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Progress Report on the Balquhidder Catchment Studies 1986/7.

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and J A Hudson

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by

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1. Introduction

The Balquhidder catchments' instrumentation started in 1981, initially investigating the water use of two similar catchments but with different vegetation covers.

In the Kirkton catchment a mature forest extends over the lower altitude areas with grass, bilberry and some heather covering the areas outside the forest. Several small lochans exist near ridge crests where there are also some areas of peat. The Monachyle catchment lower altitude areas are covered by a coarse grass much of which is ungrazed due to the presence of the Forestry Commission deer fence. Higher parts are heather covered and there are again some peat areas. The upper Monachyle sub-catchment containing a large deep peat area covered by heather has been gauged separately from the rest of the catchment and serves as a separate study area.

After the completion of the first phase of the study in 1986 a preliminary analysis of these first four years was carried out and presented to the Consortium in May 1986.

The initial conclusions drawn from that analysis were of considerable interest in that they contradicted certain preconceptions about water use in upland Scotland.

The water balance results from the 35% forested, 55% grass, 10% heather Kirkton catchment indicated that overall annual water use was lower than that predicted for a grass cover alone by the Penman ET estimate derived from the automatic weather stations. Existing prediction methods, incorporating estimates of the interception loss from the 35% forested area, suggested that the overall water use of the catchment should have been significantly higher than ET.

Results from the heather/grass/bracken-covered Monachyle catchment indicated that overall water use by this complex was similar to that predicted for a grass cover alone using the Penman ET estimate from the weather station data. The water use of this catchment was therefore significantly higher than for the part-forested Kirkton.

Another surprising result was the finding that the Penman estimates of ET obtained from the high altitude weather stations in the two catchments were considerably higher than those from the valley bottom sites and higher than the Meteorological Office regional estimates.

These results were treated initially with some scepticism. Whilst IH at that point was reasonably confident that any systematic errors in the Penman data and in the Kirkton streamflow data had been minimised by exhaustive calibration checks, there remained some uncertainty about the Monachyle streamflow. The raingauge network analysis had shown a reasonably stable distribution pattern over the catchments, but the possibility of bias in the estimates remained. The methods of estimating snow inputs, although considered to be the best that could be devised within the topographical and resource constraints, were also possible sources of bias, despite the fact that the snow component of total precipitation is highly variable from year to year and averaged only some 10% over the period of phase I. Another possible source of bias was a net inflow of groundwater through the bands of limestone known to outcrop in the Kirkton catchment.

W.R.C. kindly undertook an exhaustive statistical analysis of the data presented in the preliminary report on phase I. In the course of this Dr Hunt identified the possible effects of a range of values of systematic error on the results presented and also identified a number of points made in the report which required clarification. This exercise, together with ongoing analysis by IH, helped to identify particular aspects of the data collection networks on which more work was required and the need for a detailed hydrogeological survey of the Kirkton catchment. Details of the steps taken on these aspects are contained in this report. They include the identification of additional raingauge sites to check the validity of the present networks, the continuing attempts to develop additional methods of snow estimation, calibration checks on the Monachyle streamflow gauging structure and the results of hydrogeological survey of the Kirkton.

In parallel with this work on the catchment data, work continued on the development of new predictive models using the information obtained from the process studies on the water use of heather and on snow interception by forest canopies. An initial application of these models to the Balquhidder catchments (Hall, 1987) showed reasonable agreement with the Monachyle water balance results, but indicated that the Kirkton results could only be predicted by assuming radically lower water use by high altitude grassland than had previously been predicted.

This was in line with an alternative explanation of the Kirkton results put forward in the preliminary report. Consensus opinion of the Consortium was that this explanation seemed sufficiently probable to merit a detailed study of the processes involved in interception and evaporation by high altitude grassland. Such a study is now in hand close to the Kirkton catchment. Details of progress will be presented separately to the Consortium.

During 1986 the land uses in both catchments changed as the study entered its second phase. The lower part of the Monachyle catchment was ploughed and planted by the Forestry Commission using best current practices for this type of terrain. Felling of the mature first crop forest in the Kirkton catchment began on the western side. This phase of the study, using essentially the same instrument networks and techniques, is designed to evaluate the effects of these two 'major soil disturbance' phases of the 60 year forestry cycle on water use, flood response and on erosion and sediment loads.

Whilst data collection has been maintained on a regular basis throughout 1986/87 the translation, processing and quality control have fallen behind during the year. This is due in part to staff losses but a major factor has been time lost through transferring the existing data bases and suites of programmes from the Honeywell mainframe to the new IBM mainframe installed by NERC at the Wallingford site. Initial indications are that this should enable speedier and more efficient processing to be carried out once the staff become familiar with the system.

2. Precipitation

Measurement and analysis

A network of 11 ground-level raingauges is used in each catchment to estimate the rainfall input. Gauges are sited in domains determined by 3 variables, altitude, aspect and slope. Snow forms a significant input to the catchments and can fall on the high altitude areas from October to May. During these snow periods some ground-level gauges can give anomalous readings and after snow accumulation they can remain buried for long periods. A smaller network of snow gauges and 5" standard gauges operate in clearings in the Kirkton Forest where it was envisaged that snow could be collected more efficiently. Details of the gauge networks have been given in previous reports, Blackie et al (1986).

Problems with the snow gauge in rain and mixed precipitation have been apparent for some time. A loss by evaporation out of the funnel in summer conditions is not a problem because the gauge is only needed in winter. But a winter overcatch relative to the ground-level gauge of up to 10% is a problem. It is thought that a combination of turbulent flow over the top of the gauge and too gentle a rim angle are causing the overcatch. Rainfall usually contributes a larger proportion of a month's precipitation and therefore any gauge should primarily be a good raingauge.

A new snowgauge, now being tested, has been designed; it is aerodynamically better and has an octapent gauge rim. If it is a success several will be deployed to determine whether established rainfall ratios between sites can be extended through snowfall periods. This should increase confidence in winter precipitation totals which have always been potentially a significant source of error.

With the gradual felling of the Kirkton forest most of the original clearing sites have been affected; however ratios of gauge catch at each site do not appear to have changed which is ~~be~~ encouraging for the future when the lower Kirkton gauging sites will be totally exposed.

As there is only a single observer, all the gauges can not be visited on the first day of each month. A time distribution method, outlined in Blackie et al (1986) has been devised using data from automatic gauges and the daily read low altitude 5" standard gauge. Assumptions have to be made that ratios between sites do not change both on a seasonal or long term basis. Harrison (1986) has shown there to be a seasonal variation in the ratio of catches between low and high altitude gauges but for the Balquhidder gauges where they are compared to a catchment mean there appear to be no similar variations. Figures 1 and 2 show the ratios of gauge catch to the catchment mean for rain only periods. There is some departure from the mean for each gauge but no apparent consistent seasonal pattern and ratios do not seem to be closely related to altitude.

Table 1 shows monthly mean catchment input figures and table 2 a summary of the annual mean catchment inputs 1983-1986. Mean values, as in previous years, are arithmetic means; the domain-weighted mean has been found to differ from the arithmetic mean by less than 1% (Blackie 1987). Mean annual rainfall values for each of the gauges in both catchments are plotted against altitude in Figures 3 and 4. The regression lines indicate that the Monachyle values have a steeper relationship with altitude though the relationships are poorly defined. Regressions in which the western and eastern facing gauges are separated show closer agreements. This analysis goes some way to relating gauge catch to the physical characteristics of the catchments, necessary when assessing the networks (Hudson et al 1985).

Catchment Precipitation Means 1982-87

Five years of monthly raingauge data are now available from both catchments. This is a reasonable length of time to start working on catchment means and distributions.

Annual mean precipitation totals are given in table 2. The west-east trend in precipitation totals is illustrated with the Monachyle on average being 15% higher than the Kirkton.

Average annual rainfall maps for both catchments are shown in Figures 5 and 6, derived from individual gauge annual averages. These maps are open to individual interpretation as only 11 sites exist in each catchment and there are no gauges outside the watersheds; however the interpretations shown in the figures do highlight the general rainfall distributions within the catchments. Once again the west-east trend can be seen although this is almost eliminated by the topographical influences on an individual catchment scale. Altitude and aspect dominate as shown in previous regressional analyses, Figures 3 and 4. Monachyle appears to be more topographically influenced with the steepest rainfall gradients on the western flank resulting from the more closed nature of the lower catchment compared to the Kirkton. Both catchments have low rainfall (relative) areas, although gauges in these areas are still being checked. Another area needing further work is the high altitude area of south-west Monachyle.

The implications of these isohyetal maps when related to vegetation will be considered by future catchment modelling exercises.

Network assessment

Five new gauges have recently been deployed in the catchments to assess the representativeness of several of the largest domains. At least 12 months' comparative readings will be needed before any conclusions about the accuracy of the domain method of measuring precipitation can be ~~made~~ reached.

One additional domain in the south-west of Monachyle will have a gauge installed on a permanent basis. This domain was originally thought to be too isolated and snow affected for too long a period to justify installing a gauge but this area has now been identified as an important high input area.

Gauge C3Y in the Kirkton has previously given values systematically lower than its neighbours, being some 20% lower than the network mean. A second gauge was installed some 20 m away in 1986 and 10 comparative readings have been obtained. Figure 7 shows these results. Although there is some scatter of points the regression line is very close to the 1:1 line. The new gauge on average reads 4% higher than the original gauge but more comparative readings are necessary before this can be confirmed. The initial indication is however that this domain does in fact receive a lower precipitation input.

Intensity of rainfall

Comparisons have been made of rainfall intensities at sites in Balquhidder and Plynlimon for several periods. Results so far are inconclusive with some months showing more intense rainfall at Balquhidder and others when intensity is very similar. Evidence has also been found of some variation in intensity through the Balquhidder catchments with the northern-most portions of the catchments, particularly the upper Monachyle, experiencing lower intensity rainfall, resulting from a more open westerly airflow along Glen Dochart to the north.

The relevance of this intensity variation to the water balance results is that, in the areas where rainfall intensity is highest, the vegetation will be wet for less time and therefore less moisture is available on foliage to be evaporated and so interception loss will be less marked. This could be a partial explanation of the different water balance results found at Balquhidder and Plynlimon.

Historical rainfall in Balquhidder

Rainfall records from the Balquhidder Glen are the only data sets available over a sufficiently long period to use in an assessment of how typical the years have been since the catchment experiments started. One station, Blaircreich, 2 km west of Monachyle, has continuous records of annual rainfall from 1910-85. Records from another station, Stronvar, do extend back further but they finish in 1951.

