RIVER CHANNEL PLANFORM CHANGES IN UPLAND SCOTLAND : WITH SPECIFIC REFERENCE TO CLIMATE FLUCTUATION AND LANDUSE CHANGES OVER THE LAST 250 YEARS (VOL. II)

Lindsey Jo McEwen

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CHAPTER 6

Landuse controls at both basin and channel reach level

6.1 Introduction

As discussed in Chapter 2.10, there is much controversy over the effects of different types of landuse and landuse change on both the basin hydrological cycle and the hydraulic properties of the channel, each potentially affecting floodplain stability. At the basin level, changes in vegetation or agricultural activity, construction of roads and expansion of existing settlements may exacerbate or diminish rates of storm runoff and cause variation in the rates of sedimentation and erosion (Chapter 2.10). Floodplain areas may have their thresholds of stability disrupted and/or lessened by such disturbances.

Upland Scotland is deceptive; in comparison to the lowlands, it seems practically devoid of human influence. However landuse changes still exist and, though sometimes not as obvious as in the lowlands, they exist on a variety of scales. Each of the study regions has its distinct history of landuse change and, although their reconstruction is a complete research topic in itself, it is necessary to assess what is known about landuse history in order to put the controls of planform change in this present study into context. In none of these areas can climatic fluctuations or high magnitude random events be said to be working on a catchment whose properties have remained unaltered. As Pennington (1974) points out, there is comparatively little detailed evidence in Scotland about vegetational history during the historic period. The information that is available is derived from a variety of sources including estate records, government reports and contemporary literature. Estate records were checked to confirm the reliability of the surveyor. Similarly, published works are few in number but where these do exist, they provide valuable background information (eg. Steven and Carlisle, 1959; Innes, 1983).

At their maximum extent during the Atlantic period, deciduous forests extended to at least 763 metres on the slopes of well-drained Scottish mountains. It is known that at the time of the Scoto-Saxon invasion of 1097, Scotland was still largely covered by natural woodland. This has subsequently been reduced in areal extent both as a result of climatic change (Lamb, 1964) and the impact of man (Pennington, 1974). The climatic lowering of the tree-line is evident from the large number of tree stumps buried in Scottish hill peats eg. on the Cairngorms (Pears, 1975). However, it is difficult to find data to support a case that suggests that deforestation has caused increased runoff through time. It is easy to enumerate the number of trees felled at a particular period but more difficult to put such information in its hydrologic context. It is necessary therefore to ask one major question; have major landuse changes taken place post 1750 which could possibly have changed the periodicity of extreme runoff and sediment mobility, or was the change in landuse since that period in relative terms insignificant to what had taken place before that date?

It is not only deforestation that may cause a significant change in the hydrologic regime; under certain situations, afforestation may decrease surface runoff (Chapter 2.10.1 and 2.10.2). Each of the study areas has undergone periods of replanting over the past 250 years. However, it is important to remember that the hydrologic implications of afforestation may have also changed over this period, depending on forestry practice. Important factors include the length of time the land surface is left either unvegetated or partially vegetated, and whether an extensive drainage network is installed. In Forestry Commission plantations, both successive thinning and clear felling at an average of 50-100 years take place (Edlin, 1969b). Prior to planting, the land is usually drained (Binns, 1979) and Green (1979b) made a distinction between field, forest and hill drainage in upland Scotland. However, not only present ditching practices must be considered but also periods of drainage installation in the past. Modern ditching practices in the preparation of the ground for new plantations can have important implications in the speed with which flow may reach the channels. Henman (1963), describing the Forestry Commission's ground preparation for afforestation, stated that ploughing at 5 to 6 feet (1.5-1.8 m) was standard practice to provide "temporary" drainage:-

> "This drainage effect is of little significance after the establishment stage, compared with the effect of a well-designed drain system, but it can assist or hinder the main system's surface drainage function, depending on how the turfing furrows lie with respect to the contour drains." (Henman, 1963, p11).

In terms of possible sedimentation involved, the following quote should be noted:

> "In hilly country the bulk of the main drains will be provided by natural water-courses, and when the drainage from a large area is directed into these valley-side streams, instead of finding its way slowly down the slope, "rejuvenation" of the streams may occur and erosion may be considerable. A certain amount of erosion must be accepted as an inevitable consequence of drainage on steep hillslides, and this must be taken into account when planning roads, bridges...." (Henman, 1963, p16).

However, Fountain Forestry (pers. comm.) install a drainage system which leads runoff water into silt traps to prevent it reaching the main waterways. They state that 90% of the silt that will come off, does so in the first six months after ploughing. Thus, ploughing can be envisaged as increasing the drainage density of the catchment and its effect on regime depends mainly on the percentage of the catchment that has been treated. Personal communication with many local farmers and landowners supports the view that forestry ditching has increased the magnitude and frequency of flash flooding. It is of course hard to prove and no known research has been carried out specific to this problem within the three study areas. From the literature review (Chapter 2.10.2), the impact of forest ditches is at their greatest in the years immediately after ploughing. Roberts (1919) however presents an alternative view:

"It appears not unlikely that rainfall would runoff more quickly from ground saturated almost to its surface, which is often the case before it is underdrained, than from ground in a better agricultural condition and more pervious owing to the laying of underdrains. Land underdrained might be expected to behave more like a sponge and a storage reservoir." (Roberts, 1919 p9).

The critical factor is probably slope; the draining of marshy relatively low-lying ground will have different hydrological significance than the ditching of steep slopes. It would also be expected to activate less potentially mobile sediment. It is known that between 1750 and 1850, drainage of bogs, lochs and floodplains were frequent modes of land improvement (O'Dell and Walton, 1962). Apart from forestry, pasture degeneration due to bad management practices, eg. burning and subsequent overgrazing, may cause increased mobilisation of sediment on the slope/channel interface due to debris flows, sheet erosion (Innes, 1983) and gullying (Fairbairn, 1967). Duck and McManus (1984) found a change in sediment supply (increase in grain size) within sediment cores from reservoirs in the Ochil Hills. This was related to a period when thousands of acres of marginal and more upland areas were ploughed for the first time during World War 2. It is also suggested that as many other areas underwent similar landuse change, the result of these changes in terms of fluctuations in sediment yield and rates of soil erosion may be found elsewhere.

Landuse changes occur not only at the basin level; a change in the vegetation of the floodplain and disruption of the root/ soil layer may make the banks of the channel more erodible. Isolated trees on the floodplain may increase or decrease bank erosion depending on location and frequency. Similarly, the construction of mill lades and the division of streamflow can be expected to have both local and downstream effects in terms of stream power. Damming of reaches may cause localised sediment traps with downstream depletion in the availability of sediment.

Remedial measures also may have considerable impact on the channel cross-section eg. the use of rip-rap and gabions. Even in the 17th and early 18th century, there were certain recognised practices which attempted to conserve agricultural land adjacent to stream channels. Detailed descriptions of such measures include:

> "Large banks of earth have been formed sloping towards the river....perpendicular ramparts of stones and sods have been constructed... Bulwarks of stone contained in a wooden frame are built to defend the banks and sometimes a large sloping caul of loose stones is formed to divert the course of the river, where it threatens an irruption." (Walker, 1808 p116).

Walker however notes that even if these measures are sometimes successful, they are more frequently otherwise and they are always laborious and expensive to construct. Other measures are outlined which involve the driving of stakes into the banks to a height "a little higher than the greatest flood". It is claimed:

> "Such stakes, thus situated can neither be displaced nor shaken by any force of water; they stop and entangle every sort of refuse brought down by the river; they intercept the mud and gravel that gradually forms a bank." (Walker, 1808 p116).

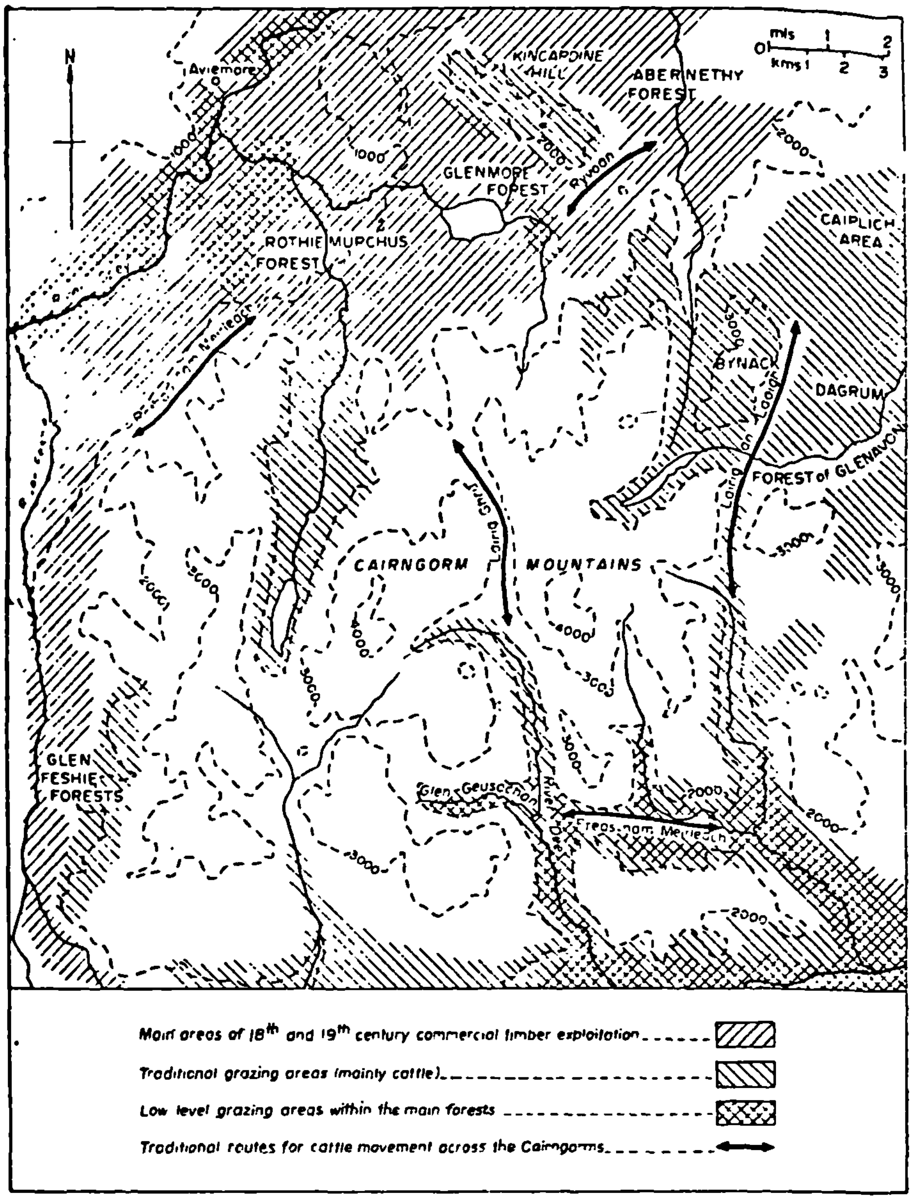
The effectiveness of such measures must be highly temporary. However, in comparison with some of the strategies used by modern farmers to stop bank erosion, these techniques appear to be quite effective. Frequently, rubbish is used as infilling material to strengthen areas susceptible to high erosion, sides may be concreted or wired with gabions or the banks may be artificially regulated with stone slabs. These are but a few of the piecemeal anti-erosion strategies seen during field work and are generally susceptible to undermining, even with moderate flow events.

6.2 Dee study area: Reconstructed history of landuse change

There has been considerable landuse change at the basin level over the past 300 years, mainly associated with important timber felling in the 18th and 19th centuries. The main areas of such commercial timber exploitation are shown by Pears (1968), as seen in Figure 6.2.(i). The Old Statistical Account (1791-1799) states that the greater part of the united parishes of Crathie and Braemar were originally King's forest and known as the Forest of Mar.

The native climax vegetation of this region is the ancient Caledonian Pinus sylvestris forests, which at one time blanketed the area, but now survives in remnant woodland. It is stated that the former Caledonian forest extended from Glen Lyon and Rannoch to Strathspey and Strathglass and from Glen Coe east wards to the Brae of Mar (Nairne, 1891). This included both the Dee and Spey study areas. Two main fragments occur in Deeside above Crathie, namely the Ballochbuie and Mar forests. The Ballochbuie forest is mainly in the Allt Garbh and Gelder catchments, while the Mar is scattered in the Quoich, Luibeg, Lui and Derry catchments. Both these forests have been discussed in detail by Steven and Carlisle (1959), as annotated in Figure 6.2.(ii). Natural reduction in pine forest area has taken place over a longer timescale and was brought about by the development of blanket peat, which had initiated at the beginning of the Atlantic period (5,500 B.P.) (Jousley, 1973). In the Parish of Crathie and Braemar, there is widespread evidence of this lowering of the tree-line:

Figure 6.2.(i)



Cairngorm mountains: some aspects of landuse changes

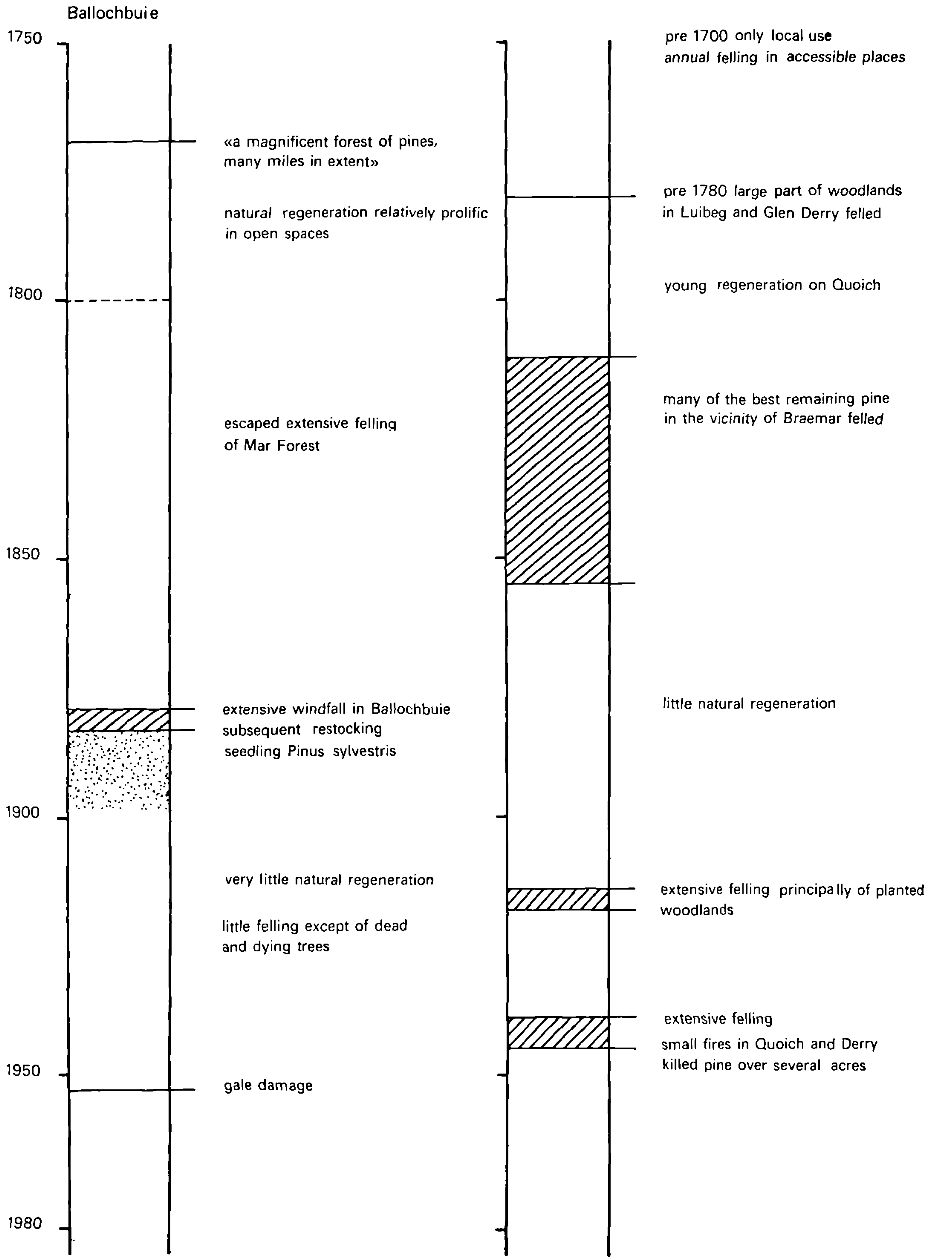
(Source: Pears, 1968 p47 Figure 1)

"In the deepest mosses or morasses within the immense range of extensive forest, there are to be found large logs, or roots of wood (even where there is not a tree now to be seen standing) which affords the most incontrovertible evidence, that they have formerly been overun by timber". (Old Statistical Account, 1791-1799 p463).

Over the past 300 years, forests have been managed both for their timber and for the raising of deer, and there has been both deforestation and periodic afforestation in this area. In the 1750s on Roy's map, the extent, but not the species, of woodland is shown (Figure 6.2.(ii)). The Quoich floodplain, for example, is indicated as having its floodplain covered with woodland; the Ey, in contrast, was sparsely covered with groups of trees on localised areas of the floodplain and some on the higher slopes. Estate maps around 1826 also indicate woodland all along the slopes near the Dee (RHP 811). The Clunie, according to Roy's map, had scattered trees mainly by the channel side. In contrast, the Gelder was considerably less wooded than it is today. This pattern corresponds well to the extent of forest as indicated by estate plans and other contemporary sources. For example, MacIntosh (1895) indicates that above Braemar the hills of Glen Clunie were partly wooded for some distance. About 3 km above Braemar the wood ceased, except for straggling plants and bushes along the margins of the stream. This is in considerable contrast to the treeless nature of the glen in 1984.

Figure 6.2.(ii)

Landuse history within the upper Dee catchment



Information source,: Steven and Carlisle, 1959

It is known (again from estate records and contemporary sources) that major deforestation had taken place generally in the upper Dee and and especially in the Mar Forest, in the first half of the 19th century (Figure 6.2.(ii)). Ballochbuie forest escaped the extensive felling similar to Mar forest during the first half of the 19th century because of its associations with Queen Victoria, and most of the felling was the result of wind damage. Deforestation was thus not only man induced; wind and fire damage caused periodic large-scale felling of trees (Holtnam, 1971). Clearly, the percentage of catchment area affected is important. In some areas, natural regeneration of Pinus sylvestris seedlings was prevented by deer grazing or burning with quick reoccupation of the cleared ground by heather/ moss cover. In other areas, large scale replanting is known to have taken place:

> "There are extensive natural fir woods and also large plantations of Scotch firs and other trees. Mr Farquason of Invercauld alone has planted above 14 millions of the former and upwards of a million of larch with a great variety of others." (Old Statistical Account, 1791-1799 p463).

Replanting also took place at Ballochbuie, using seeds germinated from the original forest.

The hydrological significance of such vegetative cover, when mature, must be fairly similar to the mature native pinewoods. The original pinewoods were Pinus sylvestris with trees of varying ages, intermixed with a variety of other species. If however birch or alder is naturally regenerated in pine clearings, it is suggested that when it has grown to a certain level, its hydrological behaviour will be similar to the pine forest. This will of course be dependent on the area of cover, as in terms of interception and evapotransporation surface area the pine forest will be more efficient. Birch, however, being short-lived does not form the permanent woods that Pinus sylvestris does and, with natural regeneration, birch does not remain such a stable element in the landscape.

There is little information about the possible hydrological implications of such changes. However, Roberts (1919) stated that there had been much deforestation during the 80 years prior to 1919 and he endeavoured to see whether there had been any impact in runoff hydrology over that period. Because of the higher stages attained by the events of 1829, 1877 and 1881 cf. 1913, he argued that the largest floods occurred when the forest was most extensive, but clearly considerable deforestation had already taken place prior to that time. It is however difficult to separate the differential rainfall inputs for events where there is no gauged rainfall record. Nevertheless, it is important to realise that these flood events would probably have been major runoff events independent of the landuse involved. There must be a threshold beyond which landuse controls are not important; Robert's views must therefore be treated with caution.

Inspection of present day landuse in the area showed evidence of large scale deforestation. For example, between the confluences of the Quoich and the Lui, the slopes are a mass of tree stumps (Plate 6.2.(i)). Despite this, the neighbouring Ballochbuie forest (Nature Conservancy, 1973) still had 685 acres (2.8 km^2) of reasonably stocked Caledonian pine forest (Dunlop, 1975). There has not been much Forestry Commission planting and associated drainage ditching in this area. However, there has been some planting on the Balmoral estate over old farming strips on the Dee floodplain sold to the Forestry Commission (seen in background in Plate 6.2.(ii)) and also some localised new planting in the Quoich catchment and Glen Clunie. There have also been more recent attempts at regeneration of the Caledonian forest by the Balmoral estate.

In terms of land drainage, there is evidence of some improvement in the mid 18th century but this seems to be localised on the floodplain rather than the slopes; for example, drainage ditching of "wet and bushy" land is indicated with the march ditch between the estates of Lord Braco and Invercauld (mid 18th century) (RHP 31322). Again at Tullochoy, from the Invercauld estate papers (19th February, 1772), the lands are described as very improveable, with a good deal of fine birch wood (Michie, 1901). Over a century later, Roberts (1919) discussing the whole Dee catchment, states that a considerable area of land has been reclaimed and underdrained during the previous 50 years ie. since the 1870s up to 1919. However, he asserts there was no evidence to show that this under-drainage has increased floods or reduced summer flows.

Plate 6.2.(i)

Large scale deforestation on the slopes between the Lui and Quoich confluences

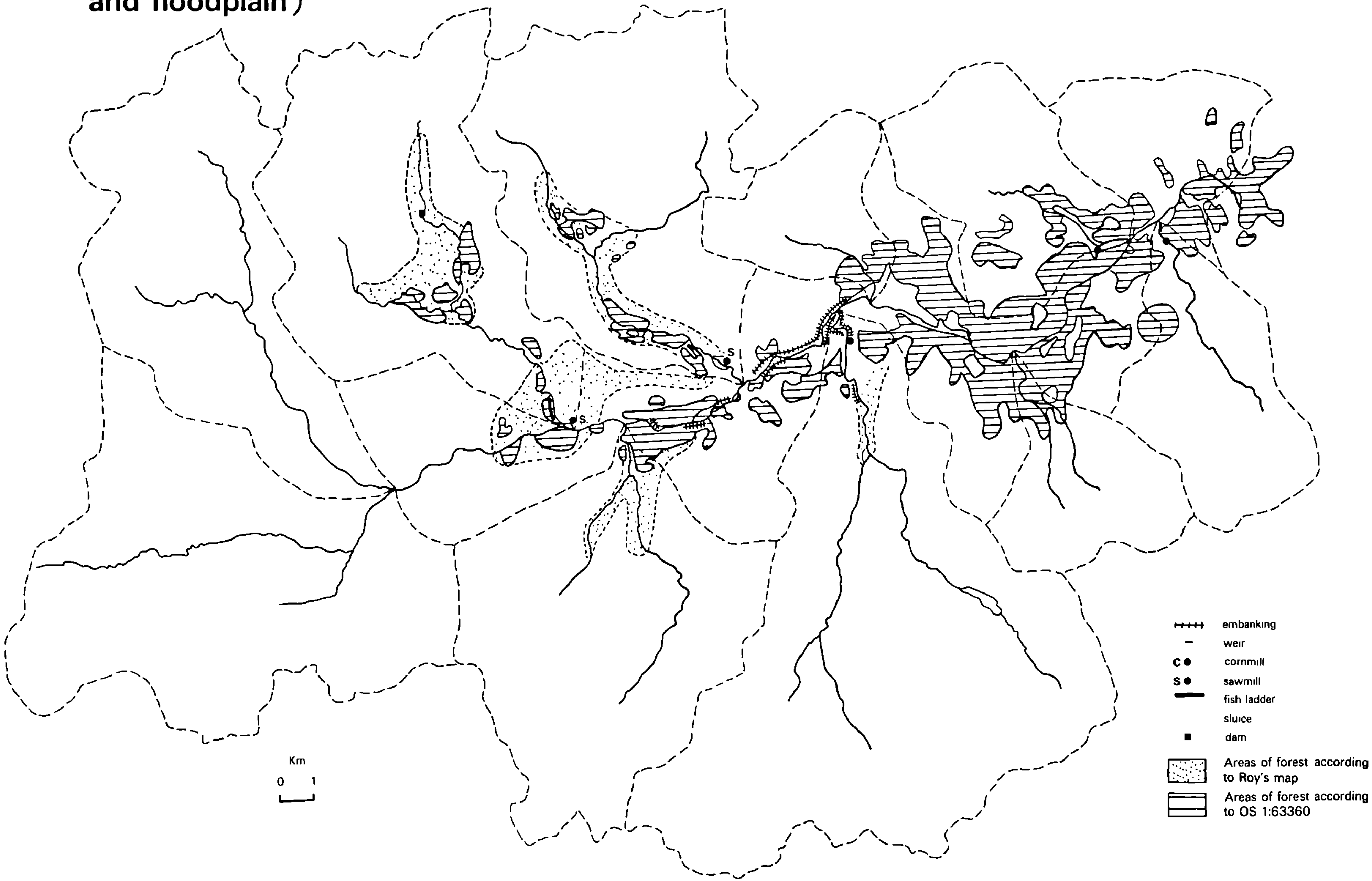
Plate 6.2.(ii)

The bulldozed lower reaches of the Garbh Allt

The Dee study area is probably the least affected in terms of man-made alteration to the natural channel but this is only relative. Mill lades, associated with the logging industry but now no longer obvious, were frequently shown on early estate plans. These divided flow locally along the lower reaches of the tributaries below the meltwater gorges. This would cause reduction of flood flows within the natural channel and thus a more rapid decrease in stream power than under natural conditions. For example, mill lades are found on the lower Quoich on mid 18th century estate plans (RHP 31322) and it is documented that the sawmill was built at the mouth of Glen Quoich in 1695 (Cordiner, 1780). Similarly, the 1826 estate plan showed a sawmill lade at the mouth of the Lui and the ruins of a dam on the Derry Water (RHP 811). The cess pool on the Gelder was originally dammed to power a sawmill. The locations of mill lades from the first and second edition maps are shown in Figure 6.2.(iii). Flow is also divided within the meltwater gorge on the lower Lui in a large fish ladder, however alterations within the rock controlled reaches will be of less geomorphic significance than artificial channel division along reaches of lesser confinement.

In terms of remedial measures preventing planform change or frequent inundation, there was much evidence of embanking from mid 18th century estate plans (RHP 31322), especially on the mainstream Dee. For example, there was evidence of an old meander bend, downstream of the Quoich catchment, already embanked by the mid 18th century. At Allanmore near Auchendrane in the mid 18th century, there was also "strong bulwarking" on the banks of the Dee. Evidence of early

Figure 6.2.(iii) **Comparison of the extent of present day forestry with wooded areas according to Roy's map and estate plans within the Dee study area (also modifications to the channel and floodplain)**



channelisation was seen in an annotated Invercauld estate plan (1734) (RHP 3491) of the River Clunie above its confluence with the Dee (Figure 6.2.(iv)), which "shows the condition of the low grounds and the March agreed upon by Invercauld and Auchendrane". In this area, the river was clearly reworking agricultural land at a considerable rate with large areas being frequently reused by the channel. A similar channel is confirmed by Roy's map (Figure 6.2.(v)). There was evidence that the channel was already embanked at this time. By the first edition in 1869, complete and more effective channelisation had taken place.

