily; shallow water (max. depth 1m); induced by mechanical circulation (pumps, airlifts, water mills) during summer	Infrequent during summer; deep water (max. depth ≃ 3m); induced by adventitious climatic conditions.

TABLE 7—STATISTICAL SIGNIFICANCE OF VARIABLES EMPLOYED IN MULTIPLE REGRESSION ANALYSIS OF THE VARIABILITY IN SOME FEATURES INVOLVED IN HOLOMIXIS AND RE-AERATION OF A FARM DAM

An arbitrary value of 1 was assigned to wind directions from NE to SE inclusive and zero for other directions

Dependent variables	Determining Variables				
	Maximum air temperature (previous day)	Minimum air temperature	Wind speed at 09 00 hours	Wind direction at 09 00 hours	Hours of temperature equilibration at 3m with surface
Maximum water temperature at surface	*** (+)	—	—	—	—
Minimum water temperature at surface	—	*** (+)	—	—	—
Hours of temperature equilibration at 1m with surface	*** (—)	* (—)	** (+)	n.s.	—
Hours of temperature equilibration at 2m with surface	*** (—)	** (—)	*** (+)	* (+)	—
Hours of temperature equilibration at 3m with surface	*** (—)	*** (—)	** (+)	* (+)	—
% O_2 at 09 00 hours	*** (—)	n.s.	n.s.	n.s.	*** (+)
% O_2 change from previous day	n.s.	(*) (—)	n.s.	n.s.	*** (+)

Level of statistical probability: $P < 0{\cdot}001$, ***; $P < 0{\cdot}01$, **; $P < 0{\cdot}05$, *; $P > 0{\cdot}05$, n.s.

89501—(5)

TABLE 8—AVERAGE STATISTICS OF FARM DAMS FOR SALINITY, VOLUME AND TOTAL SALT CONTENT AT MINIMUM AND MAXIMUM SALINITY

	April–May (maximum salinity)			August (minimum salinity)		
	mg/l	m^3	kg	mg/l (inflow)	m^3	kg
1974	616	651	386	295 (181)	1 854	540
1975	523	800	412	358 (235)	1 656	583
1976	589	882	506	450 (202)	1 362	608
Overall....	573	771	428	351 (207)	1 676	571

TABLE 9—VARIATION IN SECCHI DISK DEPTH, Z_{SD}cm

	1974			1975			1976		
	March	June	December	March	June	December	March	June	November
D1	7·0*	6·0	8·0	6·5	7·3	10·0	6·0	7·3	....
D2	7·0*	9·5	10·0	28·0	8·3	(mass mortality Feb.–Mar. 1975)			....
D3	41·0*	11·0	8·0	28·0	6·0	12·0	12·0	13·0	....
D4	11·5	9·0	39·0	43·5*	9·0	14·0	29·0	(mass mortality Sept.–Oct. 1975)	
D5	8·0*	11·0	73+	35·0	26·3	(mass mortality Jan.–Feb. 1975)			
D6	2·5	3·5	6·3	3·5*	3·3	5·0	3·3	3·3	3·5
D7	4·5*	5·5	7·0	5·0	3·8	8·5	7·3	7·8	....
D8	13·5	11·5	45·5	68·0(†)	....	....	....	....	....
D9	5·0*	7·5	5·5	9·0	9·8	10·0	8·3	8·0	....
D11	9·0	5·0	5·5	7·0*	6·8	13·0	10·0	8·8	7·5
D12	23·5	7·0	8·5	17·0*	7·8	18·0	10·5	8·5	26·0
D13	13·0*	9·0	13·5	13·5	9·0	10·8	10·0	8·8	....
D14	8·0	5·0	7·5	13·0*	7·0	17·0	7·3	9·5	14·0
D15	8·5	9·0	13·0	37·0*	9·5	30·0	12·5	10·0	5·5
D17	....	....	....	12·0*	13·0	17·0	25·8	39·5	59·0
D18	....	....	....	36·5*	38·5	75+	20·0	7·5	27·0

* Stocked with marron in this month. (†) Intended stocking in this month discontinued.

TABLE 10—MEAN, STANDARD DEVIATION AND RANGE OF VALUES FROM FEBRUARY AND JULY WATER ANALYSES OVER THREE YEARS FOR FIFTEEN FARM DAMS

(n = 67)

	mg/l	me/l	me/l%
pH	7·5 ± 0·3 (6·9–8·4)	....	....
K_{20}	639 ± 193 (320–1 250)	....	....
T.D.S. (evaporation)	442 ± 137 (230–880)	....	....
Ca^{2+}	19·4 ± 7·7 (5–35)	0·968 1	14·2
Mg^{2+}	18·4 ± 7·5 (7–36)	1·513 6	22·3
Na^+	90·6 ± 36·3 (33–198)	3·941 1	58·0
K^+	15·2 ± 11·1 (3–53)	0·388 7	5·7
CO_3^{2-}	Nil	....	....
HCO_3^-	145·0 ± 59·1 (55–275)	2·376 6	35·0
Cl^-	138·8 ± 63·1 (52–315)	3·915 5	57·6
SO_4^{2-}	21·0 ± 13·6 (2–52)	0·437 4	6·4
NO_3^-	2·5 ± 3·5 (0·01–15)	0·040 3	0·6
Salinity	451	13·6	....

TABLE 11—AVERAGE VALUES OF TOTAL SUSPENDED SOLIDS (T.S.S.), CONDUCTIVITY (K_{20}), SALINITY AND SODIUM ABSORPTION RATIO (S.A.R.) FROM BIANNUAL WATER ANALYSES OVER THREE YEARS

Dam	T.S.S. (mg/l)	K_{20}	Salinity (mg/l)	S.A.R.
1	621	482	350	3·30
2	184	951	631	4·38
3	282	735	489	3·44
4	239	738	557	3·74
5	93	493	375	2·36
6	2 134	544	419	6·05
7	816	999	724	5·38
8	250	500	407	3·16
9	385	725	499	4·73
11	493	503	350	2·71
12	196	730	451	3·60
13	401	621	393	4·29
14	599	482	346	2·42
15	320	402	286	1·94
17	122	801	609	3·26
18	167	569	449	1·51

TABLE 12—COMPARISON OF THE ORGANIC/CLAY PROPERTIES OF THE DAM WATERS CONTRIBUTING TO THE SEDIMENTS

Dam	Sediment			Water	
	% organic	Apparent depth (cm)	Total suspended clay	Total organic	% organic of Total Suspended Solids
D1	10·7 ± 1·4	19 ± 7	535 ± 172	137 ± 33	21 ± 9
D2	11·9 ± 0·8	39 ± 9	76 ± 73	118 ± 46	72 ± 26
D3	12·5 ± 1·1	34 ± 5	165 ± 109	92 ± 35	46 ± 27
D4	10·8 ± 1·2	31 ± 7	69 ± 64	143 ± 88	73 ± 25
D5	12·3 ± 2·2	38 ± 5	26 ± 63	90 ± 28	89 ± 22
D6	8·4 ± 1·0	47 ± 6	1 666 ± 525	285 ± 71	14 ± 4
D7	11·0 ± 3·1	23 ± 3	594 ± 251	232 ± 81	30 ± 10
D8	11·7 ± 1·1	61 ± 9	330 ± 40	90 ± 76	24 ± 8
D9	12·1 ± 0·3	32 ± 3	291 ± 127	86 ± 40	26 ± 12
D11	11·9 ± 1·9	34 ± 4	339 ± 116	94 ± 62	29 ± 13
D12	13·0 ± 1·9	21 ± 6	81 ± 99	95 ± 70	61 ± 33
D13	11·5 ± 1·3	35 ± 11	342 ± 101	109 ± 38	27 ± 5
D14	11·2 + 0·8	32 ± 4	364 ± 205	130 ± 52	32 ± 13
D15	11·9 ± 1·8	13 ± 3	260 ± 193	46 ± 48	36 ± 20
D17	12·3 ± 0·7	38 ± 3	13 ± 19	76 ± 57	92 ± 13
D18	13·0 ± 3·5	53 ± 4	34 ± 80	71 ± 55	89 ± 24

TABLE 13—COMPARISON OF SURFACE AND SUBSURFACE (2 m) PIGMENT VALUES μg/l

Values for 2 m in parenthesis. Samples taken at midday

	D3						D6					
	Cholorphyll "a"		Pheopigments		"430 corrected"		Chlorophyll "a"		Pheopigments		"430 corrected"	
November 1975	5	(0)	28	(60)	6·1	(5·9)	64	(64)	56	(93)	22·8	(24·8)
December	134	(160)	0	(0)	9·2	(9·2)	0	(0)	97	(45)	26·8	(17·6)
January 1976	0	(0)	30	(30)	5·6	(4·5)	96	(43)	31	(122)	28·8	(32·8)
February	21	(11)	9	(4)	6·4	(3·8)	54	(64)	96	(86)	33·6	(32·4)
April	0	(0)	20	(35)	2·1	(3·2)	43	(21)	227	(278)	55·2	(53·6)
May	43	(5)	0	(13)	7·5	(5·2)	187	(40)	356	(437)	123	(85·5)
June	14	(19)	31	(47)	10·3	(13·0)	178	(107)	271	(330)	100	(86·7)
July	....		....		....		187	(561)	561	(1 310)	154	(339)
August	....		....		....		1 337	(1 818)	0	(0)	425	(523)
September	....		....		....		615	(642)	0	(0)	225	(315)

"430 corrected"—Optical density at 430nm corresponding to a sample of one litre.

TABLE 14—PIGMENT ESTIMATIONS ON DRIED CLOVER

Test material: Dried subterranean clover (*Trifolium subterraneum*) supplied by the Department of Agriculture W.A. in mid 1973; 5 gm dry weight were placed in one litre of tap water on February 2, 1976 and stored in a "dark" cupboard.

	Equivalent optical density readings at wavelengths nm of			430 / 665b	665b / 665a	Chlorophyll "a" ug/g dry weight	Pheopigment ug/g dry weight
	430	665b	665a				
February 2, 1976 (dry)....	43·1	12·8	11·80	3·37	1·08	266	1 943
March 10, 1976*	18·8	8·7	8·6	2·16	1·02	42·8	1 559
April 20, 1976	2·7	0·84	0·84	3·19	1·00	0·0	158
May, 20, 1976	2·2	0·88	0·88	2·39	1·00	0·0	165
June 29, 1976	2·8	1·1	1·1	2·57	1·00	0·0	254
July 16, 1976	7·6	3·2	3·2	2·38	1·00	0·0	595

b, a = before, after acidification

* the solution was shaken each month and then allowed to settle, i.e. no large fragments were included in the test.

TABLE 15—CORRELATION BETWEEN TOTAL ORGANIC CONTENT AND ALGAL PIGMENTS BY MONTH FOR ALL THE DAMS

	Total organic (mg/l)	Chlorophyll "a" + pheopigments (ug/l)	Correlation coefficient "r"
July 1975	156 ± 67	73 ± 46	0·26 n.s.
August	129 ± 71	58 ± 58	0·29 n.s.
September	114 ± 56	36 ± 56	0·36 n.s.
October	110 ± 37	72 ± 35	0·67*
November	107 ± 56	74 ± 56	0·36 n.s.
December	126 ± 56	63 ± 72	0·19 n.s.
January 1976	153 ± 90	90 ± 122	0·89***
February	145 ± 92	55 ± 36	0·57
March....	160 ± 89	92 ± 159	0·87 ***
April	143 ± 49	48 ± 79	0·66 *
May	160 ± 88	102 ± 147	0·87 ***
—D6	140 ± 56	62 ± 51	0·60 n.s.
June	169 ± 75	125 ± 118	0·79 **
—D6	150 ± 35	95 ± 61	0·08 n.s.
July—D6	122 ± 60	106 ± 129	0·86 *
August—D6	134 + 64	64 ± 50	0·46 n.s.
September—D6	144 ± 37	37 ± 25	0·41 n.s.
October—D6	127 ± 30	19 ± 12	0·39 n.s.
November—D6	102 ± 37	22 ± 11	0·52 n.s.

Level of statistical probability: P < 0·001, ***; P < 0·01, **; P < 0·05, *; P > 0·05, n.s.

TABLE 16—BIANNUAL ESTIMATIONS OF PHOSPHOROUS AND NITROGEN IN FARM DAM WATERS

(Analysis—Government Chemical Laboratories, Perth)

Total phosphorous in solution —P mg/l

	D1	D2	D3	D4	D5	D6	D7	D9	D11	D12	D13	D14	D15	D17	D18
March 1974	·03	1·0	0·4	·35	·06	·37	·48	·04	·04	·08	·02	·06	<·02	....	....
July 1974	·16	·13	·03	·08	·02	·15	·16	·05	·06	·16	·03	·52	·02	....	....
February 1975	·02	·03	·02	·06	·02	·11	·05	·02	·02	·02	·02	·07	<·02	·02	·03
July 1976	·02	·02	·02	·04	·06	·15	·05	·02	·04	·03	·02	·03	·06	·02	·03
February 1976	·20	....	·13	·23	....	·53	·27	·12	·26	·28	·14	·24	·13	·08	·18
August 1976	....	....	....	·17	....	·34	·98	....	·40	·20	....	·07	·30	·02	·19

NH_3, NO_3–, Organic } —N mg/l

	D1	D2	D3	D4	D5	D6	D7	D9	D11	D12	D13	D14	D15	D17	D18
March 1974	·25 ·02 2·15	·87 ·02 3·03	·51 ·02 3·29	·33 ·02 7·07	·18 ·37 1·82	·29 ·74 7·61	·41 ·35 6·29	·38 3·9 2·02	·23 ·59 2·37	·45 ·03 3·45	·36 ·02 2·14	·20 ·80 4·2	·21 ·19 1·29	....	....
July 1974	·39 ·05 1·23	·23 ·02 ·24	·23 <·02 ·52	·81 ·02 ·36	·14 1·23 2·24	·43 ·16 2·96	·38 ·14 2·26	·06 1·36 ·97	·36 ·07 1·29	·63 ·33 ·66	·08 ·99 ·76	·34 ·04 1·55	·16 ·16 ·30	....	....
February 1975	·16 0·7 2·0	·08 ·02 2·2	·08 ·04 2·1	·14 ·02 3·8	·40 ·02 2·4	·39 ·18 5·2	·17 <·02 4·0	·11 ·02 2·1	·15 ·02 4·5	·10 ·03 3·3	·12 ·02 2·6	·41 ·02 2·9	·13 ·07 1·3	1·7 ·03 2·7	·70 3·8 3·8
July 1975	·16 ·30 ·43	·28 ·03 1·92	·78 ·20 1·38	·50 ·14 1·66	·32 <·01 1·82	1·37 ·89 3·30	·19 ·70 2·25	·15 ·80 1·20	·63 2·6 1·41	·39 ·35 1·94	·19 2·1 1·4	·25 ·88 1·84	·33 ·55 ·77	1·93 ·31 1·50	·50 ·87 1·73
February 1976	·09 ·07 2·46	....	·16 ·57 1·51	·88 ·04 4·24	....	·23 ·18 3·84	<·02 ·02 2·34	<·02 <·02 ·93	·62 ·41 2·19	·02 ·03 2·64	·02 2·14 1·70	·09 ·52 2·66	·08 ·10 2·18	1·08 ·07 1·66	1·79 ·02 2·54
August 1976	....	....	....	·58 ·27 2·4	....	·46 ·84 2·8	·17 ·31 <·02	....	·24 3·3 1·6	·08 ·46 1·6	....	·11 1·1 1·7	2·7 1·4 3·0	·53 ·63 1·8	3·4 1·6 1·2

TABLE 17—RESULTS OF GOVERNMENT CHEMICAL LABORATORY ANALYSES OF SURFACE WATER SAMPLES FROM KOJONUP FARM DAMS BEFORE AND AFTER A THUNDERSTORM ON 10 APRIL 1973

(40 mm recorded at Kojonup post office). Analysis included suspended material (mg/l)

	Department of Agriculture dam number				
	11*	14†	15†	16†	17†
5 April, 1973 (Lab. No. 7339-361/73)—					
pH	8·6	8·5	8·3	8·2	8·7
Turbidity APHA units	95	750	260	140	300
Colour, Hazen units	15	50	10	10	20
Odour	nil	nil	nil	nil	nil
Salinity	4 110	700	410	990	1 260
Nitrogen, N	....	....	....	....	....
Ammonia	1·1	0·3	0·2	0·2	0·5
Nitrate	<0·1	<0·1	0·1	0·1	0·1
Organic	3·0	5·8	2·0	4·3	11
Phosphorous, Total P	0·22	1·0	0·16	0·22	0·96
Dissolved oxygen	15·0	8·1	9·2	8·2	11·0
16 April, 1973 (Lab. No. 8422-427/73)—					
pH	6·6	7·0	6·8	6·6	6·8
Turbidity	100	480	520	160	250
Colour	280	280	300	400	750
Odour	nil	foul	foul	foul	foul
Salinity	370	410	270	410	400
Nitrogen, N	....	....	....	....	....
Ammonia	0·6	1·6	1·9	3·4	8·0
Nitrate	0·1	0·1	0·1	0·1	0·1
Organic	2·6	7·5	5·3	7·6	13·0
Phosphorous, Total P	1·8	6·0	3·4	6·2	10·0
Dissolved oxygen	5·2	1·5	0·7	0·8	0·9

* Fenced to stock. † Cattle had access to dam banks.

TABLE 18—CHECK LIST OF PASTURE, CROP AND TREE SPECIES ON DAM CATCHMENTS

PASTURE—	
Vulpia spp	silver grass
Hordeum spp	barley grass
Trifolium subterranean	clover
Arctotheca calendula	cape weed
Lolium rigidum	rye grass
CROP—	
Hordeum distichor	barley (2-row)
Hordeum vulgare	barley (6-row)
Avena sativa	common oats
TREES—	
Eucalyptus rudis	flooded gum
Eucalyptus marginata	jarrah
Eucalyptus wandoo	white gum
Eucalyptus astringens	mallet
Eucalyptus calophylla	red gum
Casuarina spp	sheoak
Acacia acuminata	jam

TABLE 19—SUMMARY OF AUSTRALIAN PARASTACID BIOMASS (B), TOTAL PRODUCTION (P) AND COHORT TURNOVER RATIO (TR) DATA

* Mean surface area of farm dams taken as 0·1 ha.
† Original Delury-type estimates in Morrissy (1970a), corrected for underestimation (one-third).
‡ Cropped dams.
§ Summer estimates for mixed year-classes excluding 0+.

(a) *Cherax tenuimanus*

D (—/m²)	w (g)	B (kg/ha)	P (kg/ha)	TR	age (years)	Source
		(i) South-western Australian wheatbelt farm dams				
·05	148	75‡	....	....	§	Morrissy (1970a) Area* Estimate†
·11	253	288	....	....	§	
·12	78	96‡	....	....	§	
·16	228	362‡	....	....	§	
·29	84	165‡	....	....	§	
·35	86	300‡	....	....	§	
·40	110	438‡	....	....	§	
·42	84	354‡	....	....	§	
·12	300	363	458	2·40	2	Morrissy (1974a) Area*
·24	146	344‡	....	....	§	
·30	36	108‡	559	3·20	2	Present study
·47	89	415	437	2·83	2	
·60	50	300	723	3·06	2	
·63	31	194‡	384	2·57	2	
·74	49	362‡	420	2·54	2	
·86	23	227‡	460	2·63	2	
·86	44	382	415	2·61	2	
1·01	39	392‡	467	2·05	2	
1·10	54	596	675	2·27	2	
1·47	58	847	868	2·36	2	
1·60	56	888	1 033	2·64	2	
2·22	24	528‡	860	2·42	2	
		(ii) South-western Australian river (Warren River)				
17·7	0·5	89	....	....	0·25 +	Morrissy (1974c)
1·25	38	476	....	....	§ ±	
		(iii) Pemberton ponds (intensive culture)				
3·2	22	712	3 490	5·70	1·25	Morrissy (1974c)
18·8	13	2 483	5 600	3·17	1·25	
24·6	15	3 659	7 400	3·63	1·25	
6·7	42	2 786	9 200	4·37	2·25	
4·7	44	2 076	2 581	2·85	1·0	Morrissy (1979)
2·9	112	3 184	3 954	2·05	2·0	
	(Predicted for Augusta-Margaret River climate from seasonal pond trials)					
4·1	15	616	843	2·44	1·0	
3·6	62	2 251	2 874	2·30	2·0	
		(Predicted for Pemberton climate from seasonal pond trials)				

(b) *Cherax albidus* (= *destructor*) (N.S.W. farm dam)

D (—/m²)	$\bar{w}$ (g)	B (kg/ha)	P (kg)/ha	TR	age (years)	Source
1·88	16	320	672	2·10 (annual)	mixed	Woodland (1967)
1·15	20	229	607	5·53	1	Calculated from Woodland's (1967) cohort data
·19	48	90	753	5·77	2	
·01	79	5	775	7·78	3	

TABLE 20—TURNOVER RATIOS

(a) Mean ratios for farm dam marron

Months	3–6	6–12	12–18	18–24 (12 dams)	24–30 (5 dams)
Cumulative ratio	0·76	3·69	3·09	2·55	2·59
Period ratio	0·76	2·85	1·18	0·26	0·35

(b) Ratios calculated from Momot and Gowing (1975) for West Lost Lake, 1966year-class

Months	0–6	6–18	18–30	30–42
Cumulative ratio	2·36	4·59	5·04	5·48
Period ratio	2·36	2·24	0·77	0·08

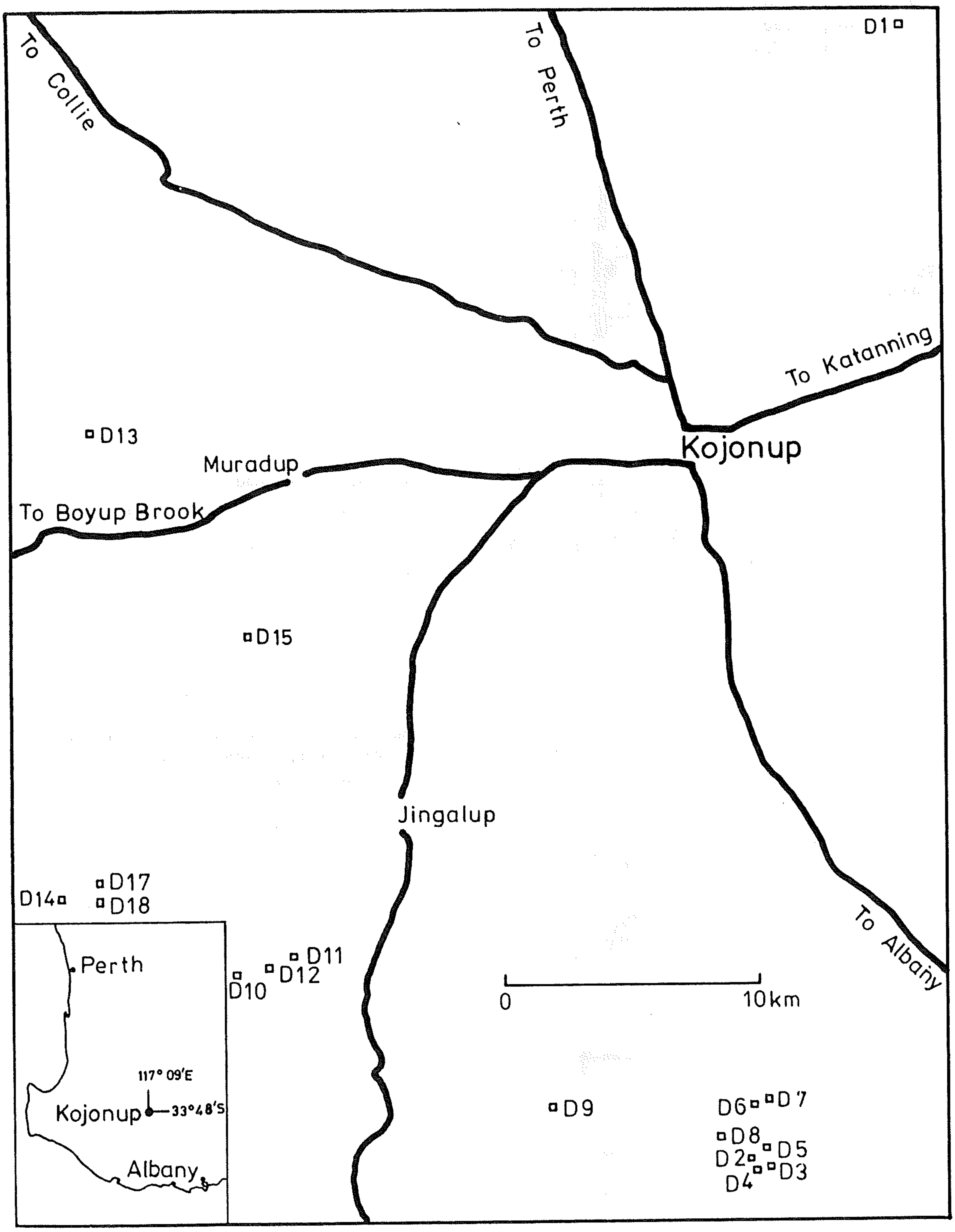

Figure 1—Locality Map.

