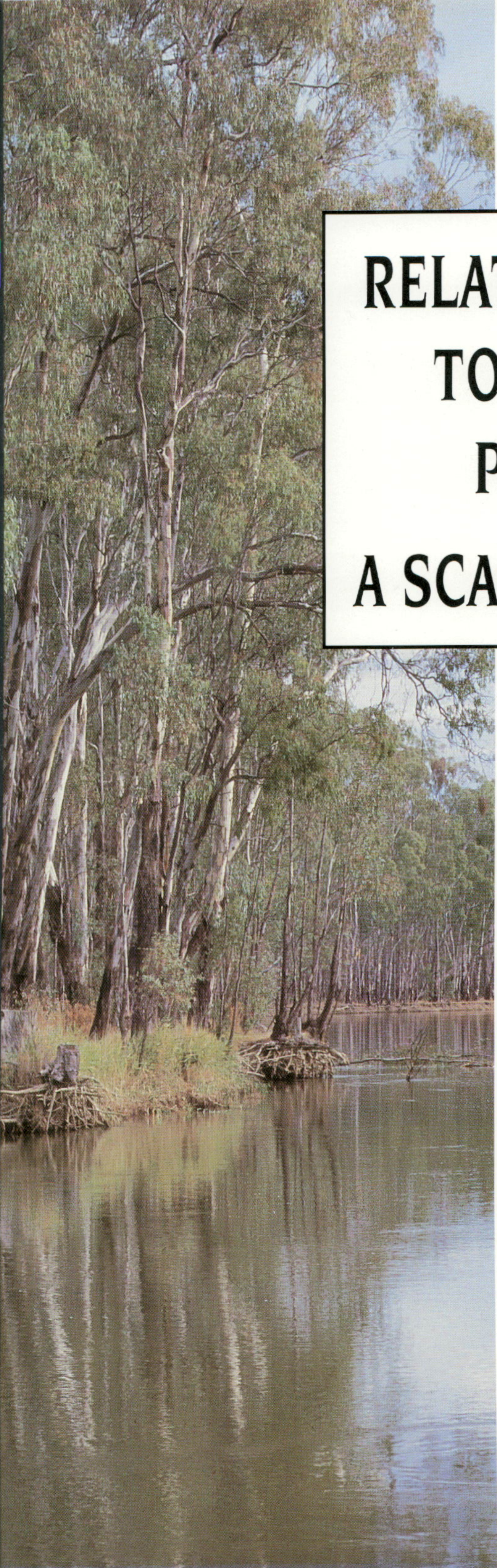

RELATING BASEFLOW TO CATCHMENT PROPERTIES

A SCALING APPROACH

G. C. Lacey

Report 96/8
December 1996

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

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PREFACE

In the discussions that led to the selection of core research projects for the Cooperative Research Centre for Catchment Hydrology, it was recognised that advancing the understanding of catchment similarity and regional behaviour would have important long-term benefits for hydrology. This is because of the need to transfer data from catchments with information (gauged) to those where no such measurements are available (ungauged).

A specific objective therefore for CRC Project D2 'Regionalisation and Scaling of Hydrologic Data' was to determine what descriptors are useful for particular aspects of catchment behaviour (e.g. flood response, yield). Once these are selected, regional relationships and the effect of catchment size (scale) can be studied.

This report by Geoff Lacey (University of Melbourne) is an important contribution to the description of the baseflow component of catchment yield. His development of a new geology-vegetation index to help classify catchment behaviour appears to hold significant promise for a number of applications. (As Geoff mentions, already it has been found useful in predictive equations for design losses in ungauged catchments, developed as part of CRC Project D1 'Improved Loss Modelling for Design Flood Estimation and Flood Forecasting').

It is hoped that readers of this report will undertake their own applications of the concepts presented here, and provide feedback to the CRC on their results.

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SUMMARY

This report explores the scaling of baseflow. It examines the influence of a geology-vegetation index and a number of dimensionless catchment properties on baseflow index for 114 catchments in Victoria, with areas up to 192 km^2. The catchment properties considered include three topographic indices, two climatic indices, forest cover and forest growth stage.

The geology-vegetation index was developed to represent catchment geology and soils. It comprises 12 groups, based on geology and ecological vegetation class. The indigenous vegetation community of the catchment is used, in combination with geology, as an indicator of soil state.

Baseflow index is an appropriate dimensionless quantity for the scaling of baseflow. The most important factor determining its value is the transmissivity of the rocks and soils, as expressed in the geology-vegetation index.

The rock types that tend to give high baseflow are rhyodacite, Tertiary basalt, granite and Upper Ordovician sedimentary. In some cases this is due to the fracturing and weathering of the rock; in others the soil formed from the rock is more important. If the baseflow contribution comes mainly from the soil (e. g. with granite) there is a big difference between the baseflow index values for wetter and drier ecosystems. There is a correspondence between the pattern of baseflow index values for the catchments and the values of specific capacity (a measure of transmissivity) obtained from boreholes.

There appears to be no scale effect with catchment size up to an area of 100 km^2. The baseflow behaviour of all catchments examined in this range is evidently governed by the same physical processes. The evidence is inconclusive as to whether or not there is a scale effect outside this range.

No trends are found in plots of baseflow index against any of the three dimensionless topographic parameters: slope index, drainage index and flat area ratio, within any of the geology-vegetation groups.

Climate has an effect on baseflow index. The dimensionless ratio, rainfall/potential evapotranspiration, causes an increase in the latter for some but not all of the geology-vegetation groups. Examination of annual trends in a catchment (Picaninny Creek) that was clearfelled in 1972 show no evidence that baseflow index is affected by forest growth stage.

A procedure for prediction of baseflow index in ungauged catchments is developed, using the mean value of baseflow index for each of the geology-vegetation groups.

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Rory Nathan has provided most of the catchment data, making available his two databases, and has patiently answered many queries about these. Mike Papworth, Alicia Lucas and Ian Watson provided data for the Maroondah and Reefton catchments.

Charles Lawrence, David Heislers, Andrew Shugg and Alan White have provided much valuable information and advice on the geological and hydrogeological aspects of the project. In addition, David Heislers has provided on disk much data from borehole records.

Fred Watson carried out the baseflow separation for the Maroondah and Reefton catchments and provided rainfall data for the Maroondah catchments (Sections 4, 5.7). Some of this data was first collected or catalogued by Melbourne Water, Department of Natural Resources and Environment (Victoria) and Bureau of Meteorology. Rodger Grayson carried out the analysis of the effect of the flat area ratio (Section 5.4).

Bill Peel has provided information and data on the ecological vegetation classes, being developed in the Department of Natural Resources and Environment.

Tom McMahon, Rodger Grayson, Richard Hartland and Fred Watson took part in field trips. Marcus Little and Kelly Pentreath carried out field work to measure possible leakage under one gauging station and to verify the vegetation in some catchments.

Andrew Western and Graham Moore have given advice on computer processes. Jacqui Wise has provided much assistance in administrative procedures.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

The object of this report is to explore the scaling of baseflow. This involves finding a relation between baseflow and a number of catchment properties, all expressed in dimensionless form; a relation that can be applied to a wide variety of catchments. In this instance the dimensionless quantity, baseflow index, will be related to dimensionless topographic, climatic and other parameters and an index representing geology and soils. If a procedure can thus be found for the scaling of baseflow, it can be used to estimate baseflow index in ungauged catchments.

1.1 Background

Two factors led to this study. The first was the completion of a review of scale in hydrology (Lacey 1995), leading to proposals for a practical scaling project. The second was the program of continuing research directed to the Melbourne water supply system, which is dependent on yield from the Maroondah catchment area. The possibility of using information from catchments for which historical data is available to estimate behaviour of ungauged catchments is of special interest to the Cooperative Research Centre for Catchment Hydrology.

The project would address the fundamental question of how to scale from one catchment to another. However, out of the range of hydrological phenomena, a choice must be made as to which problem to investigate first. The possibilities include: stream discharge, flow-duration curves, flood frequency curves, annual peak flow, and baseflow. It was decided to investigate the scaling of baseflow. This seemed a simpler problem than most of the alternatives, being therefore appropriate for an initial study, and it would provide important information on low flow conditions.

The scaling of a hydrological problem involves the establishment of dimensionless parameters for the problem, so that a solution can be applied to a wide variety of catchments. It is important to recognise that different physical processes may dominate at different scales. For example, hillslope runoff processes may dominate the response at sub-catchment scale; the channel network geometry becomes more important in meso-scale basins (up to the order of 100 km^2); while in large basins the spatial variability of precipitation becomes very important (Gupta & Dawdy 1995).

There are special difficulties in the task of scaling in hydrology. These include: (a) the large number of variables and physical laws that govern the phenomena, (b) the spatial distribution of such properties as soil hydraulic conductivity and soil moisture condition, (c) the stochastic nature of such variables as storm intensity and storm duration, and (d) the systematic distribution of catchment attributes (topography, soils, etc.).

There have been a number of successful cases of scaling soil water phenomena (matric head, hydraulic conductivity and infiltration parameters) in the field (Warrick et al. 1977; Sharma et al. 1980). There has also been a lot of work on the scaling of regional flood peaks (Gupta & Dawdy 1995) and on computer modelling of various hydrological phenomena (Kalma & Sivapalan 1995).

1.2 Scope of this report

While this project began in a particular regional context, the scope was soon expanded to Victoria as a whole. This report thus examines baseflow in 114 catchments in Victoria. Four ranges of catchment size are considered: up to 10 km^2, between 10 and 40 km^2, between 40 and 100 km^2, and between 100 and 200 km^2.

A 'geology-vegetation index' is developed to represent catchment geology and soils. To achieve this, the indigenous vegetation community of the catchment is used, in combination with geology, as an indicator of soil state. The relationships between baseflow index and the geology-vegetation index, three topographic indices, two climatic indices, forest cover and forest growth stage are examined. The possibility of a scale effect with catchment size is also considered.

Statistical analyses are carried out and a procedure for estimating baseflow index in ungauged catchments is developed. Comparisons are made with other studies. It is intended that the methodology and principles developed will be of a general relevance and appropriate for wider application.

2. BASEFLOW

Baseflow has been defined in a number of ways that are not all equivalent. Hall (1968) defines baseflow as the portion of flow that comes from groundwater or other delayed sources. Chow et al. (1988) define it as the slowly varying flow in rainless periods. Ward and Robinson (1990) consider that this is the sum of groundwater runoff and delayed throughflow. In any quantitative study, it is important that a consistent measure of baseflow be used. The values of baseflow used in this paper were evaluated from the daily hydrographs using a digital filter (Nathan & McMahon 1990). While some prefer other methods that may give somewhat different values, this method provides one consistent basis for examining baseflow behaviour in a range of diverse catchments.

Baseflow is one of the most important low flow hydrological characteristics of a catchment. Knowledge of low flow characteristics is important for a number of reasons, including: the development of water management strategies, especially for drought conditions; the establishing of relationships between aquatic organisms and their environment; the estimation of small to medium water supplies (Nathan 1990); and the management of salinity, water quality and algal blooms.

2.1 The factors determining baseflow

Baseflow is a function of a large number of variables and catchment properties. The following are some of the more important:

catchment area;
topographic parameters;
geology;
soil depth and permeability and their spatial pattern ;
rainfall;
evapotranspiration;

potential evapotranspiration;
seasonal rainfall pattern;
inter-catchment groundwater flow;
soil moisture storage;
forest cover;
forest growth stage.

The total streamflow is a function of some of the above variables thus:

total flow = rainfall - evapotranspiration + inter-catchment groundwater flow - soil moisture storage change,

where all quantities are measured in, say, mm/yr. The inter-catchment groundwater flow may be either negative (i.e. a deep drainage loss or loss to an adjacent catchment) or positive (i.e. a gain from an adjacent catchment or from a regional groundwater flow). It will be related to geology and other catchment (or regional) properties.

2.2 Forming dimensionless numbers

No two catchments are actually similar and we cannot obtain a complete set of dimensionless quantities that fully define their behaviour. However, it may be possible to find some dimensionless quantities that express the more dominant determining factors.

An appropriate dimensionless quantity incorporating baseflow is the baseflow index. This is defined as the volume of baseflow divided by the volume of total streamflow (Inst. of Hydrology 1980; Nathan & McMahon 1992).

While it is recognised that topography is infinitely variable, three dimensionless topographic parameters will be examined for their influence on baseflow index. The first, $L/\sqrt{A}$,will be called the drainage index, and the second, $H/\sqrt{A}$, the slope index, where

A = catchment area;
L = total length of stream network;
H = catchment relief (difference between highest and lowest elevations).

The drainage index is a measure of the degree of dissection of the catchment, and the slope index a measure of the steepness. The work of Carlston (1965) and Gregory and Walling (1968) suggests that low flow behaviour is affected by drainage density, *L/A*, while that of Zecharias and Brutsaert (1988) and Vogel and Kroll (1992) suggest that it is affected by both drainage density and relief. The drainage index used in this paper is a dimensionless counterpart to drainage density.

The third topographic index will be called the flat area ratio. This is the fraction of the catchment area that consists of flood plain. Mountainous areas might be expected to give higher baseflow index than lowlands, because of the steeper groundwater gradients. It is generally also the case that the infiltration capacity of floodplains is lower than that for hilly terrain.

In the study of baseflow, geology and soils must be considered together, as the groundwater flows through both. In spite of the assumption sometimes made in modelling, there is no impermeable boundary between the two (Shugg 1996). The treatment of rock and soil poses special difficulties: hydraulic conductivity varies vertically in the profile and horizontally throughout the catchment. Soils, for example, may be thin on the ridge tops and deep on the valley floors. For scaling to be possible, some measure of the overall state of the bedrock and soil in the catchment must be found.

A hypothesis of this paper is that such a measure is provided by the natural vegetation communities together with the underlying rock type. These provide the basis for a 'geology-vegetation index' that characterises the hydrological properties of the geology and soils in the catchment as a whole.

As with topography, many parameters would be needed to define climate adequately. Appropriate dimensionless parameters include (evapotranspiration/ rainfall) and (rainfall/potential evapotranspiration). Potential evapotranspiration is related to solar energy input, which has the effect of drying out the catchment. In this study we are unable to explore the effect of the seasonal rainfall pattern, because the seasonal patterns for most of the catchments in the (Victorian) database are fairly similar. One method of exploring this would be to use a parameter of the type: (rainfall in peak 3 months/total annual rainfall).

The inter-catchment groundwater flows are not known. If they were significant compared to total stream flow, the baseflow index would be affected. Soil moisture storage in a catchment changes on a daily and on a seasonal basis. However, it should have no significant effect on the value of the baseflow index, when this is calculated using data spanning a large number of years. The forest cover (that is the fraction of the catchment under forest) and the forest growth stage (the time since logging or bushfire) are both likely to affect baseflow.

In dimensionless terms, baseflow index can be expressed as a function of:

drainage index ($L / \sqrt{A}$);
slope index ($H / \sqrt{A}$);
flat area ratio;
geology-vegetation index;
evapotranspiration/rainfall;
rainfall/potential evapotranspiration;
seasonal rainfall pattern;
forest cover;
forest growth stage.

3. GEOLOGY, SOILS AND VEGETATION

Geology affects baseflow index in at least two ways. The first effect is direct: groundwater is stored in the rocks, especially if they are highly fractured, and this contributes to baseflow. The second effect is on the formation of the soil: different types of rocks tend to produce different types and depths of soil, under the influence of weathering, plant action, etc. and hence differences in recharge, groundwater and baseflow.

Because of the great variability of the soil profile in a catchment (especially between ridge top and valley floor), it is impossible (except in some simple cases) to attribute a particular soil type to the catchment. However there may be a regular soil association (e. g. a particular type on the ridge top, another on the slope and another on the valley floor) that is repeated throughout part or all of the catchment (Leeper & Uren 1993). Unfortunately however, very few parts of Victoria have had detailed soil surveys. In other parts the soil maps available are on too large a scale to be of any use in this investigation. Furthermore, the soil classifications in use in Australia (e. g. Northcote 1979; Isbell 1996), are relevant mainly to agriculture; they do not provide adequate information about depth, hydraulic conductivity and its anisotropy, and other properties important for baseflow.

Greeves et al. (1994) have studied the physical, chemical and morphological properties of a large number of agricultural soils in the wheat-belt of Southern N.S.W. and Northern Victoria. Their measurements include such hydrological properties as total porosity and the variation of hydraulic conductivity with depth. This kind of data are not available, however, for forested, hilly catchments.

3.1 Hydrogeology and soils indices

To cope with the variation and complexity of geology and soils, a number of indices have been used in different countries. In New Zealand a hydrogeology index has been developed, utilising the database of the New Zealand Land Resources Inventory (Hutchinson 1990). Each 'rock field', which gives the dominant and sub-dominant rock types in each layer, is assigned a six-digit code as a measure of its water storage capacity and transmissibility. The six-digit codes are then used as a basis for an index comprising 8 hydrogeology classes. McKerchar (1991) uses the New Zealand Land Resources Inventory to construct a soil drainage index (a scalar ranging from 1 to 7) and provide depth-weighted macroporosity and minimum porosity values for catchments in New Zealand.

A soil index based on 'Winter Rainfall Acceptance Potential' (WRAP) was developed by the Institute of Hydrology for the U.K. and Ireland (Gustard et al. 1989). The soil properties used to determine the 5 'WRAP classes' were: soil water regime or drainage class, depth to an impermeable layer, permeability above the impermeable layer, and slope. The Hydrology of Soil Types (HOST) Project replaced this system with a more comprehensive one, with 31 'HOST classes', derived with the aid of soil association maps (Gustard et al. 1992). The physical properties used in the classification include: soil hydrogeological properties, depth to aquifer or groundwater, and depth to a slowly permeable layer. A multiple regression analysis with baseflow index was used in the derivation of the classes. The 31 HOST classes were simplified down to 12 'Low Flow HOST Groups' that were used to study low flow behaviour.