More recently, estates have decided to remove artifically the build up of sediment above and at confluence sites of small catchments. The Invercauld estate has the right to channelise the Gleann an t-Slugain and it was bulldozed clear in 1984, thus deepening and narrowing the channel. The very active Allt Dourie at the same time had its gravels removed; the second time in 20 years. The lower Garbh Allt has clearly been channelised by the Balmoral estate (Plate 6.2.(ii)) and an earlier diversion of the river near its confluence in the 1870s is reported by Mackie (1911). The Quoich confluence has recently been bulldozed by the Mar Lodge estate and this may locally alter the baselevel of the channel. Even the distributary burst feature, which had been formed as the mainstream Dee overspilled its banks (perhaps associated with the 1937 flood event), was being infilled artifically in July, 1984 (Plate 6.2.(iii)). In contrast the Gelder is well confined by stone slab banks along its lower reaches, thus explaining its present stability cf. other confluence sites. Unfortunately, the estate manager did not know when these were installed. In general, the higher up the channel, the less obvious the disturbance by man.

Figure 6.2.(iv) Castleton of Braemar c1735 (RHP 3491)

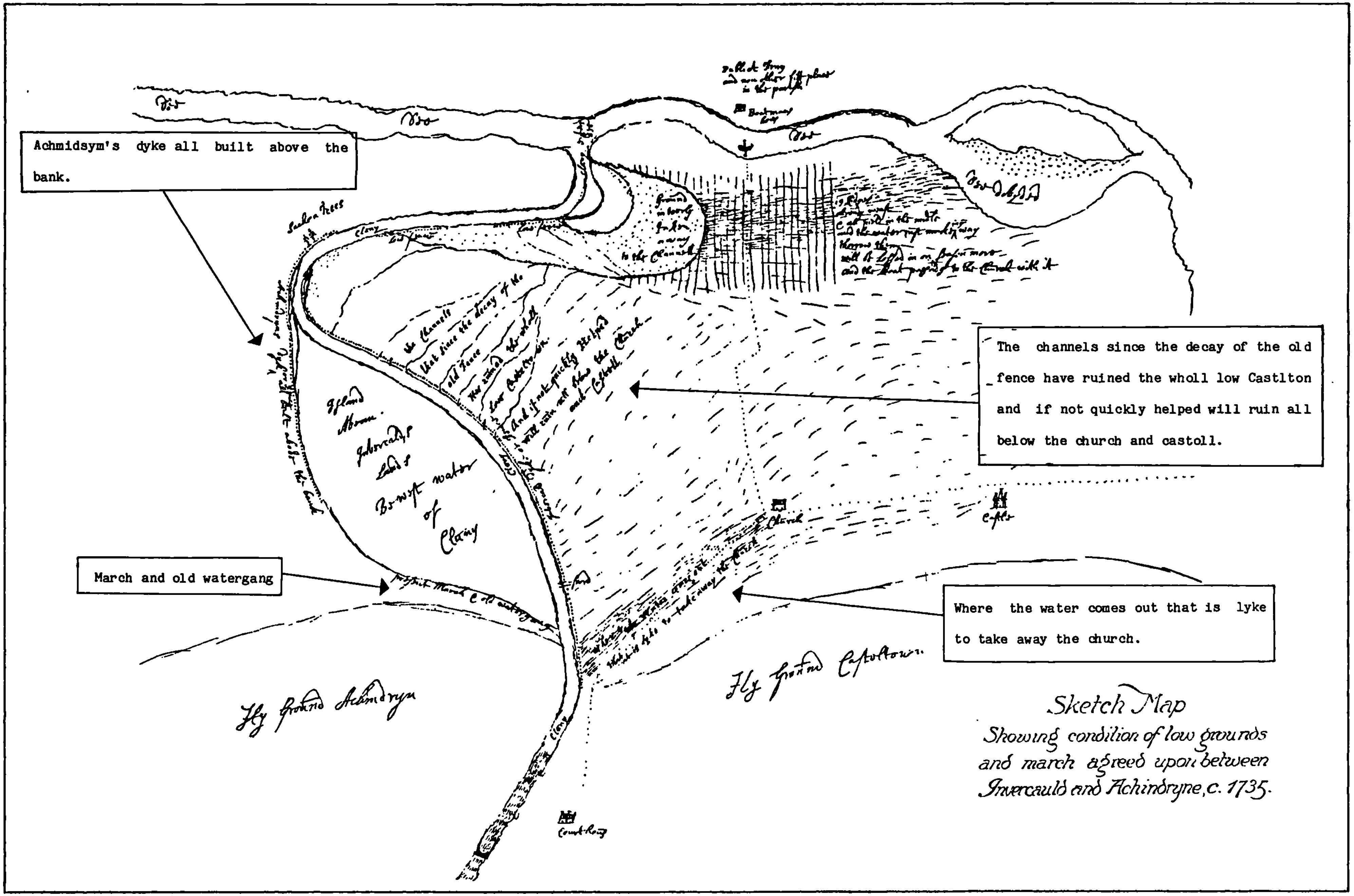


Figure 6.2.(v)

Artificial channel pattern change above the Clunie water confluence

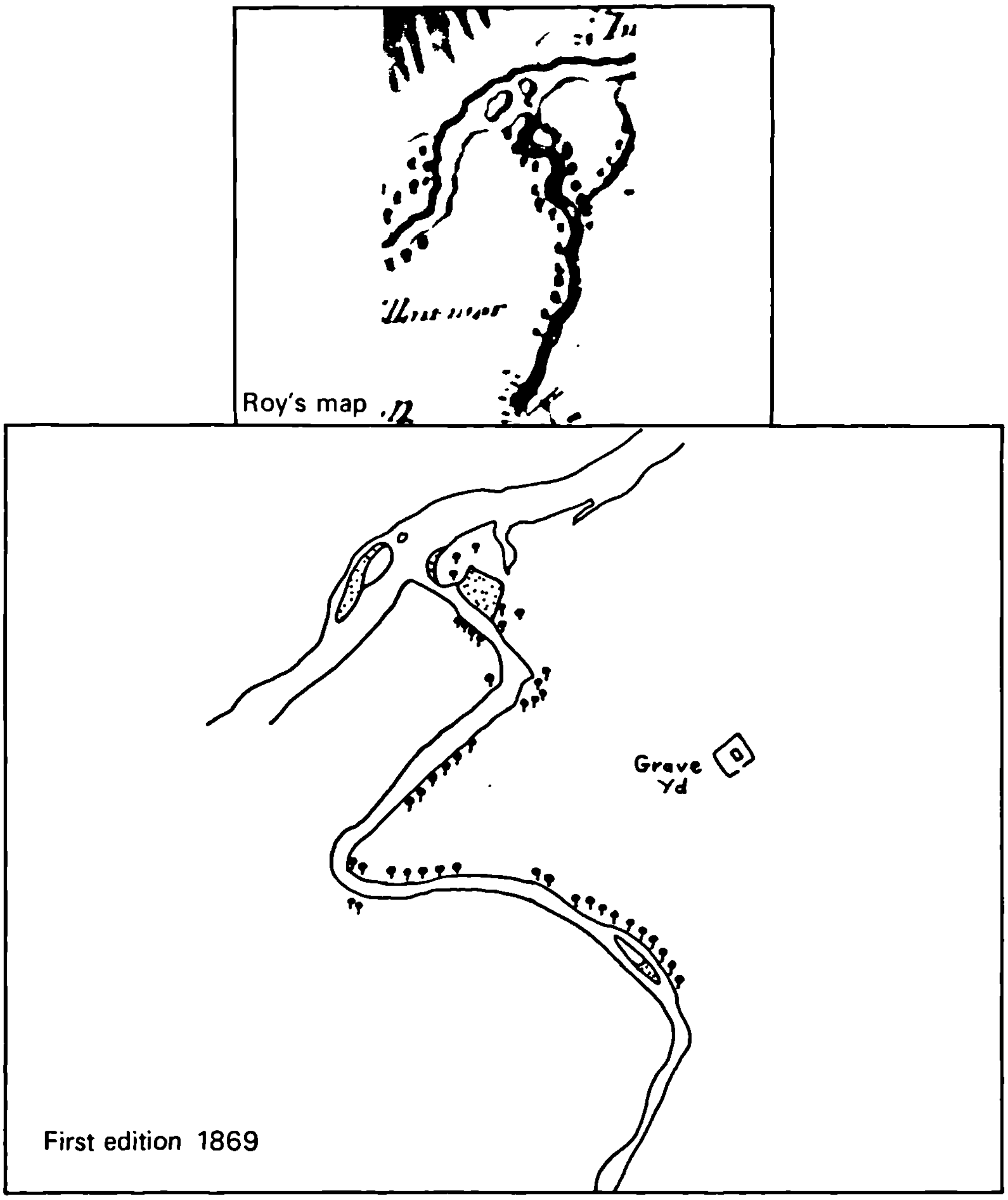


Plate 6.2.(iii)

A distributary burst through previous embanking on the mainstream Dee, probably dating from the 1937 flood event

Infilling of the distributary burst to prevent further inundation and allowing reclamation of agricultural land (July, 1984)

6.3 Spey study area: Reconstructed history of landuse change

Over the last 400 years, the Spey study area has seen extensive periods of both deforestation and afforestation (Dixon, 1975). It is known that, in the early 18th century, a widespread destruction of trees for smelting purposes took place in Strathspey. Thus in 1728, 60,000 trees were sold for 7,000 pounds from the Strathspey forest of Sir James Grant to the York Building company. However, it is also known (Campbell, 1920) that, in the middle of the 18th century, one of the chief pioneers in afforestation was the 7th Earl of Seafield, who planted many millions of Scots pine, spruce and conifers in Strathspey (Old Statistical Account 1791-1799). Although patterns of landuse change in the Spey study region are broadly similar, each catchment has its distinct history of landuse change. Their individual chronologies are annotated in Figures 6.3.(i) to Figure 6.3.(iv).

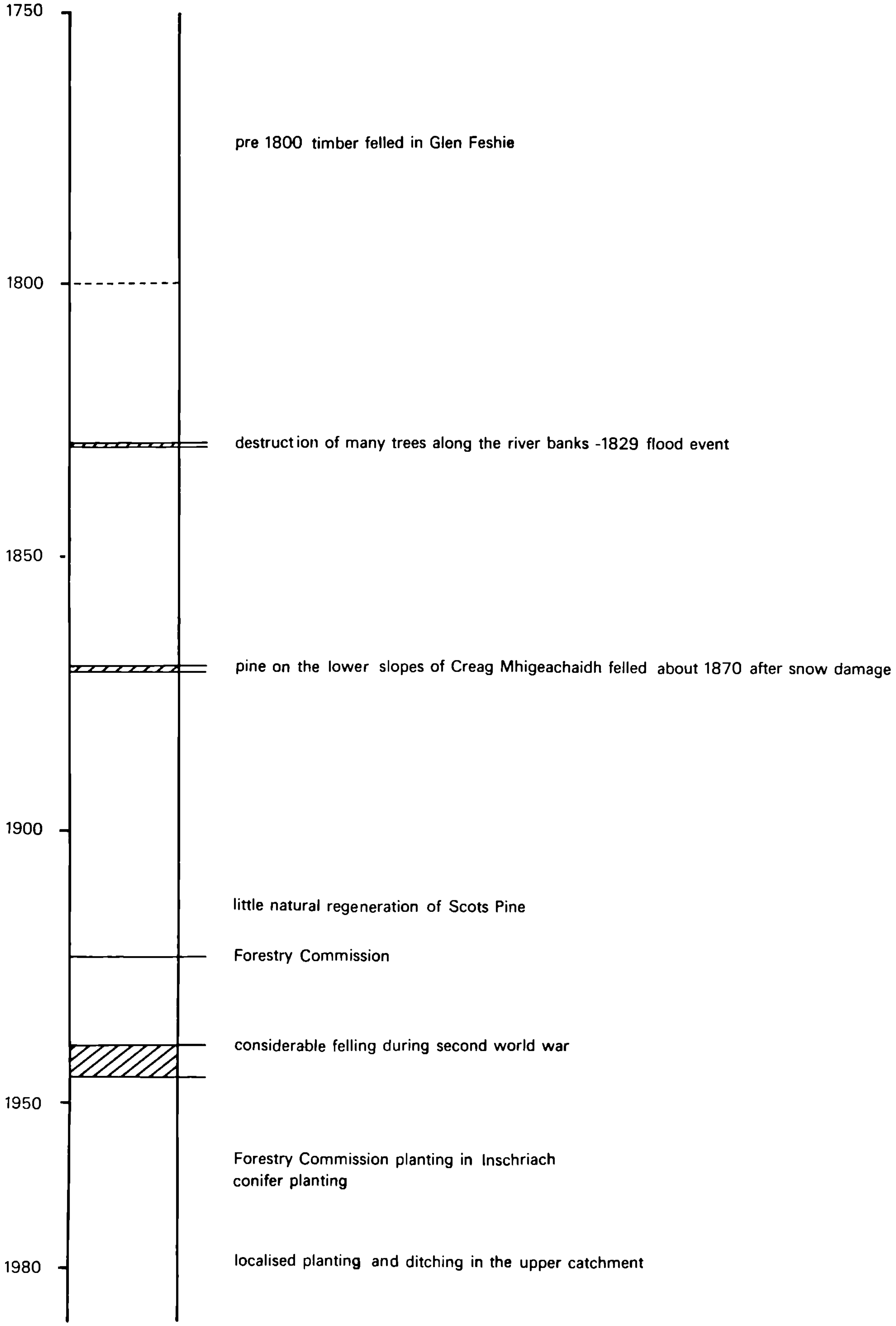
There is little reference to Glen Tromie in terms of landuse change but, on Roy's map (1750), it was heavily forested along on the valley floor (Figure 6.3.(v)). Today Glen Tromie is characterised by birch woodland and juniper shrub with some scattered birch and pine on the flood plain, and some conifer planting on the valley sides (Steven and Carlisle, 1959). Of all the Speyside tributaries, least landuse change has taken place with the Tromie catchment, as it was not associated with the 18th century logging industry.

In contrast, the Feshie catchment underwent a large amount of deforestation in the 19th century, with the timber being floated down the Spey (Figure 6.3.(i)). Specific areas of the catchment seem to have been felled at different times; for example, the pines on the lower slopes of Creag Mhigeachaidh were felled about 1870 after snow damage (Steven and Carlisle, 1959). There was thus not wholescale felling to the same extent as will be discussed for the Nethy. In 1984, there are still scattered remnants of Pinus sylvestris on the floodplain and valley sides but considerably depleted since the 1750s (cf. Roy's map). Depletion of floodplain woodland, and presumably a reduction in floodplain stability, was not however only man-induced. Large numbers of pine were destroyed during the 1829 flood event (Lauder, 1830). Downstream in Glen Feshie, there has been localised Forestry Commission planting (Inschriach Forest) with ditching, mainly over the last 20 years, though more recent localised ditching has also taken place (Plate 6.3.(i)).

In the Druie catchment (Figure 6.3.(ii)), the large scale exploitation of the Rothiemurchus forest began much later than in Abernethy. Nevertheless, before the end of the 18th century, timber was being floated down the Spey to Garmouth (Sinclair, 1791-1799). Regeneration took place and little felling occurred for a considerable time afterwards. In the 20th century, felling recommenced during the two wars but, at present, Rothiemurchus contains one of the few remaining areas of naturally regenerating Caledonian pine forest. Thinning is periodically carried out by the Rothimurchus estate.

Figure 6.3.(i)

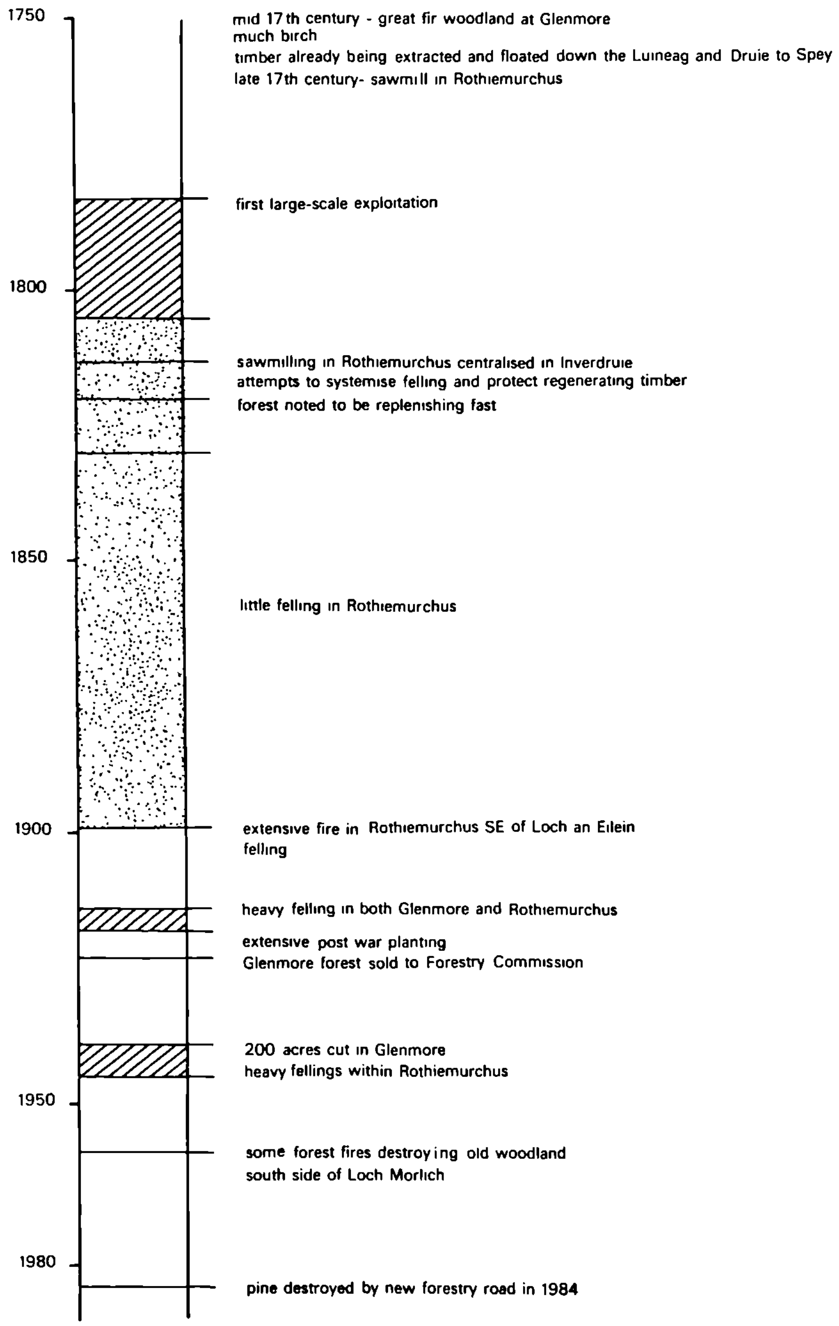
The landuse history within the Feshie catchment



Information source: Steven and Carlisle, 1959

Figure 6.3.(ii)

Landuse history within the River Druie catchment



Information source: Steven and Carlisle, 1959

Plate 6.3.(i)

Inschriach Forest (foreground) within the lower Feshie catchment

with localised new ditching on the slopes (background)

A detailed study of basin landuse changes in the forest of Abernethy from 1750-1900 AD is presented by O'Sullivan (1973) and Stevens and Carlisle (1959). Major deforestation first took place in the early 17th century when commercial forestry became important (Figure 6.3.(iii)). However, it is suggested that by the mid-18th century, a pattern not markedly different from that of the present had already emerged (O'Sullivan, 1973). Since almost every part of the forest has been felled for timber at least once, it cannot be described as native pinewood in the true sense. Deforestation is however still taking place with 80 acres (0.3 km^2) of *Pinus sylvestris* woodland felled between 1983-1984. The Nature Conservancy Council (1973) reports Abernethy as possessing 990 acres (4 km^2) of reasonably stocked pinewood. Some small afforestation has also taken place by Fountain Forestry.

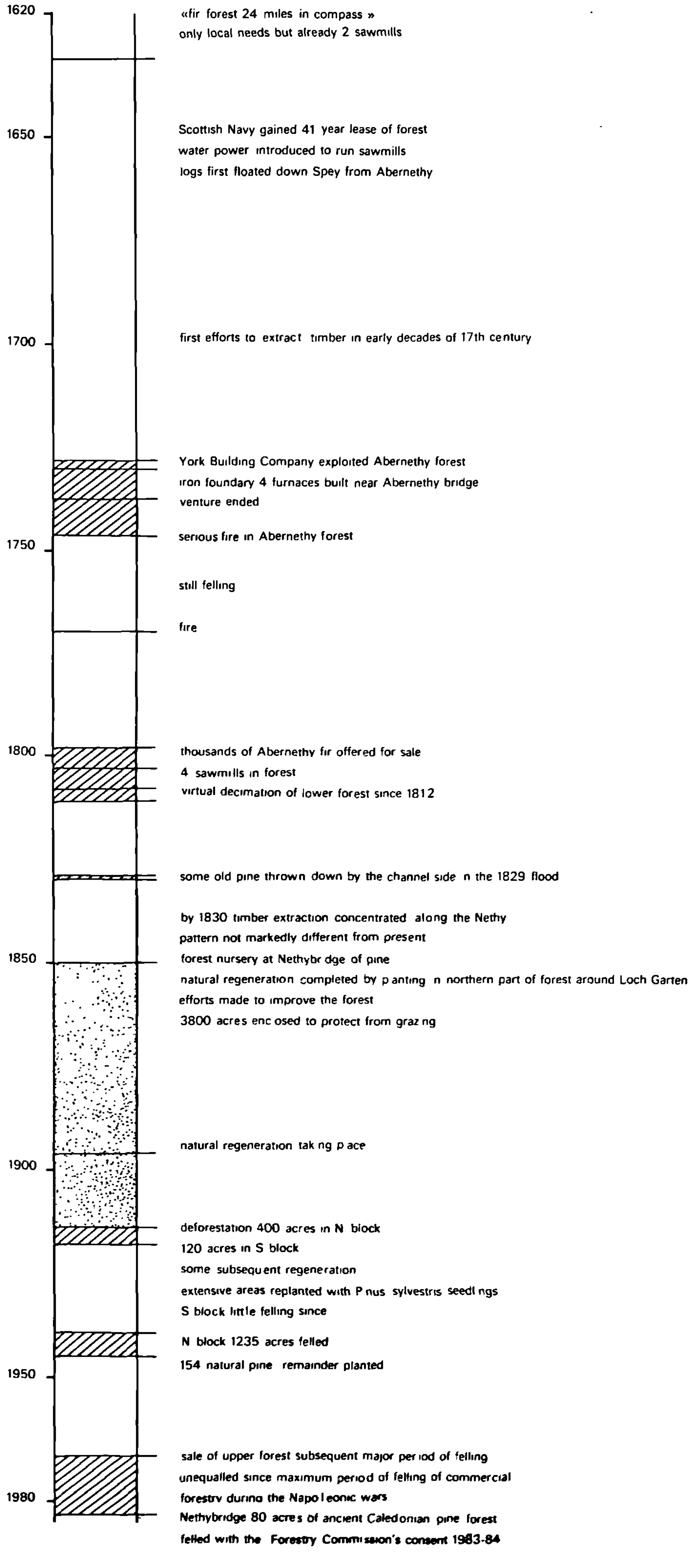
At an earlier stage in the development of the Abernethy forest, it is interesting to note the following observation on a cut on the lower Nethy, where 6 or 8 strata of tree roots were exposed:

> "The trunks of some lie horizontally embedded in the moss, others evidently have been burnt on the surface. In one part of the bank, the lowest stratum is of birch roots, about 2 feet [0.6 m] above the gravel the moss rests on. Then come three successive strata of fir roots, 18 inches [0.5 m] apart- another stratum of birch roots and above that one or more of fir, that do not seem have attained any great size. Lastly, there are firs now rooted and growing on the surface but these are small and stunted." (Lauder, 1830 p156)

Figure 6.3.(iii)

The landuse history within the Nethy catchment

Information source: Steven and Carlisle, 1959



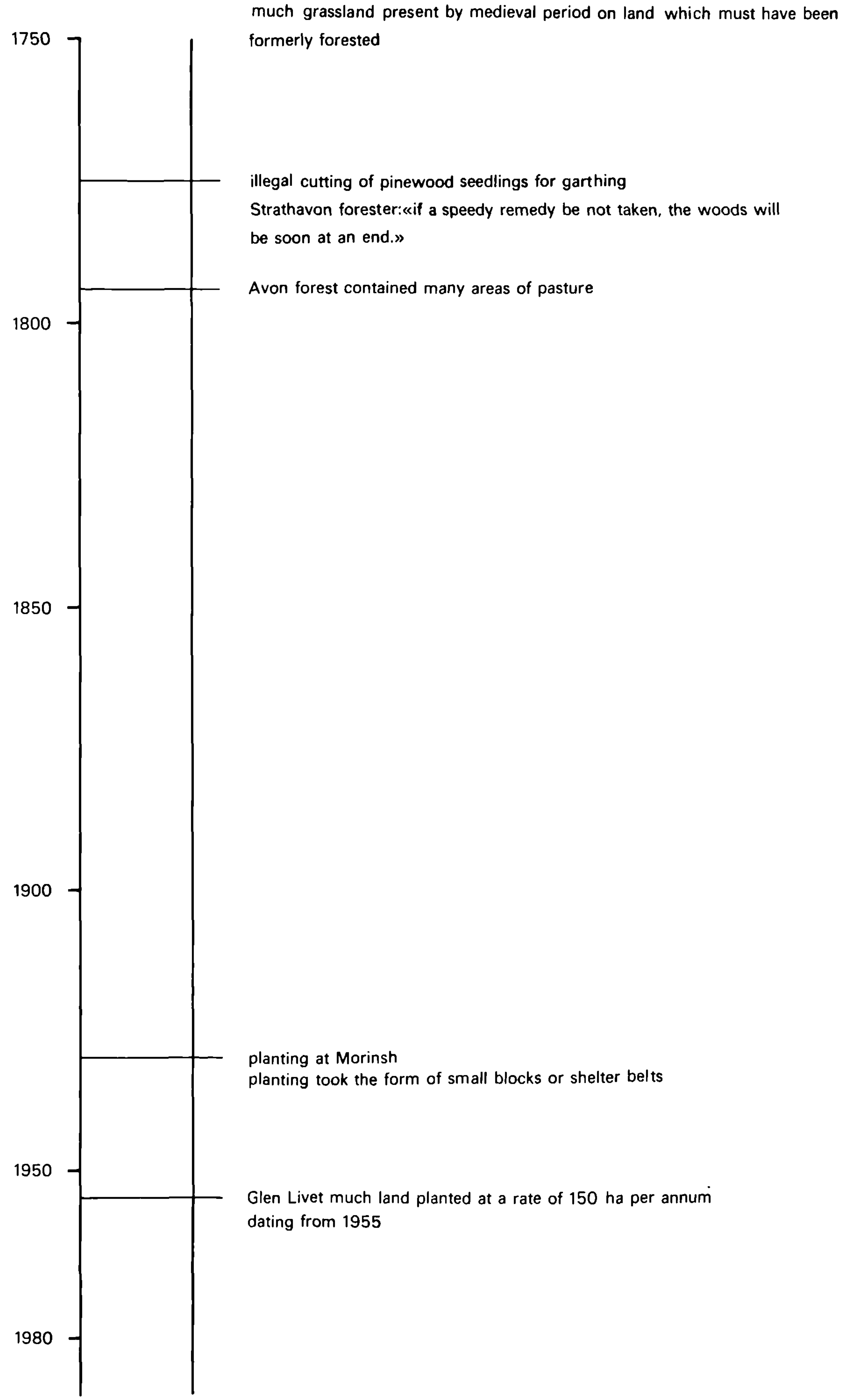
The vegetational history of the area is obviously highly complex.