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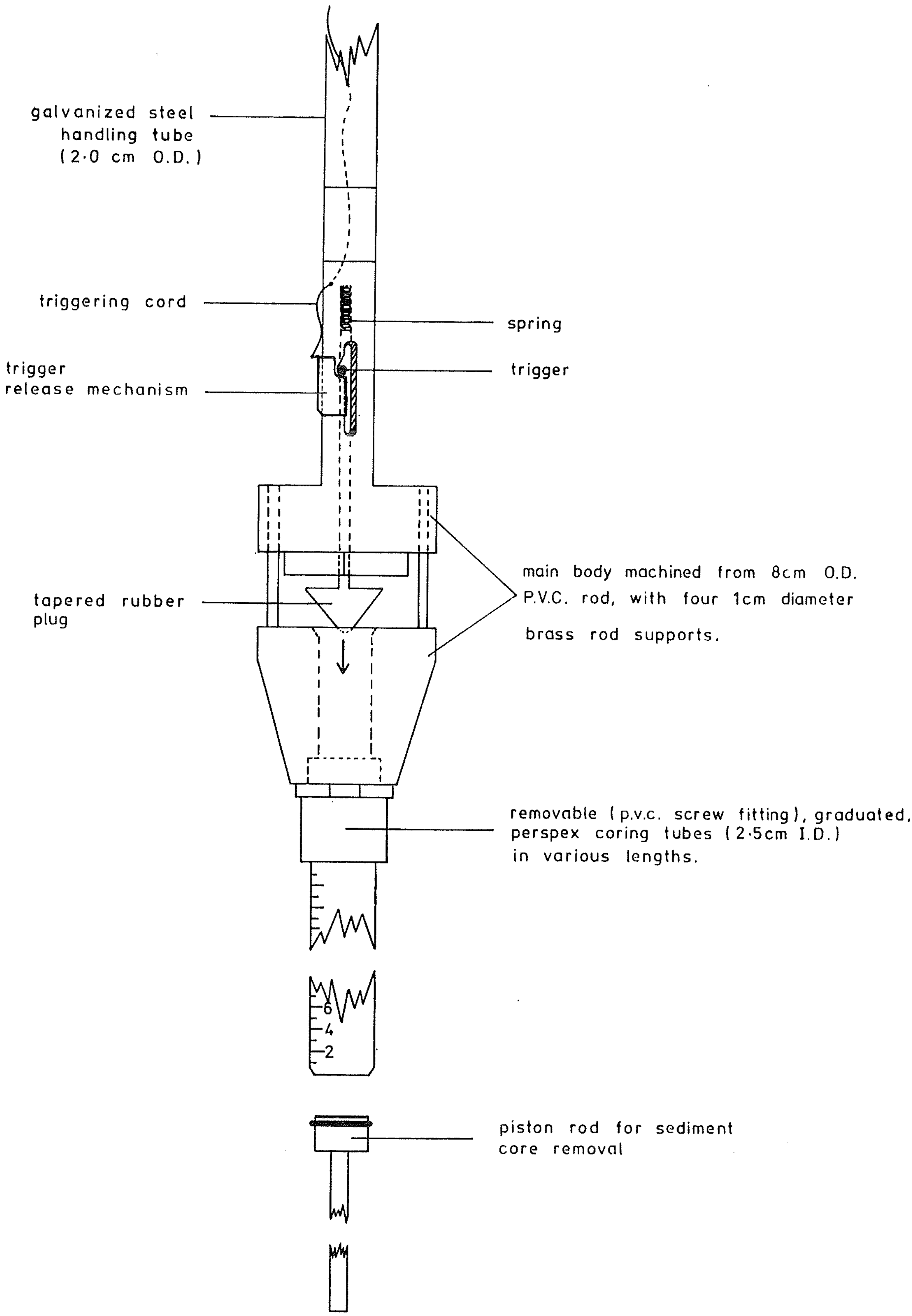

Figure 2—Sediment corer.

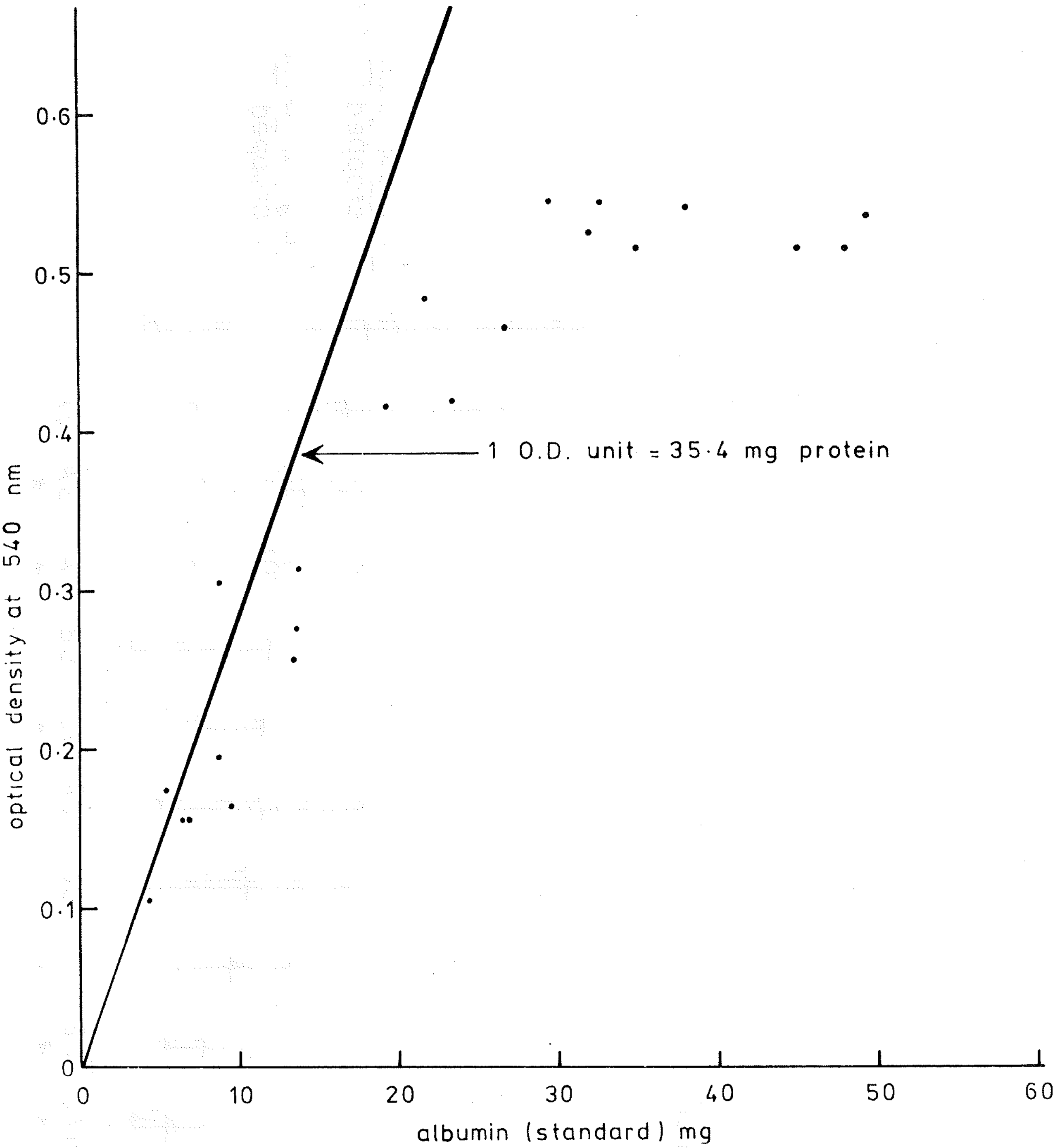

Figure 3—Optical density/albumin calibration data for protein analysis.

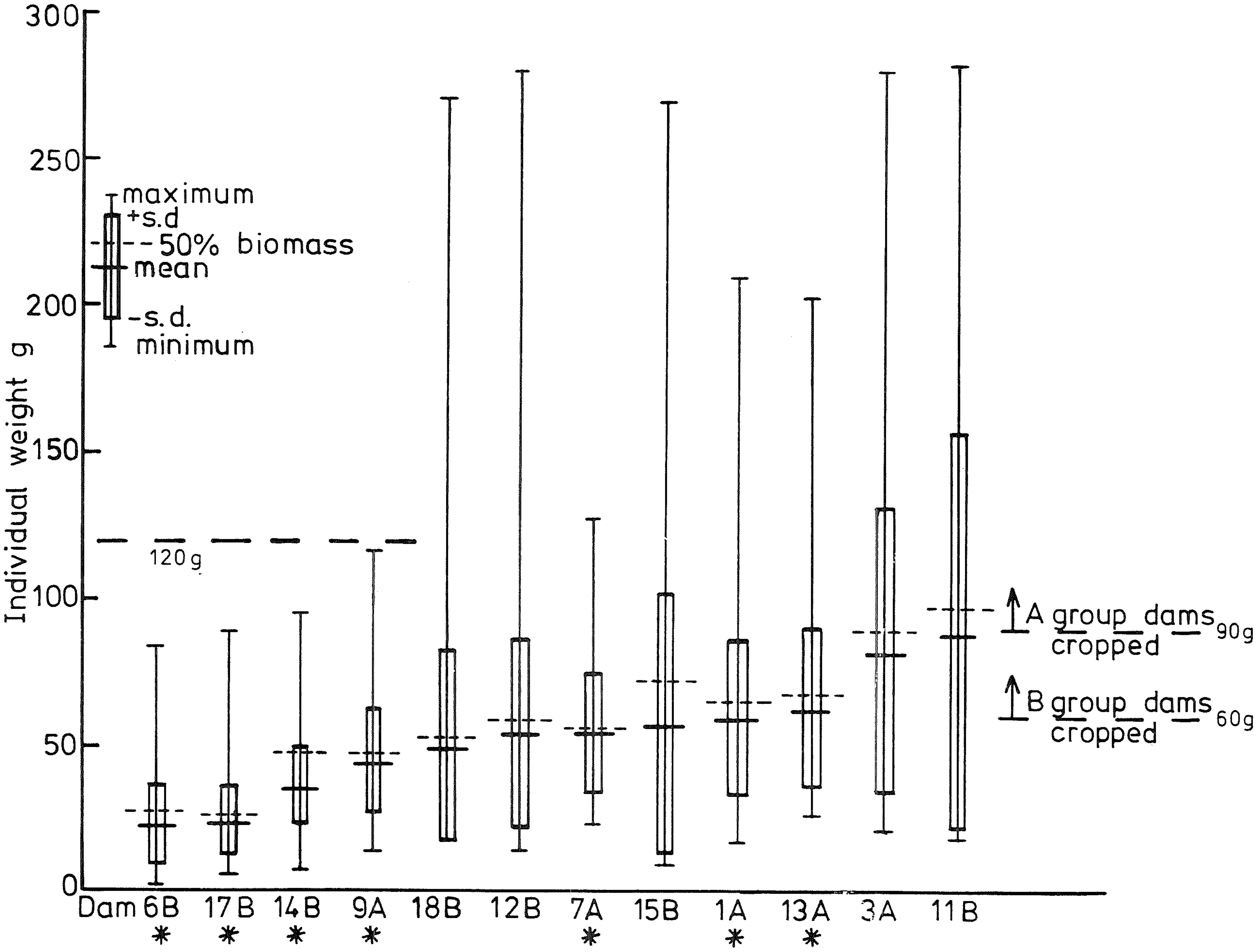

Figure 4—Size statistics of recovered marron, * cropped dams.

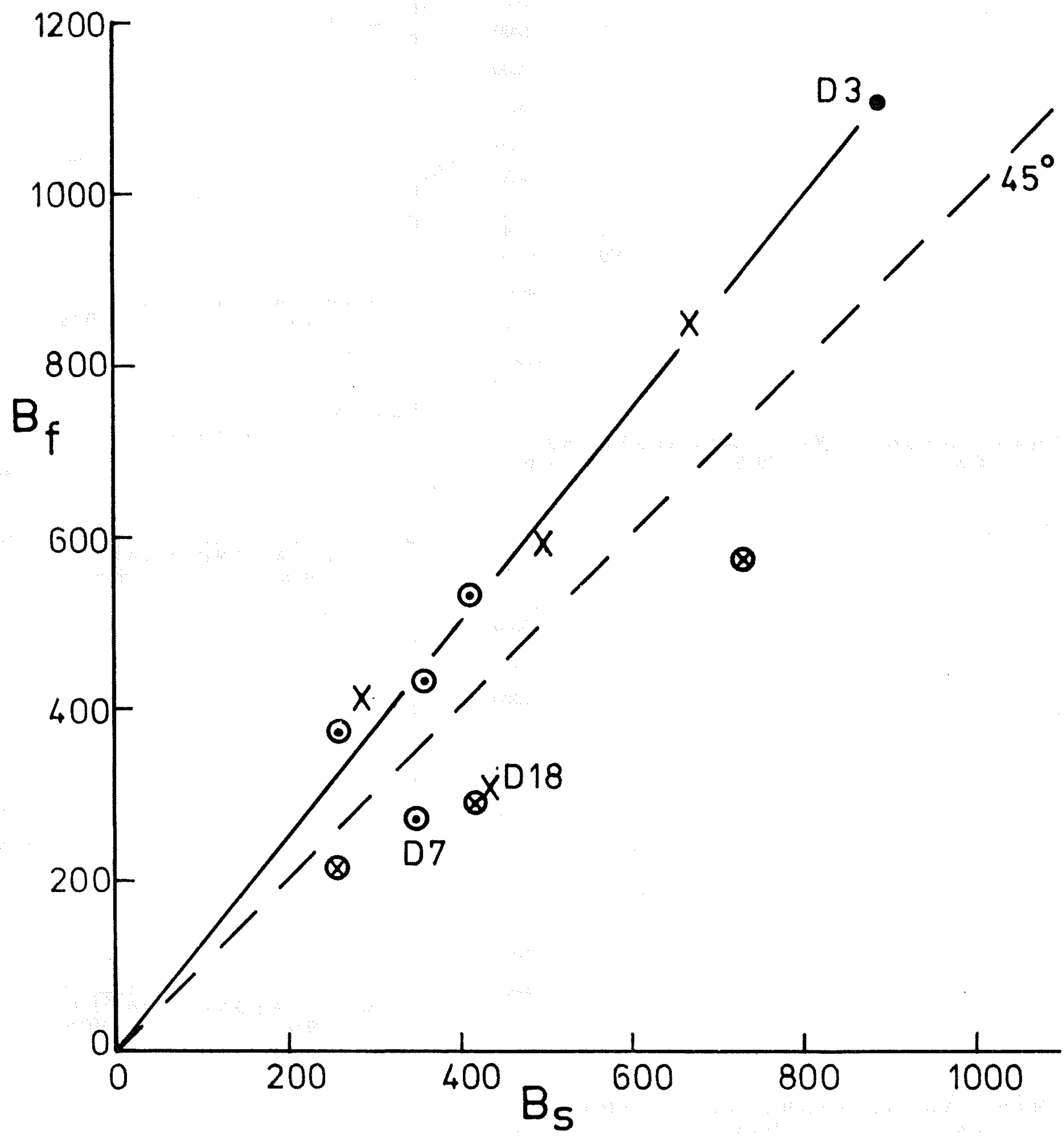

Figure 5—Relationship between the total final biomass (including any previously cropped marron), B_f, and biomass at the start of the cropping period, B_s. A-group dams, ●; B-group, X; cropped dams ⊙, ⊗. Biomass, kg/ha.

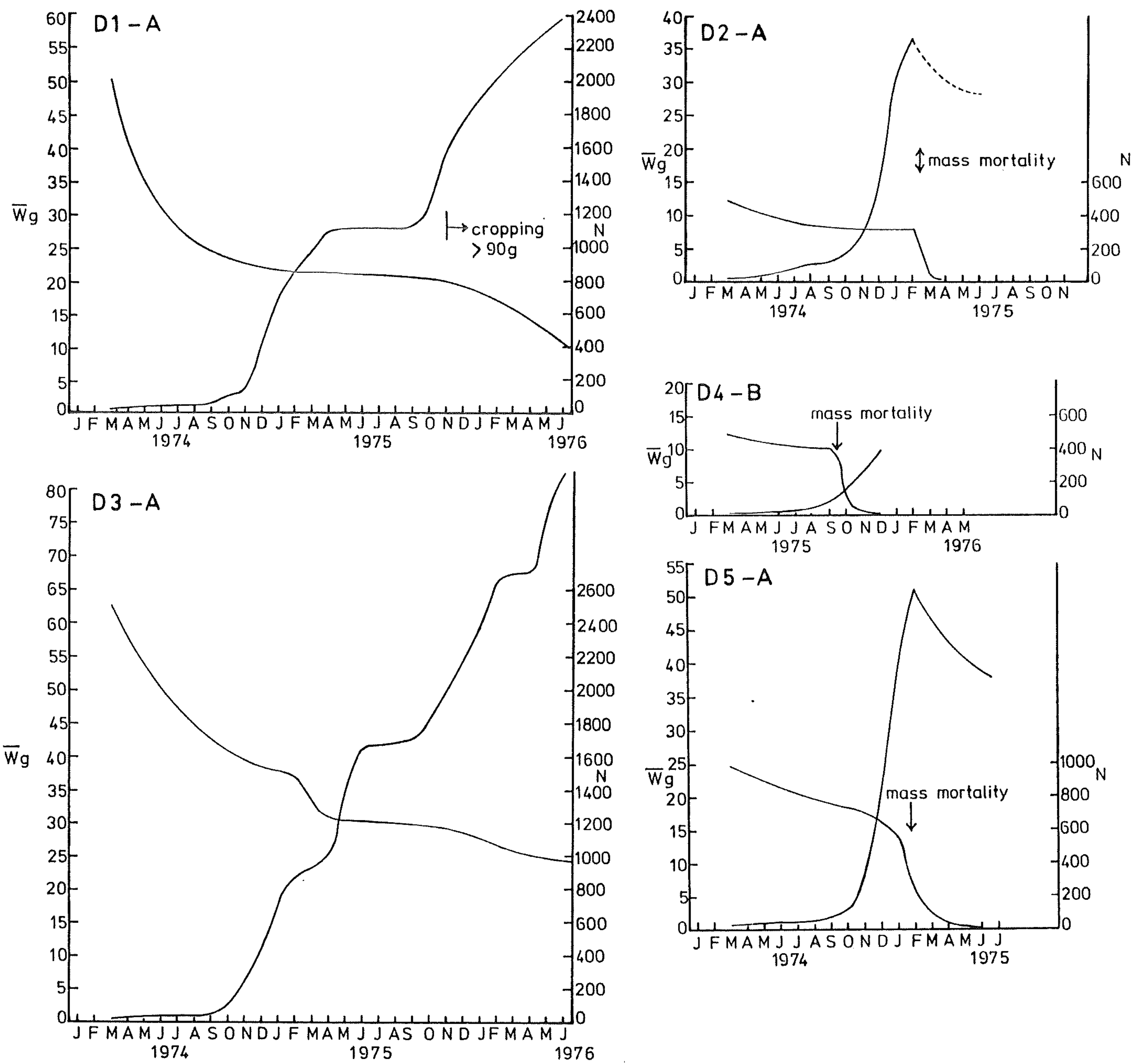

Figure 6—Monthly mean individual weight g and surviving number of marron in each dam over the period of study