Another hydrogeological index, comprising 14 classes, was developed in Germany. A regression analysis was used to relate recession constants to these classes. Other

Table 1. Boreholes data

Rock age	Lithology	No. of boreholes	Mean specific capacity (m^2/day)	Std devn
Tertiary	basalt	15	28	41
Silurian/Devonian	granite	135	18	21
Upper Ordovician	mudstone/shale	67	18	20
	sandstone	25	13	11
	metaseds (slate)	16	22	19
	weighted average		18	
Lower Ordovician	mudstone/shale	34	4	6
	sandstone	14	5	6
	metaseds (slate)	13	13	17
	weighted average		6	
Silurian/Devonian	mudstone/shale	113	10	19
	sandstone	27	5	7
	weighted average		9	

indices developed in western European countries are based on: (a) 9 'SOIL classes'; (b) 17 'major soil groups'; and (c) 7 'drainage classes' (Gustard 1993).

3.2 Hydrogeology in Victoria

Heislers (1993) compiled a database called 'Fracrock' containing geological data for thousands of boreholes in the Kiewa, Ovens, Broken, Goulburn, Campaspe, Loddon, Latrobe, Bunyip and Yarra Basins and the Northern Gippsland and Western Port Phillip Regions. He used this, in conjunction with other databases, to analyse data on salinity, bore yield, bore depth and specific capacity in terms of the rock types. Specific capacity is the ratio of discharge rate to drawdown measured during pumping. It is considered a measure of and has the same dimensions as transmissivity (L^2/T) and is therefore likely to be closely related to baseflow. The values of specific capacity for the different rock types are set out in Table 1.

There is considerable variation between the average values of specific capacity for these rock types. Tertiary basalt has the highest value (28 m^2/day). This rock can have high primary porosity (related to vesicularity or ash beds) and can also be highly fractured. These are the reasons for the high transmissivity and high bore yields. However, its properties can be quite variable. It can sometimes develop a deep weathering profile, and therefore both soil and rock may contribute to groundwater recharge and baseflow (Lawrence 1982; Heislers 1993).

Silurian/Devonian granite has an average specific capacity of 18 m^2/day. Heislers (1993) notes that granite typically weathers to a sandy soil and that granitic hillslopes are often draped by colluvial layers with potential for groundwater storage. There is low primary porosity and little fracturing of the rock. The contribution to baseflow is mainly from the soil rather than from the rock.

Ordovician, Silurian and Devonian sedimentary rocks are generally highly fractured but have relatively low primary porosity (Lawrence 1982). Upper Ordovician sedimentary rocks have high specific capacity (18 m^2/day). The boreholes are located mainly in the Kiewa and Ovens basins. Bore yields from mudstone and slate are higher in the Kiewa basin than elsewhere in Victoria (Heislers 1993), probably because of deep weathering .

Surprisingly, the specific capacity for Lower Ordovician sedimentary rocks is much lower (6 m^2/day). The boreholes are located mainly in the Campaspe and Loddon basins. Silurian and Devonian sedimentary rocks have low specific capacity (9 m^2/day), comparable to the Lower Ordovician.

Why is there such a big difference in specific capacity for the two different forms of Ordovician sedimentary rock, located respectively in the Kiewa-Ovens region and the Campaspe-Loddon region? The explanation lies in the different degrees of weathering of these rocks. Some rock formations (both igneous and sedimentary), in regions with a history of high rainfall, experience very deep weathering. Deep formations of in-situ, weathered, decomposed rock are called saprolites. Shugg (1996) has found that these are common in the Upper Ordovician sedimentary rocks of the Kiewa-Ovens region. The saprolite near the town of Stanley, for example, goes down to 60 metres. Intense faulting and fracturing have facilitated the penetration of water and the deep weathering of the rock to clay minerals. Fracturing accounts for up to 7% of the porosity of these rocks and weathering accounts for the rest.

The following rock types found in the catchments of the present study are not covered in Table 1. Rhyodacite is dense, jointed and not very permeable. However, in moist ecosystems it develops very deep permeable soils. Lower Cretaceous sedimentary rock has relatively low primary porosity and generally exhibits very little fracturing. Unconsolidated sediments have high hydraulic conductivity but vary greatly in depth and hence in transmissivity (Lawrence 1982). Metamorphic rocks rarely contain more than 2% porosity in unfractured blocks and fracturing usually only increases overall porosity by 2 to 5% (Heislers 1993).

All of the above information will be used in the development of an index to represent the geology and soils of the Victorian catchments.

3.3 Ecological vegetation classes

To overcome the problems of characterising the soil in catchments for which there are very little soil data, the concept of an environmental indicator will be used. This concept is taken from ecology (McKenzie et al. 1992, Keddy et al. 1993) and can be applied in a hydrological study. The hypothesis is made in this report that the indigenous vegetation community is an indicator of the overall state of the soil (in its capacity for recharge, accommodation of groundwater, transmissivity and supply of baseflow). For example, tall, wet forest would normally indicate a deep, permeable soil. The question as to what extent the soil (and climate) determine the vegetation or, conversely, to what extent the vegetation helps form the soil is not considered here. Furthermore, since geology is an important factor in soil type, a refinement of the hypothesis is that vegetation and geology are joint indicators of soil state.

In order to use vegetation community as an indicator, a system of classification of the communities is required. A number of different systems have been used in Land Conservation Council reports, land system studies and other reports in Victoria. These are now being replaced by a new system of 'ecological vegetation classes'. These classes represent the highest level in the hierarchy of vegetation typology developed and used across Victoria by the Department of Natural Resources and Environment. 'They consist of one or a number of floristic communities that exist under a common regime of ecological processes within a particular environment at a regional, state or continental scale' (Woodgate et al. 1994).

Land Conservation Council (1991), Woodgate et al. (1994) and Muir et al. (1995) give detailed descriptions of the ecological vegetation classes found in different parts of Victoria. This work has not yet been completed for the whole state. Table 2 gives a brief summary of the main classes occurring in the catchments of this study. The species mentioned are typical for each class; there may be variation from one area to another.

3.4 Soil and vegetation relationships

There is plenty of evidence for a relationship between vegetation and soils. Gibbons and Rowan (1993) point out that soil development, nature and distribution of soils, and plant growth are intimately connected processes. Furthermore, the vegetational relationships with soils can be described only in the context of climate, geology and topography. They simplify Northcote's (1979) soil classification down to 12 soil groups and 31 sub-groups and they give examples of vegetation communities commonly associated with each group.

More detailed examples of the relationship between soils and vegetation can be obtained from the various land systems studies in Victoria. Some examples are summarised in Table 3. The Wet Forest class (Table 2) is associated with deep soils. The Coranderrk soils report (Langford & O'Shaughnessy 1980a) found that much of the Picaninny, Blue Jacket and Slip Creek catchments (near Healsville), with Wet Forest on rhyodacite bedrock, have very deep red gradational soils (Northcote classes Gn3.11 and Gn4.11). At one site a depth of 15 metres was recorded. At Reefton Spur (near the Upper Yarra Reservoir) there are areas of Wet Forest on Devonian sedimentary bedrock with red gradational soils, sometimes greater than 3 metres deep (Wu et al. 1984). In parts of the Otway Ranges, Wet Forest on Lower Cretaceous sedimentary bedrock has brown friable gradational soils, up to 2 metres deep (Pitt 1981). It is to be noted that the soils on rhyodacite are much deeper than those on the sedimentary rocks.

Damp Forest tends to have fairly deep gradational soils; for example: (a) on rhyodacite at Mt Macedon: yellow and red gradational soils (Gn4) to 2 metres deep, (b) on granite at Mt Disappointment: red and brown gradational soils (Gn3) to 2 metres deep, (c) on Silurian and Devonian sedimentary rock at Kinglake: gradational

Table 2. Ecological Vegetation Classes

Class	Dominant species	Notes
SUB-ALPINE VEGETATION		
Sub-alpine woodland	*E. pauciflora*	Understorey: either shrubs, or grasses & herbs.
MONTANE VEGETATION		
Montane Dry Woodland	*E. pauciflora, E. rubida*	Shrubs: *Pultanaea juniperina, Daviesia ulicifolia.*
Montane Damp Forest	*E. delegatensis, E. cypellocarpa*	Lower storey: *A. melanoxylon, A. obliquinervia.*
Montane Wet Forest	*E. nitens, E. delegatensis*	Second storey: *Nothofagus cuninghamii, A. frigescens.*
MOIST FORESTS		
Wet Forest	*E. regnans*	There may be a second storey of wattles and a third of tall shrubs and tree ferns.
Damp Forest	*E. cypellocarpa, E. obliqua*	Shrub layer: *Pomaderris aspera, Coprosma quadrifida.*
Riparaian Thicket	*Lept. lanigerum, Melaleuca squarrosa*	
Riparaian Forest	*E. viminalis*	Lower storey: *A. dealbata, A. melanoxylon, Prosanthera lasianthos.*
DRY FORESTS		
Herb-rich Foothill Forest	*E. radiata, E. bicostata, E. viminalis, E. rubida*	Shrub layer is low and sparse. Ground layer is dense & species rich.
Heathy Foothill Forest	*E. consideniana, E. obliqua*	Shrub layer: *Lept. continentale, Pultenaea gunnii, Epacris impressa.*
Shrubby Foothill Forest	*E. obliqua, E. radiata*	Shrub layer: *A. mucronata, Spyridium parvifolium, Platylobium formosum.*
Heathy Dry Forest	*E. macrorhyncha, E. goniocalyx, E. dives, E. polyanthemos*	Shrub layer: *Monotoca scoparia, Brachyloma daphnoides, Dillwynia phylicoides.*
Grassy Dry Forest	*E. macrorhyncha, E. goniocalyx, E. dives, E. polyanthemos*	Shrubs may include *A. dealbata*. The grassy understorey is rich in species.
Shrubby Dry Forest	*E. dives, E. mannifera, E. macrorhyncha*	Shrub layer: *Persoonia champaepeuce, Coprosma hirtella, Cassinia aculeata.*

Note: *E. = Eucalyptus; A. = Acacia; Lept. = Leptospermum .*

soils (Gn3, Gn4) one metre deep (Jeffery 1981), and (d) on Lower Cretaceous sedimentary rock in the Strzelecki Ranges: grey and brown gradational soils (Gn4) to one metre deep (Industry and Resources Information Section 1995). Again it is found that the soils on the igneous rocks are deeper than those on the sedimentary rocks.

The soils of the Shrubby Foothill Forest class are generally less deep and permeable and are more varied. Examples are: (a) on the granite of the Cobaw land system (east of Kyneton): yellow and red duplex soils and sandy soils to 1.5 metres deep, (b) on Devonian sedimentary rock at Reefton Spur: gradational soils up to about 1 metre deep, and (c) on the Lower Ordovician sedimentary rock of the Wombat land system (Woodend): yellowish-brown or reddish-brown gradational or duplex soils to 1.5 metres deep (Jeffery 1981; Lorimer & Schoknecht 1987; Wu et al. 1984).

Grassy Dry Forest has very shallow soils. Those on the Silurian sedimentary rock of the Springfield land system (Kilmore) are shallow stony gradational soils to 0.5 metres deep; those on the Lower Ordovician sedimentary rock of the Fryers land system (south of Castlemaine) are shallow stony soils of uniform or gradational texture to 0.6 metres deep (Jeffery 1981; Lorimer & Schoknecht 1987).

The values of soil depth in this section are the depths to bedrock and include the C horizon.

3.5 The geology-vegetation index

Information on the geology and vegetation of the catchments in this study is used to develop a geology-vegetation index to represent the hydrological behaviour of the bedrock and soils. The index, comprising 12 groups is set out in Table 4. Igneous rocks are placed first in the table, then unconsolidated sediments, then sedimentary and metamorphic rocks. The rock types covered in Table 1 are kept in the same order, that is decreasing specific capacity. Some of the catchments with Wet Forest and Damp Forest include strips of Riparian Forest and Riparian Thicket. These ecosystems are described in Table 2 but are not mentioned explicitly in the Table 4.

The granite catchments are put into two groups: C, containing the moist and montane ecosystems, and D, containing the dry systems. The Silurian/Devonian sedimentary and the Lower Cretaceous sedimentary catchments also have two groups each, corresponding to moister and dryer ecosystems.

The possibility and implications of subdividing some of the groups will be considered in Section 5.2.

4. CATCHMENT DATA

Data have been obtained for 114 catchments in Victoria, with areas up to 192 km^2. There were three sources: Melbourne Water provided the data for 17 catchments in and near the watershed of the Maroondah Dam; the Department of Conservation and Natural Resources provided that for 6 catchments in the Reefton Experimental Area; and the remainder were obtained from a database provided by Nathan (1995). The Maroondah and Reefton catchments are described by Howard and

Table 3. Examples of vegetation and soils

Ecological vegetation class	Location	Geology	Soils
Wet Forest	Coranderrk Ck, near Healesville	Devonian rhyodacite	Very deep red gradational (Gn3.11, Gn4.11)
	Reefton Spur, near Upper Yarra Res.	Devonian sedimentary	Deep red gradational (3 m deep)
	Otway Ranges	Lower Cretaceous sedimentary	Brown gradational (to 2 m)
Damp Forest	Mt Macedon	Devonian rhyodacite	Gradational (Gn4; to 2 m)
	Mt Disappointment	Devonian granite	Gradational (Gn3; to 2 m)
	Kinglake	Silurian/Devonian sedimentary	Gradational (Gn3, Gn4; 1 m deep)
	Strzlecki Ranges	Lower Cretaceous sedimentary	Gradational (Gn4; to 1 m)
Shrubby Foothill Forest	Cobaw Range, E. of Kyneton	Devonian granite	Yellow and red duplex and sandy soils (to 1.5 m)
	Reefton Spur, near Upper Yarra Res.	Devonian sedimentary	Gradational (to 1 m)
	Wombat land system, Woodend	Lower Ordovician sedimentary	Gradational or duplex (to 1.5 m)
Grassy Dry Forest	Springfield land system, Kilmore	Silurian sedimentary	Stony gradational (to 0.5 m)
	Fryers land system, S. of Castelmaine	Lower Ordovician sedimentary	Stony uniform or gradational (to 0.6 m)

Table 4. Geology-vegetation index

Group	Geology	Ecological Vegetation Classes
A	Devonian rhyodacite	(a) Wet Forest; (b) Damp Forest; (c) Montane Wet Forest; (d) Montane Damp Forest; (e) mix of Damp Forest & Shrubby Foothill Forest.
B	Tertiaty basalt	Damp Forest.
C	Devonian granite	(a) Wet Forest; (b) Damp Forest; (c) Montane Wet Forest; (d) mix of Montane Wet Forest & Sub-alpine Woodland; (e) mix of Montane Wet Forest & Montane Dry Woodland; (f) mix of Damp Forest with Herb-rich Foothill Forest or Shrubby Foothill Forest.
D	Silurian or Devonian granite	(a) Herb-rich Foothill Forest; (b) Shrubby Foothill Forest; (c) Shrubby Dry Forest; (d) Grassy Dry Forest;
E	Tertiary unconsolidated	(a) Damp Forest; (b) Herb-rich Foothill Forest.
F	Upper Ordovician sedimentary	(a) Mix of Montane Damp Forest & Sub-alpine Woodland; (b) Herb-rich Foothill Forest; (c) Shrubby Dry Forest; (d) Grassy Dry Forest.
G	Upper Ordovician metamorphic	(a) Mix of Herb-rich Foothill Forest with Shrubby Dry Forest or Grassy Dry Forest; (b) Grassy Dry Forest.
H	Silurian or Devonian sedimentary	Mix of Wet Forest & Damp Forest.
I	Silurian or Devonian sedimentary	(a) Mix of Damp Forest with Shrubby Foothill Forest, Herb-rich Foothill Forest or Heathy Foothill Forest; (b) mix of Herb-rich Foothill Forest & Grassy Dry Forest; (c) Heathy Dry Forest; (d) Grassy Dry Forest.
J	Cambrian or Lower Ordovician sedimentary	(a) Herb-rich Foothill Forest; (b) Shrubby Foothill Forest; (c) Grassy Dry Forest.
K	Lower Cretaceous sedimentary	Wet Forest.
L	Lower Cretaceous sedimentary	Mix of Wet Forest & Damp Forest.

O'Shaughnessy (1971), Langford and O'Shaughnessy (1977), O'Shaughnessy et al. (1981), and Wu et al. (1984).

The data are set out in Table 5. Most of the catchments are identified by the gauging station number (Rural Water Commission 1990) as well as the name of the stream. The catchment areas and stream lengths were provided by the sources. So were the catchment reliefs, in the case of the Maroondah and Reefton catchments. For the other catchments the reliefs were measured from topographic maps. This was done only for the catchments with areas up to 40 km^2. Rainfall in the Maroondah catchments (Black Spur 1 to Crotty Ck) was estimated by Watson (1996), using Melbourne Water data. In the other catchments it was obtained from the sources. However, in some cases the rainfall values from the database were amended using data from the MOSAZ Model Parameter File (Nathan et al. 1996).

The baseflow indices for all catchments were determined from the daily streamflow data, either by Nathan (1995) or by using the same digital filter, recommended by Nathan & McMahon (1990).

4.1 The geology-vegetation groups

For the geology-vegetation group for each catchment to be determined, it was necessary to know the geology and the ecological vegetation class. The geology of each catchment was determined from the 1:1 000 000 Geological Map of Victoria, supplemented by the 1:250 000 Geological Map series. Many catchments have more than one rock type and in such cases the dominant type was used. In a few catchments the areas of two rock types are not very different (e.g. 0.6/0.4) but these turn out to be close in their hydrological properties (indicated by specific capacity in Table 1).

The ecological vegetation classes for most catchments were determined from a number of 1:100 000 maps of the Central Highlands and North-Eastern Victoria, printed from the GIS Corporate Library of the Department of National Resources and Environment. In regions not covered by these maps, the maps in Land Conservation Council reports (1974-1991) and land system studies were used (Jeffery 1981; Lorimer & Rowan 1982; Lorimer & Schoknecht 1987; Pitt 1981; Rowe 1972; and Rundle & Rowe 1974).