The information available about landuse change in Strathavon is presented in Figure 6.3.(iv), with sources from Gaffney (1960), Turnock (1979) and Pears (1968). According to Gaffney (1960), the old deer forest of Glen Avon consisted mainly of the upper basin of the River Avon above Glenbuilg and Inchory; the Glenavon forest being fully exploited as a grazing ground in the mid 18th century. In stark contrast to this, Steven and Carlisle (1959) report a stand of only 12 Pinus sylvestris trees near Linn of Avon; this being the only remaining natural pine woodland in the catchment. Unfortunately, no maps exist to show the locations of the extensive tree cutting of early timber companies but there are several indications of felling operations close to where the present tree-line runs. Pears (1968) sites Gilchrist (1871) where "useful and profitable timber" at 458 m was found in Rothiemurchus.

Other forms of disruption to the catchments include more recent road-building and, within the Druie catchment, accelerated soil erosion has occurred in association with the expansion of the skiing industry (McVean and Lockie, 1969; Bayfield, 1974). There has been considerable debate as to whether such landuse changes have increased the magnitude of flash floods and sediment mobility (see McEwen, 1981).

Figure 6.3.(iv)

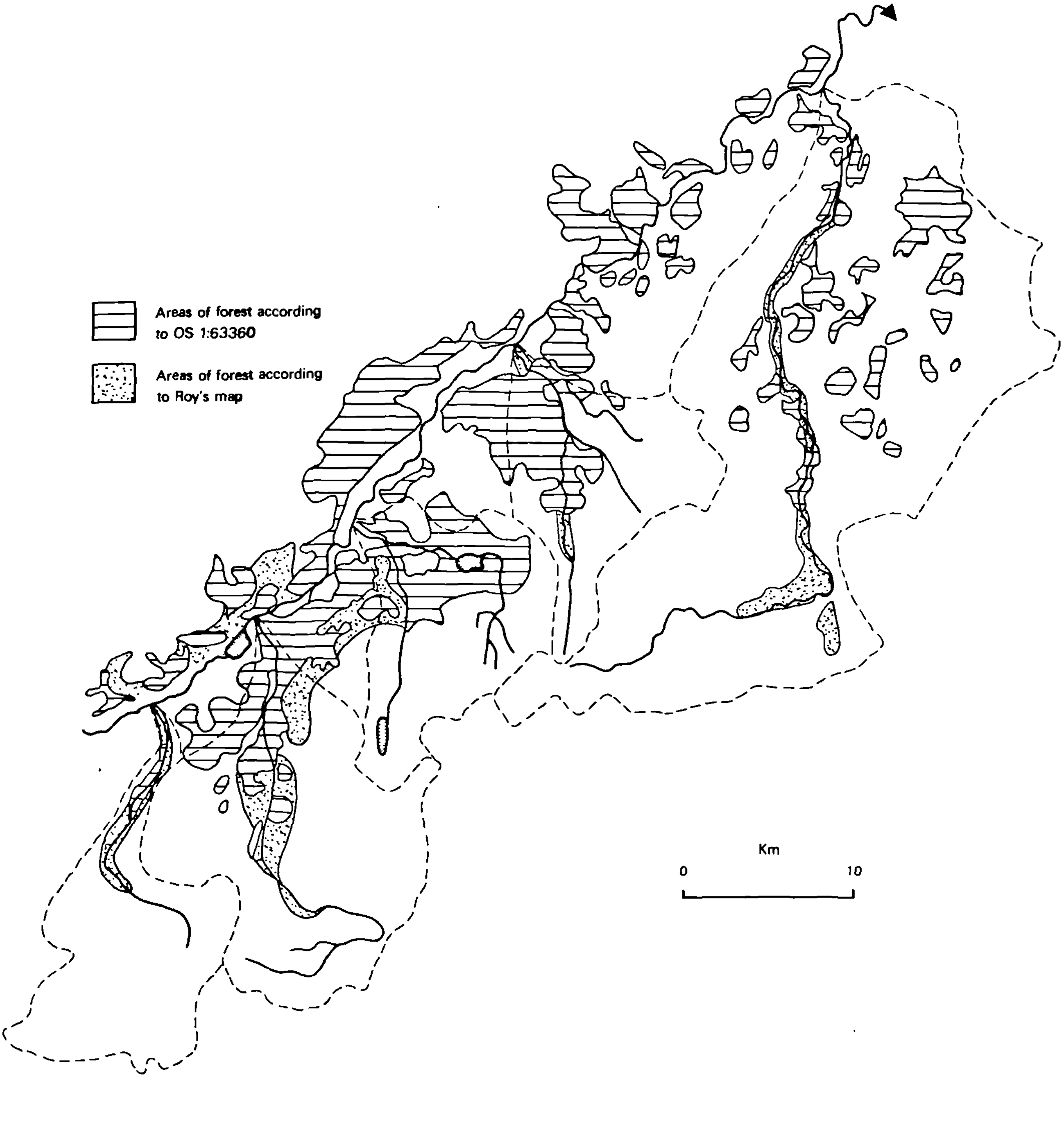
Landuse history within the Avon catchment



Information source: Steven and Carlisle, 1959 Gaffney (1961) Pears (1975) Turnock,1979

Figure 6.3.(v)

Comparison of the extent of present day forestry with wooded areas according to Roy's map



There were also several examples of damming causing a minor increase in the water surface area of the catchment and the possible reduction in magnitude of flood flows (Chapter 2.10.3). Major damming has taken place on the upper Tromie, associated with the Allt Bhran scheme. The Speyside Drainage Project (Dept. Agric. for Scotland, 1952-1958) stated that within the Spey catchment where the water was dammed (151.2 km^2), flood flow reduction could be as high as 35%, though assessment was problematic. In some areas, the frequency of flows was regulated in the early 18th century. On the upper Nethy, there were numerous dams to provide water for timber floating eg. Faeschelach Dam (1858 plan of of Abernethy, RHP 13995) and diversions created in the 19th century. A new cut 24.4 m deep in the upper Nethy had been constructed to divert drainage from one dam to another (RHP 13992; Figure 6.3.(vii)). The lower Druie was also dammed for sawmill power. Even smaller tributaries such as the Burn of Dalvey can be seen from early estate plan dated 1790 (RHP 8966) to have had several mill lades and a dam. Loch Einich and Loch Morlich were also both dammed and installed with sluices so that water was available for timber floating when required. Thus, flood flows may have been artificially increased or decreased, depending on whether water excess was dammed or released.

Much of man's alteration or modification of the natural channel has been associated with the timber industry. Sawmill lades caused a frequent division of the lower reaches of the tributaries (Figure 6.3.(vi)). Lades were also associated with agricultural development eg. the cornmills below Tromie Bridge (Figure 6.3.(vi)), already present by the first edition (1867-1871).

Figure 6.3.(vi)

Modifications to the channel and floodplain within the Spey study area

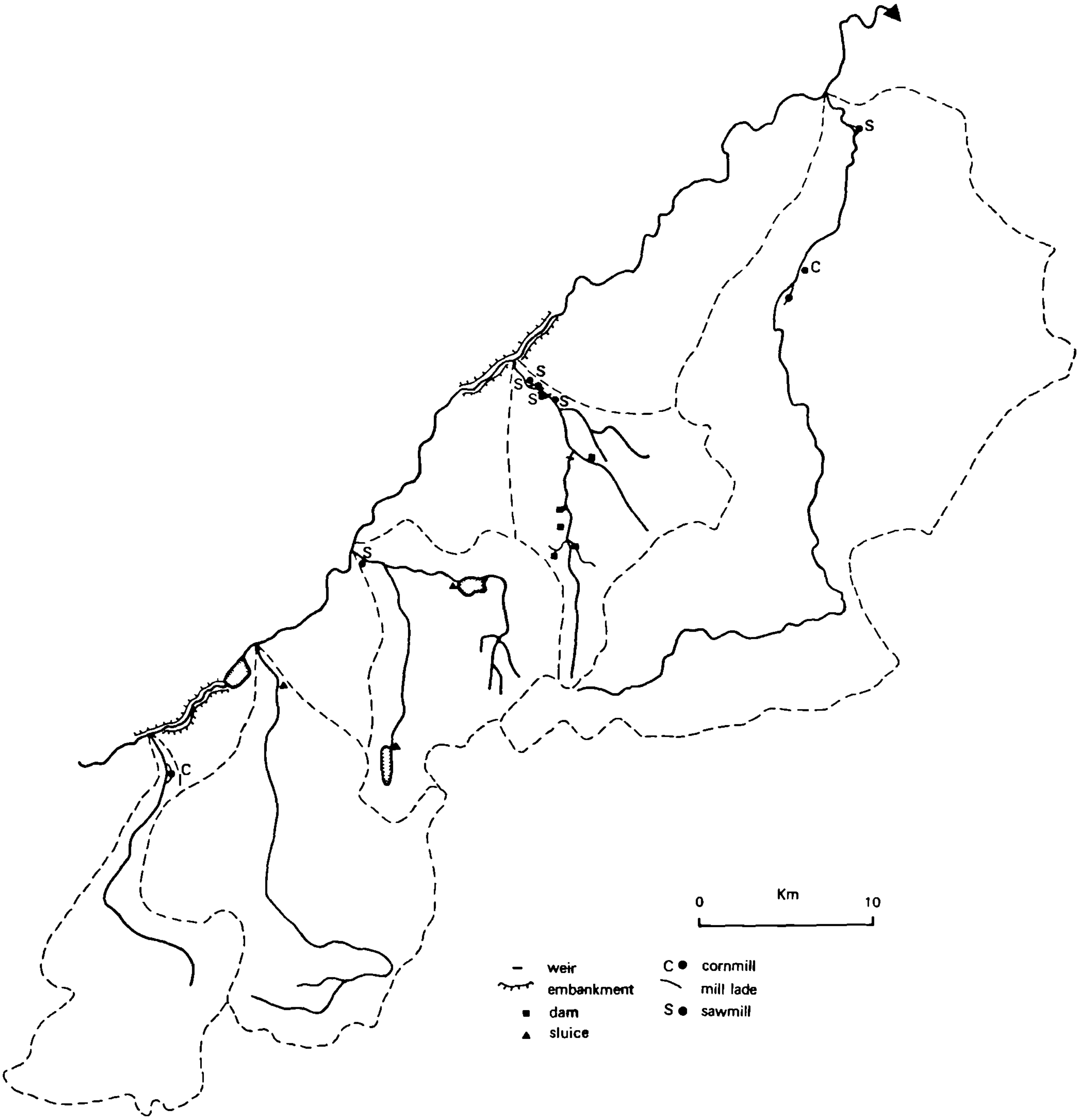
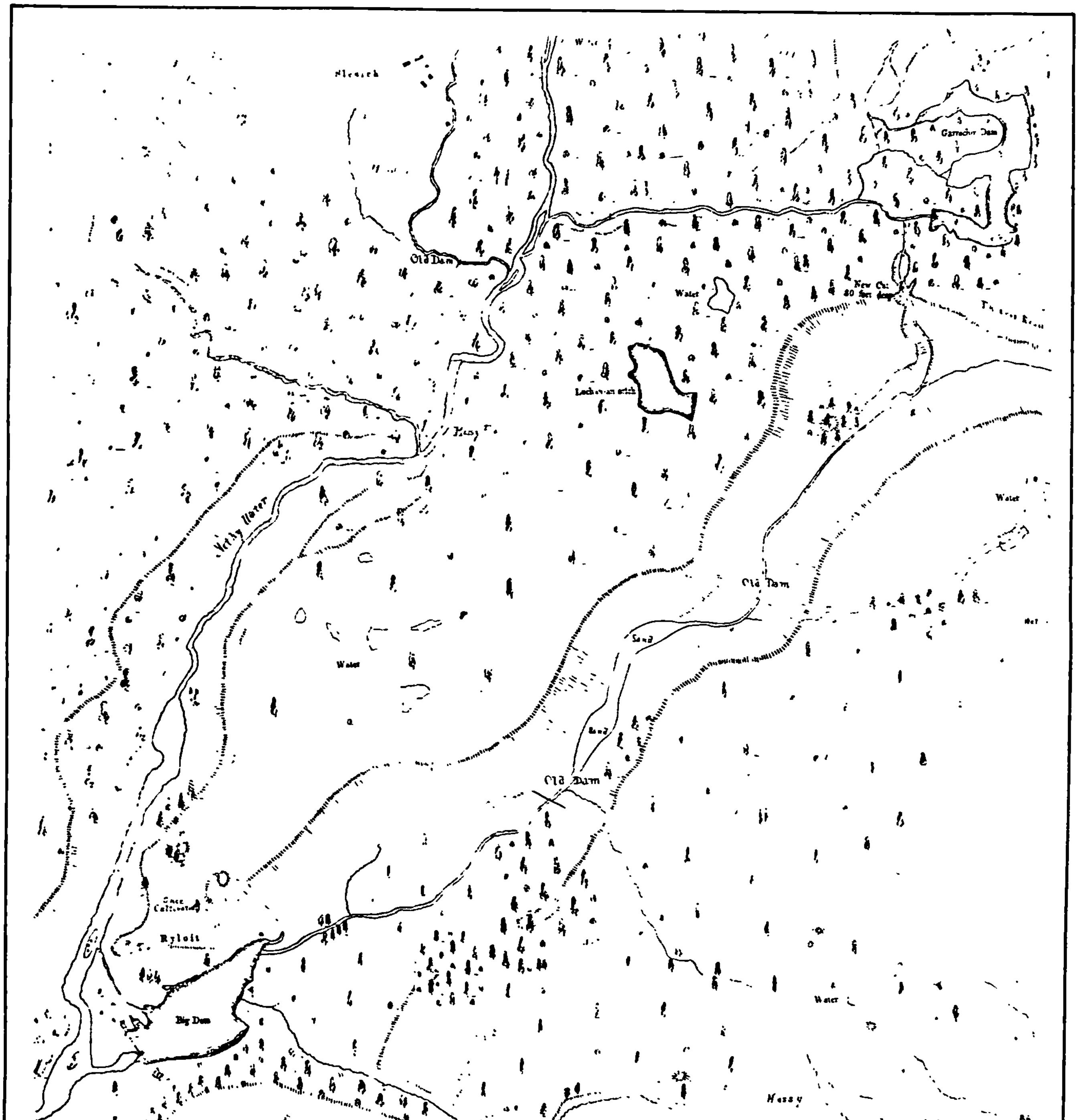


Figure 6.3.(vii)

Plan of the upper Nethy (1858) showing extensive damming (RHP 13995)



The improvements in floodplain drainage could be studied using Roy's map (1750) and the Seafield papers. Thus, before the first edition O.S. 1:10,560 map (around 1860), some lakes had already disappeared eg. a loch near Loch Alvie and also Loch Kinrara. The grounds of Eastern Meadows and the low grounds of Ballintomb, near the confluences of Spey with Nethy and Dulnain and inundated by the Spey when in high flood, are shown in an estate map by William Forbes in the 18th century (RHP 8906). The whole area seems marshy and water logged and drains had been installed. There was also some improvement in the tributary valleys; Lauder (1830) discussed the casting of a drain at the farm of Dell in the Nethy catchment in 1825. The impact of such drainage, in terms of a more rapid response to the 1829 flood, was implied by Lauder (1830):

> "Any given quantity of rain must now produce a much greater flood than it could have done before the country became so highly improved. Formerly, the raindrops were either evaporated on the hillside or were sucked by an arid or a spongy soil, before so many could coalesce as to form a rill. But when we consider the number of open cuts made to dry hill pastures- the numerous bogs reclaimed by drainage- the ditches of enclosure recently constructed, and the long lines of roads formed with side drains, back drains and cross conduits- we shall find that of late years the country has been covered with a perfect network of courses, to catch and concentrate the rain-drops as they fall and to hurry them off in accumulated tribute to the next stream. (Lauder, 1830 p7)

"The widespread drainage of agricultural land which had been carried out in recent years had led the water off with a speed which overtaxed the capacity of streams and rivers, while in many places embankments made by the Commissioners had dammed back the floods, forcing through the bridges a mass of water far in excess of their capacity". (Lauder, 1830 in Haldane, 1973 p174).

By the first edition (1860-1870), the Spey floodplain was thus heavily drained.

Alteration to the channel through straightening was also prevalent before 1850. Roy's map shows the mainstream Spey to be much more meandering than on the first edition of the O.S. map, especially upstream of Loch Insh. However, even prior to Roy's survey, the York Building Company in the 1730s had removed navigational obstructions, which had previously prevented the economical export of timber along the Spey (Sinclair, 1791-9). In terms of protective measures, much of the Spey was embanked pre-1829. In fact from estate records, the impact of subsequent floods in 1830 and 1831 was made more destructive due to the fact that these embankments had been breached in Aug, 1829.

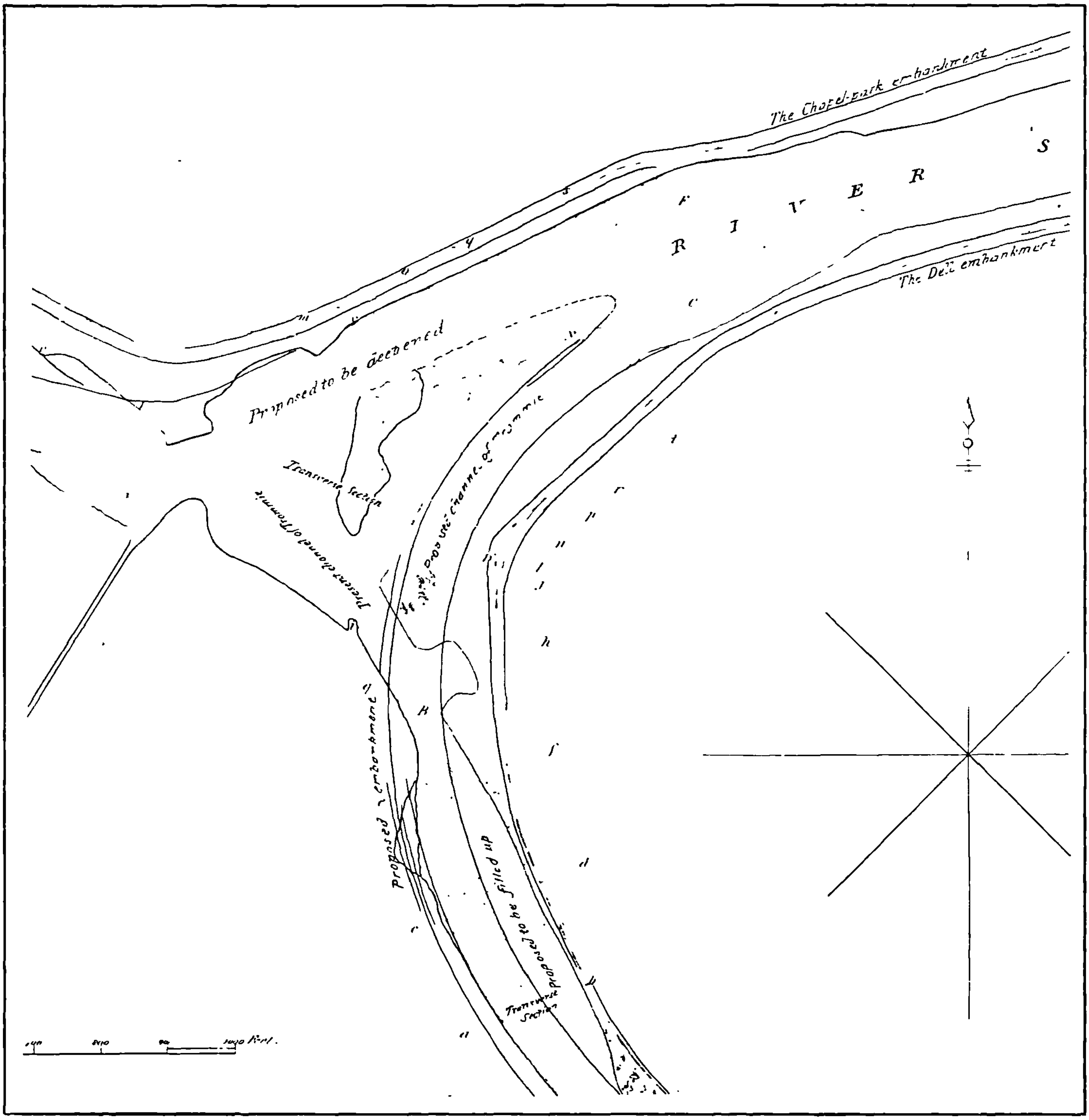
"I regret to hear the accounts you give of the mischief done by the latest floods to the bulwark embankments at Wester Curr, Ballintomb and the Meikle meadows. When the state of the rivers and the weather will permit, something will need to be done to repair them. It is natural to suppose that the pressure of the waters when flooded must be peculiarly trying opposite to the influxes of the Nethy and the Dulnain and whatever is done in these places should therefore be strong and substantial." (Seafield estate papers, 28th July, 1831; GR/248/1564, p415-6)

If the 1829 flood had not occurred, the damage in subsequent events (see Appendix 1.3) would not have been so severe. The Spey itself, though embanked, was not channelised although there was an idea in the 18th century to straighten the Spey. From the estate plans, it was possible to see differing expenditures on embanking in response to the severity of flooding but also to the growing awareness of flood problems (Munro, pers. comm.). The problems still exist; McVean and Lockie (1969) describe the loss of substantial areas of formerly reclaimed carse land, especially along the Spey between Kincraig and Ruthven. A second reclamation was however found to be uneconomic (Speyside Drainage Project, 1952-1958)

Examples of channelisation, abundant in this study area, frequently highlighted the problems of rivers at confluences (revealed in Chapter 4). On 27th Dec, 1858, an estate plan by Morrison (RHP 1312/4) shows the confluence of the Rivers Tromie and Spey (Figure 6.3.(viii)). On this diagram, the line of a proposed new channel for the Tromie is shown and directions for deepening the Spey's channel by removing 15400 yd^3 [11781 m^3] of material are annotated. At this point the Spey was already embanked on both sides; the Tromie channel was to have 7600 yd^3 [581 m^3] excavated and this material was to be used in infilling and reclaiming other areas. Embankments were also to be built. The Tromie

Figure 6.3.(viii)

An estate plan (1858) of the Tromie/ Spey confluence, showing the proposed channel of the River Tromie and deepening of the Spey (RHP 1312/4)



was wide and braiding at this point, in contrast to the straight/ sinuous channel planform on the first edition and the meandering planform of Roy's map. The proposed straightening may be an artificial response to the channel widening after the 1829 event.

A sketch by P. Mackey in 1862 (RHP 2200) also showed the proposed new channel of the River Feshie at its confluence with the Spey (Figure 6.3.(ix)). If this artificial alteration was implemented, it had been already extensively reworked by 1873 (see Section 7.3.1). The rivers at both these sites must have been undergoing progressive sedimentation and channel widening at the expense of agricultural land. Upstream on the Feshie, in the 1829 floods, a strong bulwark was carried off and the Druie broke an embankment above the Dell of Rothiemurchus. Lauder (1830) also describes repair to an embankment on the lower Nethy, again after the 1829 flood. This was made of three rows of strong piles driven into the bank, with young fir trees laid diagonally across between the piles. Each layer of pine trees was overlain by 15 cm of gravel, and whole pine trunks were then placed between the stakes. These layers were repeated until the embankment was of sufficient height. Finally, large stones were thrown on top to provide further stability. Lauder (1830) reports that this structure quickly appeared like an ordinary bank, as the sand and mud brought down by the river was trapped. It was also very effective, surviving the "appendix flood" of 27th Aug, 1829 on the Nethy. It is also in complete contrast to some of more recent measures to combat bank erosion, which tend to be smaller scale and less effective.