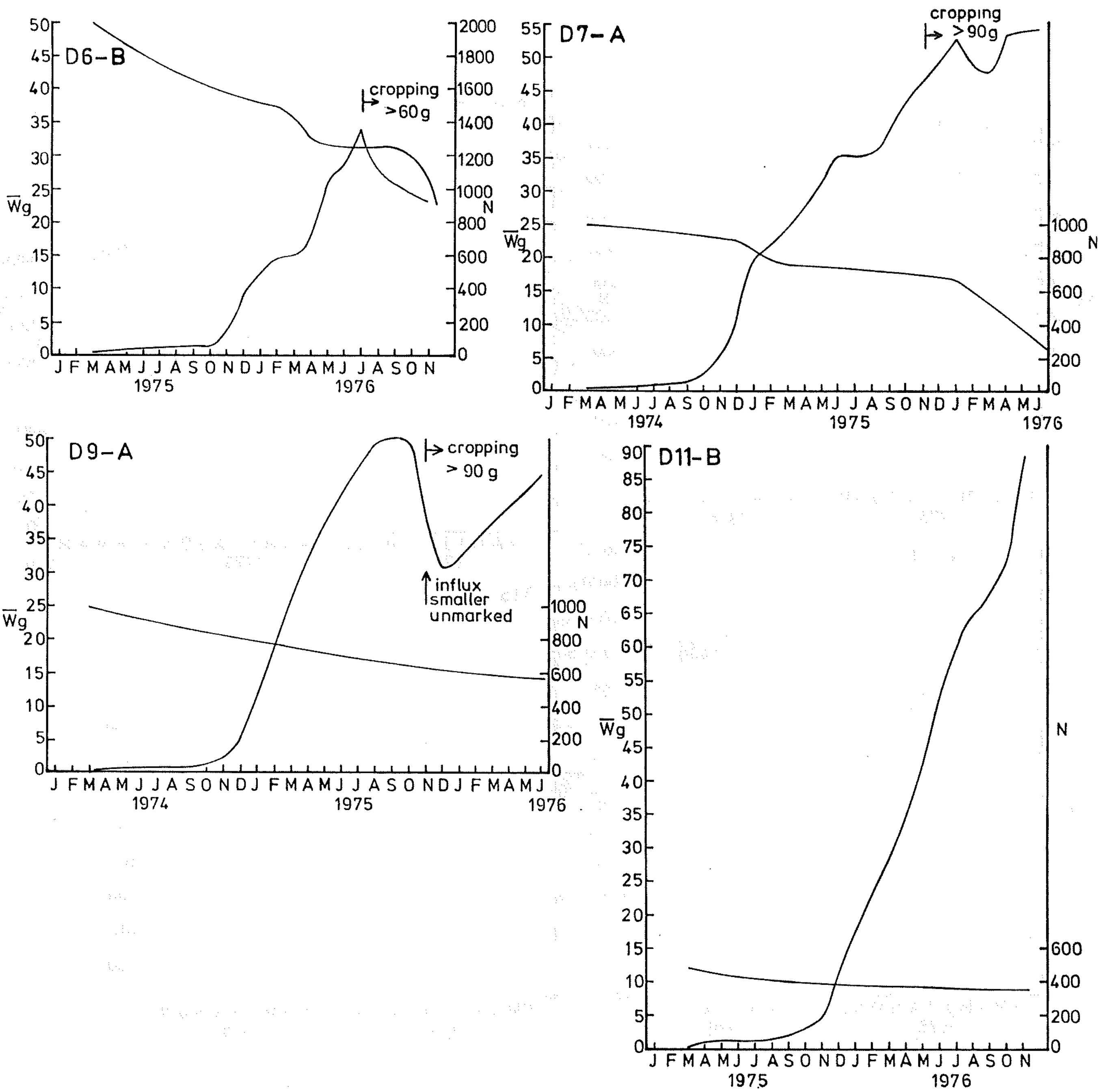

Figure 6—*continued.*

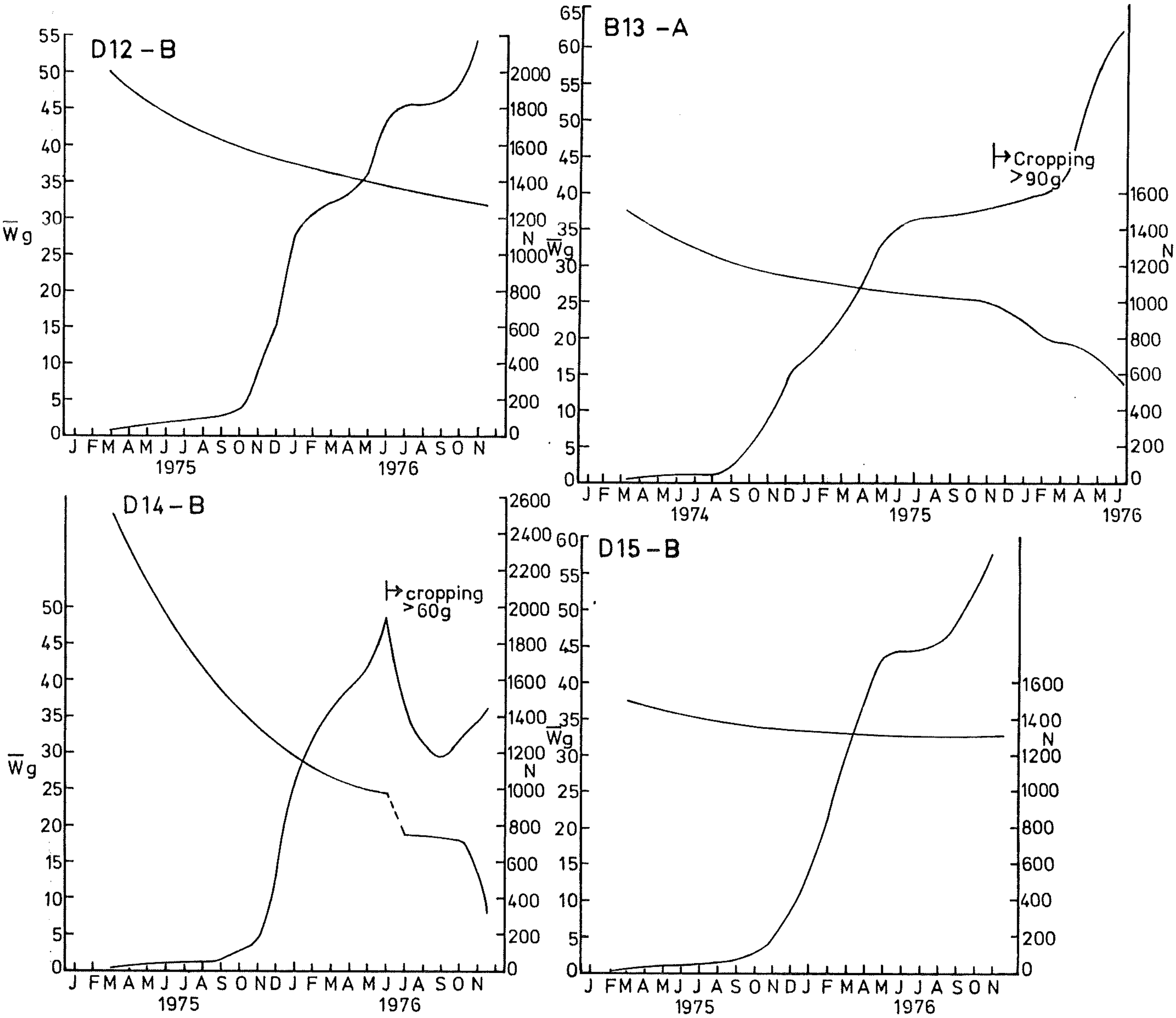

Figure 6—*continued.*

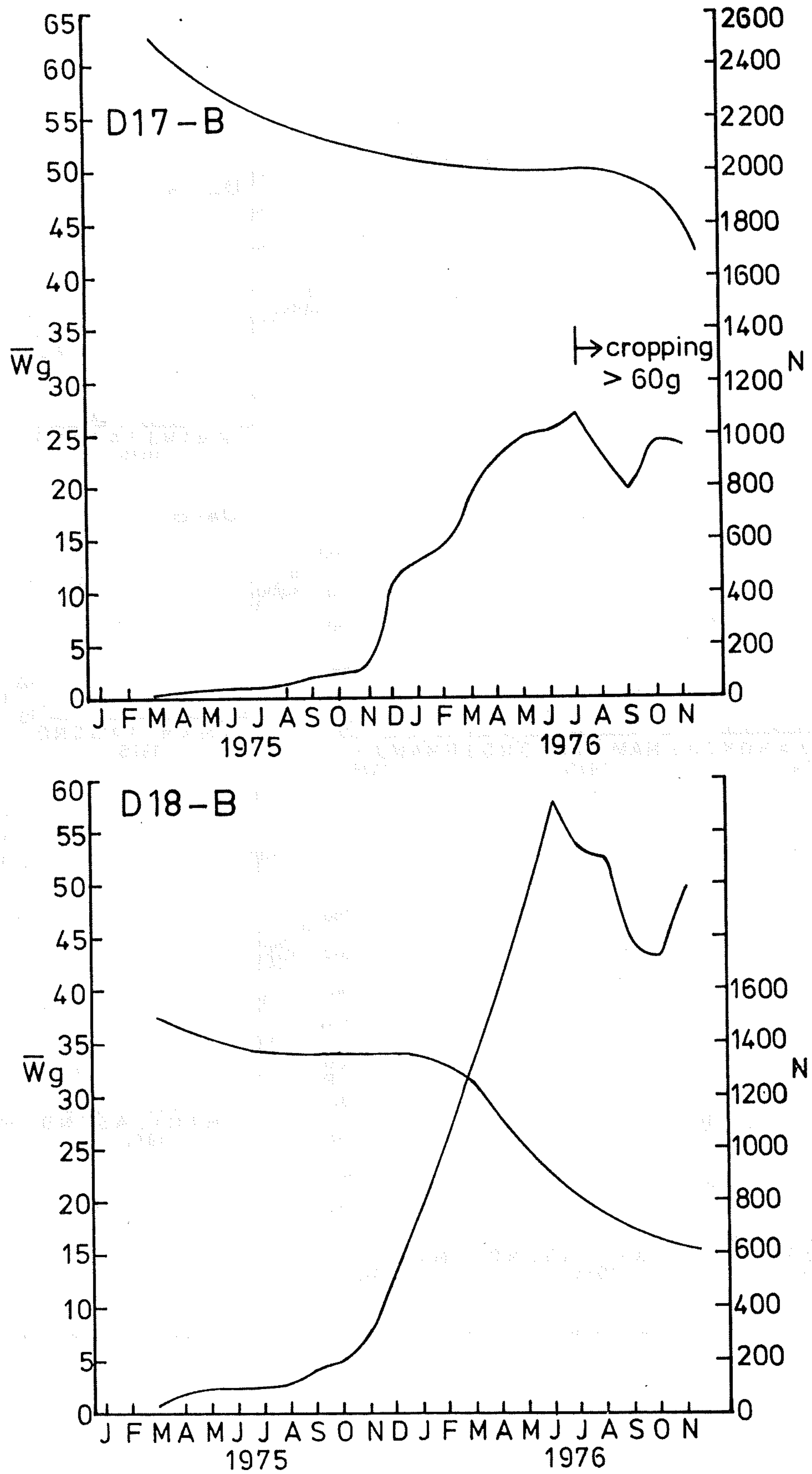

Figure 6—*continued.*

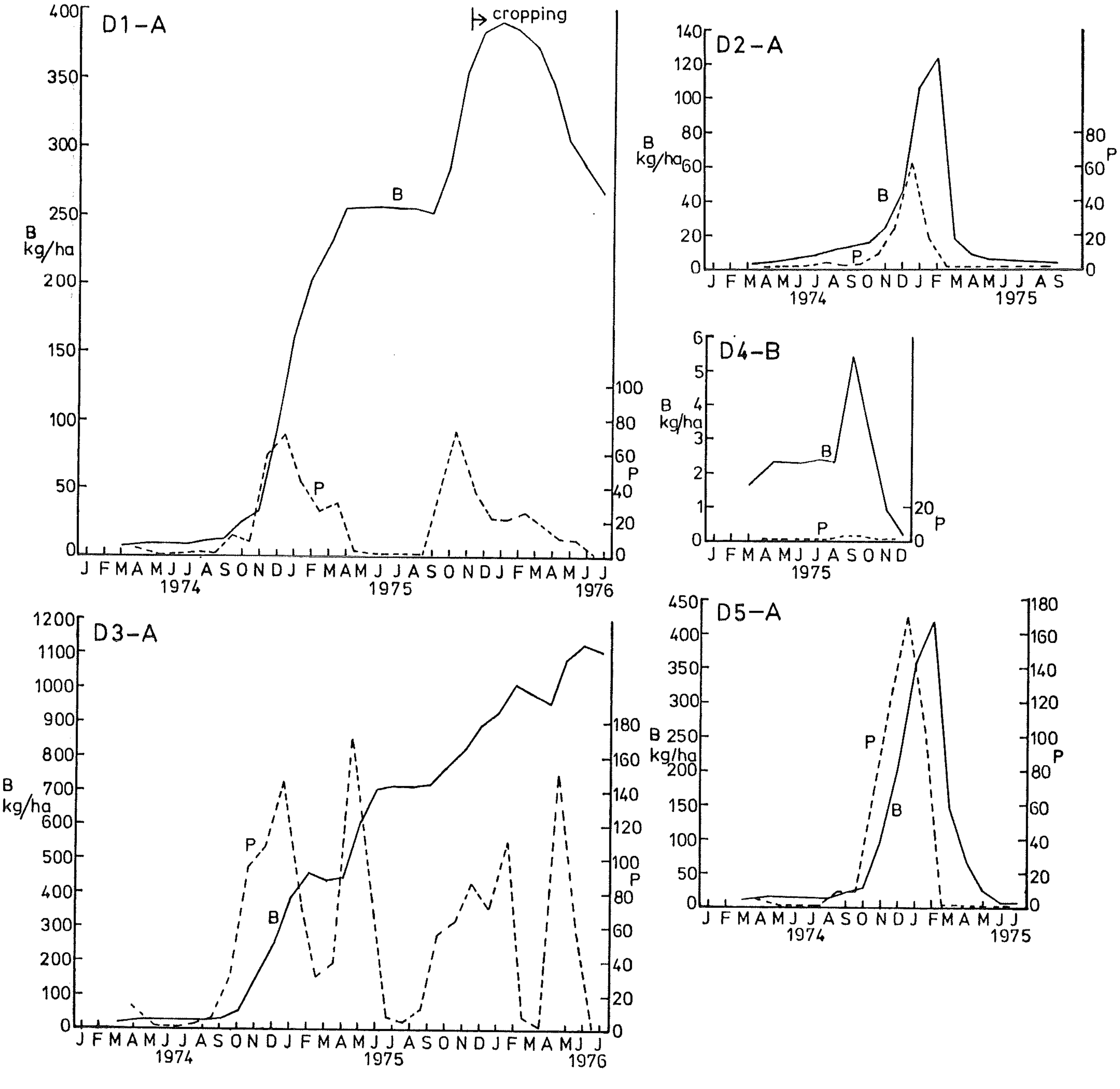

Figure 7—Monthly biomass (B) and production (P) of farm dam marron, kg/ha.

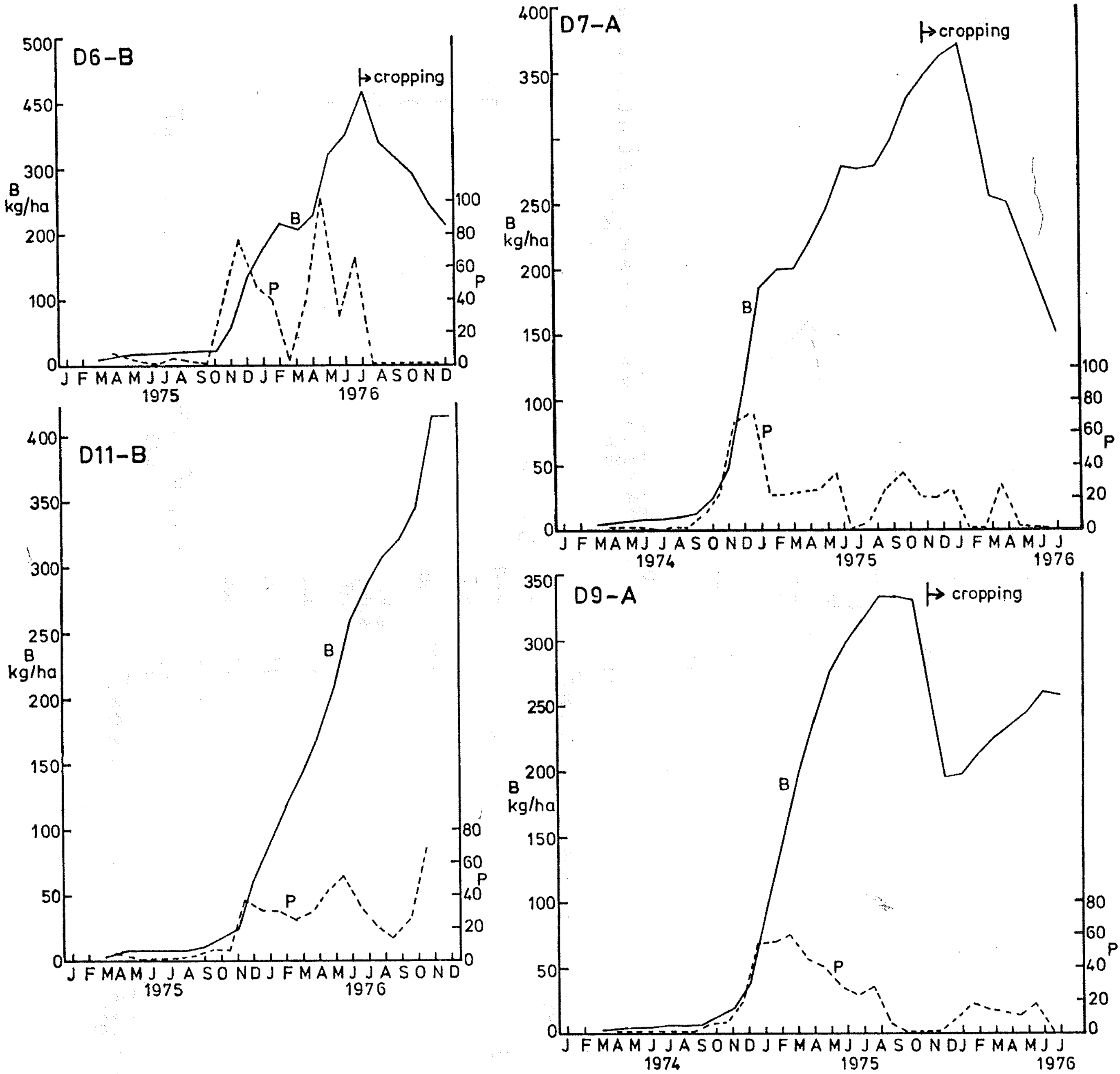

Figure 7—*continued.*

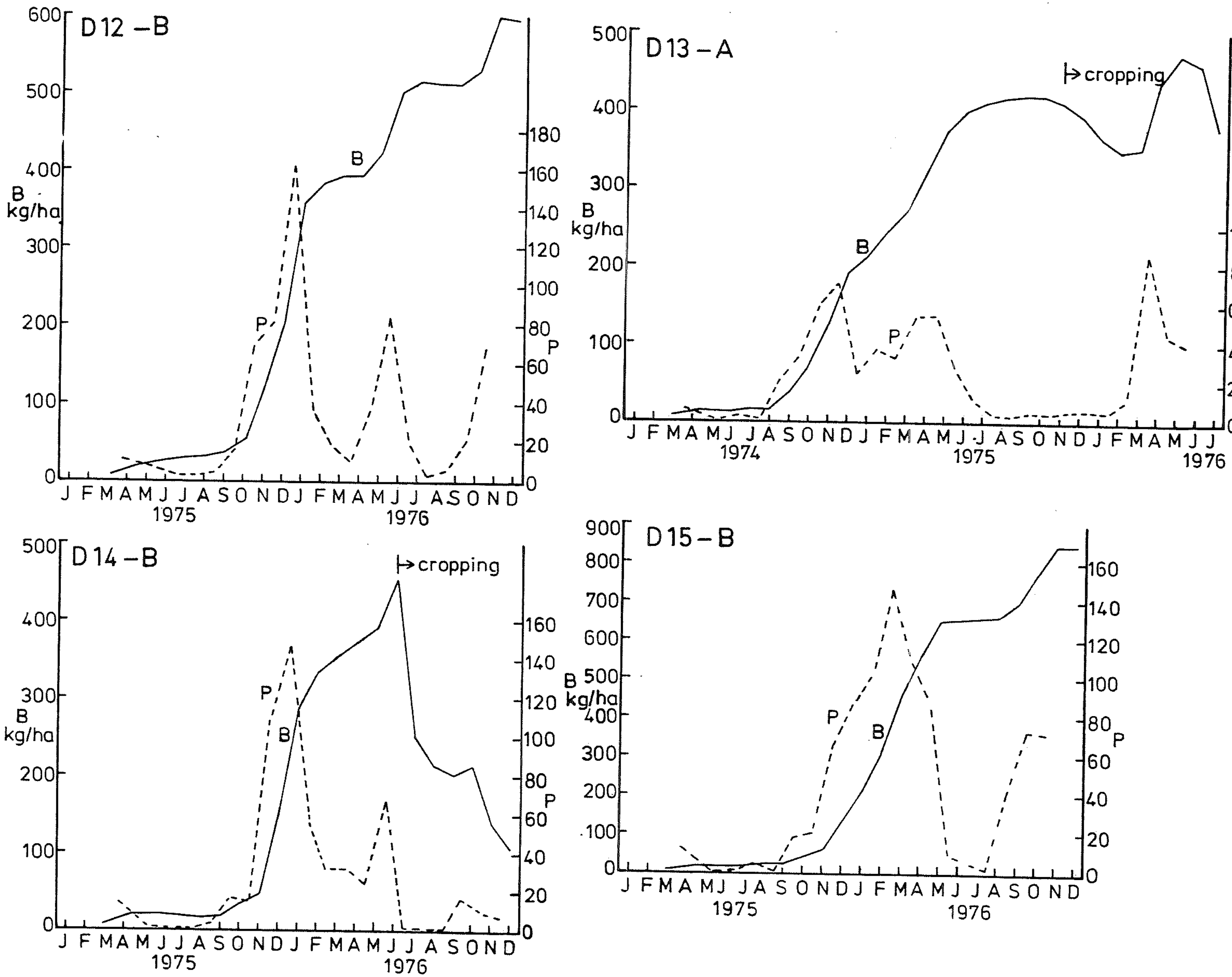

Figure 7—continued.

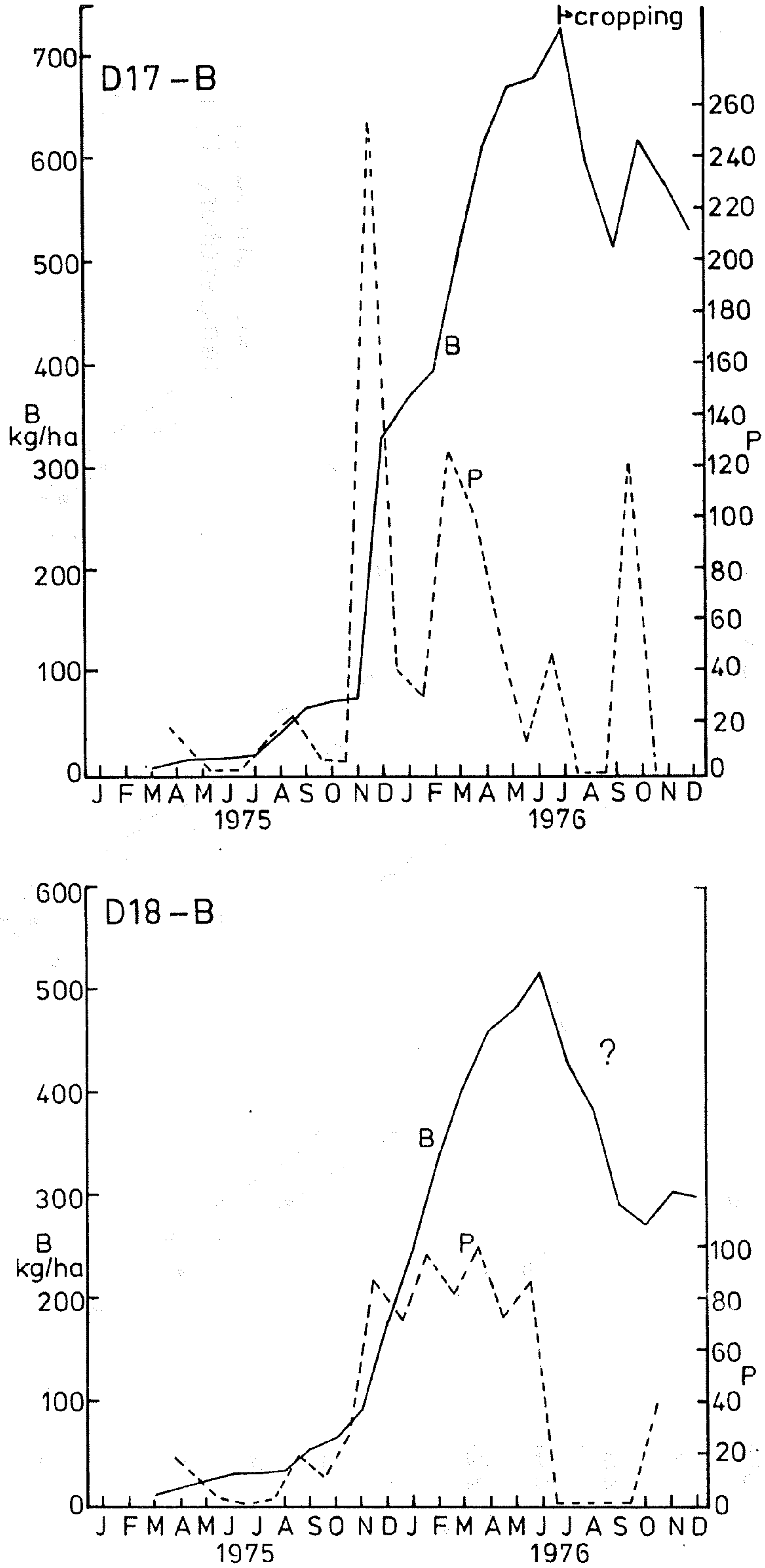

Figure 7—*continued.*

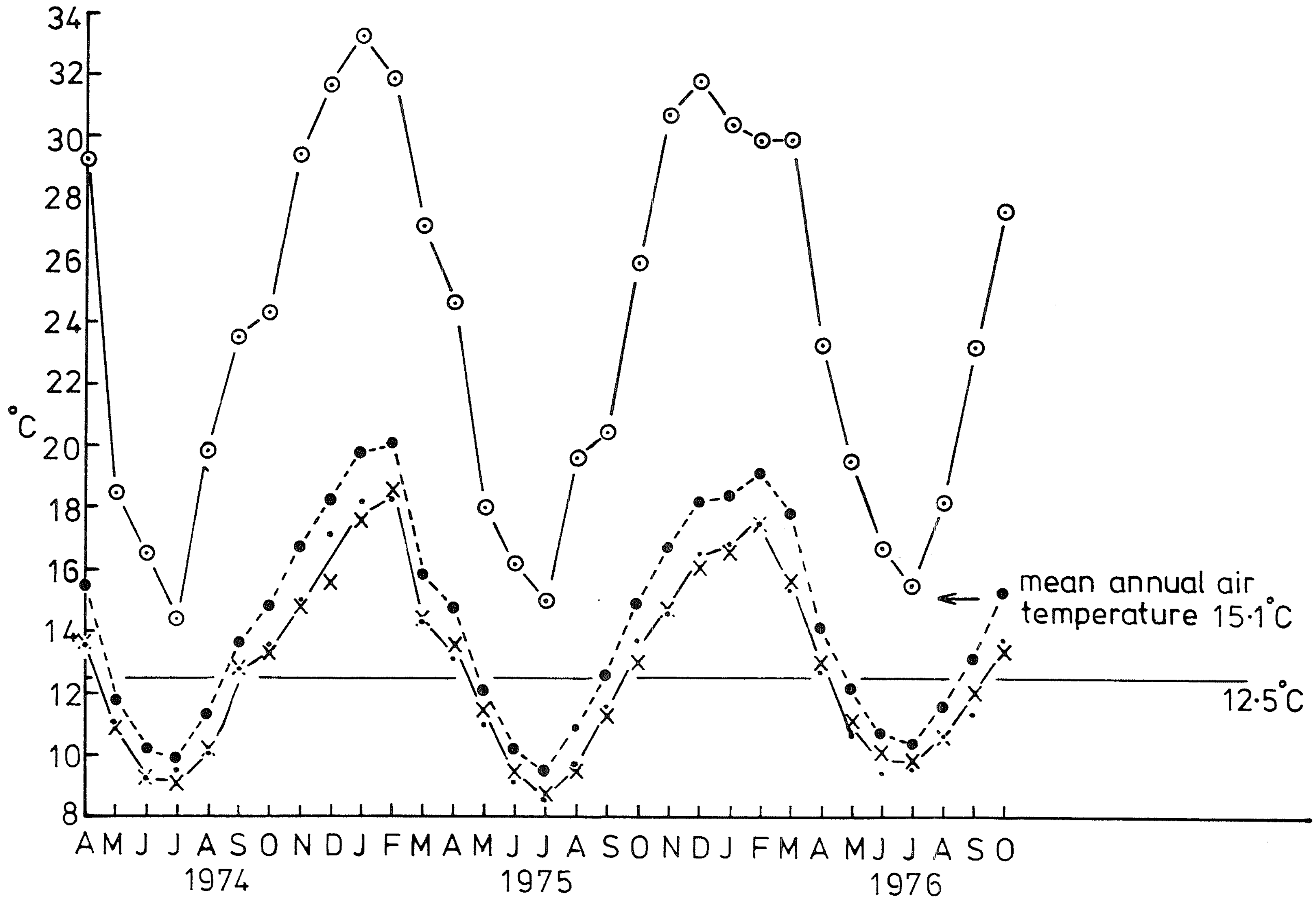

Figure 8—Monthly surface maximum, ⊙, minimum, •, and bottom minimum, X, water temperatures for the average farm dam. Derived monthly water temperature for the average dam water mass, - - - ●, see text.

