Institute of Freshwater Ecology

THE EFFECTS OF SOIL TYPE ON NUTRIENT LOSSES AND RUNOFF IN THE CATCHMENT OF BASSENTHWAITE LAKE

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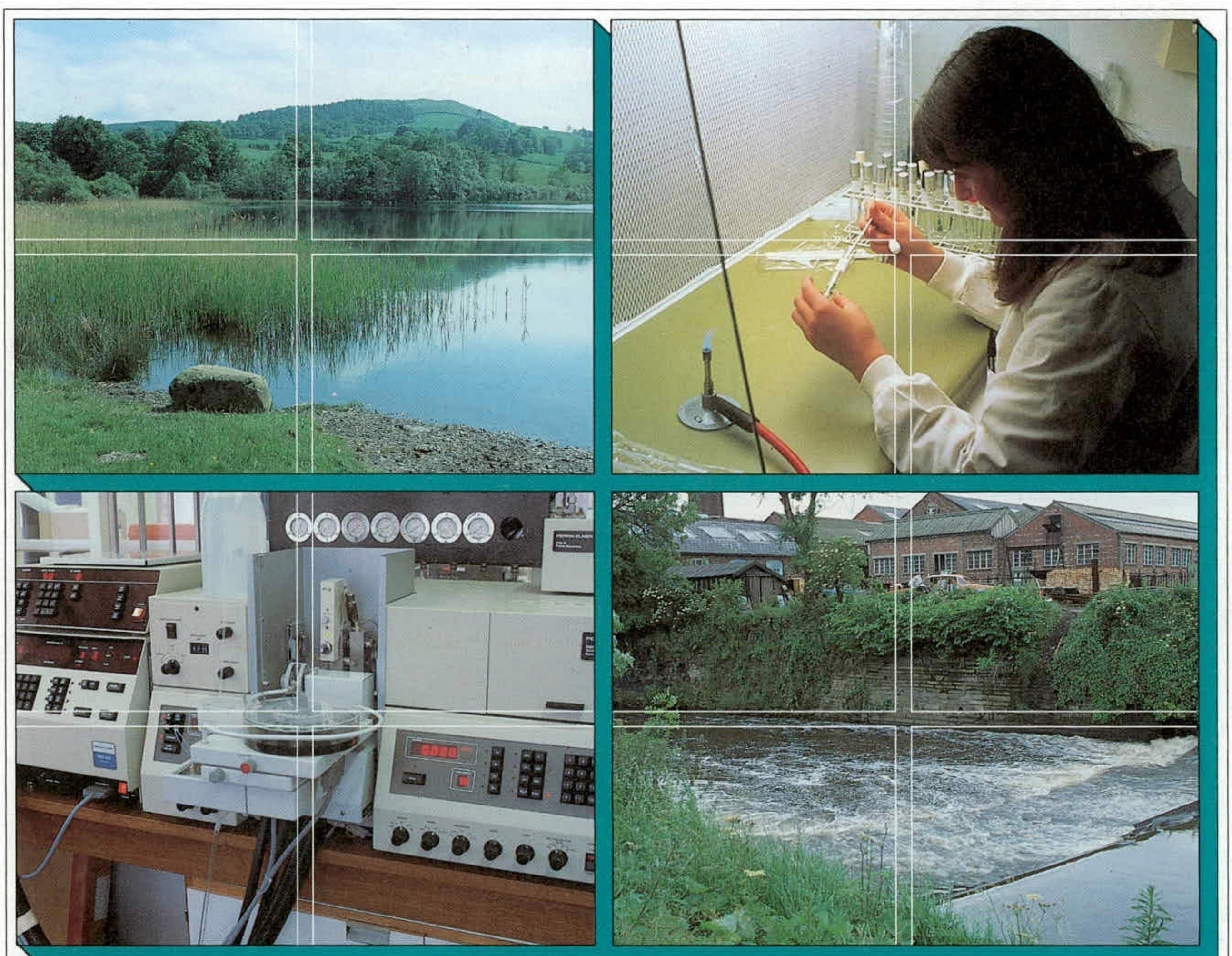
Report to National Rivers Authority, North West Region (March 1996)



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ABBREVIATIONS

$\rho_{vsat}(T_k)$	saturation absolute humidity at T°K
API	Antecedent Precipitation Index
API_{30}	30-day Antedent Precipitation Index
API_5	5-day Antecedent Precipitation Index
ASCII	American Standard Code for Information Interchange
a_x	fraction of the catchment area which has soil of HOST class x
CWI	Catchment Wetness Index
D	daylength
DPR_{CWI}	dynamic percentage runoff term relating to catchment wetness
DPR_P	dynamic percentage runoff term dependent on event rainfall
ESRI	Environmental Systems Research Institute
GIS	Geographical Information System
HOST	Hydrology of Soil Types
IFE	Institute of Freshwater Ecology
IH	Institute of Hydrology
LDNPA	Lake District National Parks Authority
MLURI	Macaulay Land Use Research Institute
NERC	Natural Environment Research Council
OP	orthophosphate
OS	Ordnance Survey
P	precipitation
PAT	polygon attribute table
PET_H	potential evapotranspiration
PR_{RURAL}	percentage runoff in a rural catchment
r^2	coefficient of determination
SMD	Soil Moisture Deficit
SOIL	soil index
SPR	standard percentage runoff
SSEW	Soil Survey of England and Wales
SSLRC	Soil Survey and Land Research Centre
SSSI	Site of Special Scientific Interest
STW	sewage treatment works
T_c	air temperature (°C)
T_k	air temperature (°K)
TP	total phosphorus
WRAP	winter rainfall acceptance potential
$WRAP_n$	proportion of the total catchment area in WRAP class n

SUMMARY

The spatially referenced dataset created within a Geographical Information System (GIS) by May *et al.* (1995) has been extended to include information on soils within the catchment of Bassenthwaite Lake. Fifteen different soil series were found within the catchment boundary. These were used in their entirety for the rainfall-runoff calculations, but were grouped into 10 summary soil types, based on their dominant soil subgroup, for the total phosphorus (TP) export calculations.

Three main soil types dominated the catchment area. These were shallow, acid, peat (23%) on the uplands, well-drained loam with bare rocks, crags and scree (38%) on the lower slopes and fine loam (16%) in the valleys.

TP export coefficients for each soil type were calculated from values for orthophosphate (OP) which had been determined for this catchment by Lawlor & Tipping (1996). These markedly improved the estimates of TP losses from subcatchments 4 and 5 compared to those determined by May *et al.* (1995) using export coefficients from the literature. This improvement was due, mainly, to the better estimation of TP losses from coniferous forest. The data from the 1995 survey (Lawlor & Tipping, 1996) suggested that actual TP losses from this type of land cover were only 10% of that given by Harriman (1978). Some of this apparent reduction in TP load may be due to recent changes in forestry practice which was aimed at reducing soil erosion and nutrient runoff.

There seemed to be a close relationship between soil type and land cover. Shallow, upland peat was dominated by upland moor (84%), while well-drained loam with bare rocks, crags and scree was primarily used for forestry (74%) and improved pasture was usually found on fine loam (52%).

The publication of the Hydrology of Soil Types (HOST) classes report (Boorman *et al.*, 1995) during the latter half of this study provided an opportunity to test a rainfall-runoff model for the catchment based on rainfall records and soil type. There was a good correlation between the measured and predicted flows when the method was applied in its original form. However, the level of correlation could be improved by introducing an antecedent running mean into the flow predictions. This tended to smooth out the rather sudden changes in predicted runoff which occured due to short term variations in the rainfall data. This appeared to be a better reflection of the real situation.

1. INTRODUCTION

1.1 Background

Bassenthwaite Lake is one of the larger water bodies in the English Lake District. It is classified as a Grade 1 SSSI on account of its resident Vendace (*Coregonus albula*) population, which is one of only 2 remaining populations in the UK (Maitland & Lyle, 1991). Although a protected species (Wildlife & Countryside Act, 1981), the Vendace are now threatened by gradual increases in hypolimnetic de-oxygenation (Hilton & McEvoy, 1993) which are thought to be an effect of eutrophication.

As a result of concerns about eutrophication, a nutrient loading study was undertaken in 1993 (Hilton, May & Bailey-Watts, 1993). This study showed that phosphorus was the main nutrient limiting algal abundance in the lake, especially during the summer months. Further analysis of the data suggested that, of the 18,400 kg total phosphorus (TP) y^{-1} entering the lake, 49% was attributable to sewage discharges (point sources), while the remainder came from non-point (diffuse) sources within the catchment (Figure 1a).

Point sources of TP were targeted first for control, because these were easier to quantify and manage than diffuse sources. As more than 75% of the TP load from sewage treatment works (STWs) emanated from a single, large works at Keswick, plans were put in place to upgrade this STW. It was estimated that this upgrade would reduce the TP output by about 80%.

Once this upgrade had been achieved, diffuse sources within the catchment would contribute a relatively greater proportion of the TP load to the lake (74% *cf.* 51%) (Figure 1). So, the next step in the lake restoration process was to identify and quantify these TP losses. Using a Geographical Information System (GIS)-based 'export coefficient' approach, incorporating land cover information provided by the Lake District National Parks Authority (LDNPA) and published TP loss coefficients from the literature, May *et al.* (1995) estimated the total TP load to the lake from diffuse sources within the catchment to be approximately 6,800 kg yr^{-1}. This was about ⅓ of the measured TP load (18,400 kg) in 1993. Diffuse TP losses, together with those thought to come from sewage effluent, accounted for only 86% of the TP entering the lake. The authors concluded that the remaining 14% of the TP load may have come from septic tanks within the catchment (Figure 2).

Table 1. Land use categories and related export coefficients used by May *et al.* (1995).

ARC/Info Land-use Code	Land class category	TP Export Coefficient (kg ha^{-1} yr^{-1})	Reference
100	Urban/rural settlement (runoff, only)	0.83	*Bailey-Watts, Sargent, Kirika & Smith (1987)*
200	Upland moor	0.1	*Harper & Stewart (1987)*
300	Improved pasture	0.25	*Harper & Stewart (1987)*
400	Coniferous forest	0.42	*Harriman (1978)*
500	Cleared/new forest	2.0	*Harriman (1978)*
600	Broadleaved forest	0.15	*Dillon & Kirchner (1975)*
700	Mixed forest	0.15	*Hancock (1982); Dillon & Kirchner (1975)*
800	Bogs & peat	1.0	*Casey, O'Connor & Green (1981)*
900	Inland bare rock	0.1	
1000	Rough grazing	0.07	*Cooke & Williams (1973)*
1100	Arable	0.25	*Cooke & Williams (1973)*
1200	Other	0.1	

May *et al.* (1995) also found that the TP export coefficients obtained from the literature (Table 1) did not accurately reflect the measured TP losses from some land cover types within this catchment. In particular, they found that they had significantly overestimated TP losses from subcatchments 4 and 5 which contained relatively high proportions of coniferous forest (32% and 27%, respectively) (Figure 3). This suggested that the published coefficient for coniferous forest (0.42 kg ha^{-1} y^{-1}) was much higher than the actual TP loss from this type of land use, in this catchment. Additional work to improve estimates of TP losses from different land use and soil types within the catchment were recommended. This work was carried out during 1995 by Lawlor & Tipping (1996). Although the full report of this study was not available at the time of writing, the nutrient export coefficients determined by these authors are used in the present study.

In spite of the problems outlined above, May *et al.* (1995) clearly showed the potential of the GIS-based export coefficient approach in improving estimates of TP losses from diffuse sources within lake catchments. In view of this, further work, aimed at refining TP loss estimates within the catchment began in early 1995. The results of these investigations are reported here.

In order to achieve the long term aim of integrating the nutrient loss model for the catchment with the dynamic model for the lake (Hilton *et al.*, 1993), it is necessary to introduce some form of temporal variation into the predictions of nutrient loss. One possible method of achieving this is to develop a model relating nutrient loss to temporal variation in stream flow (runoff). However, the collection of detailed stream flow data over a 1 year period for input to the model would be a time consuming and expensive operation. For this reason, it was decided that the most cost effective solution to this problem would be to develop a method of predicting temporal changes in runoff from daily measurements of rainfall. The opportunity of achieving this was provided by the timely publication of the Hydrology Of Soil Types (HOST) classes report at the end of 1995 (Boorman *et al.*, 1995). This work is discussed in detail in Section 5 of this report.

1.2 Objectives

The original aims of the project were as follows:

1. to extend the spatially referenced dataset created by May *et al.* (1995) to include information on soils within the catchment

2. to examine the effect of sub-catchment differences in soil type on the export of nutrients from the Bassenthwaite catchment

3. to evaluate a range of hydrological models and select the most appropriate model for predicting the seasonal change in runoff and streamflow

4. to improve NRA's population equivalent figures for the main sewage treatment works by including data from the 1991 census and the most recent estimates of tourist numbers

5. to examine the possible effect of seepage from septic tanks on the export of phosphorus from selected subcatchments.

Unfortunately, the data required to complete objectives 4 and 5 could not be obtained within the time constraints of the project. For this reason, the present study focuses on objectives 1, 2 and 3, above.

2. DATABASES

Most of the spatial datasets used in this study are described by May *et al.* (1995). Only additional datasets used in the present study are detailed below.

2.1 Soils data

Data provision

A digital soil map for the Bassenthwaite catchment was supplied, under licence, by the Soil Survey and Land Research Centre (SSLRC) of Cranfield University, England. The data comprised the dominant soils association, in 100 x 100 m blocks, for an area of the Lake District bounded by OS grid reference NY 100 000 in the south-west and NY 500 400 in the north-east.

The data were supplied in ASCII format, each data point consisting of an Ordnance Survey (OS) grid reference and an associated numeric soil code. A key to allow cross-referencing between these soil codes and the published legend for the 1:250,000 soil map of England and Wales (SSEW, 1983) was provided in ASCII format.

Data description

The soils data are part of a 100 m resolution digital soils map of England and Wales prepared, mostly, from reconnaissance mapping over a wide geographical area and at a scale of 1:250,000. Although the mapping is based on soil analyses carried out for a large number of sites, in the past, the choice of sampling sites has often been determined, at least in part, by the local land cover (Hollis, *pers. comm.*). More recently, soils have been sampled at 5 km intervals allied to the National Grid, this providing a more objective sample of the properties of British soils (Boorman *et al.*, 1995).

Classification of soils

In England and Wales, soils are differentiated by observable and measurable characteristics of the upper 1.5 m of the soil profile. These are described in detail by Avery (1980). In summary, they can be divided into 2 main types:

1. characteristics inherited from the soil parent material

2. characteristics resulting from alteration of the original parent material by soil forming processes such as decomposition of plant matter, weathering, *etc.*

The soils are differentiated according to a 4 level heirarchical system comprising: major group, group, subgroup and series [see Avery (1980), Clayden & Hollis (1984), for details]. In general, the first 3 classes are based on broad textural groups, presence or absence of certain diagnostic horizons and soil water regime, while the latter is distinguished by textural classes, mineralogy and substrate lithology.

The data supplied by SSLRC comprised 15 different soil associations. These are summarised in Table 2 (see 'Description'), together with the following information:

1. alphanumeric soil code
2. geological properties influencing soil characteristics
3. soil properties affecting rooting depth cultivations and drainage
4. predominant cropping and landuse patterns

Data manipulation

The original ASCII dataset was imported into a polygon representation of a 100m grid. The boundaries between adjacent polygons of the same soil series were then dissolved to provide a polygon coverage for all soils. A coverage containing only those soils which occurred within the Bassenthwaite catchment was created by clipping this rectangular soils coverage to the shape of the catchment using a digitised catchment outline. The original data comprised 15 different soil

Table 2. Description of SSLRC soil associations found within the catchment of Bassenthwaite lake.

Soil code	Description	Geology	Soil & Site Characteristics	Cropping & Landuse
311b	SKIDDAW	Palaeozoic slaty mudstone & siltstone	Very shallow, very acid, peaty upland soils over rock, often on steep slopes. Some deeper peaty-topped soils with ironpan. Thick peat on gentler slopes. Bare rock locally.	Stock rearing on wet moorland habitats of moderate grazing value in the uplands and mountains. Recreation.
311e	BANGOR	Acid, igneous rock.	Very shallow, very acid, peaty-topped upland soils. Often on steep slopes. Thick in peat in hollows and on gentler slopes. Much rock & scree locally.	Stock rearing on moorland habitats of poor grazing value in the uplands and mountains. Recreation.
541c	EARDISTON 1	Devonian and Permo-Triassic reddish sandstone, silty shale & siltstone	Well drained, reddish, coarse loamy soils over sandstone, shallow in places, especially on brows. Some reddish fine silty soils over shale & siltstone. Risk of water erosion.	Cereals, potatoes, some field vegetables & orchards; grassland with stock rearing in Welsh borderlands.
541q	WALTHAM	Drift over carboniferous limestone.	Well drained, fine loamy soils over limestone, locally deep. Shallow loamy soils in places. Bare rock locally.	Permanent grassland with stock rearing in Cumbria; some cereals in drier districts.
541u	ELLERBECK	Glaciofluvial drift	Very stony, well-drained loamy soils on hummocky ground. Some similar but less stony soils.	Stock rearing on permanent grassland in moist lowlands; some cereals, sugar beet and potatoes in drier lowlands.
611a	MALVERN	Igneous rock	Well drained, very stony, loamy soils on moderate to steep bouldery slopes. Crags & scree locally extensive.	Stock rearing in moist uplands on permanent grassland and good value rough grazing; widespread deciduous woodland habitats.
611c	MANOD	Palaeozoic slate, mudstone & siltstone.	Well-drained fine loamy or fine silty soils over rock. Shallow soils in places. Bare rock locally. Steep slopes common.	Stock rearing & woodland in upland.; some dairying and cereals in Devon and Cornwall with woodland on slopes.
651b	HEXWORTHY	Granite and other acid igneous rock.	Gritty loamy very acid soils with a wet peaty surface horizon; thin ironpan often present. Bare rock and boulders locally. Some steep slopes.	Wet moorland habitats of moderate and poor grazing value; recreation; coniferous woodland; dairying in improved ground; military use.
711n	CLIFTON	Reddish till.	Slowly permeable, seasonally waterlogged reddish fine and coarse loamy soils, and similar soils with slight seasonal waterlogging. Some deep, coarse loamy soils seasonally affected by groundwater.	Cereals & grassland, some potatoes in Staffordshire; grassland in northern region.
713f	BRICKFIELD 2	Drift from Palaeozoic & Mesozoic sandstone and shale.	Slowly permeable, seasonally waterlogged, fine loamy soils. Associated with fine loamy soils with only slight waterlogging and some deep well-drained fine loamy soils.	Dairying and stock rearing on permanent or short-term grassland; some cereals in drier areas.
721c	WILCOCKS 1	Drift from Palaeozoic sandstone, mudstone and shale.	Slowly permeable, seasonally waterlogged fine loamy and fine loamy over clayey upland soils with a peaty surface horizon. Coarse loamy soils affected by groundwater in places. Very acid where not limed.	Wet moorland habitats of moderate and poor grazing value; some improved grassland; coniferous woodland; military use.
811b	CONWAY	River alluvium	Deep stoneless fine silty and clayey soils variably affected by groundwater. Flat land. Risk of flooding.	Dairying and stock rearing on permanent grassland.
813d	FLADBURY 3	River alluvium	Stoneless clayey, fine silty and fine loamy soils affected by groundwater. Flat land. Risk of flooding.	Stock rearing on permanent grassland with occasional winter cereals; more cereals in drier districts.
1011a	LONGMOSS	Raised peat bog.	Thick very acid peat soils. Largely undrained and perennially wet. Many areas cut over or partly burnt.	Lowland bog or wet moorland habitats of low grazing value; some coniferous woodland; peat extraction.
1011b	WINTER HILL	Blanket peat	Thick very acid raw peat soils. Perennially wet. hagged and eroded in places.	Wet moorland and wetland habitats of poor grazing value; coniferous forest; military use.

associations (Table 2). These were used without modification for the rainfall/runoff predictions using HOST classes (Section 5), but were grouped into 10 summary soil types, based on their dominant soil type (Table 3), for use in the nutrient export studies (Section 4.2).

Table 3. Grouped soil types used in the nutrient export studies.

Soil type *(This study)*	Soil associations *(SSEW, 1983)*	Soil code *(SSEW, 1983)*
1. Shallow, acid upland peat	SKIDDAW BANGOR	331b 311e
2. Well-drained loam, some bare rock	EARDISTON WALTHAM ELLERBECK	541c 541q 541u
3. Reddish fine & coarse loam	CLIFTON	711n
4. Fine loam	BRICKFIELD	713f
5. Fine loam with peaty horizon	WILCOCKS	721c
6. Stoneless, fine silt & clay	CONWAY	811b
7. Stoneless, clay, fine silt & loam	FLADBURY	813d
8. Thick, very acid peat soils	LONGMOSS WINTERHILL	1011a 1011b
9. Gritty loam, very acid	HEXWORTHY	651b
10. Well-drained loam with bare rocks, crags & scree	MALVERN MANOD	611a 611c

2.2 HOST Classes

Hydrology of soil type (HOST) classes (Boorman *et al.*, 1995) were supplied by SSLRC for each soil association within the catchment (Table 4). However, these comprised a single value which reflected the dominant HOST class of each soil association. Although these values were used at the start of the project, they were later superseded by the more detailed information on HOST classes which was published by the Institute of Hydrology (IH) in November 1995 (Boorman *et. al.*, 1995). These updated HOST classes are also shown in Table 4.

Table 4. HOST classes supplied by SSLRC and Boorman *et al.* (1995) for soil associations within the catchment of Bassenthwaite Lake.

Soil Series	HOST Class	HOST Class	Relative Composition
	(SSLRC, pers. comm.)	*(Boorman et al., 1995)*	
BANGOR	27	27	57.14%
		9	42.86%
BRICKFIELD	24	24	53.30%
		21	26.67%
		6	20.00%
CLIFTON	24	24	68.42%
		18	21.05%
		10	10.53%
CONWAY	9	9	76.47%
		8	23.53%
EARDISTON 1	4	4	67.16%
		18	17.91%
		3	14.93%
ELLERBECK	5	5	100.00%
FLADBURY	9	9	85.00%
		8	15.00%
HEXWORTHY	15	15	100.00%
LONGMOSS	12	10	100.00%
MALVERN	19	19	71.43%
		4	28.57%
MANOD	17	17	87.50%
		22	12.50%
SKIDDAW	27	27	53.33%
		15	33.33%
		29	13.33%
WILCOCKS	26	26	88.89%
		10	11.11%
WINTER HILL	29	29	100.00%

2.3 TP Export coefficients for soil types

Estimates of orthophosphate (OP) loss rates in relation to soil types 1, 2, 4, 5, 6, 7, 8 and 10 were provided by Lawlor & Tipping (1996). These had been derived from a detailed survey of stream water chemistry at the sites shown in Figure 4. The exact location of these sites, and the main soil types drained by each stream, are shown in Table 5. Subcatchment boundaries upstream of the sampling points used by Lawlor & Tipping (1996) were derived from the stream network and elevation contours on a 1:50,000 Ordnance Survey Landranger Series paper map (Map no. 90).

Table 5. Water chemistry sampling points used by Tipping *et al.* (1996) to determine OP and TP export coefficients in relation to soil type; major soil type of each stream catchment is also shown.

Site no.	River / Stream	Site	NGR	Soil Type	Export coefficients (kg ha^{-1} y^{-1})	
					OP	TP
1	Thornsgill Beck	Rocking House Farm	NY382254	8	0.052	0.135
2	Kitto Beck	At Troutbeck	NY388263	4(a)	0.07	0.182
3	Glenderamackin	Mill Bridge (Threlkeld)	NY324252	4(b)	0.054	0.14
4	Beck Wythop	At A66	NY214284	10(a)	0.016	0.042
5	Wythop Beck	Eskin Bridge	NY185293	5	0.084	0.218
6	Wythop Beck	Wythop Mill	NY178295			
7	Wythop Beck	Netherscale	NY177301			
8	Wythop Beck	At A66	NY198311	7	0.543	1.412
9	Field Drain	Broadness Farm	NY225298	2	0.093	0.242
10	Skill Beck	Forestry Cafe	NY235282	10(b)	0.031	0.081
11	Derwent	Low Stock Bridge	NY237268			
12	Wath Beck	High Stock Bridge	NY244250	6(b)	0.19	0.494
13	Field Drain	At Wath Beck	NY245261	6(a)	0.064	0.166
14	Helvellyn Gill	At Nature Trail	NY317169	1	0.016	0.042

To enable comparison with earlier work by May *et al.* (1995), it was necessary determine a conversion factor for estimating TP loss rates from the measured export coefficients for OP. This factor (2.6) was calculated as the mean TP/OP ratio for feeder streams with no known influence of sewage effluent, using data from the 1993 nutrient loading survey (May *et al.*, 1995). The resultant OP and TP export coefficients for each soil type are shown in Table 5.

2.4 Rainfall data

Daily rainfall data from December 1992 to August 1993 was provided by NRA, North West Region, for 5 sites either inside or close to the Bassenthwaite catchment. Some of these sites (i.e. those relating to the calculation of flow for the River Derwent at Portinscale) are shown in Figure 11.

2.5 Air temperature data

Mean daily air temperatures for Ambleside were supplied by the Institite of Freshwater Ecology (IFE), Windermere laboratory.

3. INVESTIGATIVE METHODS AND ANALYSIS

3.1 The Goegraphical Information System (GIS)

This project was carried out using ARC/INFO (v. 7.0), a Geographical Information System (GIS) which was developed by the Environmental Systems Research Institute Inc. (ESRI). The GIS of the Bassenthwaite catchment was originally created by May *et al.* (1995) and contained the following map overlays (coverages):

- lake outlines
- drainage networks
- catchment and subcatchment boundaries
- land cover
- sources of sewage effluent
- rain gauge locations
- flow and water quality sampling sites for 1993

The following coverages have been added during the present study and registered to the existing data coverages:

- soils
- water quality sampling sites for 1995

The attribute data provided with the spatial data for soils were associated with the appropriate soil codes so that particular soil series and their related descriptions (Avery, 1980) could be identified. These coverages were combined, subtracted or subsampled to perform the spatial analyses described below.

4. SOILS OF THE BASSENTHWAITE CATCHMENT

4.1 Description

Fifteen different soil series were found within the catchment of Bassenthwaite Lake (Table 2). For the nutrient export calculations, these were grouped into 10 summary soil types, based on their dominant soil subgroup (Table 3). The geographical extent of each of these soil types is shown in Figure 4.

The total area of each soil type was determined for the whole catchment (Table 6), and for each of the subcatchments shown in Figure 4 (Appendix I), by combining the soils coverage with the catchment and subcatchment boundaries and invoking the STATISTICS command from within ARCEDIT. In general, the soils of the catchment were composed of 3 main types. These were

Table 6. Aerial extent of different soil types within the catchment of Bassenthwaite Lake.