Figure 6.3.(ix) An estate plan (1862) of the lower Feshie showing the proposed new channel of the River Feshie (RHP 2200)

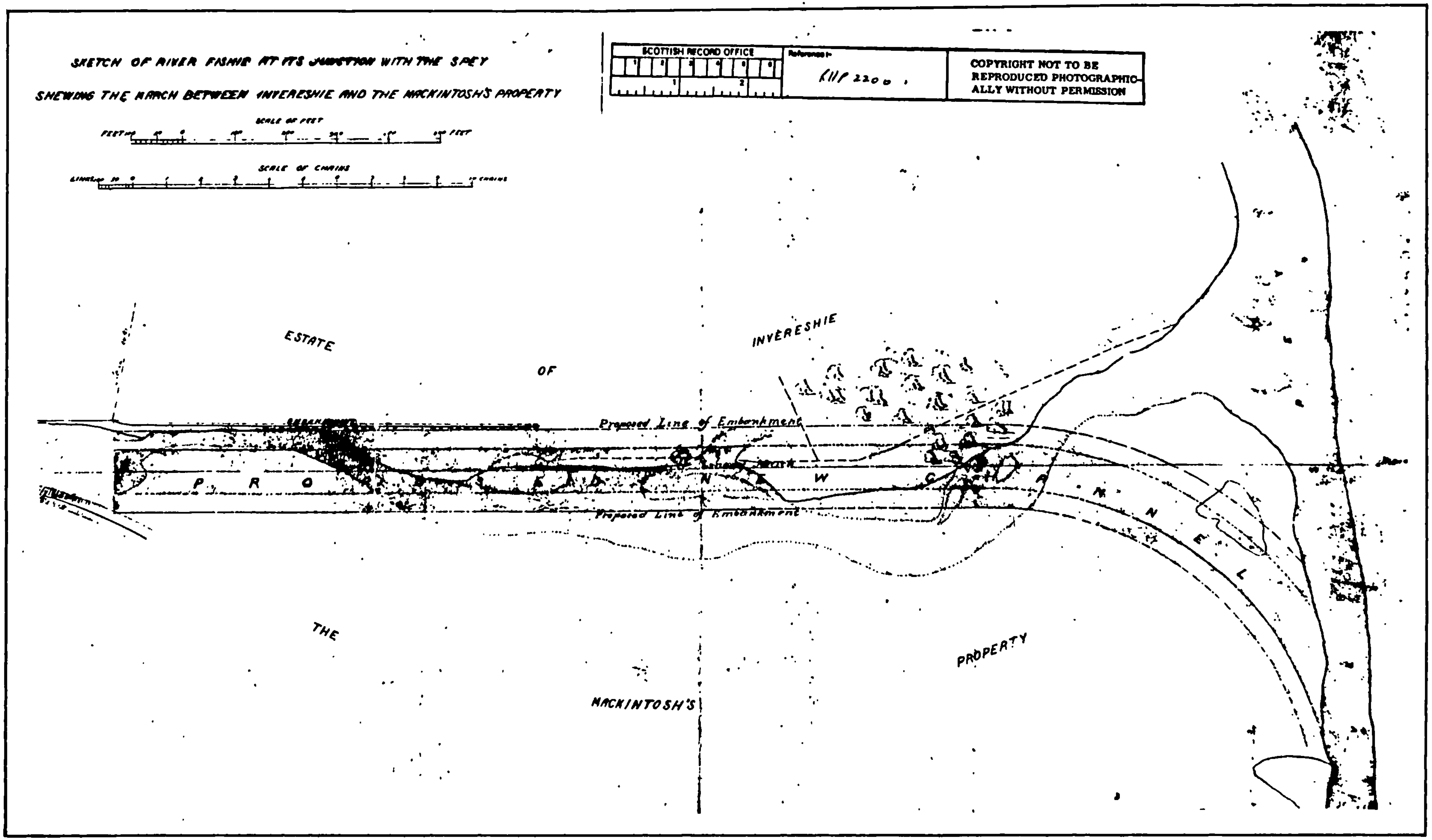


Figure 6.3.(x) Plan of the proposed alteration of the River Nethy (1771; RHP 8893)

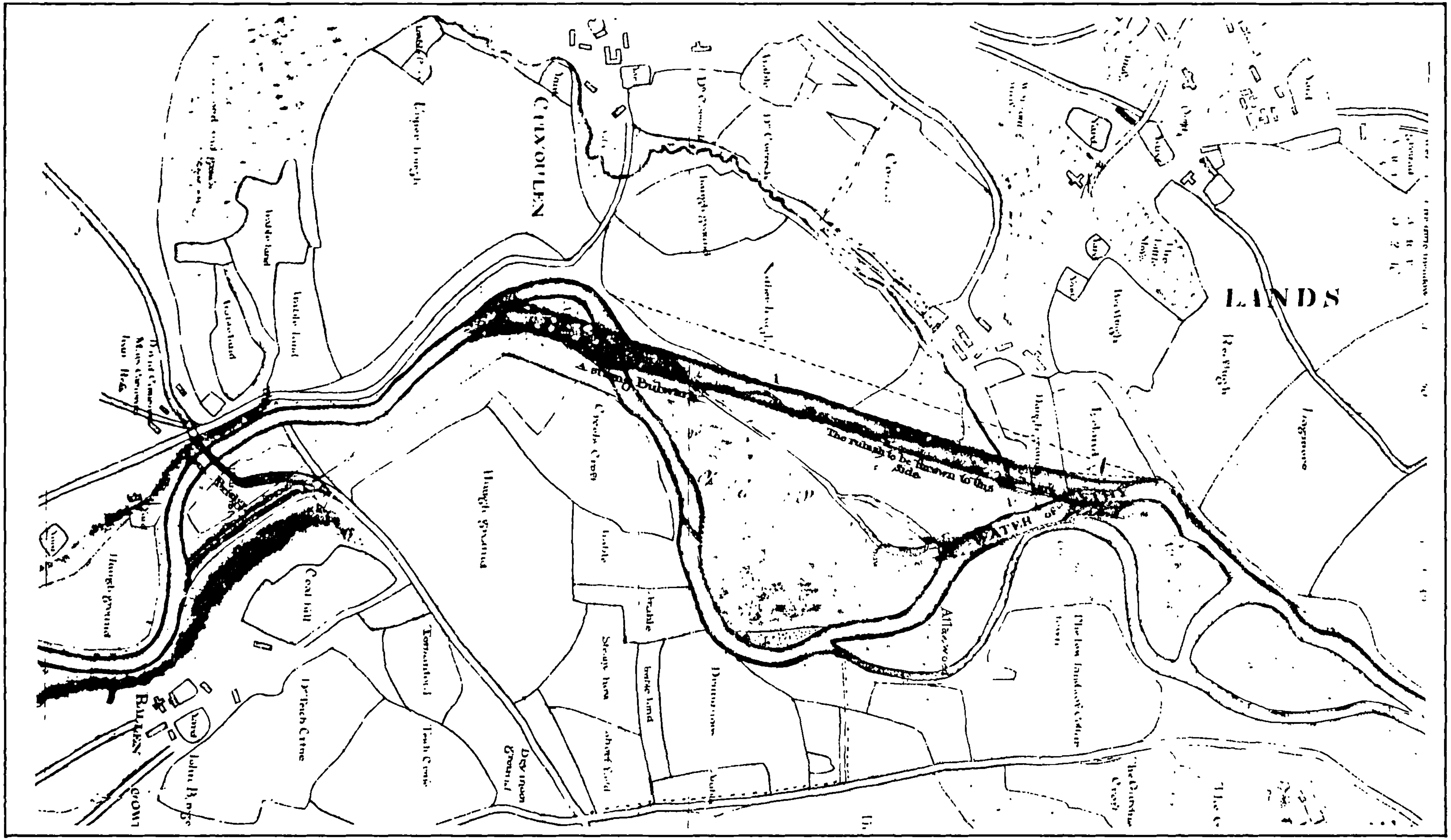


Plate 6.3.(ii)

Rip rap preventing bank erosion on a former anabranch of the lower Druie (dating pre-1903)

Channelisation also took place in the lower middle reaches of rivers. The plan of the proposed alteration of the River Nethy, surveyed by P. May in 1771 (RHP 8893), indicates the cutting through of a long anabranching area with the construction of strong bulwarks, accompanied by a considerable reduction in sinuosity (Figure 6.3.(x)). The actual cut (with banks 10-15 feet deep [0.3-0.45 m]) was made through the moss of Cluihaig in 1813 to make the steam free of impediments for floating logs. In 1829 however, this work was demolished and the stream returned to its former channel (Lauder, 1830). This evidence suggests channel modification structures were constructed as early as pre-1800 and any interpretation of channel stability in Chapter 9 must consider this.

More recent protective measures were found along many of the more active sites, identified in Chapter 4. Main methods were stabilising the base of the banks with rip-rap, reinforcing the bank with wire and steel rods and bulldozing sediment against eroding banks (Plate 6.3.(ii)).

6.4 Tweed study area: Reconstructed history of landuse change

In the 11th and 12th centuries, it is known that the Tweed basin was still covered by natural woodland (eg. Gilbert, 1983). However, extensive clearance took place after the 12th century, due to both forest clearance for cultivation and the devastating fires of invading armies. Jed forest (oak and pine) remained the longest (Maxwell, 1909) but, by the 15th and 16th centuries, it was reported that there was little or no woodland on the Lammermuirs (Leland, in White, 1973). Roy's map (1750) showed an open woodless landscape, still dominated by the open field system, quite in contrast to the situation in Speyside or Deeside. Run-rigs were clearly the dominant landuse over most of the lowlands at this time. In the 19th century, there followed a period of afforestation:

> "Although Berwickshire and Roxburghshire are now so beautifully wooded, down to the middle of the 17th century, the district was almost wholly destitute of trees. The great natural forests of Lammermoor, Cheviot and Jed had vanished." (Crockett, 1926 p48)

Even so, the % coverage in the 18th century was still comparatively low. However, as more recent research has noted:

> "The pattern of hill vegetation is again undergoing comparative and dramatic change. Throughout the region, the tell-tale furrows of deep-drainage ploughs are scouring the landscape; in nearly every valley, the dark regiments of young conifers are beginning to change what had been regarded as he traditional open landscape....but the scale of operations has suddenly increased and new forests are replacing sheep-walks on large private estates." (White, 1973 p50)

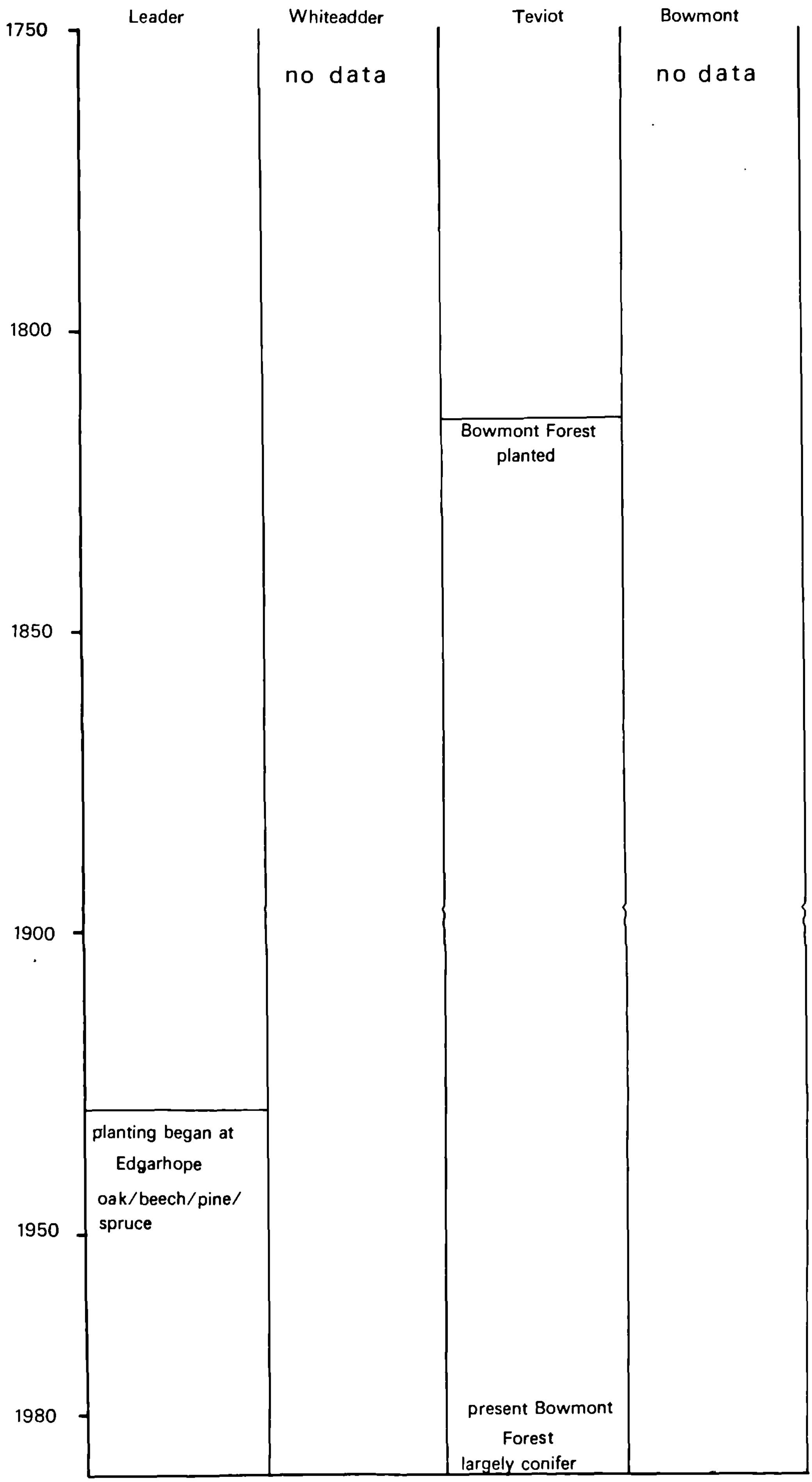
Thus, in certain areas, Forestry Commission planting is taking place at a great rate. In 1973, the Forestry Commission in Berwickshire and Roxburghshire had about 5% of the land covered with forest (not including private estates). A large proportion of the remaining land surface is therefore wasteland/scrub, pasture or rough-grazing. The deforestation/ afforestation chronologies for each catchment are shown in Figure 6.4.(i). For example, the present Bowmont forest was planted after 1815 in the Kale catchment. It must be noted however that percentages of afforestation are much lower than reported by Acreman (1985) for the Ettrick catchment (see Chapter 2.10.2).

In terms of other landuse changes, there was also a considerable amount of hill drainage in the Tweed valley, pre-1900. This drainage was mainly quickly instigated post-1846, when Parliment granted money for the improvement of estates and before 1857, there was little drainage. Young (1879), when discussing the effects of land drainage on the productivity of salmon rivers, stated:

> "In the hills the sheep drains, the cuts to draw off water from the pools in the mosses, and burning of heather, combined with the drainage of the arable lands, cause rain to run off more rapidly than it used to do, making floods both more violent and shorter in duration than formerly. In the early part of the present century [19th] when our system of land drainage was comparatively imperfect and incomplete, our rivers, in rainy weather, took days to rise and days to fall. Now, on the other hand, with multitudinous drains leading into

Figure 6.4.(i)

Landuse history within the Tweed study area



them from every hillside and field, they rise and fall in a day." (Young, 1879 p262; see also Appendix 1.8.1)

The same phenomenon is confirmed by other contemporary observers:

"Until comparatively recent times, occasional heavy falls of rain kept the river flooded for days when it formed a broad sheet of turbid water often destructive to crops on its more level banks, but now from the general practice of draining, falls of rain are carried rapidly off, and if the river suddenly rises, it as suddenly subsides, rarely causing any serious injury during these paroxyms." (Chambers, 1864 p12)

There was clearly some ditching pre 1800, as can be seen from estate plans eg. the 1740 plan of the Barony of Stobo, where a drainage canal is noted (RHP 1902). However, it was much less effective due to the lower percentage area covered. More recently, Learmonth (1950) postulates that runoff rates were increased during the 1948 event, on steep slopes, especially in areas affected by the "herringbone system of hill-drainage":

"The 1948 flood event apart, it may be a matter of national importance that recent hill drainage schemes are causing violent and flashy spates in many and widespread areas". (Learmonth, 1950 p149)

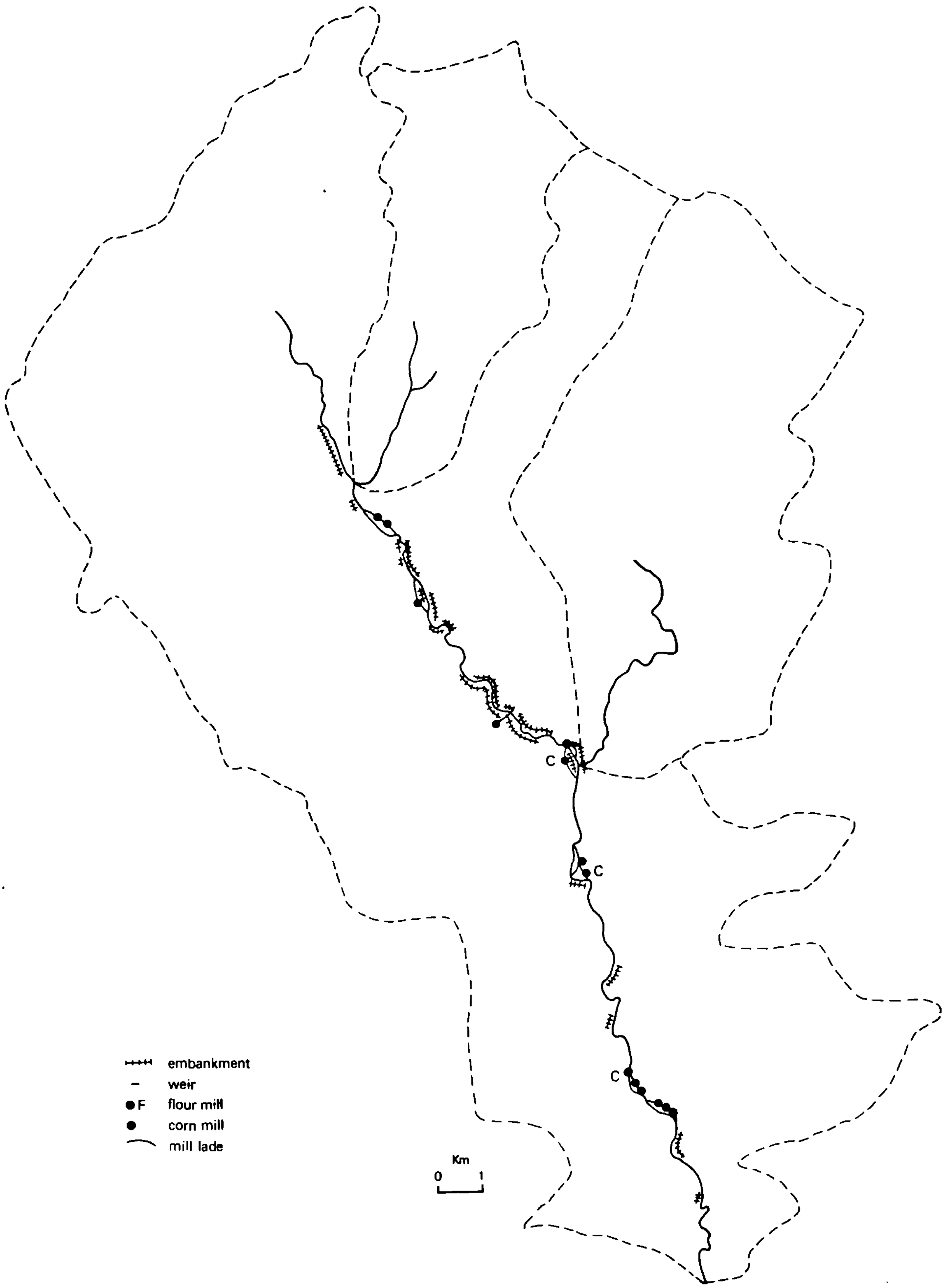
Changes to the percentage water surface area of the Whiteadder catchment occurred in 1966 with the drowning of the upper Whiteadder in a major reservoir construction. However, less than 2% of the total catchment area lies upstream of this construction and it was deemed to have little effect on flood peaks.

In contrast to the assertion that the Tweed was one of the few large British rivers "whose speed of flow is still essentially unaffected by man's activities" (Ledger, 1981 p1), there is considerable evidence on the first edition (O.S. 1:10,560 series) for planform alteration at a variety of scales. Disruption of the actual channel and its floodplain can be sub-divided into two categories, namely those involved with agriculture and the woollen industry, and those as restorative measures after channel disruption or preventative measures against channel change.

In terms of the first category, Roy's map indicated that a large number of mill lades existed by 1750. For example, the Leader valley was associated with corn and flour mills, causing a division of flow down substantial stretches of river. There has also been local disruption of channels associated with power for the woollen industry, which dated from the end of the 18th century (Donaldson, 1951). However, the majority of channel disruption was after that time when all tributaries had weirs and mill-lades to some extent (Figures 6.4.(ii) to 6.4.(vi)). These weirs acted as major sediment traps eg. at Kelso, reducing the velocity and competence of the river, and must have caused considerable sediment depletion downstream. Consequently, in many cases there was a

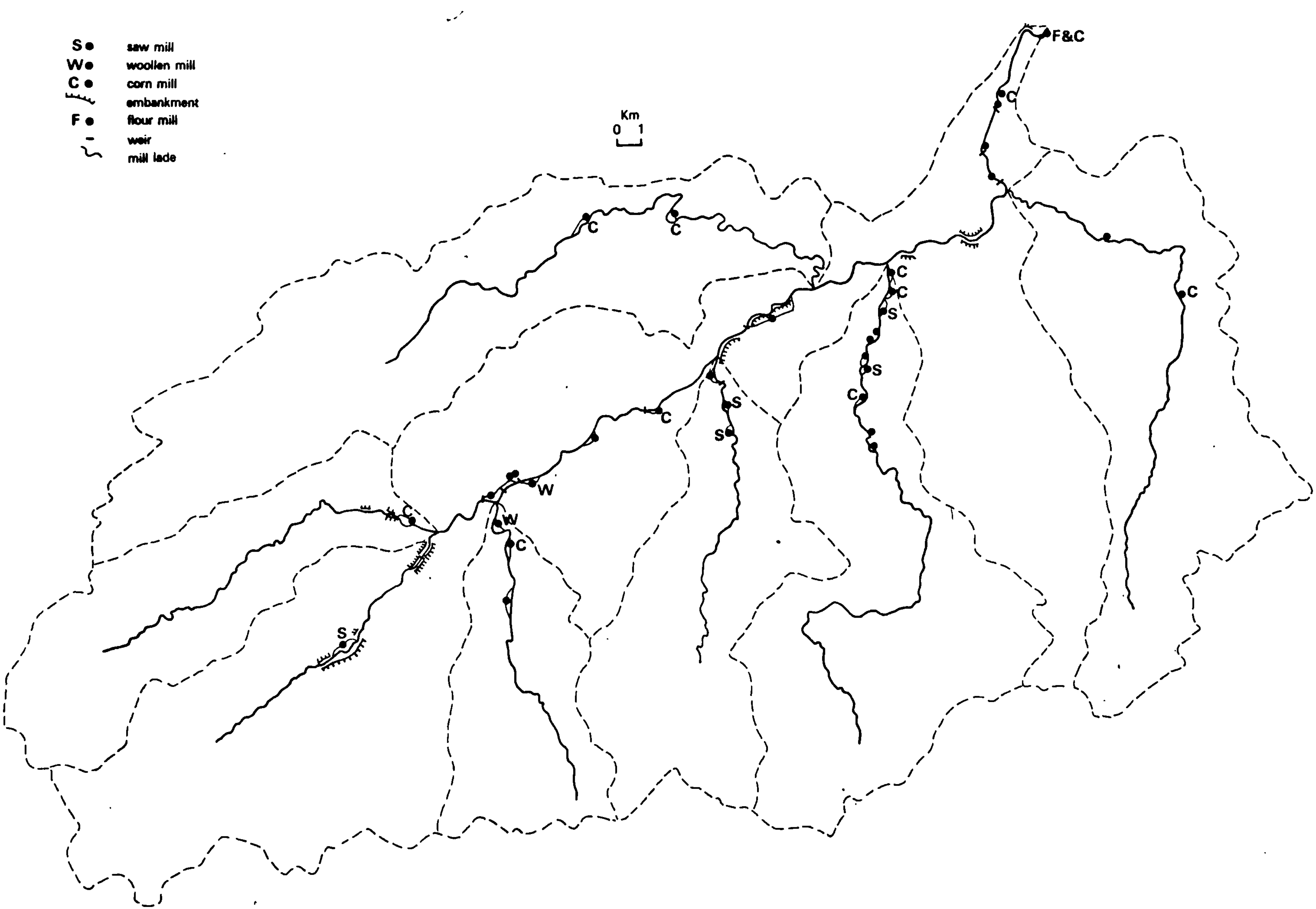
Figure 6.4.(ii)

Modification to the channel and floodplain within the Leader catchment



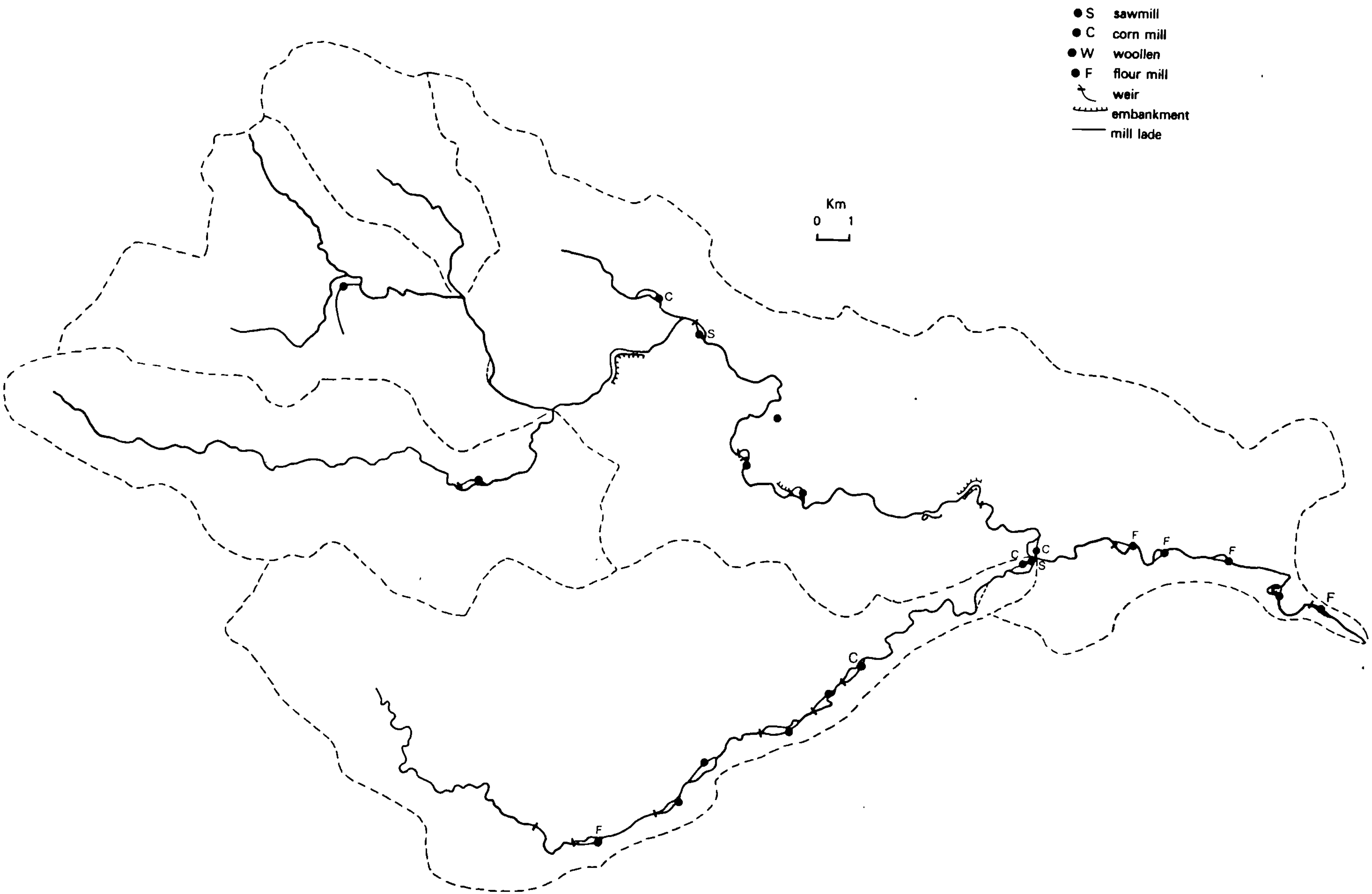
Modification to the channel and floodplain on the River Teviot

Figure 6.4.(iii)



Modifications to the channel and floodplain on the River Whiteadder

Figure 6.4.(iv)



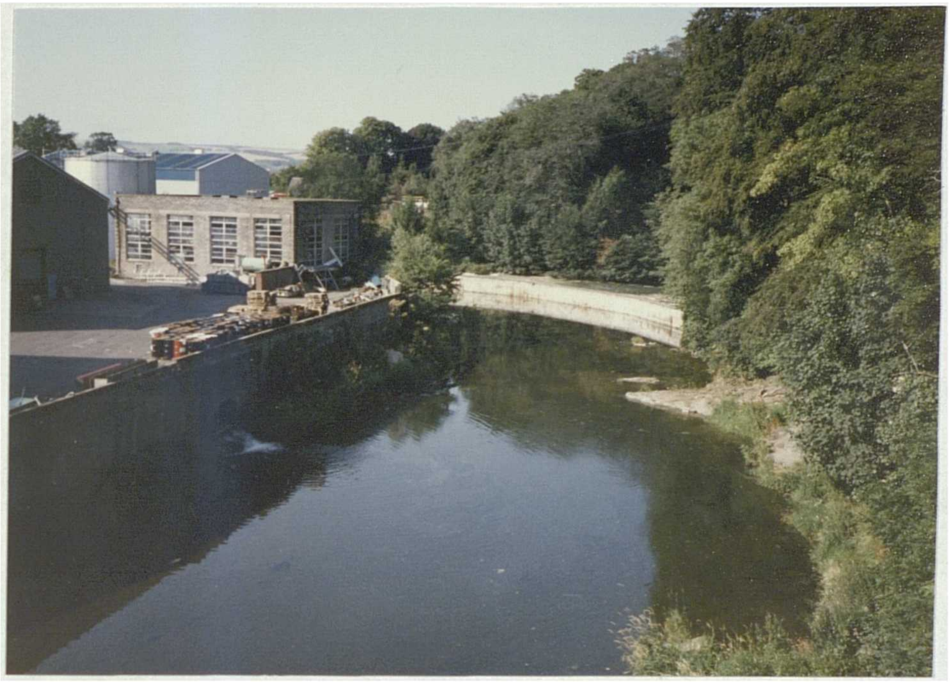
change in channel width and presumably channel capacity, both upstream and downstream of the weir. Mill-lades, occurred at a variety of scales, subdividing the flow and thereby relieving the discharge within the natural channel at more moderate flows (Young, 1879). Disuse and silting up of lades has occurred post-1850 on many Tweed reaches. The date of construction varied but, for example, the plan of the estate of Whitehall in the early 19th century (Blackadder, 1821; RHP 3703) showed Chirnside watermill and a plan of Greenlaw (1842) showed a mill and lade on the Blackadder (RHP 224/2).