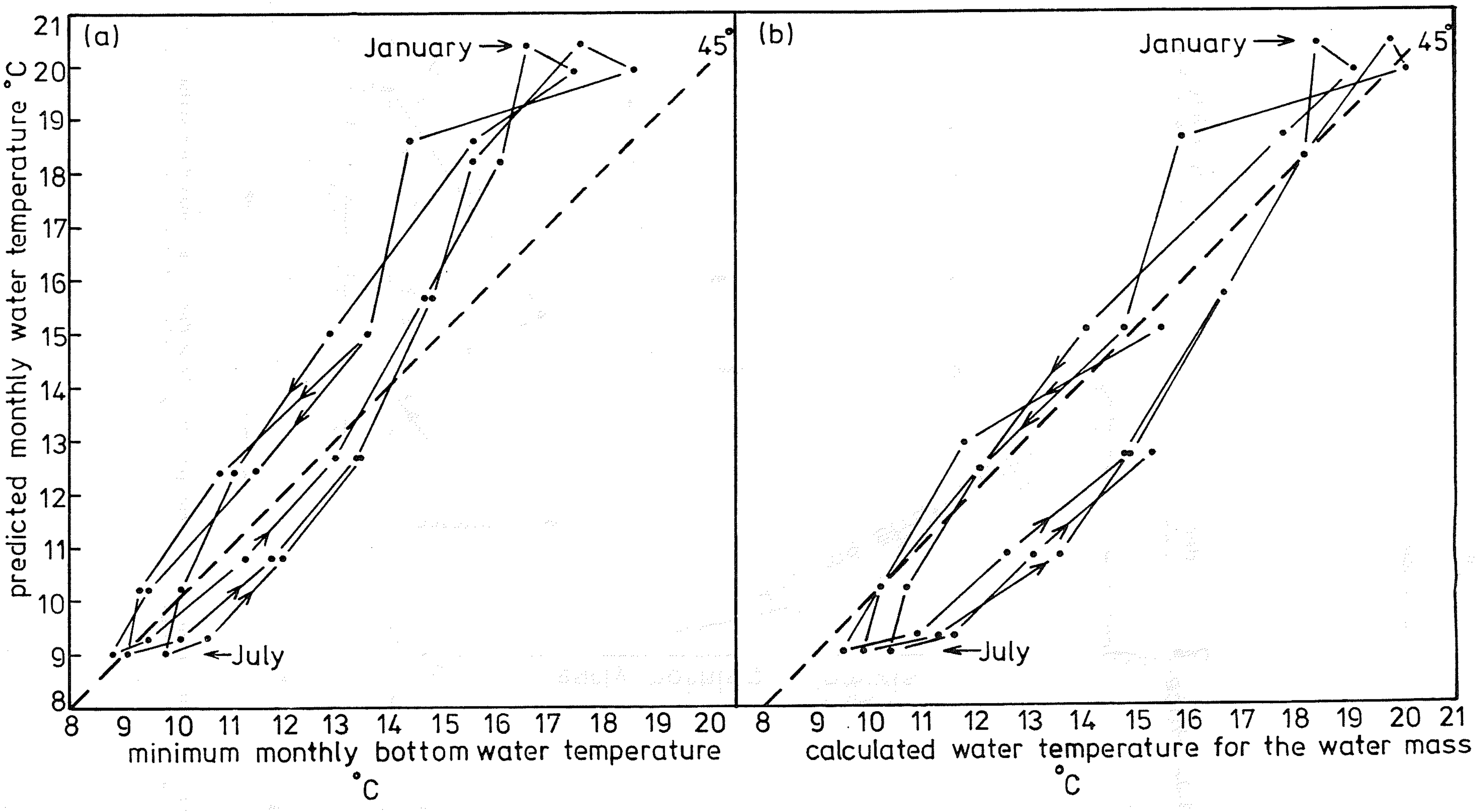

Figure 9—Comparison of monthly water temperature predicted from long term Kojonup mean air temperatures with, (a), minimum monthly bottom water temperature and, (b), the derived water temperature, for the average dam water mass (Fig. 8).

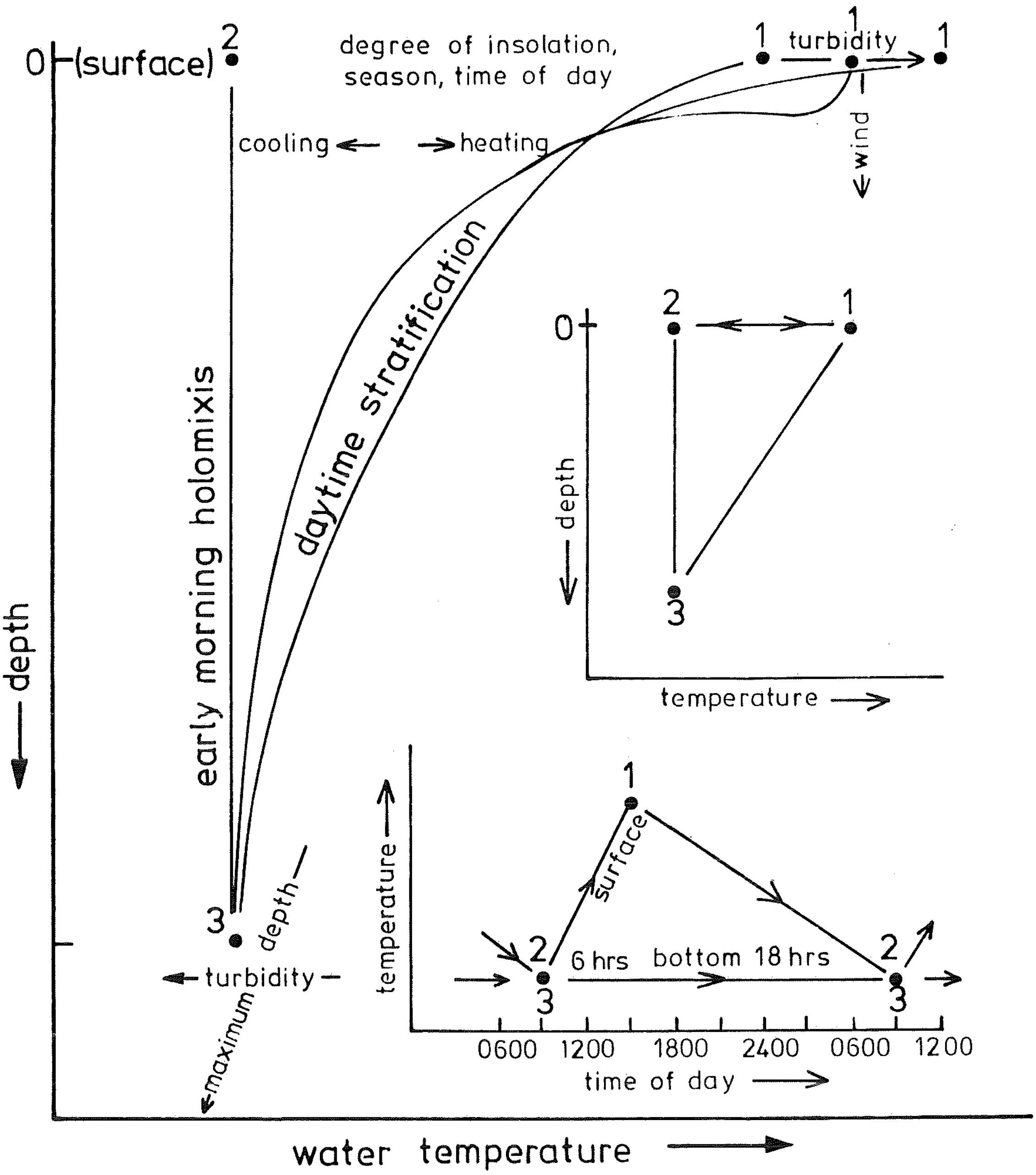

Figure 10—Water temperature model for a turbid, polymictic farm dam. ● 1 maximum surface water temperature; ● 2 minimum surface water temperature; ● 3 minimum bottom water temperature.

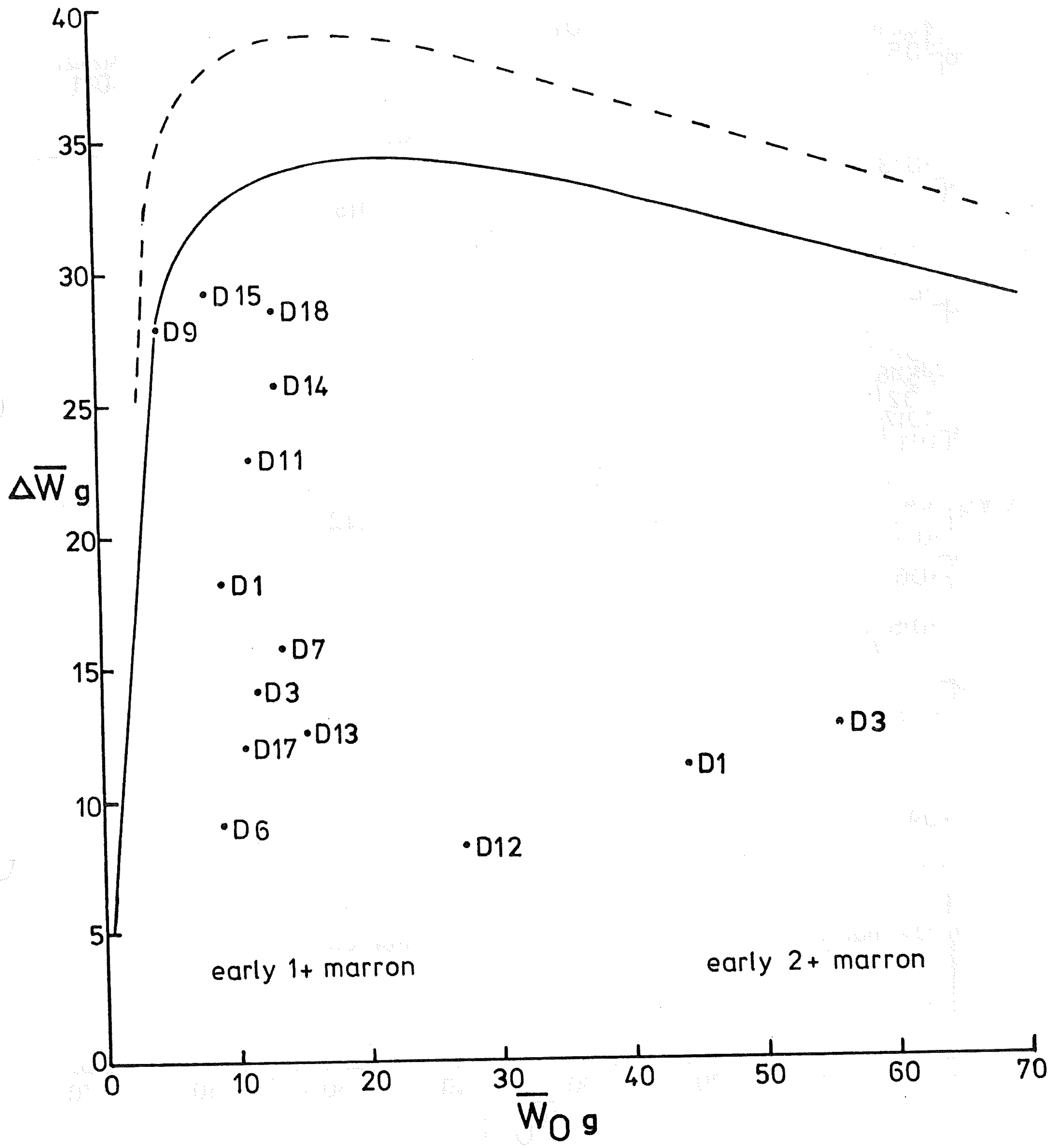

Figure 11—Increase in mean individual weight, $\triangle \overline{W}_g$, of farm dam marron, initial size $\overline{W}_O$, over the four month 'summer' period, December—April, compared with growth curves (——mean, – – – upper limit to observations) from intensive pond culture at the Pemberton Fish Hatchery (Morrissy 1979).

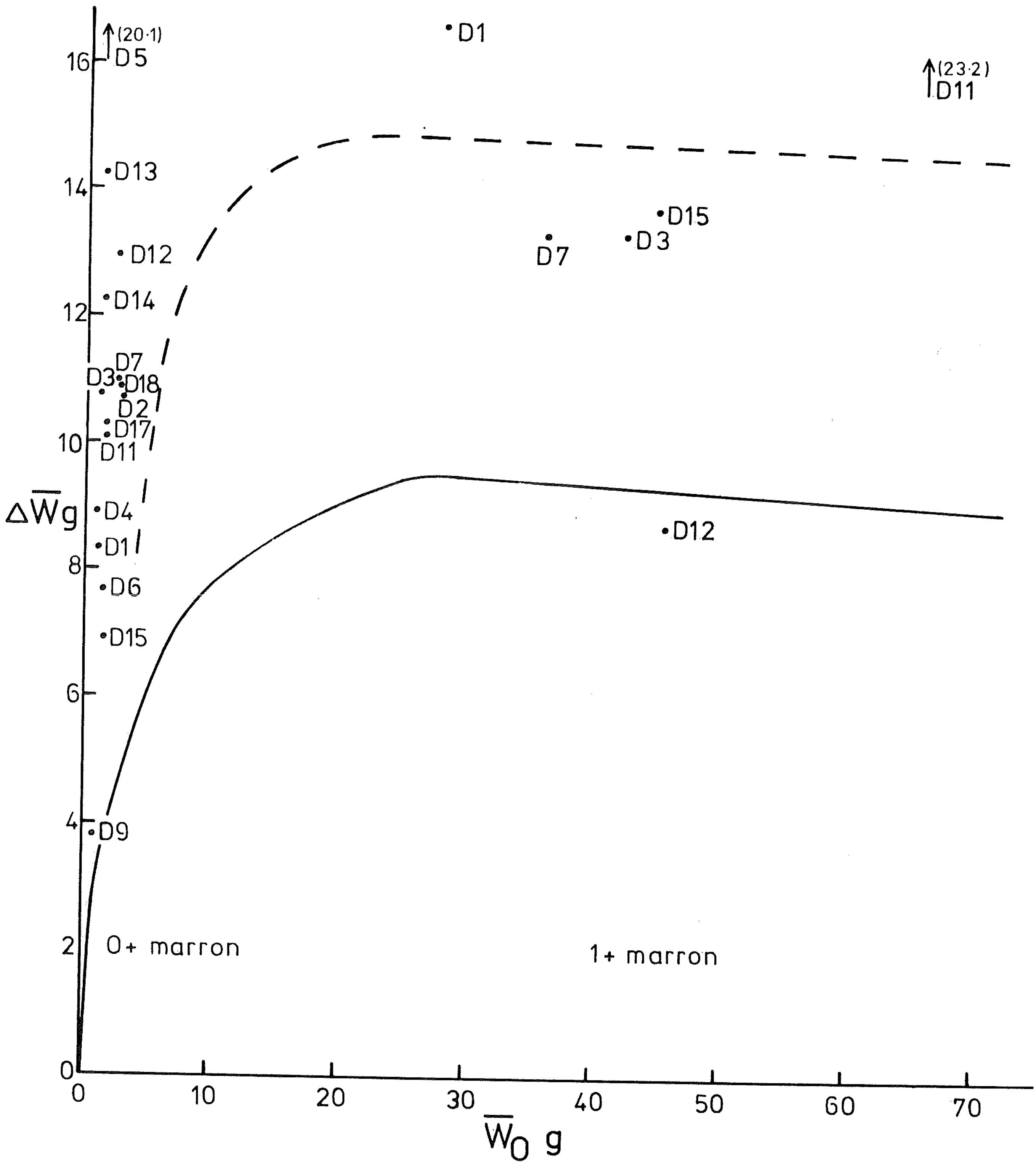

Figure 12—Farm dam growth over the 'spring', August—December, period compared with curves derived from intensive pond culture (see Fig. 11).

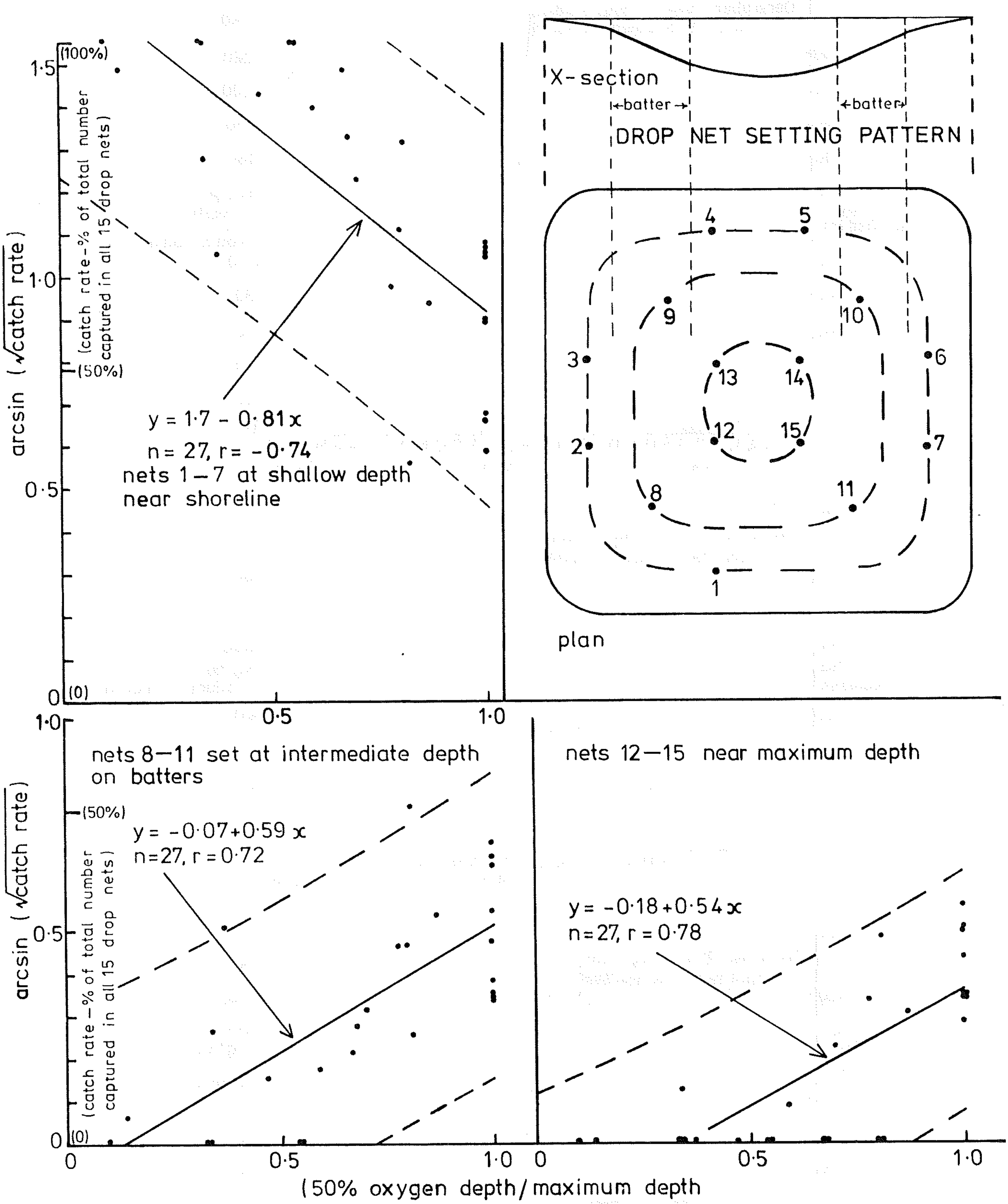

Figure 13—Relationship between catch rate at different depths and degree of oxygen depletion during summer. Mean regression curve ——; 95% confidence limits for data points – – – –. Also shown, diagrammatically, is the drop net setting pattern.

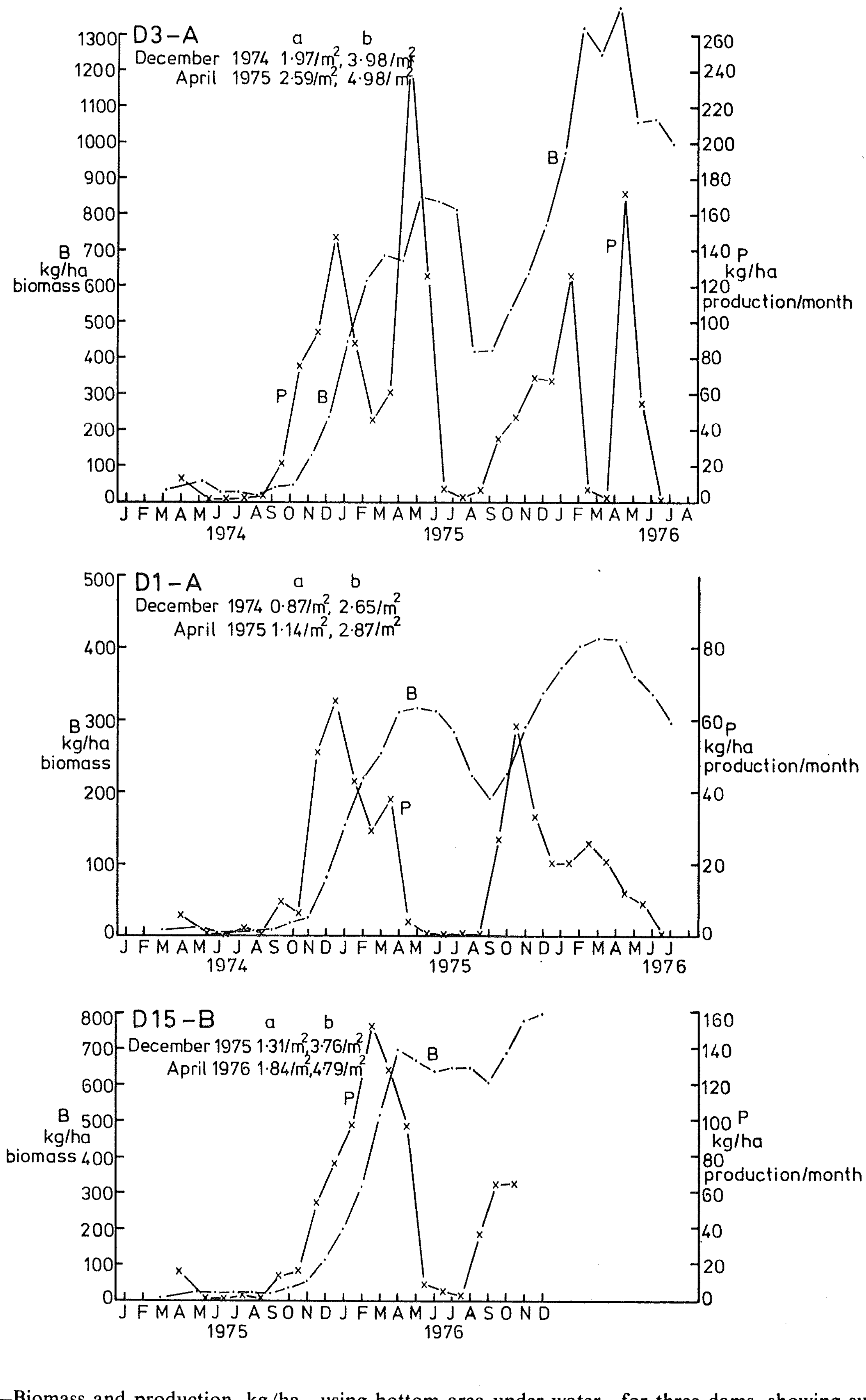

Figure 14—Biomass and production, kg/ha—using bottom area under water—for three dams, showing summer and winter responses to unfavourable conditions. Density values, a and b, are for total bottom area under water and bottom area under 1 m or less depth of water, respectively.

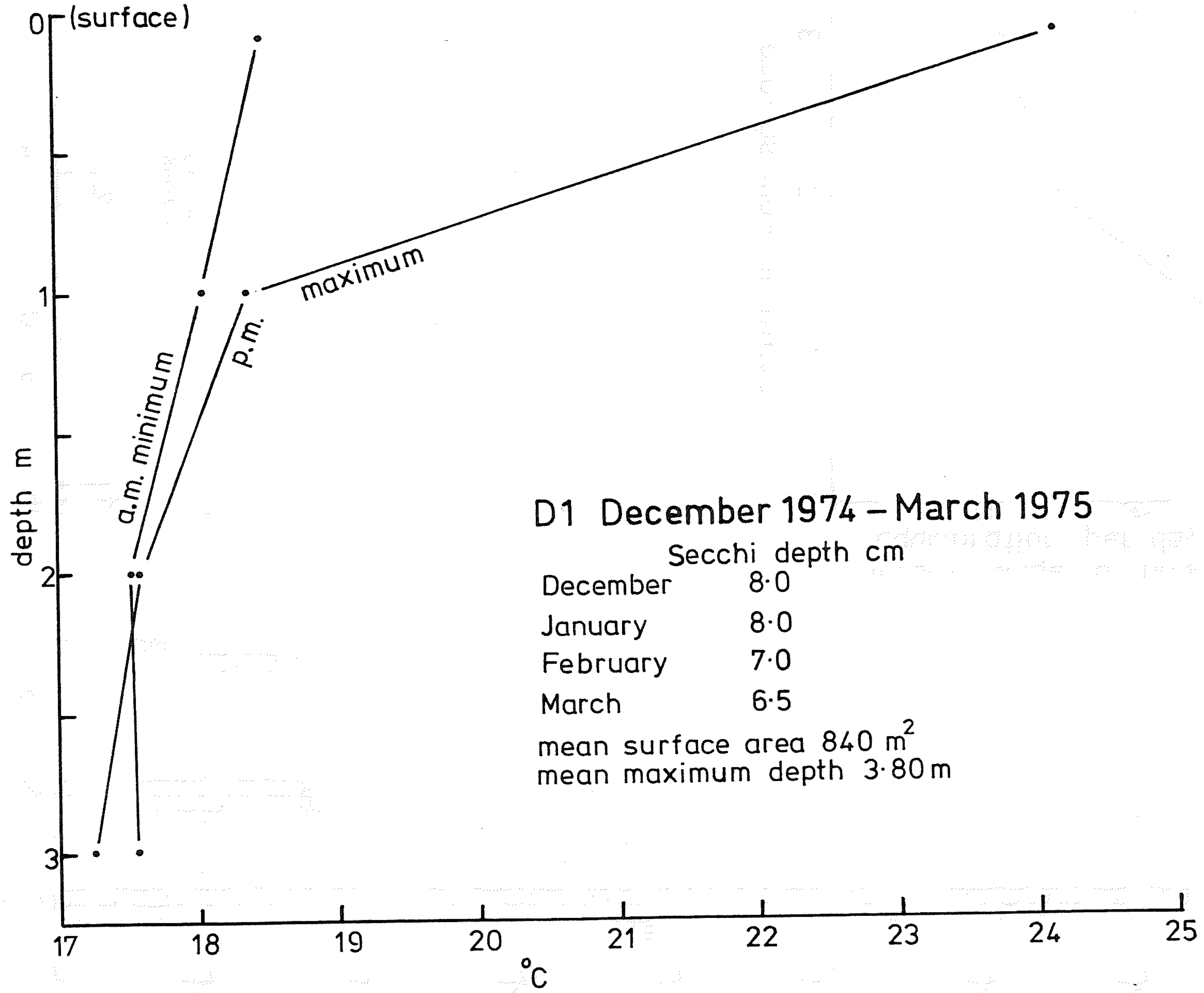

Figure 15—Mean water temperature with depth over a summer period for D1.