The Blaircreich annual totals appear in Figure 8. Mean rainfall during the period 1910-85 was 92.85 inches (2358 mm) and for the period 1940-85, during which the Forestry industry has been in progress the mean rainfall was 89.53 inches (2274 mm). For the catchment experiments' phase I years 1983-85 the annual totals from Blaircreich were:-

	Rainfall, inches (mm)
1983	95.91 (2436)
1984	91.26 (2318)
1985	94.37 (2397)
Mean	93.85 (2384)

Mean rainfall 1983-85 is therefore only 1% away from ~~both~~ the 1910-85 and 1940-85 mean values. This is very encouraging when considering the long term implications of the Balquhidder study; however the rising trend in the last 30 years and frequent large departures from the mean also have to be considered. 5% from th

3. Streamflow gauging

Output from both catchments is continuously monitored by two Crump weirs, 5 m wide in Monachyle and 7 m wide in Kirkton. Flow less than the recommended minimum stage of 30 mm can occur during the summer dry period so low flow flumes operate in series with the Crump weirs. A further gauge was installed in the upper Monachyle sub-catchments as this area formed a potentially anomalous flow pattern due to the abundance of deep peat. Full details of the planning and installation of the structures have been given in previous reports.

Five minute values of stage are recorded onto cassette tapes on micro-data loggers. Stage is converted to 15 minute flow data and stored on main-frame computer in this form. Daily or period flows can be calculated for water balance use. In the event of failure of the logger, back-up systems exist of punch tape and chart recorders. It is planned gradually to phase out the micro-data loggers which are to be replaced with Mussel loggers and solid-state stores. Data will then be checked before being sent to Wallingford thus reducing the length of any missing data.

Because conditions are not ideal for the operation of the weirs, independent checks had to be carried out on the theoretical ratings. Dilution gaugings showed good agreement with the theoretical under low flow conditions at all 3 gauging sites but at Kirkton during high flows the dilution gauging showed an overestimation of flow compared to the theory. A current metering exercise was carried out and a new rating produced for this weir. Full details are in Blackie et al (1986).

The Monachyle Crump weir was thought not to have the same problems as the Kirkton because approach conditions were better and the sediment accumulation in the weir was small. However a similar current metering exercise was carried out to confirm these ideas. As in the Kirkton, a rigid bridge, spanning the wing walls, was used to brace the metering pole. An improved method of moving the pole enabled complete traverses to be carried out quicker than previously thus reducing the error caused by the rapidly changing stage. Up to 6 Braystokes impeller type current meters were again used with the smaller, more sensitive meters positioned near the bottom. Count times were 100 secs. with 11 verticals taken at 0.5 m intervals across the weir. Discharge was computed using the point velocity measurements and cross sectional areas. Stage was assumed to be the mean of the start and finish values measured in the stilling well.

Results of the current metering exercise are shown in Figure 9. These results show a discrepancy between the theoretical rating and the point discharge values from the current metering, with the latter apparently underestimating discharge by an average 5.4%. This is opposite to the results from the Kirkton where the explanation of a current metering overestimation of discharge was the large amount of sediment in the weir and its effect on the cross-sectional area of flow and on approach velocities. If the results for Monachyle are correct then they will increase the estimate of water use by the Monachyle catchment vegetation.

Several possible reasons for the discrepancy have been identified but so far these are not well enough understood to consider producing a new rating equation. Few points have been obtained below 300 mm which is the most frequent range / stage / of flow. The current metering equipment was one possible source of error so it was sent for calibration checks. The equipment has recently been returned having been shown to be accurate so further gaugings will now be undertaken to complete the lower stage range.

Sediment is another possible reason for the discharge discrepancies. Above the weir a stable accumulation has built up with a narrow tongue some 20 cm high extending into the weir approach area. This tongue reduces the cross sectional area of flow from the one used in the theoretical rating so reducing the calculated discharge for a given stage. Also the sediment and the slight left-hand bend upstream of the weir combine to create an asymmetrical flow which becomes very pronounced at high flows, (Figure 10). It is possible that a result of this asymmetry is a sloping water surface so the stage measured in the well will not be the mean stage. Unfortunately the turbulence of the water surface at high flows prevents any measurement being made across the weir of water surface height. One possible solution will be to instal pressure transducers in the weir approach to measure stage near either side of the flow.

During very cold weather in winter the water in the gauging structures freezes over. Conditions have never been so bad as to stop flow completely under the ice but floats can be frozen solid, sometimes missing flood events or producing errors when a thaw occurs and wires slip over pulleys. Up to 3 months' data can be ice-affected in a cold winter but this problem has hopefully been solved at the most susceptible site, the upper Monachyle, by using pressure transducers. These are a recognised means of obtaining stage but are subject to electronic drift. Comparisons are continuously being made between the transducers and microdata stage values. Some drift has been experienced but this can be corrected by using a pair of transducers. Continuous flow data ve ha~~s~~ been obtained during the 1986-87 winter from the upper Monachyle.

At the Kirkton and lower Monachyle sites the low flow structure wells freeze very easily due to their relatively small diameter. The Crump weirs suffer from the wells freezing and ice forming in the weir approach. Where possible ice is broken out of the wells and manual spot values of stage taken. The ice in the weir must also be broken to prevent it adhering to parts of the crest thus creating a back pressure which can be released into the well, producing artificially high stage values. Although lengthy periods of data can exist when floats were frozen, infilling can be undertaken, interpolating between spot dip-flash values if these are accompanied by good field observations of catchment conditions. Unrectifiable errors can occur when floods flow through a frozen weir but this only happens 1 or 2 times each winter.

4. Automatic weather stations

The network of automatic weather stations (AWS) at Balquhidder has gradually increased throughout the period of the experiment. Originally only 2 were in operation but there are now 6. These are:-

Lower Monachyle -	over ungrazed hill grass
Upper Monachyle -	heather
Tulloch Farm	cut grass
Kirkton High	grazed hill grass
Kirkton Forest	forest
Ledcreich	grazed hill grass

Two of these were installed during 1986: Ledcreich as part of the process studies on the high altitude grass terrace (see separate report) and the Kirkton forest installed following doubts expressed in the previous report on how representative the Kirkton AWS was of the catchment.

The forest station was established at canopy level in an upper eastern block of the Kirkton Forest which will not be disturbed for several years. A 60 ft highway tower was erected and sensors positioned close to the plane of the canopy. The net sensor arm was extended by 5 m to eliminate reflections from the tower and the raingauge funnel mountings extended upwards by 5 m to escape turbulence. The raingauge recording assembly was positioned on the ground as spurious bucket tips can be induced by tower vibrations. For safety reasons the logger was also placed at the base of the tower.

Checks on individual sensors are regularly made by manual measurements next to automatic sensors. Bearing in mind that the AWS records mean or total values over 5 minute intervals and manual readings are comparatively instantaneous, good agreement has always been reached. Data from the stations are providing a unique meteorological data set and have been used for site comparisons (Johnson 1985). For the catchment experiment their main use is in the computation of Penman potential transpiration, ET.

Whilst data capture from the stations appeared to be reasonably good during the year, a number of problems have been identified during processing of the logger tapes. A particular problem has been intermittent stoppages of the tape transport mechanised in the loggers. This results in loss of time synchronisation and means that, whilst the data are actually there, their distribution over time has to be corrected manually before they can be used. This problem has also occurred with the same type of loggers used on the streamflow structures, particularly in cold weather. Since no replacement loggers of the same type are available, efforts are now being made to have them replaced with solid state systems.

The limited staff time available over the past year to give individual attention to these faulty tapes has meant that relatively little of the weather station data can be presented at this time as complete monthly estimates of Penman ET. Particularly badly hit was the Kirkton AWS which was used as the reference station in the Phase I analysis. The most complete record is that from the Upper Monachyle site. Since the between site regressions and the observed annual totals during Phase I showed close agreement between these stations, the monthly ET values from the Upper Monachyle are presented in Table 1 for comparison with the catchment water balance data.

5. Water balance results

With less than one year's fully quality controlled data available to add to the figures presented in the Phase I report in 1986, there is little to add to the water balance analysis at this stage. Monthly P-Q figures are included in Table 1 to March 1986 and August 1986 for Monachyle and Kirkton respectively. These are of limited interest individually as estimates of water use because the storage changes within each catchment in any month can be of greater magnitude than P-Q. Even between-catchment comparisons on these short time intervals can be misleading because of the very different storage-discharge characteristics of the two catchments, as illustrated by the hydrograph and flow duration comparisons presented in the Phase I report. There does however appear to be some convergence of the cumulative values in the sense of a relative decrease in the Monachyle. Whether this is of long term significance will become apparent when the remainder of the 86/87 period data reach a usable state.

The calendar year totals of P-Q for 1983, 84, and 85 are included in Table 2, together with Penman ET. These too are approximations to actual water use, since they do not contain any correction for catchment storage differences between the beginning and end of the years.

The current best estimates of water use by the two catchments are the P-Q differences in these three year totals. As can be seen from Table 2 these indicate a mean water use by the Monachyle very close to the Penman ET estimate with that by the part-forested Kirkton some 100 mm lower.

If further work confirms the need to adjust the Monachyle structure rating along the lines discussed in section 3 above, this would increase the mean annual Monachyle water use estimate by 100 mm. Confirmation or otherwise of this adjustment will emerge from the work in the rest of the year.

6. Geology and Hydrogeology of Kirkton Glen

The geological and hydrogeological survey of Kirkton Glen was carried out in August 1986 by BGS, Edinburgh. A full copy of their report appears in appendix A, with a summary given below.

The geological survey shows that the rocks were deposited around 550-560 Ma, originally consisting of greywackes overlain by limestones with further greywackes above. The sequence was strongly folded and metamorph~~a~~sed o/ forming part of the inverted limb of the Tay Nappe. The limestone consists of several grey banded, recrystallised units with schist and quartzose greywackes interbeds, and thick amphibolite sills. Fine grained sheets and dykes are abundant in the southern part of the catchment. These fracture readily "probably locally forming zones of enhanced groundwater baseflow". There is a concentration of NNW trending faults in the north of the glen possibly acting as water movement paths but "there appears to be little evidence for significant flow across the topographical divide".

The northern and eastern tributaries flow much stronger than those on the western side, where they are relatively few. Baseflow from the limestone at the head of the glen and springs on the eastern flank sustain the major tributaries. On the western flank no spring sources are apparent. Flow to the main west bank tributary is (barely) sustained by storage from the two lochans. Groundwater flow relies on secondary rather than primary or intergranular permeability, cracks in an otherwise impermeable strat~~a~~. um/ Groundwater storage is limited to shallow depths where open fractures and joints associated with weathering are most frequent. Retention times are brief , "consequently the majority of groundwater flow is shallow with water moving from areas of higher ground to springs and seepages at lower elevations". Infiltration is least on the poorly jointed west flank, moderate on the cracked rock east flank, and greatest on the limestones at the head of the glen. The limestone along the eastern bank does not appear to transmit much groundwater.