In catchments where the indigenous vegetation has been wholly or partly cleared or is undergoing regrowth after logging, it is the original vegetation that is considered the indicator of soil state. It is assumed that the change in land use has not greatly altered the soil profile. Of course, such changes will greatly alter the evapotranspiration and this will be considered separately. The maps give the vegetation on public land only. So in some cases involving cleared land or private land estimates had to be made as to the original vegetation, on the basis of information from adjacent areas.

A number of field trips were undertaken to verify our understanding of geology, vegetation and soils in several catchments. In two cases it was necessary to determine the boundary between two adjacent rock types, in order to assign the correct geology-vegetation group. In nearly all cases the ecological vegetation classes obtained from the maps or reports were found to be correct. It was also

Table 5. Catchment data

Catchment	Area (km²)	Geoveg index	Stream length (km)	Relief (km)	Rainfall (mm/yr)	Forest cover	Baseflow index
Tambo Basin							
223402 Timbarra R	15.50	C	19.07	0.330	689	0.94	0.69
223403 Tambo R	38.90	C	43.18	0.330	689	0.97	0.64
La Trobe Basin							
226008 Tyers R West	80.30	C	100.38		1756	1.00	0.62
226012 Tanjil R East	12.40	C	18.97	1.000	1898	0.53	0.64
226016 Waterhole Ck	41.00	E	41.00		826	0.30	0.44
226017 Jacobs Ck	36.30	I	38.12	0.280	1103	0.74	0.41
226023 Traralgon Ck	189.00	L	217.35		1058	0.58	0.34
226212 Morwell R West	23.30	K	48.93	0.300	1372	0.96	0.56
226213 Morwell R West	12.40	K	26.04	0.300	1372	1.00	0.56
226218 Narracan Ck	64.70	B	69.23		965	0.03	0.72
226219 Toorongo R	70.10	C	98.14		1432	0.94	0.76
226220 Loch R	97.10	C	147.59		1497	1.00	0.73
226222 La Trobe R	62.20	C	93.30		1482	1.00	0.79
226403 Tanjil R West	17.10	C	29.93	0.450	1879	1.00	0.66
226404 Billy Ck	40.00	L	48.00	0.470	1005	0.31	0.31
226405 Middle Ck	69.00	L	96.60		956	0.55	0.35
226406 Little Morwell R	53.60	E	64.86		1003	0.56	0.60
226407 Morwell R	114.00	L	180.12		1191	0.59	0.47
226409 Ten Mile Ck	48.70	B	35.06		1007	0.45	0.60
226410 Traralgon Ck	89.00	L	120.15		1039	0.80	0.34
226411 Flynns Ck	98.40	E	103.32		955	0.53	0.29
226415 Traralgon Ck	128.00	L	165.12		898	0.76	0.33
South Gippsland Basin							
227203 Franklin R	46.60	L	91.34	0.400	1000	0.65	0.42
227210 Bruthen Ck	18.10	L	29.68	0.460	1100	0.54	0.39
227211 Agnes R	67.00	L	116.58		1100	0.49	0.42
227213 Jack R	34.00	L	61.88	0.620	1200	0.45	0.42
227219 Bass R	52.00	L	90.48		1100	0.10	0.25
227228 Tarwin R East	44.30	L	80.18		1121	0.41	0.40
Bunyip Basin							
228206 Tarago R	77.00	C	100.10		1100	0.90	0.65
228217 Toomuc Ck	41.00	D	81.18		850	0.45	0.29
Yarra Basin							
Black Spur 1	0.17	A	0.24	0.072	1615	1.00	0.91
Black Spur 2	0.10	A	0.35	0.073	1600	1.00	0.78
Black Spur 3	0.08	A	0.29	0.068	1541	1.00	0.85
Monda 1	0.06	A	0.26	0.083	1910	1.00	0.85
Monda 2	0.04	A	0.16	0.097	1832	1.00	0.87
Monda 3	0.07	A	0.25	0.101	1816	1.00	0.83
Monda 4	0.06	A	0.21	0.080	1779	1.00	0.80
Ettercon 1	0.12	A	0.43	0.050	1824	1.00	0.84
Ettercon 2	0.09	A	0.36	0.035	1821	1.00	0.75
Ettercon 3	0.15	A	0.59	0.125	1704	1.00	0.79
Ettercon 4	0.09	A	0.22	0.062	1714	1.00	0.84
Myrtle 1	0.25	A	0.78	0.144	1630	1.00	0.79
Myrtle 2	0.30	A	0.99	0.204	1580	1.00	0.87
Picaninny Ck	0.53	A	0.86	0.563	1224	1.00	0.75
Blue Jacket Ck	0.65	A	1.64	0.542	1365	1.00	0.78
Slip Ck	0.62	A	0.93	0.545	1438	1.00	0.77
Crotty Ck	1.22	A	2.76	0.189	1841	1.00	0.87
Reefton Spur 1	0.70	I	4.18	0.280	1233	1.00	0.25
Reefton Spur 2	0.76	I	2.94	0.325	1250	1.00	0.36
Reefton Spur 3	0.95	I	3.86	0.295	1265	1.00	0.31
Reefton Spur 4	1.07	H	4.21	0.240	1249	1.00	0.51
Reefton Spur 5	1.56	H	6.48	0.375	1308	1.00	0.57

Table 5. (contd)

Catchment	Area (km^2)	Geoveg index	Stream length (km)	Relief (km)	Rainfall (mm/yr)	Forest cover	Baseflow index
Reefton Spur 6	5.21	H	19.92	0.395	1440	1.00	0.63
229106 McMahons Ck	40.00	H	55.20		1497	1.00	0.69
229109 Starvation Ck	31.60	C	48.98	0.600	1503	1.00	0.72
229210 Plenty R West	10.40	C	11.96	0.450	792	0.95	0.65
229214 Little Yarra R	140.00	C	210.00		1437	0.79	0.73
229217 Running Ck	20.20	I	30.10	0.310	977	1.00	0.40
229219 McCrae Ck	5.40	C	7.02	0.320	1494	0.91	0.65
229220 Don R	18.10	A	13.94	0.880	1182	0.60	0.69
229221 Falls Ck	4.40	C	2.99	0.190	823	1.00	0.74
Maribyrnong Basin							
230209 Barringo Ck	6.00	A	11.94	0.340	1105	0.94	0.72
Werribee Basin							
231209 Werribee R	101.00	J	129.28		1020	0.71	0.36
231213 Lerderderg R	153.00	J	212.67		900	0.94	0.36
Barwon Basin							
233214 Barwon R East	17.00	L	24.31	0.460	1377	1.00	0.35
Otway Basin							
235202 Gellibrand R	53.00	L	78.44		1326	0.94	0.46
235205 Arkins Ck	3.90	K	5.46	0.210	1964	1.00	0.59
235216 Cumberland R	38.00	L	39.75	0.660	1117	1.00	0.45
Glenelg Basin							
238208 Jimmy Ck	23.00	I	36.34	0.130	625	0.98	0.48
Kiewa Basin							
402206 Running Ck	126.00	G	191.52		1088	0.86	0.58
402208 Swampy Ck	15.00	G	22.95	0.480	1003	0.80	0.45
402209 Twist Ck	14.00	F	27.02	0.460	977	0.89	0.52
402210 Commissioners Ck	6.50	G	15.99	0.410	1064	0.45	0.45
402211 Kinchington Ck	8.00	F	18.00	0.430	1056	0.71	0.55
402212 Back Ck	12.20	F	20.01	0.460	1018	0.58	0.56
402213 Kinchington Ck	117.00	D	225.81		995	0.38	0.41
402214 Swamp Ck	28.50	G	45.89	0.520	1116	0.76	0.50
402215 Yackandandah Ck	64.80	F	128.95		1027	0.83	0.64
402216 Nine Mile Ck	21.20	F	37.95	0.200	1408	0.60	0.66
402217 Flaggy Ck	23.60	G	51.92	0.830	983	0.49	0.45
402218 Simmonds Ck	10.10	F	14.04	0.590	1278	1.00	0.62
402219 Middle Ck	71.40	G	107.81		931	0.21	0.35
402221 Middle Ck	41.90	G	62.85		1097	0.25	0.42
402406 Kiewa R West	88.00	F	216.48		2168	0.95	0.59
Ovens Basin							
403216 Buffalo Ck	67.30	D	104.32		1488	0.91	0.50
403217 Rose R	176.00	F	253.44		1142	1.00	0.43
403218 Dandongadale R	181.00	F	282.36		1255	1.00	0.49
403224 Hurdle Ck	155.00	F	244.90		893	0.64	0.41
403229 Black Range Ck	54.40	F	108.80		1219	0.86	0.54
403232 Morses Ck	128.00	F	207.36		1179	0.94	0.49
403236 Barwidgee Ck	168.00	D	309.12		1021	0.62	0.47
Broken Basin							
404208 Moonee Ck	94.00	D	79.90		981	0.84	0.60
Goulburn Basin							
405205 Murrindindi R	108.00	C	151.20		1278	0.89	0.76
405233 Spring Ck	28.50	D	19.95	0.170	1079	0.16	0.47
405236 Island Ck	48.70	I	45.78		1011	0.76	0.53
405238 Mollison Ck	166.00	D	469.78		790	0.21	0.31
405244 Merton Ck	54.40	I	64.74		736	0.22	0.27
405250 Snobs Ck	35.70	A	43.91	0.800	1447	1.00	0.68
405251 Brankeet Ck	122.00	D	129.32		861	0.66	0.49
405252 Glen Ck	36.30	I	46.10	0.710	722	0.42	0.26

Table 5. (contd)

Catchment	Area (km^2)	Geoveg index	Stream length (km)	Relief (km)	Rainfall (mm/yr)	Forest cover	Baseflow index
405254 Tallangallook Ck	44.00	I	52.80		722	0.48	0.38
405256 Cordury Ck	40.40	I	71.91		1160	1.00	0.52
405257 Snobs Ck	54.30	A	72.22		1210	1.00	0.67
405261 Spring Ck	66.60	I	113.22		746	0.11	0.27
405262 Creightons Ck	81.00	D	103.68		766	0.31	0.45
405265 Mill Ck	26.20	D	34.06	0.500	650	0.80	0.24
405274 Home Ck	192.00	I	320.64		787	0.20	0.25
405278 Godfrey Ck	80.00	I	128.80		720	0.42	0.34
405404 Murrindindi R	46.60	C	61.05		1288	0.86	0.78
405406 Falls Ck	19.40	C	24.06	0.320	1122	1.00	0.72
Campaspe Basin							
406208 Campaspe R	39.00	J	39.78	0.060	875	0.97	0.31
Loddon Basin							
407221 Jim Crow Ck	166.00	J	249.00		750	0.64	0.35
Avoca Basin							
408202 Avoca R	78.00	J	120.90		590	0.47	0.28
Wimmera-Avon Basin							
415217 Fyans Ck	34.00	I	65.96	0.510	1000	1.00	0.42

possible to determine the vegetation on private land not covered by the maps. Some values of forest cover in Table 5 were amended on the basis of the field observations.

5. EFFECTS OF CATCHMENT PROPERTIES ON BASEFLOW

The effects of the dimensionless catchment properties on baseflow index will be examined, in particular the effects of geology-vegetation index, topographic and climatic parameters, forest cover and forest growth stage.

5.1 Effect of geology-vegetation index

Baseflow index has been plotted against the geology-vegetation groups for all catchments in Figure 1. Four different catchment area ranges (less than 10 km^2, 10 to 40, 40 to 100, and greater than 100 km^2) are indicated by different symbols. The values of range, mean and standard deviation for each group are summarised in Table 6. In most groups the baseflow index values are clustered in fairly narrow vertical bands. An analysis of variance shows that this effect is highly significant ($P<0.0001$).

The highest values of baseflow index occur for rhyodacite (group A). This is probably due mainly to the very deep permeable soils formed in the Wet Forest and Damp Forest ecosystems on this bedrock. The two catchments on Tertiary basalt (group B) also have high baseflow index. This rock can have high primary porosity, can be highly fractured and also tends to form deep permeable soils in the Damp Forest ecosystems.

Figure 1. Baseflow index vs geology-vegetation groups

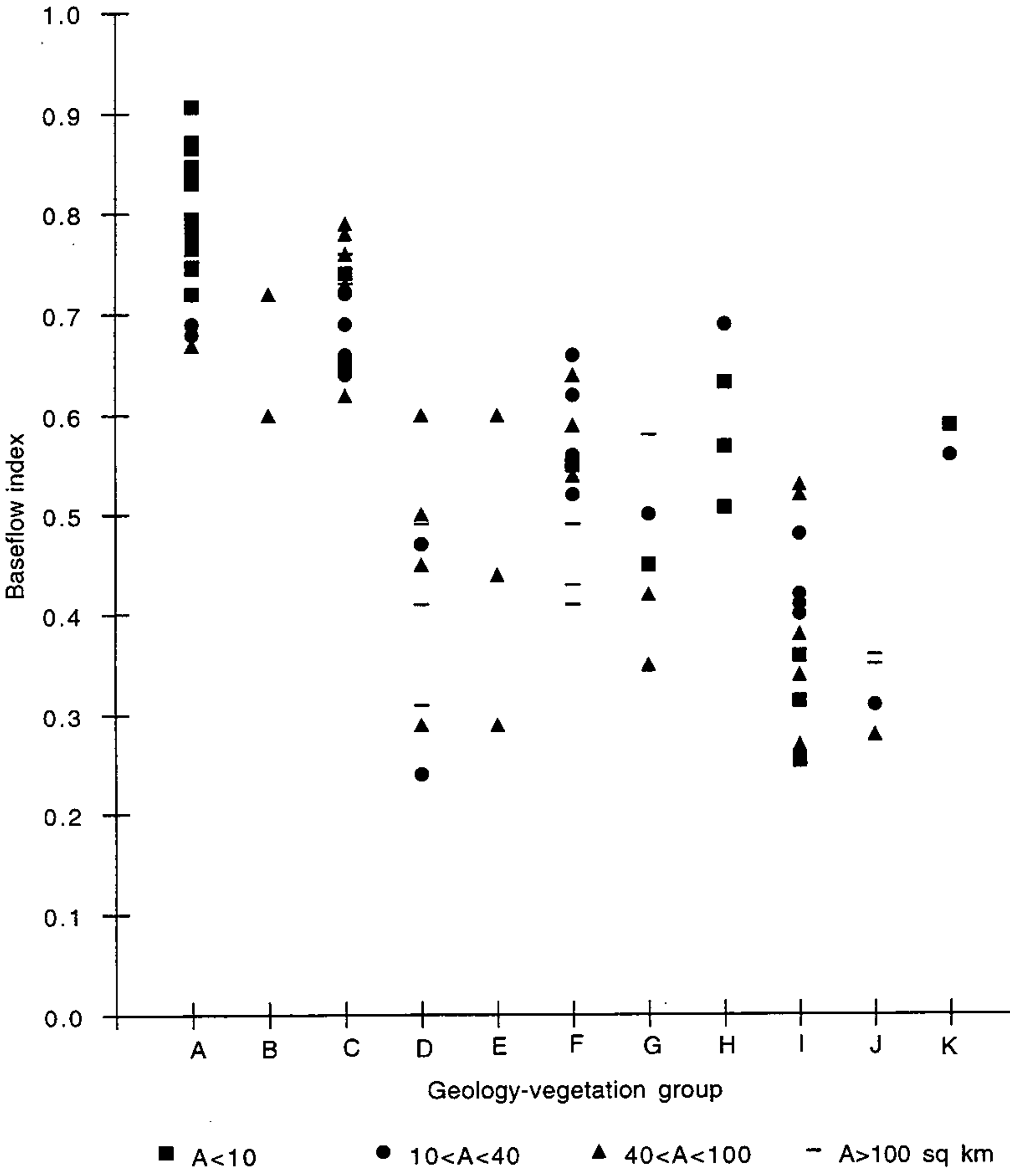


Table 6.   Summary of results

Geology-vegetation group	Number of catchments	Baseflow index		
		Range	Mean	Std devn
A	21	0.67-0.91	0.794	0.068
B	2	0.60-0.72	0.660	0.085
C	17	0.62-0.79	0.702	0.055
D	10	0.24-0.60	0.423	0.111
E	3	0.29-0.60	0.443	0.155
F	12	0.41-0.66	0.542	0.079
G	7	0.35-0.58	0.457	0.071
H	4	0.51-0.69	0.600	0.079
I	15	0.25-0.53	0.364	0.096
J	5	0.28-0.36	0.332	0.036
K	3	0.56-0.59	0.570	0.017
L	15	0.25-0.47	0.380	0.062
Total	114		0.545	0.074

The large number of catchments on Devonian granite with moist and montane ecosystems (group C) fall in a narrow band with high baseflow index. Since there is low primary porosity and little fracturing in granite, the high values would again be mainly the consequence of deep permeable soils. The catchments on granite with dry forest (group D) have a wide spread of baseflow index values, all of them lower than for group C. The lower values reflect the shallower soils on these ecosystems.

In view of the wide spread of baseflow index values in group D, it was decided to examine carefully the catchment with the lowest baseflow index (0.24), namely Mill Creek in the Tallarook Range (Goulburn Basin). The gauging station is located on the downward slope of the plateau, so the question arose as to whether there could be any significant leakage of groundwater past this station. The discharge was measured at four locations in this creek, ranging from 50 m upstream to 800 m downstream of the gauging station, on five different occasions during July 1996 (Little 1996). No significant variation in discharge was found along this length. Thus there appears to be no leakage of groundwater.

The wide spread for group D is apparently the result of different degrees of weathering of these granite catchments, leading to wide variation in the soil profiles and hydrological properties. A comprehensive program of soil testing could determine if the profile distributions account for the variation in baseflow index. Extensive studies on the geology of granite in Victoria indicate that the weathering cannot be accounted for in terms of different composition of the rock in the various areas (Alan White, pres. comm. 1996).

The three catchments on Tertiary unconsolidated sediments (group E) also span a wide range of baseflow index values. These sediments have high hydraulic conductivity but are of variable depth.