Channel modification as a response to planform disruption frequently occurred. After the major flood of 12-13 Aug, 1948, attempts were made to reform the channels, for example on the Whiteadder where large quantities of material had been eroded from the channel bed and banks and deposited on the haughs.

> "At Allanton on the Whiteadder, 20,000 tons of material was lifted from the bed and banks of the river and spread over an area of about 5 acres [2 ha]. Blocks of stone of between 4 and 5 tons were deposited on the haugh." (Scott, 1950 p128).

Material from the channel widening, clearance of obstructions from the bed and from flood deposition on the haughs was deposited beside the stream to produce a protective replacement bank. Localised channelisation also occurred to produce a more stable cross-sectional form (see Plate 6.4.(i)). Other rivers which underwent this treatment included the Leader, the Blackadder, the Teviot and its tributaries and Bowmont Water.

Plate 6.4.(i)



Localised channelisation on the lower Whiteadder

In terms of preventative measures, embanking occurred along several reaches and the locations of pre-first edition embanking are shown in Figures 6.4.(ii) to 6.4.(iv). From the first edition map (1850-1860), there had already been embanking of the mainstream Tweed eg. by Melrose. Upstream, in 1849, there was a plan for a proposed embankment (RHP 1439). Extensive embanking also occurred on such tributaries as the Leader (Figure 6.4.(ii), especially by the second edition. Some embanking was in fact much earlier; for example on the Teviot at Hassendean:

> "The wide plain between Back Brae, Dovecote Knowe and Hassendean bank on the one side and Deanfoot on the other was the sort of subject empire over which it roamed at its own wild will, changing from side to side with each ice flood and inundation...I have spoken to an old man that lived at the cottage at Hassendean when the Teviot ran by the foot of the brae with salmon below [70-90 years ago?]. At that time, the Teviot formed the northern boundary of the Calvers estate. A great ice flood in 1795 sent it back partly into its original course and after that these great mounds and hutches were built under Cockers Scaur, which retain it in its present channel. Long after, its course took a sweep away from near Denholm Mill across to the Willowtrees at Grindon Burn and thence back to the pool that still exists called Francis Hole. About 1808 the new cut was made by which the Teviot was turned into its present channel and still later in 1824 a cut

> was made down by the Spital plant to prevent it from wandering around by Deanfoot and Drythropple". (Trans. Haw. Arch. Soc. 1866, p12)

Frequently, the introduction of such protective measures occurred after a major event eg. the 1948 flood event on the Tweed, Leader and Whiteadder, as described by Learmonth (1950), or the 1938 flood on the Teviot (see Plate 6.4.(ii)). Other more haphazard alterations to the channel cross-sectional form have been attempted by individual farmers, but these usually have only temporary and local effects eg. on the Bowmont (Plate 6.4.(iii)). In some reaches extensive gabions prevent further erosion eg. on the Teviot (Plate 6.4.(iv)).

Plate 6.4.(ii)

Embanking providing flood protection to agricultural land on the middle Teviot

Plate 6.4.(iii)

Infilling with stones and rubbish as bank protection on the Bowmont Water

Plate 6.4.(iv)

Gabions prevent further bank erosion on the middle Teviot

6.5 Summary

There is thus considerable variation in landuse change history between study areas. In terms of deforestation, the Dee and Spey study areas underwent considerable deforestation in the 18th and 19th centuries whereas, within the Tweed study area, extensive deforestation had taken place much earlier. The impact of agricultural drainage however was more acute post-1850 within the Tweed study area. Within both the Spey and Dee study areas, most lade construction occurred in the lower middle to confluence reaches, while within the Tweed catchments alteration to the the natural channel was much more widespread. All areas had examples of channel alteration prior to the 18th century.

CHAPTER 7

A series of case studies: Rates of channel change in specific high activity reaches

7.1 Introduction

From the map-based study, the frequency and characteristics of channel pattern change clearly differed with a variety of variables eg. width of available active area and availability of sediment. In addition, with the *information derived from* Chapter 5, the periodicity of both moderate and extreme flood events within a particular catchment are known. Thus, the impact and effectiveness of known flood events, of varying magnitudes and estimated RIs, can be studied. It should however be noted that extrapolations of the magnitude of runoff events from the mainstream record to tributaries may however be unreliable and each flood was considered separately.

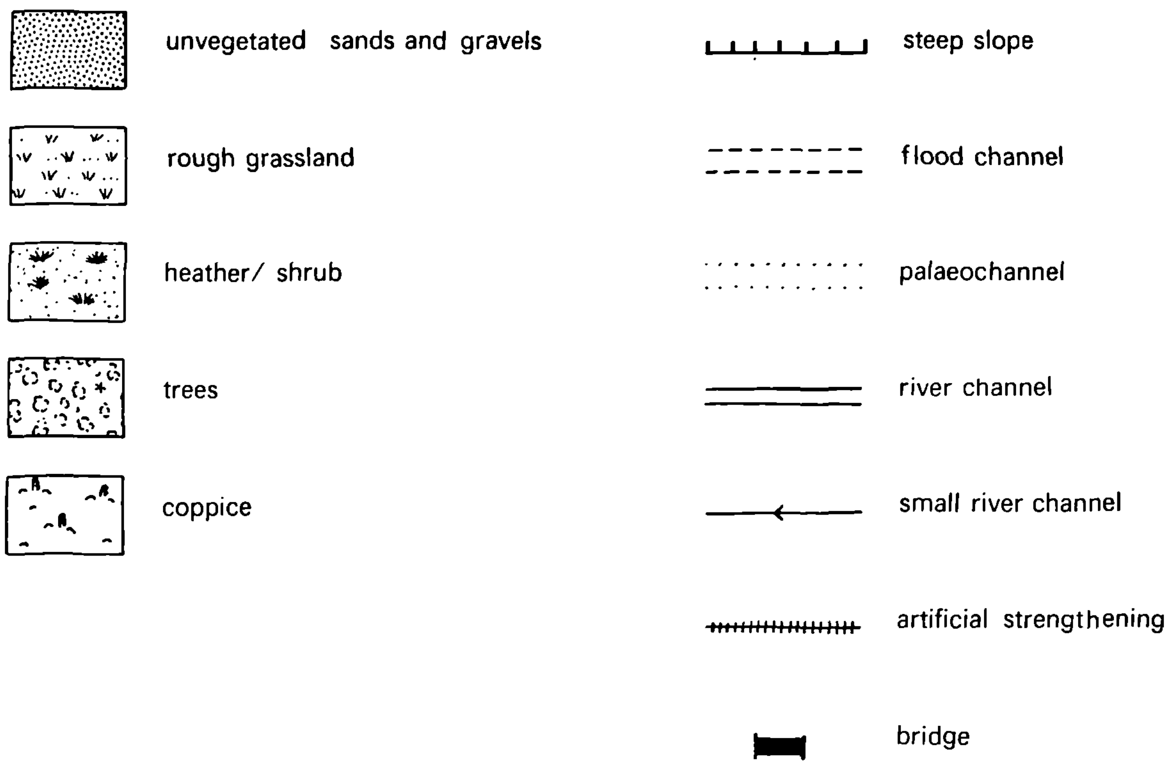
To assess the frequency and modes of channel pattern change which occurred in more detail at a meso-scale of resolution, sequential aerial photographs of selected sites were mapped and compared. These reaches were chosen because they seemed particularly interesting or active from the macro-scale map analysis. Within the Scottish upland context, aerial photography commenced around 1946, so any available record was post that date. For each study region, a series of 7 to 10 case studies were carried out, highly dependent on material availability. A Bausch and Lomb Zoom Transferscope facilitated this transfer of information on to either a 1:5,000 or 1:10,000 O.S. map base, depending on the scale of the area studied and the resolution of detail. Thus, a series of channel planform comparisons were produced (see Figure 7.1.(i) for key).

Coverage was highly limited by availability of photographs, especially within the Tweed study area, and pre-selected active sites had to be either reselected or reduced in number. Unfortunately, it was also rare to get pre- and post-flood photography but one had to be prepared to work within the limitations of the data source. Additional problems occurred within the Tweed area in that certain sites, selected because of their inherent activity, had frequently undergone artificial straightening post-1948 (Section 6.4), thus reducing the information derived from aerial photograph interpretation. However, this was typical of many middle reaches within the Tweed study area and was almost unavoidable when looking at more active, mainstream reaches on the Teviot, Leader and Whiteadder. In these cases, this study had to examine how effective such preventative measures had been in terms of the known magnitude and frequency of post-1948 flood flows. Tributary streams, which had undergone much less man-induced alteration of the natural planform, were also analysed.

This chapter is organised in the following manner. Initially, basin and site specific characteristics, as evident from the channel system typology (see Table 4.3.(i)- copy in back pocket), will be presented in tables and the information derived from Chapter 4 will be incorporated. These comparisons will be backed up by the detail from Roy's military map (around 1750) and estate plans where available. This map

Figure 7.1.(i)

Key for aerial photograph analysis maps



information will then be interpolated with information from a variety of sources, ranging from gauged discharge records to a flood history gleaned from a mixture of historical sources (Chapter 5). For each study reach, a tabulated flood history will be presented. Finally, after each set of case studies, there will be an evaluation of the range of channel response to these flood histories.

7.2 Study reaches within the Dee study area

The reaches studied within the Dee study area are as follows:

(1) The Quoich Water confluence

(2) The Ey Burn confluence

(3) The Gleann an t-Slugain confluence

(4) The middle Lui Water

(5) The Clunie Water below the Baddoch Burn confluence

(6) The Luibeg Burn

(7) The upper Derry Burn

(8) The River Dee by Clunie Cottage

The location of these reaches within the Dee study area is shown in Figure 7.2.(i).

7.2.1 Dee study reach 1: The Quoich Water confluence

The Quoich debouches through a rock controlled section (see Figure 3.2.3.(i)) and enters an area of more stable, uniform cross-section, confined to the west by large fluvioglacial deposits and to the east by a high bank stabilised with trees. Below the bridge, the river widens with channels of much higher W:d ratio and culminates in a large low-level gravel fan. At this point, the contributing basin area is 57.1 km^2. Position within the channel system typology is outlined in Table 7.2.1.(i).

Location of study reaches within the Dee study area

Figure 7.2.(i)

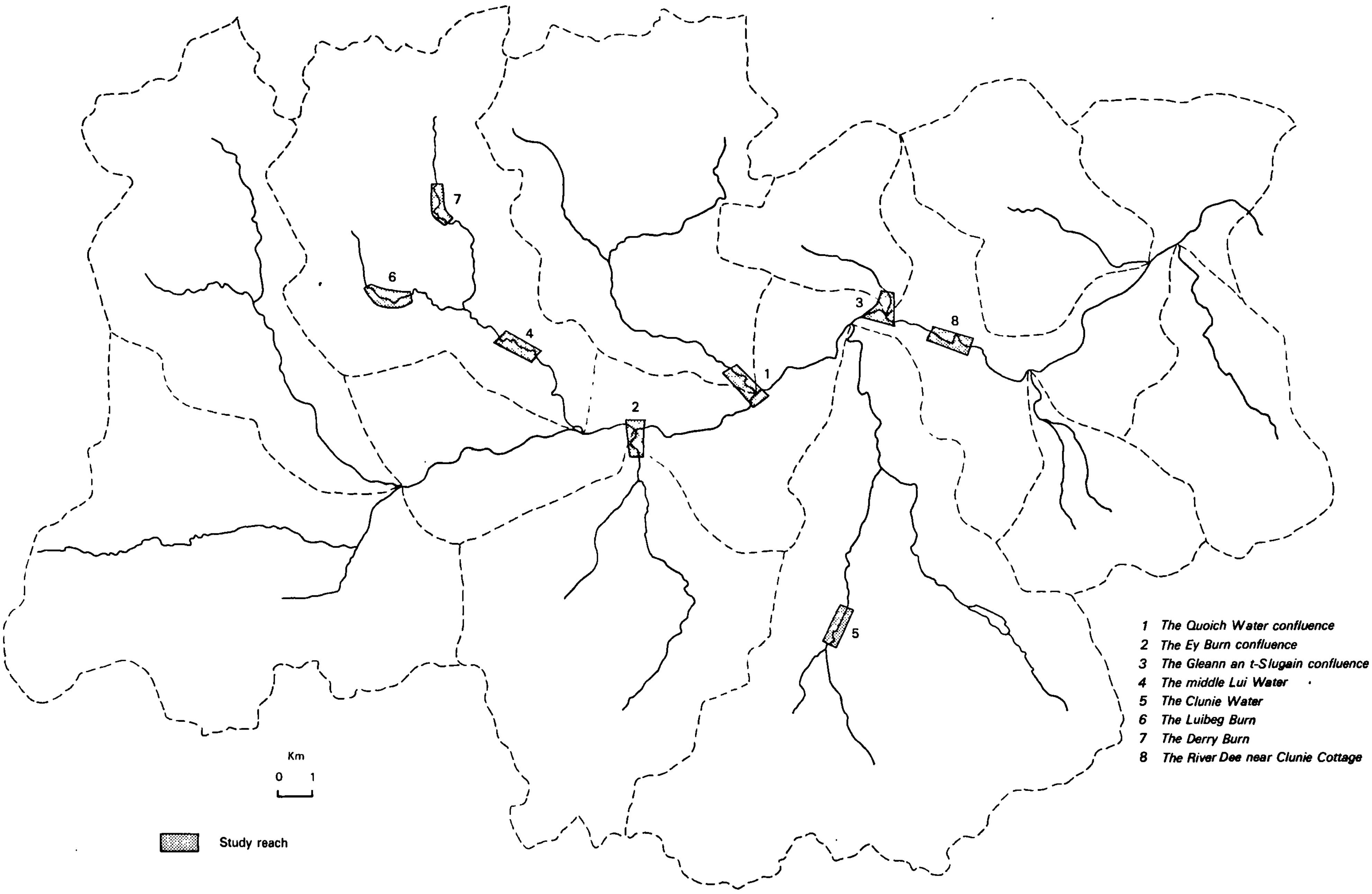


Table 7.2.1.(i)

Position of Dee study reach 1: The Quoich Water confluence within the map-based channel system typology

A (a) Basin area: 57.1 km^2

(b) Average height: 330 m

	1866	1902	1971
B (a) UPSEDMT:	1	1	1
(b) LOCSEDMT:	2	2	2
C FLOOD:	0	1	0
D (a) FLOODPLN VEGETATION:	8	8	6
(b) BANK VEGETATION:	8	8	6
(c) BAR VEGETATION:	8	8	8

E MAXWID 100

F (a) CHANPATT:	-	8	3
(b) ISLANDS:	-	8	2
G (a) ACTIVITY:	8	8	8

Figure 7.2.1.(i)

Dee study reach 1: The Quoich Water confluence

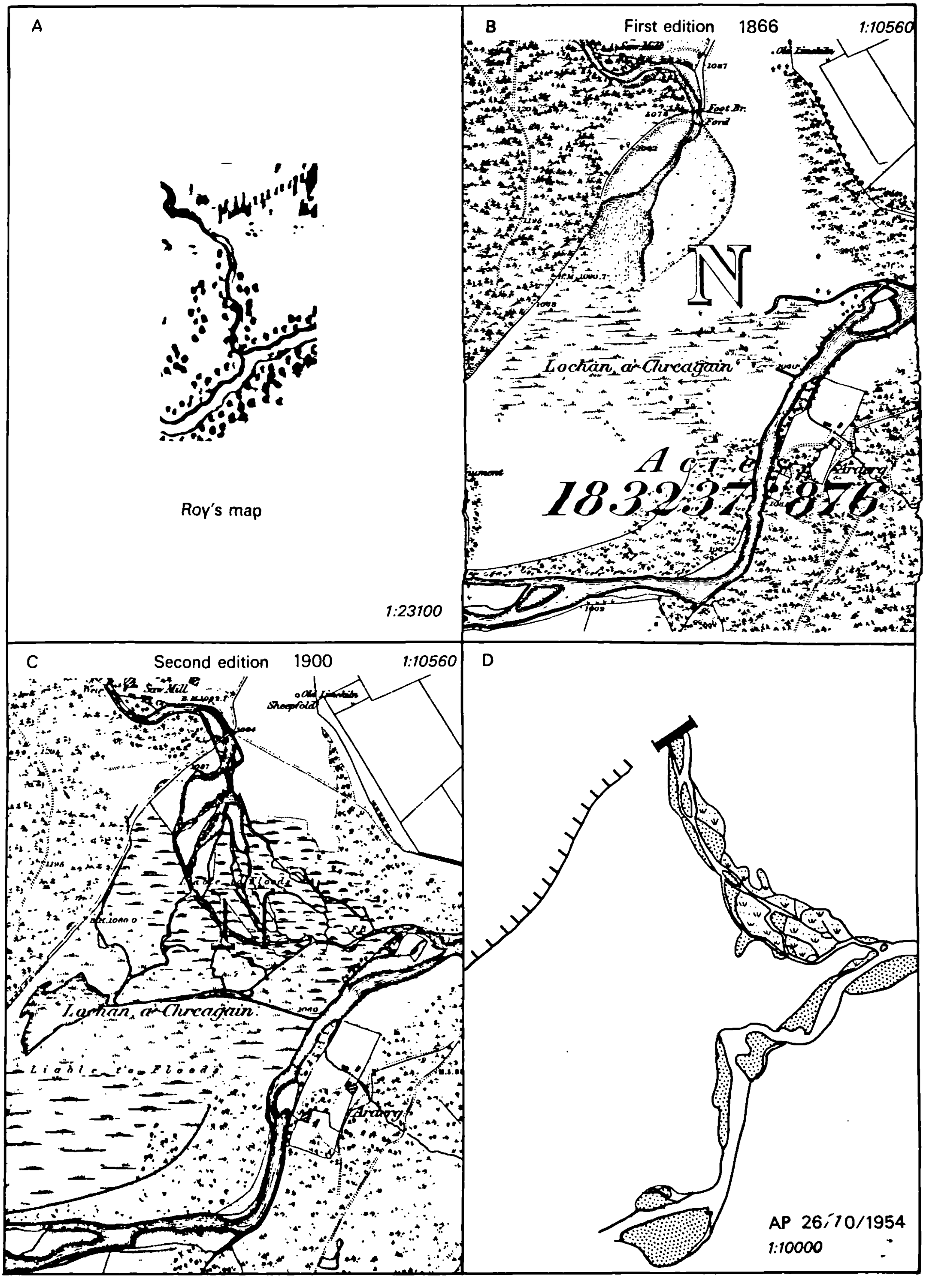
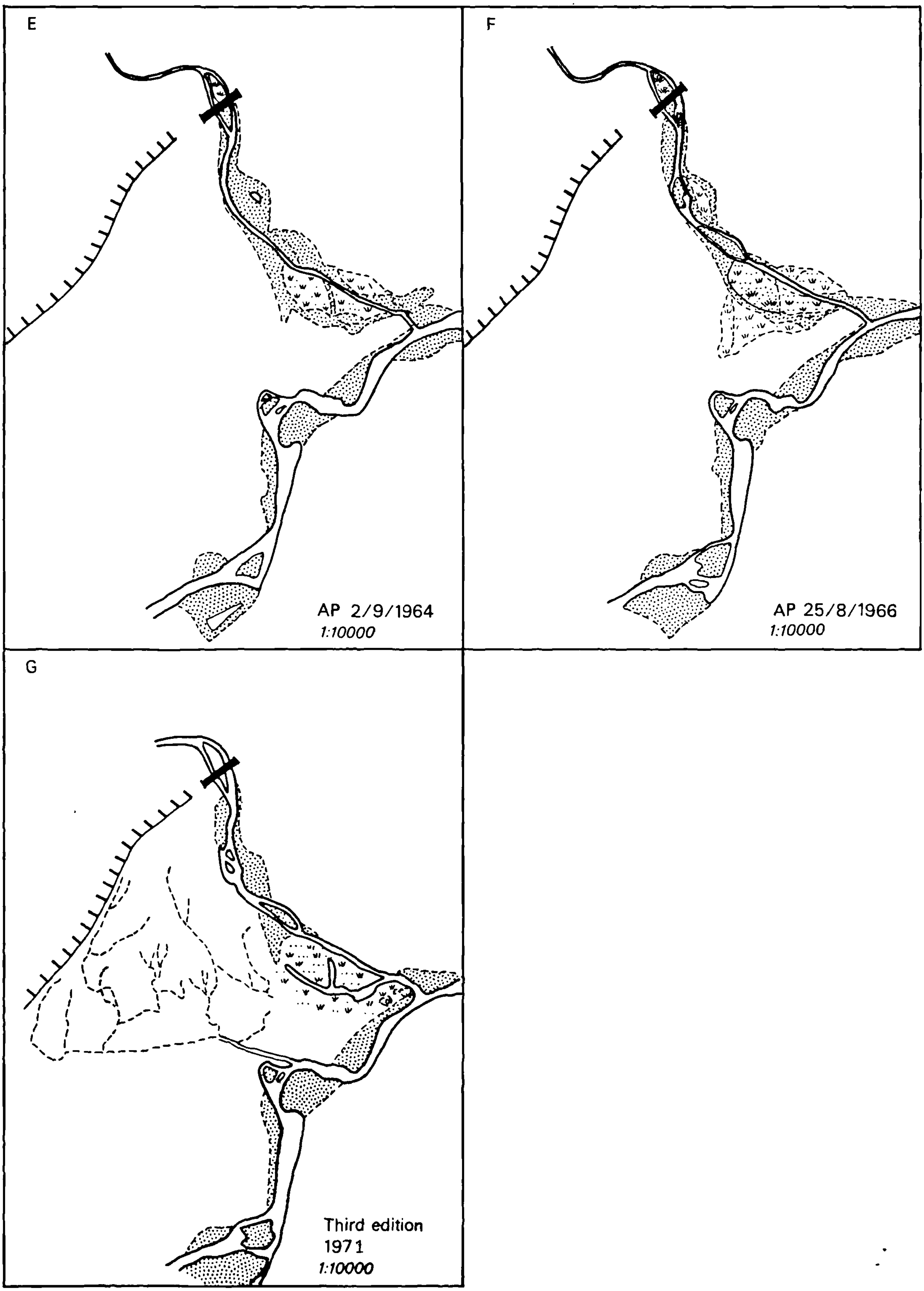


Figure 7.2.1.(i) cont.

Dee study reach 1: The Quoich Water confluence



On Roy's map (1750s), the Quoich was shown to follow a sinuous tree-lined path to join the Dee at approximately right angles, as shown in Figure 7.2.1.(i).A. Several estate plans confirmed this, for example the plan of part of Mar Forest in 1826 (RHP 811), which showed the Quoich as a single, fairly straight channel with two small bars right at the confluence with the Dee. The mid 18th century plan of the Mill at Allanaquoich (RHP 31322) showed the same pattern but with some gravels by the confluence and woodland close by to the east.

It was clear from studying the planform on the first edition map (1866) that a major disruption to the system had since taken place; instead of continuing down to the confluence, the channel turned abruptly west after leaving the bedrock confinements below the Linn of Quoich (Figure 7.2.1.(i).B). It then culminated as a major distributary fan with an extensive amount of local sands and gravels, and entered a large marshy lochan area (Lochan a' Chreagain). The flow was finally channelled into at least two distributaries and made its way to the mainstream Dee. It was evident that a large amount of sediment had been brought downstream and deposited in this area. This sediment had originated from sources both above the Linn of Quoich and also from the hillslopes below. From Lauder's (1830) account, it was clear that the 4th Aug, 1829 floods had caused this major disruption and it is simplest to report in detail his thorough account:

"The river Cuach or Quoich, which falls in from the left bank, committed great havoc... Issuing from the gorge, the Cuach swept away three acres [1.2 ha] of a well-grown young larch wood, surrounded a group of cottages, and manoeuvred with main body of its stream, now in front, and now in the rear of them, so as to keep the unfortunate inmates in a state of distraction. The result was that, by the providential mercy of God, the mere spot of earth on which the foundations of the houses stand, was left in the midst of a deep excavation, extending for many hundred yards around them, and the river now runs on the side of them opposite to that where it had its course before the flood. From the point where the houses are situated, the Cuach used to run across a very wide and extensive haugh, for perhaps one third of a mile, to join, nearly at a right angle, the Dee, that has its course close to the base of the southern hills. ...... The flood having brought down an immense slice of a high hill of gravel and stones not far from the cottages, filled up the channel below, broke out to the left, and rushed across the eastern division of the farm in a diagonal line, spreading one wide flood of devastation over 150 acres [60 ha]. It then filled up the mouth of this new channel, as it had done the first, and, bursting away to the right, it cut a third, still deeper, along the line of Mr Cumming's wall of enclosure, and then spread itself abroad over the upper part of the western end of the farm, and converted 60 acres [24 ha] of valuable meadow into a permanent lake. Tired with running in this direction, it filled up the new-made channel under the wall, and heaped stones and gravel so high on it as to leave only its cope visible, and completed its operations by opening a forth bed in a diagonal line between the first and the third, in which I saw it running. All these cruel gambols were performed by this wicked stream in the course of a few hours, leaving two-thirds of the once beautiful and valuable surface of the farm lying in scarified river beds, or covered to a great depth with sand and gravel, and the rest of it in a large lake, where wild fowl may breed." (Lauder, 1830 pp291-293)

This was thus a catastrophic disruption, with considerable sediment input to the system (see also Barrow and Craig, 1912). The estimated RI of the discharge was high, being at least 250 years and possibly up to 1000 years (Figure 5.4.1.(iii)).