"At no point along the surface divide of the catchment are there large rock masses at sufficient elevation to cause any significant groundwater flow beneath the divide into the catchments. At the head of the glen a small volume of groundwater may drain into the catchment but flow is likely to be very small and not significant in terms of water balance calculations within the Kirkton Glen catchment".

The hydrochemistry of the surface and spring waters indicates three distinct groups s/ of water. Category 1 (pH 5.0-6.5) is peaty, slow moving or stagnant water from high ground. Category 2 (pH 6.5-7.5) is upland water not affected by limestone; it is only weakly mineralized due to the relatively insoluble nature of the rocks. Category 3 (pH 7.5-8.5) is spring discharge and associated streamflow from limestone; it has increased calcium and bicarbonate concentrations as a result of reaction in the limestone aquifer. The degree of mineralization is relatively slight indicating a brief retention time within the limestone. The catchment outflow water (pH 7.0) represents a mixture of all sources.

7. Tributary discharge analysis

Using a salt dilution gauging technique the discharges of the Kirkton tributaries were measured by proportional analysis with the total Kirkton discharge. Results showed that 15 tributaries flowed from the western flank of the catchment and 17 from the east but, of the 10 largest flowing tributaries, only 2 were on the west and 8 on the east. Total tributary discharge was 89% of the Kirkton discharge, the remainder coming from seepage into the main channel. Of this tributary flow, 37% was from the west and 63% from the east; if the catchment was subdivided to include a northern sector then 31% was from the west, 21% from the north and 48% from the east.

These results confirmed the comments made on tributary discharges and distributions in the BGS report although the amount of flow from tributaries fed from lochans is probably less than the report estimated.

Further gaugings of the tributaries later in the 1986 summer showed that the contribution from the northern tributaries decreased as the summer dry spell continued and the catchment gradually "dried out" from the higher altitude areas.

8. Sediment studies

Sediment discharge monitoring from both catchments started in 1983. Suspended and bed loads are independently sampled and concentrations of sediment are related to water discharge. Sediment discharge rating equations were produced and work continues on the analysis, determining how sediment discharge varies with rising or falling stages, seasons and antecedent conditions.

Similar monitoring has continued since both land uses changed to attempt to determine reasons for any changes in discharge ratings. Land uses were considered to have changed in the Monachyle when the cultivation started and in the Kirkton when road improvements started prior to felling. Stirling University are closely involved with the Institute of Hydrology and have extended the project to investigate the sources of sediment before and after land use change. Tributary bedload traps, automatic sediment samplers, erosion pins and channel surveys have been undertaken. Provisional results from all the pre-land use change work were presented at an IASH Symposium in 1986, Stott et al (1986).

In the Monachyle catchment the cultivation by the ploughs only affected about 6% of the catchment area. Therefore, although sediment fans can be seen developing at the lower ends of plough lines, the effect at the catchment outflow might not be significant enough to detect above the general scatter of sample points. Plough lines were terminated some 15-20 m from the main stream and 10-15 m from tributaries but cross drains do direct the flow into some natural drainage lines. Cultivation was carried out early in the year so some vegetation growth started during the summer 1986 in the exposed soils; this has helped to stabilise the area at a very early stage.

The Kirkton Forest inside the catchment area has been felled by some 17%. Extraction to stacking areas has been done by skyline and forwarder, both generating minimal sediment by careful use. However large logging lorries carrying heavy loads and turning in confined areas have caused a great deal of disturbance necessitating road repiars. Both of these have become the major cause of a large increase in sediment discharge from this catchment..

9. Discussion

As a result of the detailed discussion and criticism of the preliminary findings from Phase I of the Balquhidder catchment studies, notably by WRC and by process studies colleagues, a number of investigations of possible sources of error in the data were initiated in 1986.

Some of these have already produced firm conclusions. Most notable is that emerging from the BGS hydrogeological survey of the catchments which appears to eliminate sub-surface inflow as a factor in the apparently low water use by the part-forested Kirkton catchment. Whilst still incomplete, the current meter rating of the Monachyle streamflow structure has already indicated that water use by the heather/grass cover in that catchment was not overestimated. Indeed the indications to date are that it may be significantly higher than the Penman ET estimate, in contrast to that of the Kirkton which was found to be lower than ET. More time must elapse before the newly installed raingauges can give useful information on the validity of the existing network values. Preliminary indications from the first of these installed in the Kirkton are that the very low rainfall recorded in domain C3Y is a genuine effect.

Other checks instigated in 1986/87 will take at least a year to produce any useful results. These include the installation of additional weather stations in the valley bottom or on the western side of Kirkton to check on the ET estimates obtained from the existing stations, and the use of the newly developed snow gauge to test the present method of estimating catchment snow inputs.

The most important check of all of course is the detailed study of the water relations of high altitude grassland. The initiation of this study is described in a separate report. Results should begin to emerge from it in 1988.

Until further evidence from these checks is forthcoming nothing has emerged which disproves the conclusions of the Phase I report; namely, water use by the Kirkton catchment, under 35% mature forest, 55% upland grass and 10% heather, is, on average, significantly lower than that estimated for grassland alone in this area using the Penman estimate. It is also lower than that from the adjacent Monachyle catchment under a mixed cover of heather, grass and bracken.

Concurrently with these checks data are being accumulated from the catchments as the land use is undergoing changes in both initial planting in the Monachyle and clear felling of the forest in the Kirkton. It is too early to draw any conclusions from these data on the effects on water use or flood response but some preliminary indications of the effects on sediment losses have been obtained. In the first year little increase in loss was observed from the Monachyle whereas losses did increase from the Kirkton. Within-catchment movement of sediment was evident in Monachyle but the control measures adopted appeared to contain these in the first year. The prime source of the additional sediment loss in Kirkton was observed to be from the road system rather than from the areas of active felling.

Many outstanding questions remain to be answered on the effects of the various phases of the forestry cycle. For example, what will be the effect on both snow and liquid water storage of progressive felling of mature forest?; will the apparently high water use of a typical heather/grass covered catchment increase or decrease as young trees develop?

The existing instrumented catchments at Balquhidder, with the progressive refinements and 'fine-tuning' of their networks, are a valuable means of investigating these and many other questions relating to the effects of afforestation in Highland Scotland.

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Table 1

Monthly Water Balance Data

	MONACHYLE				KIRKTON			
1985	P	Q	P-Q	ET	P	Q	P-Q	ET
J	98	79	19	7	84	70	14	3
F	94	118	-24	15	80	118	- 38	12
M	125	88	34	24	114	84	30	24
A	185	145	40	56^x	165	154	11	52
M	120	88	32	81^x	107	85	22	81
J	86	29	57	83^x	85	49	36	82
J	268	193	75	65^x	257	176	81	65
A	442	365	77	58	368	300	68	55
S	298	247	51	35	268	211	57	36
O	219	245	- 26	34	180	250	- 70	32
N	219	144	75	3^x	194	105	89	6^x
D	389	446	- 57		346	357	- 11	
Total	2543	2187	356	461^x	2248	1959	289	448^x
1986								
J	354	296	58	-	328	216	111	
F	21	20	1	3	~~21~~ 18	20	~~1~~ - 2	
M	367	397	- 30	40	~~367~~ 334	301	~~66~~ 33	
A	115			58	108	100	8	
M	435			81	373	332	41	
J	86	53	33	117	88	76	12	
J	114			88	108	51	57	
A	182	146	36	71	179	138	41	
S	67			60	51			
O	342				278			
N	529				410			
D	535				456			
Total	3147				~~2767~~ 2731			

^{x} Estimated from incomplete data

Table 2

Monthly Water Balance Data

	MONACHYLE				KIRKTON			
	P	Q	P-Q	ET	P	Q	P-Q	ET
1982	3088				2388			
1983	2812	2147	665		2336	1726	610	497
1984	2589	2026	563	634	2159	1781	378	640
1985	2543	2187	356	461	2248	1959	289	448
1986	3147				2767 31			
1983-85								
Totals	7944	6360	1584		6743	5466	1277	1585
Means	2648	2120	528		2248	1822	426	528

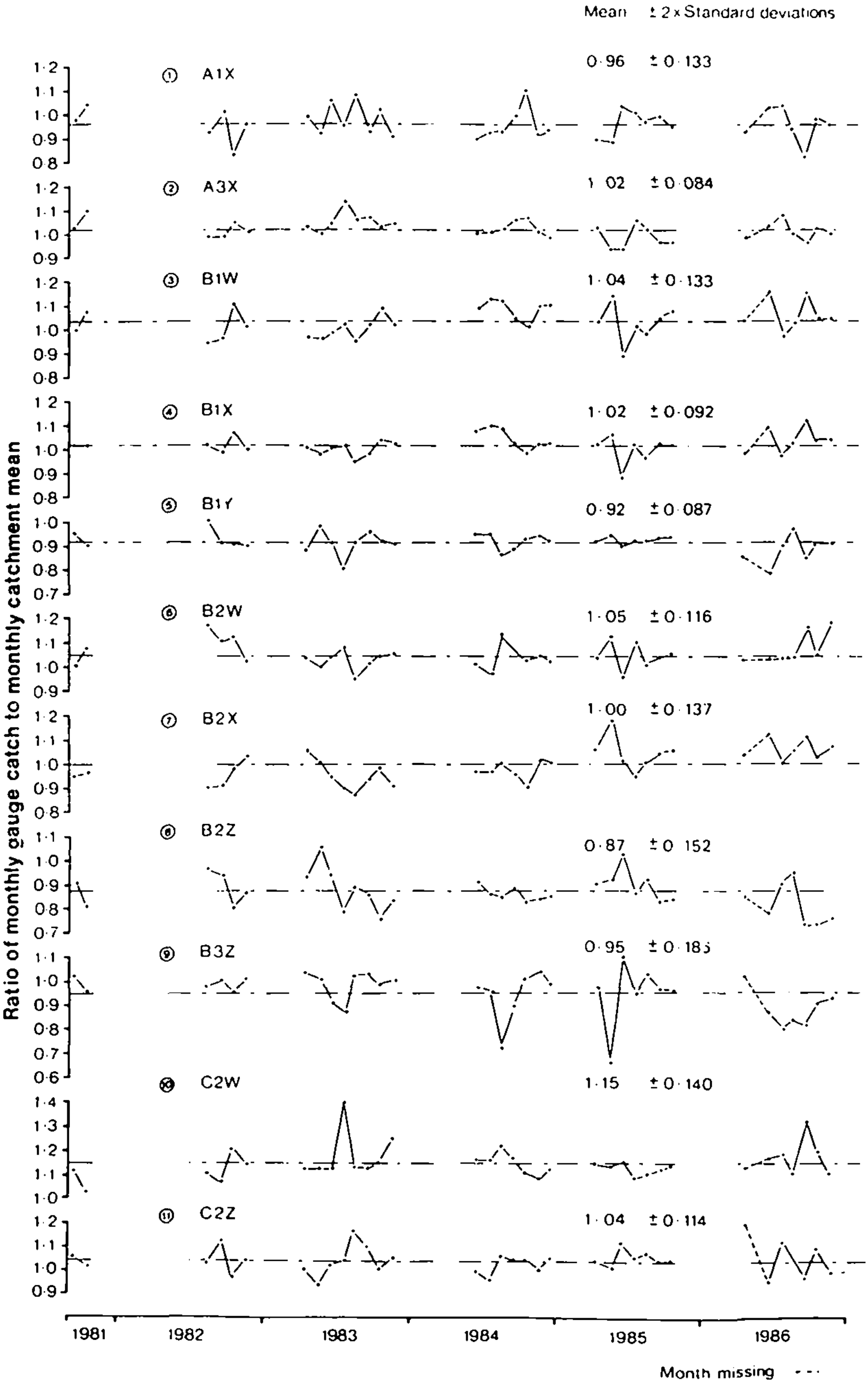


Figure 1. The persistence of the within-network relationships of the Monachyle raingauges.