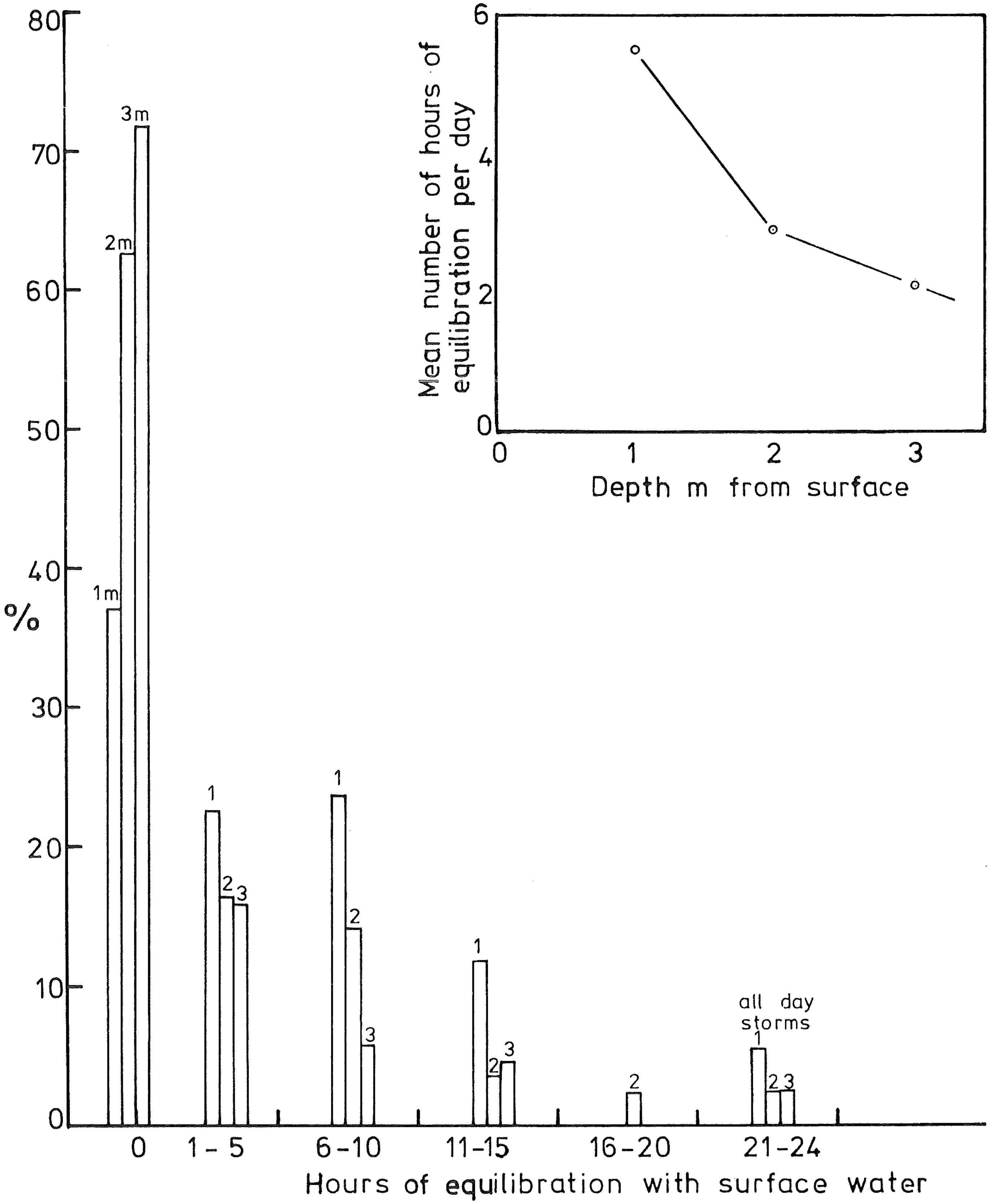

Figure 16—Daily frequency of temperature equilibration of sub-surface (1, 2, 3 m from surface) and surface water from December 1974 to March 1975 in D1.

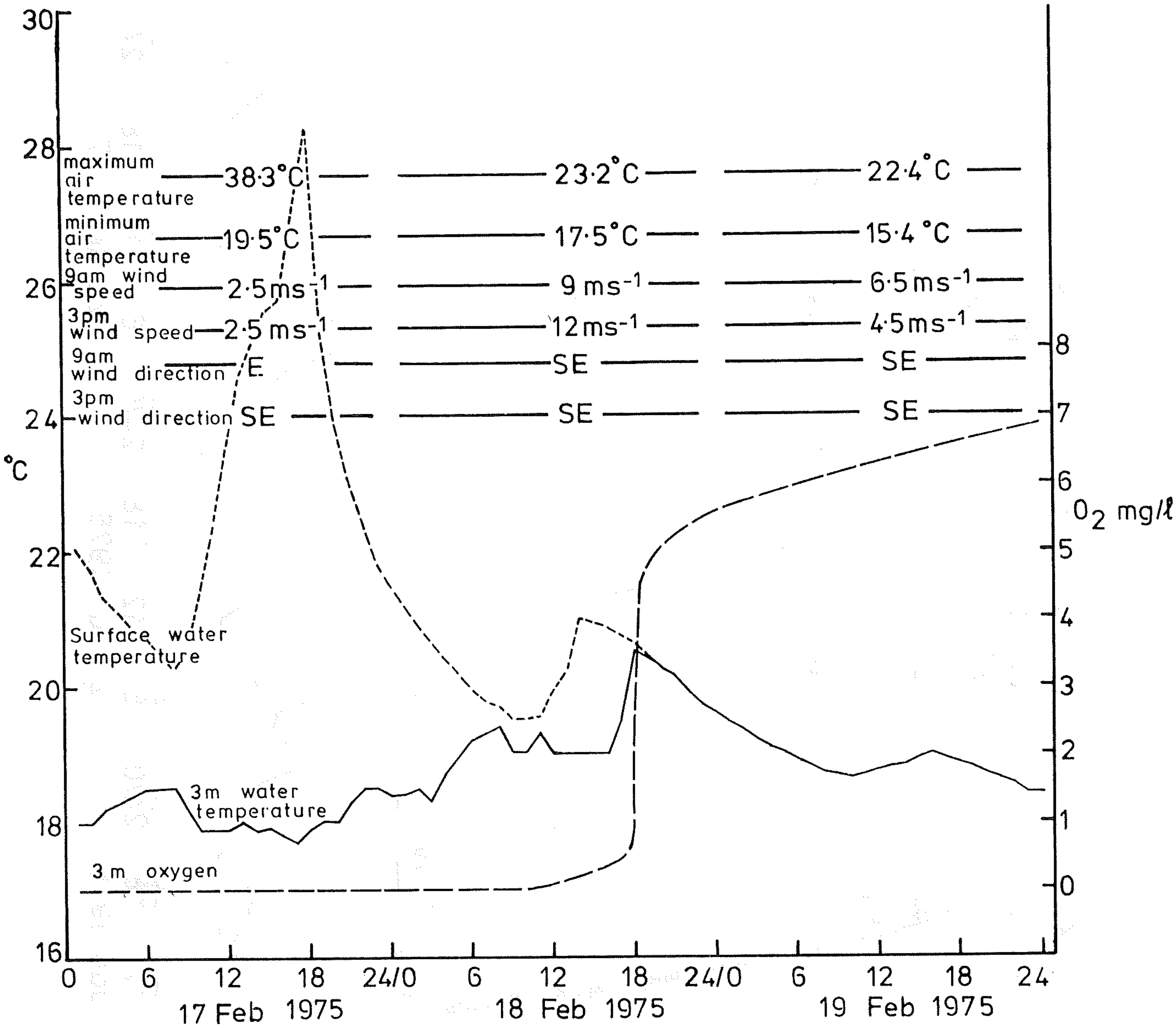

Figure 17—Holomixis and reaeration to 3 m depth in D1 generated by a stormy "cool change" from the south-east commencing about midday (18 February, 1975).

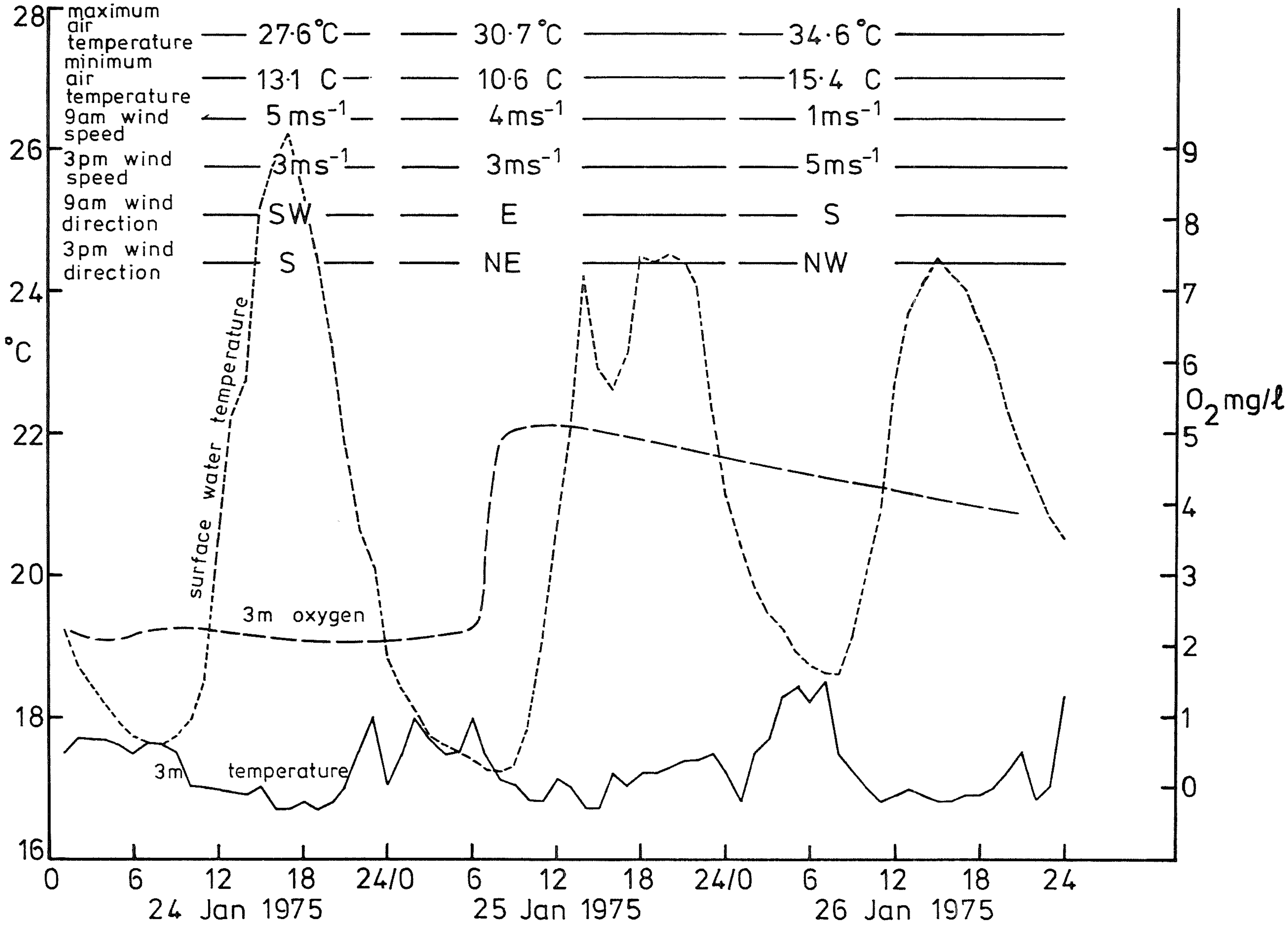

Figure 18—Mid-morning holomixis and reaeration to 3 m depth for about two hours in D1 on a cooler than usual morning with a light wind from the east.

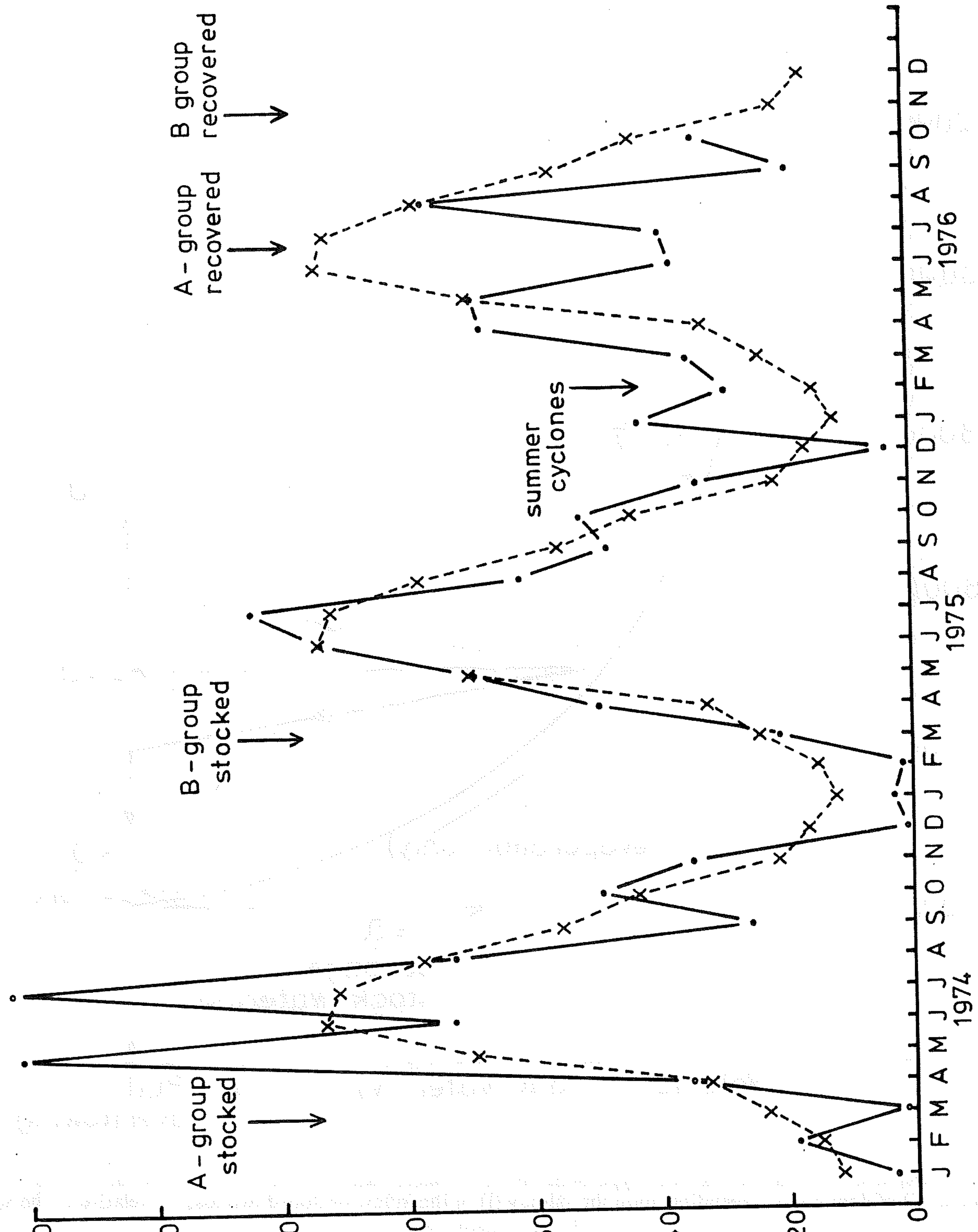

Figure 19—Monthly rainfall at Kojonup -●-●- compared with long term monthly mean rainfall -x-x-.

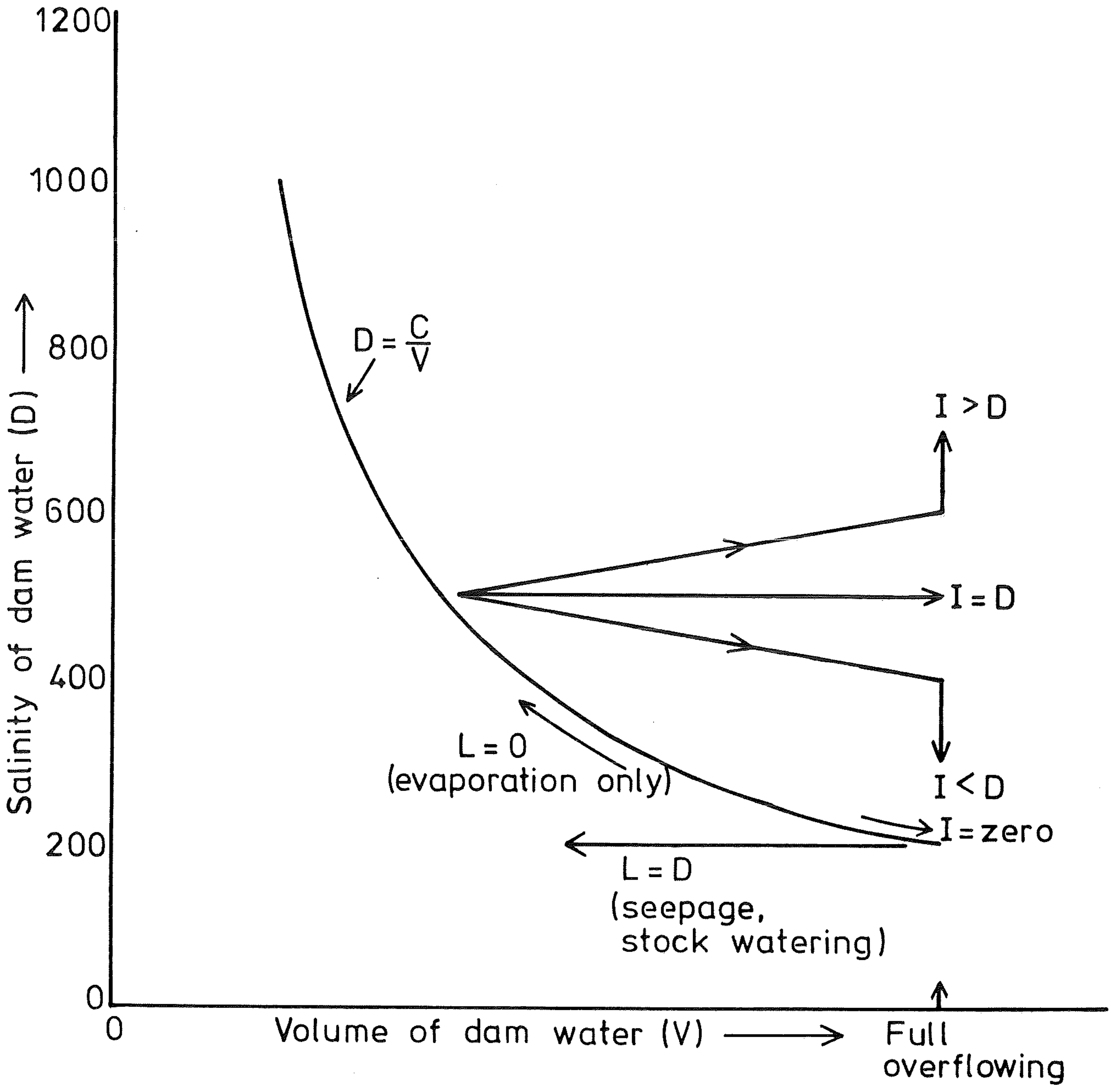

Figure 20—Departures from the classical hyperbolic dilution-concentration curve ($D = C/V$) for a constant total salt content (C) of dam water, depending upon the salinity (I) of the inflow or drawdown loss (L) relative to the salinity (D) of the dam water.

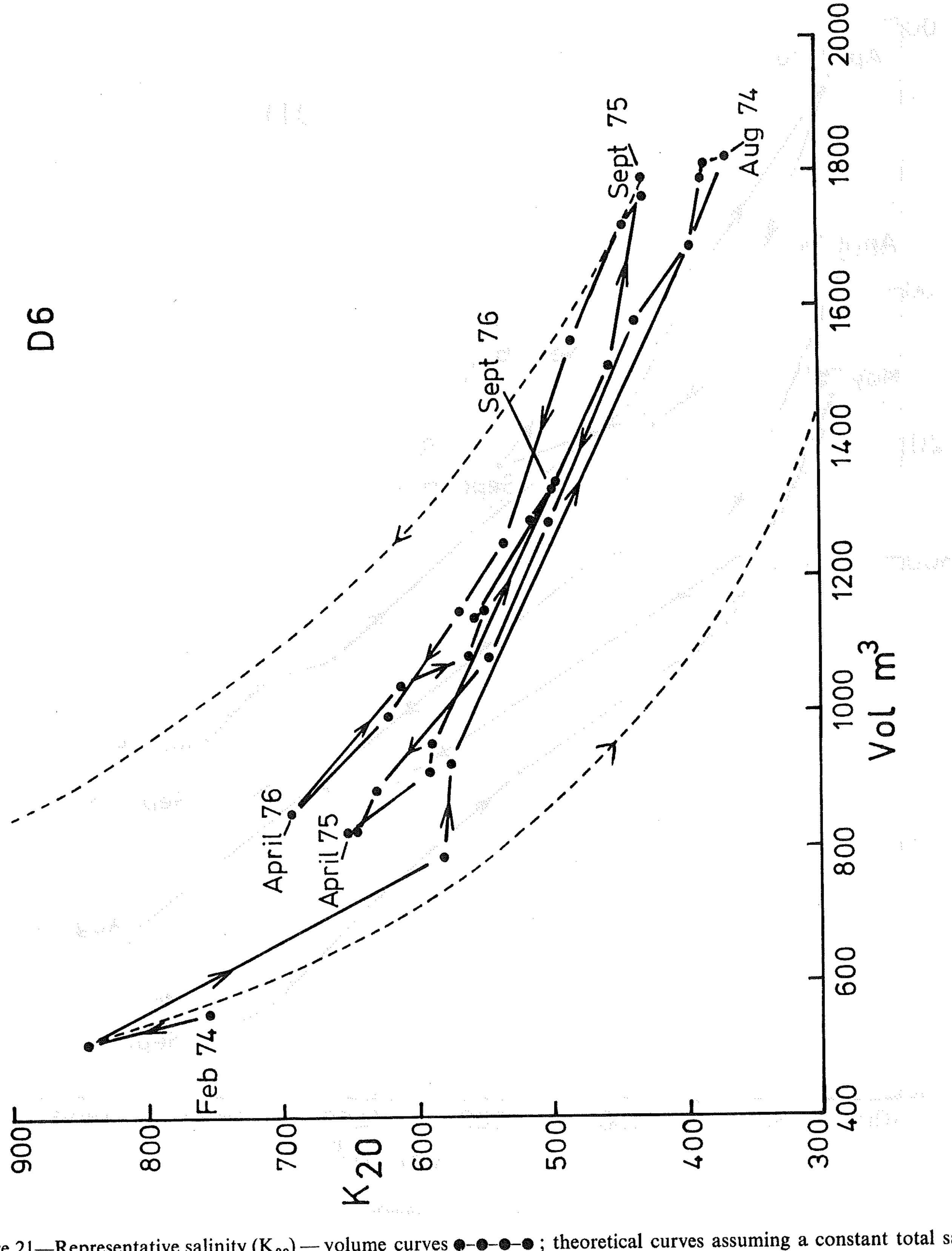

Figure 21—Representative salinity (K_{20}) — volume curves ●-●-●-● ; theoretical curves assuming a constant total salt content over a particular filling or drawdown cycle are shown as – – – – – – for comparison.