SOIL TYPE	SOIL DESCRITION	AREA (HA.)	AREA (%)
1	Shallow, acid, upland peat	8249	23
2	Well-drained loam, some bare rock	1760	5
3	Reddish fine & coarse loam	20	0
4	Fine loam	5720	16
5	Fine loam with peaty horizon	922	3
6	Stoneless fine silt & clay	658	2
7	Stoneless, clay, fine silt & loam	138	0
8	Thick, very acid peat soils	3763	11
9	Gritty loam, very acid	610	2
10	Well-drained loam with bare rocks, crags & scree	12945	38
		36135	100

well-drained loam with bare rocks and scree (38%), shallow, acid upland peat (23%) and fine loam (16%). The shallow upland peat occurred mostly on the uplands, while well-drained loam with bare rocks and scree was mostly found on the lower slopes and fine loam tended to cover the valley bottoms. Small areas of the remaining soil types, each amounting to less than 5% of the total catchment area, were scattered throughout the catchment.

4.2 Estimating TP losses from each soil type

TP export coefficients were available for some of the soil types found within the catchment (see Section 2.3). In order to provide a single TP loss coefficient for each soil type, multiple values for a given soil type were averaged, and missing values were approximated to that of the nearest equivalent soil type. These values (Table 7) were used to estimate TP losses from the catchment and subcatchments according to their component soil types .

Table 7. TP export coefficients used to estimate TP losses from the Bassenthwaite catchment in relation to different soil types; mean values (@) and estimated values (*) are marked.

Soil type	TP Export coefficient ($kg\ ha^{-1}\ y^{-1}$)
1	0.042
2	0.242
3	0.161 *
4	0.161 @
5	0.218
6	0.33 @
7	1.412
8	0.135
9	0.218 *
10	0.123 @

The area of each soil type in each subcatchment was estimated by overlaying the subcatchment boundaries onto the soils map and producing summary areal statistics (Appendix I). These values were then used to estimate TP losses from each subcatchment by multiplying the areas of each soil type by the export coefficients shown in Table 7. The results of these calculations are shown in Table 8, together with the TP losses estimated on the basis of land cover and published export coefficients by May *et al.* (1995).

TP loads from known sources of sewage effluent within the subcatchments were calculated from the OP loads for these sources given by May *et al.* (1995). In outline, each value was multipled by the mean TP/OP ratio for each STW, as calculated from the effluent chemistry data supplied by NRA. These TP/OP values were 1.19, 1.28, 1.2, 1.3 and 1.2 for Thornthwaite, Keswick, Armathwaite, Bassenthwaite and Embleton STWs, respectively. The estimated TP loads from these point sources were then subtracted from the measured TP load from the corresponding subcatchments, thus giving an estimate of the 'measured' TP load from diffuse sources. These values are compared to the TP runoff estimates calculated from the land cover and soils data in Table 8 and Figure 6.

The results show that, in most cases, estimating TP losses from soil type and associated export coefficients which had been determined for the Bassenthwaite catchment gave a closer approximation to the measured values than the alternative method based on land cover and published export coefficients (determined for other catchments) (Figure 6). The most marked improvement was seen in subcatchments 4 and 5. Here, May *et al.* (1995) had already shown that the published export coefficient used for coniferous forestry was far too high for use in the Bassenthwaite catchment. Better estimates of TP runoff were also found for subcatchments 10, 11, and 12, but these improvements were relatively small compared to those for subcatchments 4 and 5. In contrast, TP losses from subcatchments 1 & 2, 6, 13, 14 & 15 using the soils data method fitted the observed data less well than those calculated by May *et al.* (1995).

It is difficult to do a fair comparison between these methods to determine whether it is better to use soils data or land cover to estimate TP losses from catchments, because one set of export coefficients were determined for the Bassenthwaite catchment, itself, while the other was determined for other catchments. In general, it is probably the use of locally derived export coefficients, rather than the change from land cover data to soils data, which results in the overall improvement in the TP runoff estimates.

Table 8. Comparison of TP losses from each subcatchment estimated from measured, soils and land cover data.

Subcatchment	Measured TP loss [diffuse + point source] (kg y^{-1})	Estimated TP load from sewage effluent (kg y^{-1})	'Measured' diffuse TP loss [col (2)-col(3)] (kg y^{-1})	Diffuse TP loss estimated from land cover (kg y^{-1})	%Error	Diffuse TP loss estimated from soils (kg y^{-1})	% Error
1&2	952	0	952	1,021	7	561	-41
3	104	104	0	19		5	
4	10	0	10	54	440	16	60
5	12	0	12	49	308	15	25
6	385	240	145	268	85	319	120
8	535	Not known		150		90	
9	202	Not known		19		12	
10	486	245	241	419	74	255	6
11	22	0	22	37	68	28	27
12	35	0	35	63	80	50	43
13	68	0	68	90	32	34	-50
14&15	15,600	7213	8387	4433	-47	2986	-64

4.3 The relationship between soil type and land cover

The main land cover types within the catchment are shown in Figure 5 and summarised in Table 9. More than half of the catchment (53%) is covered by upland moor which occurs, primarily, on the higher ground. A further 21% is covered by improved pasture, mostly found on the lower slopes and in the valley bottoms. Visual comparison of Figures 4 & 5 suggests that there is a close correlation between soil type and land cover. This was investigated by combining the soils and land use coverages and summarising (1) the types of land cover found on each soil type (Figures 7 & 8; Appendix II) and (2) the types of soils associated each land cover type (Figures 9 & 10; Appendix III).

Table 9. Areal extent of different land cover types within the catchment of Bassenthwaite Lake.

LAND COVER	AREA (HA.)	AREA (%)
Urban/rural settlement	614	2
Upland moor	18560	53
Improved pasture	7233	21
Coniferous forest	1628	5
Cleared/new forest	465	1
Broadleaved forest	923	3
Mixed forest	1189	3
Bogs & peat	398	1
Inland bare rock	1668	5
Rough grazing	1790	5
Arable	74	0
Other	199	1
	34741	100

Figures 7 and 8 show that most soil types are associated with a single dominant land cover type and a range of minor ones. For example, soil type 1 is dominated by upland moor (84%), while soil type 2 is usually covered by improved pasture (66%). Most of the other soils show a similar pattern of land cover. However, there are 2 exceptions to this. Soil types 3 and 9 are each almost completely covered by a single land cover type. These are improved pasture and upland moor, respectively.

The pattern of soil types associated with each land cover type is far more complex (Figures 9 & 10). For example, although soil type 5 is almost always covered by improved pasture, improved pasture is found on a range of soil types, including soil types 4 (52%), 10 (24%) and 2 (15%). Forests (coniferous, broadleaved and mixed), in contrast, are usually associated with soil type 10, although they are also commonly found on soil types 2, 4 and 8.

In general, a close association between soil type and land cover is evident from these data. As land cover is unlikely to significantly influence soil type, it seems likely that soil type is an important factor in determining what the land will be used for. However, consideration should also be given to the fact that land cover may have been taken into account when some of the sampling sites for the soil surveys were selected (see Section 2.1). If this is the case, then these 2 datasets are not totally independent.

4.4 Comparison of nutrient export coefficients

By selecting subcatchments from the nutrient survey of Lawlor & Tipping (1996) which are dominated by one particular land cover type, it is possible to estimate TP export coefficients for some land cover types within the Bassenthwaite catchment. The stream at sampling site 4 (soil type 10a) drains a subcatchment consisting of 78% coniferous forestry. Hence, it can be inferred that the TP export coefficient for this type of land cover is similar to that for soil type 10b, i.e. 0.04 kg ha^{-1} yr^{-1}. This is only 10% of the export coefficient for coniferous forest used by May *et al.* (1995) and probably explains why these authors overestimated TP losses subcatchments with a high proportion of coniferous forest.

By similar argument for sampling sites 9 and 13, whose subcatchments are dominated by improved pasture (49%) and upland moor (90%), respectively, it is possible to infer that the TP export coefficient for improved pasture is approximately 0.24 kg ha^{-1} yr^{-1} while that of upland moor is about 0.17 kg ha^{-1} yr^{-1}. These value compares favourably with those used for these land cover types by May *et al.* 1995, i.e. 0.25 kg ha^{-1} yr^{-1} and 0.1 kg ha^{-1} yr^{-1}, respectively.

5. ESTIMATING RUNOFF FROM RAINFALL

5.1 Introduction

The derivation of relationships between rainfall over a catchment, and the resulting stream flow from a catchment, is fundamental to studies which aim to predict runoff from rainfall data. The reason for attempting such predictions is that stream flow data are often needed for hydrological and water quality studies, but these are rarely available in the degree of detail required. So, elaborate, expensive and time consuming field campaigns are often undertaken to collect the data required. However, extensive rainfall records usually exist for any given area, so, if it is possible to predict stream discharges on the basis of rainfall data, a costly data collection phase can be partially or wholly avoided. Ideally, such a model would provide a reliable method of prediction which depends only on readily available data to characterise a catchment.

The complexity of determining the discharge, or runoff, from a catchment depends primarily on the temporal resolution which is required in the study. On an annual basis, simple linear correlations between rainfall and runoff may be sufficient for determining the water yield of a catchment. However, if the study is investigating fluctuating features, such as flood peaks, or nutrient concentrations in the receiving waters (as in this study), then higher temporal resolutions may be required. For the purposes of this study, the temporal resolution attempted in the prediction of stream flow (ie. daily) was determined by two factors.

1. the requirement by the dynamic lake model (PROTECH) for daily input values
2. the availability of daily rainfall data for the Lake District.

5.2 Water movement within a catchment

When rain falls onto a soil surface, some of that rain will flow over the surface and into the streams draining the catchment. Much of the remainder will drain through the soil, under the influence of gravity, until it reaches the water table or an 'impermeable' soil layer (lateral hydraulic conductivity < 10cm day^{-1} (Boorman *et al.*, 1995)). Here, water either accumulates or travels laterally, perhaps emerging as a spring or augmenting stream flow further down the catchment.

The dominant pathway of water falling onto a catchment depends on the characteristics of the underlying soils and substrates. If the soils and underlying substrate can drain freely, most of the rainfall will permeate into the deeper layers, having little immediate influence on stream flow patterns, but maintaining low flows in the longer term. In contrast, rain falling onto soils which are totally impermeable, or have an impermeable layer very close to the surface is very quickly lost as surface or sub-surface runoff. This rapidly affects stream flow and leaves little water in the catchment to maintain flows between rainfall events. Although these are extreme situations, they serve to illustrate one of the problems of estimating runoff from rainfall and show that some characterisation of the underlying soils in a catchment is necessary for such predictions.

The characterisation of soils for such a purpose should consider the soil properties which most influence the hydrological response. These are hydraulic conductivity, soil moisture retention and pathways of water movement (Boorman *et al.*, 1995). However, these properties are difficult and expensive to measure and only partially available for some soil associations. For practical and economic reasons, alternative soil properties, for which there are extensive data collections and associated map data, must be used to characterise the soils. This has been attempted by a consortium led by the IH, which produced a soil classification for the whole of the United Kingdom, based on the hydraulic properties of soils. This classification is known as Hydrology Of Soil Types (HOST) classification (Boorman *et al.*, 1995).

5.3 The Hydrology of Soil Types (HOST) Classification

The HOST classification scheme was developed by The Soil Survey and Land Research Centre (SSLRC), The Macaulay Land Use Research Centre (MLURI) and the IH. It followed on from an earlier classification of soil hydrological properties known as the Winter Rainfall Acceptance Potential (WRAP) carried out by the IH (NERC, 1975). The WRAP classification was designed to indicate the infiltration potential of a soil and, as such, is the inverse of runoff potential. This system characterised the soils using four soil and site properties. These were soil water regime, depth to an impermeable layer, permeability of the soil horizons and slope of the land. Using these characteristics the soil was classified into one of 5 classes and a soil index for any catchment could then be calculated on the basis of the proportions of these different classes within a catchment, as follows:

$$SOIL = 0.15WRAP_1 + 0.30WRAP_2 + 0.40WRAP_3 + 0.45WRAP_4 + 0.50WRAP_5$$

where:

n	is the soil class number
$WRAP_n$	fraction of the total catchment area in WRAP class n
SOIL	is the soil index

This soil index (SOIL) was then used to determine the Standard Percentage Runoff (SPR) or the proportion of the rainfall directly contributing to short term increases in stream flow.

It became apparent that there were limitations in the WRAP approach. These limitations were related to the small number of WRAP classes and the lack of detail in the soil maps upon which they were originally based. With the advent of more detailed soil survey data, the HOST classification was developed to improve on this methodology. This development depended on a) the distribution of soil types as shown in 1:250000 maps and b) a database of soil properties derived from the national soils databases held by the collaborating institutions. The soil characteristics used as a surrogate for direct measurement of the soil hydraulic properties were the depth to gleying, depth to a slowly permeable layer, integrated air capacity and the presence of a peaty surface layer. These properties, which have been used by soil scientists to infer and classify the hydrology of soil (Bibby *et al.*, 1982, Robson & Thomasson, 1977), can be derived from soil profile descriptions (Avery, 1980). In addition to these characteristics, a geological component to describe the soil parent material was also included.

The rules defined by this descriptive approach led to the derivation of a consistent set of surrogate soil hydrological properties across the UK. These were classified on the basis of combinations of characteristics into 29 HOST classes. Multiple regression analysis was used to determine the relationship between these classes and catchment flow parameters. The latter was calculated from daily records for over 1000 sites available from the National Water Archive at the IH.

5.4 Calculating percentage runoff

The original Flood Studies Report (NERC, 1975) identified an empirical method of calculating runoff from rainfall which required only catchment scale input parameters. This method determined the total percentage runoff for a rural catchment, as follows:

$$PR_{RURAL} = SPR + DPR_{CWI} + DPR_{P}$$

where:

PR_{RURAL}	is the total percentage runoff in a rural catchment
SPR	is the Standard Percentage Runoff
DPR_{CWI}	is the dynamic percentage runoff term relating to catchment wetness
DPR_{P}	is the dynamic percentage runoff term dependent on event rainfall (precipitation)

The dynamic terms in this equation were revised in Flood Studies Supplementary Report No. 16 (IH, 1985) to give the following:

$$DPR_{CWI} = 0.25\ (CWI - 125)$$

$$DPR_{P} = 0.45\ (P - 40)^{0.7} \qquad \text{for } P > 40\text{mm}$$

Otherwise $DPR_{P} = 0$

where:

CWI	is the Catchment Wetness Index
P	is the rainfall (precipitation) depth (mm)

5.5 Estimating the Catchment Wetness Index

When estimating runoff from rainfall, soil wetness may change the capacity of the soil to store water, thus affecting the flow pathways. Very dry soils may have the capacity to store water and limit the flow response, while wet or waterlogged soils may increase the short term response of flow to rainfall. A Catchment Wetness Index was developed to reflect the antecedent moisture conditions of the catchment and allow runoff estimates to be influenced by soil wetness.

In earlier studies, the Antecedent Precipitation Index (API) was designed as a measure of the antecedent moisture condition of the catchment (Kohler & Lindsey, 1951). For the UK, this was originally calculated as an exponentially decaying index which took the following form:

$$API30_d = P_{d-1} + k.P_{d-2} + k^2.P_{d-3} + k^3.P_{d-4} + \ldots\ldots + k^{29}.P_{d-30}$$

where:

P	is the Precipitation in mm.
d	is the current day
k	is the decay factor, usually set at 0.9.
$API30_d$	is the 30-day Antecedent Precipitation Index for the current day

A modification to the API was suggested in The Flood Studies Report (NERC,1975), which looked at antecedent conditions over a shorter time period (i.e. 5 days) and increased the decay function when calculating the index, as follows:

$$API5_d = 0.5^{1/2} \left(P_{d-1} + (0.5)P_{d-2} + (0.5)^2P_{d-3} + (0.5)^3P_{d-4} + (0.5)^4P_{d-5} \right)$$

where:

$API5_d$	is the 5-day Antecedent Precipitation Index for the current day

It was suggested that this index should be combined with a measure of Soil Moisture Deficit (SMD) to produce a Catchment Wetness Index (CWI). This took the following form:

CWI = 125 + API5 - SMD

where:

API5	is the short term (5-day) Antecedent Precipitation Index
SMD	is the Soil Moisture Deficit.

This CWI could then be used in the Total Percentage Runoff calculations.

As there were two identifiable methods of calculating API, and of using it to calculate CWI, this study looked at the effect of these two variations on the resulting runoff predictions, by comparing them with the measured values. The two variants used for calculating CWI were as follows:

CWI = 125 + API5 - SMD

and

CWI = 125 + API30

As the present study was attempting to identify a method for estimating runoff from rainfall using catchment scale parameters, it was important that all parameters in the runoff equations could be calculated from readily available catchment scale data. This was taken into account when identifying a suitable a method of calculating soil moisture deficit.

5.6 Estimating Soil Moisture Deficit

When soil is saturated it will hold no more water. Once it has stopped raining, saturated soil gives up some of its water until it retains a certain amount against the force of gravity. At this point the soil is regarded as being at 'field capacity'. From this point onwards, any depletion in the amount of water stored in the soil is regarded as a Soil Mositure Deficit (SMD) and can be defined as the amount of water necessary to restore the soil to field capacity (Shaw, 1994).

Continuing depletion of the soil moisture is caused by evaporation from the soil surface and by the demands of vegetation for water. These demands are encompassed in the term evapotranspiration. SMD can be calculated by a simple formula:

$$SMD = E_t - P$$

where:

E_t	is evapotranspiration (mm)
P	is precipitation (mm)
SMD	is Soil Moisture Deficit (mm)

Daily values of SMD would be calculated as follows:

$$SMD_d = SMD_{d-1} + E_{t(d)} - P_d \quad \text{if } SMD < 0 \text{ Then } SMD = 0$$

where:

d	is the current day

However, evapotranspiration is not a readily available parameter, so it was necessary to develop a way of calculating it, in order to make the method work. Several methods of calculating E_t are available, some based on empirical relationships, others on physical principles. Although the methods based on the physical principles of evaporation from a surface are likely to give more accurate results for E_t than those based on empirical relationships, they are dependent on data that are not readily available within a catchment unless field measurements are taken. As this study was trying to avoid using methods which necessitated labourious field campaigns, the empirical approach was evaluated first.

5.7 Estimating Evapotranspiration

Evapotranspiration is a collective term for all processes by which water in the liquid or solid form, at or near the earth's land surfaces, becomes atmospheric water vapour (Dingman, 1994). Hamon(1963) estimated daily potential evapotranspiration as follows:

$$PET_H = 0.00138D[\rho_{vsat}(T_k)]$$

where:

PET_H	is potential evapotranspiration (cm day^{-1})
D	is daylength (hours)
T_k	is the air temperature (°K)
$\rho_{vsat}(T_k)$	is the saturation absolute humidity (g m^{-3}) at T°K

Daylength is readily available from published tables (MAFF, 1967). However, some method of calculating $\rho_{vsat}(T_k)$ was necessary. Dingman (1994) detailed the method for such a calculation as follows:

$$e_{sat} = (\rho_{vsat}(T_k) * T_k) / 217$$

this can be expressed as:

$$\rho_{vsat}(T_k) = (e_{sat} * 217) / T_k$$

where:

e_{sat} is the saturation vapour pressure (mb)

Digman (1994) also gave an expression for the calculation of e_{sat} as a function of temperature.

$$e_{sat} = 6.11 \exp^{(17.3 * Tc) / (Tc + 237.3)}$$

where:

e_{sat}	is the saturation vapour pressure (mb)
T_c	is air temperature (°C)

From this it can be seen that evapotranspiration can be calculated as a function of air temperature and daylength. It follows that Soil Moisture Deficit can be calculated from temperature, rainfall and daylength, all of which are readily available for all parts of the country on a daily basis from the Meteorological Office and other organisations.

5.8 Estimating Standard Percentage Runoff

Standard Percentage Runoff (SPR) has already been defined as the proportion of the rainfall directly contributing to short term increases in stream flow. In order to calculate SPR for inclusion in the calculation of PR_{rural} (see Section 5.4), it was necessary to use the HOST classification. Boorman *et al.* (1995) identified an expression similar in form to that of the soil index used previously in The Flood Studies Report (NERC, 1995). They conducted a multiple regression analysis between HOST classes and runoff data for over 1000 sites in order that to develop an expression which could give the SPR of a catchment on the basis of the HOST class composition of the catchment. This expression was used in the present study and took the following form:

$$SPR = a_1 HOST_1 + a_2 HOST_2 + a_3 HOST_3 + ... + a_{29} HOST_{29}$$

where:

SPR	is the Standard Percentage Runoff term
a_x	is the fraction of the total catchment area which has soil of HOST class x
$HOST_x$	is the SPR for HOST class x (as given by Boorman *et al.* (1995), Appendix B)

A general methodology for estimating stream flow or runoff for the subcatchments of Bassenthwaite Lake was derived from the above equations.

5.9 Calculating runoff from rainfall for the subcatchments of Bassenthwaite Lake

The equations outlined above were tested and modified using the continuous daily flow records available for the River Derwent at Portinscale (subcatchment 15) as validation for the model. The following data provided input to the equations:

- daily air temperature
- daily rainfall
- digital soils data
- digitised subcatchment boundary
- HOST classes for each soil type

First, GIS was used to overlay the subcatchment boundary onto the soils data and provide summary statistics relating to the areal coverage of each soil type within the subcatchment boundary. This information, which could be determined from the Polygon Attribute Table (PAT), was expressed in Sq. Metres and as a fraction of the total subcatchment area. By relating this summary table to a look up table of HOST class composition for all soil assciations within the catchment, it was possible to determine the total area of each HOST class in the Portinscale subcatchment. This resulted in a table of area fractions for each of the 29 possible HOST classes. This table was then related to another look up table which had SPR values for each of the 29 HOST classes. This allowed a composite SPR for the whole subcatchment to be calculated. This entire procedure, as outlined above, is illustrated for the Newlands Beck subcatchment in Figure 12. The composite SPR for the subcatchment was then used in conjuction with the dynamic terms (DPR_{CWI} and DPR_P) to calculate the total percentage runoff, PR_{RURAL}.

The first attempt at implementation of the methodology (method 1) adopted all the terms as specified above and resulted in a percentage runoff term being calculated for each day. Each daily percentage runoff term was then applied to the corresponding rainfall for that day to calculate the resultant runoff or stream flow. Thus a time series of predicted flows was calculated for the period of the validation data, i.e. 1 January 1993 to 31 August 1993 (Hilton *et al.*, 1993).

Table 10. Results of regression analyses on measured and predicted flows in the River Derwent at Portinscale.

Regression statistics	HOST (1)	HOST + residual rain (2)	HOST + residual rain + 3day smoothing (3)	HOST + residual rain + 4day smoothing (4)
API30 method				
slope	0.62	0.89	0.98	0.94
$r^2_{(d)}$	0.30	0.40	0.78	0.82
slope	0.79	1.08	0.97	0.92
$r^2_{(d-1)}$	0.49	0.60	0.77	0.78
slope	0.68	0.94	0.87	0.85
$r^2_{(d-2)}$	0.37	0.45	0.62	0.66
API5-SMD method				
slope	0.44	0.61	0.68	0.66
$r^2_{(d)}$	0.26	0.38	0.72	0.77
slope	0.59	0.76	0.68	0.65
$r^2_{(d-1)}$	0.46	0.58	0.73	0.74
slope	0.51	0.67	0.62	0.60
$r^2_{(d-2)}$	0.34	0.45	0.60	0.63

The procedure outlined above was run twice, first using CWI = 125 - API30 and second using CWI = 125 - API5 - SMD, to estimate the catchment wetness index. The resultant time series are compared with the measured flows in Figure 13. It is apparent from these plots that both methods predict the magnitude and temporal location of flow peaks and troughs with some degree of accuracy. However, it is also evident that the predicted flows have a much larger fluctuation than are occurring in the field measurements.

The linear regression analyses of measured and predicted flows for method (1) (Table10) give some indication of the goodness of fit but, it should be borne in mind that the model does not take into account any lag period between rainfall and runoff which may significantly affect the correlation between measured and predicted data points. The value of r^2 for the API30 method is 0.3 with a regression line slope of 0.62 (Table 10), which does not indicate a particulary good fit between the predicted and measured data. The ideal situation would have been for both parameters to have values of 1, indicating a perfect fit between the two datasets.

There are two possible reasons for the low correlation between predicted and measured data using method (1). The first is that that there may be a lag period between rainfall and resulting stream flow in the real situation which is not reflected in the model, as suggested by the apparent misalignment of the flow peaks in Figure 12. Introducing a 1-day lag into the regression analysis for the API30 method increases the value of r^2 to 0.49 and the slope of the regression line to 0.79, which tends to support this theory. The second possible reason for the poor regression fit is that the troughs in the predicted flow time series have a much steeper angle than in the measured time series (Figure 12). The shallower slope on the measured data is, primarily, due to subsurface flow rather than overland, short term, flow which method (1) is designed to calculate. Subsurface flow is the flow generated by rainfall which has percolated throught the soil and into the stream system. This type of flow takes a much greater time to reach the stream system than overland flow. Thus, the actual stream flow is influenced not only by rainfall that has fallen on the day of measurement, but also by that which fell prior to that day but did not contribute to overland, short term flow.

With this in mind, method (1) was modified to add the percentage of the daily rainfall which did not contribute to PR_{RURAL} (i.e. $PR_{RESIDUAL}$) to the following day's calculation, as follows:

As

$$PR_{RESIDUAL(d)} = 100 - PR_{RURAL(d)}$$

then

$$P_{RESIDUAL(d)} = P_{AVAILABLE(d)} * PR_{RESIDUAL(d)} / 100$$

so

$$P_{AVAILABLE(d+1)} = P_{DAILY(d+1)} + k.P_{RESIDUAL(d)}$$

where:

k is the decay factor introduced to account for some of the residual rain not being available to augment flow; for this study, k was set to 0.9.

The model was run again with this modification and this is subsequently referred to as method (2). The time series plots for this method can be seen in Figure 14. When compared with the plots for method(1), the predicted peaks in flow are higher and the predicted flow troughs are less marked. The decay from peak to trough and the rate of increase from trough to peak is generally slower than predicted by method (1) and closer to the measured time series. However, the predicted peaks still occur before the measured peaks, suggesting that the time lag between rainfall and subsequent stream flow has not been accommodated completely. This apparent improvement in fit is reflected in the regression analyses (Table 10) which show that the r^2 value for the API30 method ($r^2_{(d)}$) has increased to 0.40 with a slope of 0.89 and that for the 1-day lag applied to the API30 method ($r^2_{(d-1)}$) is 0.60, with a slope of 1.08. These results also tend to support the theory that the time lag between rainfall and the corresponding increase in stream flow is not adequately accounted for by the model.