As the first edition map (1866) was surveyed 37 years after, it was clear that there had been little modification of the post-flood channel characteristics over this timespan. It was impossible to measure the braiding index or sinuosity from this map-base. By the second edition (1900), the channel pattern was highly disrupted and multibranched but individual channels, indicating definable channels, had now been mapped and these channels combined to join with the Dee in a similar place as pre-1829 (Figure 7.2.1.(i).C). The extreme nature of the reticulate distributary pattern was indicated by the very high braiding index of 8.80, well in excess of any other in the Dee sample. Sinuosity was also high at 1.56. Some of the abundant gravel had been stabilised but the dominant floodplain vegetation was still marsh. The Lochan a' Chreagain still persisted, but was more restricted in size and the whole area was described as "liable to floods" ie. subject to frequent inundation.

Attempting to reconstruct the magnitude and frequency of flood events between 1866 and 1900, and assess their geomorphic effectiveness, several flood events occurred in the upper Deeside catchment (see Figures 7.2.1.(ii) and Appendix 1.1). However, it is reported (British Rainfall, 1885) that during a rainfall of "unprecedented severity", which took place generally over upper Deeside on 12th Aug, 1885, a portion of the Quoich bridge was swept away. It was calculated that this 24 hour rainfall had a RI of over 200 years at Braemar and was probably much higher over the Quoich catchment. Such a high flow must have given the Quoich competence to shift its channel into a reticulate bar condition, which made the likelihood of it returning to a pre-1829 alignment more possible. The excess sediment available for transport had to some extent been redistributed and stabilised. It is interesting to contemplate the disruption the 1885 event may have caused, had the 1829 event not occurred. Whereas after 1829, it helped rework the sediment and realign the flow, without the 1829 flood it could have been completely disruptive. The inter-arrival time of major events is thus very important. There were also several more moderate rainfall and runoff events over this period, which may have assisted in this planform adjustment. It is known, for example, that downstream at Balmoral, two major flows occurred in 1872 (see Appendix 1.1).

The first aerial photograph record was 26/10/1954 and here although the palaeo-distributary network was still obvious, the main direction of channel flow had reverted upstream to a near pre-1829, channel alignment, with occasional medial bars (Figure 7.2.1.(i).D). However, downstream near the confluence, there was a network of anabranches before flow briefly joined in one channel to enter the Dee. Unvegetated channel-side gravels were still available for reworking but these were considerably more restricted than in 1900. It was known (Chapter 5, Figure 5.4.1.(i)) that major flood events within the upper Dee occurred in 1911, 1914, 1928 and 1937, with a more moderate event on the Quoich in 1920 (Figure 5.4.1.(iii)). Events such as those in 1914 (clearly more important on the higher ground) and 1937 must have had the competence to divert flow, plugging up the old anabranches.

The next aerial photograph allowed assessment of changes that could occur over the brief period of 8 months. Thus, by 1/6/1955, there was some reactivation of gravels adjacent to the channel, perhaps caused by high winter flows, as well as down in the lower anabranch area. Since then, during lower flows, the basic planform seemed to have changed little, despite localised shifting around bars.

By 2/9/1964, the active area had widened further and the upstream subreach had become more sinuous, whilst down in the former anabranch area, the river had reverted to flow in a single channel (Figure 7.2.1.(i).E). The other former channels had little sign of vegetation and held ponded water, so it was possible that the switch was fairly recent. The only flood event known in this period was the 13th Aug, 1956 event (24 hour rainfall RI of over 120 years at Derry Lodge), which may have affected the catchment to a lesser extent than the neighbouring Lui catchment. Thus, minor channel adjustments may occur during more moderate flows. In contrast, by 25/8/1966, the channel rather than being dominantly single upstream, was now split around shoal bars with localised shifts in the location of the main channel (Figure 7.2.1.(i).F). The lower reach was still retained in a single channel but the actual confluence seemed to be undergoing a slow sedimentation, as material was transported down the fan, again presumably during more moderate events. This basic planform persisted on the third edition map (1971), with a large amount of gravels proximal to the channel for reworking at higher stages. Between 1900 and 1971, sinuosity decreased from 1.56 to 1.11 while braiding index had undergone a major reduction from 8.80 to 1.26.

More recent oblique photography in June, 1984 (see Plate 7.2.1.(i)) showed that the middle reaches of the fan have still not stabilised over the 150 years since the Aug, 1829 event. Sediment was extensively reworked in Aug, 1885, and this initially brought the channel back within a pre-1829 alignment, aided by subsequent more moderate events. Lower flows appear to do little geomorphic work. However, given the massive influx of sediment to be reworked, it seems unlikely that the Quoich will ever retain its more stable pre-1829 equilibrium form, with a sinuous channel shifting around localised, unstable medial bars. This is because it may have crossed a threshold to a new metastable equilibrium. With the much higher availability of sediment in this area, planform controls have changed and a shift in equilibrium condition may have occurred over the last 150 years. However, the

Plate 7.2.1.(i)

The Quoich Water confluence

(June, 1984)

actual confluence now seems stabilised to the west with trees, indicating no recent disruption. When compared with photographs taken in June, 1984, no significant upstream change or stabilisation has taken place. The geomorphic effectiveness of the 1829 event has lasted 150 years but the river is now much closer to a quasi-equilibrium planform with frequent bars/ split channel, than its former more sinuous channel.

7.2.2 Dee study reach 2: The Ey Burn confluence

The Ey Burn confluence also possesses a distributary fan, but delimited by terrace features, this has a more restricted available active area than that of the lower Quoich Water. Upstream sediment supply is also much less abundant, being mainly derived from upstream erosion of fluvioglacial terrace material. At the apex of the fan, the area drained is 59.3 km^2. Position within the channel system typology is outlined in Table 7.2.2.(i).

On Roy's map (1750), the river planform was portrayed as having quite accentuated, tortuous meander bends with a localised, stable island midstream. Palaeochannels, evident from aerial photograph analysis, confirmed the general location of these channels. Banks were also shown to be well covered with trees (Figure 7.2.2.(i).A). The impression was that the channel was fairly stable at that time. By 1826, on the estate plan of Mar forest (RHP 811), the Ey was shown as having a slightly sinuous planform ie. a possible slight reduction in sinuosity since 1750. However, on the first edition map (1869), the Ey

Table 7.2.2.(i)

Position of Dee study reach 2: The Ey Burn confluence within the map-based channel system typology

A (a) Basin area: 60.5 km^2

(b) Average height: 345 m

	1869	1903	1972
B (a) UPSEDMT:	0	0	0
(b) LOCSEDMT:	0	0	1
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	5	5	5
(b) BANK VEGETATION:	3	3	3
(c) BAR VEGETATION:	0	3	8

E MAXWID 100

	1869	1903	1972
F (a) CHANPATT:	5	5	5
(b) ISLANDS:	1	5	2
G (a) ACTIVITY:	2	2	8

Figure 7.2.2.(i)

Dee study reach 2: The Ey Water confluence

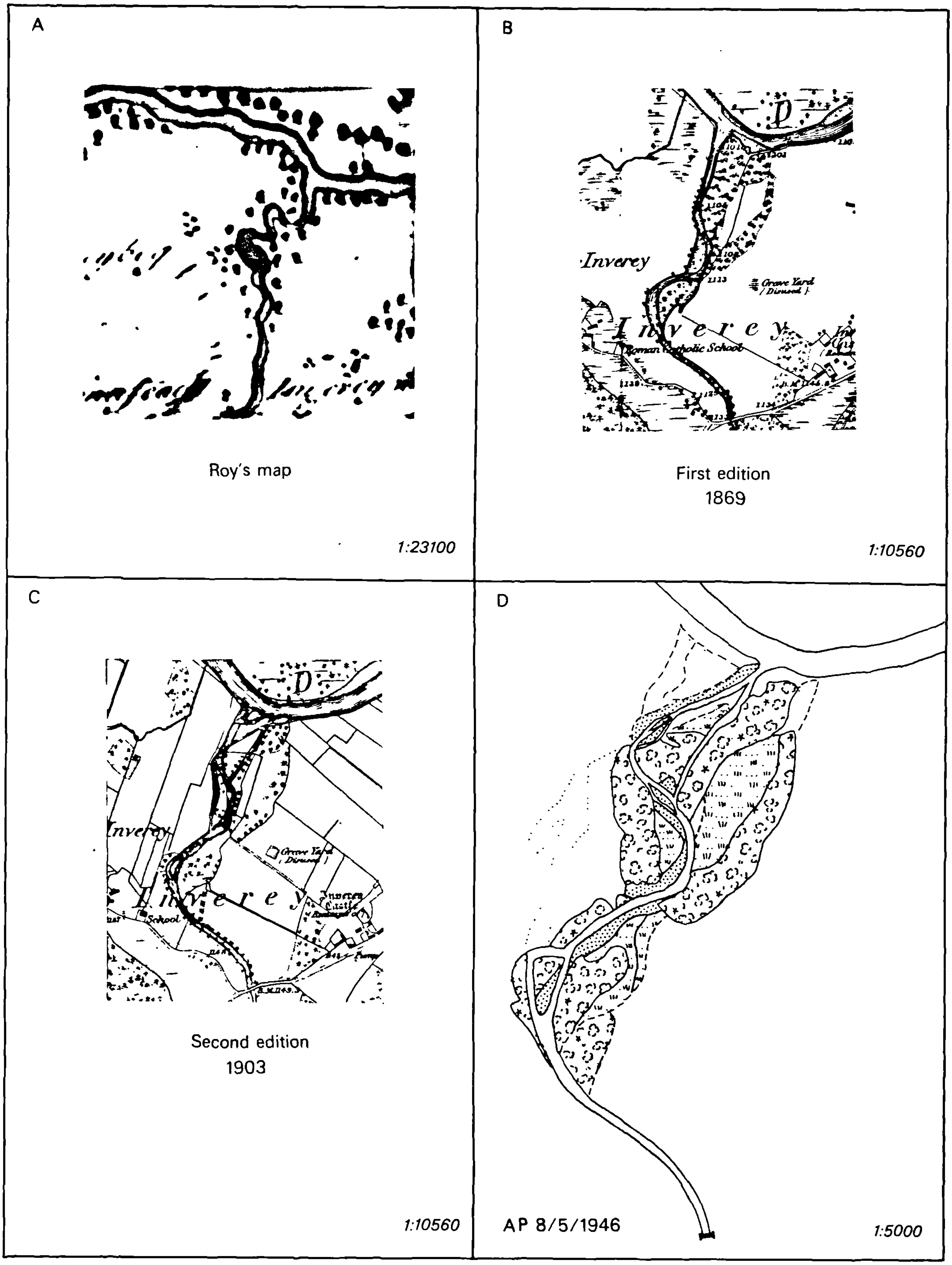
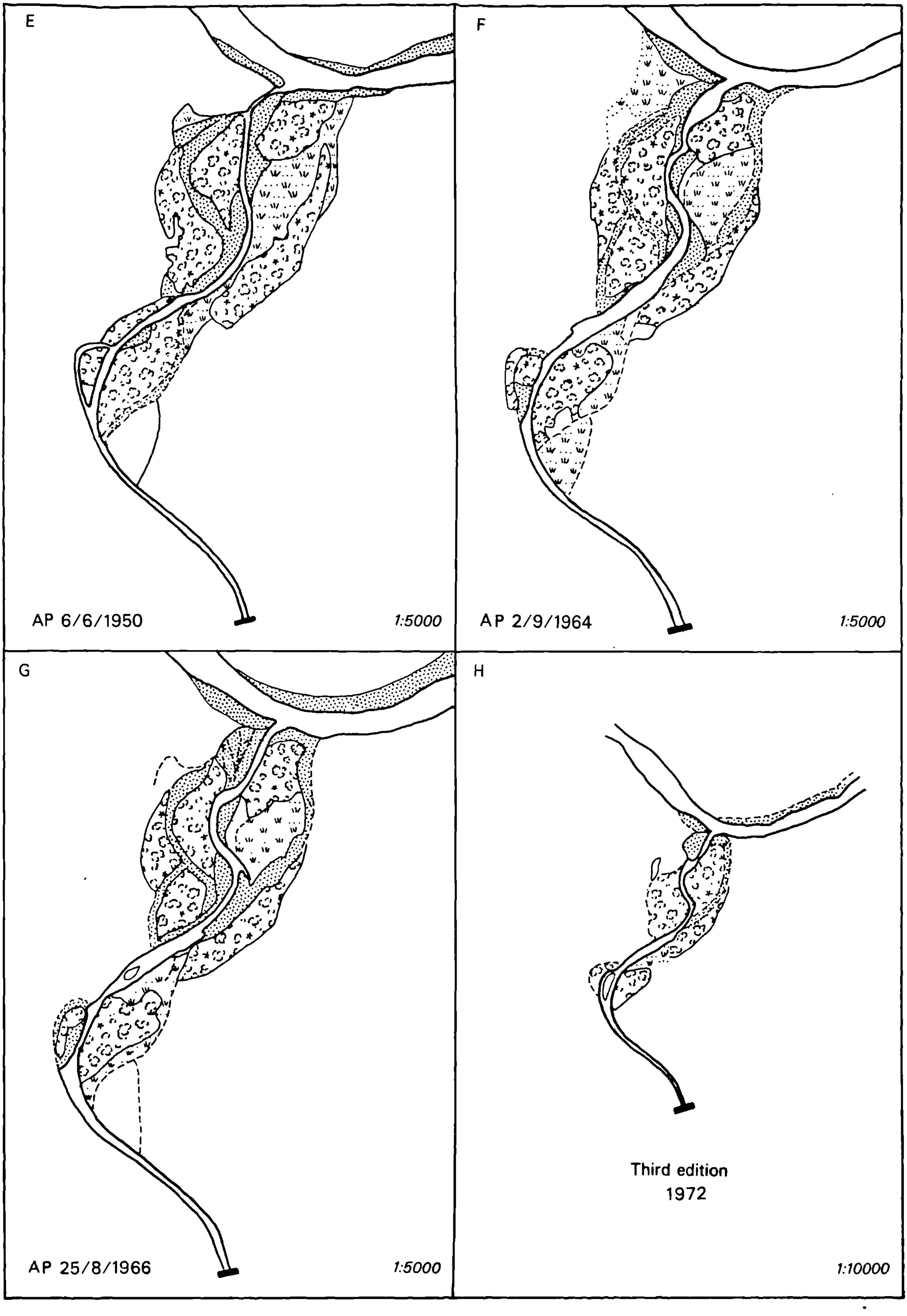


Figure 7.2.2.(i) cont.

Dee study reach 2: The Ey Burn confluence



was much straighter at the actual confluence, having changed its point of entry to the Dee (Figure 7.2.2.(i).B). Nevertheless, this seemed relatively stable with localised trees bordering one bank and woodland on the other. In contrast, the channel had clearly been more active upstream of the confluence, with bare and progressively colonising sediment shown by the channel side, remnants of the meanders cut through since Roy's map. It appears that although the Aug, 1829 flood must have affected this area, it was clearly not as disruptive as within the Quoich confluence. The Ey's catchment was more distant from the most intense rainfall.

However, when the Ey was studied on the second edition map (1903), major changes had taken place since 1869 (Figure 7.2.2.(i).C). Associated with an increase in the width of the active area, the whole system had become fragmented and disrupted. There appeared already to have been some stabilisation of bars, but probably this was the original tree cover still intact. This suggested that expansion of channel planform took place by extra-channel avulsion, ripping through the floodplain rather than by reworking upstream or local sediment into bars. Thus, in terms of the braiding index, there was an increase from 1.00 to 1.68 over 34 years. Sinuosity in contrast, only changed slightly from 1.22 to 1.27 and in terms of total lateral shift, 29 metres was the maximum with an average of 12 metres. Some significant geomorphic force must have occurred between 1869 and 1903, but it was difficult from the chronology of moderate to extreme events known to have affected the mainstream Dee, to determine which caused such disruption on the lower Ey. It may, for example, have been in Aug, 1894 when a major event occurred in the neighbouring Clunie catchment.

Unfortunately, localised convective storms affecting individual catchments are not always recorded. Alternatively, it may have been the increase in more moderate events in the 1870s to 1880s, pushing the system over intrinsic thresholds. However, it is doubtful if such major disruption could be entirely a response to an intrinsic threshold.

43 years later, from aerial photograph evidence (8/5/1946), the main channel had increased in sinuosity and the braiding index had decreased (Figure 7.2.2.(i).D), associated with a split rather than braided planform. The banks and the bars were more stabilised by trees and the actual confluence site with the Dee was narrowed and stabilised. Obviously, the 1920 and 1937 events must have had little geomorphic impact on the Ey, other than reverting the channel to a simpler planform. After another 4 years (6/6/1950), flow has reverted to a single sinuous channel and the restabilisation of the bars and banks seems to have advanced further (Figure 7.2.2.(i).E).

In contrast to this period of planform change associated with a reduction in width of active area and relative inactivity, in the following 14 years up to 2/9/1964, another major disruption occurred. A new flood channel (possibly reusing the 1750 alignment) was cut under the first terrace to the east, with old channels also reactivated through the trees to the west. It was difficult to assess from the aerial photograph, but the channels seemed disused by 1964 so they must have been cleaned out to accommodate a sudden increase in discharge. However, the actual channel had subsequently reverted back to its pre-flood alignment although there had been an increase in sinuosity and channel widening. Basically in terms of channel planform, the pre-existent bars, though trimmed, remained the same, obviously stable enough to withstand the flow. This may have occurred during the winter flooding in 1951 (Figure 5.4.1.(i)), or again perhaps in some localised convective storm, which did not register as a major event on the mainstream Dee. Thus, flood disruption may cause a temporary increase in active area, but flow does not necessarily maintain a disrupted planform post-flood, over a long period. The aerial photographs are too widely spaced for more precise assessment.

By 25/8/1966, little further change had occurred, with an area of gravels by the channel remaining unvegetated while the bars continued to stabilise (Figure 7.2.2.(i).G); a similar pattern was apparent from the 1972 map (Figure 7.2.2.(i).H). Thus, overall between 1903 and 1972, sinuosity remained the same but there was a reduction in BI from 1.68 to 1.14. However, in Aug, 1983 when field checking was carried out, the channel at the confluence had been disrupted again into a more braided planform especially at the confluence, although the old palaeochannels to the east had been grassed over. There was evidence of deep scour pools by the channelside, and empty and inactive channels slanting across the active area, which were obviously a riffle at high stage. This disruption must be attributed to the large flood of Oct, 1982, which removed bridges upstream (pers. comm. Mr. Lovat Fraser, head stalker). Thus since 1869, the channel planform has been disrupted by geomorphically active flood flows at least three times, with a periodic expansion of the active area and reuse of former channels. Recovery from these events, associated with a reduction in BI and active area, back to a more quasi-equilibrium state occurs in less than 10 years. However, whether the planform condition, as depicted on Roy's map, represents a point on the same equilibrium scale is open to debate. No conclusive statement can be made without other evidence.

7.2.3 Dee study reach 3: The Gleann an t-Slugain confluence

The Gleann an t-Slugain study reach drains a much smaller area at its apex (16.2 km^2), than the neighbouring Quoich Water fan. The channel slope is also higher at the apex than either the Quoich or Ey fans. This very complex, low level gravel fan, with a sinuous channel planform, has undergone considerable change in channel pattern since 1750, with a periodic reoccupying and reworking of old channels. Position within the channel system typology is outlined in Table 7.2.3.(i).

Roy's map (1750) showed the river using its easternmost channel (Figure 7.2.3.(i).A), which may have been more stable at that time since the settlement of Milltown was in close proximity to the river's banks. This was confirmed by the 1808 plan of the Invercauld estate by George Brown (RHP 3645), which indicated a sinuous channel, with only a localised split around a bar. Considerable disruption was known to have occurred in this area during the 1829 floods:

> "The most extensive mischief done by the flood on the estate of Invercauld, was by the Burn of Chandlick [Gleann an t-Slugain], which cut away 6000 yds^2 [5016 m^2] from a gravel hill, and deposited the debris on the haugh land of the farm of Milton, utterly destroying about 30 arable acres (12 ha).

Table 7.2.3.(i)

Position of Dee study reach 3: The Gleann an t-Slugain confluence within the map-based channel system typology

A (a) Basin area: 16.2 km^2

(b) Average height: 327 m

	1869	1902	1971
B (a) UPSEDMT:	0	0	0
(b) LOCSEDMT:	1	1	1
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	3	3	3
(b) BANK VEGETATION:	3	3	3
(c) BAR VEGETATION:	8	0	8

E MAXWID 180

	1869	1902	1971
F (a) CHANPATT:	3	3	2
(b) ISLANDS:	2	1	2
G (a) ACTIVITY:	6	6	2

Figure 7.2.3.(i)

Dee study reach 3: The Gleann an t-Slugain confluence

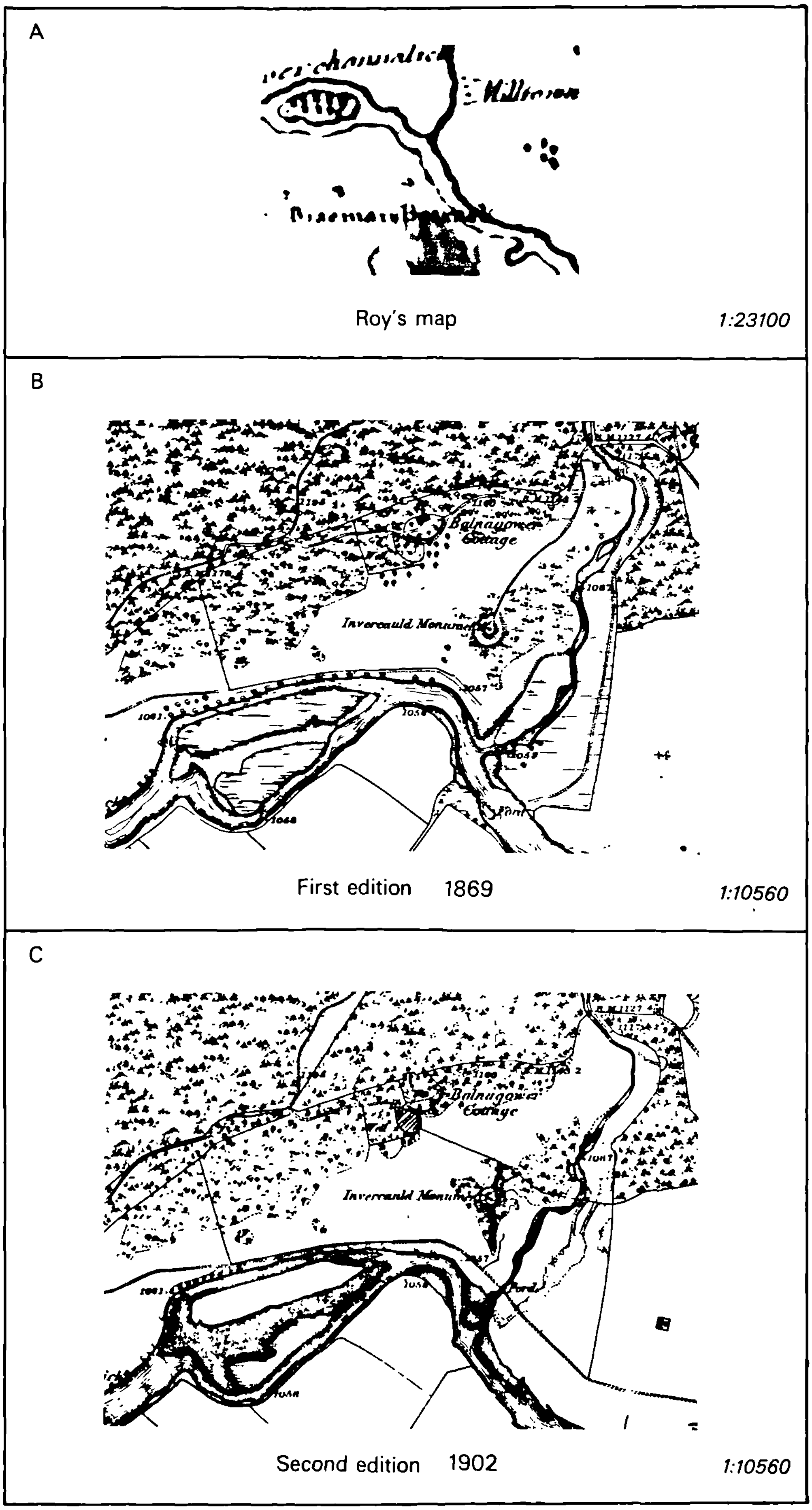


Figure 7.2.3.(i) cont.