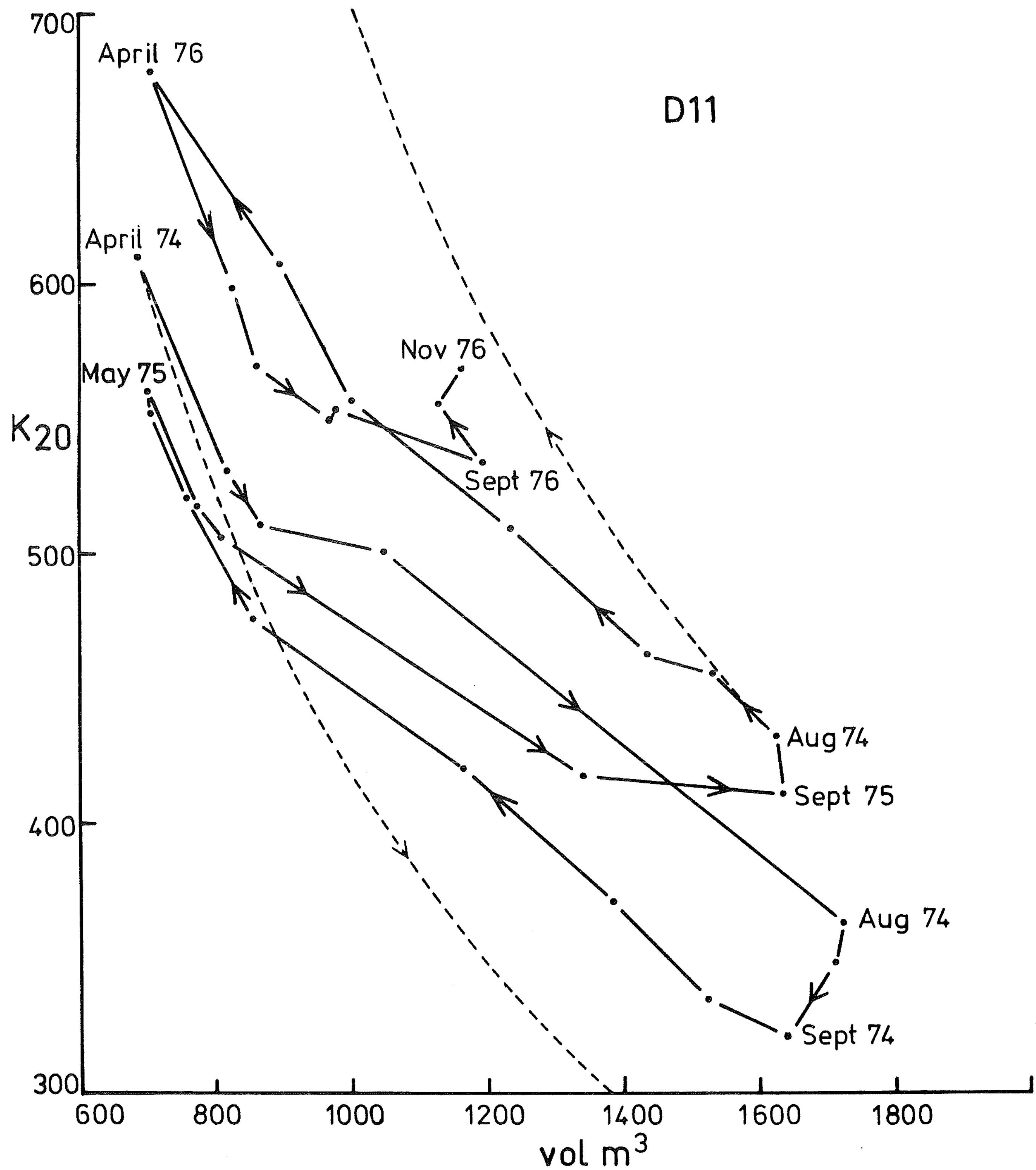

Figure 21—*continued.*

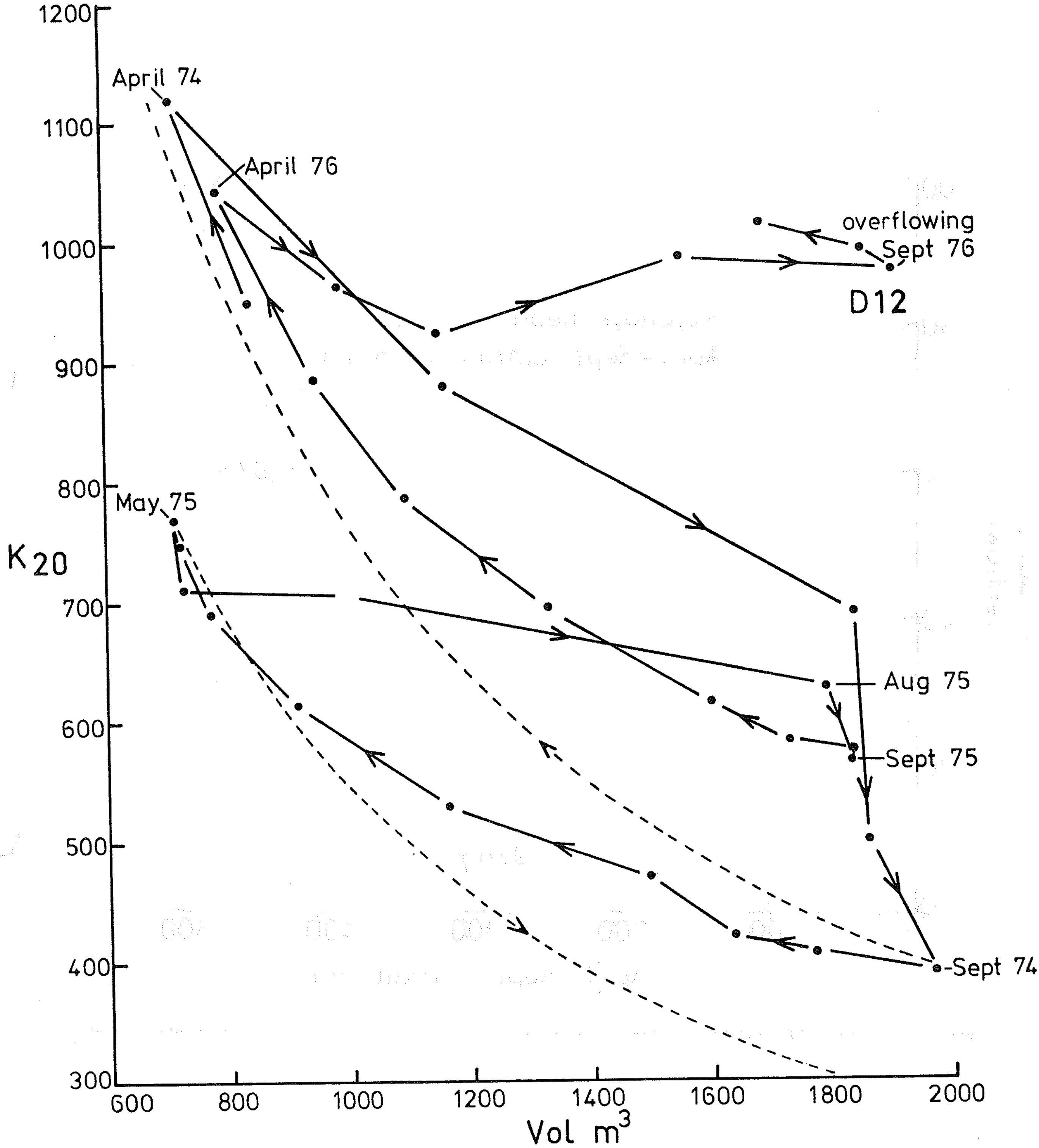

Figure 21—*continued.*

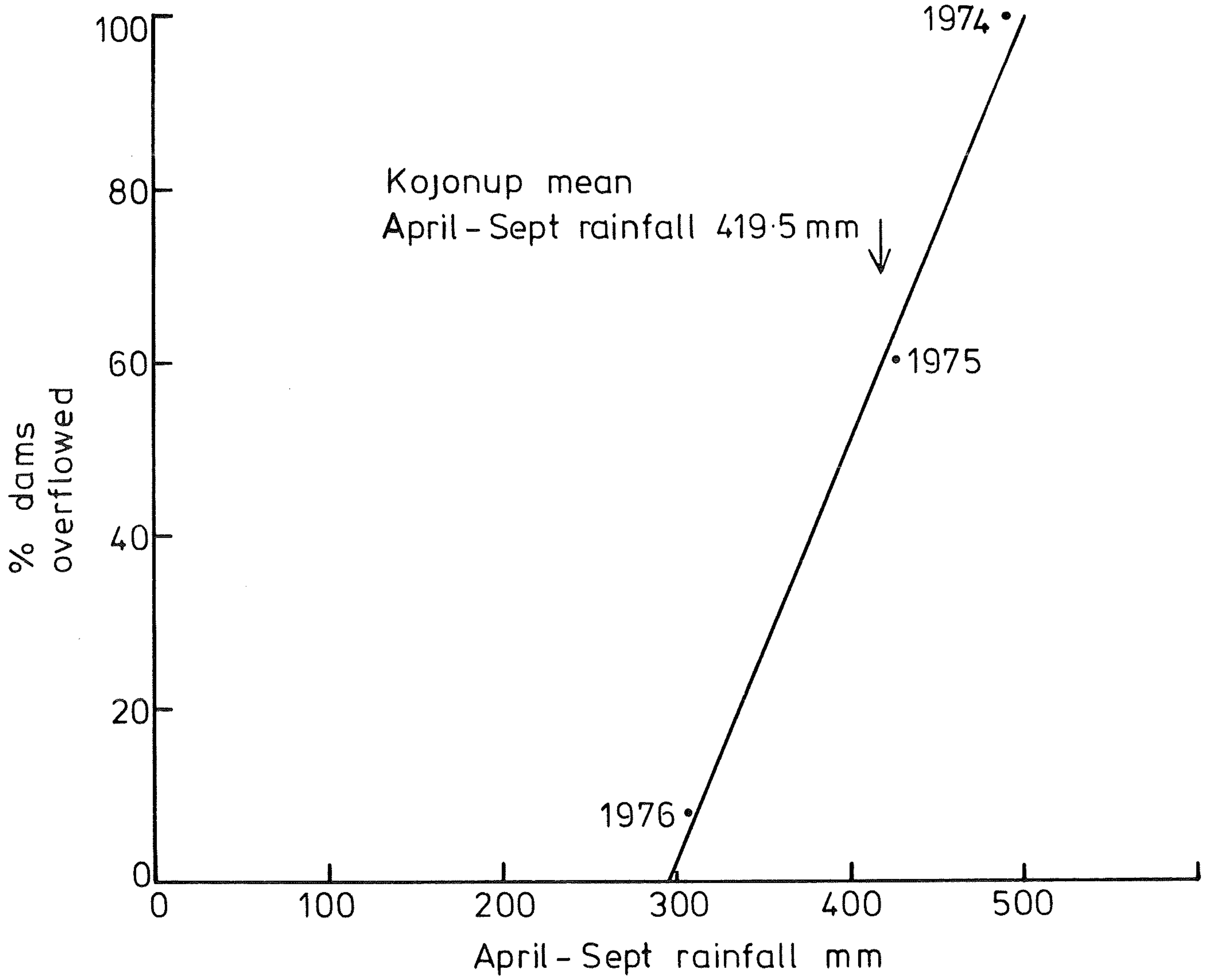

Figure 22—Relationship between the percentage of dams which overflowed each year and winter rainfall.

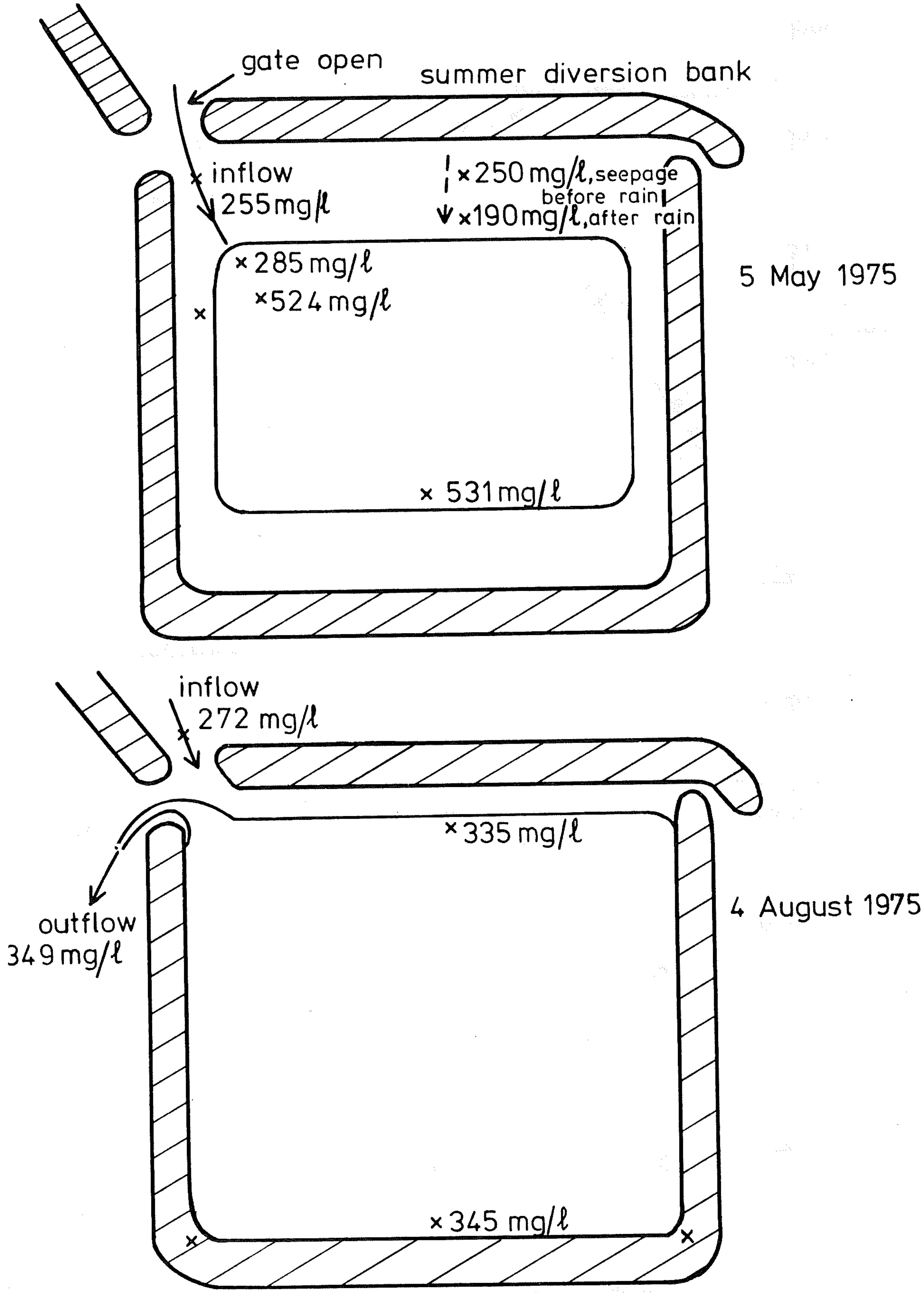

Figure 23—Salinities associated with fillings and overflow of D5. Water sampling sites are shown as x.

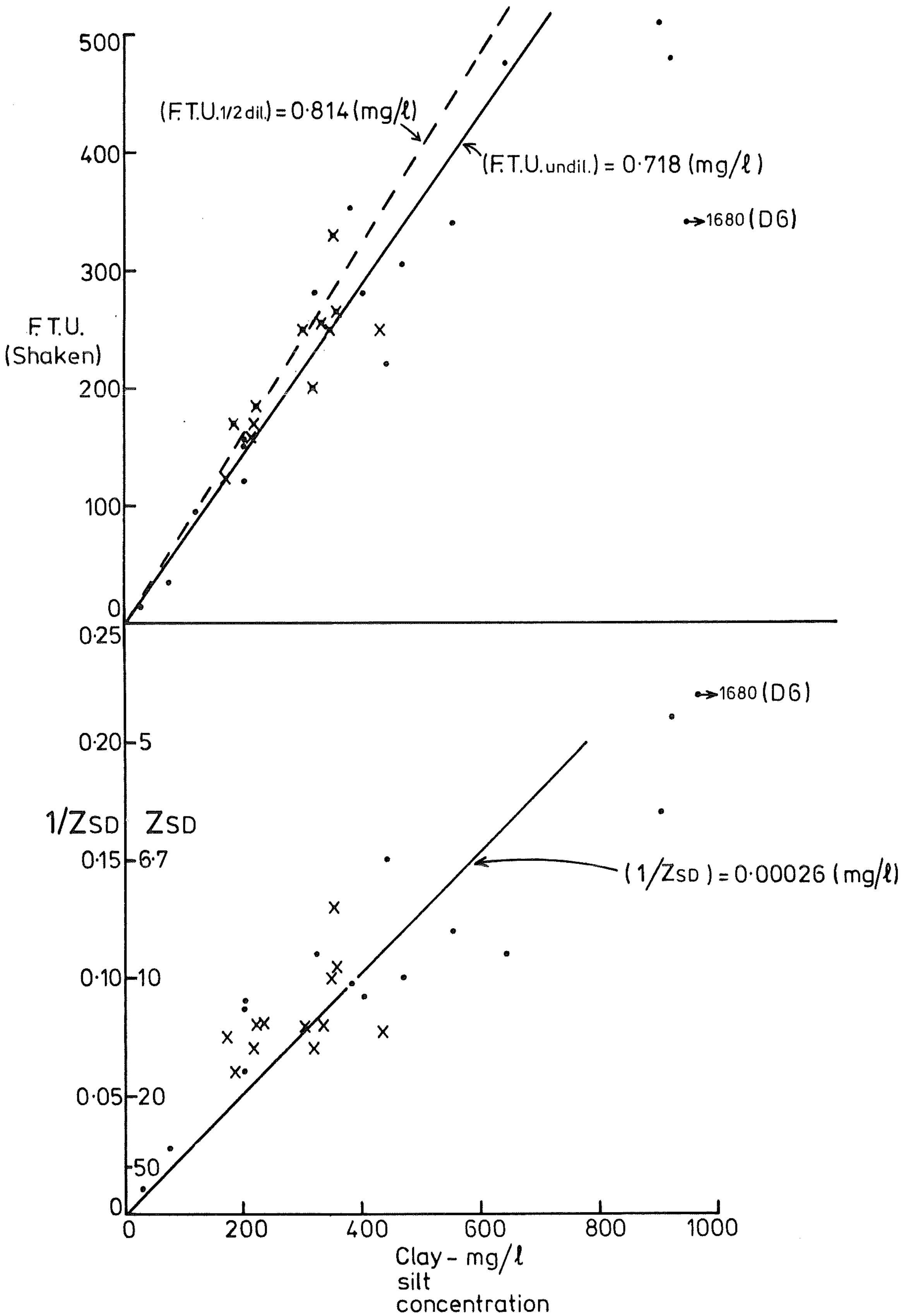

Figure 24—Relationships between nephelometric light scattering values, F.T.U. = Formazin (: Jackson) Turbidity Units, or Secchi disk depths $Z_{S.D.}$ cm and clay-silt concentrations (by the 'filtration' method). D3,x; other dams, ●.

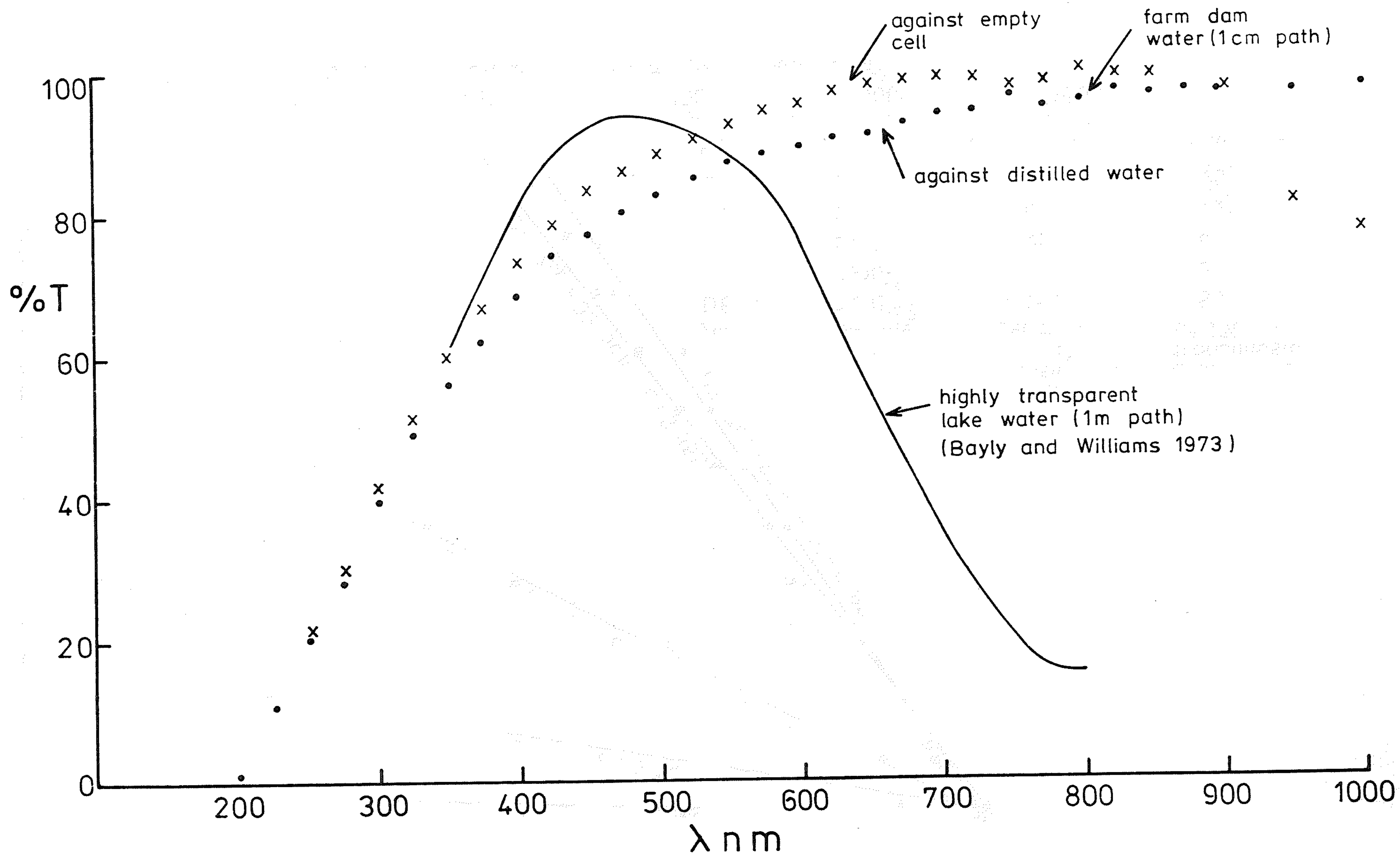

Figure 25—Per cent transmission of turbid (kaolin clay) farm dam water (D1) allowed to settle for one day compared with highly transparent lake water (after Bayly and Williams 1973).

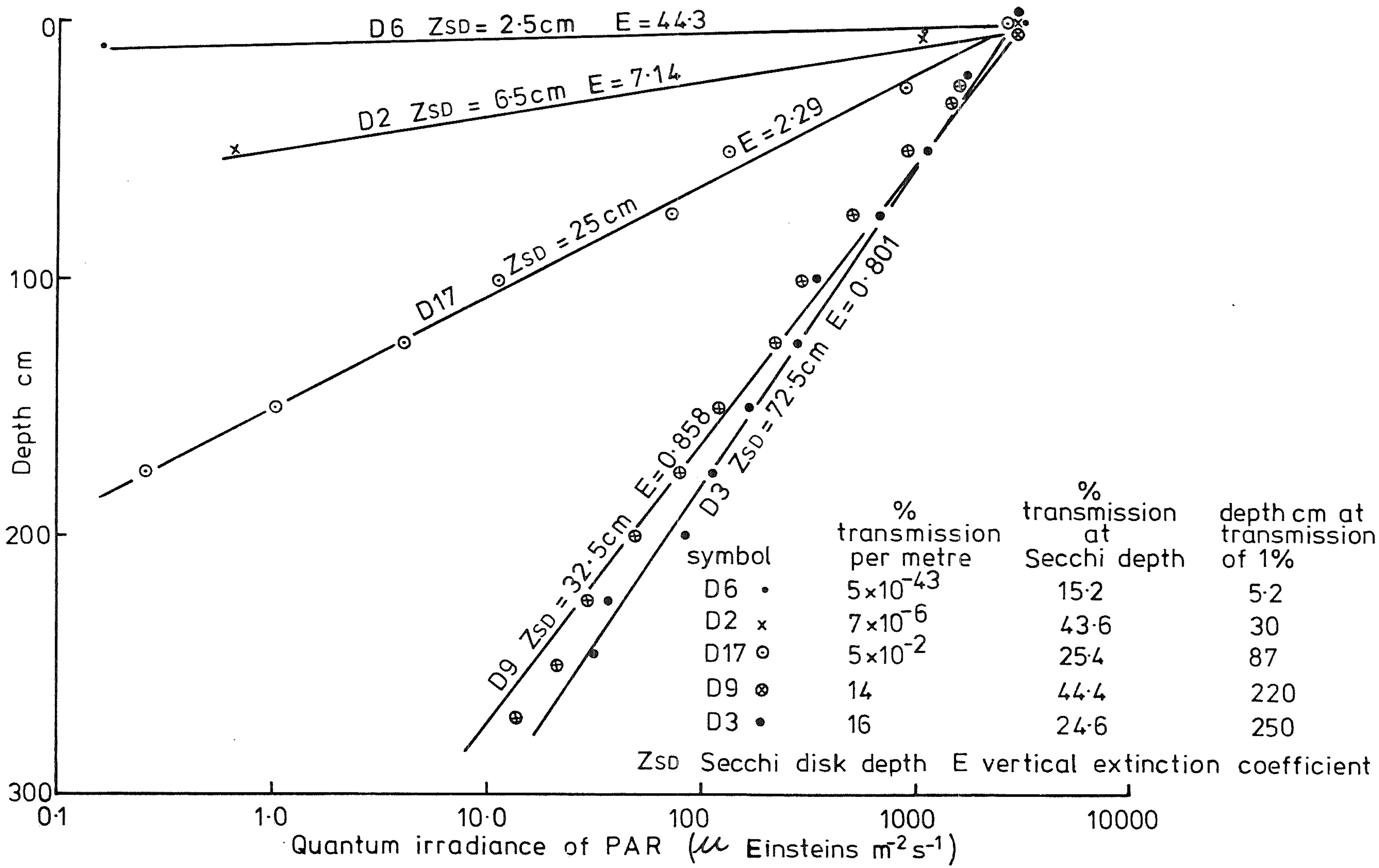

Figure 26—*In situ* measurements of absolute light transmission with depth in some farm dams.