In order to incorporate a time lag into the model and, at the same time, smooth out the over sensitive nature of the predictions, antecedent running means were used in methods (3) and (4). These were calculated over the current days prediction and its immediate two or three predecessors, respectively. The 3-day mean had the general effect of moving the predicted peaks and troughs forward to the following day. The leading and trailing edges of these predicted peaks were moved forwards by between 0 and 1.5 days, depending on the original steepness of the rise or fall. The net effect is to move the whole predicted time series closer to the measured data. The smoothing effect of the running mean also tends to augment the delay in stream flow response to the current day's rainfall. This makes the rates of increase and decrease in flow follow the measured data more closely (Figure 15 & 16).

The regression analyses (Table 10) show that the value of r^2 for the API30 method and the 3-day running mean ($r^2_{(d)}$) is 0.78 and the 4-day mean ($r^2_{(d)}$) 0.82. The slope of the regression line for methods (3) and (4) are 0.98 and 0.94, respectively. If a 1-day time lag is introduced into either of these methods, these values of r^2 fall, suggesting that the time lag has now been adequately accounted for by the running means. As the slopes of the regression lines are now close to 1, any predicted flow value should be of a similar magnitude to the measured flows.

An identical series of analyses was undertaken for the API5 method of prediction and the results of these calculations are also shown for the River Derwent at Portinscale in Figures 13 to 16 and Table 10. In general, this method did not appear to give as good results as the API30 method, showing a tendency to underestimate flows. This seemed to be due to the Soil Moisture Deficit calculation enhancing the rate of decay of flow peaks too much. This may have been due to the simplistic method of calculating the evapotranspiration component which, in vegetated areas, is significantly affected by wind velocity. This was not taken into account in the calculation of Soil Moisture Deficit. Evapotranspiration is also affected by the total daily sunshine hours which, again, was not taken into account. Any further development of the API5 method of estimating stream flow from rainfall should investigate a more accurate method of calculating evapotranspiration.

Initially, it was felt that the API5 method should give a better prediction of stream flow from rainfall data because it took SMD into account, which is an important factor in soil hydrology from April to September/October. In contrast, the API30 method was expected to significantly overestimate rates of flow during the spring and summer months because it did not contain an explicit SMD component. The time series plots for methods (3) and (4) (Figure 15 & 16) show that this is not the case. The variation of the CWI used in the API30 method, which used a 30-day API, appeared to characterise the catchment moisture conditions better than the API5 method, which used a 5-day API. This may have been a true reflection of the situation or may have been the result of poor estimation of SMD in the API5 method.

The results of the linear regression analyses (Table 10)suggested that method (3) should be used to predict the stream flows for the other subcatchments of the Bassenthwaite catchment. Both the API30 and API5 variants were used. An important factor when calculating the runoff was the choice of rainfall gauges used to obtain the rainfall data, as these affected the final result for any particular subcatchment. For the puposes of this study, a subjective assessment of the most suitably located gauges was carried out for each subcatchment and a simple arithmetic mean of the rainfall for each day was calculated from the gauges chosen. Time series plots of the measured and predicted stream flows for subcatchments 1, 2, 3, 4, 5, 6, 9, 10, 11, 12, 13 and 14 are shown in Appendix IV.

The results suggest was that the timing of significant changes in flow was predicted well in most cases, except in subcatchment 6 (Figure IV(f)). The good alignment between the short sections of close interval flow measurements for subcatchments 1, 2, 10 and 11 and the predicted values indicates that the timing and, to some extent, the magnitude of the flows have been predicted well, apart from one peak in subcatchment 1, at the end of March 1993. The angle of rise or fall of these sections, coupled with the correspondence in timing between the measured and predicted flows, suggests that the peaks and troughs would have been predicted well, if there had been any measured data to compare them with.

In general, it was difficult to assess how well the magnitude of the flow was predicted for each subcatchment because of the discontinuous nature of the measured data. Linear regression analyses were attempted for all of the subcatchments studied and the values of r^2 for these ranged from 0.18, for subcatchment 9, to 0.68, for subcatchment 5. There are a number of possible reasons for this. Firstly, the measured flows in 7 out of the 12 subcatchments tested exceeded the flow gauge limits on occasion which tended to reduce any 'goodness of fit' measure for the predicted and measured data. Secondly, the measured rainfall varied considerably among the rain gauges, suggesting variation in rainfall over the subcatchments. The choice of suitable rain gauges to estimate rainfall for each subcatchmen seemed to be importantt, especially when there are no rain gauges inside the subcatchment and there was some uncertainty as to which were the most suitable rainfall data for a number of the subcatchments. It would be useful, but potentially time consuming, to use the GIS to interpolate rainfall surfaces across the whole catchment on a daily basis, in order to obtain a better estimate of rainfall in any one subcatchment. Thirdly, it may be necessary to accommodate some measure of slope and distance to streams into the model in order to account for topographic and size differences between subcatchments. Small, steep subcatchments would be expected to respond much more quickly to rainfall events than large, shallow subcatchments. Preliminary assessment of slope and total area characteristics for the subcatchments with poor correlation statistics tends to suggest that slope may be an impotant factor to take into consideration.

Again, the API30 method proved to be the better method for prediction as the API5 method consistently understimated the magnitude of the few peaks that were available for comparison.

6. DISCUSSION

The so-called export coefficient approach is widely used to estimate TP runoff from land cover within a catchment, especially now that geographical information systems (GIS) are widely available. However, the results of these calculations are rarely validated against data collected from intensive field surveys, as they are in the present study. May *et al.* (1995) showed that TP export from some types of land cover in the catchment of Bassenthwaite Lake was not adequately predicted using export coefficients from the published literature. This was especially true for areas of coniferous forest, where TP losses were overestimated by as much as 400%.

At first sight, these results suggest that the TP export coefficients determined for coniferous forests in Scotland could not be used on the same type of land cover in the Lake District. However, it seems more likely that recent changes in forestry practice, aimed at reducing soil erosion and nutrient runoff, have reduced TP losses from afforested catchments since these earlier determinations. This study suggests that these changes may have reduced TP losses from coniferous forests from 0.42 kg ha^{-1} yr^{-1} to 0.04 kg ha^{-1} yr^{-1}, a reduction of about 90%.

Although, historically, phosphorus export coefficients for different types of land cover have been developed for TP, it is actually the load of bioavailable phoshorus (OP) which is of most concern to water managers because it is this soluble fraction which tends to promote algal growth. This report discusses predictions of TP losses from the catchment in order to compare the results with those of May *et al.* (1995). However, the field survey work carried out by Lawlor & Tipping (1996) actually determined export coefficients for soluble reactive phosphorus (SRP, otherwise known as OP) for areas within the Bassenthwaite catchment. This provides an opportunity for the GIS model to be re-run at a later date to predict OP loads to the lake. As Lawlor & Tipping (1996) also calculated export coefficients for the other main algal nutrients, namely NO_3 and SiO_2, determination of the load of these nutrients to the lake from diffuse sorces will also be possible.

The export coefficient approach, as it stands, predicts only the *annual* nutrient load to a lake from diffuse sources. In order to achieve the long term aim of using the output from the GIS as input to the dynamic lake model (Hilton *et al.*, 1993) it is necessary to introduce temporal variation into the nutrient loss predictions. The simplest way to do this is probably to derive a relationship between nutrient runoff and rainfall, *via* the effect of rainfall on stream flow. This report has gone some way towards achieving this by developing a model for the catchment which predicts stream flow from rainfall. This model is based on a modification of the HOST classes rainfall-runoff model (Boorman *et al.*, 1995).

The results suggest that this modified rainfall-runoff model is an effective way of predicting stream flow from rainfall and catchment scale parameters. It does not require any field data as input, thus fulfilling one of the the main objectives of this study. Although the results are encouraging, the method needs to be validated on other types of catchment (with differing land cover, soil types and topography), and modified where necessary, whilst retaining its generic nature.

Another potential area for future development is to try to predict the lag between a rainfall event and the subsequent increase in stream flow, without having to resort to comparisons with field data. This would probably have to take into account land cover, soil type, slope, stream length and variations in these characteristics within the subcatchment or catchment. The proximity of these characteristics to each other may also be an important consideration. As all of these variables can be derived from the datasets currently within the GIS, it would still be possible to develop a 'hands off' or 'no field measurement' predictive model whilst incorporating these variables.

7. CONCLUSIONS

1. The use of soils data and TP export coefficients determined for the catchment did not improve on the TP runoff predictions based on land cover and published export coefficients, except in the case of afforested areas .

2. Land cover tends to reflect the underlying soil type, so either dataset could be used for calculating TP losses from diffuse sources. However, there are more TP export coefficients available in the literature for land cover than for soil type.

3. Although, historically, phosphorus losses from catchments have been measured as TP, it might be better to develop a series of export coefficients for OP, as this is the fraction of phosphorus which is bioavailable and tends to promote algal growth in lakes.

4. The HOST classes rainfall-runoff model works well for the catchment of Bassenthwaite Lake, although some minor modifications improved the level of fit.

5. The ability to predict temporal variation in runoff from daily records of rainfall, in and around the catchment, provides an opportunity to introduce temporal variation into the nutrient runoff estimations. This would allow catchment model to be linked directly to the dynamic lake model.

8. RECOMMENDATIONS

The prediction of nutrient runoff from diffuse sources within a catchment, using the export coefficient approach, would benefit from the following:

- extending the range of nutrients considered to include OP, NO_3, and SiO_2, as these also affect algal growth

- introducing temporal variation into the nutrient loss predictions, by developing a method of estimating levels of nutrient loss from rainfall, *via* its effect on runoff

- evaluating the use of a range of land cover maps, from different sources, for predicting nutrient losses from diffuse sources within a catchment

- improving estimates of TP losses from STWs and septic tanks, especially in relation to the effects of tourism on seasonal loads

- estimating historical TP levels, determined from sediment analyses and historical land cover maps, to establish a baseline against which current TP loads can be assessed and targets for improvement set

It is important, however, that any work carried out on the above contributes towards the original aim of the project which was to develop a generic model for use on any lake catchment.

9. ACKNOWLEDGEMENTS

We thank the Lake District National Parks Authority, Kendal, for data on land cover. The soils data was kindly supplied by the Soil Survey and Land Reserach Centre, Cranfield University, while the corresponding export coefficients were provided by Mr A J Lawlor and Dr E Tipping, IFE Windermere laboratory. We are also grateful to the NRA, for providing the relevant field measurements of water quality and flow, and to Simon Courtney and Jane Roberston (NERC Computer Services), for their help in solving technical problems. Some features of the maps in Figures 4, 5 and 6 are based on digital spatial data licenced from the IH.

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FIGURES

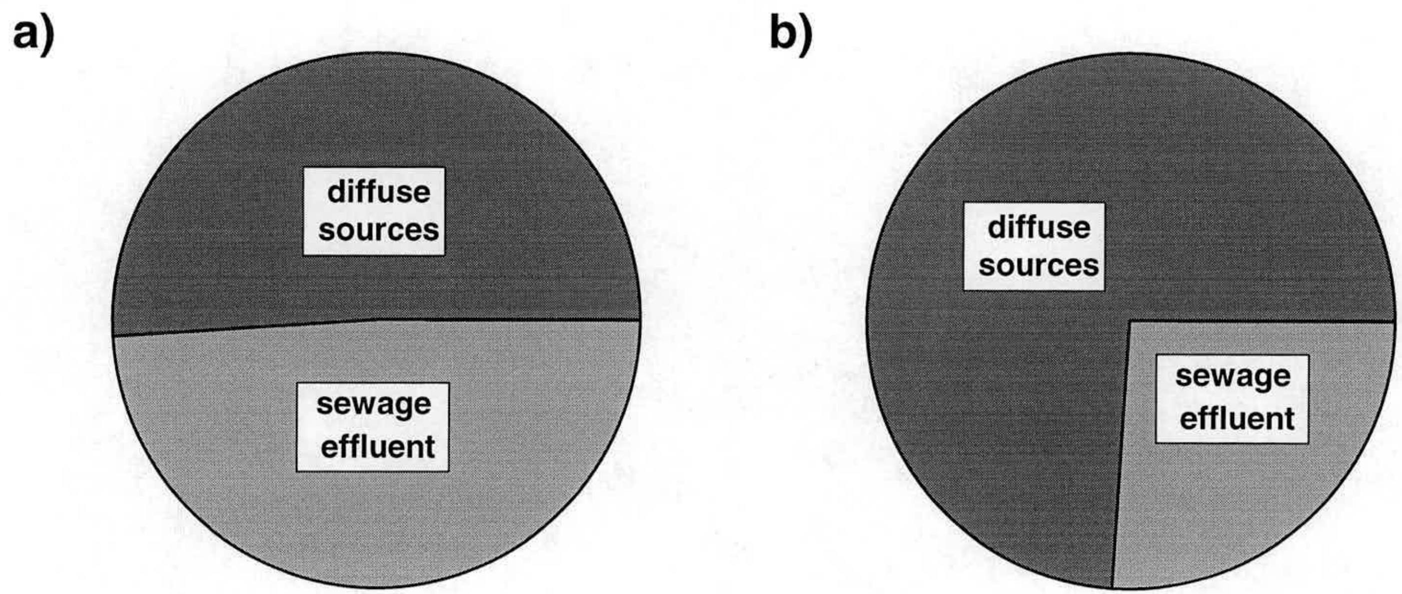


Figure 1. Relative importance of TP loads from diffuse sources and sewage effluent (a) before and (b) after the STW upgrade.

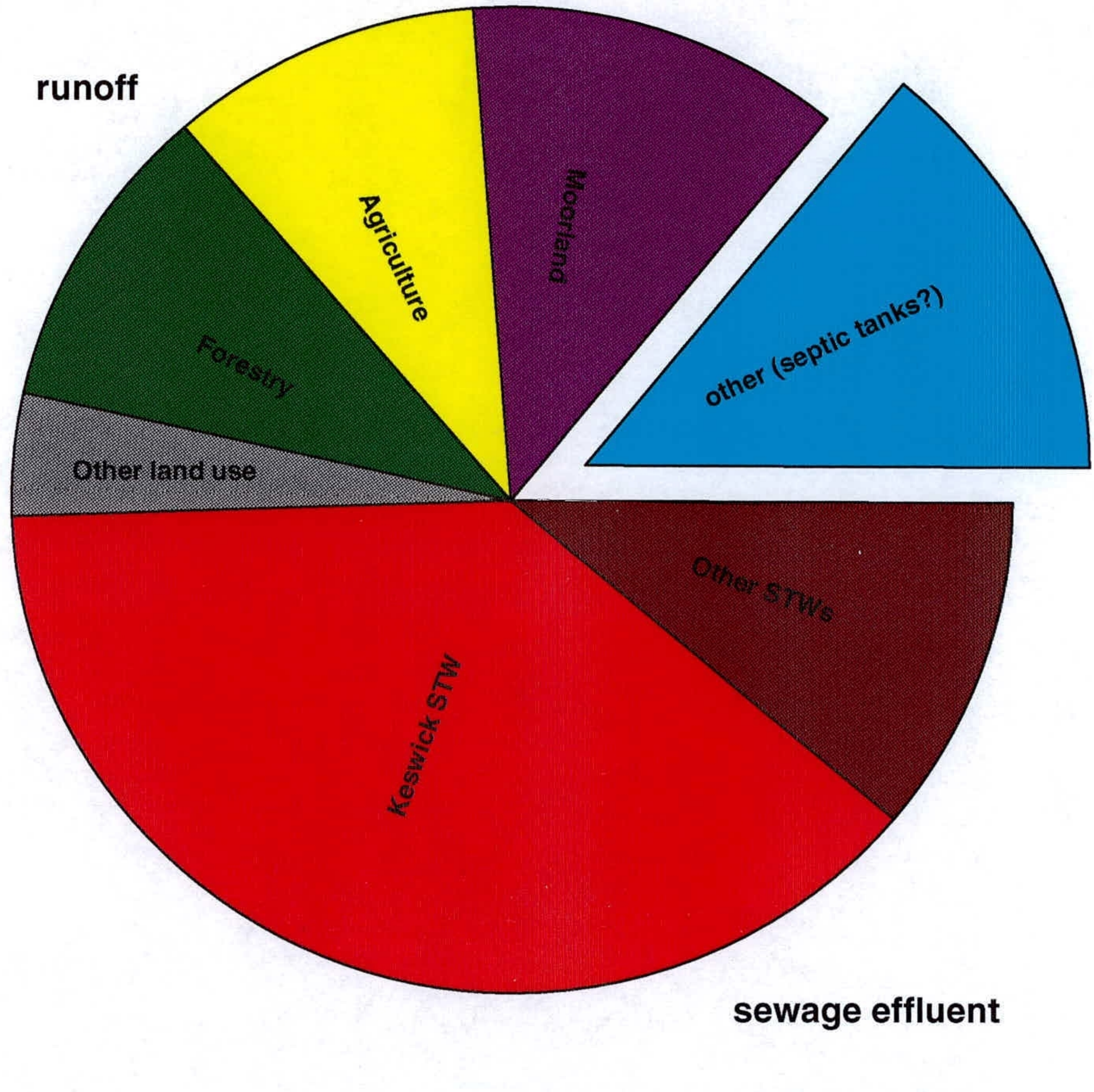


Figure 2. Relative proportions of TP load from STW effluent, different types of land cover and other sources.

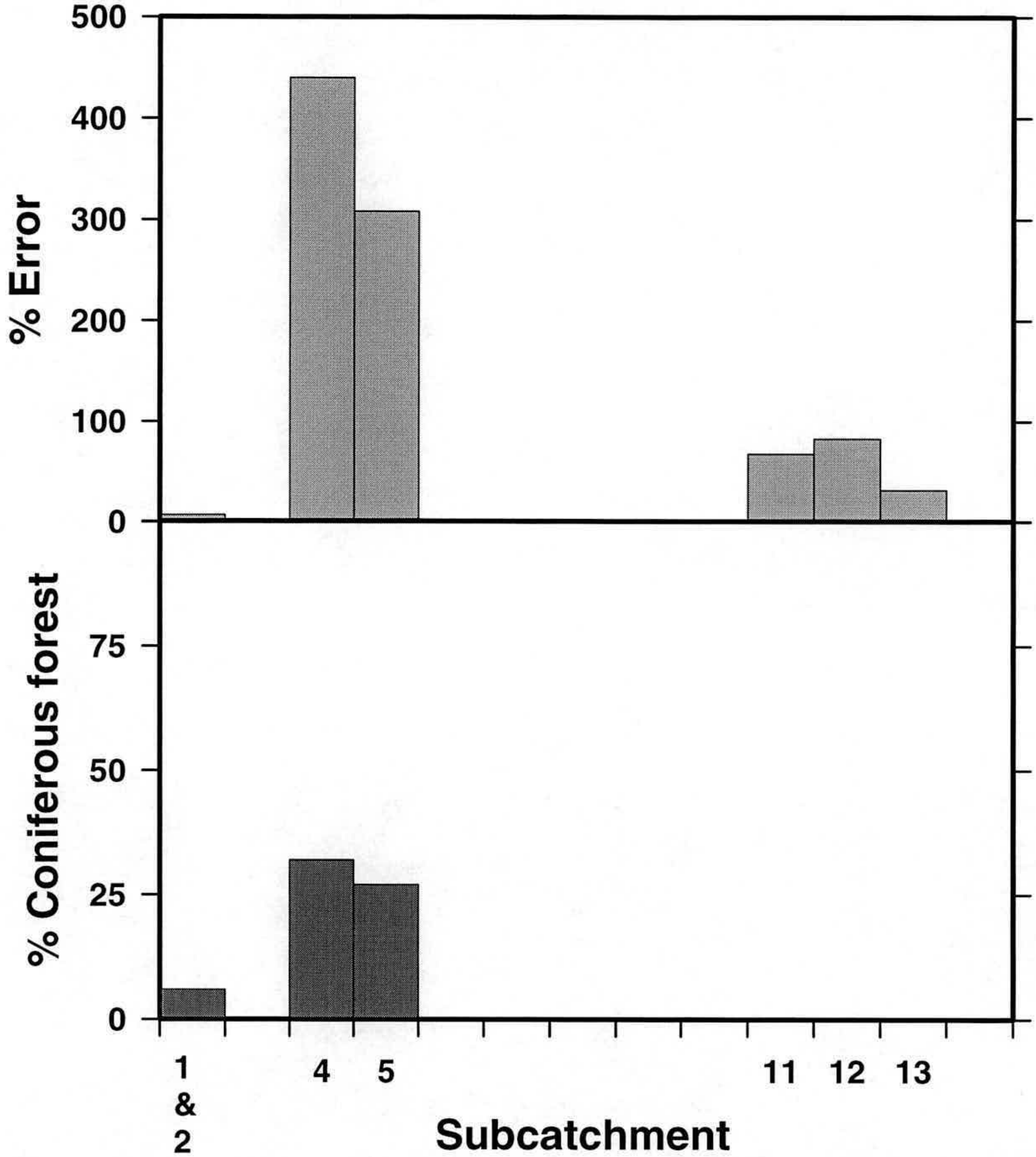
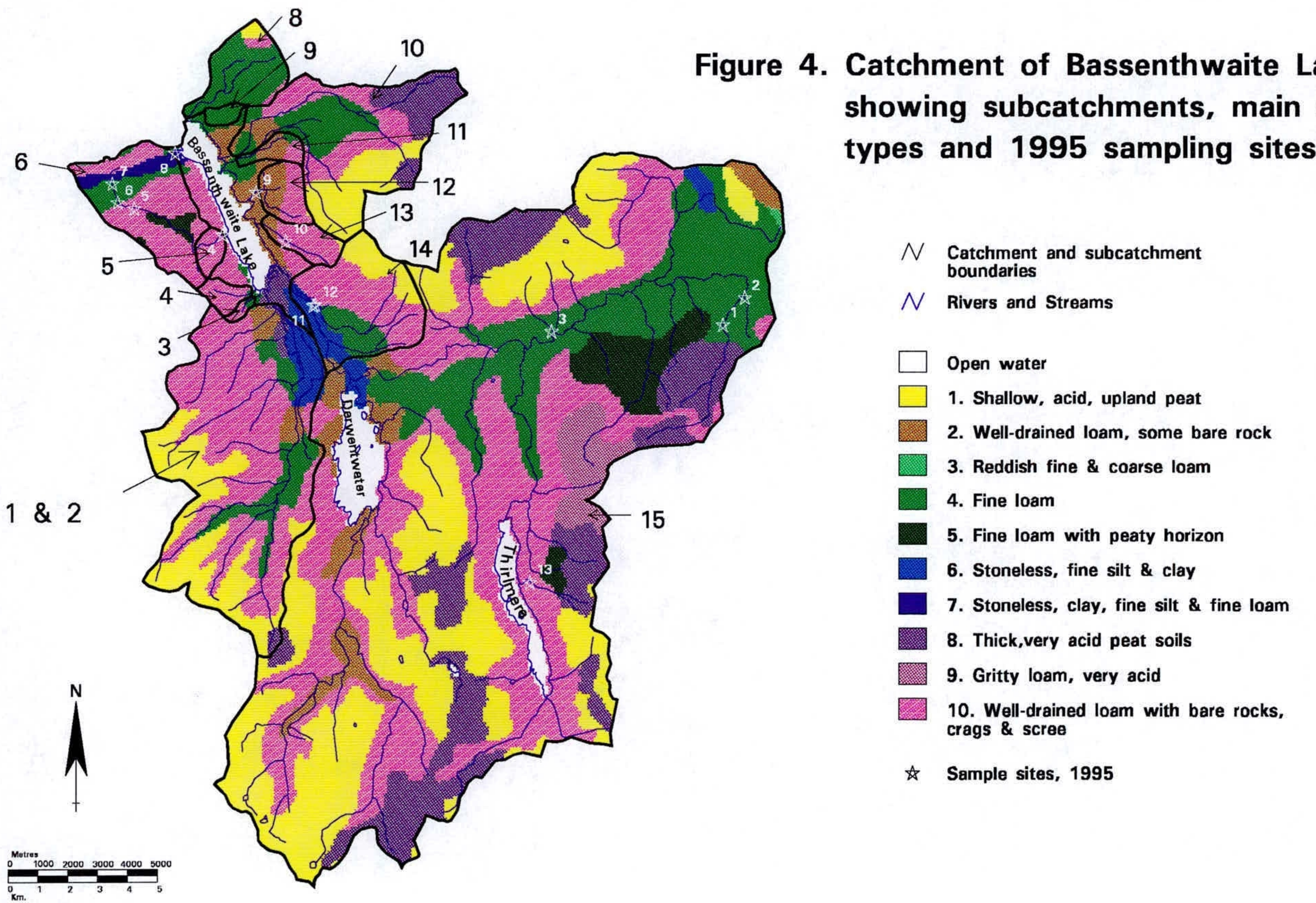


Figure 3. Relative error in TP loss estimates for subcatchments with no known point sources, in relation to percentage cover by coniferous forest.

Figure 4. Catchment of Bassenthwaite Lake showing subcatchments, main soil types and 1995 sampling sites.



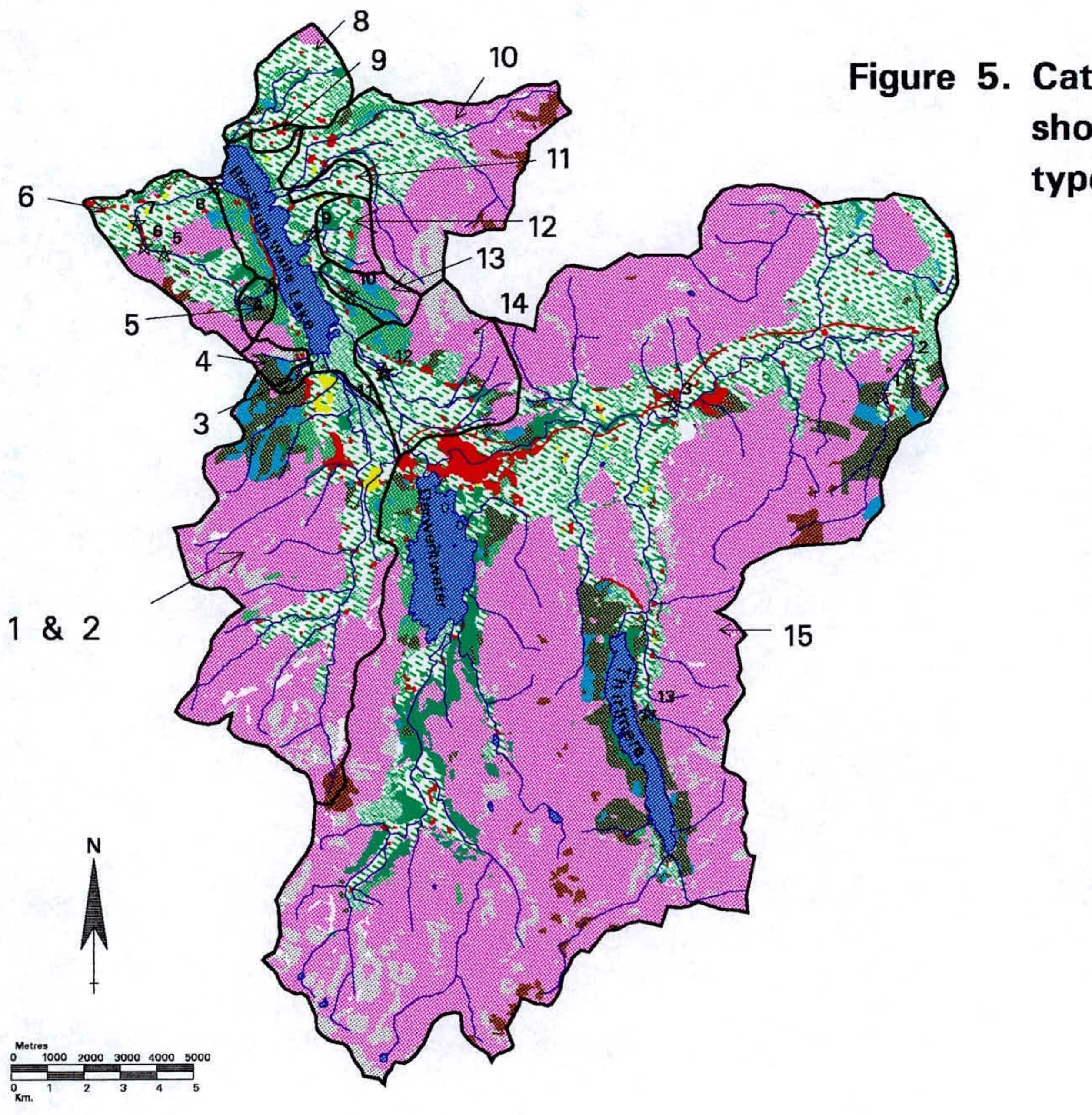


Figure 5. Catchment of Bassenthwaite Lake showing subcatchments, land cover types and 1995 sampling sites.