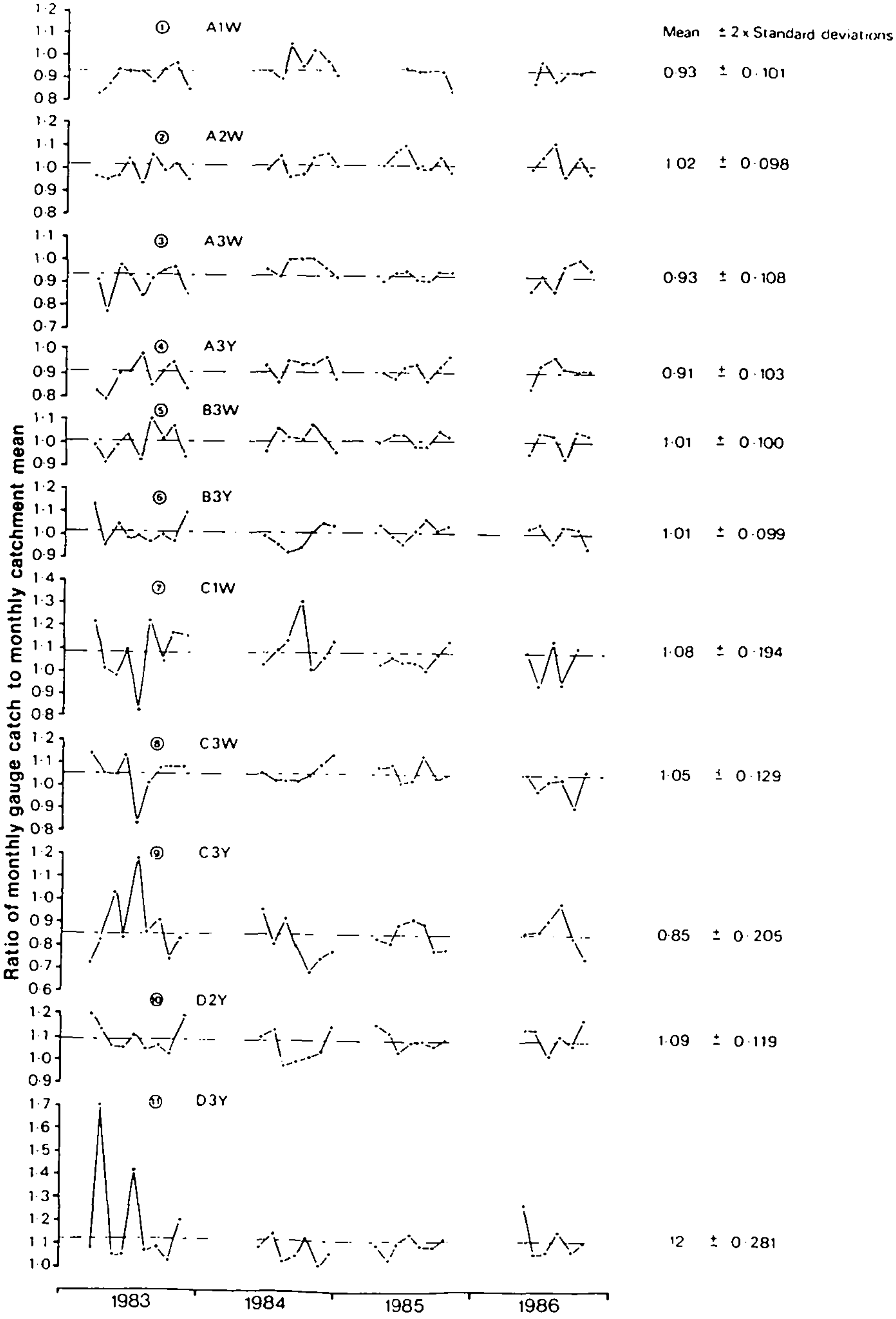
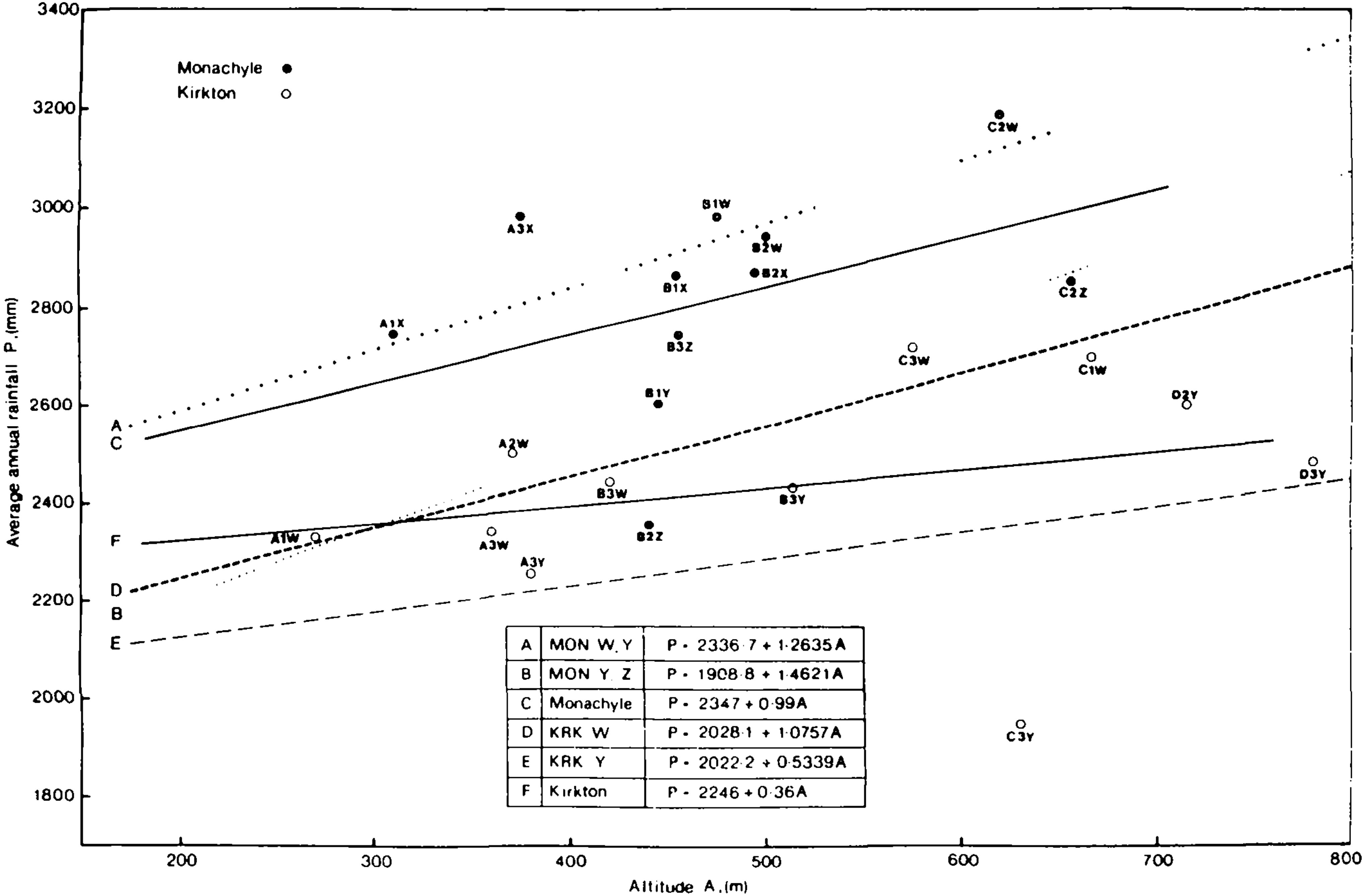
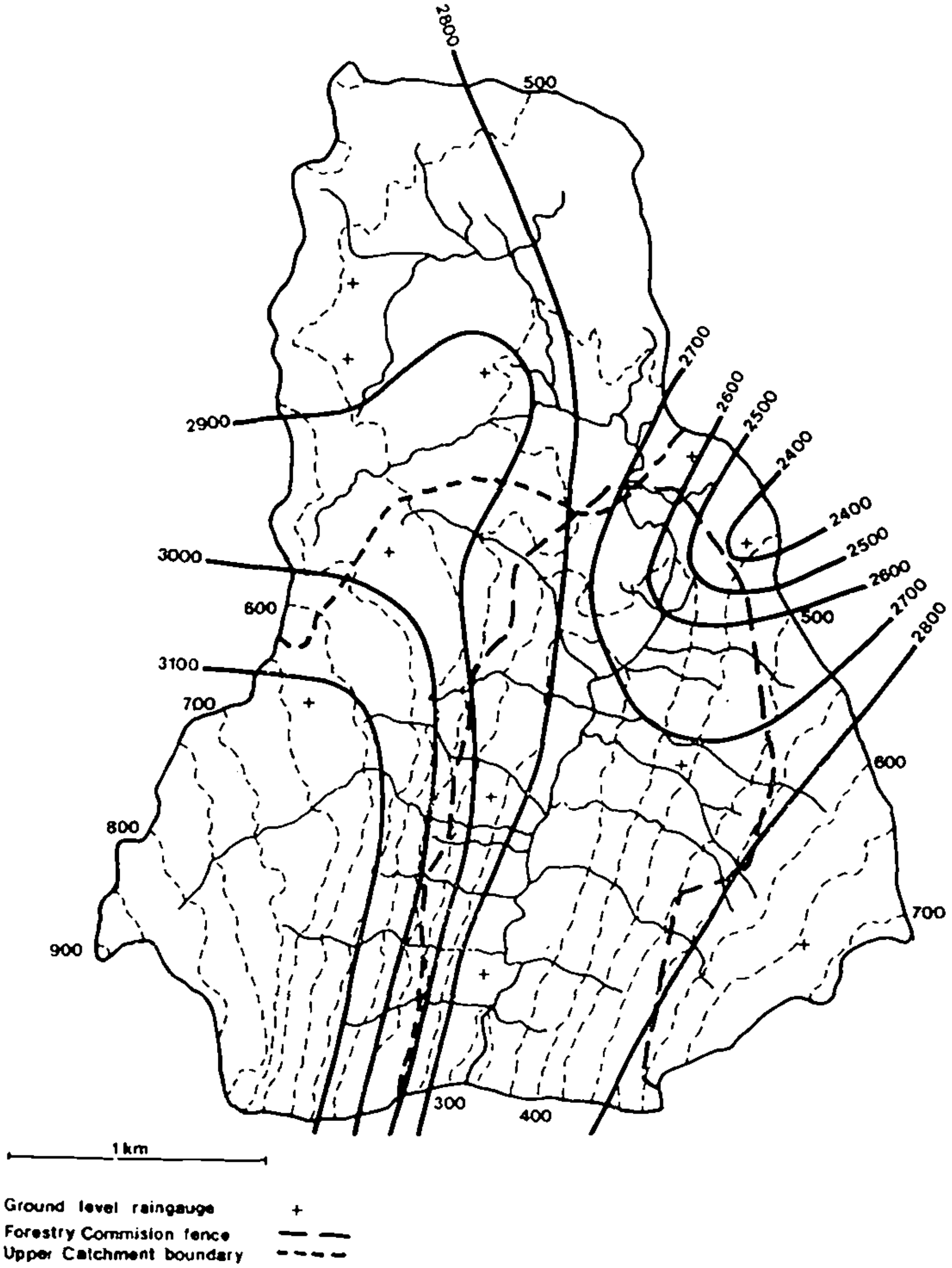