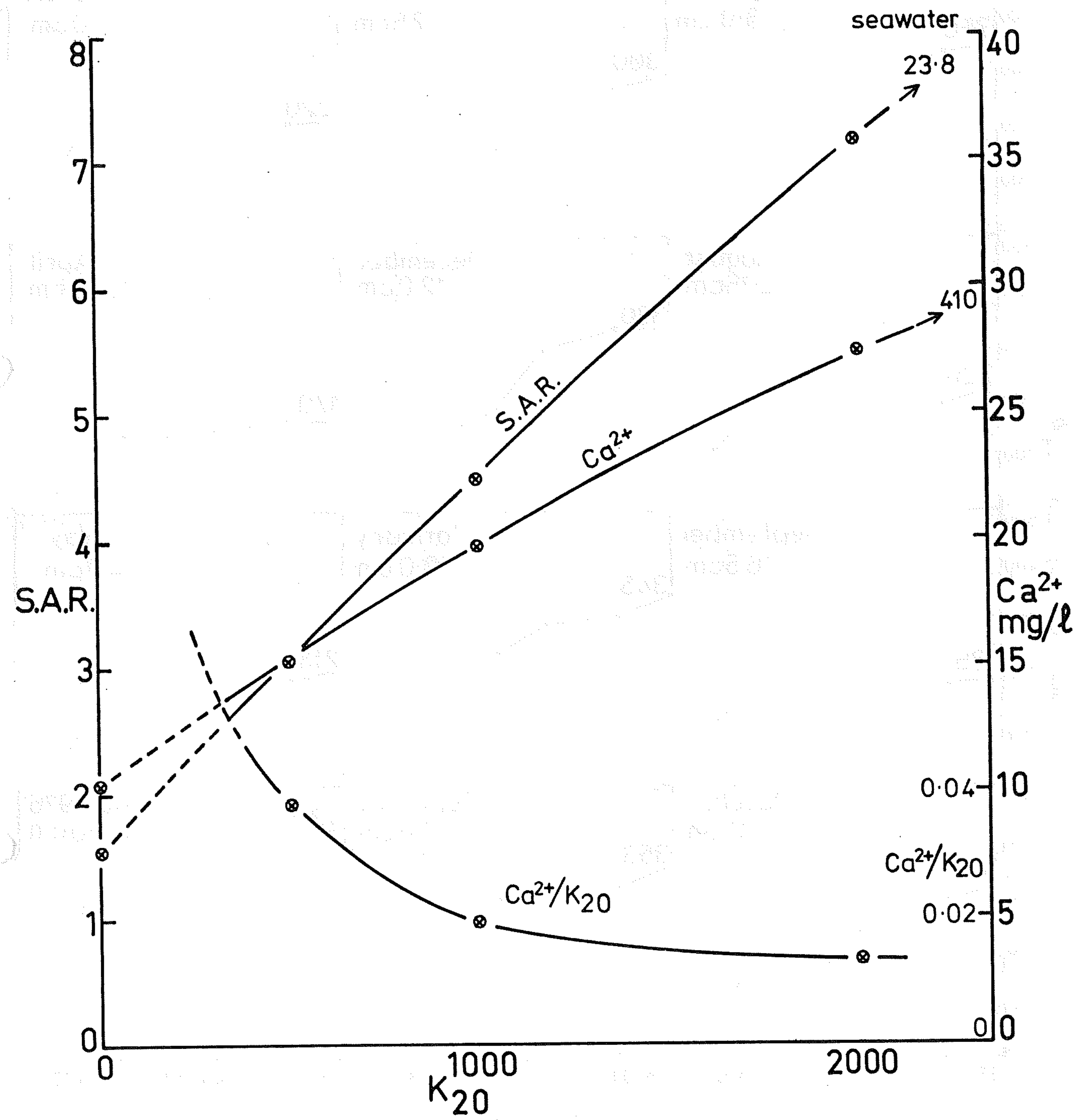

Figure 27—Changes in The Sodium Absorption Ratio (S.A.R.) and calcium concentration with increasing salinity (K_{20}).

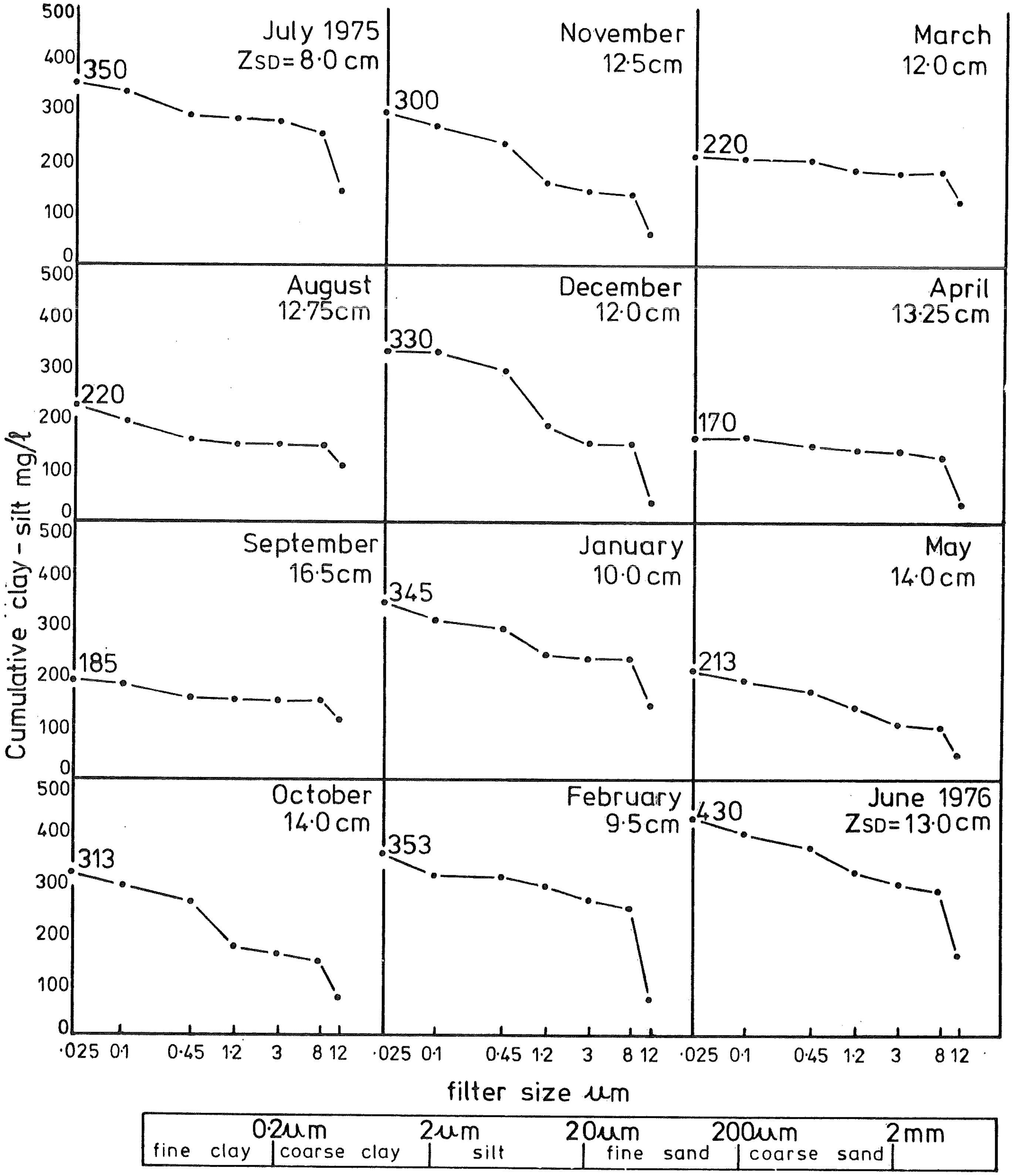

Figure 28—Monthly particle size distributions for D3 over a year.

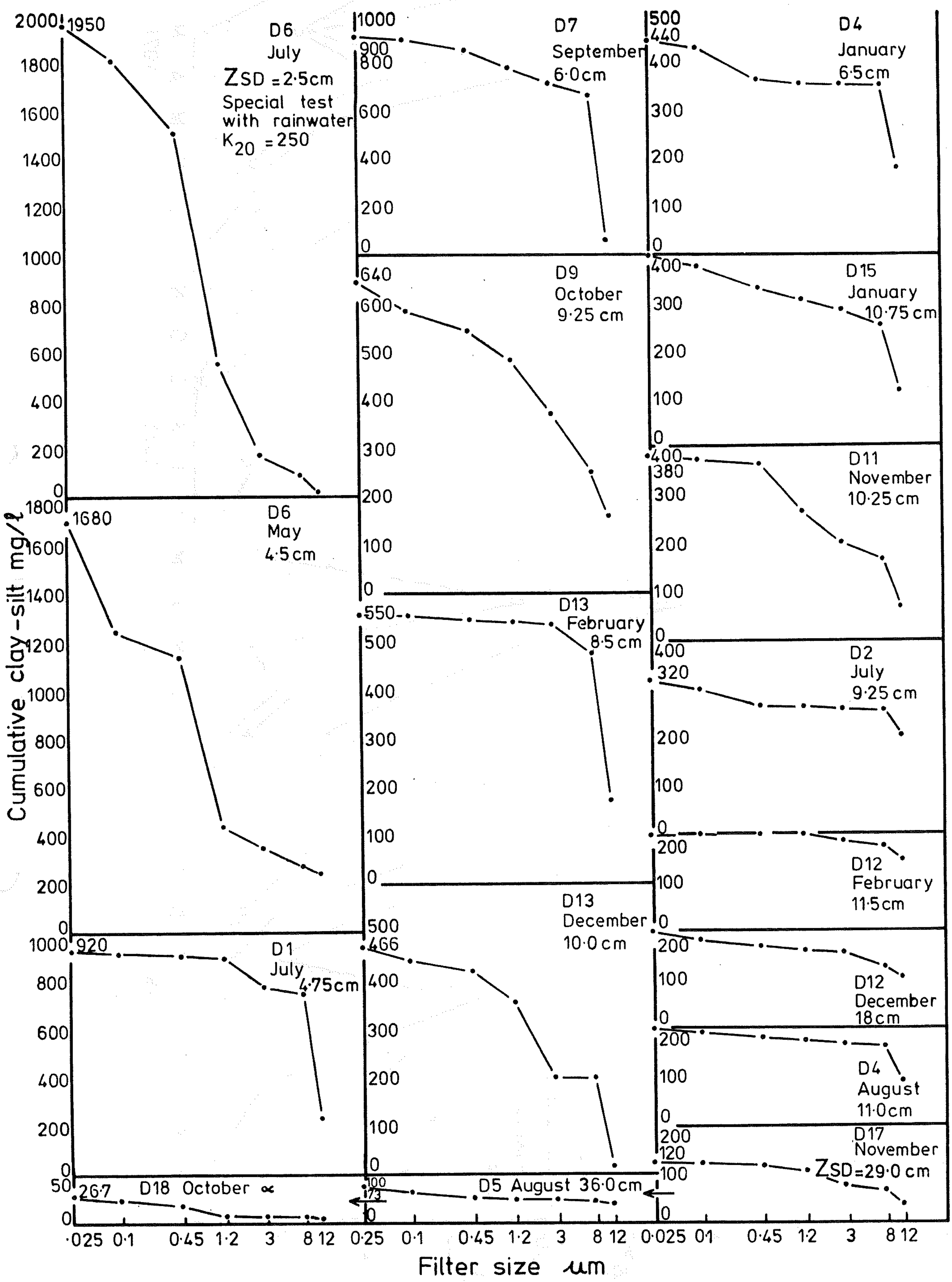

Figure 29—Particle size distributions for other dams.

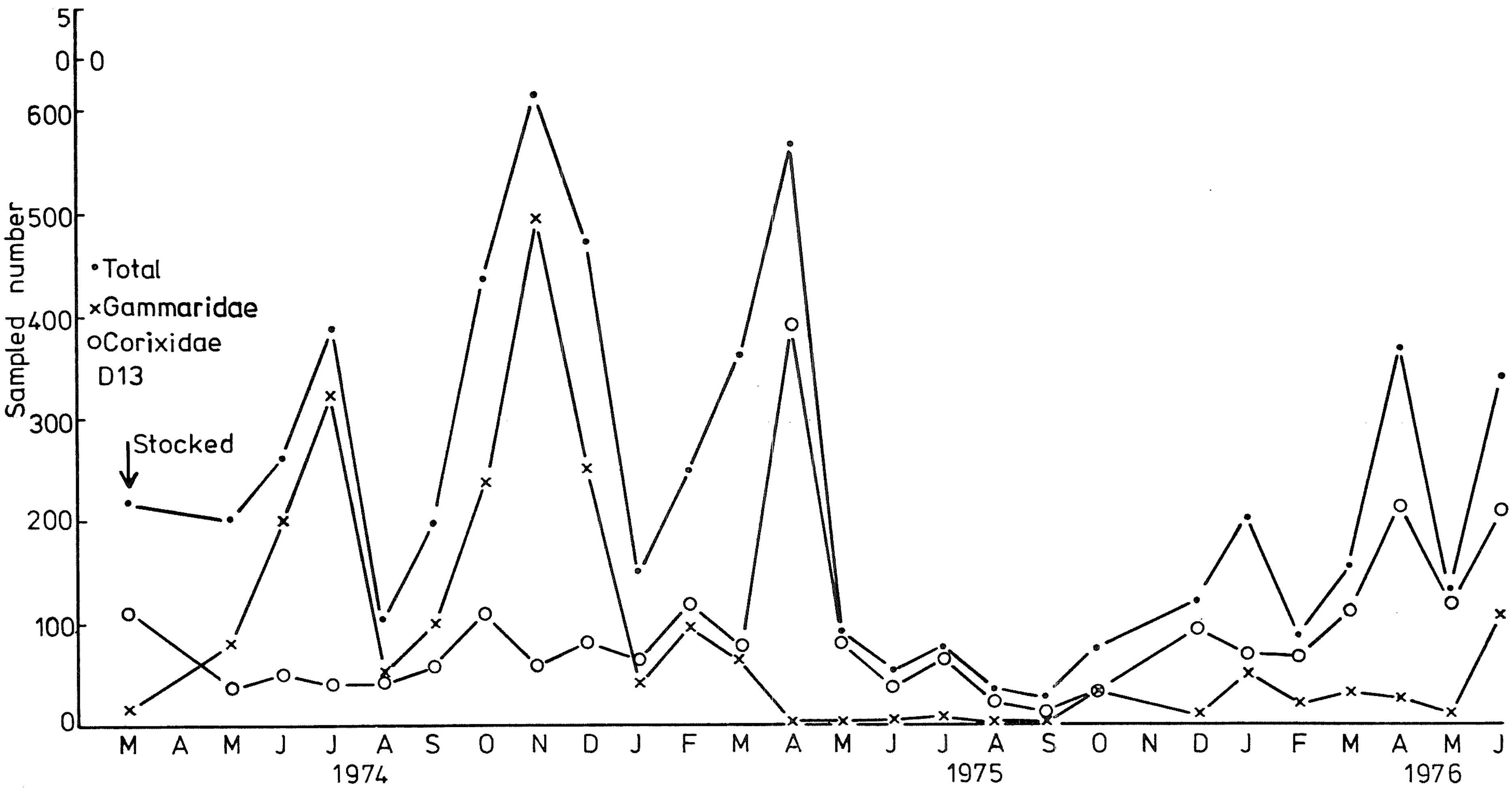

Figure 30—Seasonal changes in relative numbers of other invertebrates in D13.

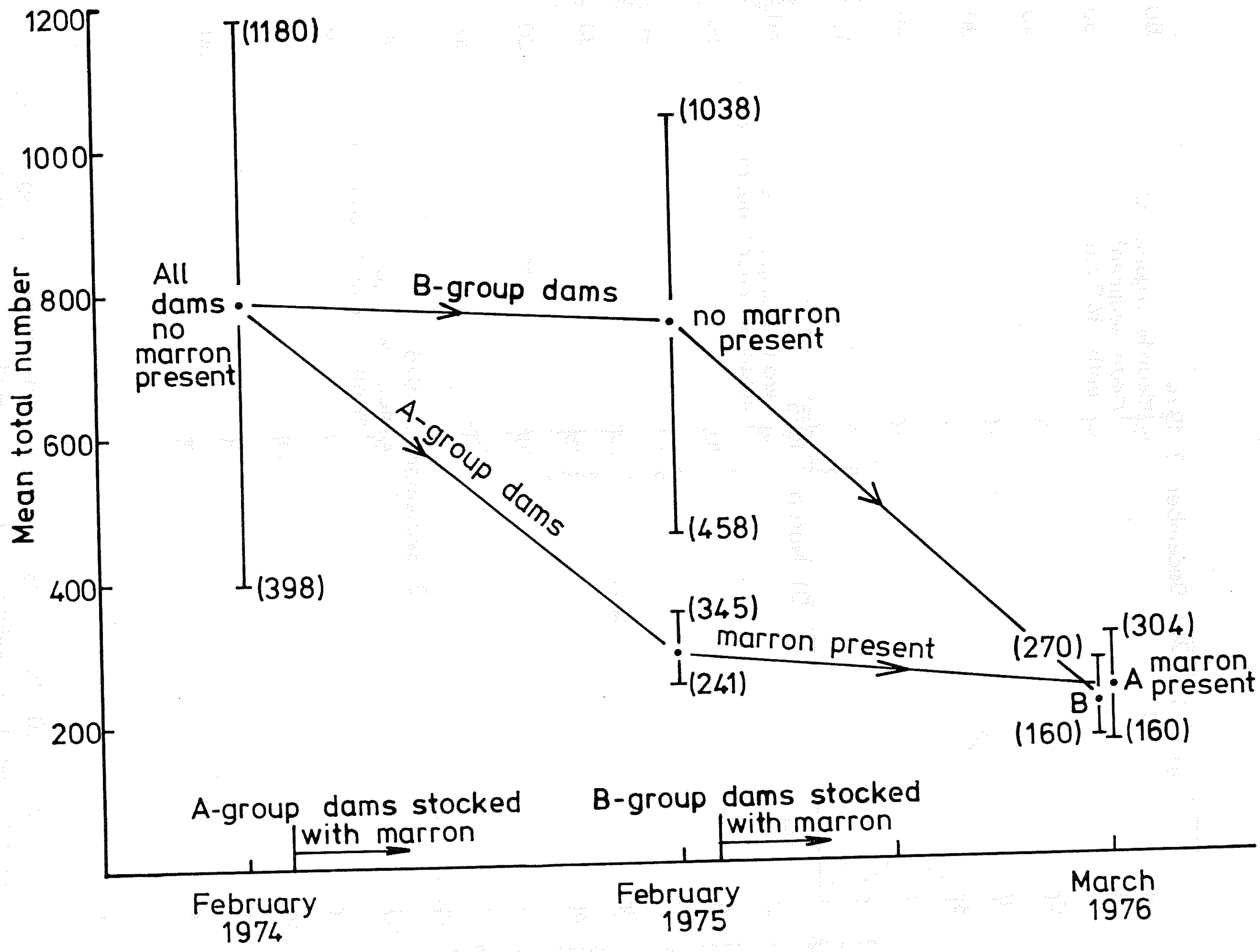

Figure 31—Mean total number of other macro-invertebrates sampled per A or B group dam in the presence or absence of marron; limits are the standard error of the mean.

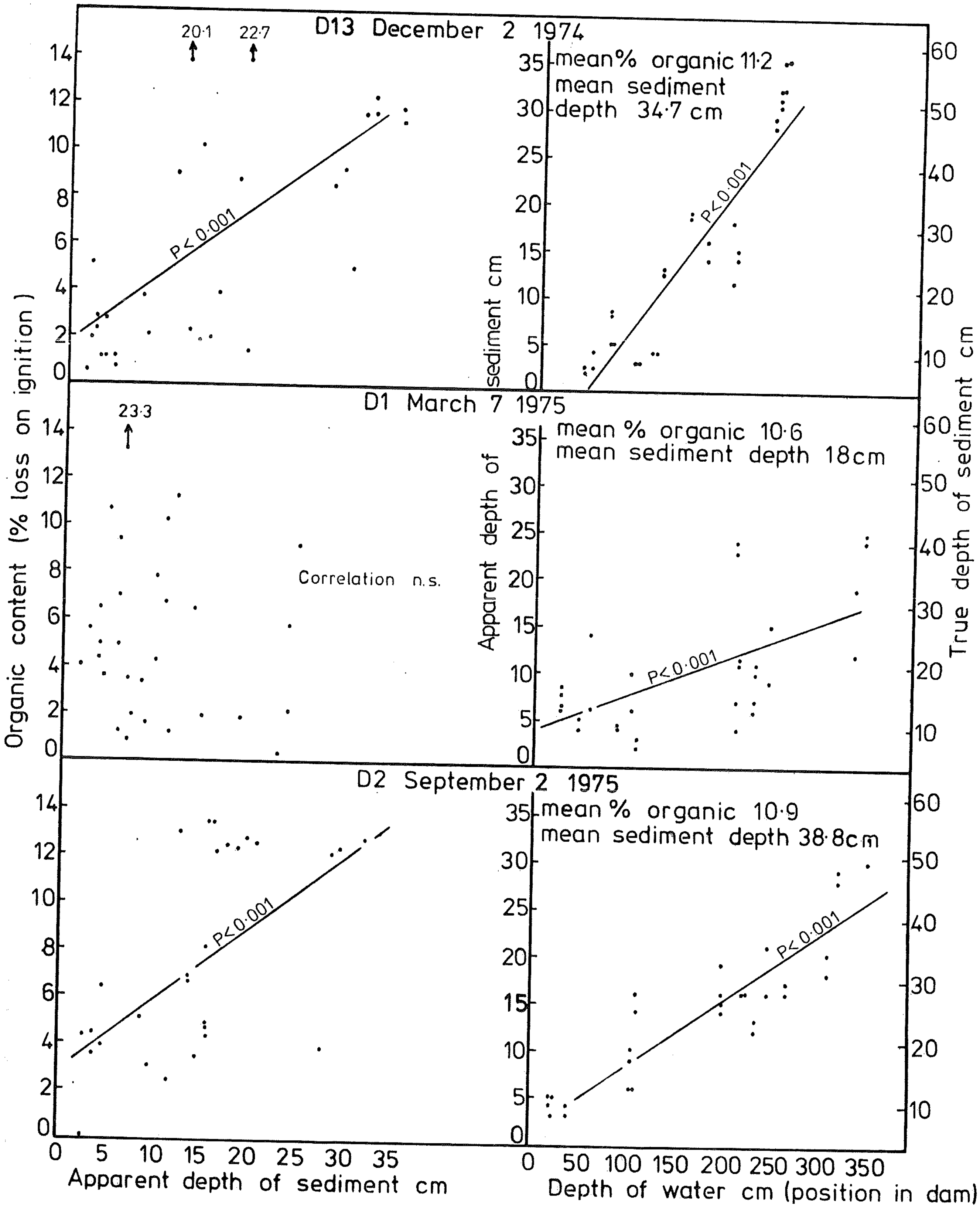

Figure 32—Relationships between organic content and core depth of sediments, and core depth and position in dams.

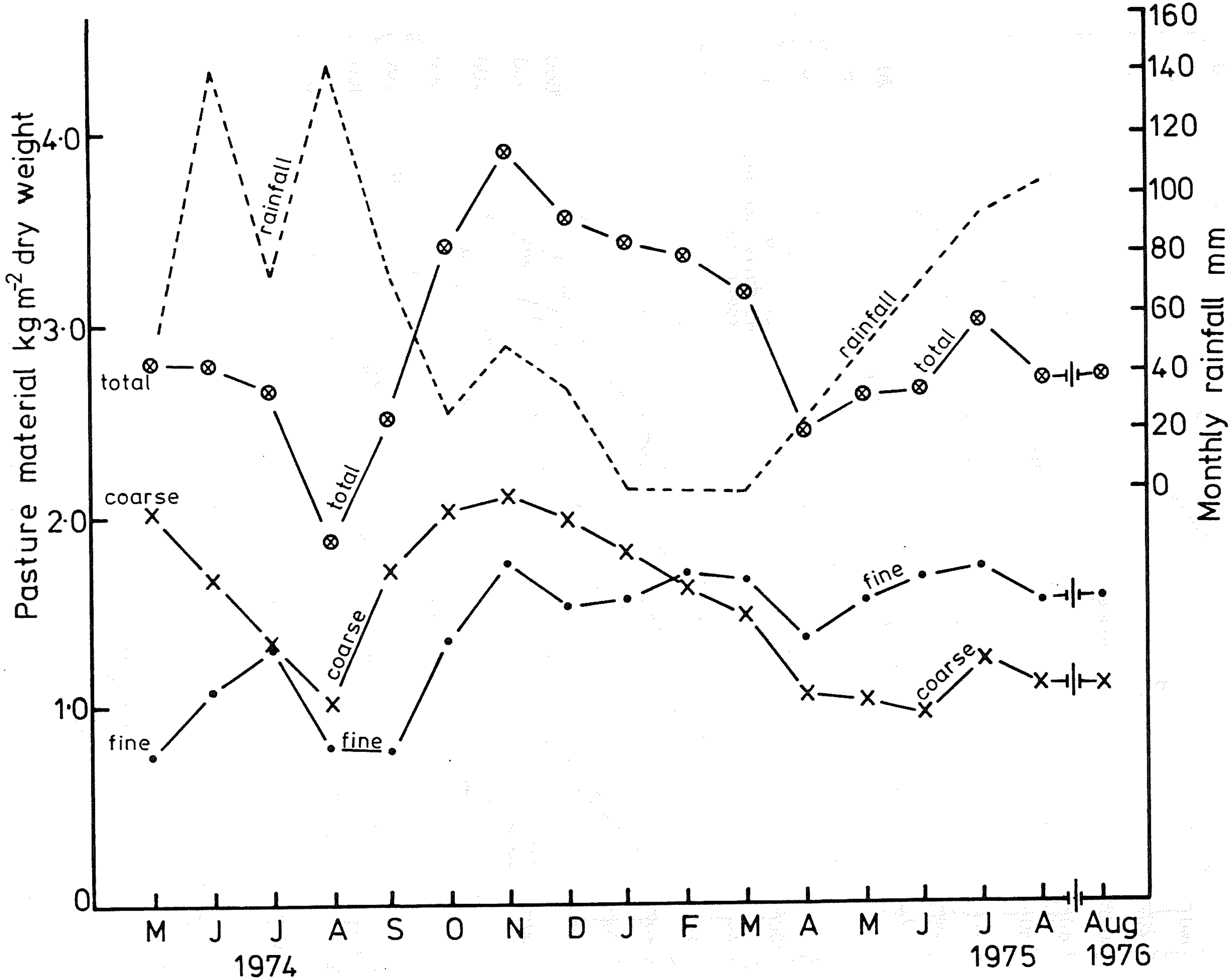

Figure 33—Mean values for catchment pasture material from all the dams together with records of monthly rainfall.