The mean baseflow index value for the Upper Ordovician sedimentary catchments (group F) is considerably higher than those for catchments on other sedimentary rocks, except for those with wet forest ecosystems (groups H and K). This is a consequence of the deep fracturing and weathering, and hence higher transmissivity, of the Upper Ordovician rocks. A catchment with Montane Damp Forest (Kiewa River West Branch) has a baseflow index value well within the range of those with Grassy or Shrubby Dry Forests, and hence shallow soils. This strongly suggests that the rock contribution is much more important than the soil contribution in these catchments.

The catchments on Upper Ordovician metamorphic rock (group G) have a lower mean baseflow index value than that for the sedimentary catchments. This is presumably because of the low degree of fracturing.

The catchments on Silurian or Devonian sedimentary rocks with moist forests (group H) tend to have significantly higher baseflow index than those with drier forests (group I). In the former case the baseflow contribution would be due to both rocks and soil, while in the drier forests, the soil contribution is less.

The behaviour of the Cambrian or Lower Ordovician sedimentary catchments, all with dry forest (group J), is similar to that for the Silurian or Devonian with similar ecosystems.

The three catchments on Lower Cretaceous sedimentary rock with pure stands of Wet Forest (group K) have higher baseflow index than those with mixed Wet Forest and Damp Forest (group L). (Two of the former points coincide in the figure.) Since this rock generally exhibits very little fracturing, the baseflow contribution from the soil is very important. The Wet Forests would be expected to have deeper soils than the more mixed forests.

5.2 Geology-vegetation sub-groups?

It may be argued that the geology-vegetation index used here is somewhat arbitrary. So the implications of subdividing some of the groups, namely those with a large variety of ecological vegetation classes, was considered. First consider group A. The Barringo Creek catchment on Mt Macedon (Maribyrnong Basin) has a drier ecosystem (mixture of Damp Forest and Shrubby Foothill Forest) than the other catchments in this group. However, its baseflow index (0.72) is well within the range for this group. So no subdivision is required here.

In Table 7 the granite catchments and the Silurian/Devonian sedimentary catchments are each divided into three groups instead of two. Group C is split into

Table 7. Geology-vegetation index sub-categories

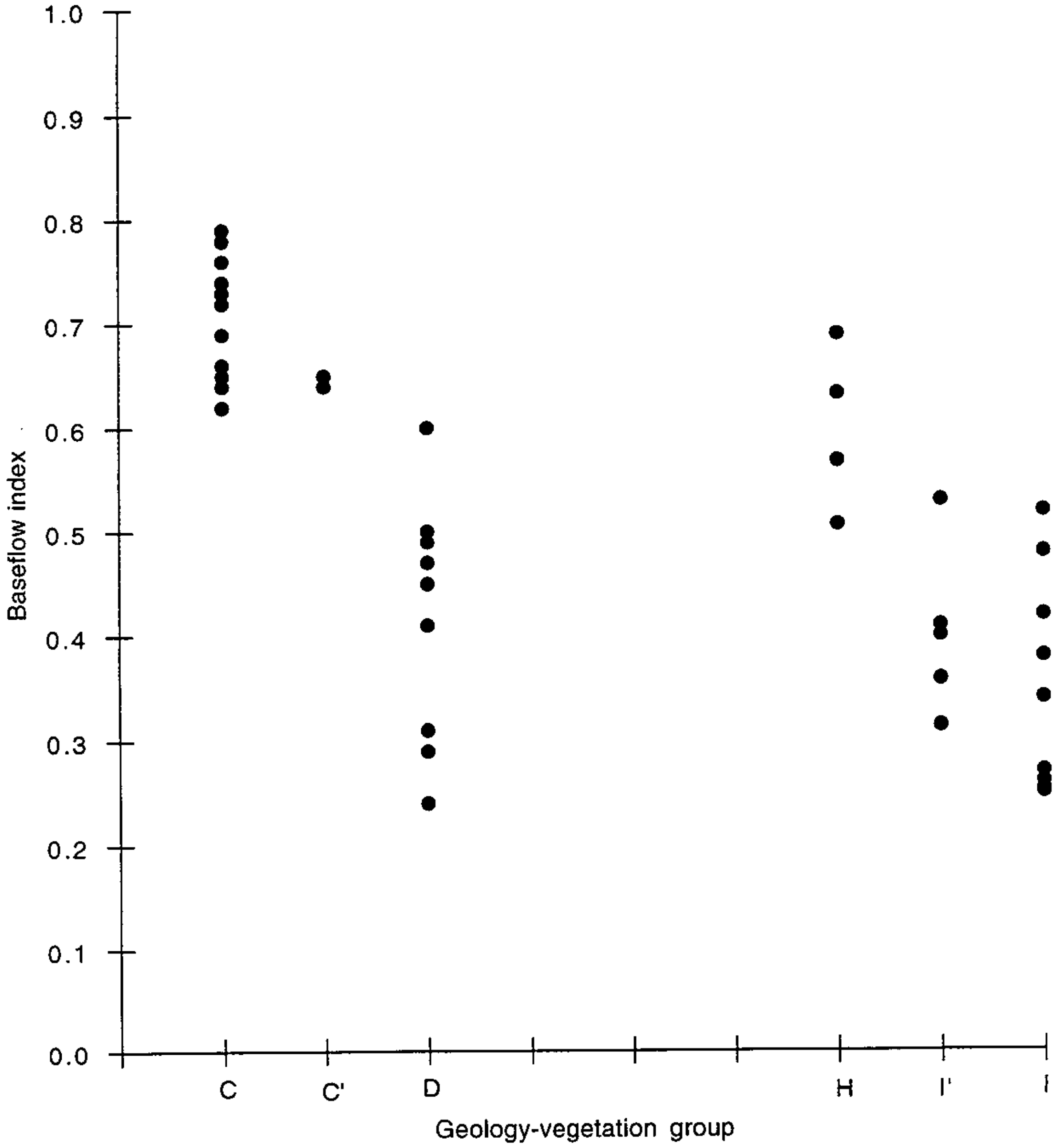
Group	Geology	Ecological Vegetation Classes
C	Devonian granite	(a) Wet Forest; (b) Damp Forest; (c) Montane Wet Forest; (d) mix of Montane Wet Forest & Sub-alpine Woodland.
C'	Devonian granite	(a) Mix of Montane Wet Forest & Montane Dry Woodland; (b) mix of Damp Forest with Herb-rich Foothill Forest or Shrubby Foothill Forest.
D	Silurian or Devonian granite	(a) Herb-rich Foothill Forest; (b) Shrubby Foothill Forest; (c) Shrubby Dry Forest; (d) Grassy Dry Forest;
H	Silurian or Devonian sedimentary	Mix of Wet Forest & Damp Forest.
I'	Silurian or Devonian sedimentary	Mix of Damp Forest with Shrubby Foothill Forest, Herb-rich Foothill Forest or Heathy Foothill Forest.
I	Silurian or Devonian sedimentary	(a) Mix of Herb-rich Foothill Forest & Grassy Dry Forest; (b) Heathy Dry Forest; (c) Grassy Dry Forest.

groups C and C', and group I into groups I' and I. The baseflow index plot for this classification is shown in Figure 2. It can be seen that group C' fits into the range of group C, while group I' almost fits into the range of group I. So there is no need for this subdivision of the groups.

There is a correspondence between the pattern of baseflow index values in Table 6 and the specific capacity values obtained from boreholes in Table 1. Basalt, granite and Upper Ordovician sedimentary rocks tend to give high values for both baseflow index and specific capacity, while Silurian/Devonian and Lower Ordovician sedimentary rocks tend to give much lower values of both. Baseflow index depends on the transmissivity of the rocks and soil, and specific capacity is a measure of this.

All these results constitute strong evidence that geology and soils are major factors determining baseflow index, and that vegetation community is an indicator of soil state. In some catchments the main contribution to baseflow appears to come from the rocks (e. g. those on Upper Ordovician sedimentary), while in others (e. g. those on granite or Lower Cretaceous sedimentary rocks) it appears to come from the soil.

Figure 2. Baseflow index vs geology-vegetation sub-groups



5.3 Scale effect

It is important to examine if there is a scale effect with catchment size, i. e. if catchment area has an influence on the baseflow behaviour examined so far. In Figure 1 four ranges of catchment area (up to 10 km^2, between 10 and 40 km^2, between 40 and 100 km^2, and between 100 and 200 km^2) are indicated with different symbols. It can be seen that for the lower three ranges (i. e. up to 100 km^2) all points in each group are part of the same population. The baseflow behaviour of all these catchments is evidently governed by the same dominant processes.

However, for the catchments with areas greater than 100 km^2 a number of points fall outside the range of the smaller catchments. This is particularly striking with the Upper Ordovician sedimentary catchments (group F) where the large catchments have lower baseflow index. It is not clear if this is a scale effect or if it is the consequence of variability in the transmissivity of the rocks. Two adjacent catchments in the Ovens Basin, Black Range Ck (54 km^2) and Hurdle Ck (155 km^2), have very different baseflow index values, 0.54 and 0.41 respectively, suggesting a scale effect. However, if there is a scale effect we would expect it to work everywhere in the same direction, whereas in geology-vegetation groups G and J the large catchments have higher baseflow index values.

In principle the scale effect could be analysed statistically with a two-way analysis of variance involving the geology-vegetation and area categories. However, this is not possible with the catchment data in this study, as the two factors do not overlap sufficiently.

5.4 Topography

Baseflow index has been plotted against three dimensionless topographic parameters: drainage index ($L/\sqrt{A}$), slope index ($H/\sqrt{A}$), and flat area ratio (fraction of the catchment area that consists of flood plain).

Typical drainage index plots are shown in Figure 3, for granite catchments (groups C and D), Figure 4, for Upper Ordovician sedimentary and metamorphic catchments (groups F and G), and Figure 5, for Lower Cretaceous sedimentary catchments (groups K and L). No trends are detected in any of the groups. This is confirmed by regression analysis.

Slope index plots are shown in Figure 6, for rhyodacite catchments (groupA), Figure 7, for granite catchments (groups C and D), and Figure 8, for Silurian/Devonian sedimentary catchments (groups H and I). Slope index was calculated for catchments with area less than 40 km^2 only. Again no trends are detected in any of the groups.

The flat area ratios for a number of granite (group D) and Lower Cretaceous sedimentary (group L) catchments were measured, using 1:100 000 topographic maps. Figure 9 shows a plot of baseflow index against flat area ratio for these catchments. No trends are observed. The highest value of the ratio is 0.4; it is possible that if catchments with a very large flat area ratio were examined this parameter might have an effect.

Figure 3. Baseflow index vs drainage index: granite catchments

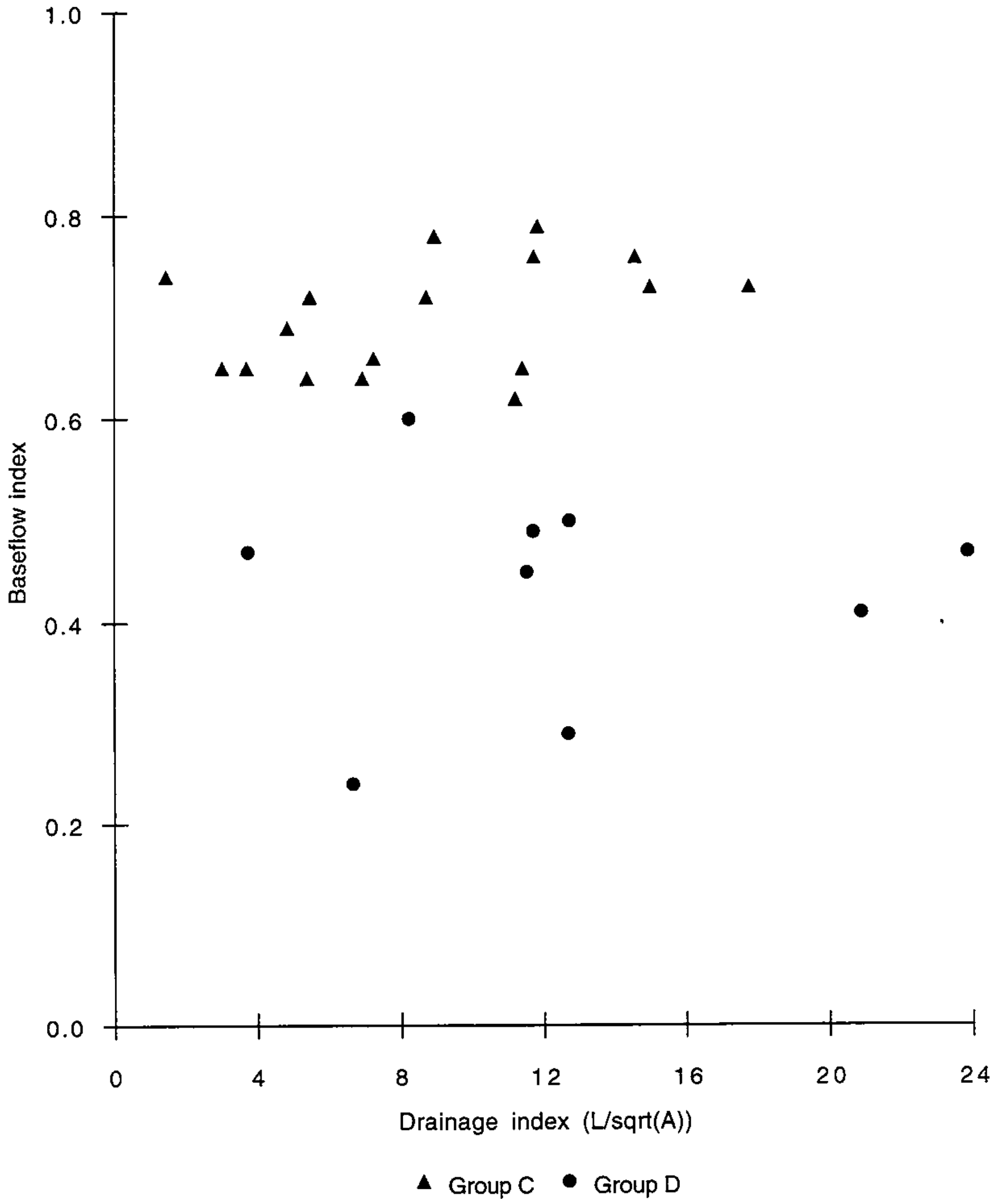


Figure 4. Baseflow index vs drainage index: Upper Ordovician catchments

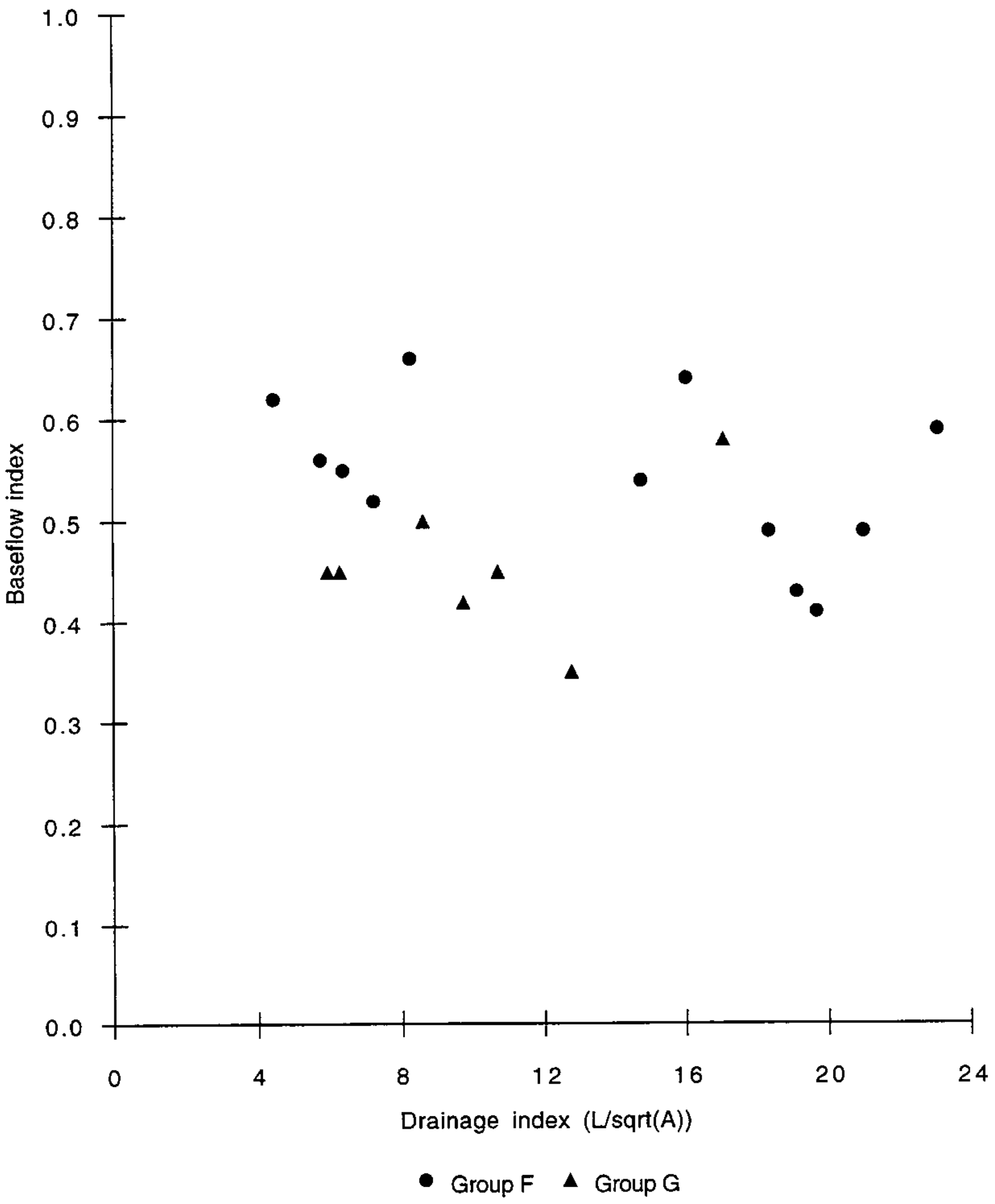


Figure 5. Baseflow index vs drainage index:
Lower Cretaceous sedimentary catchments