Figure 2. The persistence of the within-network relationships of the Kirkton raingauges.



A	MON W.Y	P - 2336·7 + 1·2635A
B	MON Y Z	P - 1908·8 + 1·4621A
C	Monachyle	P - 2347 + 0·99A
D	KRK W	P - 2028·1 + 1·0757A
E	KRK Y	P - 2022·2 + 0·5339A
F	Kirkton	P - 2246 + 0·36A

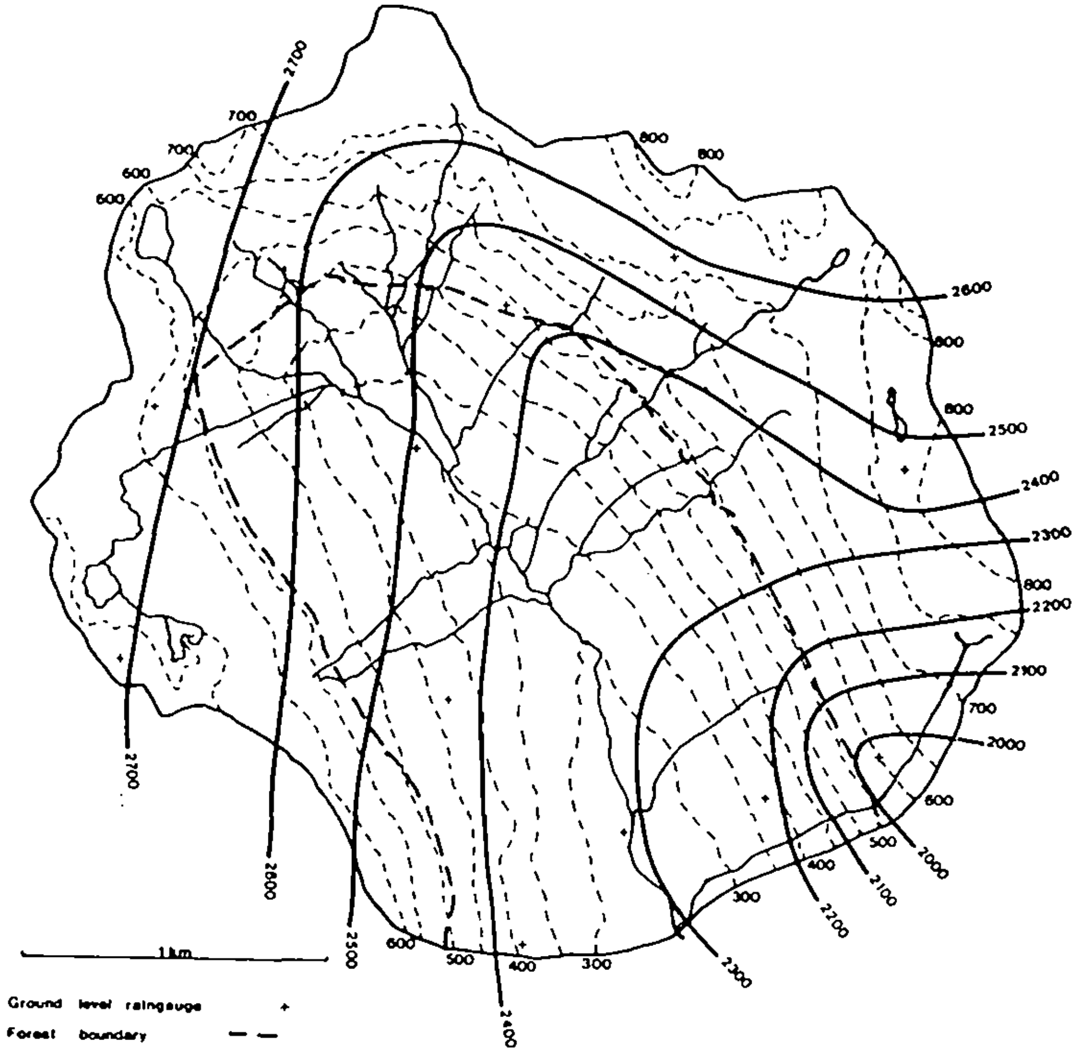
Figure 3 and 4. Variation of precipitation with altitude and with aspect in the Balquhidder catchments.



MONACHYLE CATCHMENT (area 7.7 km^2)

AVERAGE ANNUAL RAINFALL (mm) 1982 - 1986

Figure 5.



KIRKTON CATCHMENT (area 6.8 km^2)

AVERAGE ANNUAL RAINFALL (mm) 1982 - 1986

Figure 6.

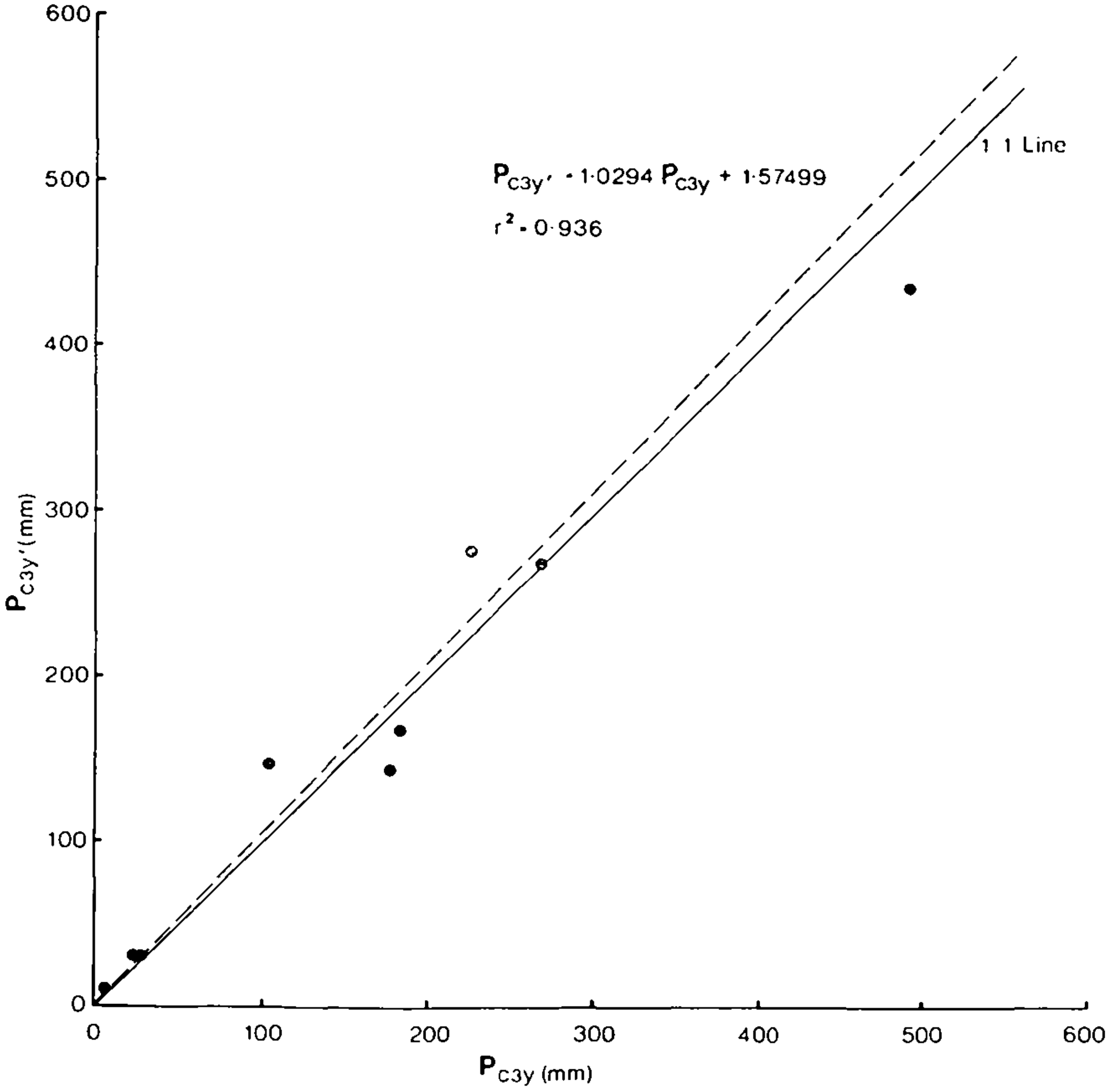


Figure 7. Comparison of new gauge, C3Y', with the existing C3Y in Kirkton domain C3Y.