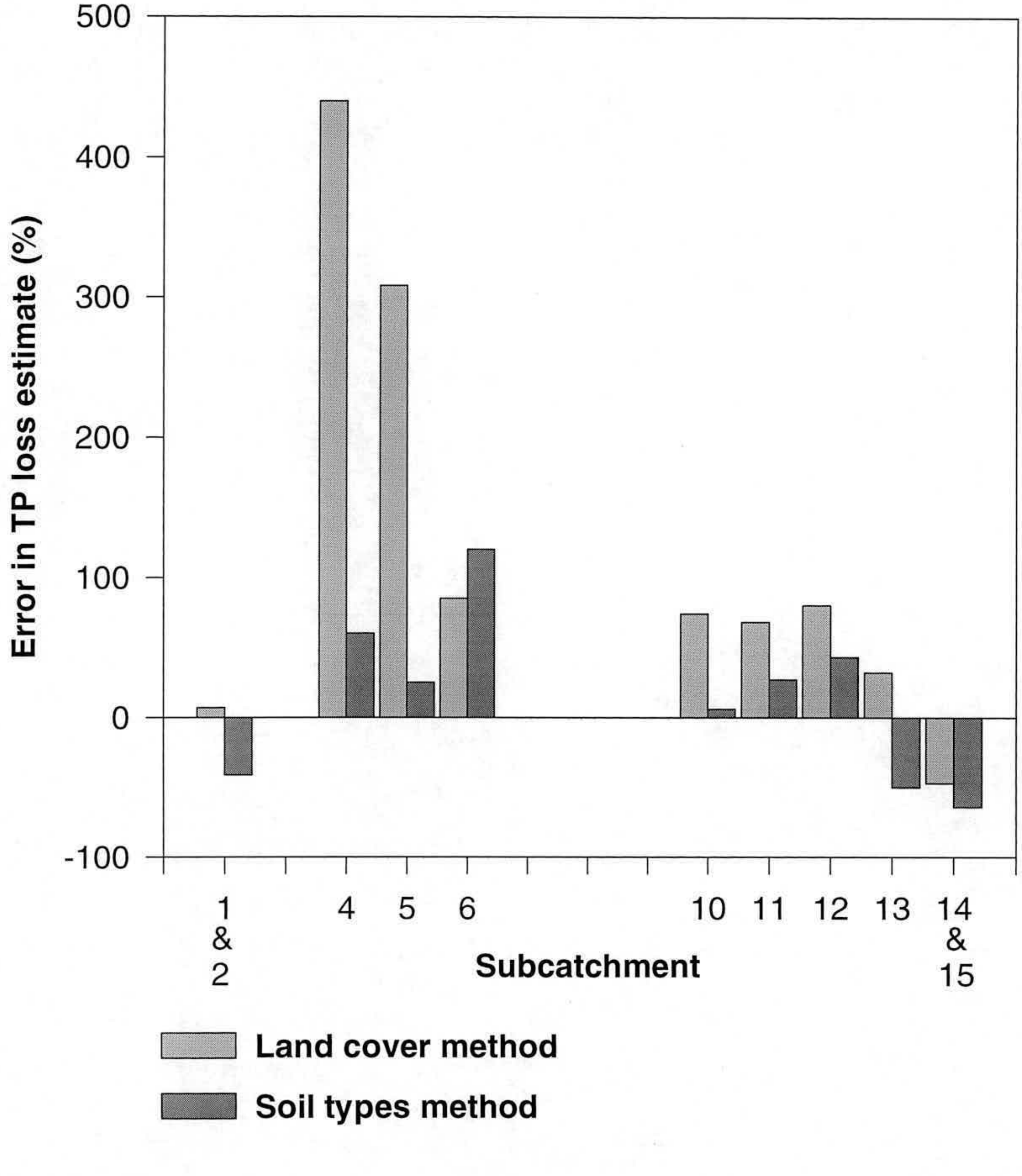


Figure 6. Estimates of TP load from diffuse sources for subcatchments of Bassenthwaite Lake.

Figure 7. Land cover in relation to soil types 1 to 5 in the Bassenthwaite catchment.

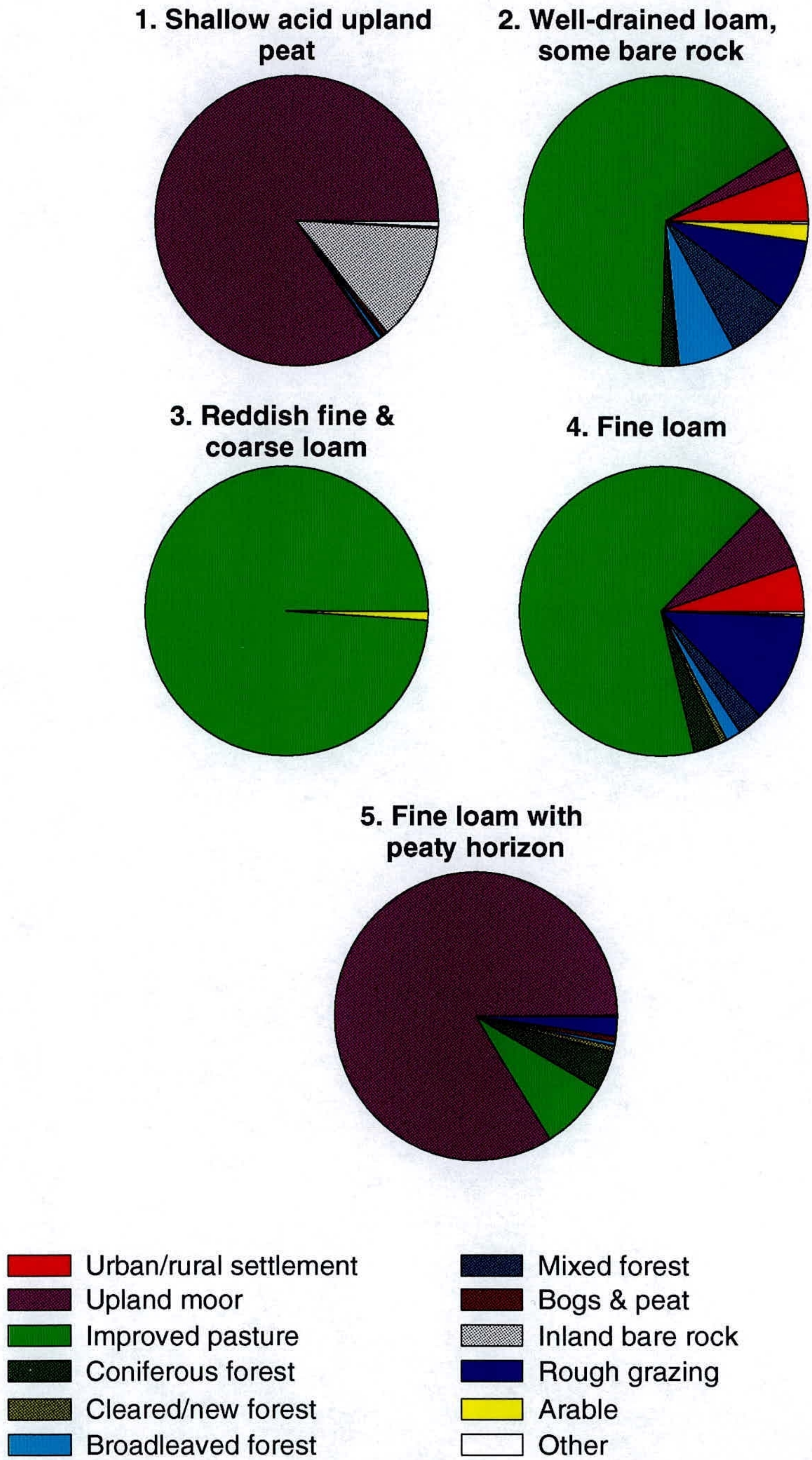

1. Shallow acid upland peat
2. Well-drained loam, some bare rock
3. Reddish fine & coarse loam
4. Fine loam
5. Fine loam with peaty horizon
Urban/rural settlement
Upland moor
Improved pasture
Coniferous forest
Cleared/new forest
Broadleaved forest
Mixed forest
Bogs & peat
Inland bare rock
Rough grazing
Arable
Other

Figure 8. Land cover in relation to soil types 6 to 10 in the Bassenthwaite catchment.

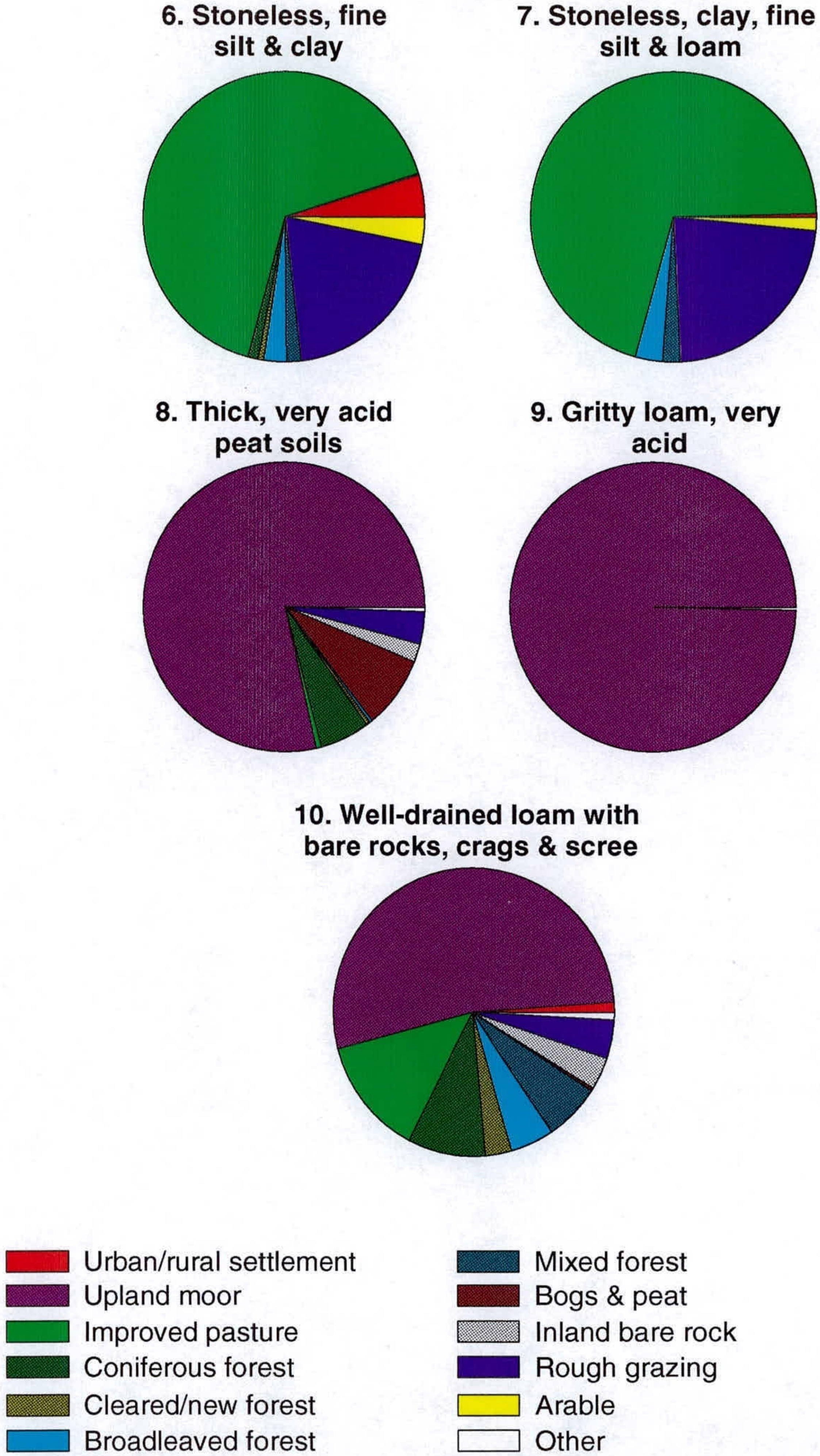

6. Stoneless, fine silt & clay
7. Stoneless, clay, fine silt & loam
8. Thick, very acid peat soils
9. Gritty loam, very acid
10. Well-drained loam with bare rocks, crags & scree
Urban/rural settlement
Upland moor
Improved pasture
Coniferous forest
Cleared/new forest
Broadleaved forest
Mixed forest
Bogs & peat
Inland bare rock
Rough grazing
Arable
Other

Figure 9. Soil type in relation to land cover in the Bassenthwaite catchment.

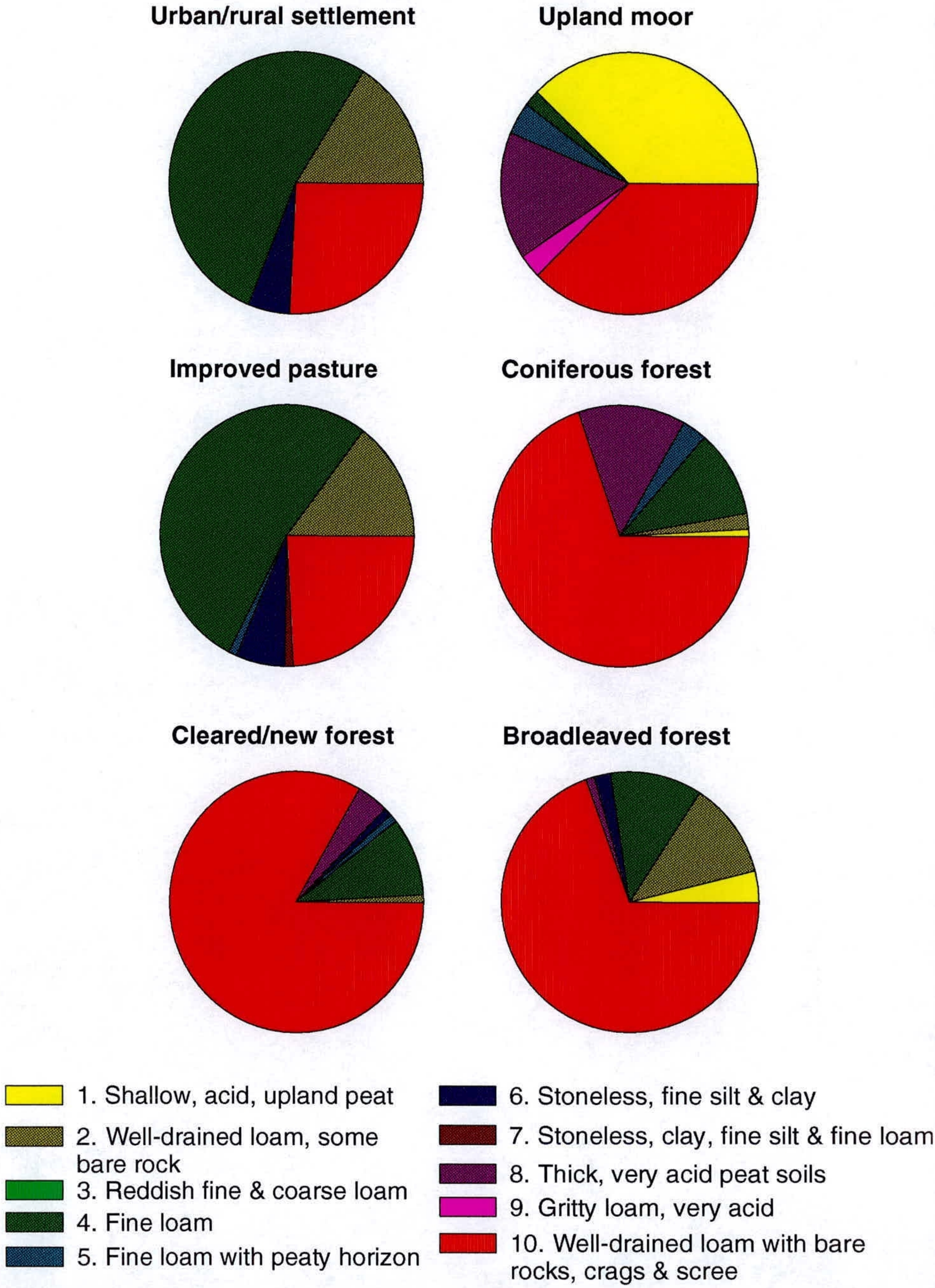
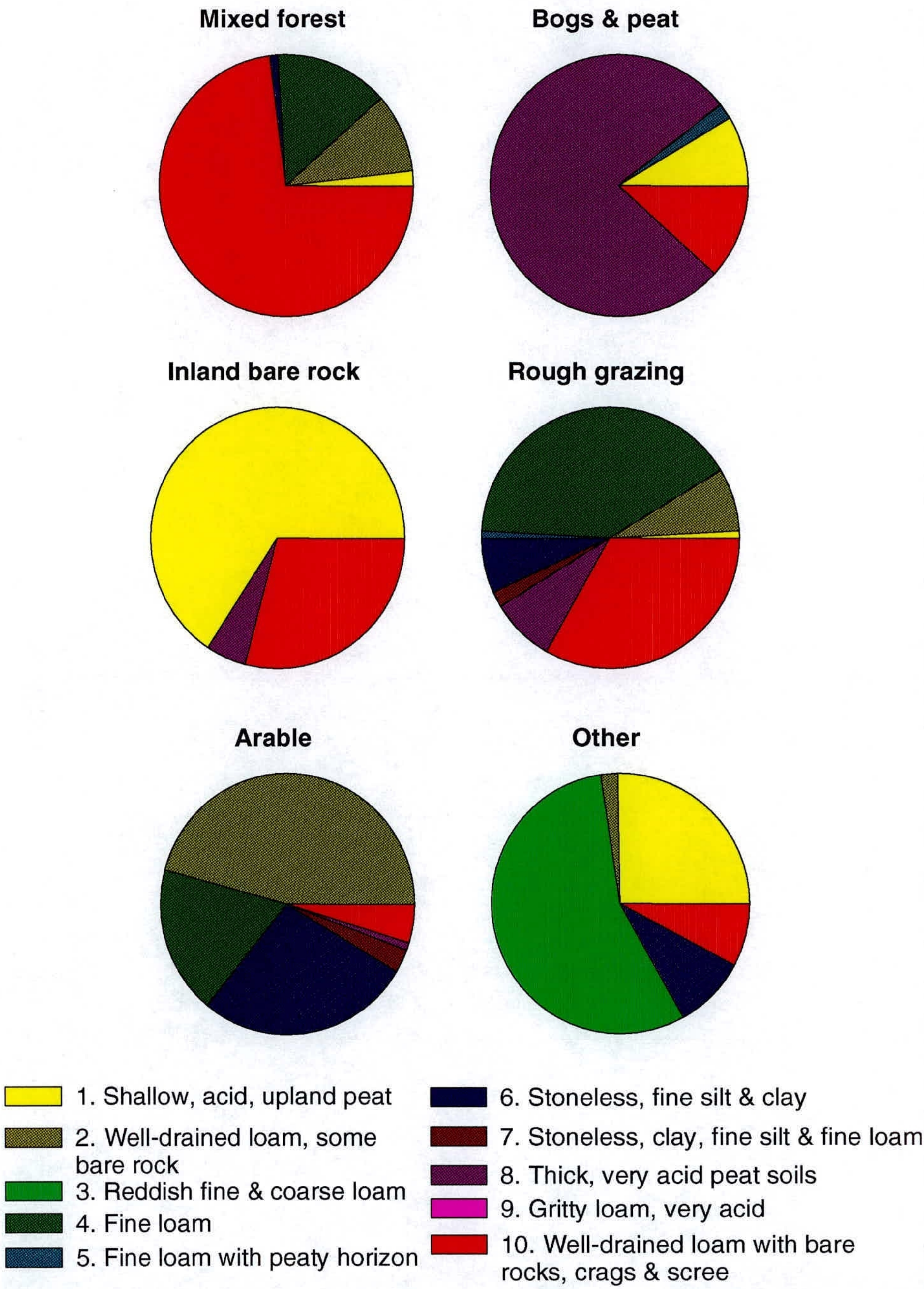

Urban/rural settlement
Upland moor
Improved pasture
Coniferous forest
Cleared/new forest
Broadleaved forest
1. Shallow, acid, upland peat
2. Well-drained loam, some bare rock
3. Reddish fine & coarse loam
4. Fine loam
5. Fine loam with peaty horizon
6. Stoneless, fine silt & clay
7. Stoneless, clay, fine silt & fine loam
8. Thick, very acid peat soils
9. Gritty loam, very acid
10. Well-drained loam with bare rocks, crags & scree

Figure 10. **Soil type in relation to land cover in the Bassenthwaite catchment.**


Mixed forest
Bogs & peat
Inland bare rock
Rough grazing
Arable
Other
1. Shallow, acid, upland peat
2. Well-drained loam, some bare rock
3. Reddish fine & coarse loam
4. Fine loam
5. Fine loam with peaty horizon
6. Stoneless, fine silt & clay
7. Stoneless, clay, fine silt & fine loam
8. Thick, very acid peat soils
9. Gritty loam, very acid
10. Well-drained loam with bare rocks, crags & scree

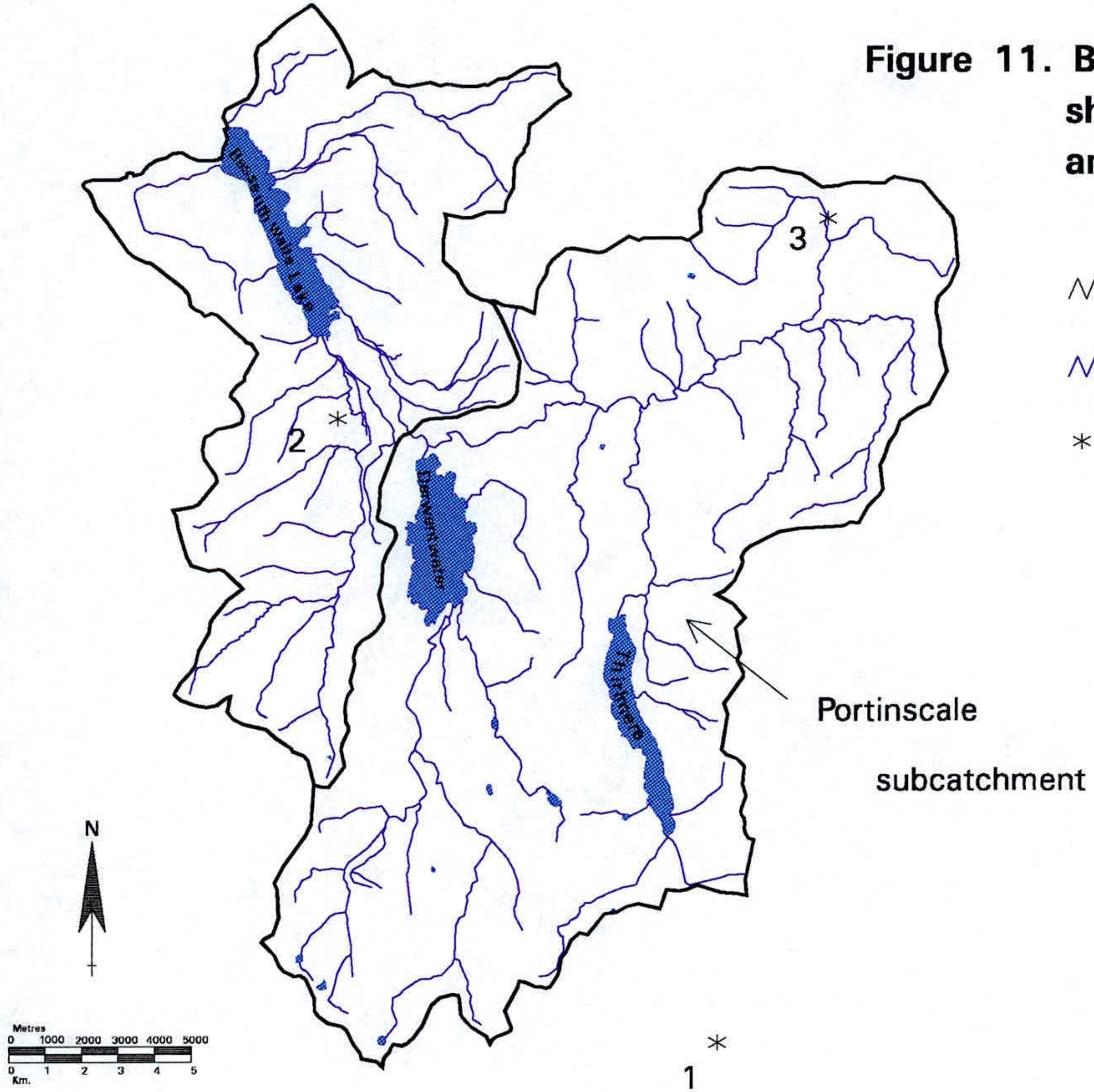


Figure 11. Bassenthwaite Lake and catchment showing rain gauge locations and Portinscale subcatchment

Polygon Attribute Table				
Area	Perimeter	ubcatsoil	subcatsoil-id	soilcode
159422.234	2893.967	2	120	246
255301.75	2845.035	3	122	234
10206205	29527.559	4	121	170
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....

1) Total area in subcatchment calculated for each soilcode. Each total is calculated as a fraction of the whole subcatchment.