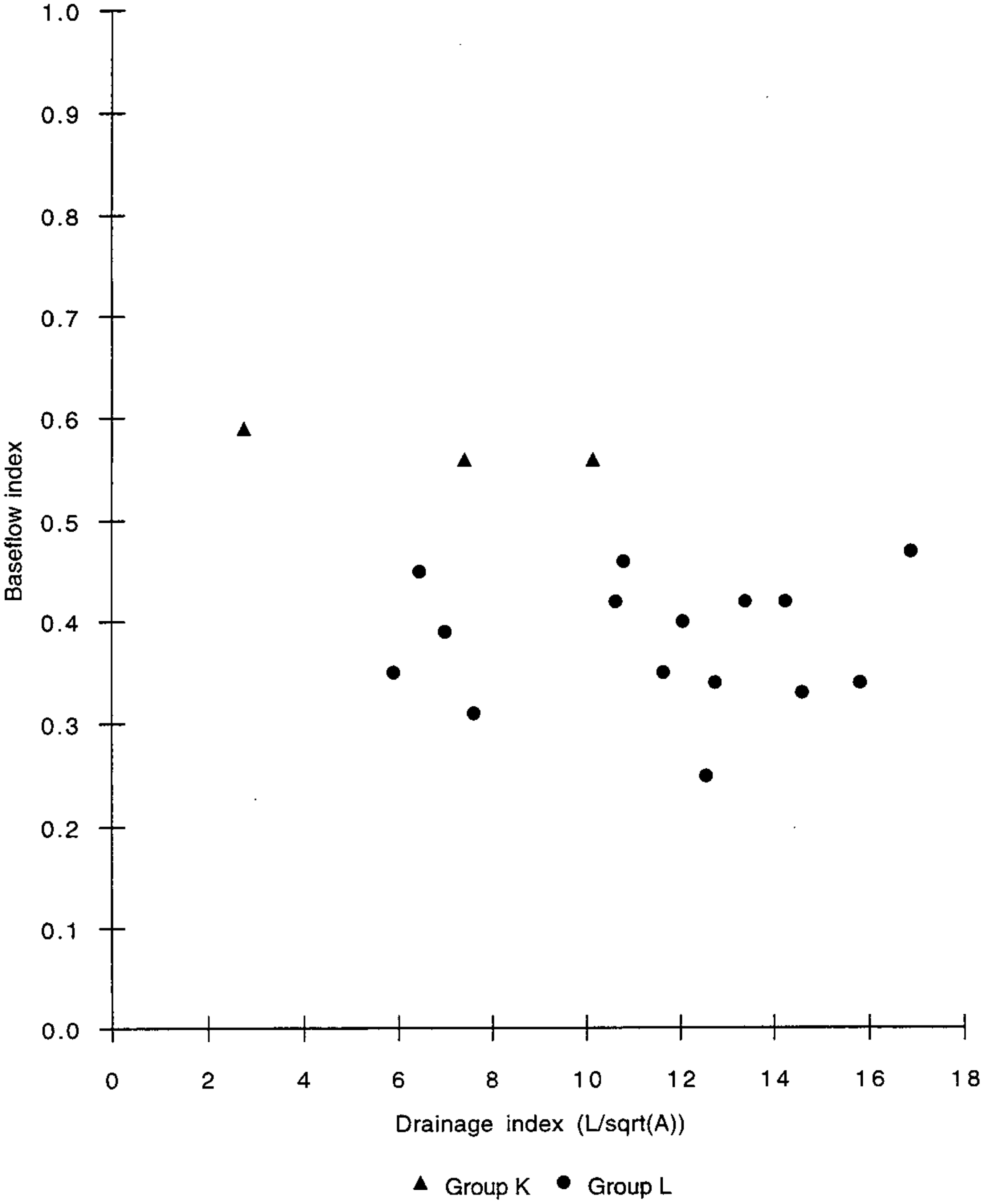


Figure 6. Baseflow index vs slope index:
rhyodacite catchments

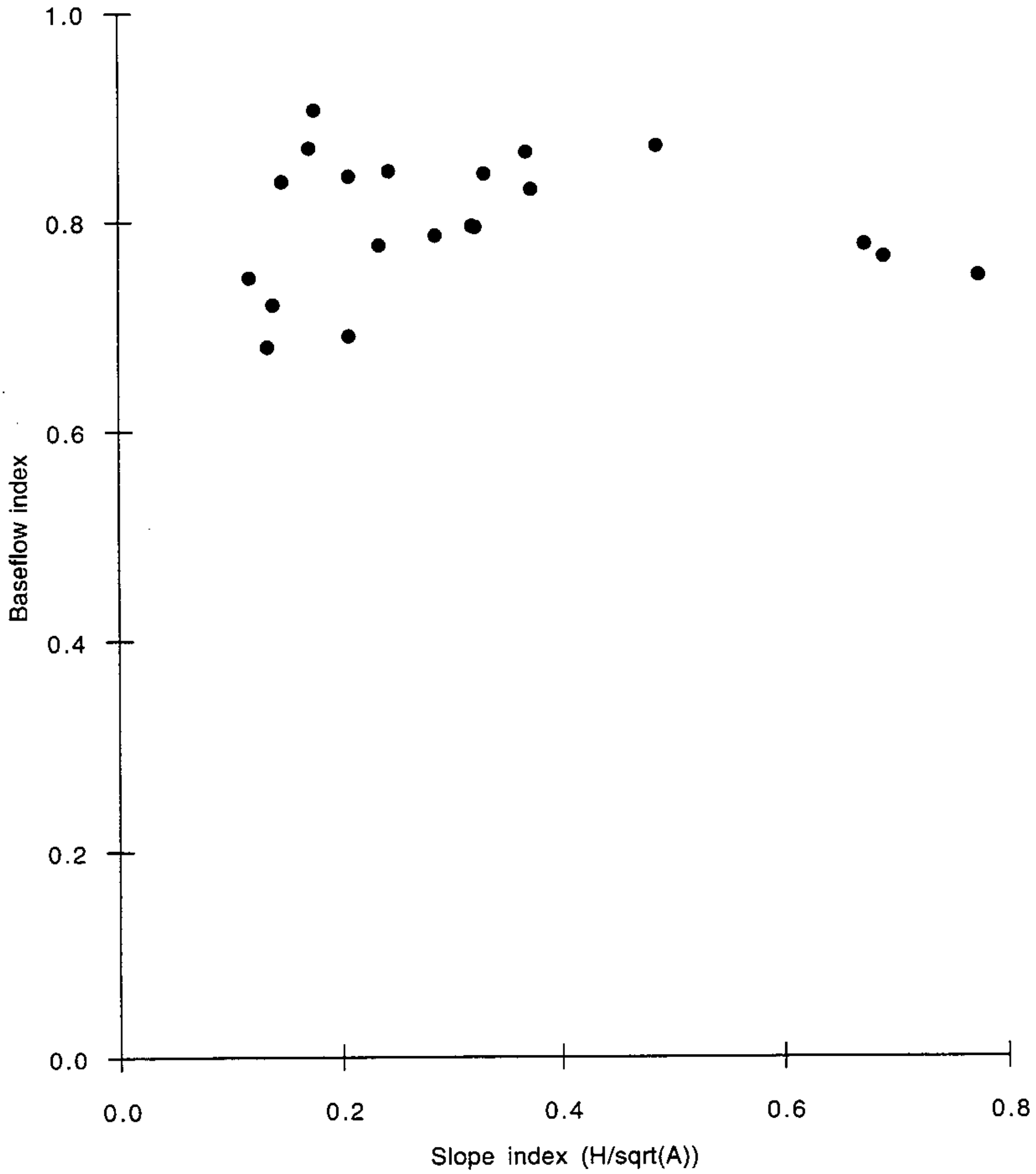


Figure 7. Baseflow index vs slope index: granite catchments

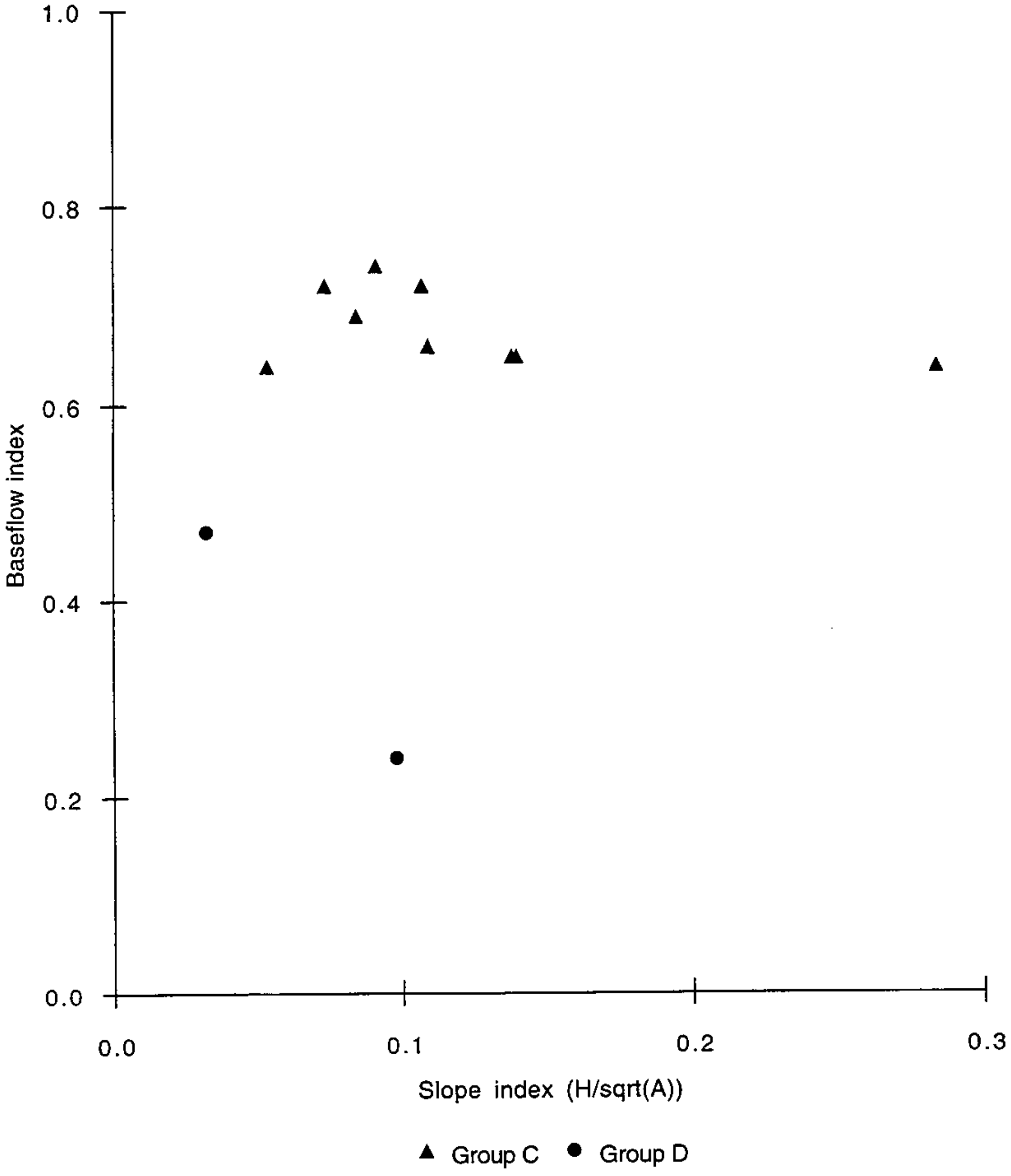


Figure 8. Baseflow index vs slope index:
Silurian/Devonian sedimentary catchments

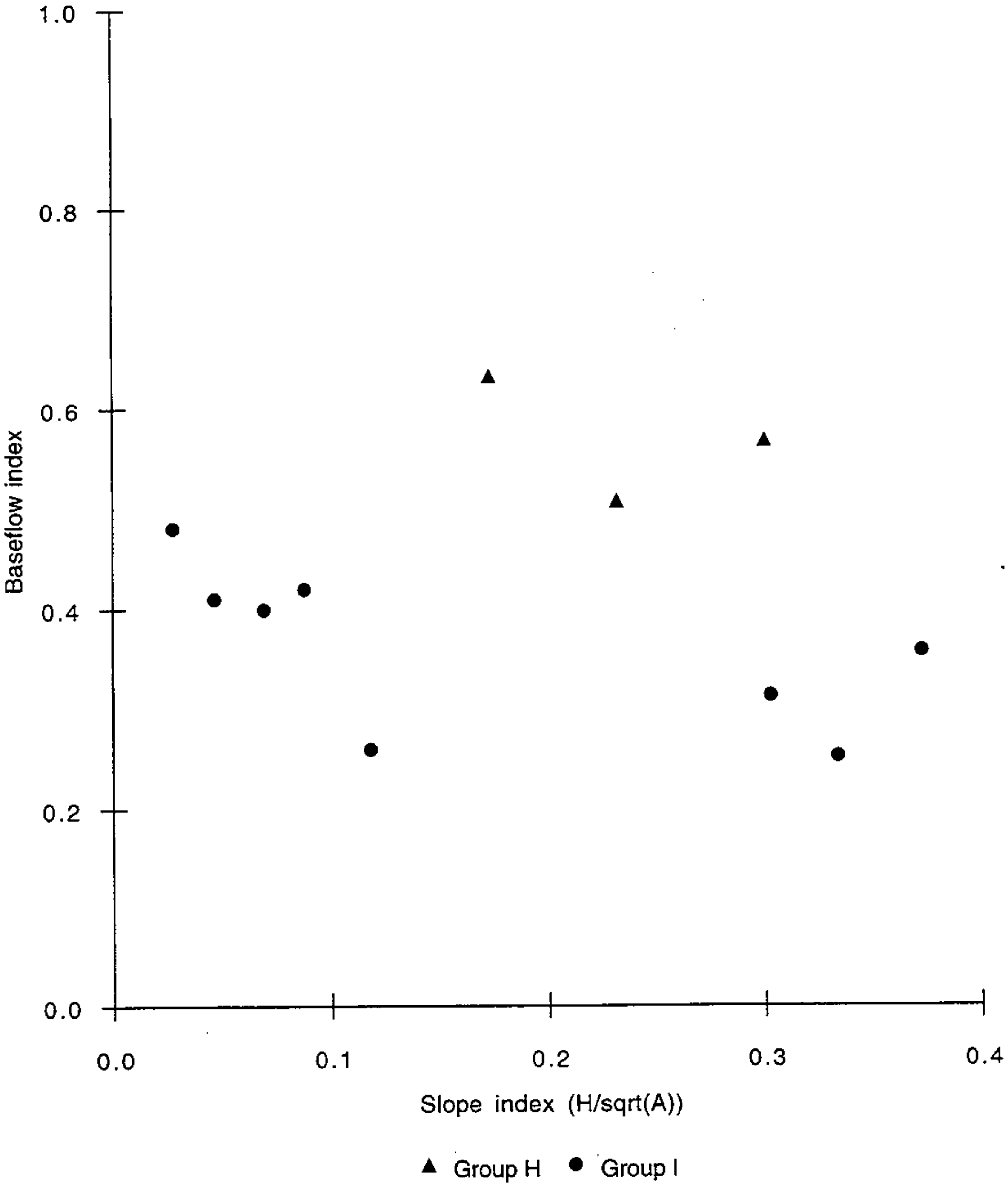
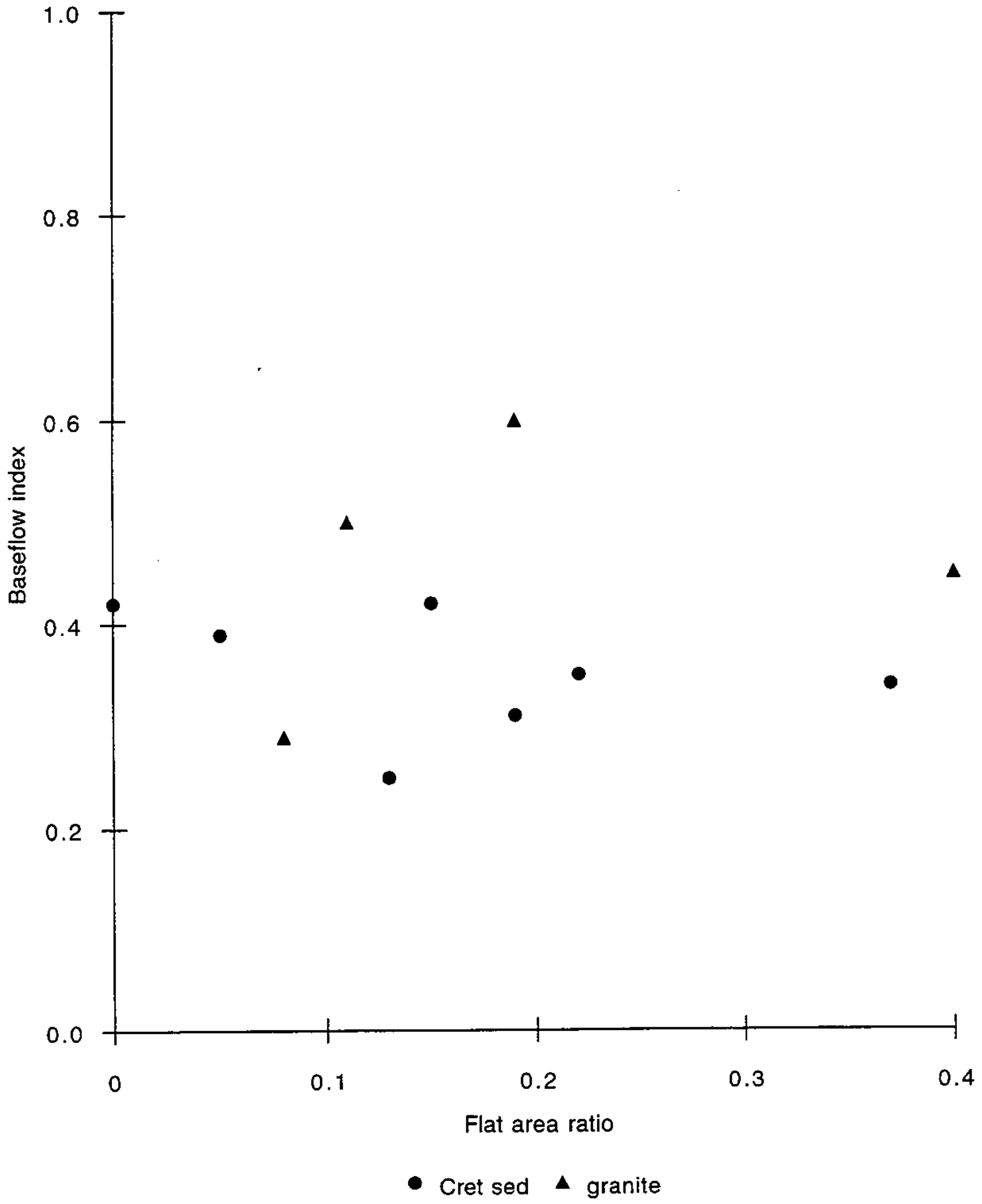


Figure 9. Baseflow index vs flat area ratio



These results indicate that topographic parameters have no discernible influence on baseflow index, within the geology-vegetation groups.