Dee study reach 3: The Gleann an t-Slugain confluence

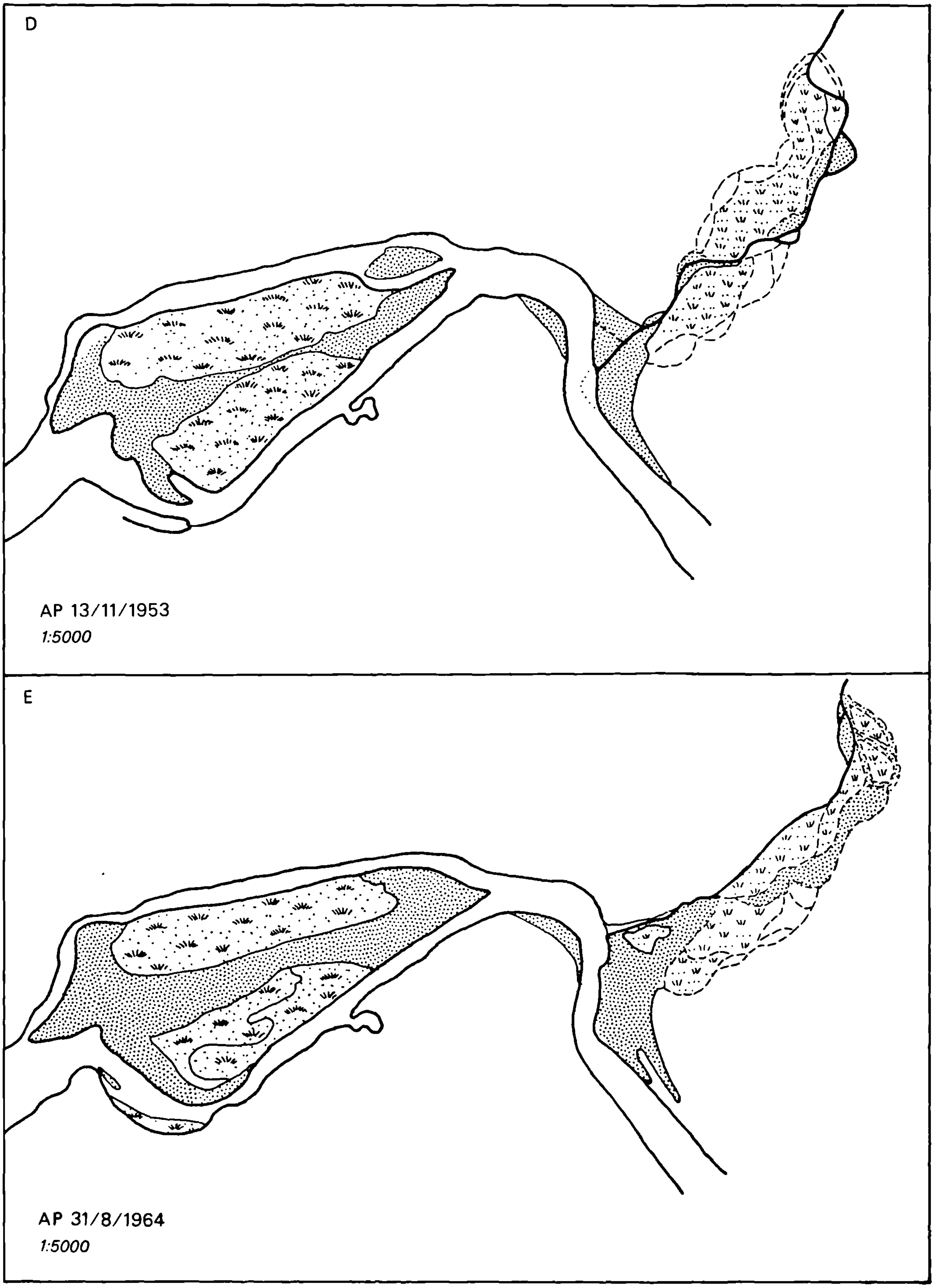
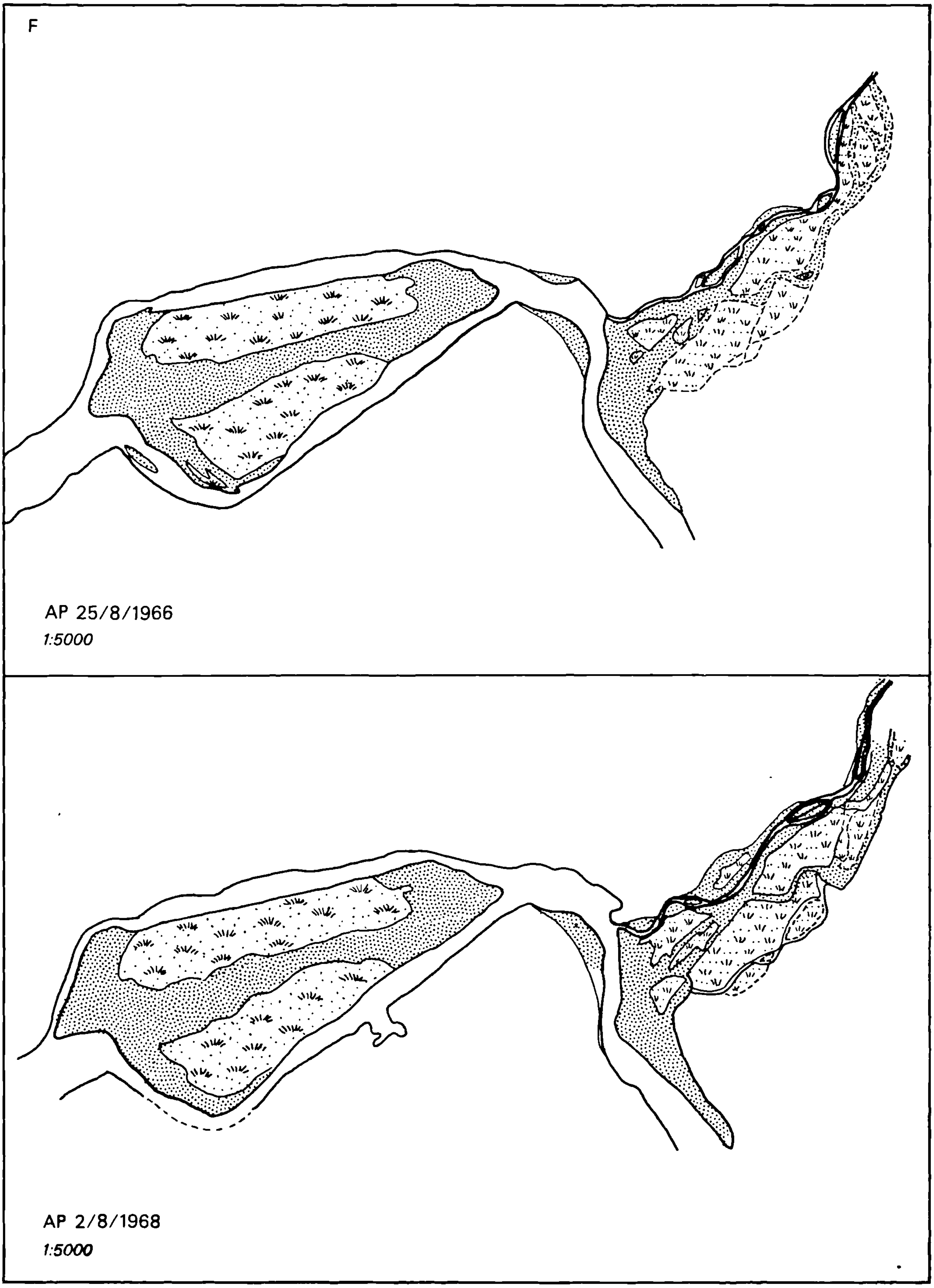


Figure 7.2.3.(i) cont.

Dee study reach 3: The Gleann an t-Slugain confluence



The stream came directly through the farm house..." (Lauder, 1830 p372)

Over the period 1869 to 1902, a considerable shift took place, extra-channel avulsion occurring near the apex of the fan and the channel rejoining the Dee near the 1869 confluence (Figures 7.2.3.(i).B and C). This planform change may possibly be attributed to the 1885 event, which was a major storm on the neighbouring Quoich catchment. The 1869 map showed bare gravels in the locality of the 1902 channel, indicating that this "switch" must have taken place before that date, perhaps in 1829. The 1902 map as well as showing the former 1869 channel, also indicated extensive bare sediments upstream. These gravels, probably flood deposition, indicated that a minor extra-channel avulsion must have taken place before or during the major change, noted above. The 1885 event on the Quoich (24 hour rainfall RI of 200 years at Braemar) is again the likely cause of this disruption. Between 1869 and 1902, there was no change in sinuosity, however the braided index showed a minor increase from 1.06 to 1.09.

By the first aerial photograph (13/11/1953), the main channel had partially returned to its 1869 course, with a major channel shift and increasing sedimentation at the confluence (Figure 7.2.3.(i).D). The active area and former channel had been revegetated and thus planform disruption had not occurred recently. Perhaps this channel switch can be attributed to the 1920 or 1937 floods.

In contrast by 1964, a reduced sinuosity channel followed a similar course to the 1902 channel (Figure 7.2.3.(i).E). Clearly, either internal thresholds have been crossed, or some geomorphic stress triggered the channel switches. The only extreme flood event which may have affected the Gleann an t-Slugain between 1953-1964 was that of Aug, 1956 (13/8/1956; 24 hour rainfall RI at Derry Lodge was 120 years). Between 1964 and 1966, there seemed to be a more gradual reworking of gravels in the channel and by 1971, the flow was still in the same 1964 alignment. More moderate flows thus allowed more localised planform shift and bank erosion. Between 1902 and 1969, again sinuosity remained similar but there had been a slight increase in BI from 1.09 to 1.14, perhaps reflecting a gradual accumulation of sediment stored in the fan.

Field checking in 1983/1984 showed the river still to be occupying its 1964 channel. The bed and the bars of the former channel have been gradually colonised by grass and pine sapplings, making the thresholds involved in reoccupation and reworking larger. Unfortunately, the Invercauld estate considered that the channel had accumulated too much sediment, with the result of continual flooding over their agricultural land. Every time the Dee rises, it also floods this area. The channel was thus bull-dozed in 1984, right through to the confluence (Plate 7.2.3.(i)). It would be interesting to see how long it takes to incorporate this major disruption to the natural system. It is likely that reworking will not take long, as clasts have been merely bull-dozed into banks by the channel-side, rather than removed. Higher flows should have the competence to undermine this.

Plate 7.2.3.(i)

Bulldozing of the Gleann an t-Slugain fan

Before: in June, 1983 (with evidence of earlier artificial removal of sediment from the channel)

After: in July 1984

Thus channel shift, although constrained in the upper reaches, seems to take place in a well-defined area, even where controls are relaxed. There is a tendency towards avulsion and reactivation of old channels, rather than a gradual reworking of channel sediments. The Gleann an t-Slugain seems to change its planform alignment on average once in 30-40 years; the threshold for change is thus high, though reworking of channel-side deposits takes place during more moderate events. Intrinsic thresholds may also be important in determining which of a sequence of flood events causes a channel switch. This is due to the gradual build up or removal of the plugs of sediment in former flood channels. The concept of recovery is therefore determined by the timescale of study, as equilibrium over a longer timespan must incorporate the switch between the two alternative channels to the confluence.

7.2.4 Dee study reach 4: The middle Lui Water

The middle Lui study reach (draining 53.1 km^2) has an irregular meandering planform, working its way around hummock-shaped fluvioglacial deposits. Localised confinement is caused by steep-faced cuts into these kames, leaving precipitous faces that have to be undercut to permit channel shift. There is thus in this reach an abundant supply of stage dependent but potentially accessible sediment, from both local and upstream sources. Material is also undermined and reworked from the base of a tributary's large fossil fan, which is also locally being reworked by the regular shifting of the present-day mountain torrent

(Figure 7.2.4.(i)). Position within the channel system typology is outlined in Table 7.2.4.(i).

From the aerial photographs and map work, old palaeochannels were clearly recognisable, indicating activity pre-1869 (see Figure 7.2.4.(i).B). Roy's map (1750) indicated periodic fairly regular meanders of different sizes and account for the alignment of old palaeochannels (Figure 7.2.4.(i).A). From the first edition (1869), the Lui had a sinuous to irregular meandering planform, with the accumulation of sediment in point bars (Figure 7.2.4.(i).B). It was clear that since Roy's map (1750), within the upper reaches there has been a major cutoff. If this map can be relied upon, the meander had undergone some reduction in amplitude before being cutoff. The resulting upper planform was a large, composite, irregular meander bend. Downstream medial bars within the channel have also been reworked and the downstream meander bend appeared to have undergone rotation since 1750. It is known that during the 1829 flood event (Lauder, 1830) that the Lui was enormously swollen and thus it is likely the upstream neck cutoff occurred at this time. It seemed that sinuosities did not have to be very high for such straightening to take place. The former channel had been left as bare sediment. The BI at 1869 was 1.00 ie. no division of flow and the overall sinuosity was 1.20, considerably reduced from that of 1750.

Between 1869 and 1903, there had again been further meander migration, with the initiation of a new, low-amplitude, composite meander bend, both translated and rotated from the position of the formerly cutoff meander (Figure 7.2.4.(i).C). The meander downstream

Table 7.2.4.(i)

Position of Dee study reach 4: The middle Lui Water within the map-based channel system typology

A (a) Basin area: 53.1 km^2

(b) Average height: 410 m

	1869	1903	1971
B (a) UPSEDMT:	0	0	0
(b) LOCSEDMT:	1	1	1
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	4	4	4
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	0	0	0

E MAXWID 15

	1869	1903	1971
F (a) CHANPATT:	6	6	6
(b) ISLANDS:	1	1	1
G (a) ACTIVITY:	8	8	8

Figure 7.2.4.(i)

Dee study reach 4: The middle Lui Water

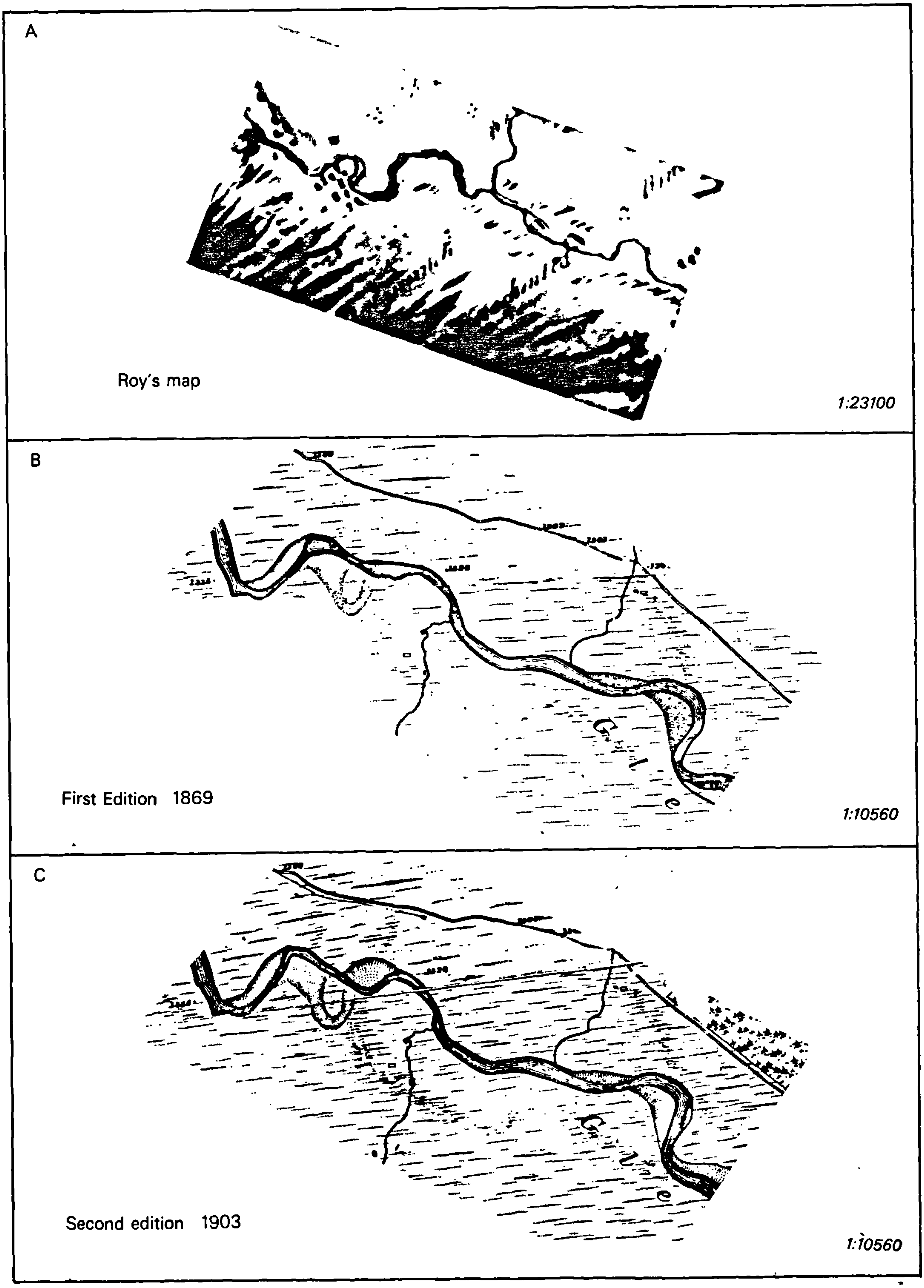


Figure 7.2.4.(i) cont.

Dee study reach 4: The middle Lui Water

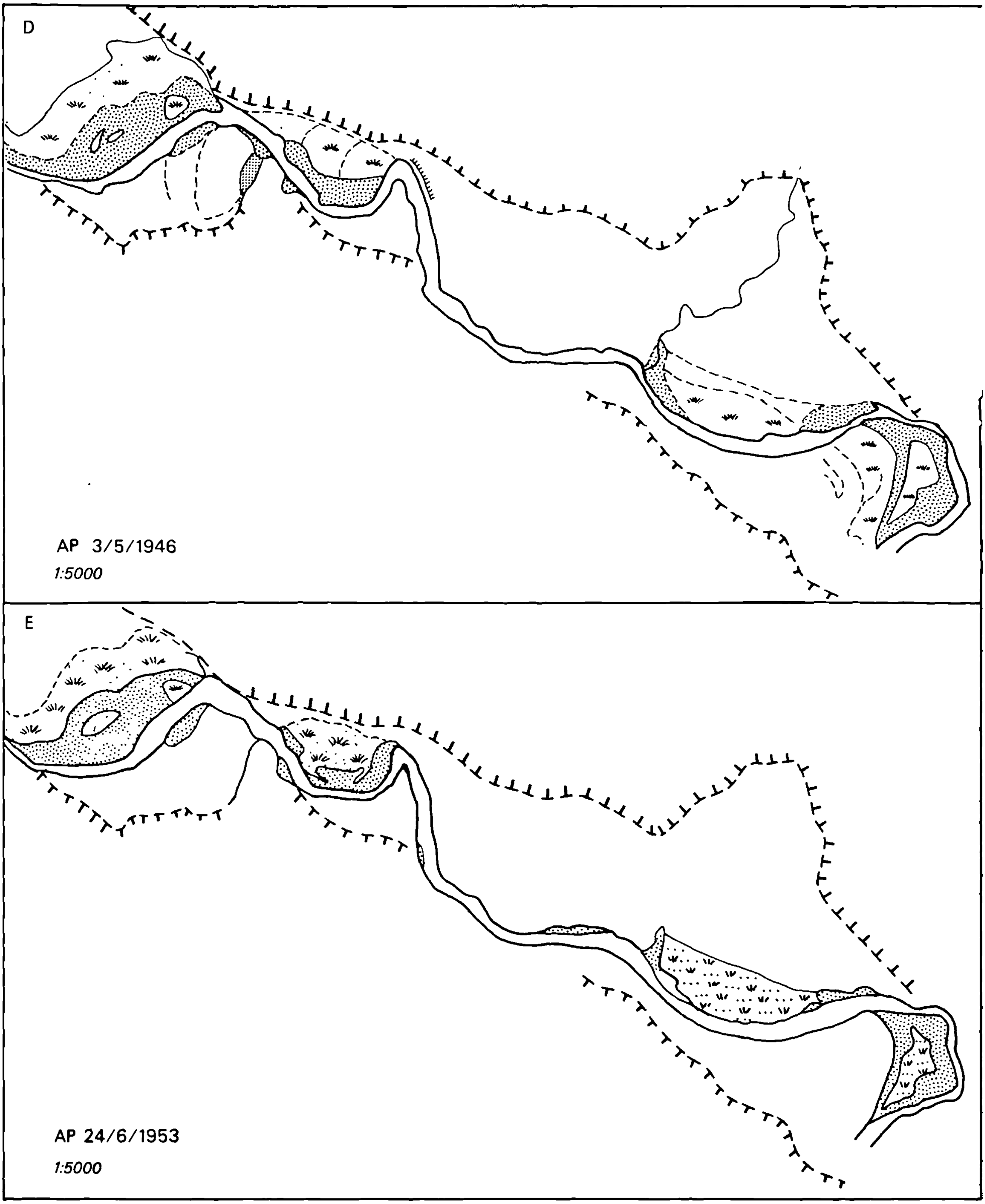
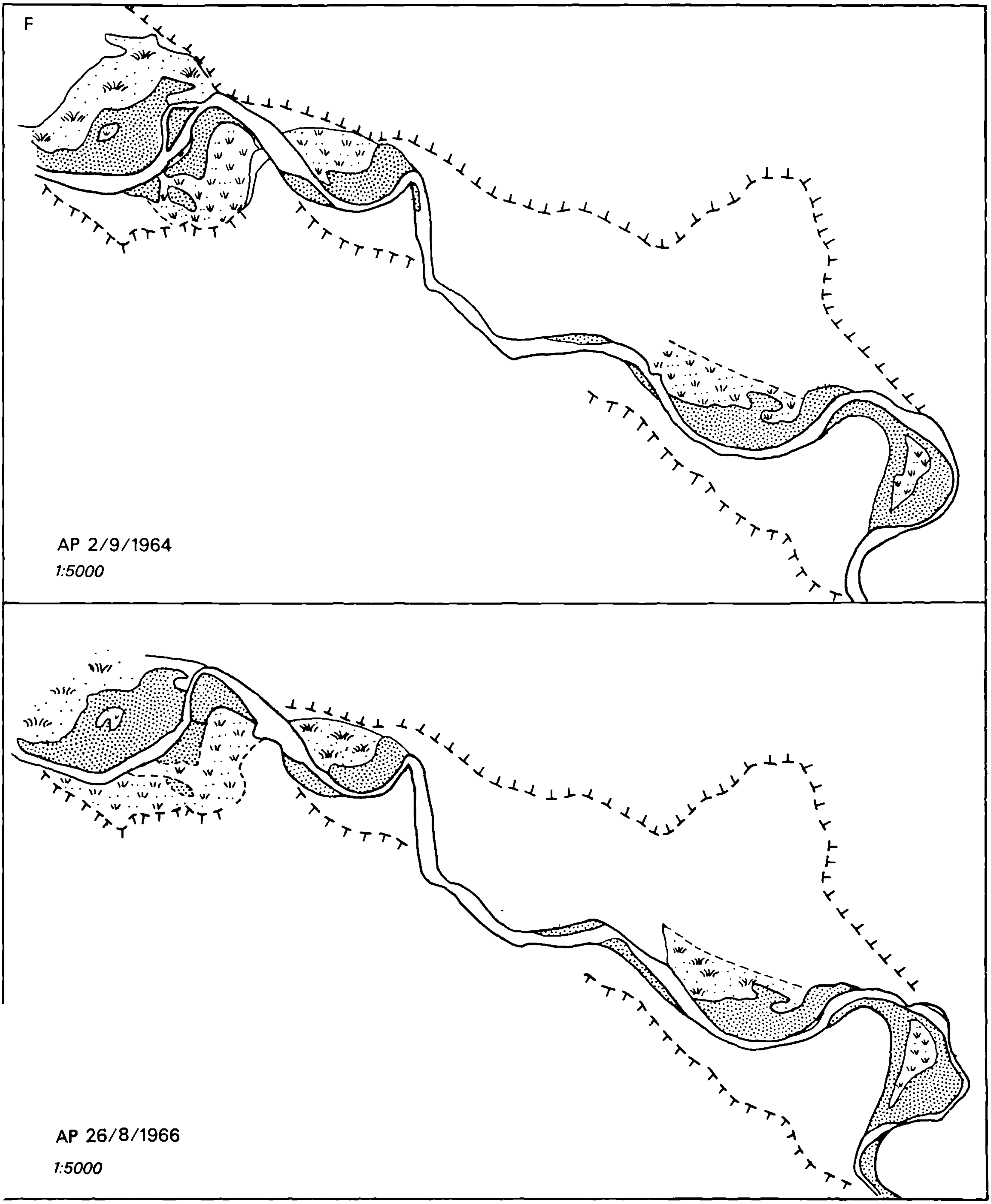


Figure 7.2.4.(i) cont.

Dee study reach 4: The middle Lui Water



had also been slightly enlargened. Thus, different areas within the irregularly meandering planform may clearly be at different stages of development, depending on the degree of cross-section confinement. Overall sinuosity for the reach had however increased from 1.20 to 1.24.

If the upstream composite meander can be subdivided into peaks, there had been a reduction of the first peak and an enlargement of the second, between 1903 and the 3/5/1946 aerial photograph (Figure 7.2.4.(i).D). This had to occur within the limits imposed by the undercutting of the west-ward kame deposits. If the rates of change within the less confined meander bends can be extrapolated, two separate meander bends would have developed, had the kame exposure not restricted movement. The meander feature further downstream underwent extension and rotation. There was also stabilisation of active gravels increasing with distance from the present channel. This pattern persisted with only minor modification by 24/6/1953 (Figure 7.2.4.(i).E).

Between 24/6/1953 and 2/9/1964, there was a major flood event on the Lui. In Baird and Lewis's (1957) report of flood disruption within the upper Lui catchment, "heavy flood deposition" was recorded all along this reach. Further down:

> "The Black bridge which carries the road way was damaged but not destroyed... its centre pier, undercut by the torrent, settled about 6" [0.15 m] to a foot [0.3 m] and moved a similar distance downstream." (Baird and Lewis, 1957 p92)

Changes in channel planform, 8 years later, however seemed slight (Figure 7.2.4.(i).F). If there had been any disruption of planform, it had recovered over that period; clearly no cutoffs had occurred, although the old meander palaeochannel had been reused. This suggests that in this reach, in contrast to the upstream reaches on the Luibeg (Dee study reach 6), even a stress of high magnitude was unable to push the river across a major threshold, mainly because of channel confinement. There had been some translation and rotation of the pre-existing meander bends and also an increase in the unvegetated active area proximal to the channel due to flood sedimentation, with reworking of point and lateral bars. Some vegetated banks, especially near the point bars had been trimmed back and even bar stabilisation was slow.

Over a period of 2 years (2/9/1964-26/8/1966), there was localised erosion, particularly accentuating the meander bends, though no major flood was known to have occurred. More moderate flows must therefore have a geomorphic impact in terms of gradual bank erosion and restabilisation.

The last record is the third edition (1971) map where the overall increase in sinuosity since 1903 was from 1.24 to 1.27. Again, the overall irregularly meandering planform is maintained. Field survey revealed localised undercutting of kame deposits and slumping of banks, indicating some gradual planform alteration. In general however, present rates of change seem slow in comparison to those indicated pre-1900 and no major cutoffs have occurred this century. The thresholds for such planform change must therefore be high, occurring only once in 250 years. The incipient meander cutoff conditions have not developed due to resistant terrace material and channel confinement, though sinuosity has increased since 1869. Even an extreme extrinsic stress, such as occurred in Aug, 1956, was unable to upset the apparent stability of the system.

7.2.5 Dee study reach 5: The Clunie Water below the Baddoch Burn confluence

This study reach (draining 27.7 km^2) is situated in the middle reaches of the Clunie Water below the confluence with the Baddoch Burn. In terms of channel description, this channel falls into the straight/ sinuous to wandering categories and although activity rates do not compare with those of active gravel fans in the lower reaches, the Clunie appears to have been quite active in its reworking of floodplain. Position within the channel system typology is outlined in Table 7.2.5.(i).