Summary Table		
area	area fraction	soilcode
159422.23	0.0048	246
3692952.75	0.1103	234
16429052.13	0.4906	170
.....	.....	.....
.....	.....	.....

2) Soilcode area fraction summary table linked via the soilcode field to a look up table defining Host Class composition for relevant soilcodes.

Soil Series to Host Class Look Up Table

soilcode	series	host_ 1	host_ 2	host_ 3	host_ 4	host_ 5	host_ 6	host_ 7	host_ 8	host_ 9	host_ 10	host_ 11	host_ 12	host_ 13	host_ 14	host_ 15	host_ 16	host_ 17	host_ 18	host_ 19	host_ 20	host_ 21	host_ 22	host_ 23	host_ 24	host_ 25	host_ 26	host_ 27	host_ 28	host_ 29	Host Total
10	Bangor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	57.14	0.00	42.86	100.00
234	Brickfield2	0.00	0.00	0.00	0.00	0.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	26.67	0.00	0.00	53.33	0.00	0.00	0.00	0.00	0.00	100.00
170	Manod	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	87.50	0.00	0.00	0.00	0.00	12.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
291	Winter Hill	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	100.00
82	Ellerbeck	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
7	Skiddaw	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	53.33	0.00	13.33	100.00
256	Fladbury3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	88.89	11.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
78	Waltham	0.00	0.00	0.00	55.56	0.00	44.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
64	Newbiggin	0.00	0.00	0.00	0.00	0.00	65.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
246	Conway	0.00	0.00	0.00	0.00	0.00	0.00	0.00	23.53	76.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
210	Clifton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.05	0.00	0.00	0.00	0.00	0.00	68.42	0.00	0.00	0.00	0.00	0.00	100.00
242	Wilcocks1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	88.89	0.00	0.00	0.00	100.00
290	Longmoss	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
168	Malvern	0.00	0.00	0.00	28.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	71.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
191	Hexworthy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00

3) The product of the link to the look up table is a table identifying the fraction of the subcatchment categorised as a particular Host Class

4) The Host Class area fraction table is linked to a look up table which determines the Standard Percentage Runoff(SPR) coefficient per Host Class

SPR Coefficient Table	
spr coefficient	host class
2	1
2	2
14.5	3
2	4
14.5	5
33.8	6
44.3	7
44.3	8
25.3	9
25.3	10
2	11
60	12
2	13
25.3	14
48.4	15
29.2	16
29.2	17
47.2	18
60	19
60	20
47.2	21
60	22
60	23
39.7	24
49.6	25
58.7	26
60	27
60	28
60	29

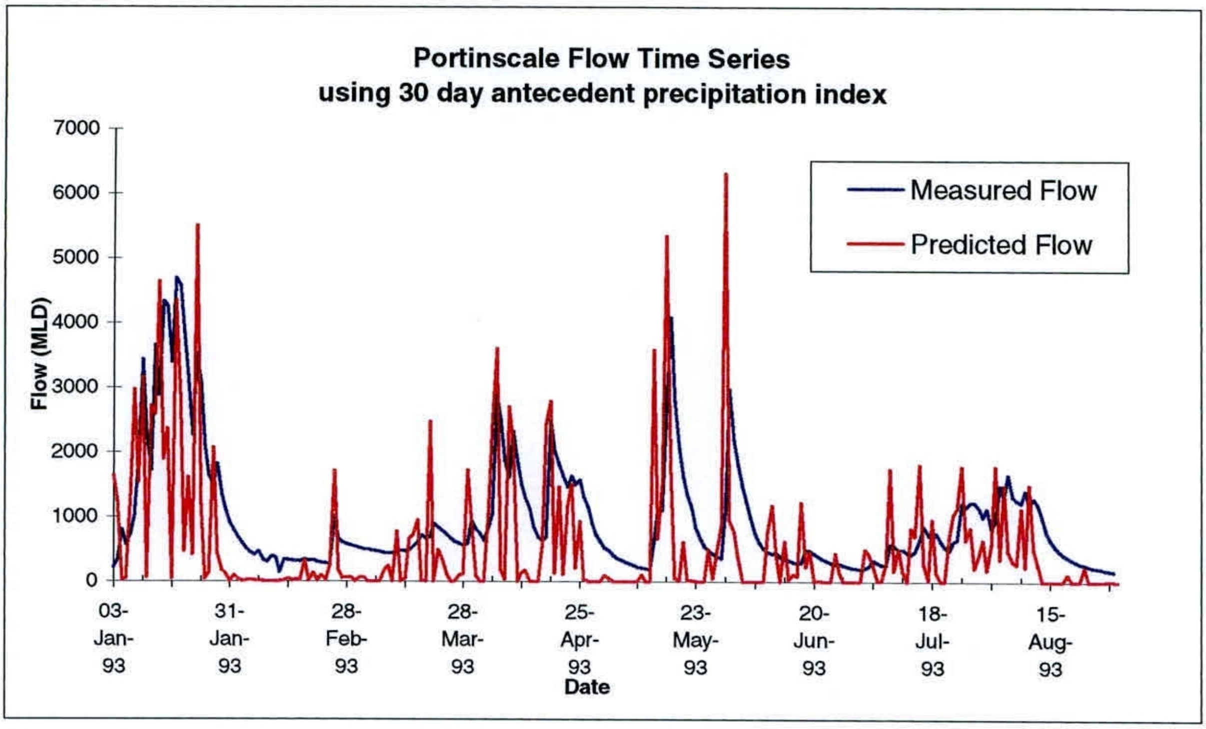
Host Class Area Table	
host class	Host class area fraction
1	0.000
2	0.000
3	0.000
4	0.000
5	0.019
6	0.022
7	0.000
8	0.001
9	0.004
10	0.000
11	0.000
12	0.000
13	0.000
14	0.000
15	0.112
16	0.000
17	0.429
18	0.000
19	0.000
20	0.000
21	0.029
22	0.061
23	0.000
24	0.059
25	0.000
26	0.000
27	0.196
28	0.000
29	0.067
total	1.000

5) The product of the look up table and the area fractions gives a composite Standard Percentage Runoff(SPR) for the subcatchment.

SPR = 42.3116

Process for defining The Standard Percentage Runoff Coefficient for the whole subcatchment. The example here is subcatchment No. 1, Newlands Beck.

Figure 12. Flow Chart for SPR determination



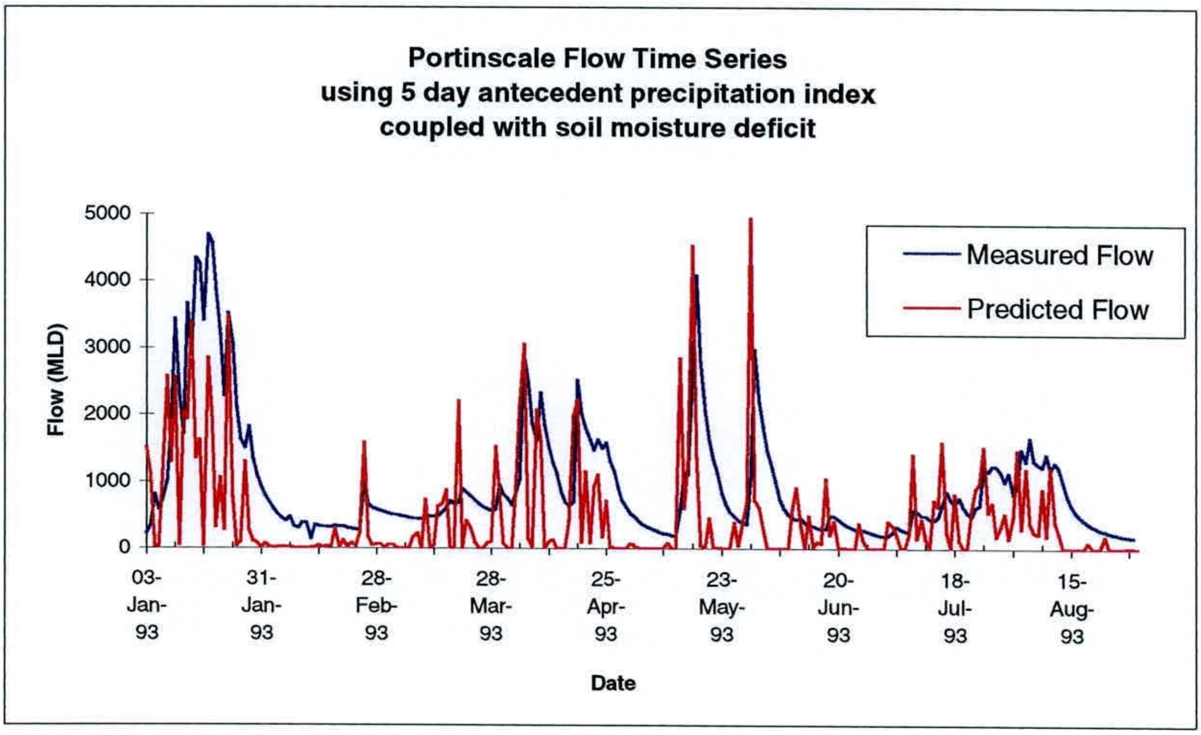
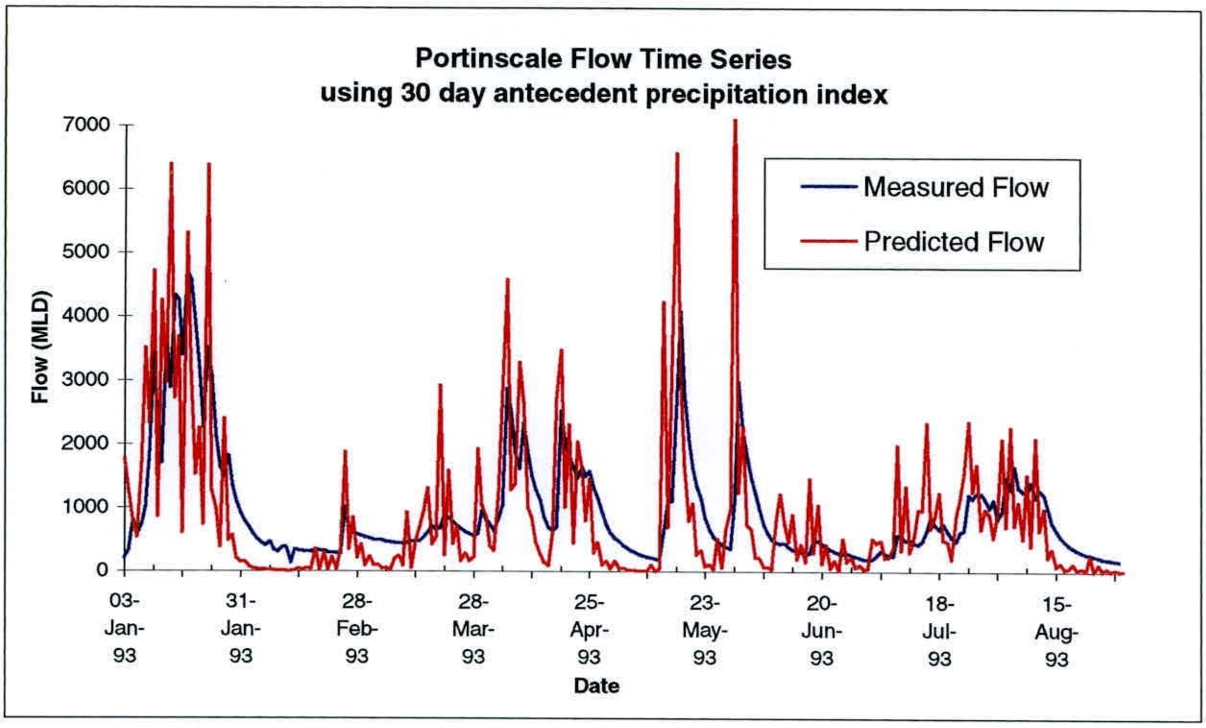


Figure 13. Flow Time Series for subcatchment 15 (method [1])



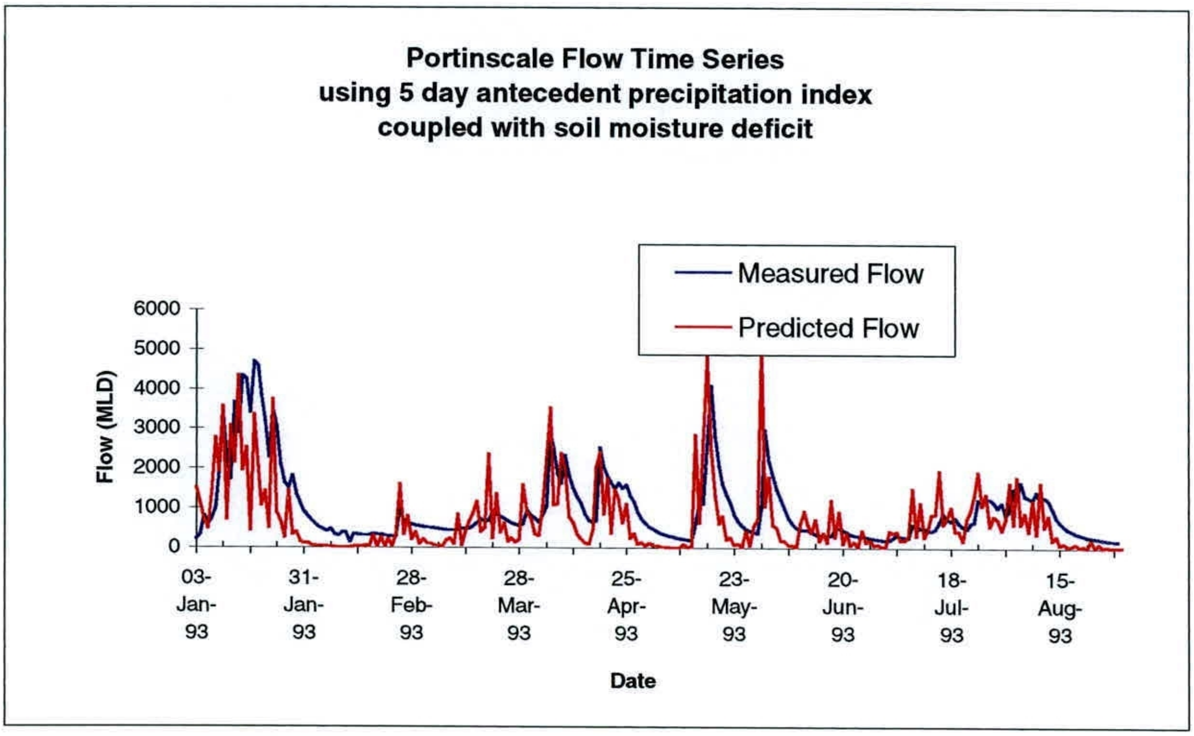
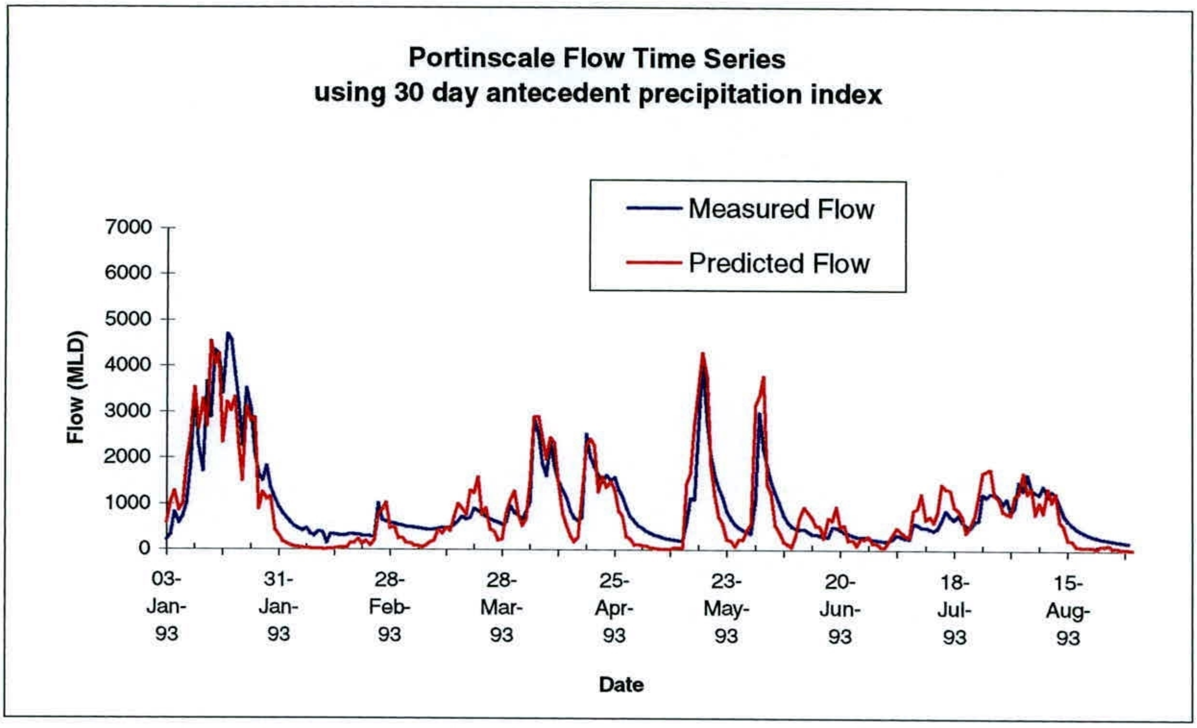


Figure 14. Flow Time Series for subcatchment 15 (method [2])



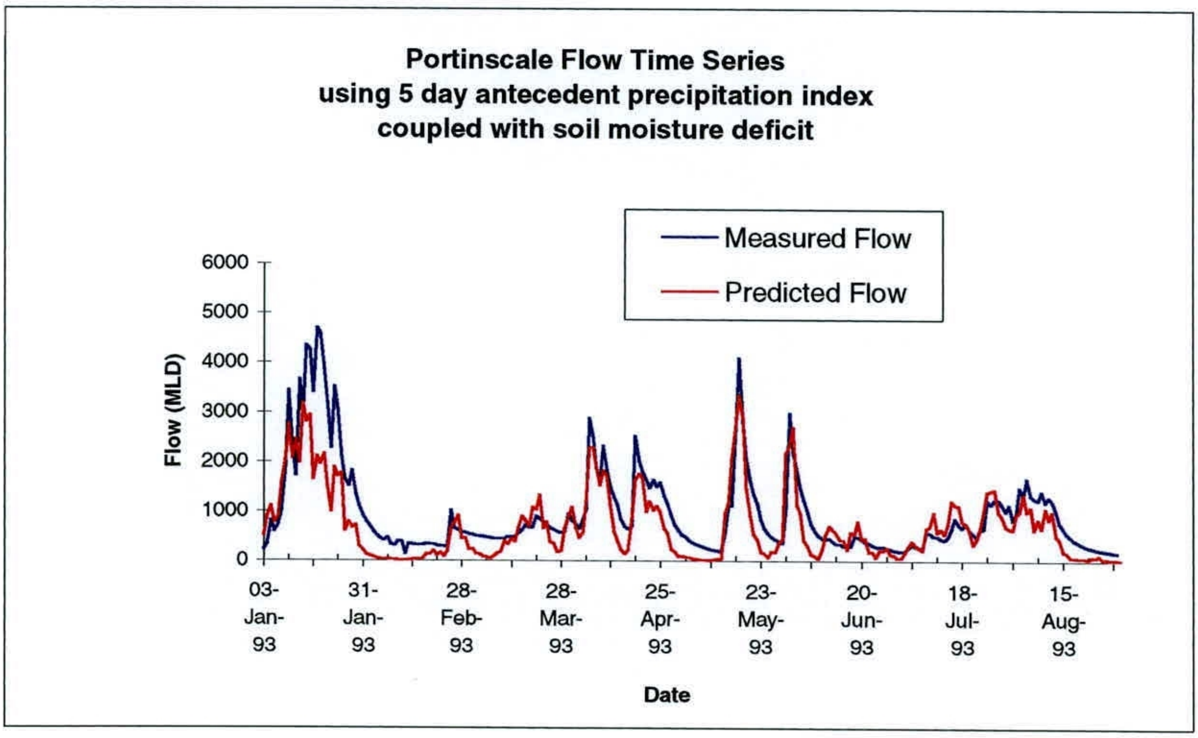
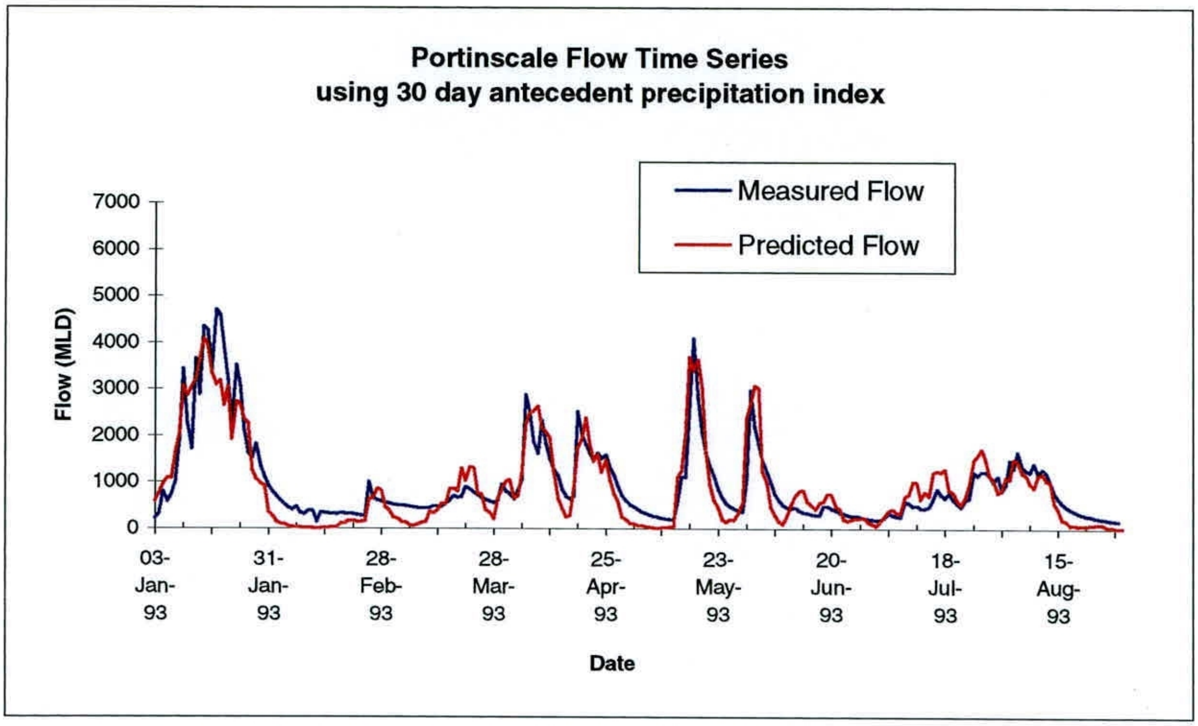


Figure 15. Flow Time Series for subcatchment 15 (method [3])



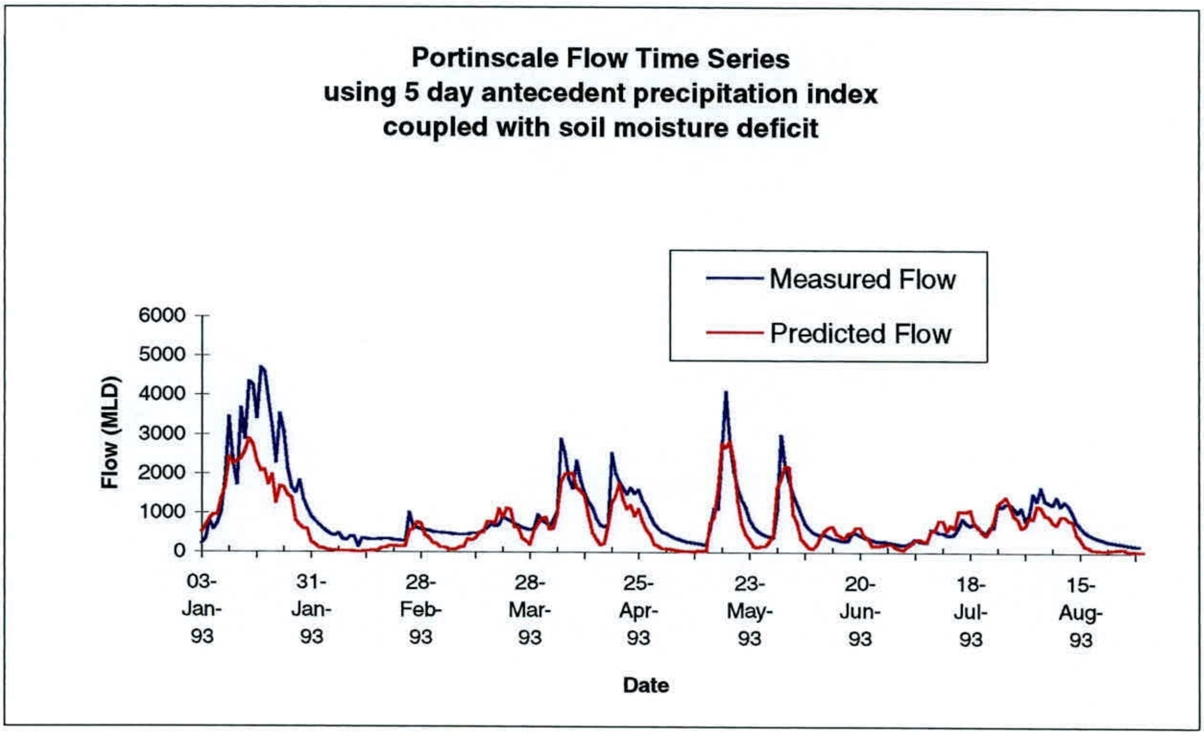


Figure 16. Flow Time Series for subcatchment 15 (method [4])

APPENDICES

Appendix I. TP export in relation to soil type in the Bassenthwaite catchment.

a) Whole catchment

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
1	8,249	24	346
2	1,760	5	426
3	20	0	3
4	5,720	16	921
5	922	3	201
6	658	2	217
7	138	0	195
8	3,763	11	508
9	610	2	133
10	12,945	37	1,592
	34,784	100	4,542

b) Subcatchments 1&2

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
1	1,225	27	51
2	180	4	44
4	512	11	82
6	239	5	79
8	95	2	13
10	2,372	51	292
	4,624	100	561

c) Subcatchment 3

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
4	11	29	2
10	27	71	3
	38	100	5

d) Subcatchment 4

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
4	5	4	1
10	124	96	15
	128	100	16

e) Subcatchment 5

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
10	121	100	15
	121	100	15

f) Subcatchment 6

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
4	190	16	31
5	86	7	19
7	124	11	176
10	765	66	94
	1,165	100	319

g) Subcatchment 8

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
1	34	6	1
4	515	86	83
10	48	8	6
	598	100	90

h) Subcatchment 9

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
4	74	100	12
	74	100	12

i) Subcatchment 10

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
1	586	27	25
2	88	4	21
4	468	21	75
8	443	20	60
10	602	28	74
	2,188	100	255

j) Subcatchment 11

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
2	70	47	17
4	35	24	6
10	42	29	5
	147	100	28

k) Subcatchment 12

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
1	5	2	0
2	129	46	31
10	150	53	18
	284	100	50

l) Subcatchment 13

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
1	8	3	0
2	31	12	8
10	212	84	26
	252	100	34

m) Subcatchment 14

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
1	243	19	10
2	21	2	5
4	213	16	34
6	179	14	59
8	3	0	0
10	638	49	79
	1,298	100	188

n) Subcatchment 15

SOIL TYPE	AREA (HA.)	AREA (%)	TP EXPORTED (KG/Y)
1	6,146	27	258
2	958	4	232
4	3,563	15	574
5	20	0	4
5	836	4	182
6	195	1	64
8	3,114	14	420
9	610	3	133
10	7,561	33	930
	23,003	100	2,798

Appendix II. Land cover in relation to soil type in the Bassenthwaite catchment.