5.5 Climate

Two dimensionless parameters representing climate have been considered: (rainfall/potential evapotranspiration) and (actual evapotranspiration/rainfall). Estimates of potential evapotranspiration were obtained for most catchments from Nathan's (1995) database and for the remaining catchments from a map of average annual potential evapotranspiration in Victoria (Nathan and Pamminger 1995).

Baseflow index has been plotted against (rainfall/potential evapotranspiration) for nine of the geology-vegetation groups in Figures 10 to 14. In some cases (groups A, D, H and L) there is an apparent upward trend. However, regression analysis shows that this is significant in groups A and H only (for which $P<0.01$). Groups C, F, G, I and K show no trend. In the case of rhyodacite (group A), the Maroondah catchments (area < 2 km^2) are marked differently from the others; however, they all appear to show the same trend.

An upward trend in baseflow index with rainfall could be the result of two factors. (a) High rainfall causes saturation of more soil layers that can contribute to baseflow. (b) It has brought about a deeper weathering of bedrock over time and the formation of deeper soils. It is interesting that in group C (Figure 11) the baseflow index values fall into a narrow range in spite of the wide range of rainfall/potential evapotranspiration values. This suggests that the second factor (i.e. deeper weathering) is the more important in developing baseflow. Weathering and soil depth are already taken into account in the geology-vegetation group. This is the main catchment property determining the baseflow index. Consideration of rainfall provides an additional refinement.

Actual evapotranspiration data were obtained for the Maroondah catchments from the rainfall estimates (Section 4) and Melbourne Water total flow data; for the Reefton catchments from Wu et al. (1984); and for the majority of catchments from the MOSAZ Model Parameter File (Nathan et al. 1996). It should be noted that the evapotranspiration estimates were obtained by water balance and therefore include deep drainage losses, if any.

Figure 15 shows a plot of actual evapotranspiration against rainfall for most of the catchments. There is a very definite trend, with most of the points fitting reasonably close to a curve. The catchments on rhyodacite show considerable scatter; this variability may be due to the small size of most of these catchments compared to the others. Three points in the plot fall well below the general trend: these are Tyers R. East Branch, Tanjil R. West Branch (group C) and Kiewa R. West Branch (group F). This is because a significant amount of their precipitation is in the form of snow and therefore evapotranspiration is low. However, the baseflow index values for these catchments are within the ranges for their respective groups. Two other low points correspond to the two gauging stations on Snobs Ck (group A). These catchments also experience snow but to a lesser extent.

Given this close association between evapotranspiration and rainfall, evapotranspiration cannot be considered an independent variable. Plots of baseflow index

Figure 10. Baseflow index vs rainfall/potential evapotranspiration: rhyodacite catchments

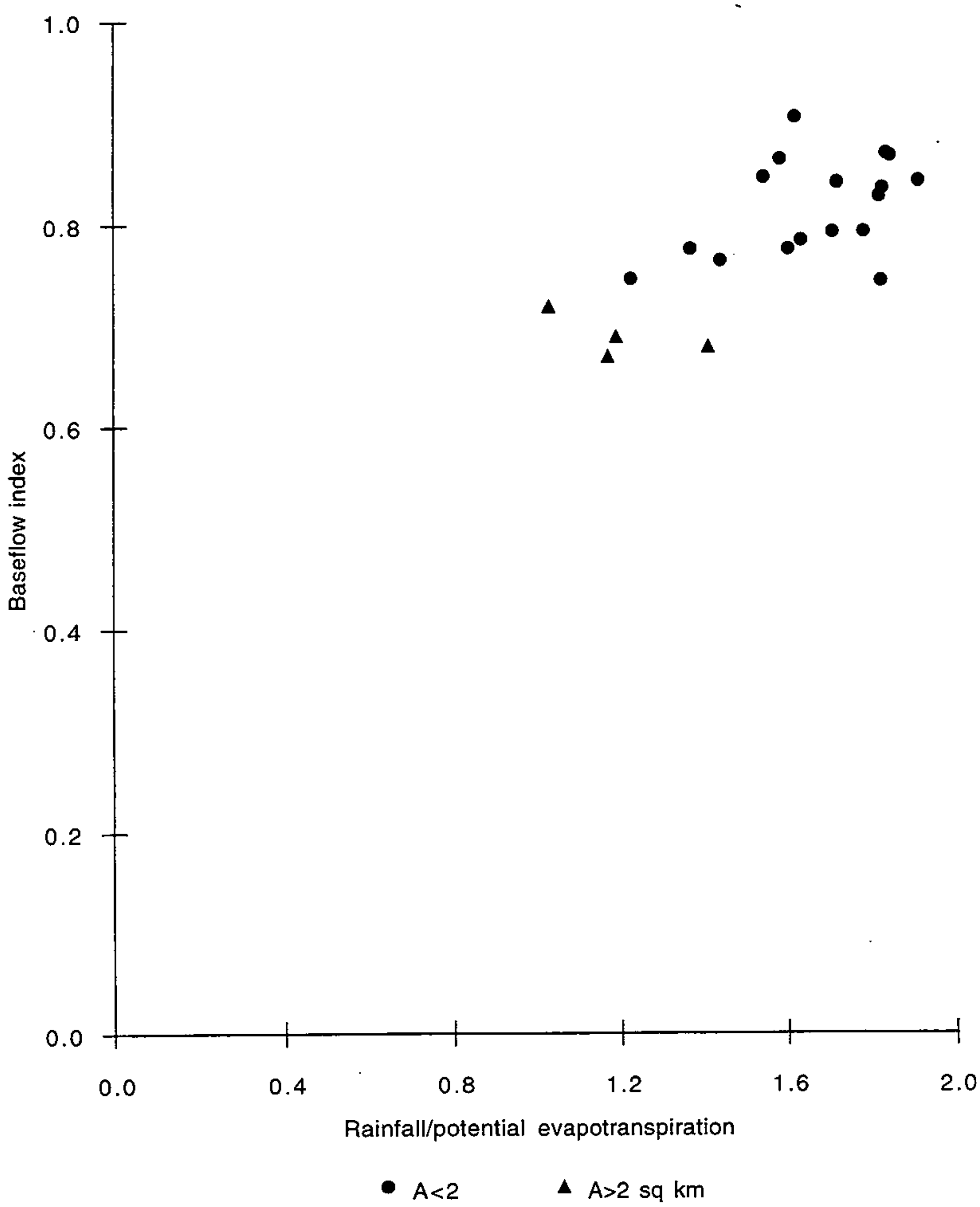


Figure11. Baseflow index vs rainfall/potential evapotranspiration: granite catchments

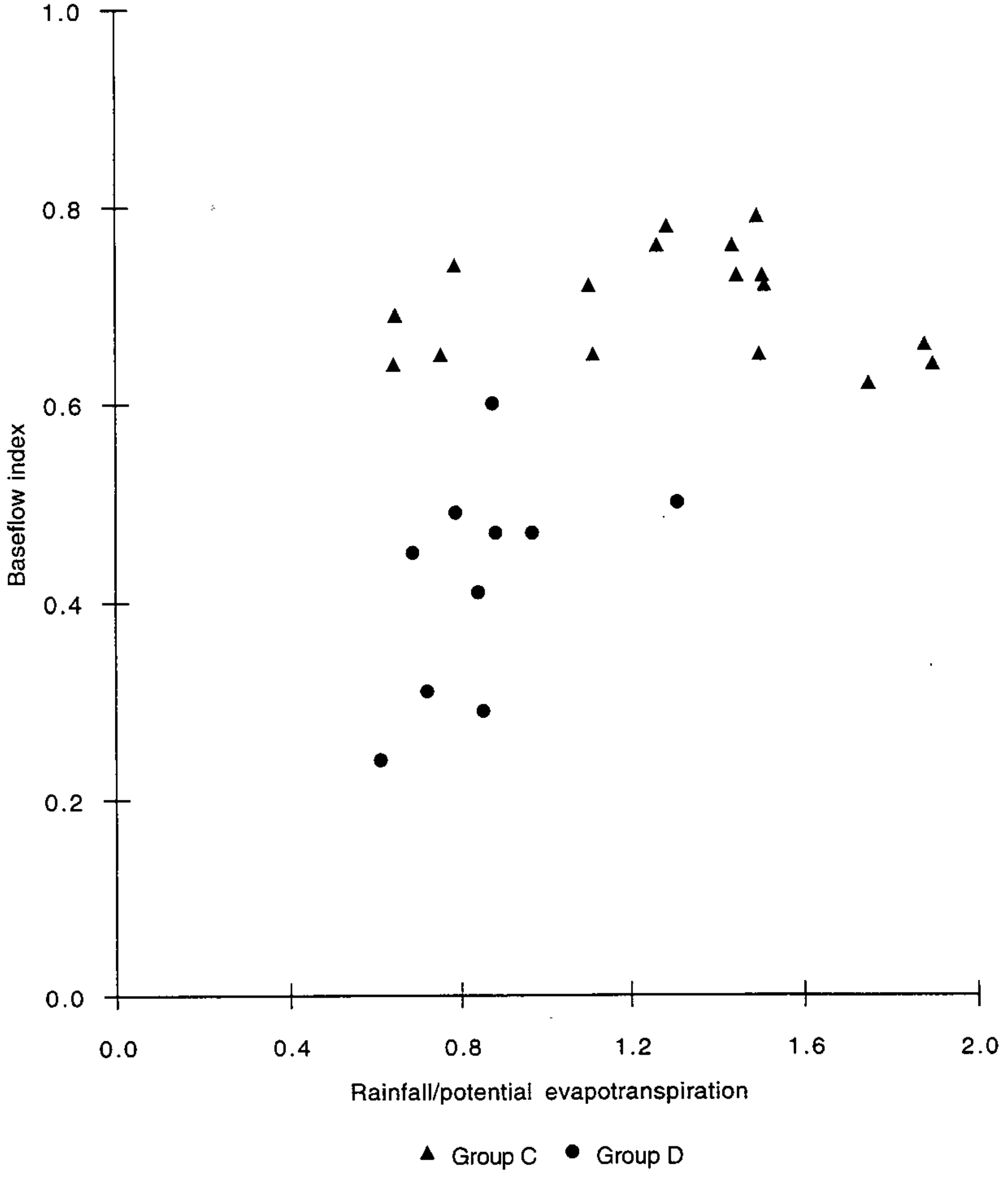


Figure 12. Baseflow index vs rainfall/potential evapotranspiration: Upper Ordovician catchments

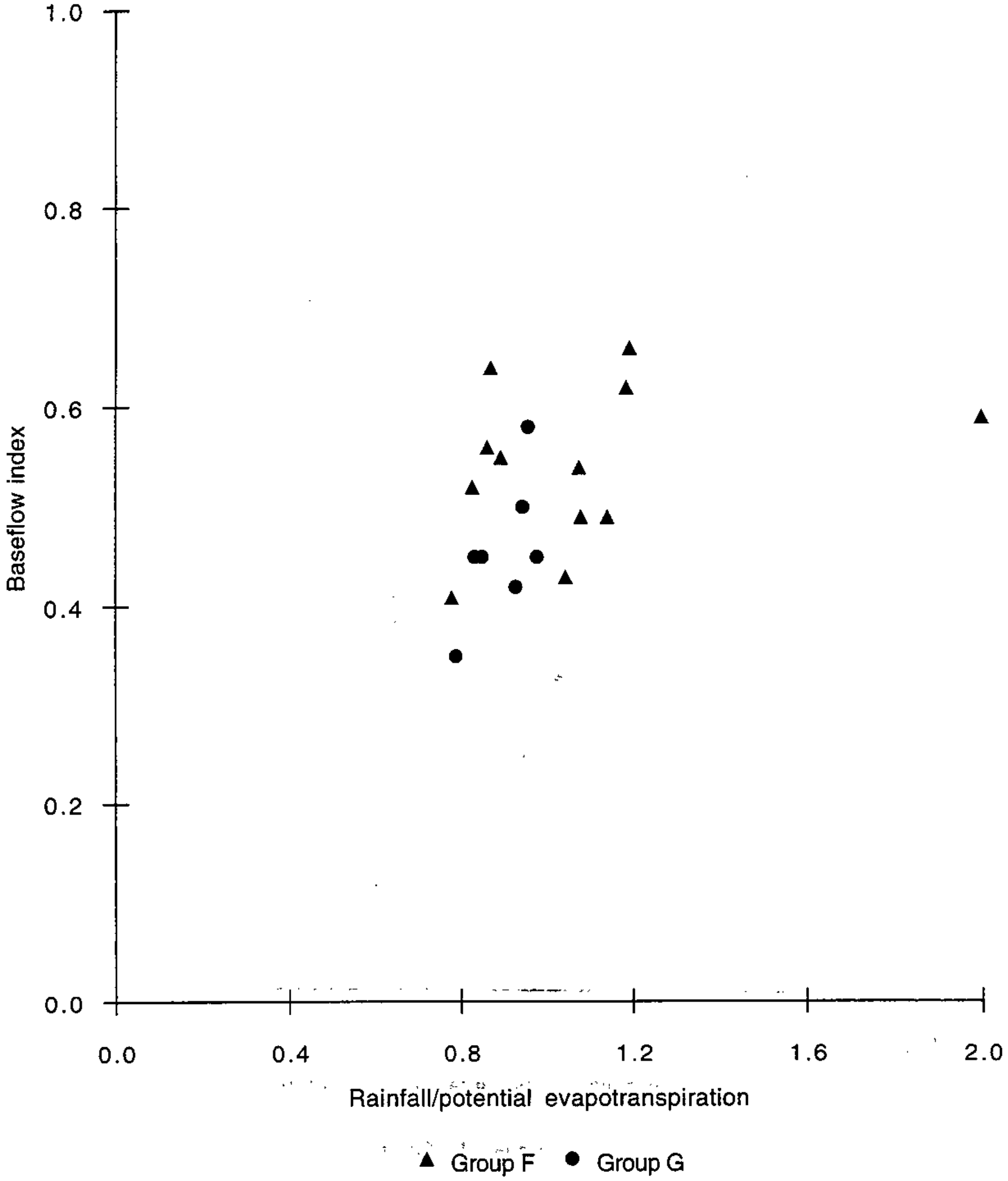


Figure 13. Baseflow index vs rainfall/potential evapotranspiration: Sililurian/Devonian sedimentary catchments

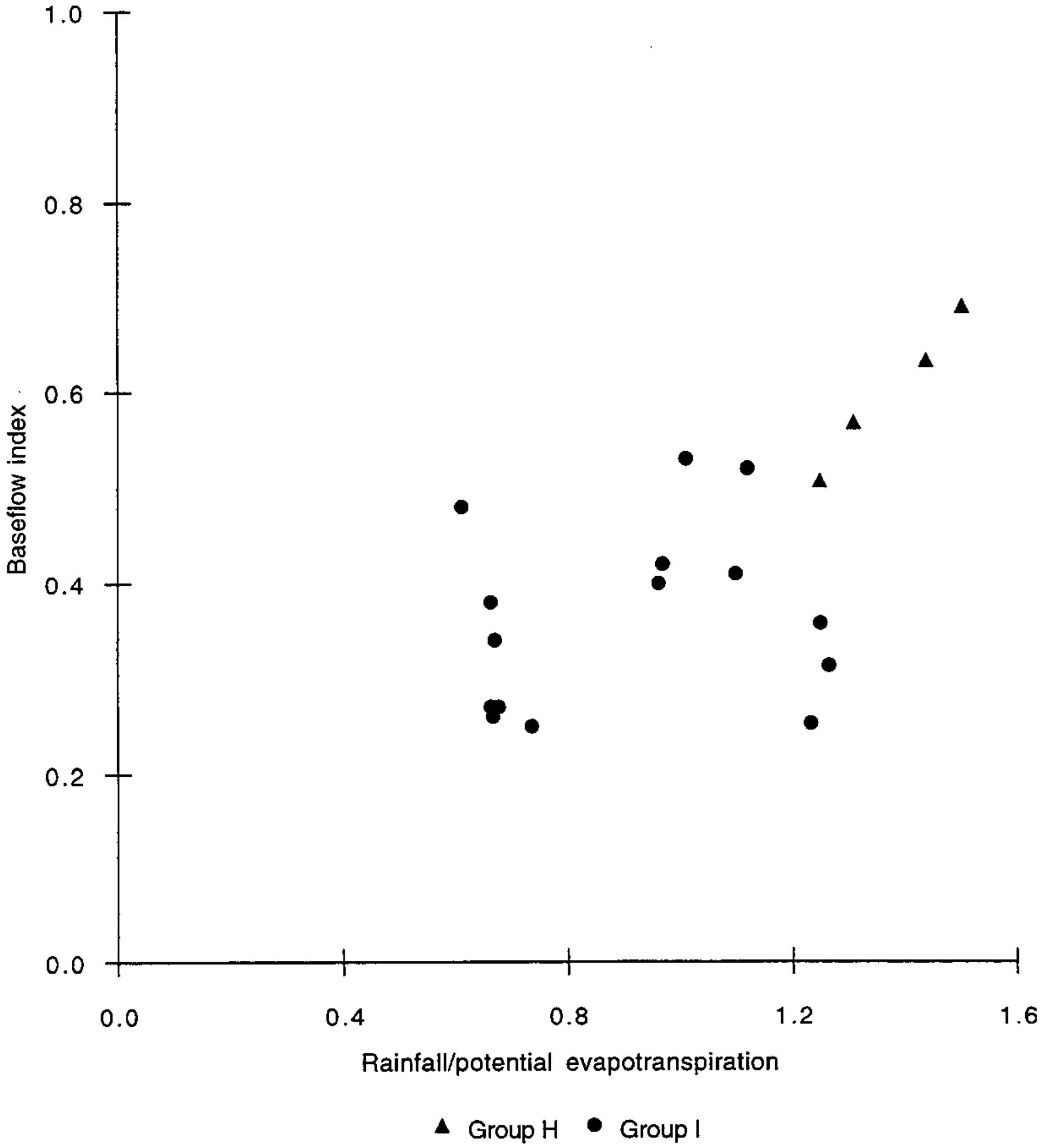


Figure 14. Baseflow index vs rainfall/potential evapotranspiration: Lower Cretaceous sedimentary catchments