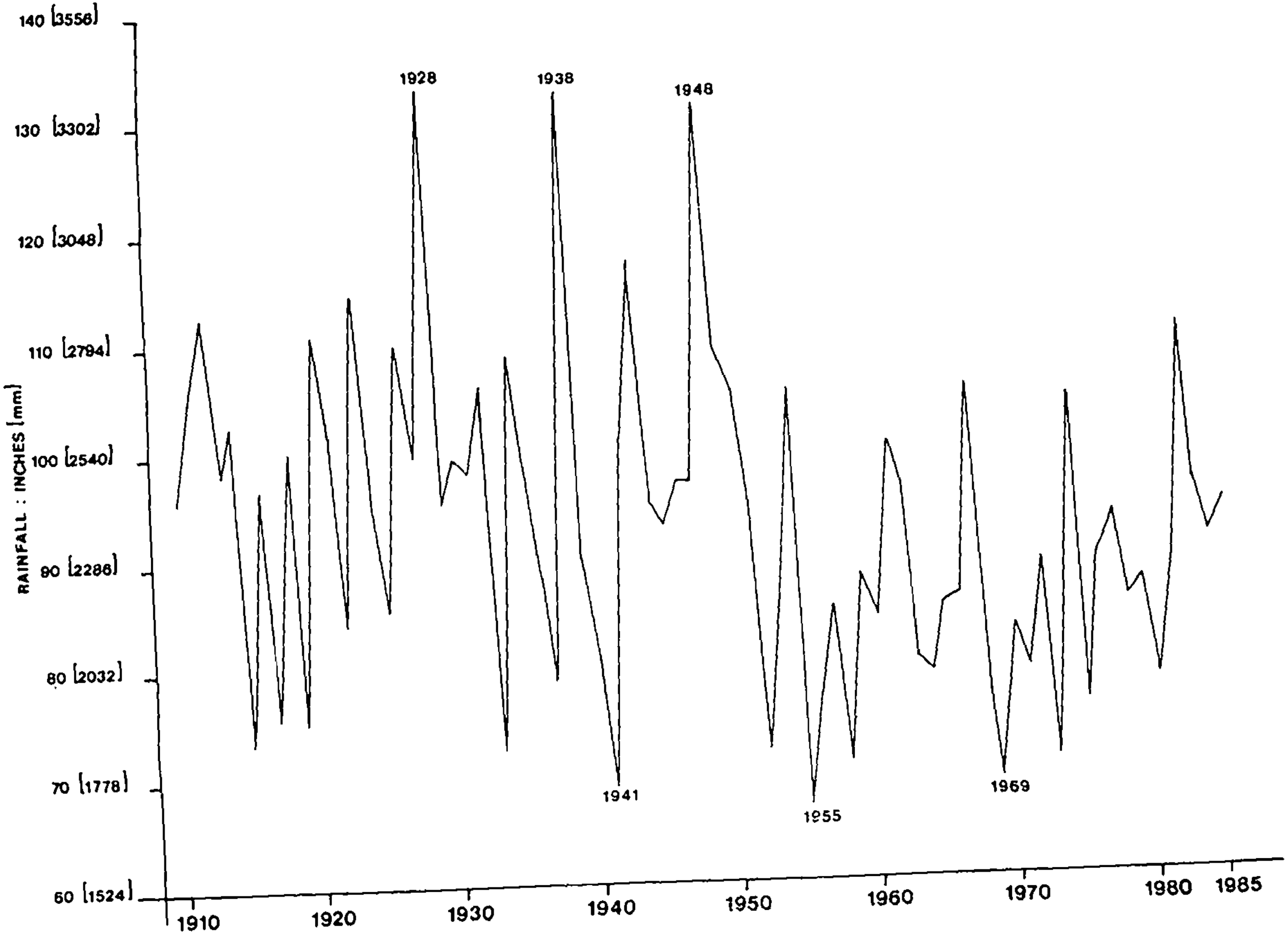


Figure 8. Blaircreich annual rainfall, 1910-85.

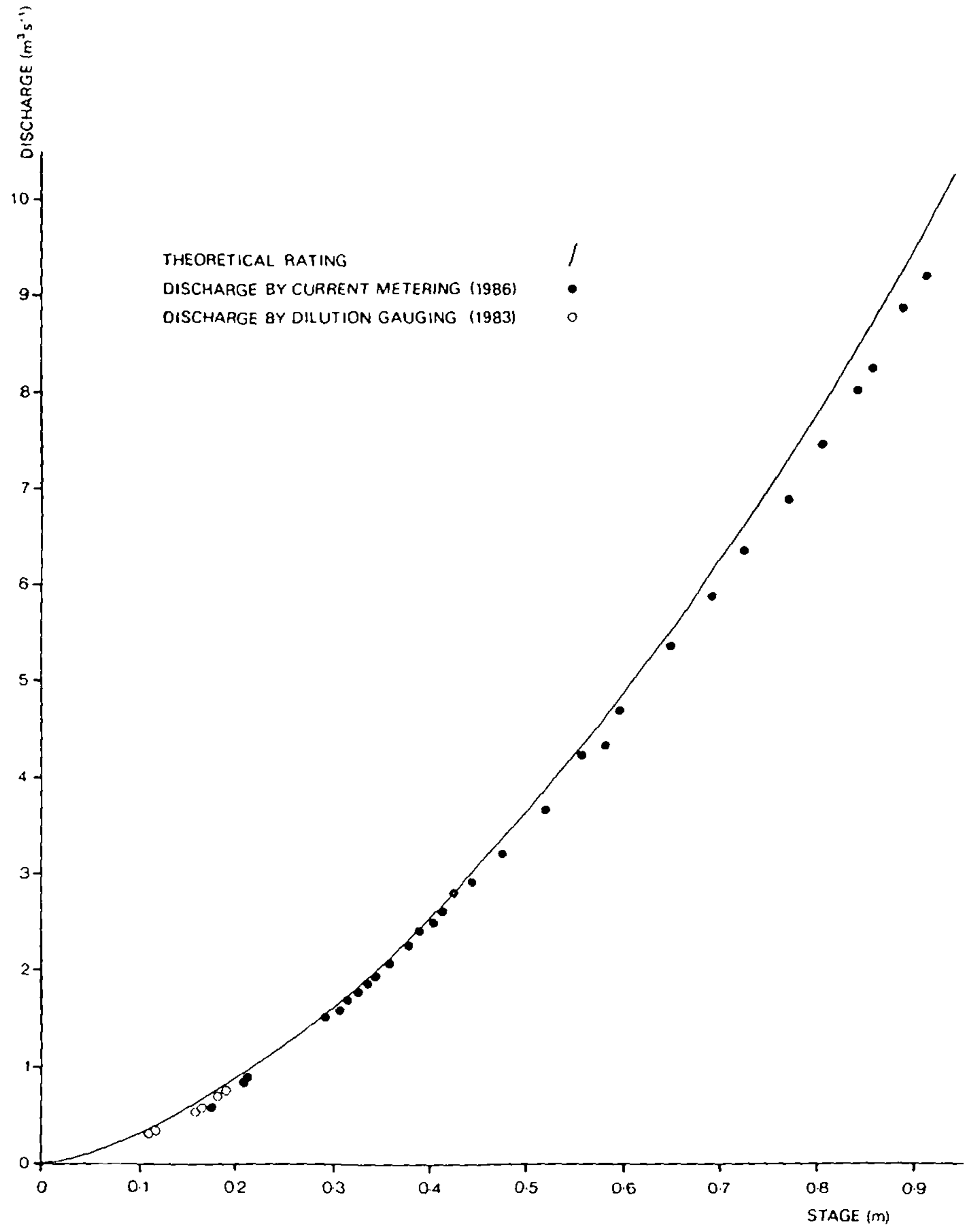


Figure 9. Current metering checks of Monachyle Crump weir.

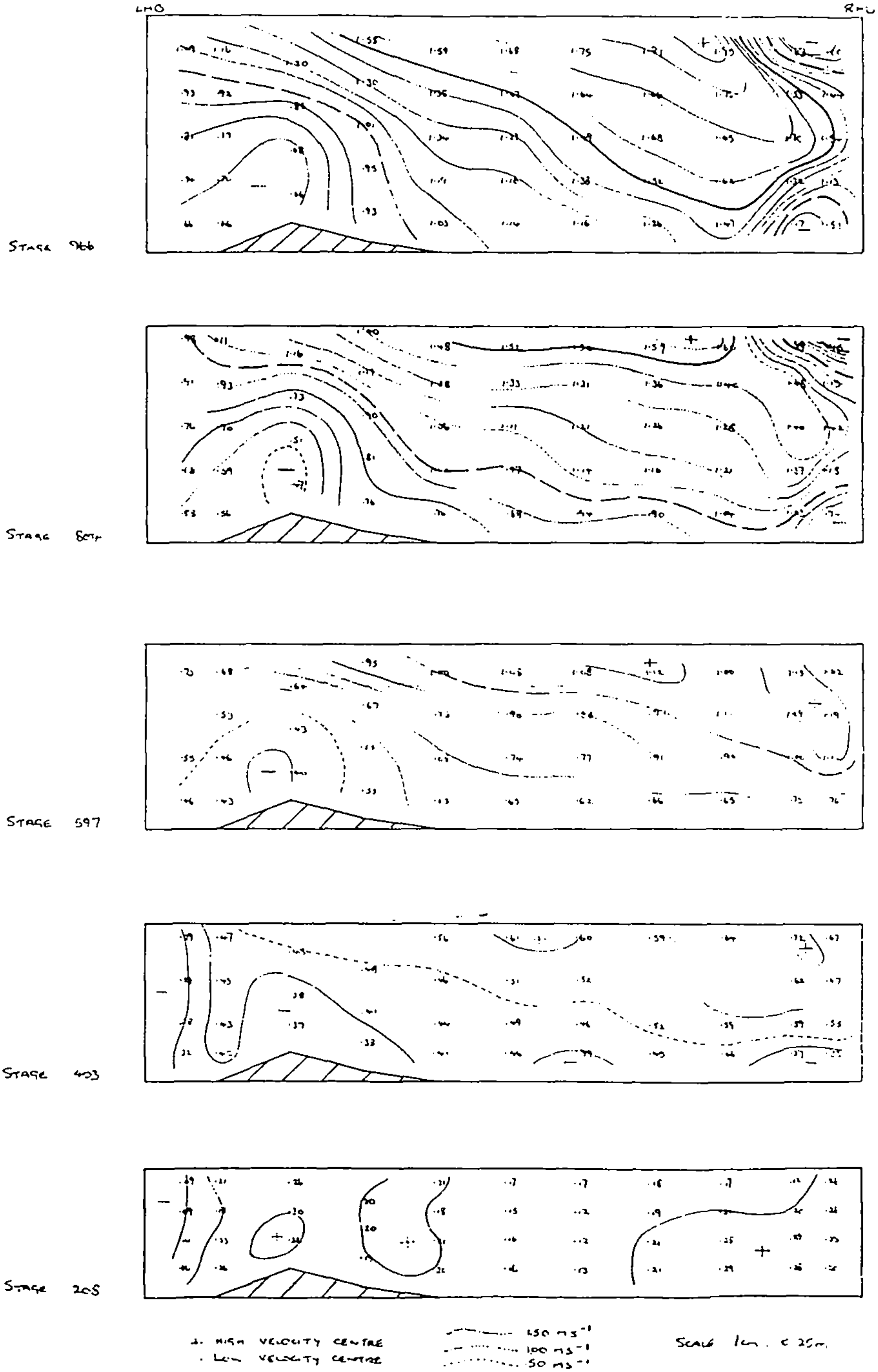


Figure 10. Monachyle weir, cross section velocity distributions at a range of stages

APPENDIX

Hydrogeology in Scotland Rept No 87-1

Geology and hydrogeology of Kirkton Glen, Balquhidder

by

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January 1987

Introduction

Kirkton Glen is a small upland catchment, some 8.5km^2 in area, situated above the village of Balquhidder, Central Region. It is one of a pair of instrumented research catchments designed to investigate the effects of afforestation in Scotland, for comparison with a similar longstanding research facility at Plynlimon in mid-Wales.