	Landuse code	Area (ha.)	Area (%)
SOIL TYPE 1			
Upland moor	200	6940.651	84.27
Improved pasture	300	5.236	0.06
Bogs & peat	800	34.655	0.42
Inland bare rock	900	1109.196	13.47
Other	1200	50.359	0.61
Rough grazing	1000	18.253	0.22
Coniferous forest	400	15.693	0.19
Broadleaved forest	600	37.684	0.46
Mixed forest	700	23.805	0.29
Cleared/new forest	500	0.757	0.01
		8236.289	100
SOIL TYPE 2			
Improved pasture	300	1103.806	65.58
Urban/rural settlement	100	100.506	5.97
Arable	1100	34.039	2.02
Broadleaved forest	600	105.271	6.25
Mixed forest	700	115.56	6.87
Rough grazing	1000	136.877	8.13
Inland bare rock	900	0.28	0.02
Upland moor	200	50.067	2.97
Cleared/new forest	500	3.91	0.23
Other	1200	4.557	0.27
Coniferous forest	400	28.265	1.68
		1683.138	100
SOIL TYPE 3			
Improved pasture	300	19.888	100.00
		19.888	100
SOIL TYPE 4			
Improved pasture	300	3738.519	65.53
Broadleaved forest	600	97.821	1.71
Urban/rural settlement	100	312.432	5.48
Upland moor	200	431.48	7.56
Rough grazing	1000	718.892	12.60
Mixed forest	700	157.274	2.76
Arable	1100	13.792	0.24
Cleared/new forest	500	46.15	0.81
Coniferous forest	400	169.078	2.96
Other	1200	18.498	0.32
Inland bare rock	900	0.996	0.02
		5704.932	100

	Landuse code	Area (ha.)	Area (%)
SOIL TYPE 5			
Improved pasture	300	72.515	7.87
Rough grazing	1000	21.15	2.30
Broadleaved forest	600	3.706	0.40
Coniferous forest	400	41.86	4.54
Urban/rural settlement	100	1.548	0.17
Bogs & peat	800	6.06	0.66
Upland moor	200	767.922	83.33
Cleared/new forest	500	6.711	0.73
Other	1200	0.027	0.00
Mixed forest	700	0.041	0.00
		921.54	100
SOIL TYPE 6			
Broadleaved forest	600	15.905	2.46
Mixed forest	700	10.313	1.60
Rough grazing	1000	130.212	20.16
Improved pasture	300	425.455	65.86
Cleared/new forest	500	3.977	0.62
Upland moor	200	1.12	0.17
Coniferous forest	400	6.97	1.08
Urban/rural settlement	100	31.802	4.92
Arable	1100	20.28	3.14
		646.034	100
SOIL TYPE 7			
Improved pasture	300	96.896	70.42
Urban/rural settlement	100	0.632	0.46
Broadleaved forest	600	4.075	2.96
Rough grazing	1000	31.3	22.75
Mixed forest	700	2.616	1.90
Arable	1100	2.079	1.51
		137.598	100
SOIL TYPE 8			
Urban/rural settlement	100	0	0.00
Upland moor	200	2937	78.41
Improved pasture	300	21	0.57
Coniferous forest	400	210	5.61
Cleared/new forest	500	18	0.48
Broadleaved forest	600	13	0.35
Mixed forest	700		
Bogs & peat	800	308	8.21
Inland bare rock	900	80	2.14
Rough grazing	1000	142	3.79
Arable	1100	0	0.01
Other	1200	16	0.44
		3746	100.00
SOIL TYPE 9			
Upland moor	200	608.328	99.71
Inland bare rock	900	0.52	0.09
Bogs & peat	800	0.588	0.10
Other	1200	0.68	0.11
		610.116	100

	Landuse code	Area (ha.)	Area (%)
SOIL TYPE 10			
Upland moor	200	6815.968	52.96
Improved pasture	300	1734.079	13.47
Urban/rural settlement	100	155.309	1.21
Rough grazing	1000	577.132	4.48
Mixed forest	700	820.724	6.38
Coniferous forest	400	1122.821	8.72
Other	1200	108.613	0.84
Cleared/new forest	500	379.29	2.95
Broadleaved forest	600	626.305	4.87
Inland bare rock	900	476.88	3.71
Bogs & peat	800	49.437	0.38
Arable	1100	3.54	0.03
		12870.098	100

Total catchment area	34576

Appendix III. Soil type in relation to land cover type in the Bassenthwaite catchment.

a) Urban/rural settlement

Soil type	Area (ha.)	Area (%)
4	312	52
10	155	26
2	101	17
6	32	5
5	2	0
7	1	0
8	0	0
	602	100

e) Cleared/new forest

Soil type	Area (ha.)	Area (%)
10	379	83
4	46	10
8	18	4
5	7	1
6	4	1
2	4	1
1	1	0
	459	100

i) Inland bare rock

Soil type	Area (ha.)	Area (%)
1	1109	66
10	477	29
8	80	5
4	1	0
9	1	0
2	0	0
	1668	100

b) Upland moor

Soil type	Area (ha.)	Area (%)
1	6941	37
10	6816	37
8	2937	16
5	768	4
9	608	3
4	431	2
2	50	0
6	1	0
	18553	100

f) Broadleaved forest

Soil type	Area (ha.)	Area (%)
10	626	69
2	105	12
4	98	11
1	38	4
6	16	2
8	13	1
7	4	0
5	4	0
	904	100

j) Rough grazing

Soil type	Area (ha.)	Area (%)
4	719	40
10	577	33
8	142	8
2	137	8
6	130	7
7	31	2
5	21	1
1	18	1
	1776	100

c) Improved pasture

Soil type	Area (ha.)	Area (%)
4	3739	52
10	1734	24
2	1104	15
6	425	6
7	97	1
5	73	1
8	21	0
3	20	0
1	5	0
	7218	100

g) Mixed forest

Soil type	Area (ha.)	Area (%)
10	821	73
4	157	14
2	116	10
1	24	2
6	10	1
7	3	0
5	0	0
	1130	100

k) Arable

Soil type	Area (ha.)	Area (%)
2	34	46
6	20	27
4	14	19
10	4	5
7	2	3
8	0	1
	74	100

d) Coniferous forest

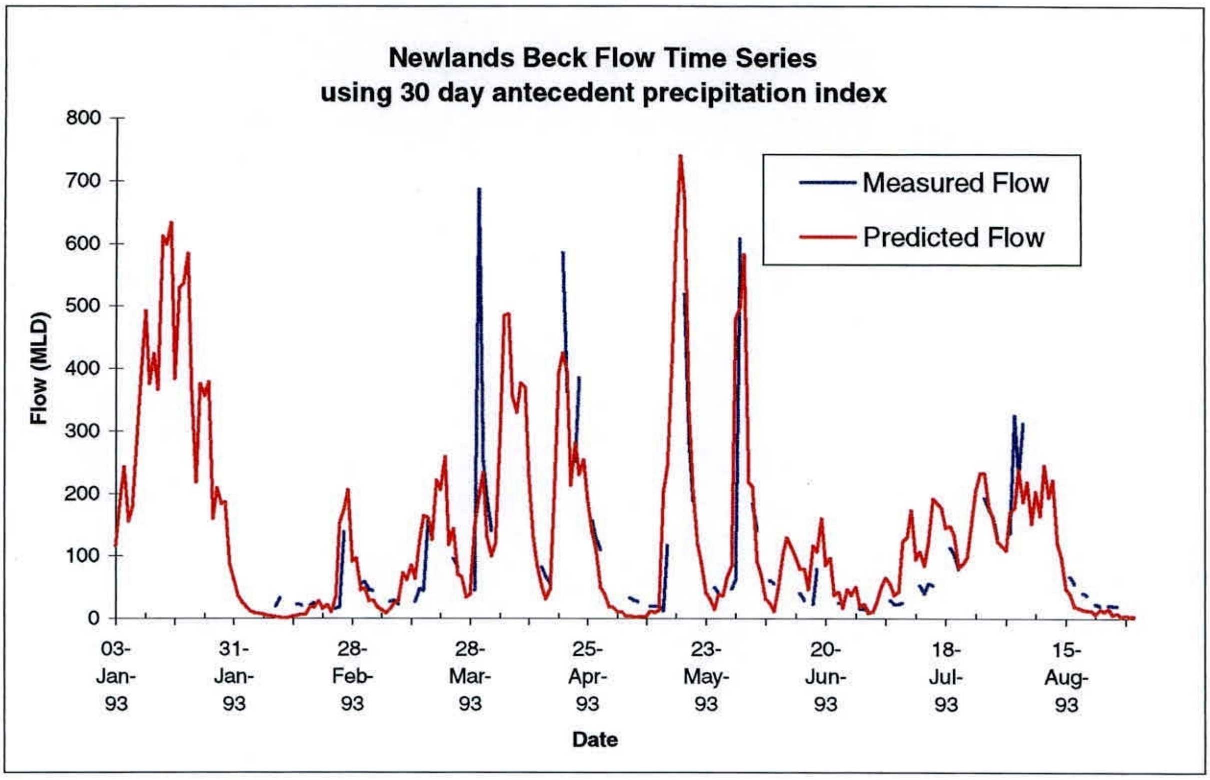
Soil type	Area (ha.)	Area (%)
10	1123	70
8	210	13
4	169	11
5	42	3
2	28	2
1	16	1
6	7	0
	1595	100

h) Bogs and peat

Soil type	Area (ha.)	Area (%)
8	308	77
10	49	12
1	35	9
5	6	2
9	1	0
	398	100

l) Other

Soil type	Area (ha.)	Area (%)
10	109	55
1	50	25
4	18	9
8	16	8
2	5	2
9	1	0
	199	100



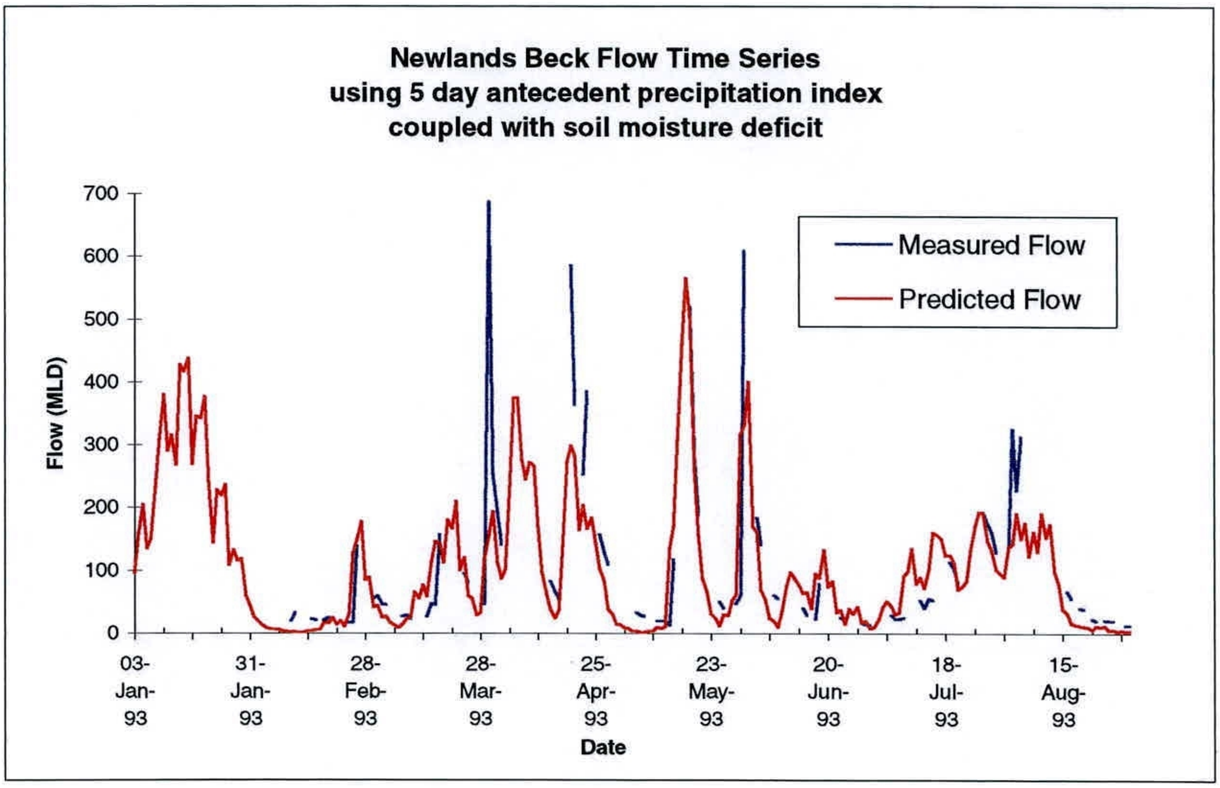
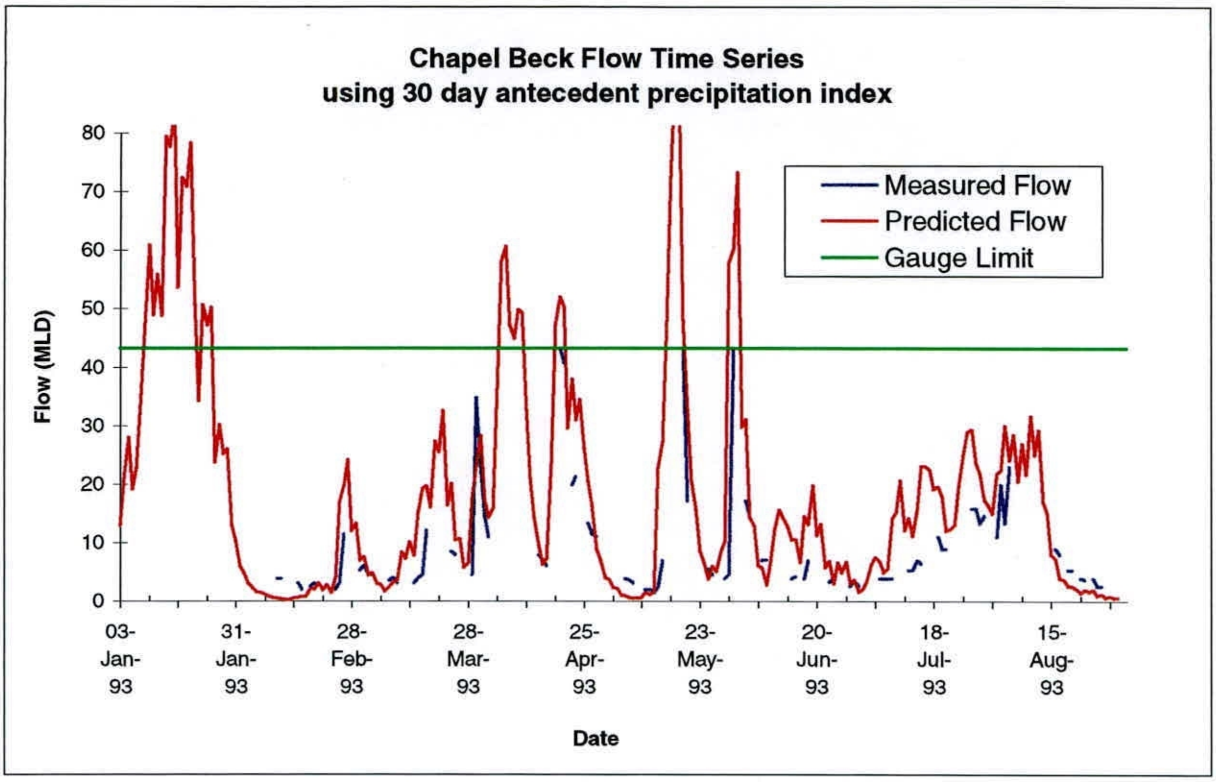


Figure IV. (a) Flow Time Series for subcatchment 1



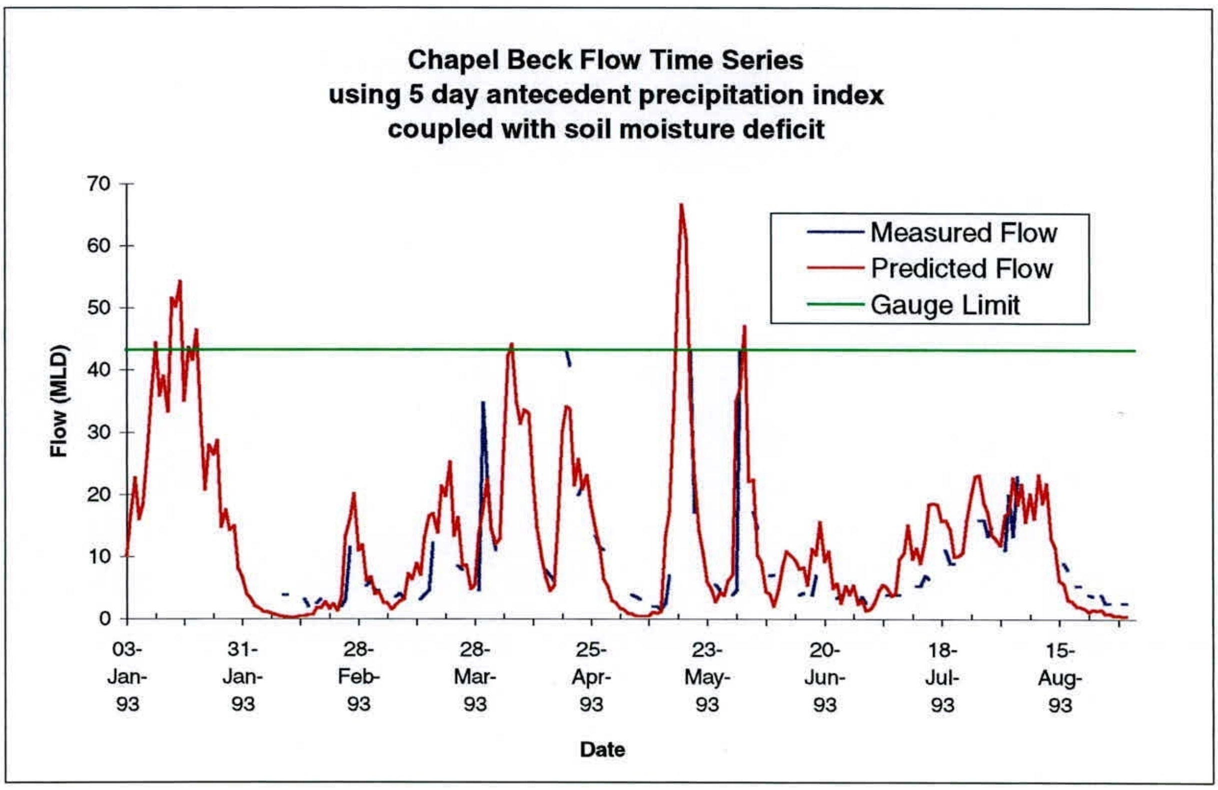
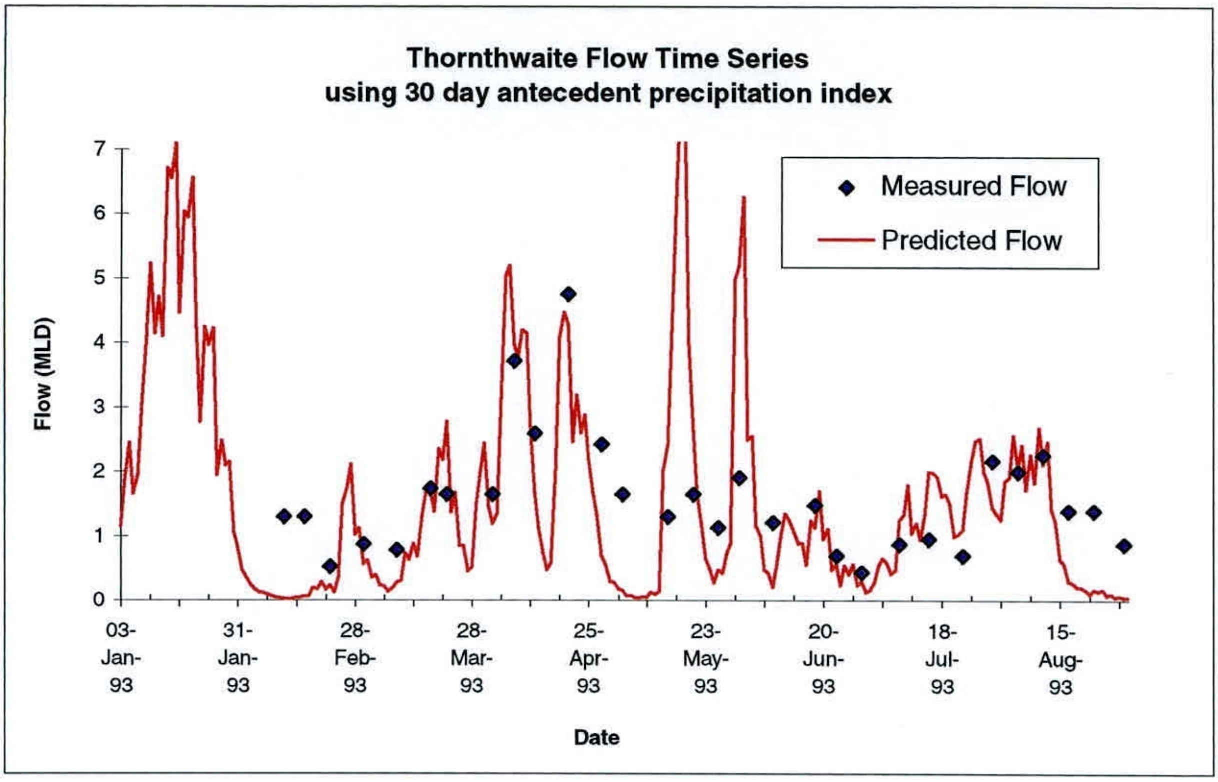


Figure IV. (b) Flow Time Series for subcatchment 2



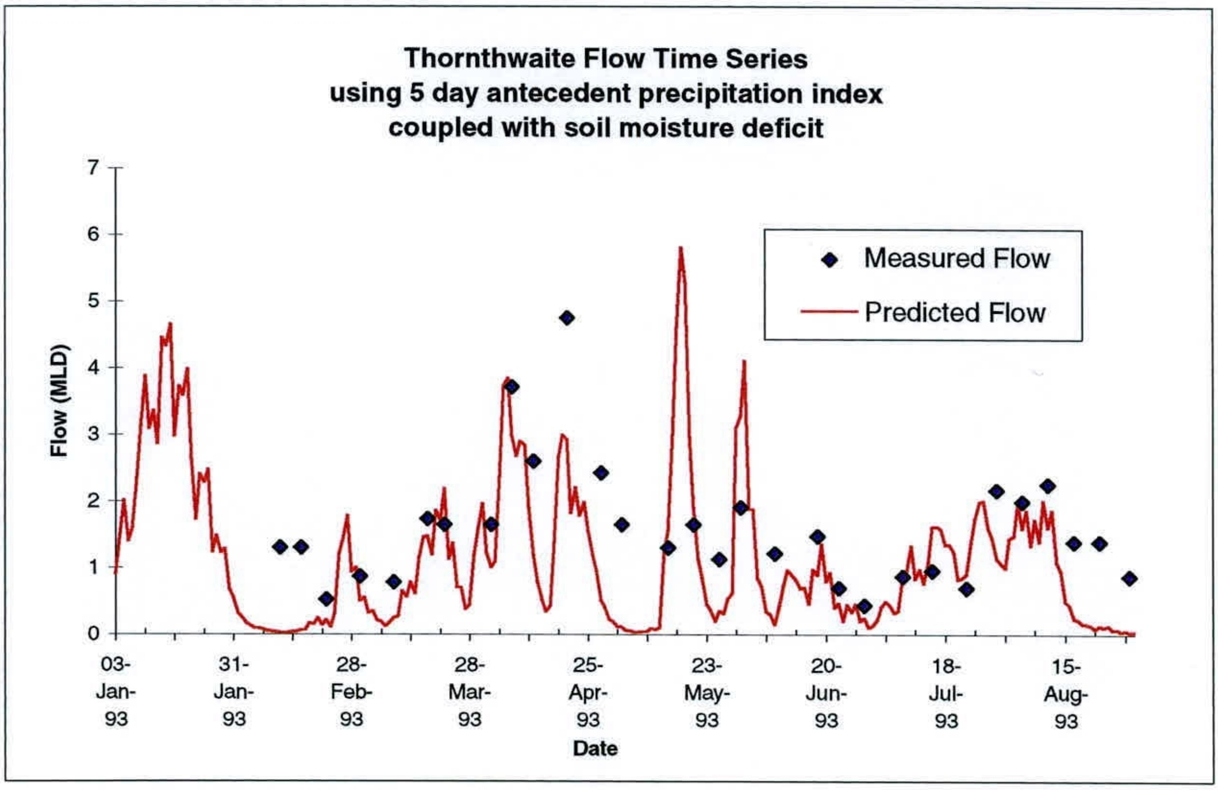
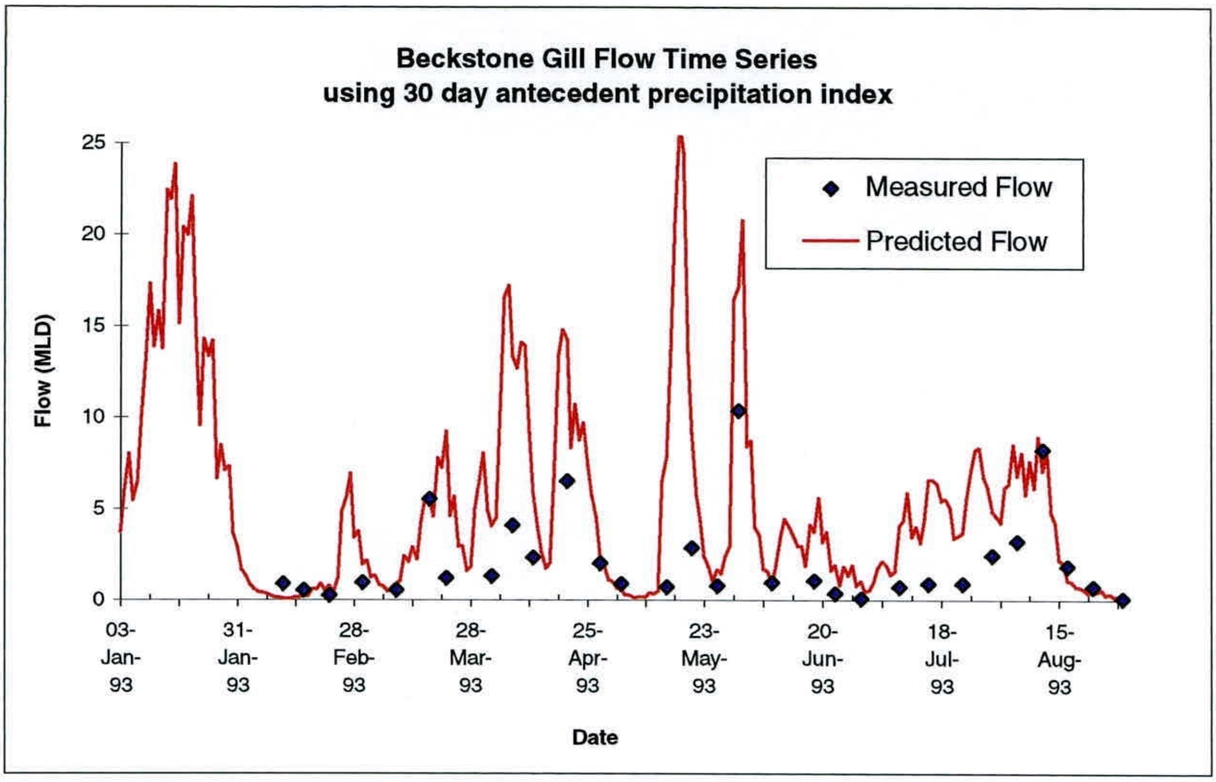