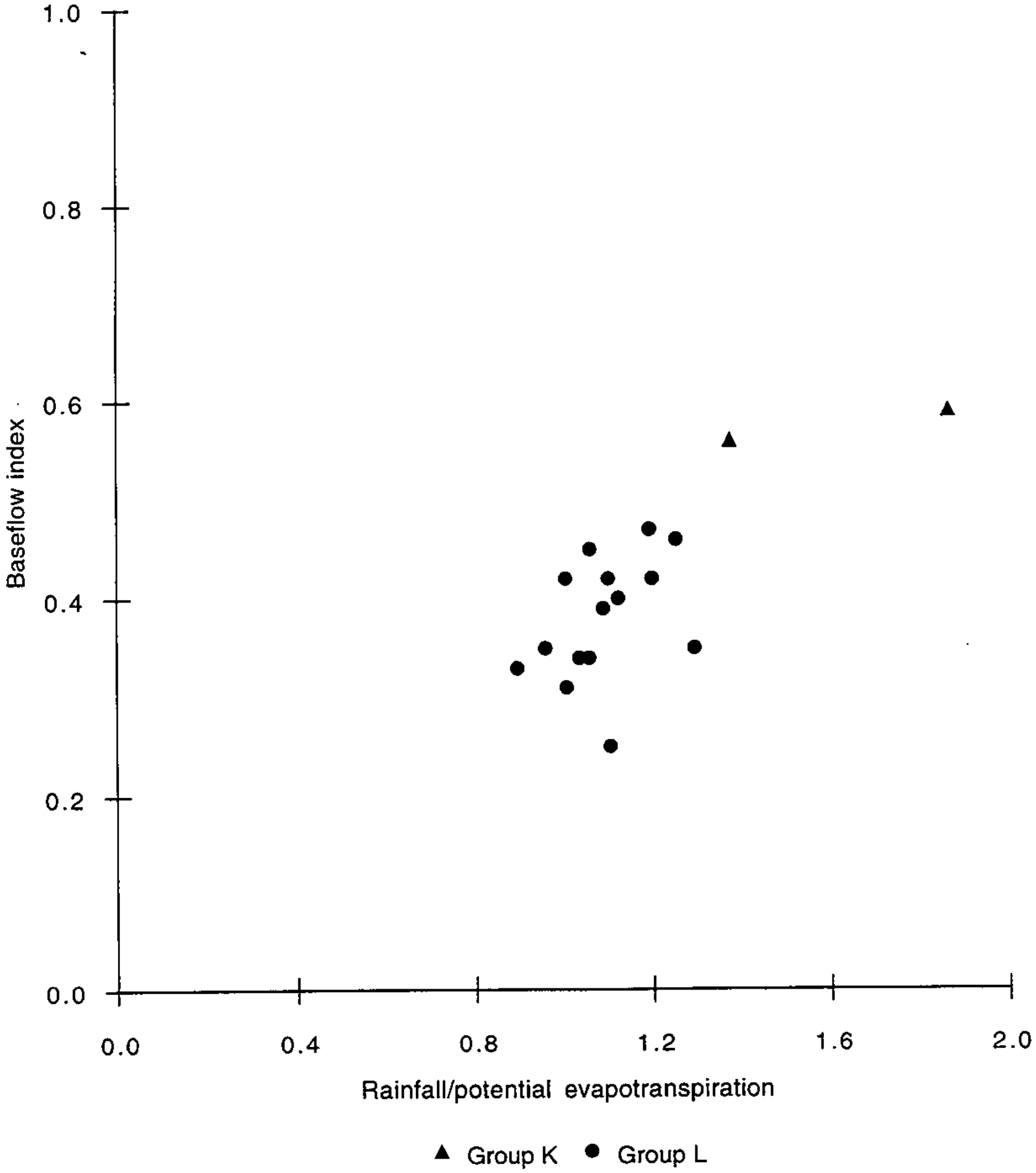
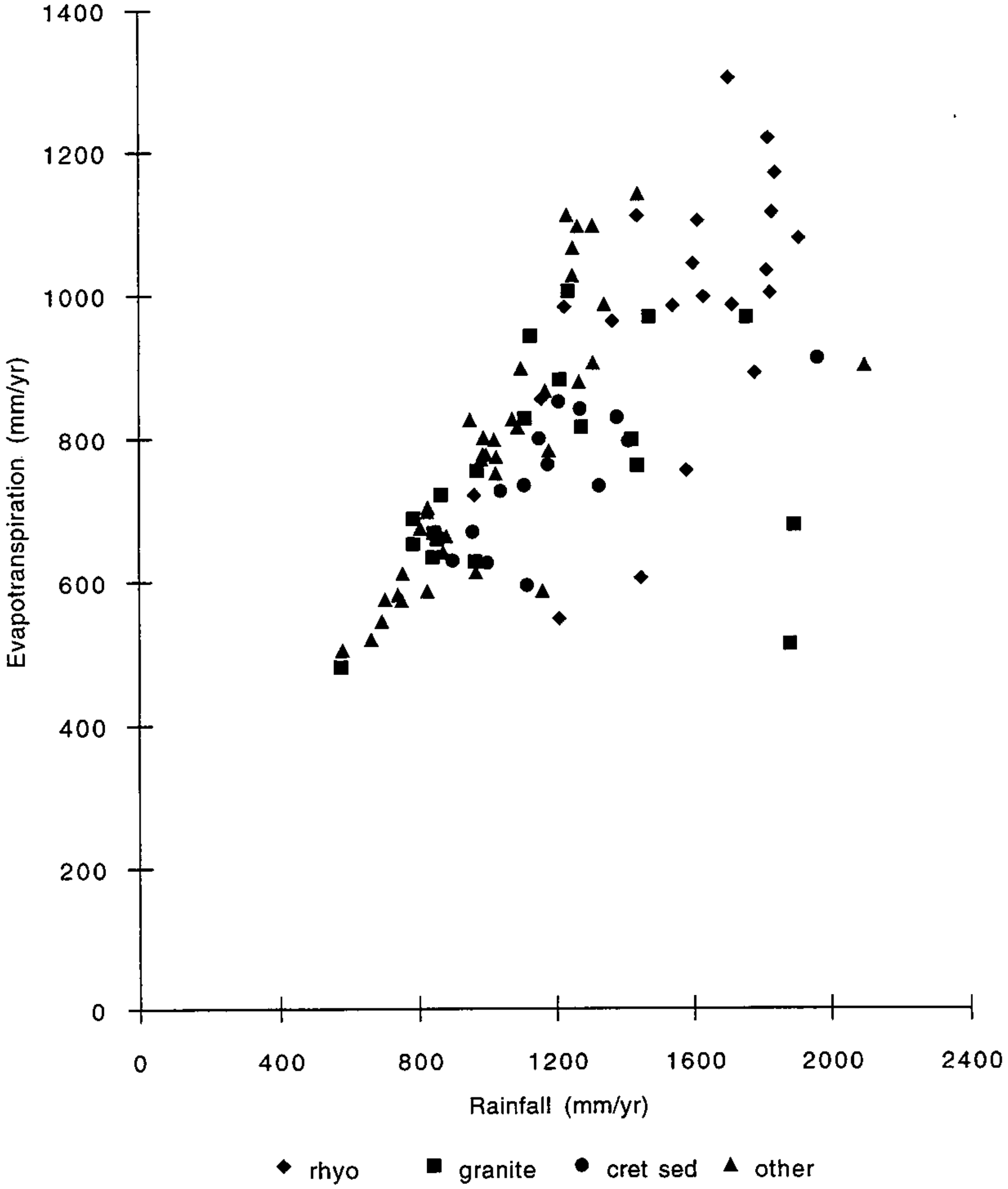


Figure 15. Evapotranspiration vs rainfall



against (evapotranspiration/rainfall) were prepared but are not shown. They have a similar form to the plots of baseflow index against (rainfall/potential evapotranspiration), except that the trends are downward rather than upward.

5.6 Forest cover

Baseflow index has been plotted against forest cover (i.e. the fraction of the catchment still under forest) for the Lower Cretaceous sedimentary catchments (groups K and L) in Figure 16. There is an apparent upward trend. This suggests that the hydrologic significance of the forest is not just related to its long-term function in forming (or responding to) the soil. It is also likely that the deep litter on the forest floor ensures that more moisture is stored in the soil and that this storage is more even throughout the year, thus giving higher baseflow.

Figure 17 shows plots of rainfall and evapotranspiration against forest cover for the same catchments. There is a slight upward trend in the case of rainfall, suggesting that on average the hills with the highest rainfall have been kept under forest. In this case the association of baseflow index with forest cover may not be independent of the trend with rainfall. There is no apparent trend of evapotranspiration with forest cover. This is very surprising, as it is usually thought that evapotranspiration is much higher in forests than in pastures.

Similar plots were done for granite catchments (group D only). However, no trends with forest cover were apparent for baseflow index, rainfall or evapotranspiration. Most catchments in the other groups have approximately full forest cover.

5.7 Forest growth stage

Picaninny Creek catchment (on rhyodacite bedrock and covered mainly with Wet Forest) was clearfelled between November 1971 and April 1972 (Langford & O'Shaughnessy 1980b). Extensive records enable us to determine the effect of the clearfelling and subsequent rapid regrowth on baseflow index. This effect is shown in Figure 18, where baseflow index, rainfall and total flow are plotted for each year from 1957 to 1990. The estimates of annual baseflow and total flow were made from Melbourne Water data and the annual rainfall estimates were done by Watson (1996).

It can be seen that there was a rapid increase in total flow immediately after the clearfelling, reaching a peak in 1974. It then rapidly decreased and after 1979 was generally lower than before 1972, presumably because of the higher evapotranspiration in the regrowth forest. There was no obvious decline in baseflow index immediately after the clearfelling. However, it dropped rapidly after 1981 and reached the very low value of 0.42 in 1983; after that it began rising again but by 1990 had not reached its 1957-90 average of 0.75. The years 1979 and 1982 experienced low rainfall and this appears to be the reason for the subsequent drop in baseflow index. A similar (but lesser) drop occurred in the plot for the nearby Slip Creek catchment (not shown), which was not logged; its lowest baseflow index value was reached in 1984. The plots therefore suggest that forest growth stage has little effect on baseflow index.

Figure 16. Baseflow index vs forest cover:
Lower Cretaceous sedimentary catchments

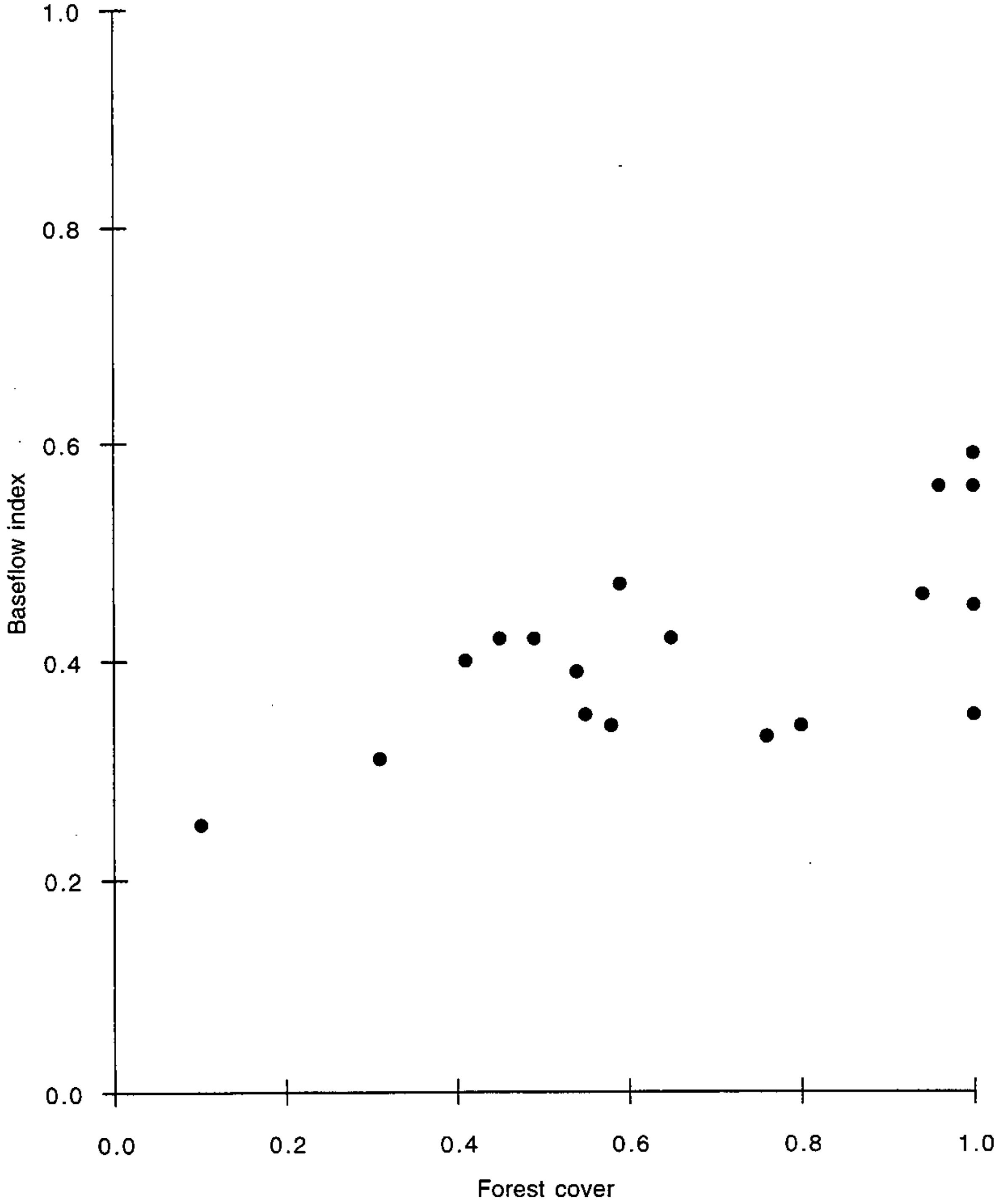


Figure 17. Rainfall and evapotranspiration vs forest cover: Lower Cretaceous sedimentary catchments