The Welsh water balance model fits only one of the two Scottish catchments. Lack of resolution at Kirkton Glen led investigations at the Institute of Hydrology in Wallingford to consider if groundwater was the cause. The reconnaissance survey described below was commissioned by the Scottish Development Department in order to assess the likelihood of underground flow into or out of the catchment.

The survey comprised two parts. As existing field mapping of the geology was both old and incomplete, the first objective was to verify the geological map of the catchment area. The second objective was to assess the likelihood of groundwater flow within the identified rock types and evaluate if flow was occurring across the surface water divide.

The Kirkton Glen catchment was visited during a period of largely dry weather (26th and 27th August 1986).

Geology

In studying the geology of the Kirkton Glen catchment particular attention was paid to the nature and extent of the Loch Tay Limestone, the location, orientation and nature of faults and regional dykes and sheets, and the overall regional structure.

The area was initially mapped by J R Dakyns of the Geological Survey of Scotland in 1887 and has recently been studied by Watkins (1984) and mapped in part by Mendum and Fettes (1985). Figure 1 shows the geology of the Kirkton Glen following these recent modifications. Although the small-scale structure of the area is complex and the rocks are regionally inverted, the overall pattern of lithologies appears to be relatively simple within this glen. The rocks belong to the Argyll and Southern Highland Groups of the Dalradian Supergroup. The inverted stratigraphy of these rocks in Kirkton Glen is summarised in Figure 2 although lateral variations are common. The metasediments were deposited at around 550 - 560 Ma, and originally consisted of greywackes overlain by limestones and then further greywackes with tuffaceous horizons. Basic sills occur in the Loch Tay Limestone and the Southern Highland Group rocks structurally below. This sequence was strongly deformed, folded and metamorphosed during the Grampian Orogeny (540 - 440 Ma). The rocks now form part of the inverted limb ('flat belt') of a large regional recumbent anticline termed the Tay Nappe. The rocks were metamorphosed to lower amphibolite facies (garnet, biotite) although subsequent retrogression has resulted in the formation of chlorite, sericite, minor carbonate and blue-green hornblende.

Green beds, formerly volcaniclastic greywackes derived largely from basic to intermediate igneous rocks, form abundant horizons in the lower part of the Kirkton Glen (see Figure 1), where they are interbedded with gritty to pelitic greywackes and amphibolite horizons. These latter bands were probably formerly both basic volcanics and intrusive sheets. Green beds and amphibolites are not found in the structurally overlying Ben Lui Schists.

Adjacent to the Loch Tay Limestone unit more gritty quartzose greywacke units are abundant (see Figure 2). The Loch Tay Limestone consists of several grey banded recrystallised limestone units with semi-pelitic schist and quartzose greywacke interbeds. Prominent thick amphibolite sills, in part feldspar-phyric also occur within this unit.

Gabbroic-textured metabasic sheets are found in the Southern Highland Group greywackes in the southernmost part of Kirkton Glen. Post-orogenic Devonian felsite sheets and dykes are abundant in the exposed stream sections. These rocks are fine-grained and fracture readily, probably locally forming zones of enhanced groundwater baseflow. A solitary thick (15m - 25m wide) Permo-Carboniferous quartz-dolerite dyke trends ca E-W and cuts across

Kirkton Glen in its lower central part. This fine to medium-grained dark-grey basic is fairly fresh and widely jointed.

Inspection of the 1:50,000 air photographs reveals prominent lineaments on the upper eastern flank of Kirkton Glen. Mapped fault breccias and stratigraphical discordances at the head of the glen show a concentration of NNW trending faults in this region. The faults in the northeast part of this region may act as water movement paths in concert with the karstic limestone in this area. There appears to be little evidence for significant flow across the topographical divide however. Minor groundwater flow may occur through limestone into Lochan Eireannaich (see high pH values) from the watershed area but such flow is likely to be minimal in relation to the overall Kirkton Glen catchment area.

The pH values shown on Figure 1 reflect the degree of groundwater buffering. In the main under low flow conditions groundwater is fracture controlled. Hence the presence of sparse carbonate (mainly calcite) as infillings or joints may exert a significant buffering effect on the acid peaty surface waters.

Groundwater flow

The low-flow conditions observed during the visit were fed almost entirely by baseflow (flow from groundwater stored in the bedrock) and by soil flow (water slowly percolating down-gradient within the top soil).

The tributaries of the east flank and around the Head of the Glen are much stronger than those flowing down the west flank where they are relatively few. Baseflow as spring discharge from the limestone at the Head of the Glen and as springs associated with fractures and landslips adjacent to a quartz-dolerite dyke on the east flank sustain the major tributaries. On the west bank no spring sources are apparent. Flow to the main west bank tributary is (barely) sustained by storage in two lochans on the shoulder of Meall Reamhar.

Groundwater flow relies on secondary rather than primary or intergranular permeability. Cracks and other fractures allow the passage of water through otherwise impermeable strata. Groundwater storage is limited and retention times brief. The development of open fractures and joints often relates to weathering and the frequency of openings is greatest at shallow depths. Consequently, the majority of groundwater flow is shallow with water moving from areas of higher ground to springs and seepages at lower elevations.

Infiltration to bedrock in the Highlands is generally less than 5% of the available rainfall, ie 60 to 100mm/a (Robins, 1987, in press). This compares favourably with outflow from the catchment as baseflow, observed during low-flow periods in 1985 to be 98mm/a. Infiltration is least on the west flank where rocks appear to be poorly jointed, greatest in the exposed limestone at the Head of the Glen, where it is faulted and jointed and may contain solution cavities, and moderate to the cracked and broken rock on the eastern side of the Glen. The limestone in subcrop along the east bank does not appear to transmit much groundwater.

At no point along the surface divide of the catchment are there large rock masses at sufficient elevation to cause any significant groundwater flow beneath the divide into the catchment. At the Head of the Glen a small volume of groundwater may drain into the catchment, but flow is likely to be very small and not significant in terms of water balance calculations within the Kirkton Glen catchment.

Hydrochemistry

The pH of surface and spring waters was measured in situ with an Orion 407A specific ion meter and a glass pH electrode (see Figure 1). There are three distinct groups of water:-

(1)	pH 5.0 - 6.5	peaty water, slow moving or stagnant, on high ground.
(2)	pH 6.5 - 7.5	upland catchment waters of streams and springs not affected by limestone.
(3)	pH 7.5 - 8.5	spring discharges and associated streamflow from limestone.

Four samples were collected for major ion analysis. Alkalinity, pH, temperature and specific electrical conductance were measured in the field and the remaining parameters were determined by Miss J M Cook and colleagues in the laboratory at Wallingford. The analyses are listed in Table 1 and the sample locations in Figure 3 where a graphical portrayal of the major ion concentrations is also shown.

Sample No 1 represents a limestone spring-fed headwater, a mixture of category 3 and category 2 waters. The pH is high and the alkalinity relatively low. Sample 2 is mineralised to a greater degree, has a high pH and is dominated by calcium bicarbonate. This sample represents limestone water from seepages around Lochan Eireannaich (category 3). Sample 3 is a mixture of peat water (category 1) with non-limestone upland catchment water (category 2). It has a low pH and is weakly mineralised. Sample 4 is typical non-limestone upland catchment water (category 2). It has a slightly acid pH, is weakly mineralised and poorly buffered.

The category 3 water is characterised by increased calcium and bicarbonate concentrations as a result of water-rock reaction in the limestone aquifer. The degree of mineralisation is slight compared to waters from, say, the English Chalk, and it indicates a brief retention time within the limestone and a short passage from recharge to discharge area.

Groundwater in contact with non-limestone rocks is less mineralised due to the relatively insoluble nature of the rocks (category 2). The peat waters are dominated by organic material (category 1). The outflow of the water at the bottom end of the catchment represents a mixture of all sources. The pH of this mixture is 7.0.

References

Mendum J R and Fettes D J 1985. The Tay nappe and associated folding in the Ben Ledi - Loch Lomond area. Scott. J. Geol. Vol 21, pp 41-56.

Robins N S 1987. Hydrogeological provinces and groundwater flow systems in Scotland. Trans. Roy. Soc. Edinburgh. In Press.

Watkins K P 1984. The structure of the Balquhidder-Crianlarich region of the Scottish Dalradian and its relation to the Barrovian garnet isograd surface. Scott. J. Geol. Vol 20, pp 53-64.