Figure IV. (c) Flow Time Series for subcatchment 3



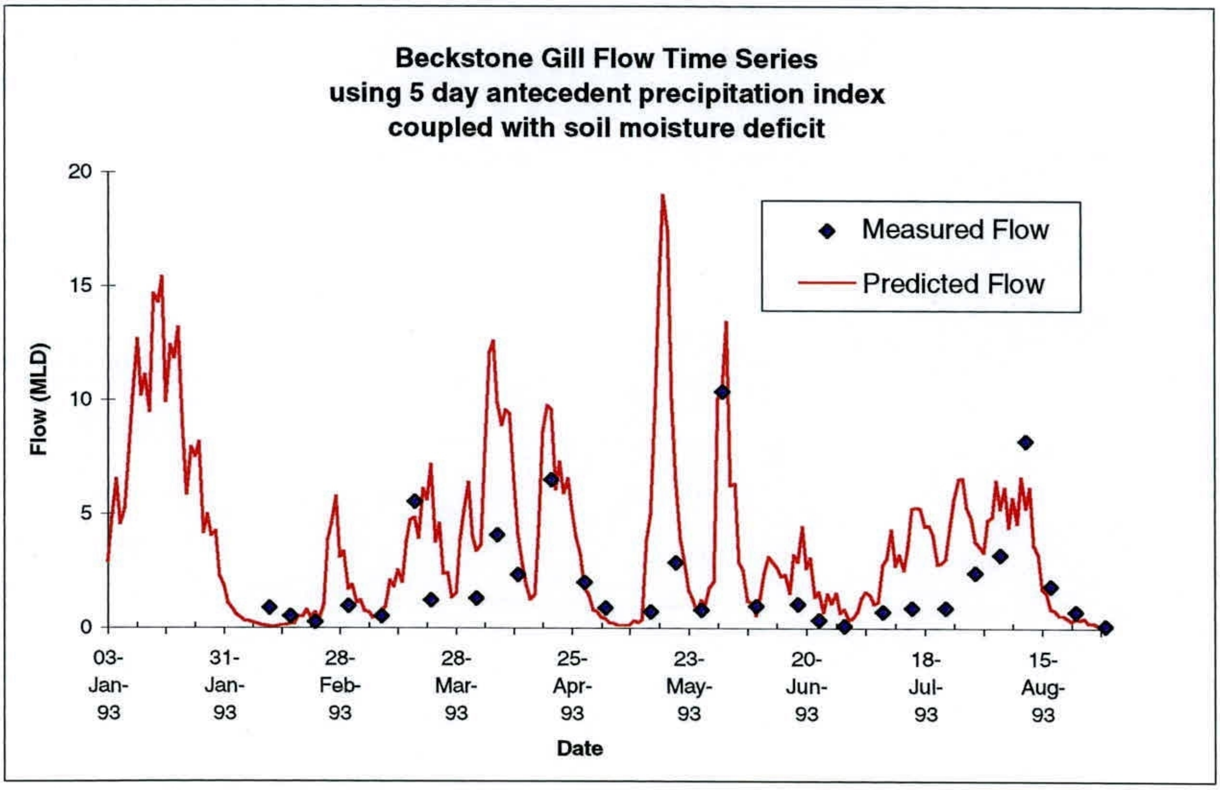
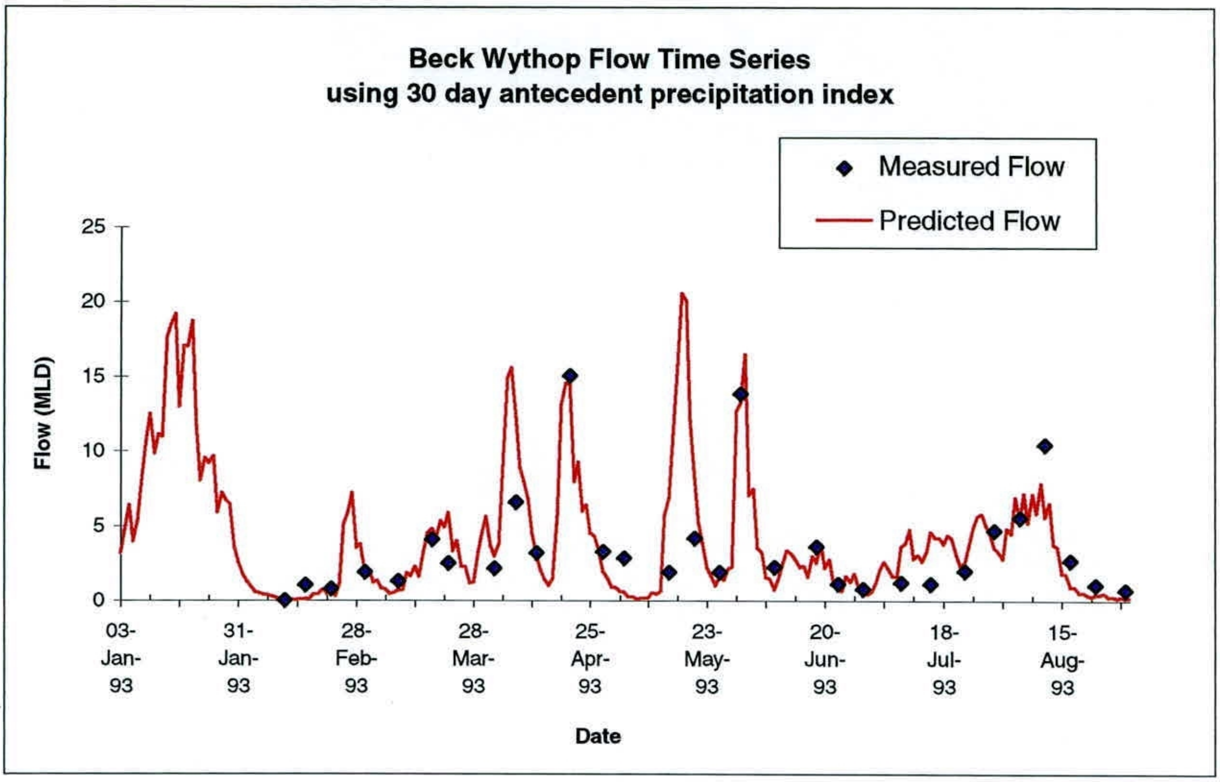


Figure IV. (d) Flow Time Series for subcatchment 4



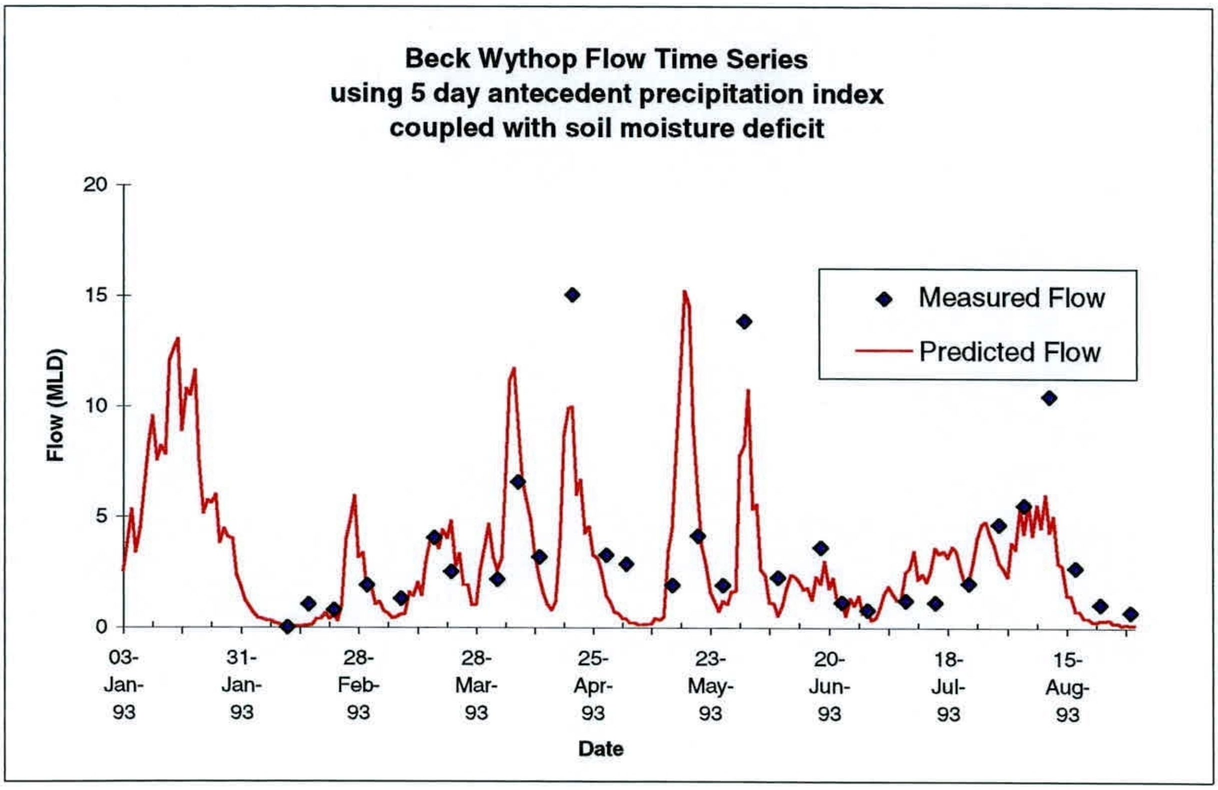
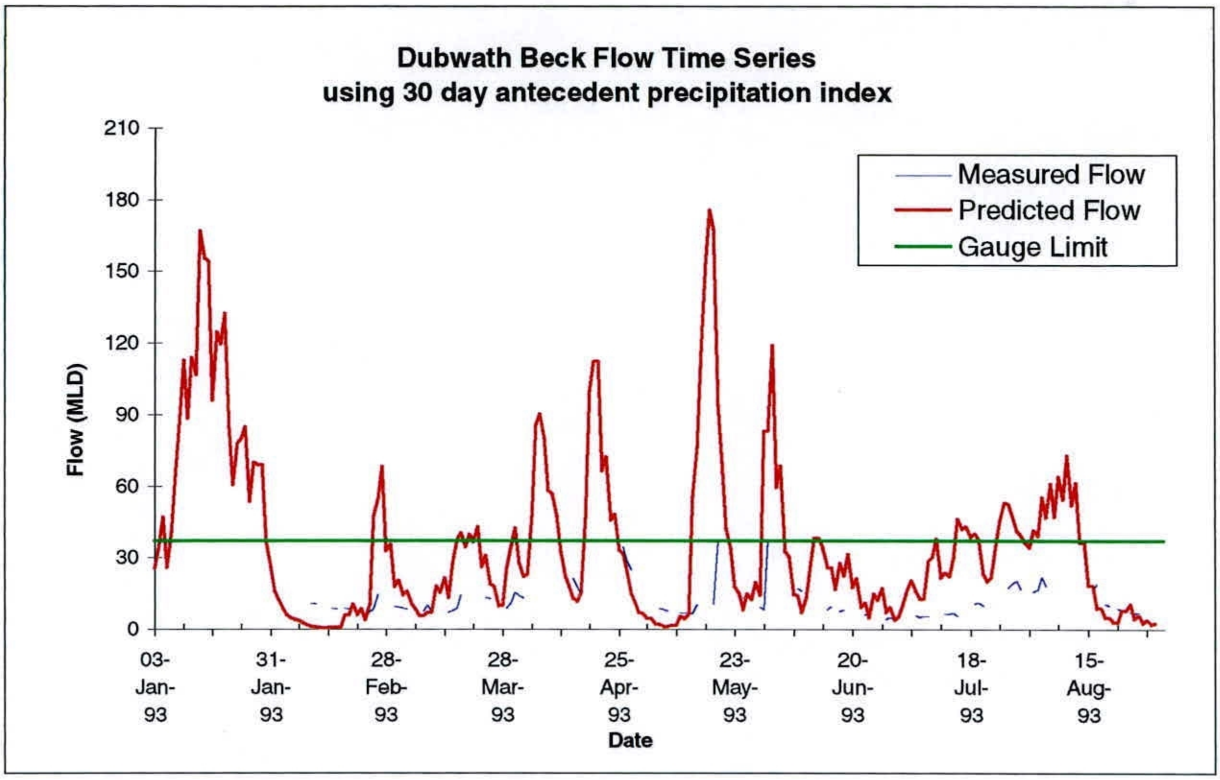


Figure IV. (e) Flow Time Series for subcatchment 5



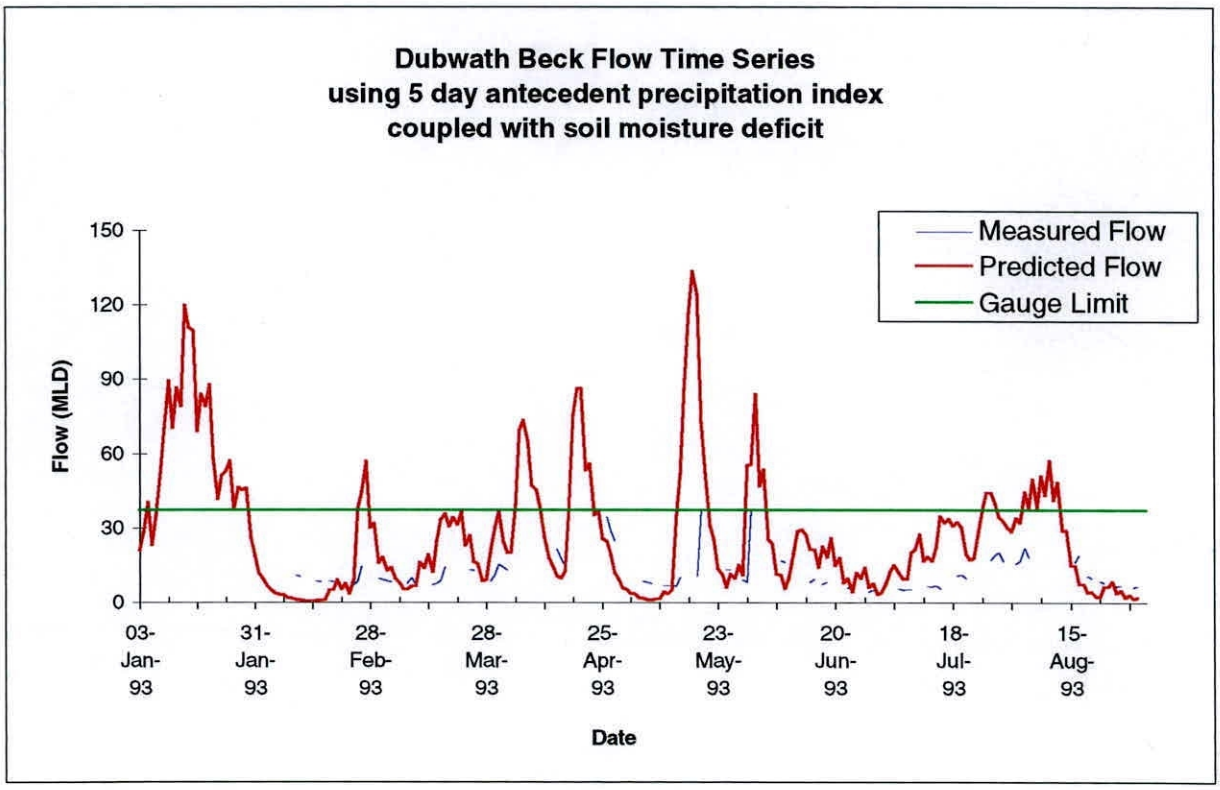
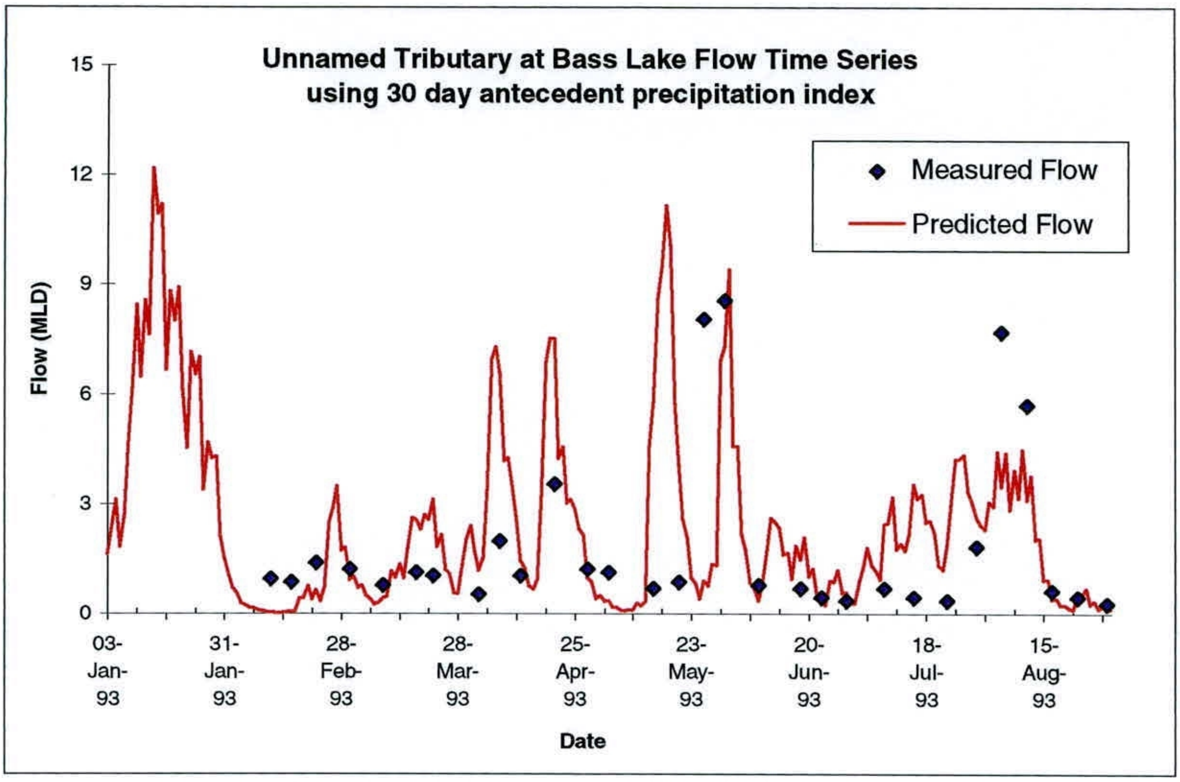


Figure IV. (f) Flow Time Series for subcatchment 6



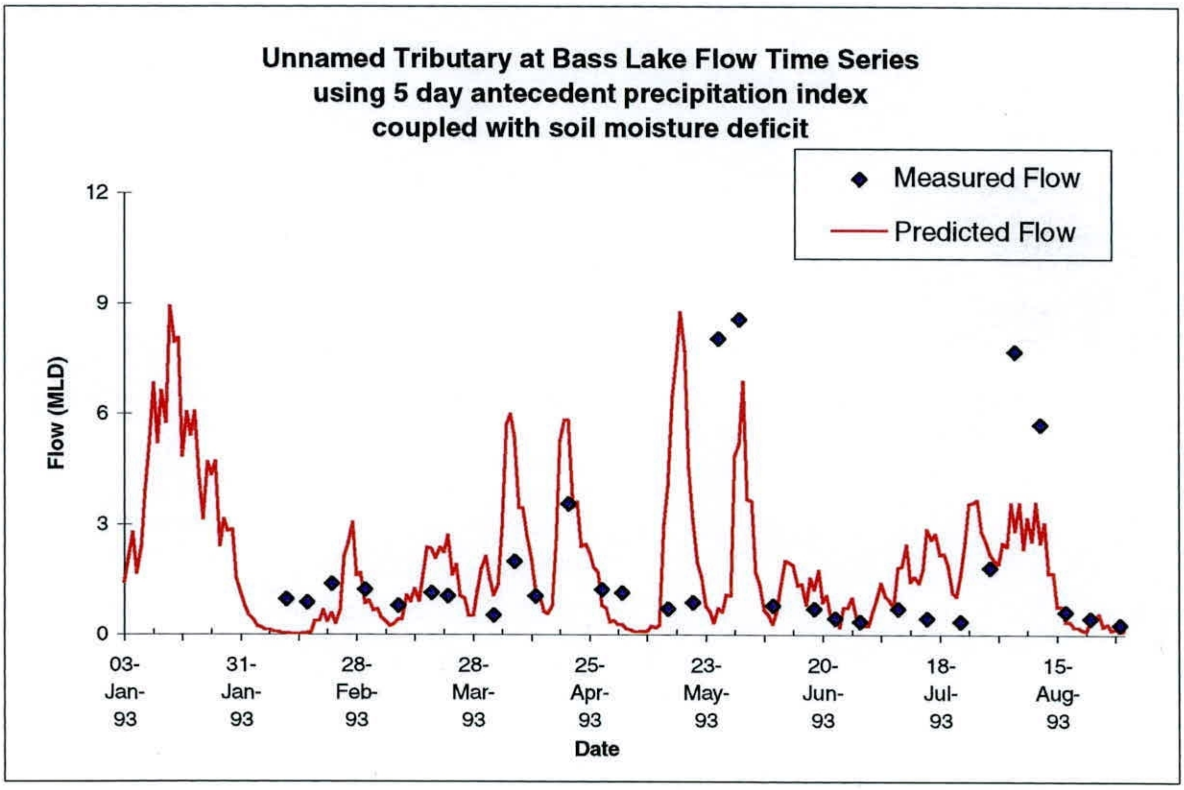
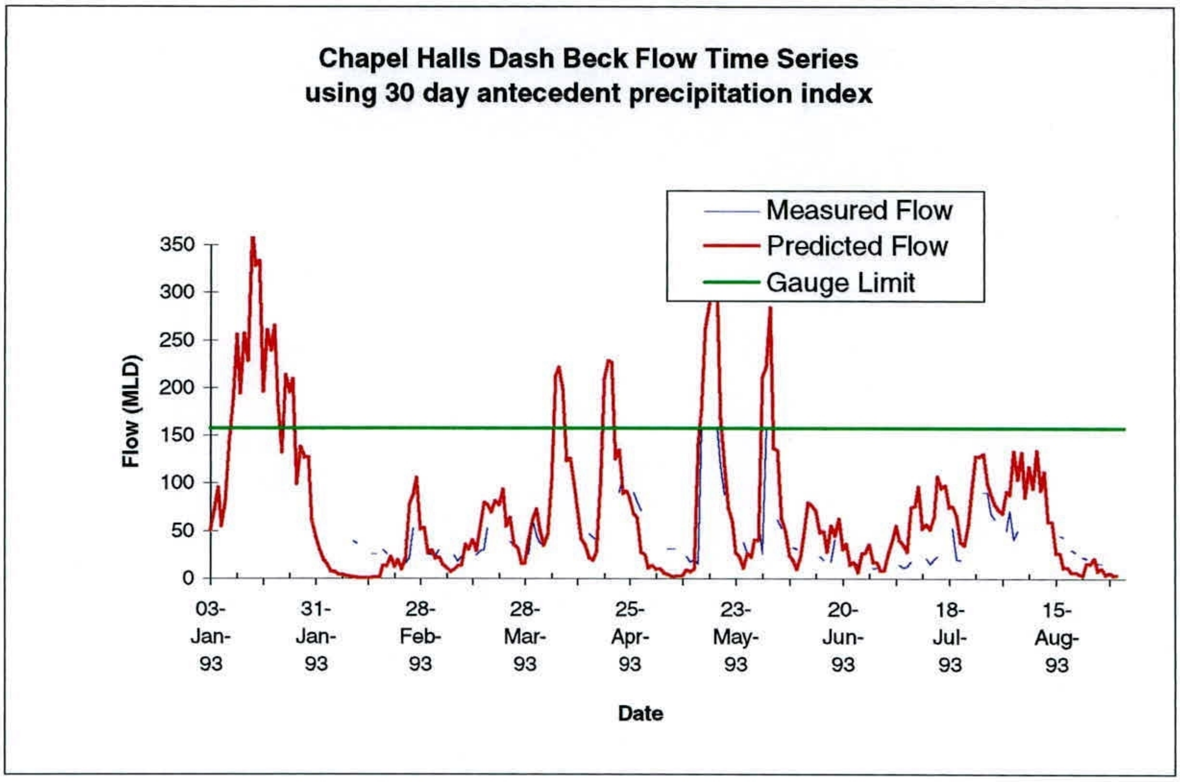