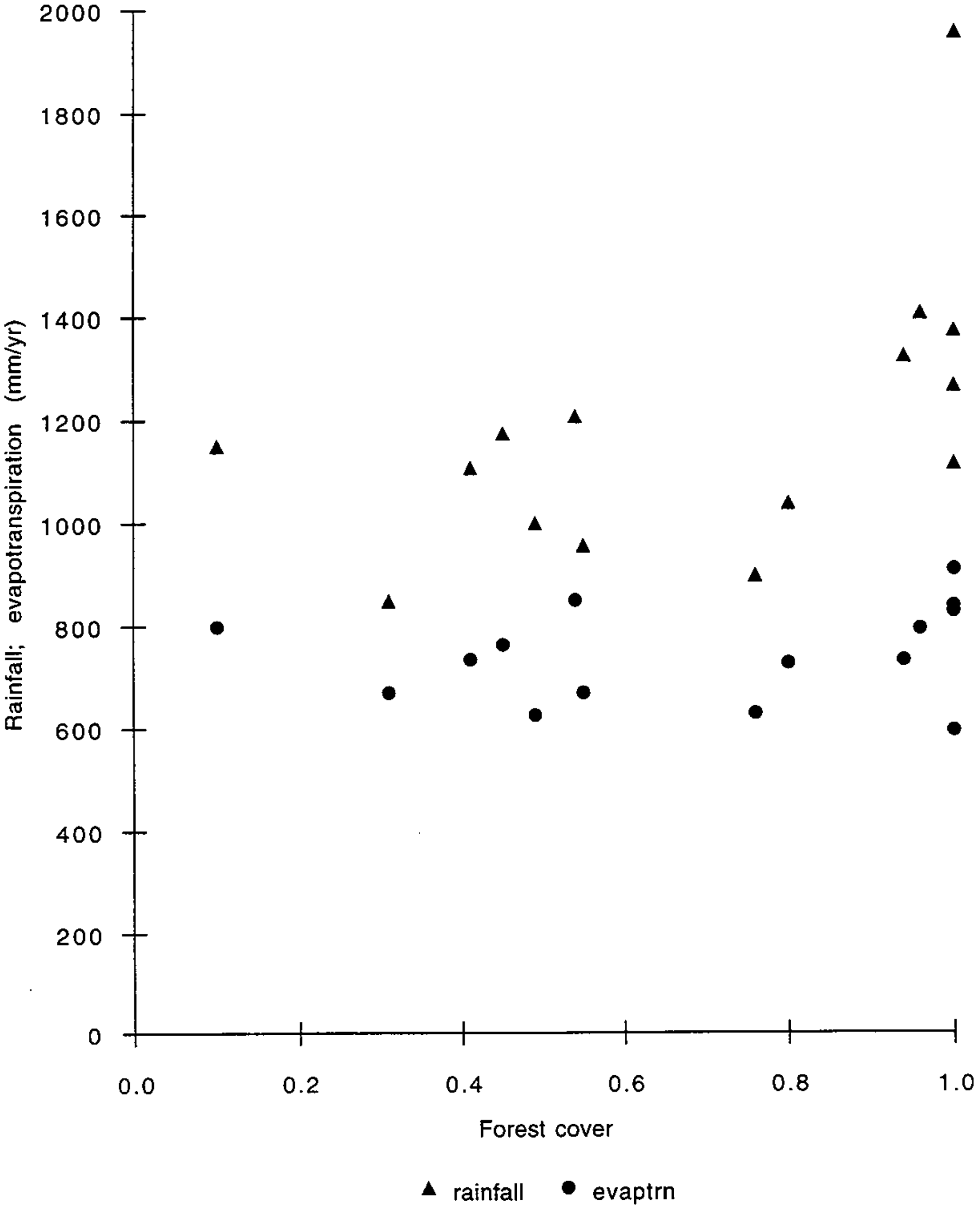
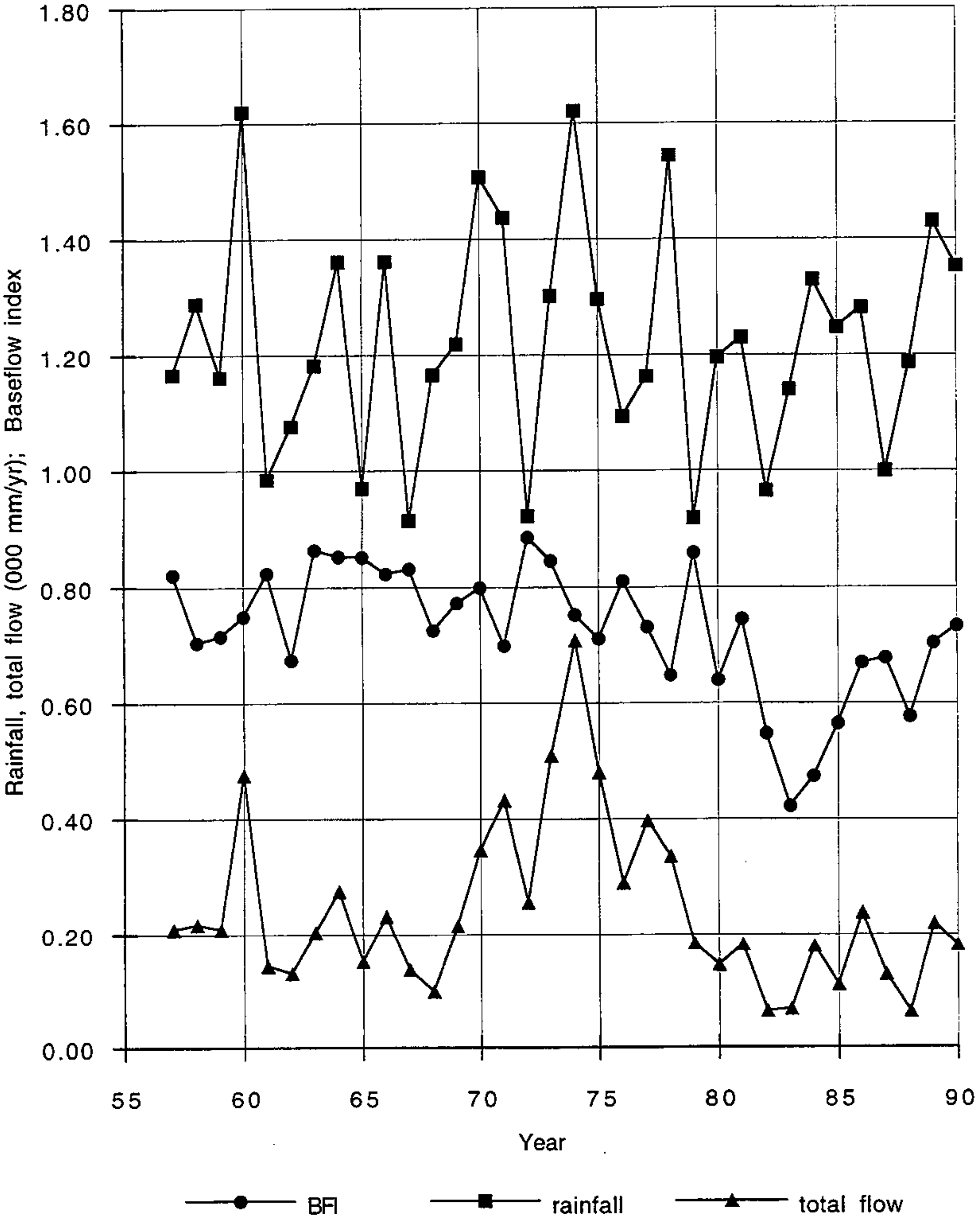


Figure 18. Effect of clearfelling: Picaninny Ck



6. BASEFLOW INDEX ESTIMATION

It has been found in the preceding sections that baseflow index is dependent mainly on the geology-vegetation group and to some extent on climate. These relationships will be examined by regression analysis. Forest cover will not be included, because a definite effect on baseflow index was demonstrated for one geology-vegetation group only, where there was also an association between forest cover and rainfall.

Since the geology-vegetation group is the most important factor determining the baseflow index (*BFI*) of the catchment, the mean value of *BFI* for the group (Table 6) can be used as an estimator of *BFI* for an ungauged catchment. A linear regression of *BFI* against the group means for the 114 catchments gives the result: $R^2 = 0.84$; standard error = 0.074 (14% of mean). (The standard error is equivalent to the average standard deviation for the groups).

To determine to what extent the scatter of *BFI* about the mean for each group can be explained by the climatic parameter, rainfall/potential evapotranspiration (*Rain/Epot*), a regression of (*BFI* - group mean *BFI*) against *Rain/Epot* has been carried out. The result is an R^2 of 0.04. The low value of R^2 shows that this parameter accounts for little of the overall scatter and there is no point including *Rain/Epot* in an estimation procedure.

6.1 Prediction in ungauged catchments

To predict *BFI* in an ungauged catchment the geology-vegetation group must first be determined. For a catchment situated essentially in a single geology-vegetation group, the predicted *BFI* can be taken as the mean *BFI* given in Table 6 for the appropriate group. These values are summarised in Table 8.

In catchments that comprise more than one geology-vegetation group, there are two alternative approaches. If one geology-vegetation group dominates, we can proceed as if the catchment is entirely in that group. If one group does not dominate (and especially when there are branching sub-catchments) a weighted average value of group means should be used. This procedure needs to be tested with data from

Table 8. Baseflow index prediction values

Geology-vegetation group	Baseflow index	Geology-vegetation group	Baseflow index
A	0.79	G	0.46
B	0.66	H	0.60
C	0.70	I	0.36
D	0.42	J	0.33
E	0.44	K	0.57
F	0.54	L	0.38

catchments with mixed groups. If the different rock types correspond to different elevations in the catchment the weighting should not be based just on the proportional area of each group, because rainfall and hence recharge are generally much higher on the higher elevations. Further research is required to develop a procedure for such difficult cases.

This method of prediction of baseflow index is flexible. Table 8 can be updated at any time if additional data becomes available, altering the mean values of baseflow index in the geology-vegetation groups.

Often an estimate of average annual baseflow will be required by catchment managers, in addition to baseflow index. Suggestions have been made to analyse either (baseflow/rainfall) or average baseflow instead of baseflow index. However, when these two variables are plotted against the geology-vegetation groups, the points do not fall into narrow bands. So it is necessary to obtain average annual baseflow in two steps: (a) Average annual total flow is estimated by one of the many regionalisation procedures available, for example that of Nathan and McMahon (1991). (b) This is multiplied by baseflow index to give average annual baseflow.

7. COMPARISON WITH OTHER STUDIES

7.1 A Victorian study of baseflow index

Nathan et al. (1996) have carried out a regression analysis for baseflow index in terms of a number of catchment properties for 164 catchments in Victoria. 91 of these catchments are also used in the present study; most of the others are greater than 200 km^2 in area. The resulting prediction equation is:

$$\begin{aligned} BFI = {} & 0.6168 + 0.000054 Area + 0.000192 Elev - 0.000448 Epot + \\ & 0.1222 Forest - 0.125 G2 + 0.000233 Rain - 0.001268 Length \end{aligned}$$

($R^2 = 0.72$; standard error = 19%)

where $Area$ = catchment area (km^2);
$Elev$ = elevation of catchment centroid (m);
$Epot$ = potential evapotranspiration (mm/yr);
$Forest$ = fraction covered by forest;
$G2$ = fraction on sedimentary rock;
$Rain$ = rainfall (mm/yr);
$Length$ = length of mainstream (km).

The equation shows positive effects of rainfall and forest cover on baseflow index, as were found in the present study. The positive effects of rainfall and elevation also reflect the fact that the ecological vegetation classes that give higher baseflow index are found on average in areas of higher rainfall and at higher elevations. The presence of sedimentary rock has a negative effect. The present study has also found that sedimentary rocks give on average a lower baseflow index than igneous rocks. The presence of *Area* and *Length* in the equation suggest a scale effect. It is difficult to make further comparisons between the two studies, because the variables used are different and because Nathan's investigation includes dimensional variables, a greater number of catchments and a much greater range of catchment areas.

7.2 U.S. and New Zealand low flow studies

Some U.S. studies found a relationship between baseflow and topographic parameters. Zecharias and Brutsaert (1988) found that groundwater discharge in a set of Appalachian catchments is significantly influenced by drainage density (L/A) and by 'average basin slope' (HL/A). A study by Vogel and Kroll (1990) on streams in Massachussets found that catchment relief (H) had an effect on annual minimum low flow values. In a further study (Vogel and Kroll 1992), they found that the low-flow statistic $Q_{7,10}$ (the annual minimum 7-day average daily streamflow which occurs on average no more than once every 10 years) is a function of average basin slope.

However, these were not scaling investigations involving baseflow index and dimensionless parameters (except for average slope which is equal to the product of slope index and drainage index), and cannot be directly compared with the present study. It is also possible that variation in the topographic parameters was associated with different geological and soil conditions.

Hutchinson (1990) describes a New Zealand study in which specific 5-year 7-day low flow ($SQ57$) is considered a function of rainfall, areally weighted slope, and variables expressing the catchment proportions of eight hydrogeology classes (See Section 3.1). Several regional equations were developed for $SQ57$ by multiple regression. The dominant variables were found to differ from one region to another, with hydrogeology being very important in nearly all cases.

7.3 European studies

The Institute of Hydrology (Gustard et al. 1989) studied the relationship between low flow indices and several catchment characteristics in the U.K. and Ireland. They developed a composite 'SOIL' index derived from a combination of the proportions of five 'WRAP soil classes' (Section 3.1) in each catchment, by means of a regression of baseflow index with the WRAP classes. A correlation matrix showed that, among the catchment characteristics, baseflow index had the strongest relationship with SOIL, followed by rainfall.

In a later study (Gustard 1993), baseflow index data for nearly 800 catchments in Great Britain were analysed as a function of 9 (Commission of the European Community) 'SOIL classes' and also as a function of 12 'Low Flow HOST Groups' (described in Section 3.1). For each SOIL class, the mean baseflow index value was calculated; then a weighted SOIL index value was derived for each catchment according to the percentage cover of each class. The same was done with the Low Flow HOST Groups. Baseflow index was regressed against each of the two indices, with the results shown in Table 9.

The study suggested that the Low Flow HOST Groups gave the better results because they were based on physical properties for one country. Finding a satisfactory common system for a wider area (North-Western Europe) is more

Table 9. Comparison of estimation procedures for baseflow index in Britain

	R^2	Std error
9 SOIL classes	0.62	0.11
12 Low Flow HOST Groups	0.67	0.11

difficult. This suggests that in developing prediction methods it is more appropriate to work on a relatively small regional scale. The New Zealand and European studies confirm the primary importance of geology and soils in determining low flow behaviour, as was found in the present study.

8. CONCLUSION

This paper has examined 114 catchments in Victoria, with a range of areas up to 192 km^2. It has evaluated the influence of a geology-vegetation index and a number of dimensionless catchment properties (three topographic indices, two climatic indices, forest cover and forest growth stage) on baseflow index.

The geology-vegetation index was developed to represent catchment geology and soils. It comprises 12 groups, based on geology and ecological vegetation class. The indigenous vegetation community of the catchment is used, in combination with geology, as an indicator of soil state.

A statistical analysis has been carried out and a procedure for the estimation of baseflow index in ungauged catchments developed. Comparisons have been made with other studies.

8.1 Particular conclusions

(1) Baseflow index is an appropriate dimensionless quantity for the scaling of baseflow. It has a strong relationship with the geology-vegetation index, a measure of the transmissivity of the rocks and soils. Within some geology-vegetation groups baseflow index has a weak relationship with the climatic parameter, rainfall/ potential evapotranspiration. Within the groups, baseflow index is independent of the three topographic parameters: slope index, drainage index and flat area ratio.

(2) There appears to be no scale effect with catchment size up to an area of 100 km^2. The baseflow behaviour of all catchments examined in this range is evidently governed by the same physical processes. The evidence is inconclusive as to whether or not there is a scale effect outside this range.

(3) To estimate baseflow index in an ungauged catchment the geology-vegetation group must be determined, and the predicted baseflow index can be taken as the mean value given in Table 8 for the appropriate group. Regression analysis has

shown that the additional use of the climatic parameter, rainfall/potential evapotranspiration, in prediction is not warranted.

In catchments comprising more than one geology-vegetation group, there are two alternative approaches. If one geology-vegetation group dominates, we can proceed as if the catchment is entirely in that group. If one group does not dominate a weighted average value of group means should be used. This procedure needs to be tested with data from catchments with mixed groups.

Table 8 should not be used outside the geographical area in which it was developed. There is no evidence from this study or from the other studies examined that a universal procedure can be formulated. However, the same methodology can be applied to data in other regions.

(4) The use of the indigenous vegetation community, in combination with geology, as an indicator of soil state has been successful, and it demonstrates the usefulness of the concept of ecological indicators. It also shows the value of an interdisciplinary approach in which the insights of hydrology, geology, soil science and ecology are combined. The new system of ecological vegetation classes, developed in the Department of Natural Resources and Environment (Victoria), has greatly facilitated the systematic development of the geology-vegetation index.

(5) The rock types that tend to give high baseflow are rhyodacite, Tertiary basalt, granite and Upper Ordovician sedimentary. In some cases this is due to the fracturing and weathering of the rock; in others the soil formed from the rock is more important. If the baseflow contribution comes mainly from the rock (e. g. Upper Ordovician sedimentary), there is little difference between the baseflow index values for wetter and drier ecosystems; if the main contribution comes from the soil, there is a big difference (e. g. with granite).

While sedimentary rocks generally give lower baseflow index values, the Upper Ordovician sedimentary rock in the Kiewa and Ovens basins is a notable exception. The values are much higher than those for Lower Ordovician in the western half of Victoria. This is because of the much higher hydraulic transmissivity in the rocks of the former region, the result of a history of fracturing and deep weathering.

(6) There is a positive relationship between baseflow index and forest cover for the Lower Cretaceous sedimentary catchments. However, these also show a positive relationship between rainfall and forest cover. No trend could be found in the case of the drier granite catchments. Catchments in most other groups have approximately full forest cover and so no overall conclusions can be drawn about this effect.

(7) There is no evidence that baseflow index is affected by forest growth stage. Examination of annual trends in Picaninny Creek catchment showed that, although there was a considerable change in total flow, there was no obvious decline in baseflow index immediately after clearfelling in 1972. There was a big drop in baseflow index about ten years later, the values gradually returning to normal in the following years. Comparison with the nearby Slip Creek catchment, which was not logged, suggests that this was the effect of low rainfall and not of the clearfelling .

8.2 Recommendations

(1) The methodology described in this report should be applied to a much larger number of catchments in Victoria. These should include catchments of mixed geology-vegetation groups and those with areas greater than 200 km^2. The mean baseflow index values in Table 6 would be upgraded and the trends shown in Figure 1 tested for such catchments. The behaviour of very flat catchments should also be investigated.

Further research is required to develop a prediction procedure for catchments where one geology-vegetation group does not dominate and the different rock types correspond to different elevations.

(2) Similar studies should be done in other parts of Australia, in particular to check the effect of geology-vegetation on baseflow index and the absence of topographic effects. The geology-vegetation groups would, in general, be different from in Victoria.

(3) The mapping of ecological vegetation classes in Victoria by the Department of Natural Resources and Environment has not yet been completed. It is important to keep in touch with this work and to fill out the descriptions of the geology-vegetation groups.

(4) Results of any new soil surveys in the catchments should be examined to see if soil profile distributions account for the variation in baseflow index within some of the geology-vegetation groups, for example the drier granite catchments, which have a relatively wide spread of baseflow index values.

(5) The effect of the seasonal rainfall pattern on baseflow index should be studied. One method of exploring this would be to use a parameter of the type: (rainfall in peak 3 months/total annual rainfall). As the seasonal patterns for most of the catchments in Victoria are fairly similar, it would be necessary to look at a much wider area.

(6) The relevance of the methodology and results of this study to other Cooperative Research Centre projects should be examined. Hill et al. (1996) are already using the geology-vegetation groups in the development of prediction equations for losses in design flood estimation. Another possible application is in the Salinity Project, which will examine salt loads from upland catchments to the Murray River. Generally, baseflow and quickflow have different salt concentrations. The forecasting of salinity and baseflow both require detailed understanding of the relationships among groundwater, geology, soils and vegetation.

NOTATION

A	catchment area.
BFI	baseflow index.
$Epot$	potential evapotranspiration.
H	catchment relief (difference between highest and lowest elevations).
$H / \sqrt{A}$	slope index.
L	total length of stream network.
$L / \sqrt{A}$	drainage index.
$Rain$	rainfall.
T	time.

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