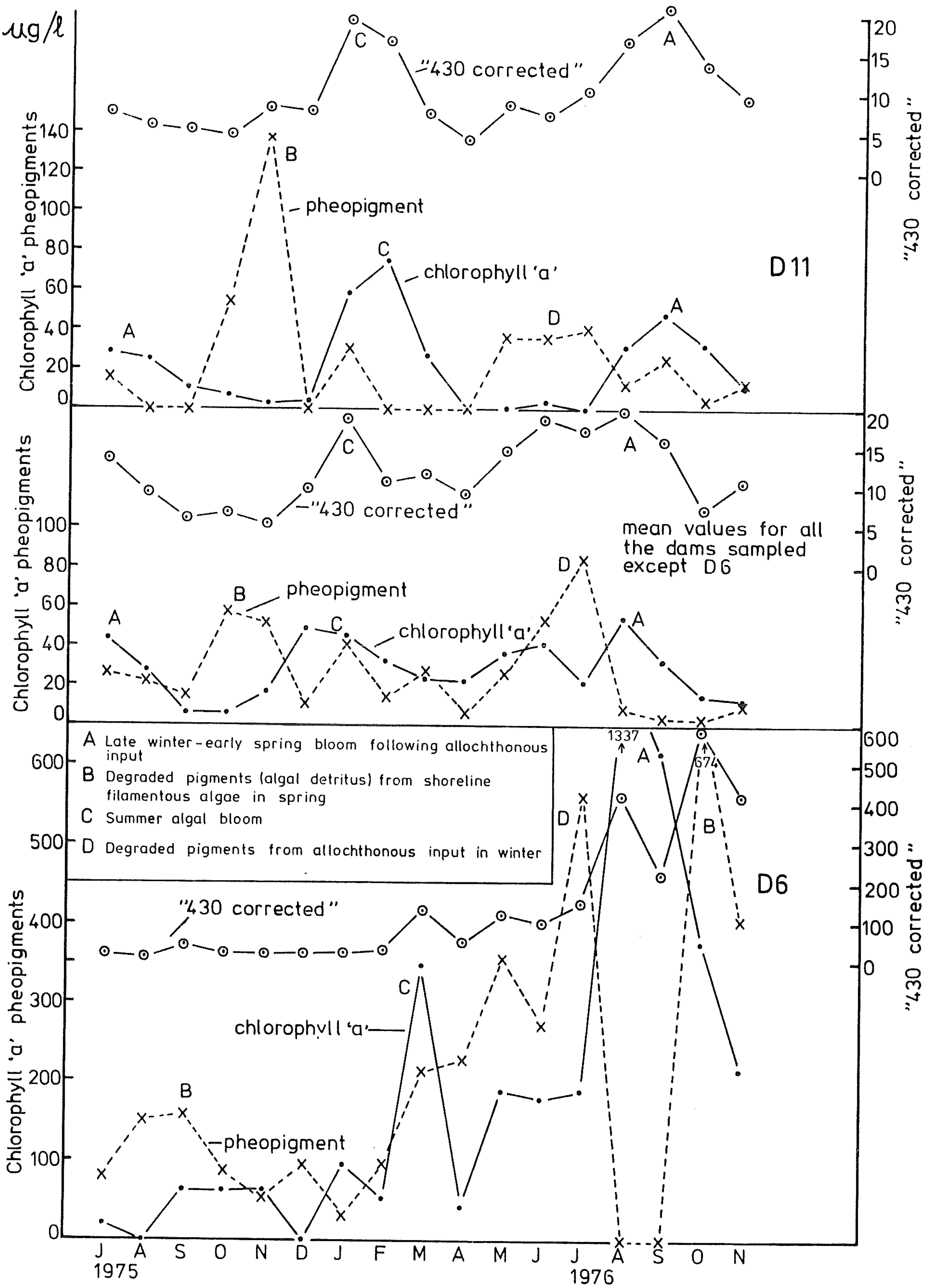

Figure 34—Seasonal changes in algal pigment concentration together with optical densities at 430 nm corresponding to a sample of one litre ('430 corrected').

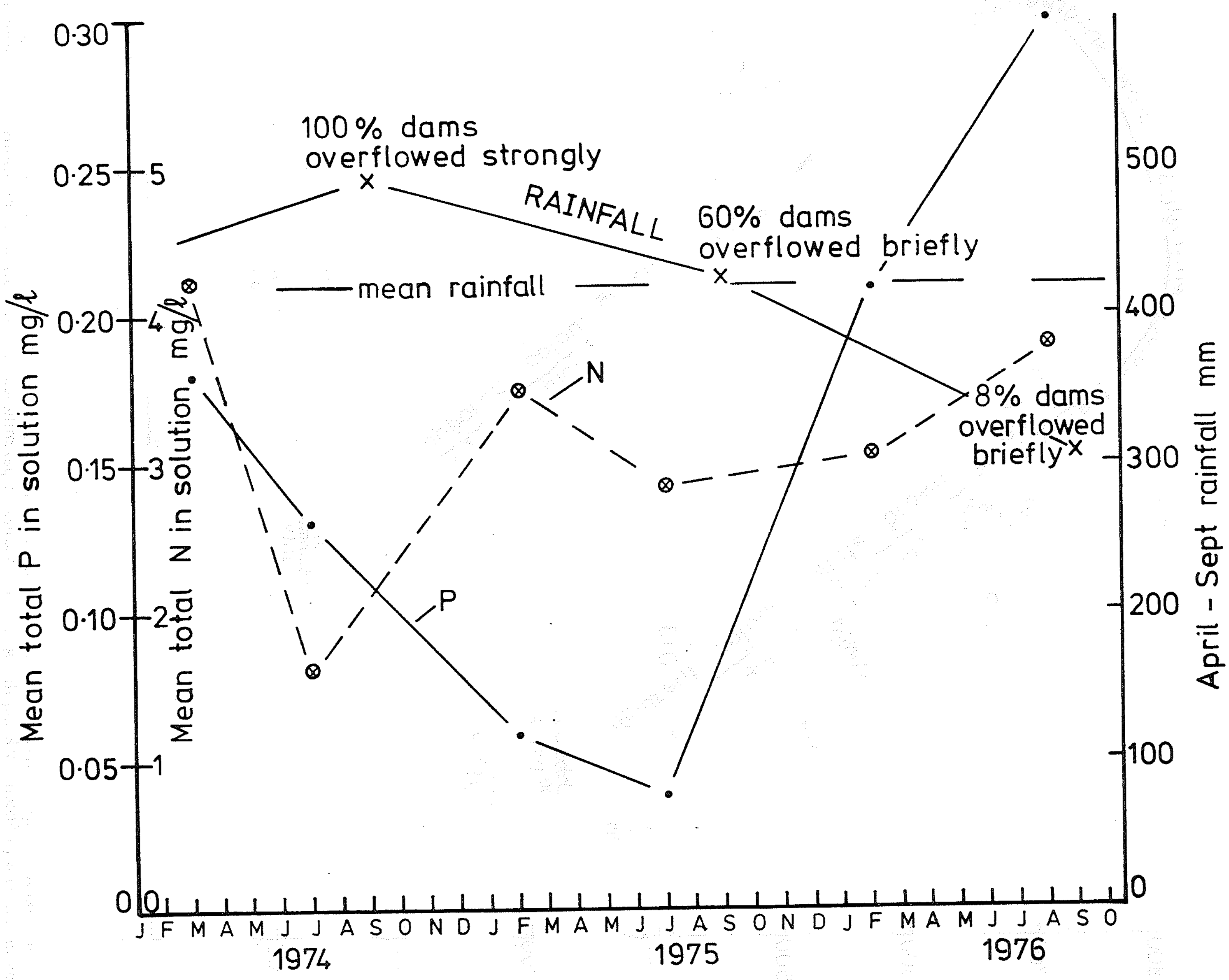

Figure 35—Changes in mean total phosphorous and nitrogen in solution over the study related to flushing conditions. The mean annual and annual rainfalls for the three years 1974–76 at Kojonup are given. Annual rainfall in 1973 was 434 mm.

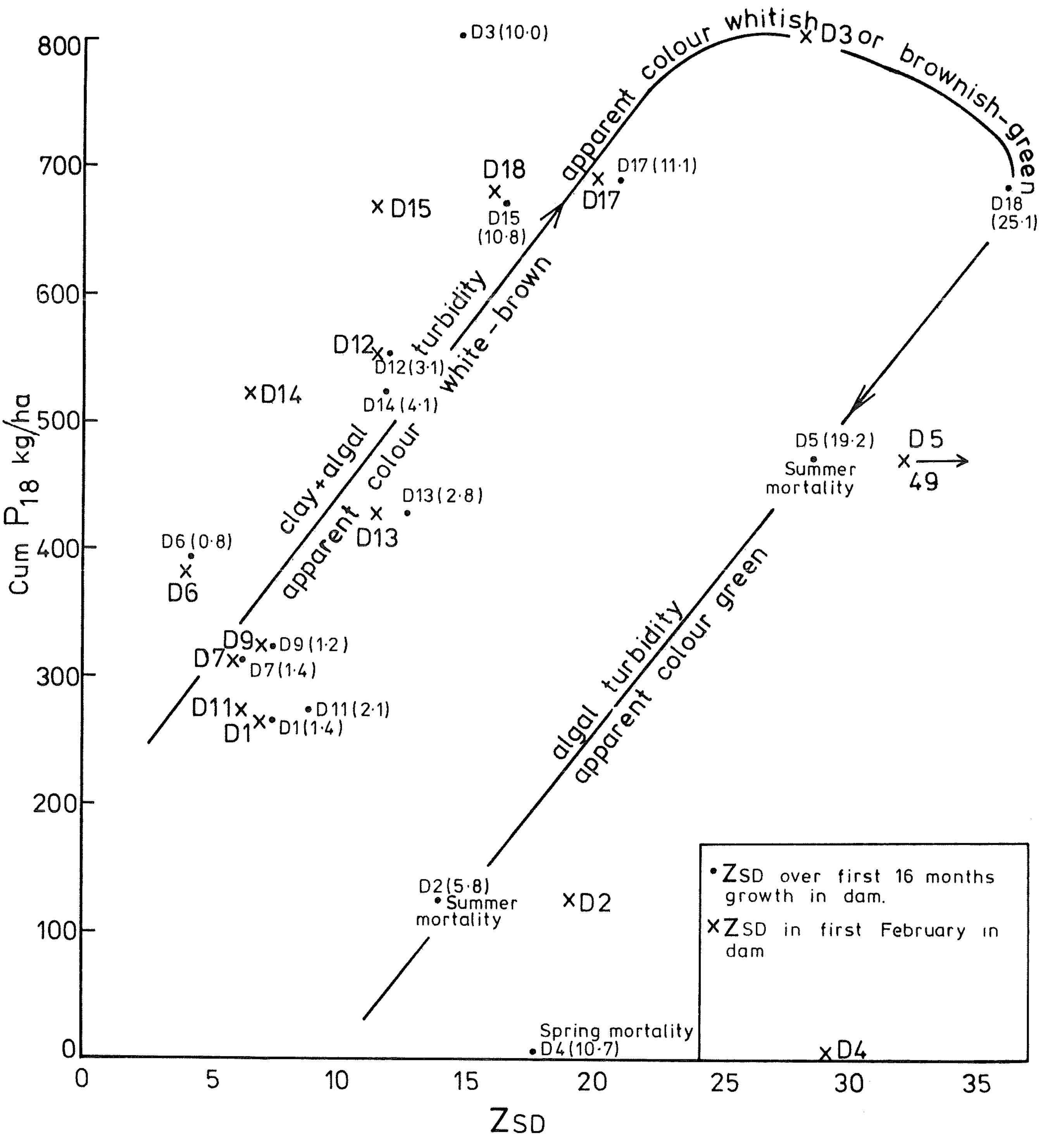

Figure 36—Relationship between cumulative production (cum P_{18} kg/ha) of marron to eighteen months of age (16 months in dams) and Secchi disk depth $Z_{S.D.}$ cm. Values in parentheses are the standard deviations of the monthly depths.

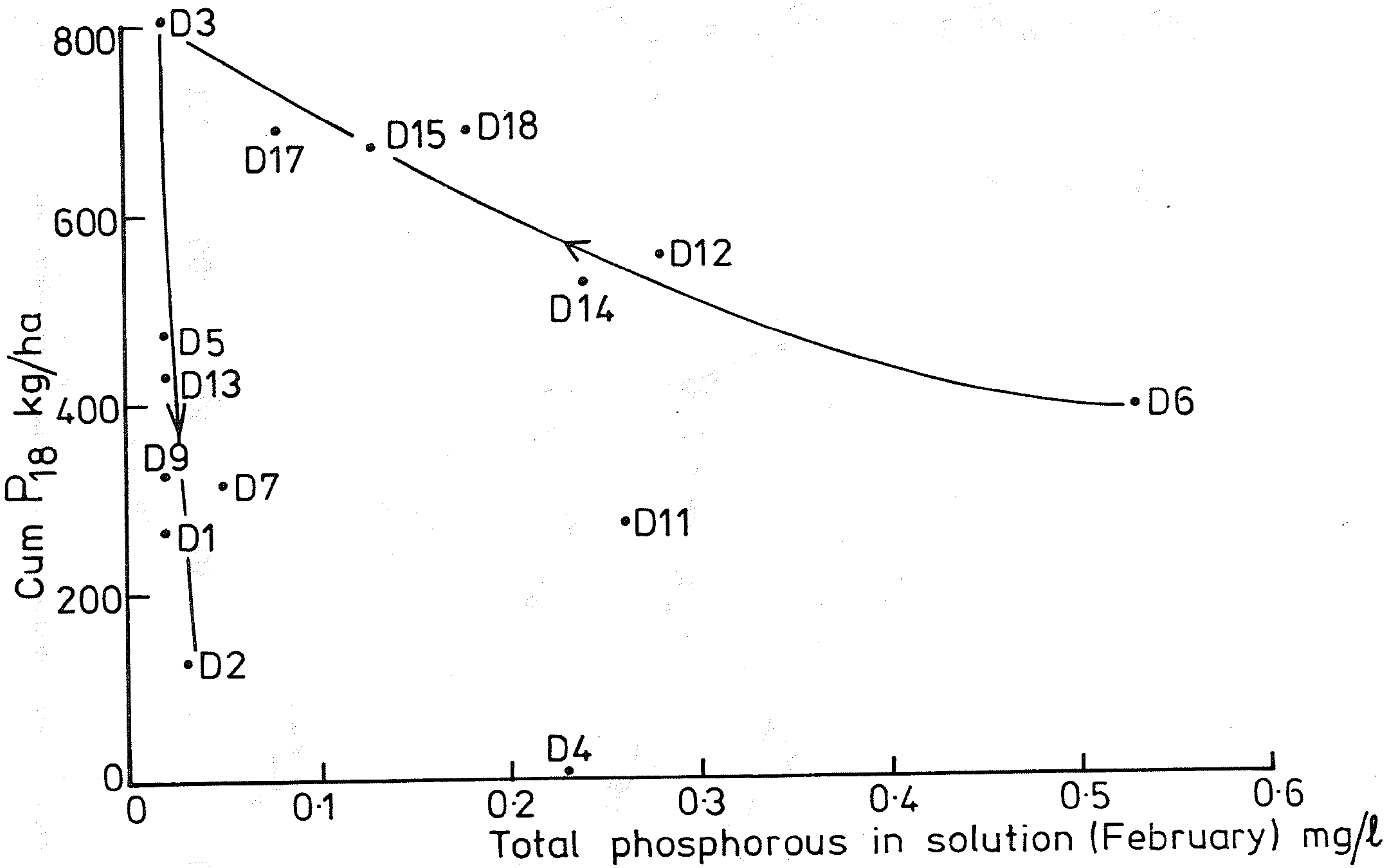

Figure 37—Relationship between cumulative production of marron and total phosphorous in solution.

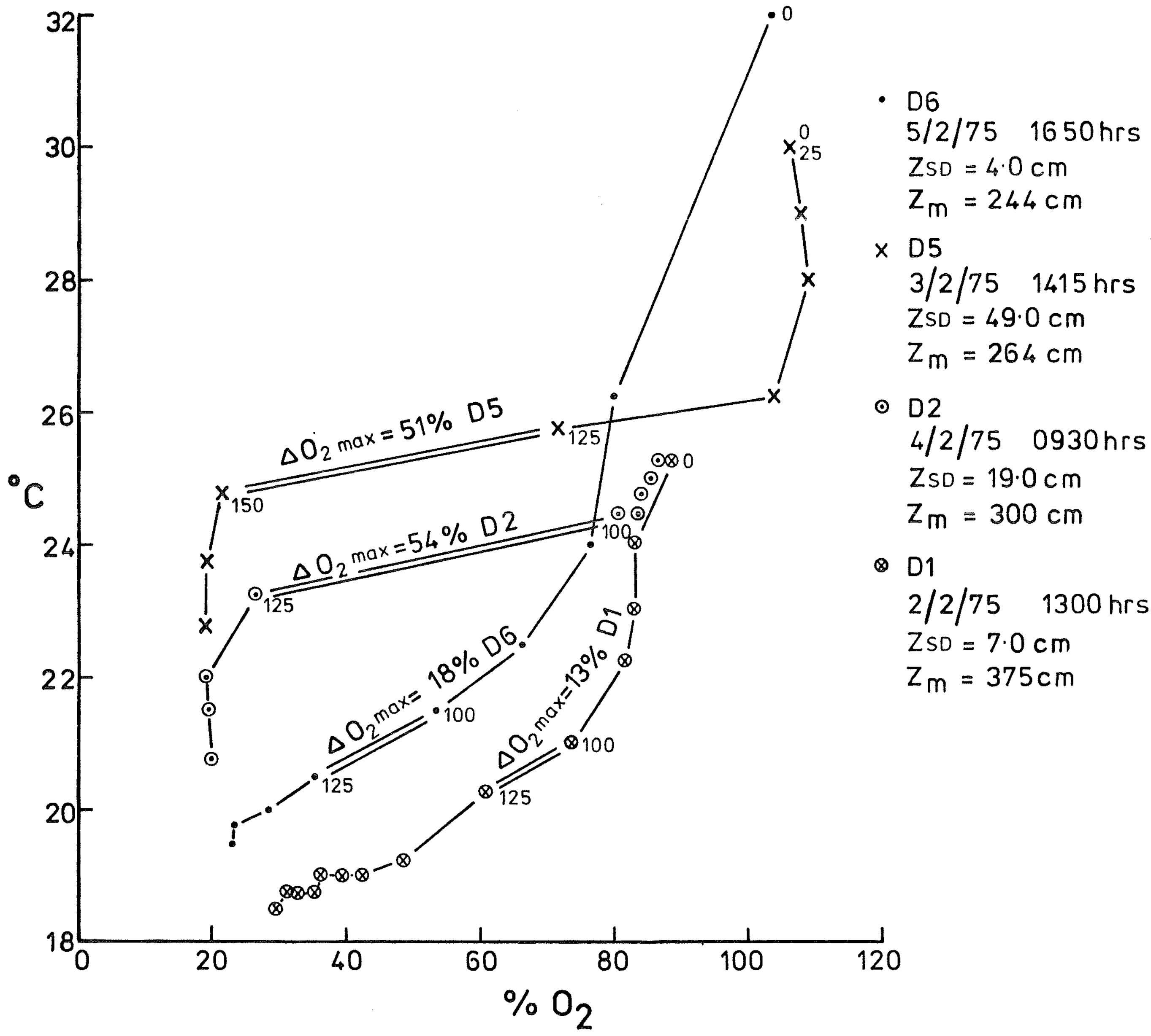

Figure 38—Comparison of oxygen/temperature curves for dams showing high and low clay turbidity. = denotes the 25 cm depth range where the rate of decrease in percentage oxygen concentration is a maximum value ($\triangle O_2$ max).

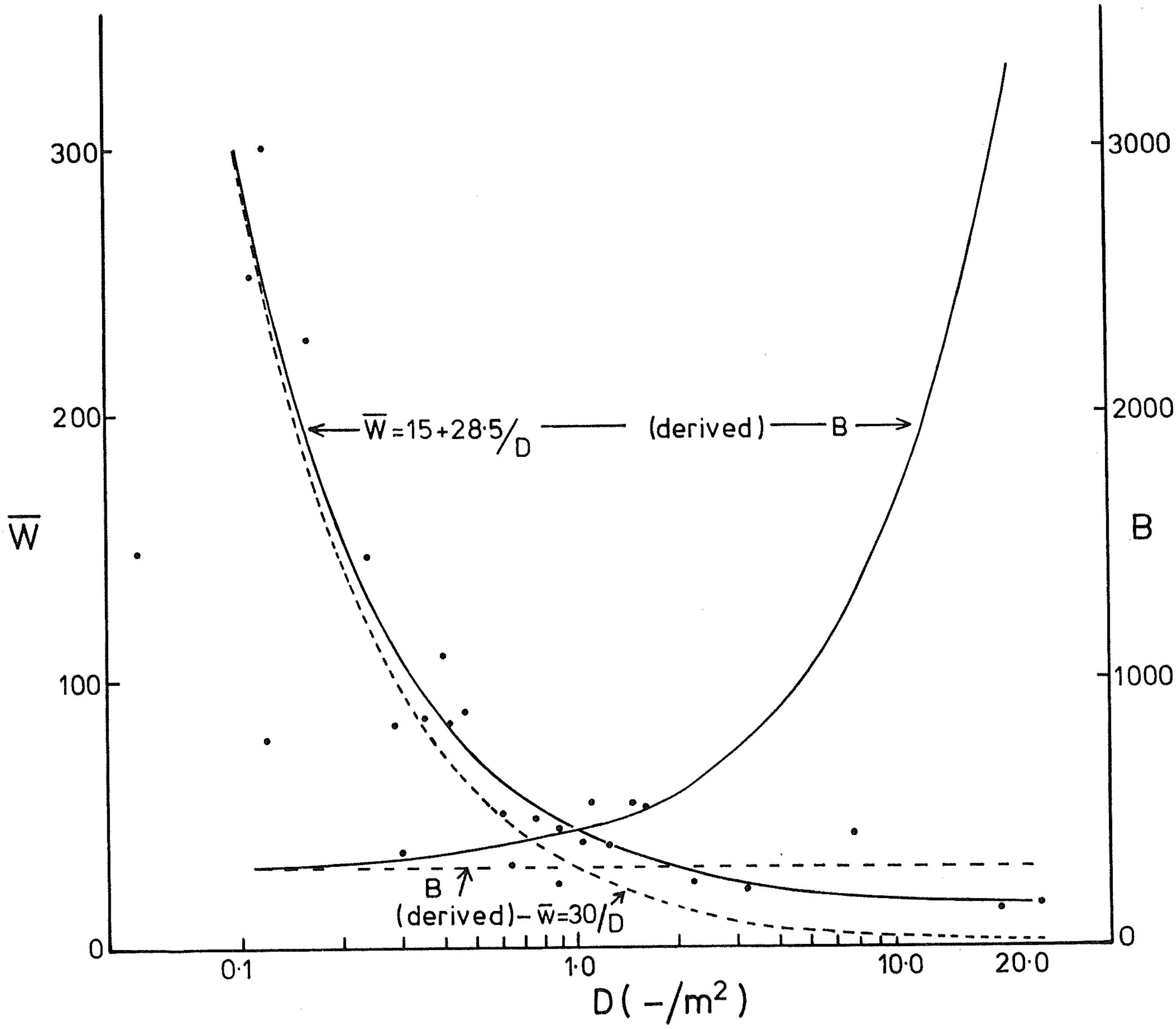

Figure 39—Preliminary relationships for marron between mean size ($\overline{w}$, g), standing crop (biomass, B kg/ha) and density (–/m²) based upon a hyperbolic model and data points (●) for $\overline{w}$ and density at approximately two years of age.

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