Figure IV. (g) Flow Time Series for subcatchment 9



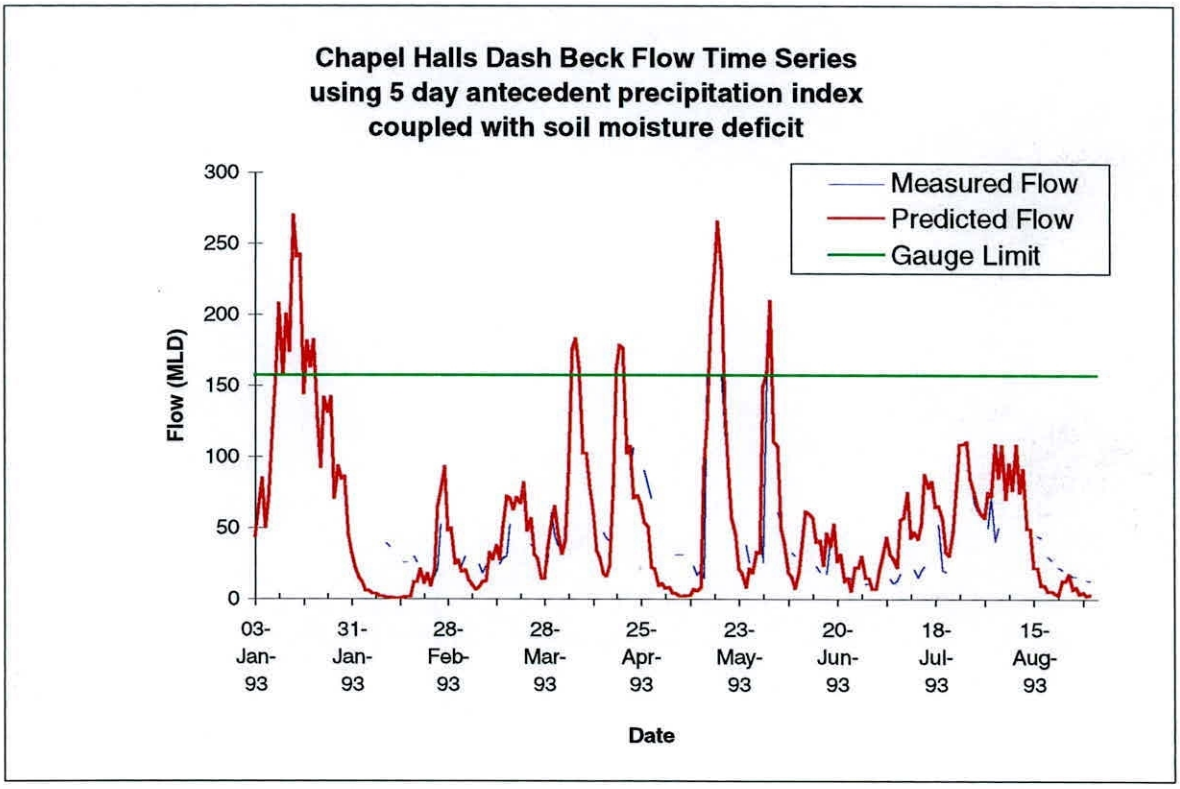
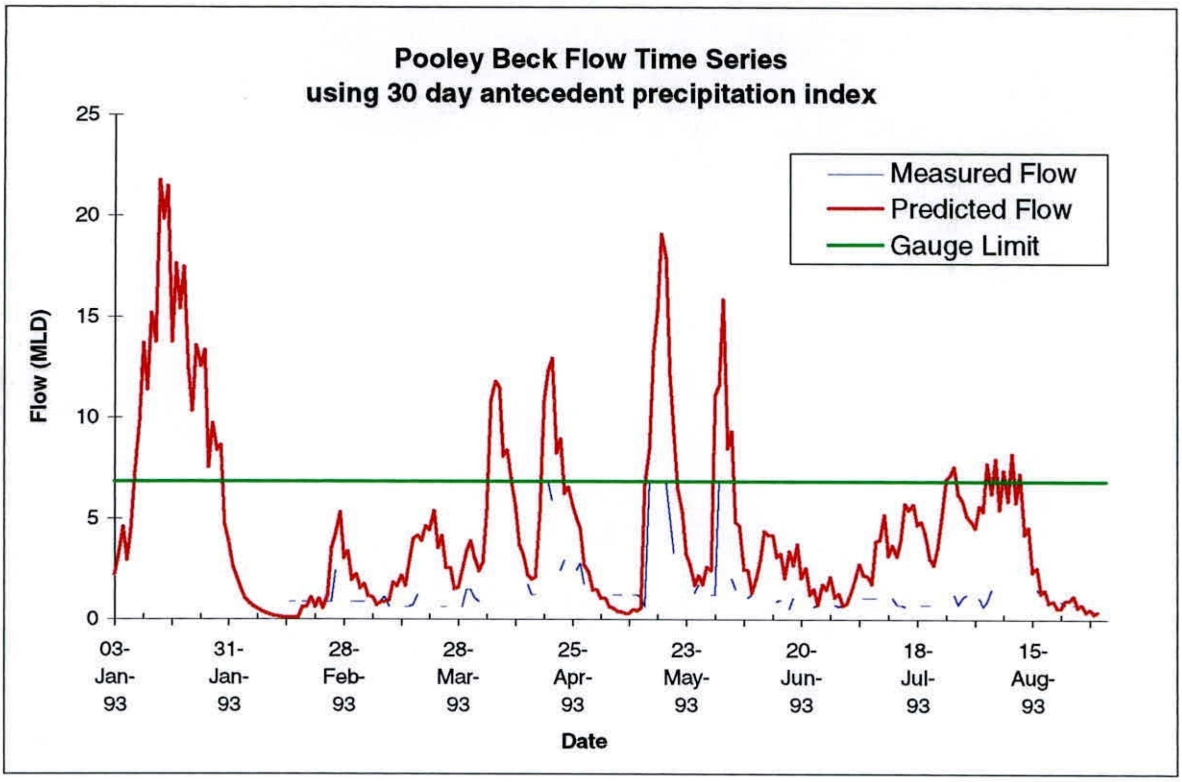


Figure IV. (h) Time series for subcatchment 10



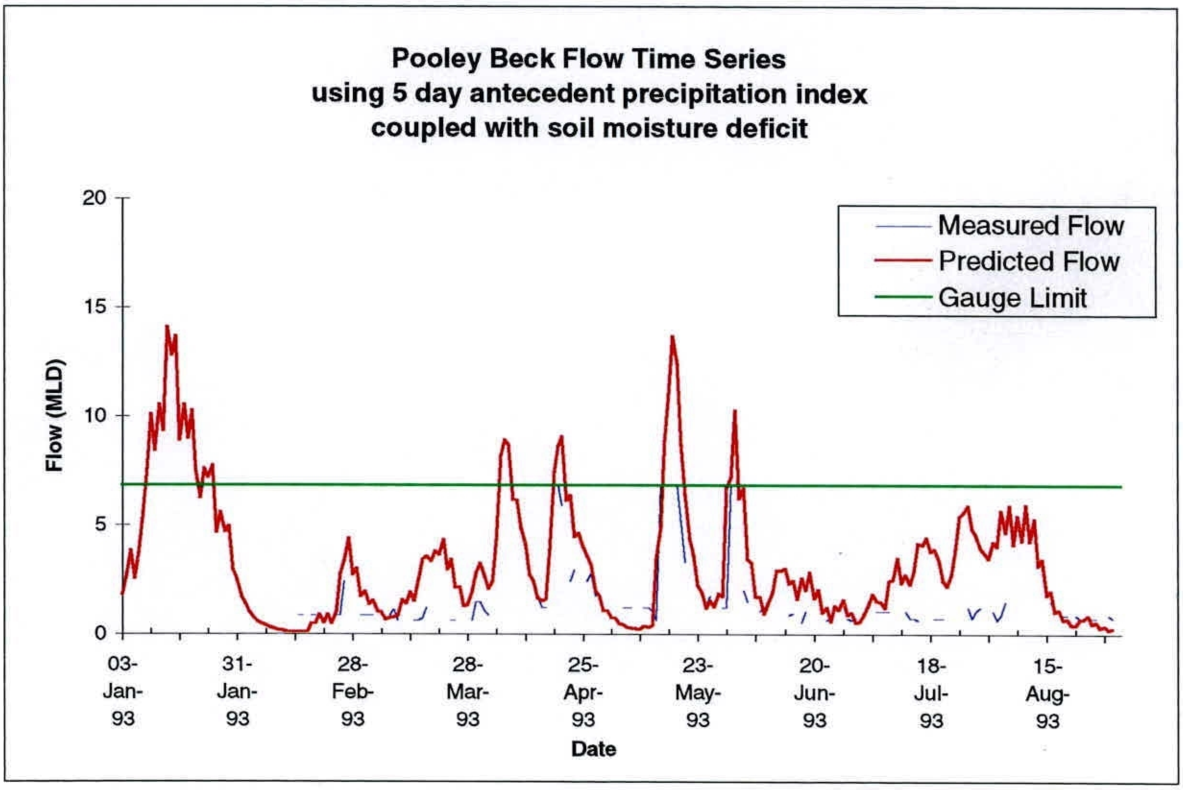
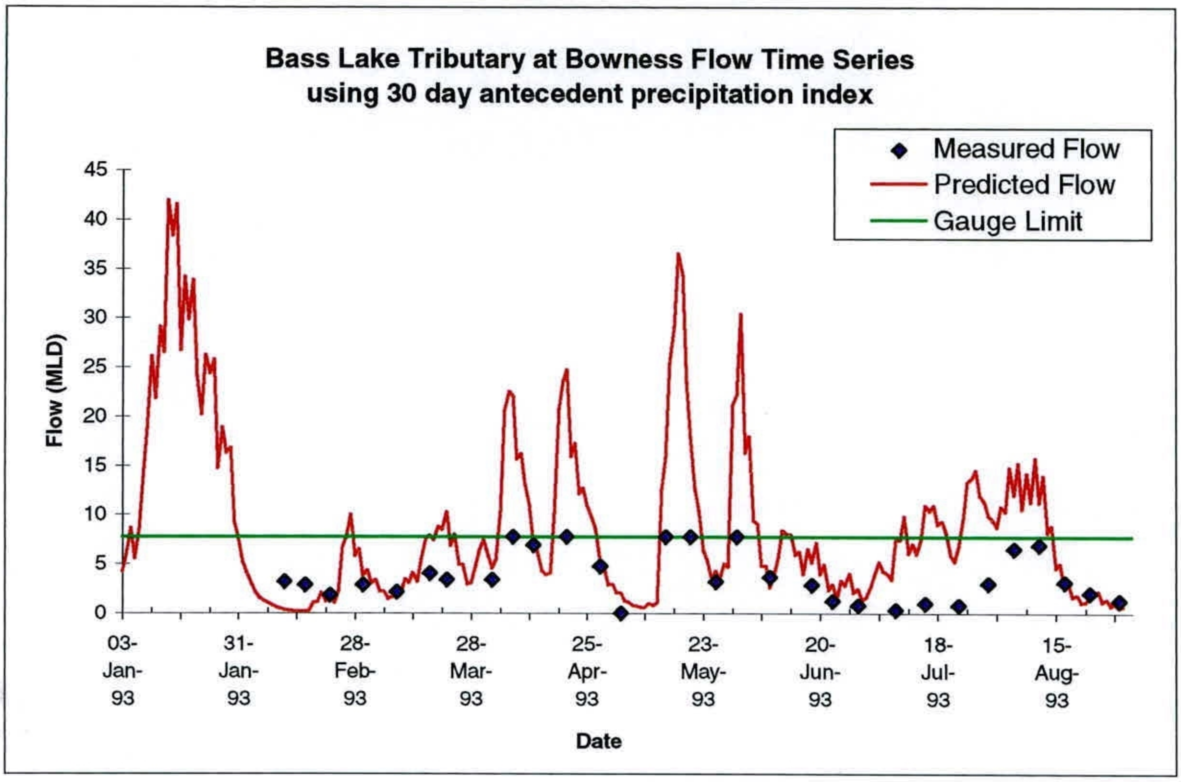


Figure IV. (i) Flow Time Series for subcatchment 11



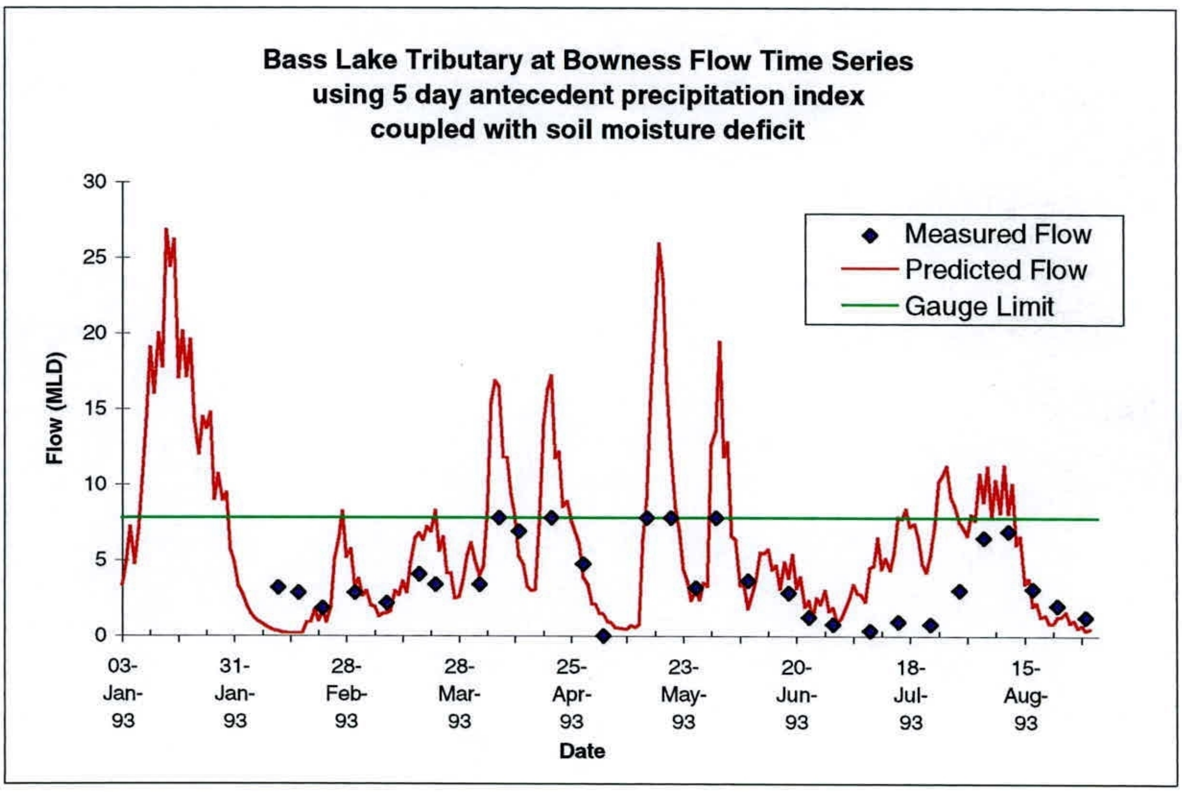
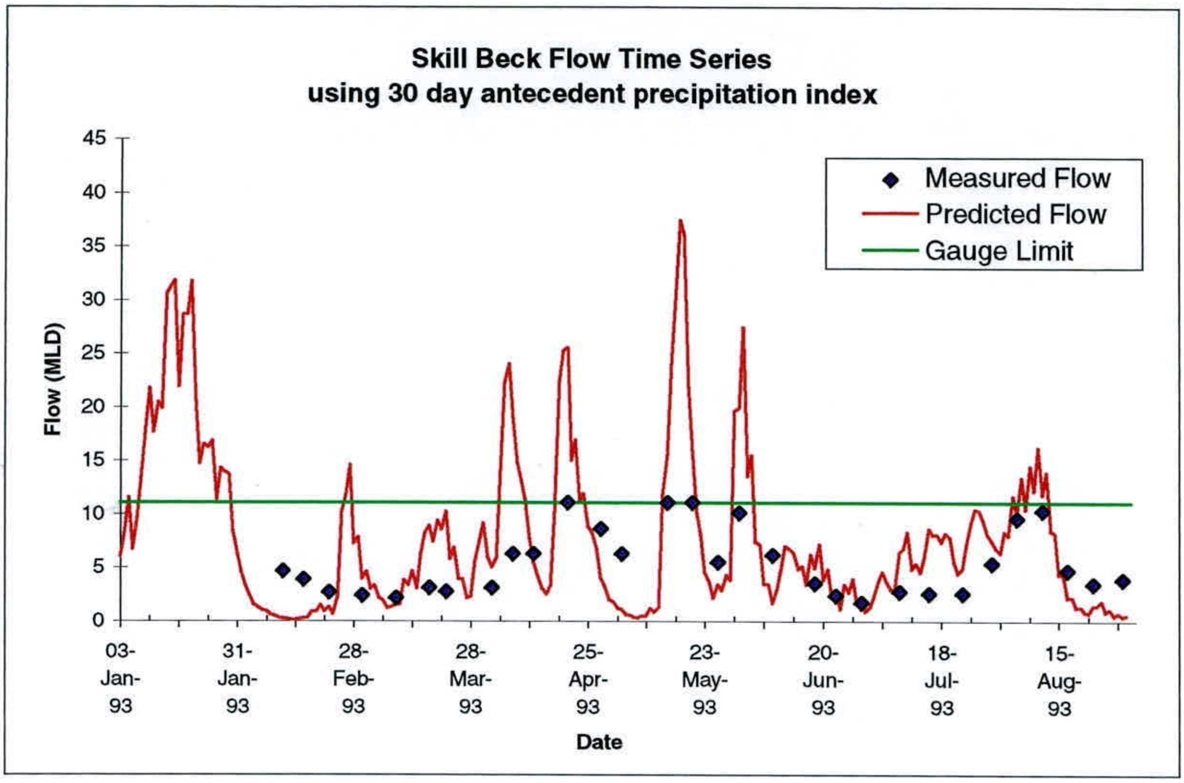


Figure IV. (j) Flow Time Series for subcatchment 12



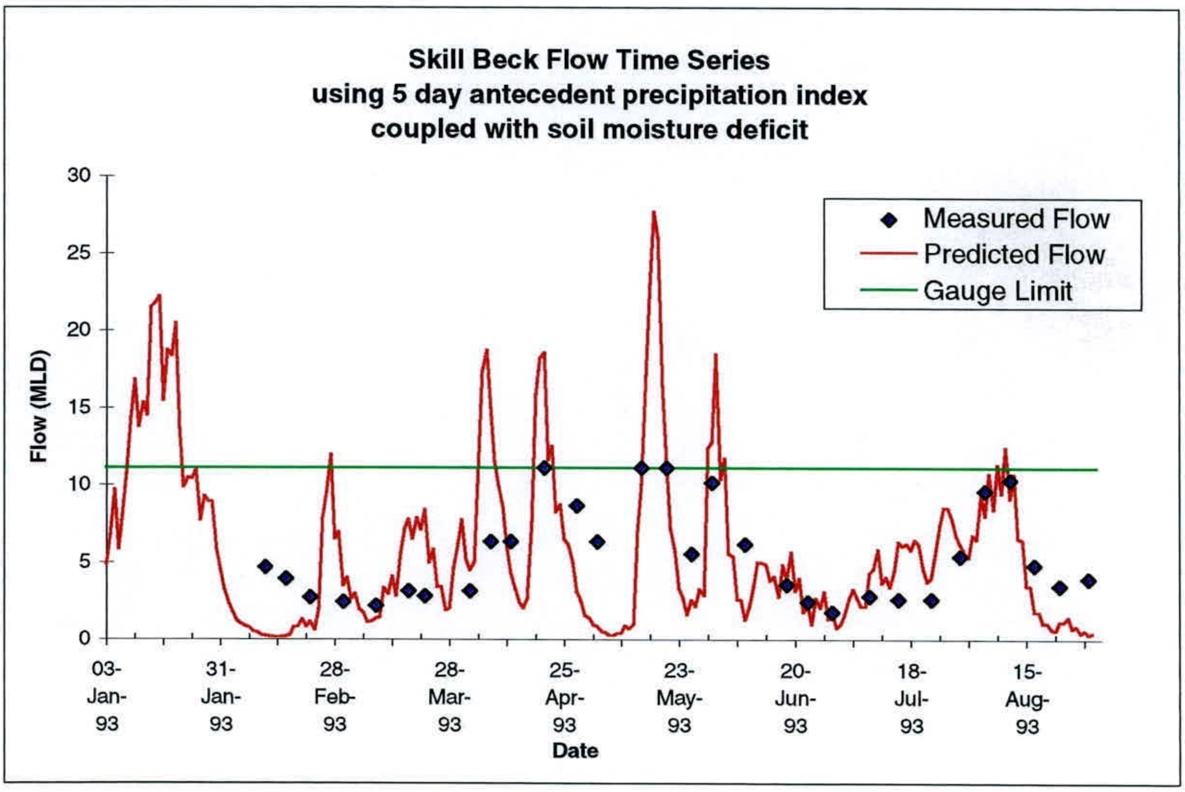
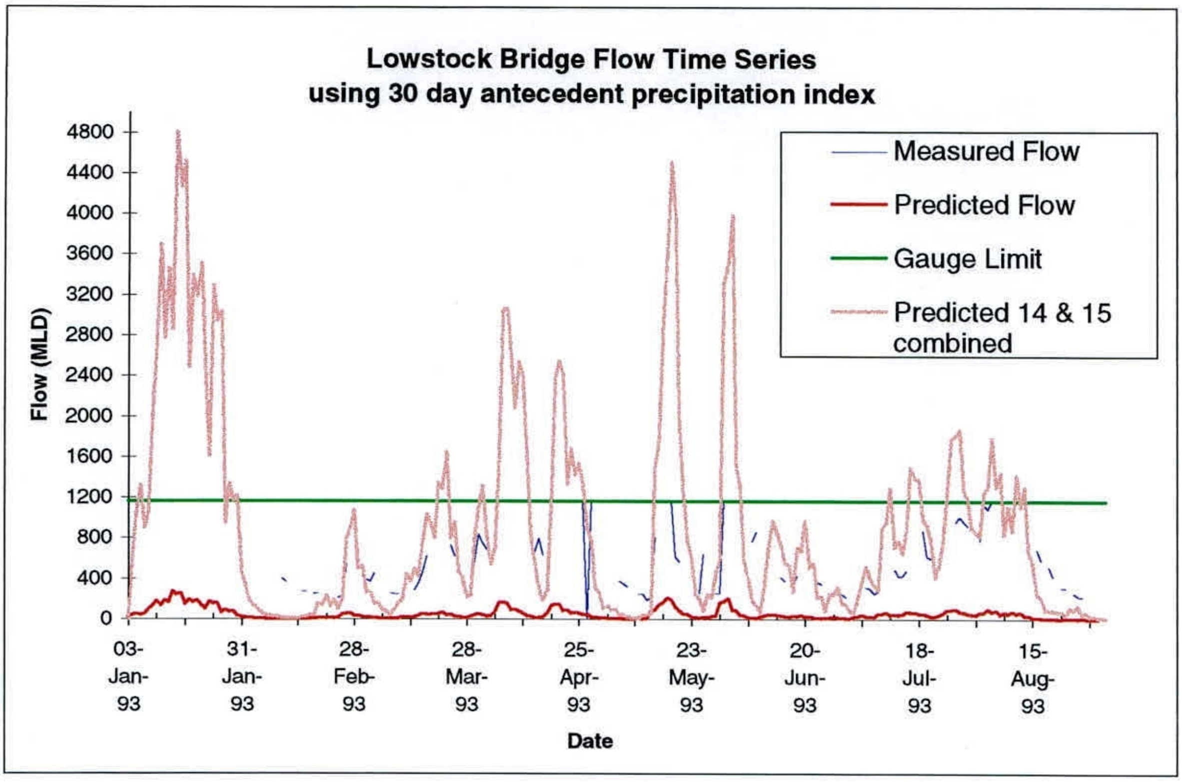


Figure IV. (k) Flow Time Series for subcatchment 13



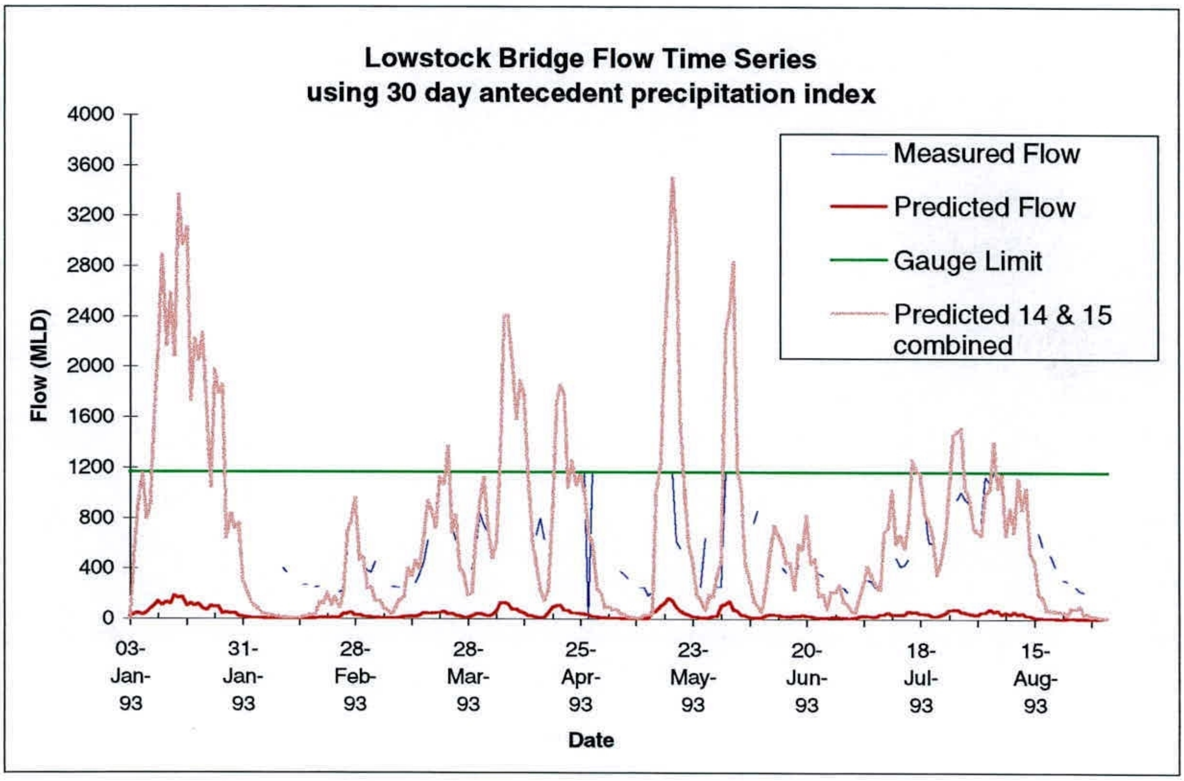


Figure IV. (I) Time series for subcatchment 14

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Institute of Freshwater Ecology
Institute of Hydrology
Institute of Terrestrial Ecology
Institute of Virology & Environmental Microbiology

Natural Environment Research Council