TABLE 1 Hydrochemical data (mg/l)

Sample No	1	2	3	4
temperature (°C)	10.1	12.5	10.0	8.0
SEC (μS/cm)	49	98	39	38
pH	8.2	8.4	6.2	6.8
Na	2.4	2.2	2.0	2.5
K	<0.7	<0.7	<0.7	<0.7
Ca	6.4	17.4	5.6	4.2
Mg	0.7	0.7	0.6	0.8
HCO_3	16.8	50	13.2	9.9
SO_4	4.2	4.5	3.6	5.3
Cl	3.8	3.7	3.1	3.3
NO_3-N	<0.04	<0.04	0.04	0.04
Sr	0.04	0.13	0.03	0.02
Ba	0.005	0.01	0.007	0.005
B	<0.02	<0.02	<0.02	<0.02
Si	0.5	0.3	0.2	0.6
Fe	0.04	0.12	0.15	0.01
Mn	0.002	0.002	0.01	<0.002

Grid references		
	1.	NN 5187 2417
	2.	NN 5147 2421
	3.	NN 5133 2340
	4.	NN 5289 2356

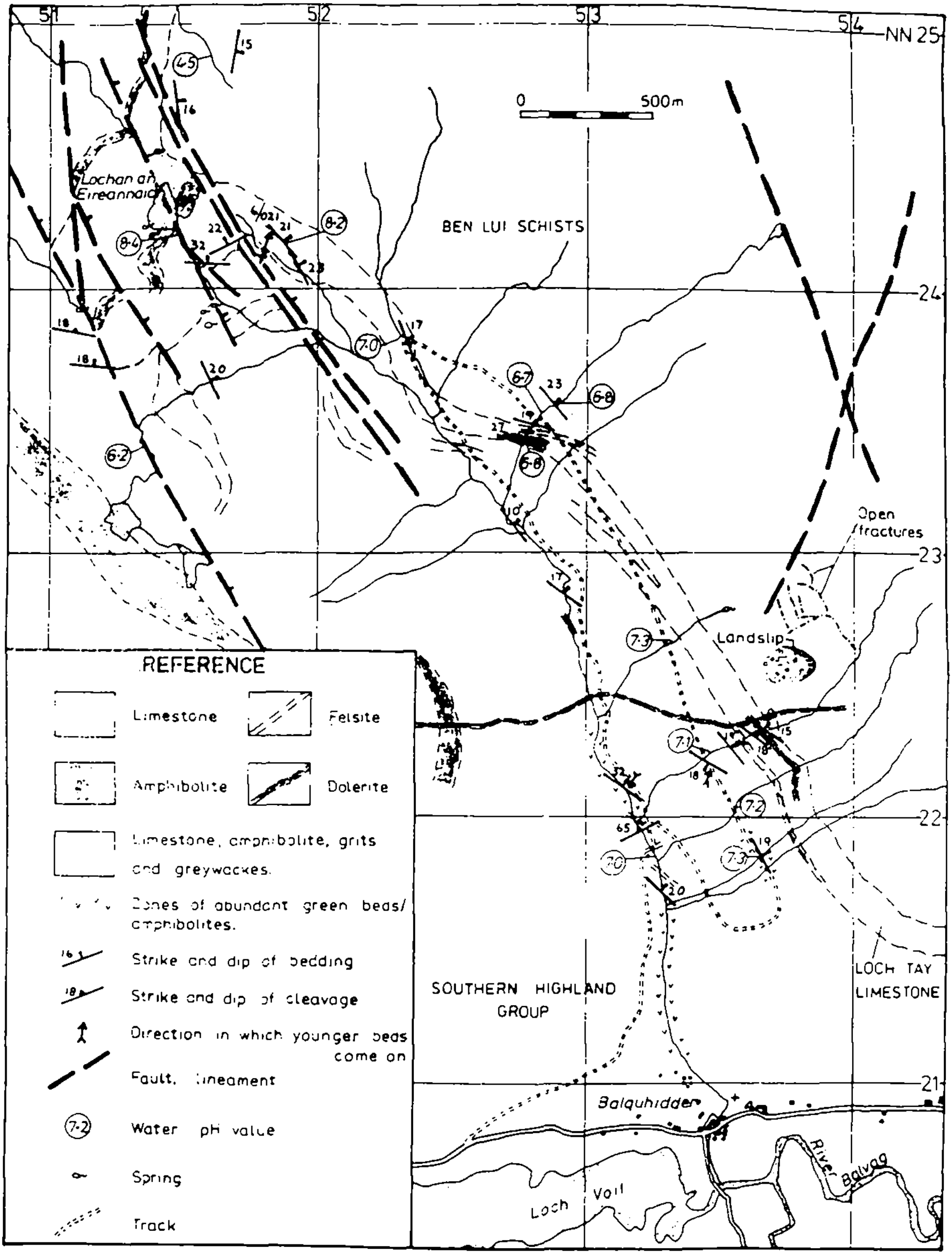

Figure 1 Geology of the Kirkton Glen

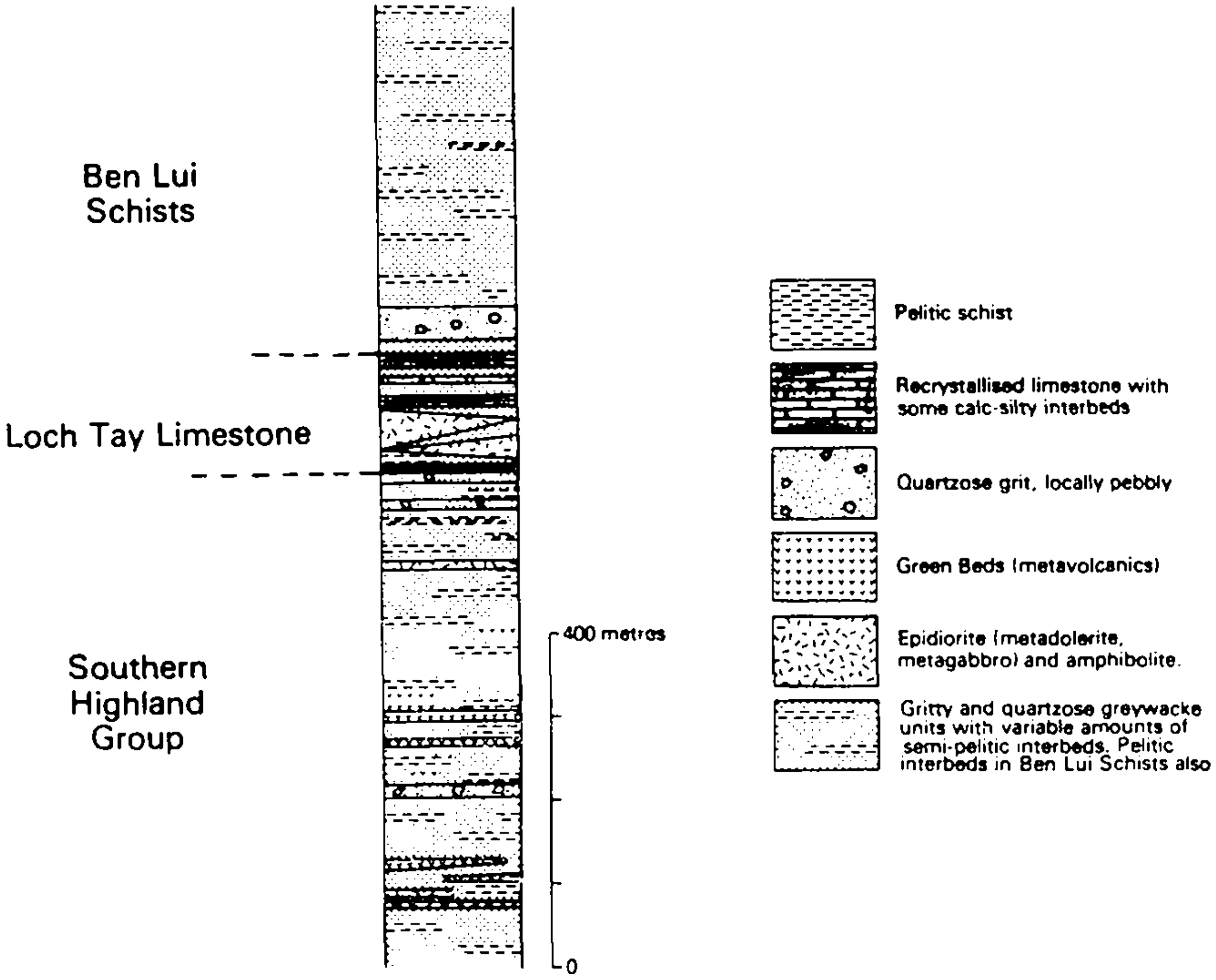

Figure 2 Stratigraphy (inverted) of the Dalradian rocks of the Kirkton Glen area (after Mendum & Fettes, 1985)

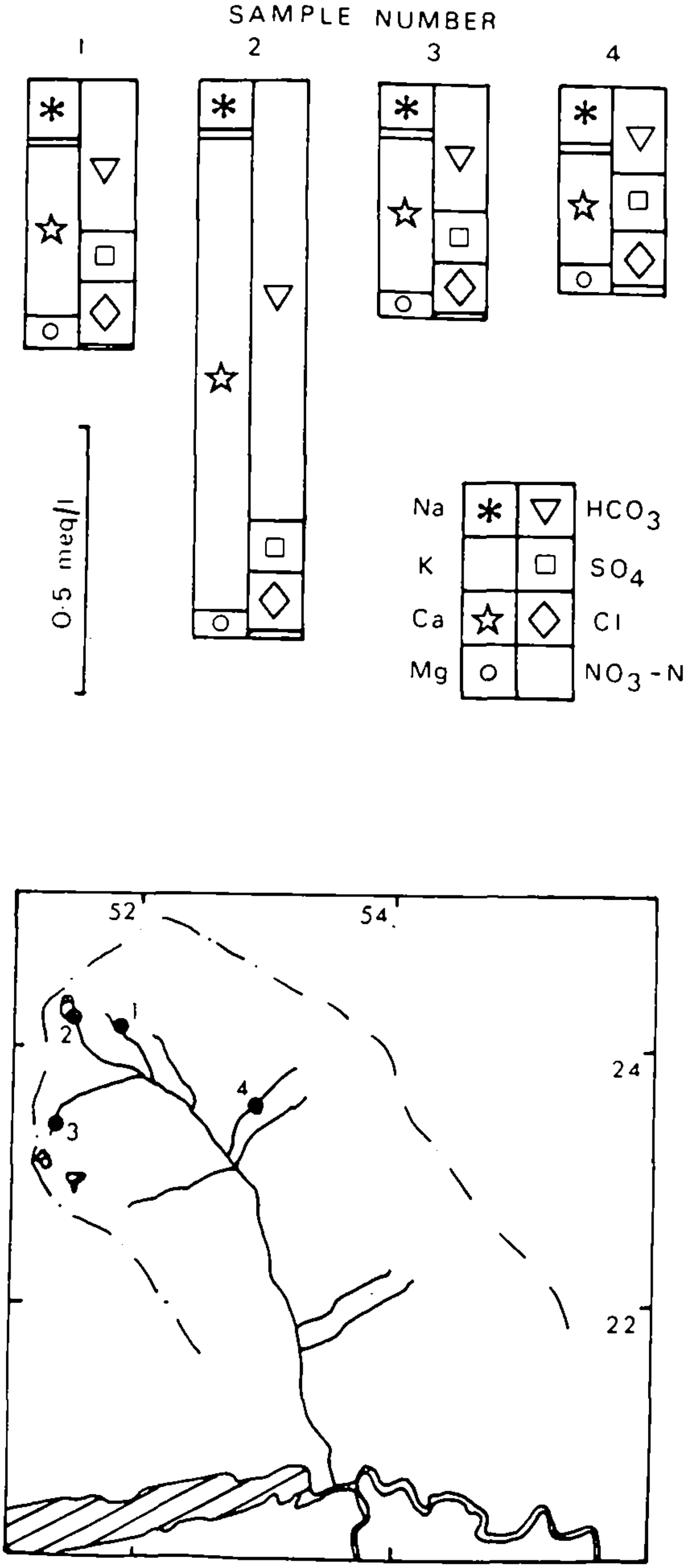

FIGURE 3. Hydrochemistry summary