From Roy's map (1750), the study reach was shown as being sinuous but also split in one large anabranch downstream. There was high sinuosity indicated in the main channel side of this anabranch (Figure 7.2.5.(i).A). By the first edition (1869), the main channel had lessened its length, smoothing out the irregular meanders with a much less sinuous (1.10) and direct channel. The westward channel was now disused but half way along, had been incorporated into the artificial drainage system (Figure 7.2.5.(i).B). At least one major flood event (Aug, 1894- 24 hour rainfall RI approximately 15 years at Braemar) is

Table 7.2.5.(i)

Position of Dee study reach 5: The Clunie Water below Baddoch Burn confluence within the map-based channel system typology

A (a) Basin area: 27.7 km^2

(b) Average height: 455 m

	1869	1902	1971
B (a) UPSEDMT:	0	0	0
(b) LOCSEDMT:	0	0	0
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	4	4	4
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	0	0	0

E MAXWID 25

	1869	1902	1971
F (a) CHANPATT:	2	2	4
(b) ISLANDS:	1	1	1
G (a) ACTIVITY:	1	1	1

Figure 7.2.5.(i)

Dee study reach 5: The Clunie Water below the Baddoch burn confluence

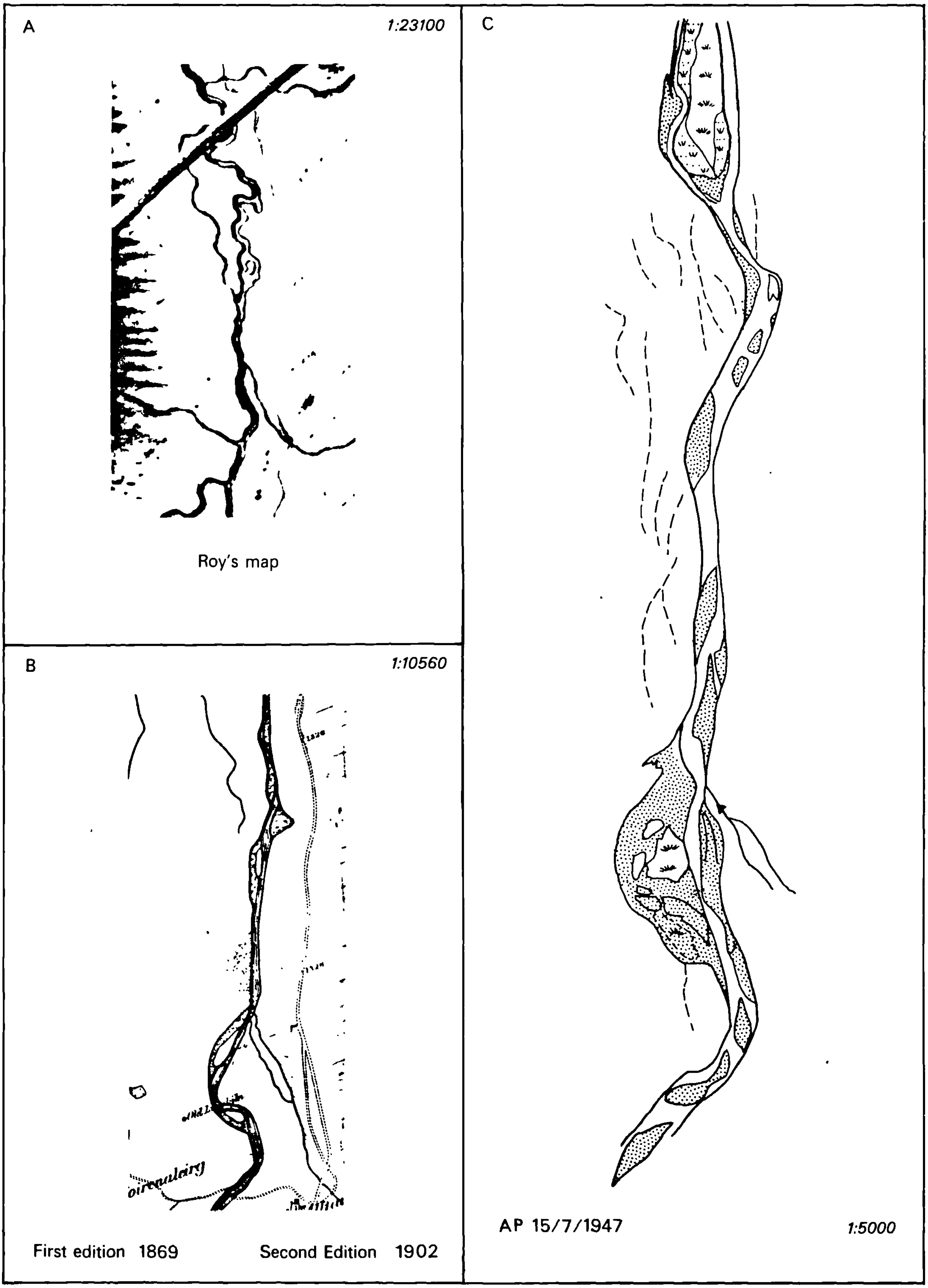
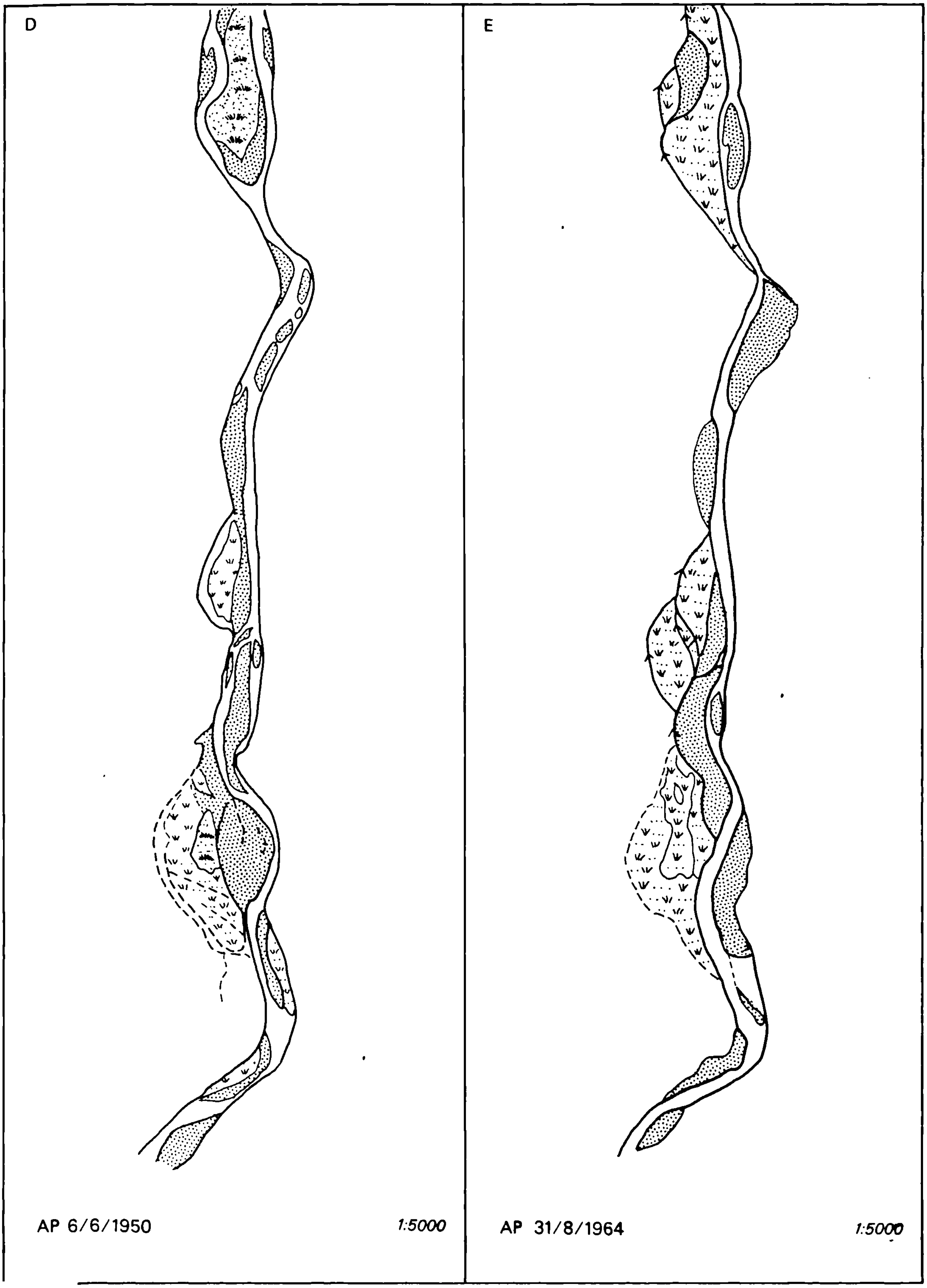


Figure 7.2.5.(i) cont.

Dee study reach 5: The Clunie Water below the Baddoch Burn confluence



reported between the first and second edition maps, but this seems to have had little geomorphic impact or effectiveness in terms of channel planform adjustment. Changes indicated both upstream and downstream confirmed that it was not merely that the area had not been resurveyed. The channels were depicted as following exactly the same course and clearly it was possible for moderate to large flows to be contained within the equilibrium channel planform.

Between the second edition and 15/7/1947, the channel had shifted in two major places, developing a more wandering planform (Figure 7.2.5.(i).C); upstream it had straightened its course, cutting through a low amplitude meander and it is possible this was its former course around the 1750s (Roy's map). This change may be partially caused by a change in flow stress with the shift in the confluence of the Allt a' Mhaide (a tributary entering from the lower left) with the Clunie, which by 15/7/1947 joined by a more direct course. Further downstream, there was another distinct change where the channel had undergone an extra-channel avulsion. The vegetation on the resulting medial bar seemed quite stable and these changes may be attributable to the 1-6th Oct, 1920 flood and to 24th Jan, 1937 (see Figure 5.4.1.(iv) and Appendix 1.2). These were clearly major flood events over this catchment, with high rainfall and runoff RI, as seen from the storm profile reconstructions (Figure 5.4.8.(iii) to (v)).

Between 15/7/1947 and 6/6/1950, areas which were left unoccupied since the last major flood event had become more stabilised (Figure 7.2.5.(i).D). In the upper reaches, there had been a further shift east of the main channel and a consequent further widening of the active area, with new medial bars. More moderate flows can thus cause considerable bank erosion. By 31/8/1964, the river had started to rework its upper area, encroaching on to areas previously restabilising (Figure 7.2.5.(i).E). Some old flood channels were reactivated to take secondary channels and to give a more anabranching pattern. Similarly, the downstream split channel of 1947 to 1950 had been disrupted into a much more anabranching planform through minor extra-channel avulsion. However, which anabranch contained the major flow seemed to be related to the angle at which the river channel enters this change sensitive area.

A major flood event must have occurred between 1950 and 1964 as the channel planform has expanded to cope with a much larger discharge, through the activation of old flood channels as well as the excavation of new ones. This may be attributed to 4-5/11/1951 (48 hour rainfall RI at Braemar of 6 years) or 19/1/1960 (with a 24 hour rainfall RI at Braemar of 8 years) storms but there was not a large RI rainfall event recorded at Braemar. This could suggest that more moderate floods have the ability to cause localised planform change. Rainfall however may have been greater at higher altitudes and the impact of convective storms cannot be discounted.

Field surveying showed that banks were frequently at a low level in relation to normal flow conditions, and from field reconnaissance it appeared that past flood channels become quickly reused at high stages rather than subject to a gradual reworking ie. BI was highly stage dependent. Frequently mid-channel bars were stabilised by vegetation and these showed evidence of high suprabar sedimentation. In contrast upstream, where the channel was steeper and confined by a higher first terrace, the channel seemed more stable.

Thus, it seems here that the geomorphic effectiveness in terms of the disruption caused by the 1920 and 1937 events event is short-term and the wandering channel has to a large extent recovered a quasi-equilibrium condition. More moderate events seem to have localised but important impact in planform change causing minor extra-channel avulsions. They are also capable of returning a split channel to a single channel form, plugging up former anabranches with sediment. This impact depends on whether the active area is expanding or contracting, controlled by the interarrival time of the last disruptive event. The Invercauld estate manager (pers. comm. Mr. Petrie) reported that the upper Clunie frequently altered its planform during winter spates and thus the thresholds for change are not high.

7.2.6 Dee study reach 6: The Luibeg Burn

The Luibeg Burn, a mountain torrent with a catchment area of 14.6 km^2, debouches from below the Parker Memorial footbridge. This is accompanied by a sudden increase in the area of adjacent floodplain, thus creating room for channel migration. Glen Luibeg contains large kames and other fluvioglacial features and these were formerly controlled by a large rock-cut meltwater channel, providing an abundance of both local and upstream sediment. This study reach falls into the sinuous category of the channel pattern classification and position within the channel system typology is outlined in Table 7.2.6.(i). It

Table 7.2.6.(i)

Position of Dee study reach 6: The Luibeg Burn within the map-based channel system typology

A (a) Basin area: 14.6 km^2

(b) Average height: 465 m

	1869	1902	1971
B (a) UPSEDMT:	0	0	0
(b) LOCSEDMT:	3	3	2
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	2	2	2
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	8	8	0

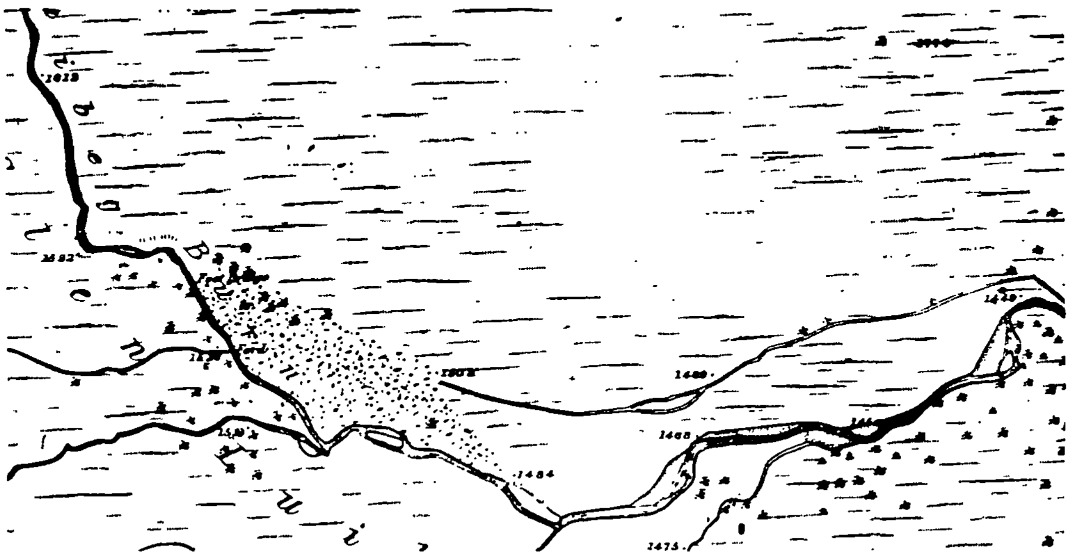
E MAXWID 30

F (a) CHANPATT:	3	3	3
(b) ISLANDS:	2	2	1
G (a) ACTIVITY:	2	2	2

Figure 7.2.6.(i)

Dee study reach 6: The Luibeg Burn

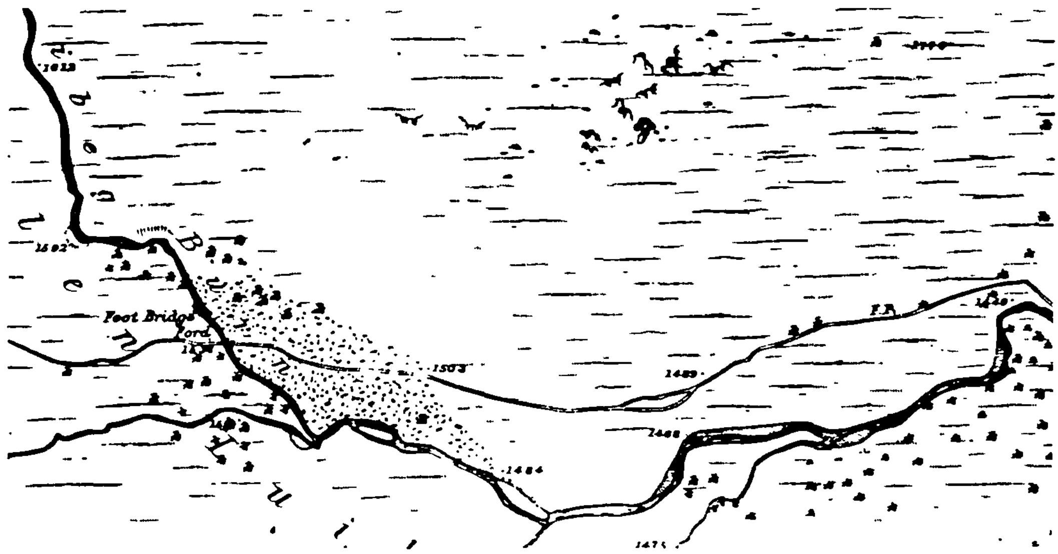
A



First Edition
1869

1:10560

B

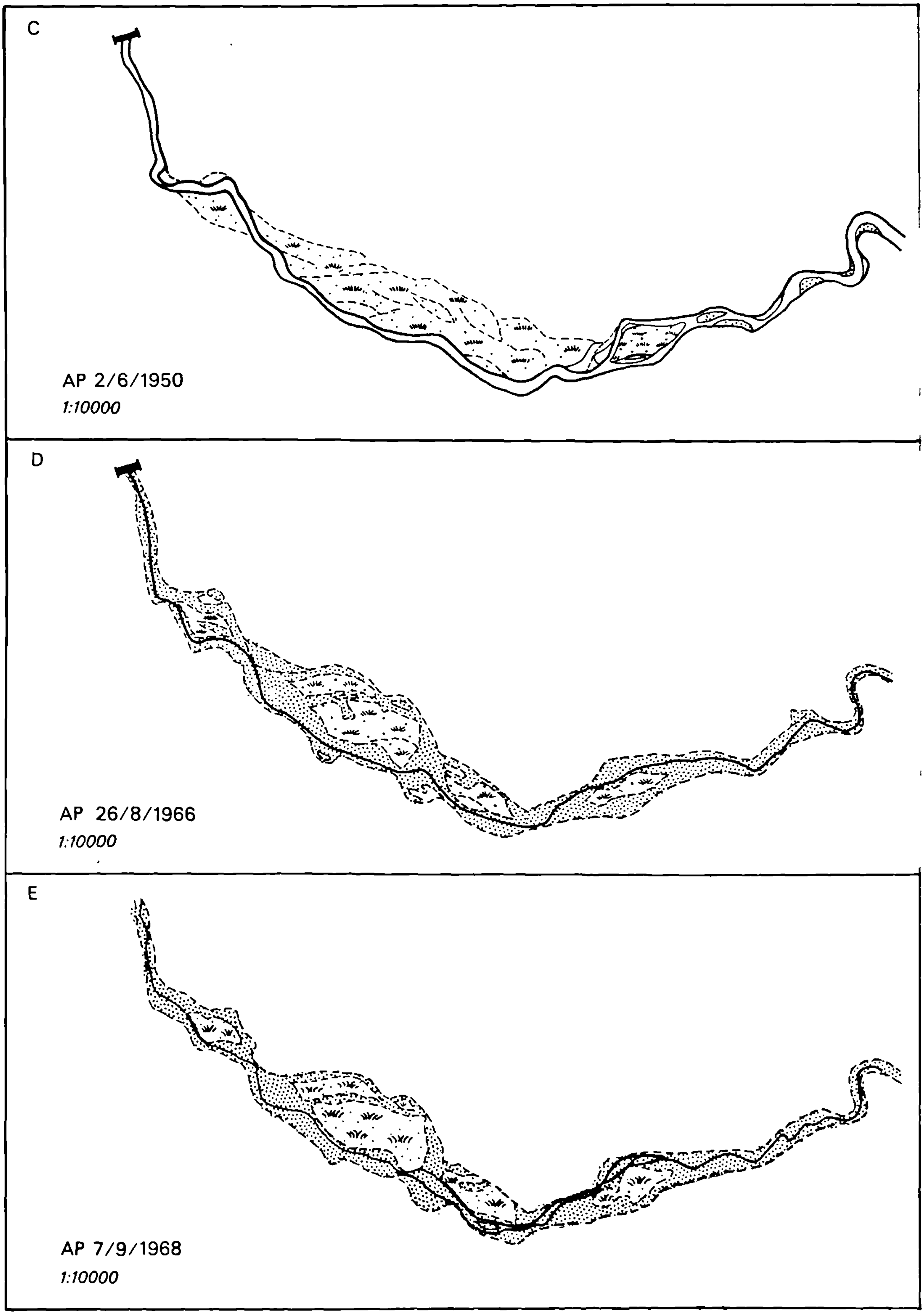


Second edition
1902

1:10560

Dee study reach 6: Luibeg Burn

Figure 7.2.6.(i) cont.



appears to have been quite active at some time in the past, in terms of its reworking of its floodplain. Whether this was the result of catastrophic or continual activity must be assessed from the flood record. Unfortunately, the channel on Roy's map (1750) was too distorted to assess the planform type with any accuracy.

Both the 1869 and 1902 editions of the O.S. map indicated a similar channel planform (Figure 7.2.6.(i).A and B). A large sheet of gravels was indicated to the north of the study area. This had obviously wiped out the footpath on the 1869 map; the force bringing down such extensive amounts of sediment can be attributed to the 1829 event (see also Appendix 1.1.1), as it is known that debris flow activity was activated on Ben MacDhui from the following report:

> "In many places the declivities are seamed with trenches some 40 or 50 feet [12-15 m] deep, appearing as if they were made by a gigantic ploughshare, which instead of sand, casts up huge masses of rock on either side in parallel mounds, like the moraines of a glacier. There are many of these furrows on the side of Ben MacDhui, nearest the Dee. Though I had long noticed them, it was not until I happened to be in that district immediately after the great floods of 1829, that I was forceably told of the peculiar cause of this appearance. The old furrows were as they had been before, the stones, grey, weatherbeaten and covered with lichen while heather and wild flowers grew in the interstices. But among them were new scaurs, still like fresh wounds, with the stones showing the sharpness of late fracture and no herbage covering the

blood-red sand. It was clear from the venerable appearance of the older scaurs, that only at long intervals do the elements produce this formidable effect, at least many years had passed since the last instance before 1829 had occurred". (Burton, 1864 pp69-71)

The sinuosity of the Luibeg reach, which falls in two sample grid squares, remained similar at both 1869 and 1902 with 1.11 upstream and 1.19-1.17 downstream. Braiding indices were also broadly comparable over this timespan (1.05-1.00 and 1.26-1.26). The first aerial photograph (2/6/1950) showed in the upper reaches that the river formed a single channel with the occasional minor bars of 1902 now forming part of the bank (Figure 7.2.6.(i).C). This same photograph also picked out the lines of some major flow that had taken place (pre-1869) but the gravel area was now stabilised. Downstream however, the channel split into two anabranches around a stable bar, but elsewhere the channel seemed to be quite stable ie. no fresh sediment. Despite the 1908 event (Figure 5.4.1.(ii), with its high rainfall RI, there was no major disruption of the channel. This may have been because it was a longer duration 48 hour event, and thus the instantaneous discharge would have been less and major sediment entrainment thresholds were not exceeded.

Between 2/6/1950 and 26/8/1966, it was clear that a major transformation had taken place; the entire potential active area had been reworked and considerably widened due to extensive bank erosion, with a series of flood channels of a large magnitude (Figure 7.2.6.(i).D). However, on comparing these lines of flow with the previously mentioned historic palaeochannels (perhaps 1829?), it is seen that the flood channels had been flushed out along these lines of weakness. Large areas of the floodplain were now unvegetated gravels and flow, although now retained within the line of the 2/6/1950 channel, was chaotic and shallow around the new gravel bars. Within the alignment of the main channel, the active area had increased in width 2-4 times. Fortunately, the storm which caused such a major disruption to flow was documented by Baird and Lewis (1957) as being on the 13-14th Aug, 1956, with a fall of 3.37 in (85.6 mm) in 24 hours at Derry Lodge and an estimated rainfall RI of 120 years. Rainfall may however have exceeded 6 in [152.4 mm] on the high ground and may thus be associated with a much higher RI. In this flood event, the Parker Memorial footbridge was carried downstream and its supporting masonary piers overturned ie. the competence was very high. The stream bed at the bridge span had more than doubled its width and downstream of this point, heavy flood deposition was recorded:

> "On the wide flat floor of Glen Luibeg about one mile upstream of Derry Lodge....flood deposition had been so active that irregular fan-shaped deposits were visibly raised above the general level of the neighbouring valley floor. The flood waters had, in places, burst the bounds of such fans and formed new channels on the lower ground on one side or the other." (Baird and Lewis, 1957 p97)

The source of much of this flood deposition was due to the reworking of upstream sediment on the Allt a' Mhaim, though debris flow activity also brought material down to the valley floor.

By 7/8/1968, the bare active areas had begun to revegetate and stabilise (Figure 7.2.6.(i).E), though the distributary flood channel pattern was still very evident. The increased active area still remained in post-flood dimensions but the percentage of the channel width containing the normal flow had decreased considerably. The 1971 map still showed a single sinuous channel surrounded by flood gravels. Even the major anabranch's flow had reverted to its old channel and the banks and floodplain were indicated as covered with heath. Despite such a major disruption to the system, the sinuosity did not change significantly. The floodplain was disrupted and reworked with the channel widened, rather than altering the actual line of flow. However, downstream BI did change from 1.26 to 1.05 between 1902 and 1971, though presumably this change was concentrated in time between 1956 and 1971.

Field survey revealed a wide area with large boulders well above the normal competence of the river flow and spread considerable beyond the present contained channel. Large numbers of disused flood channels occurred across the floodplain, well above the height of normal flow (Plate 7.2.6.(i)). The discharge required for reoccupation must be very high, as occurred in the catastrophic event of 1956, with normal to moderate flows having little geomorphic impact, being well-contained within the wide post-flood channel.

Plate 7.2.6.(i)

Extensive flood sedimentation on the upper Luibeg

7.2.7 Dee study reach 7: Upper Glen Derry

The upper Glen Derry reach falls within the irregular meander to tortuous meander categories of channel pattern description, but with occasional bar features. There are low slopes and high availability and accessibility of sediment, both within the channel bed and at its margins. This material is derived as the river reworks the surficial material of an alluvial basin, with a locally restricted baselevel (Figure 3.2.3.(i)). Position within the channel system typology is outlined in Table 7.2.7.(i). Large numbers of palaeochannels indicating extensive past reworking of the floodplain, are seen from aerial photograph evidence (see Plate 7.2.7.(i)).

On Roy's map (1750), a highly meandering planform was depicted, though too distorted for comparison. However, it was clear from standing water and abandoned areas of gravel/sand deposits on the first edition map that movement and migration had occurred pre-1866 (see Figure 7.2.7.(i).A). The river obviously at earlier times had reworked a large portion of the floodplain. The palaeomeanders seemed to be of a more typical meander type with high banks, while those today have shallow point bars. For example, a large meander cutoff obvious on the aerial photographs and the second edition map clearly developed pre-1866 (Figure 7.2.7.(i).B). Tentatively, it is suggested that a large amount of channel widening took place in Aug, 1829, changing the character of the meander planform. Thereafter, the channel form was related to higher flows, with increased amounts of sediment moving through the channel. The importance of local baselevels can also be seen with an upstream irregularly meandering, split/braiding planform associated with

Table 7.2.7.(i)

Position of Dee study reach 7: The Derry Burn within the map-based channel system typology

A (a) Basin area: 14.1 km^2

(b) Average height: 500 m

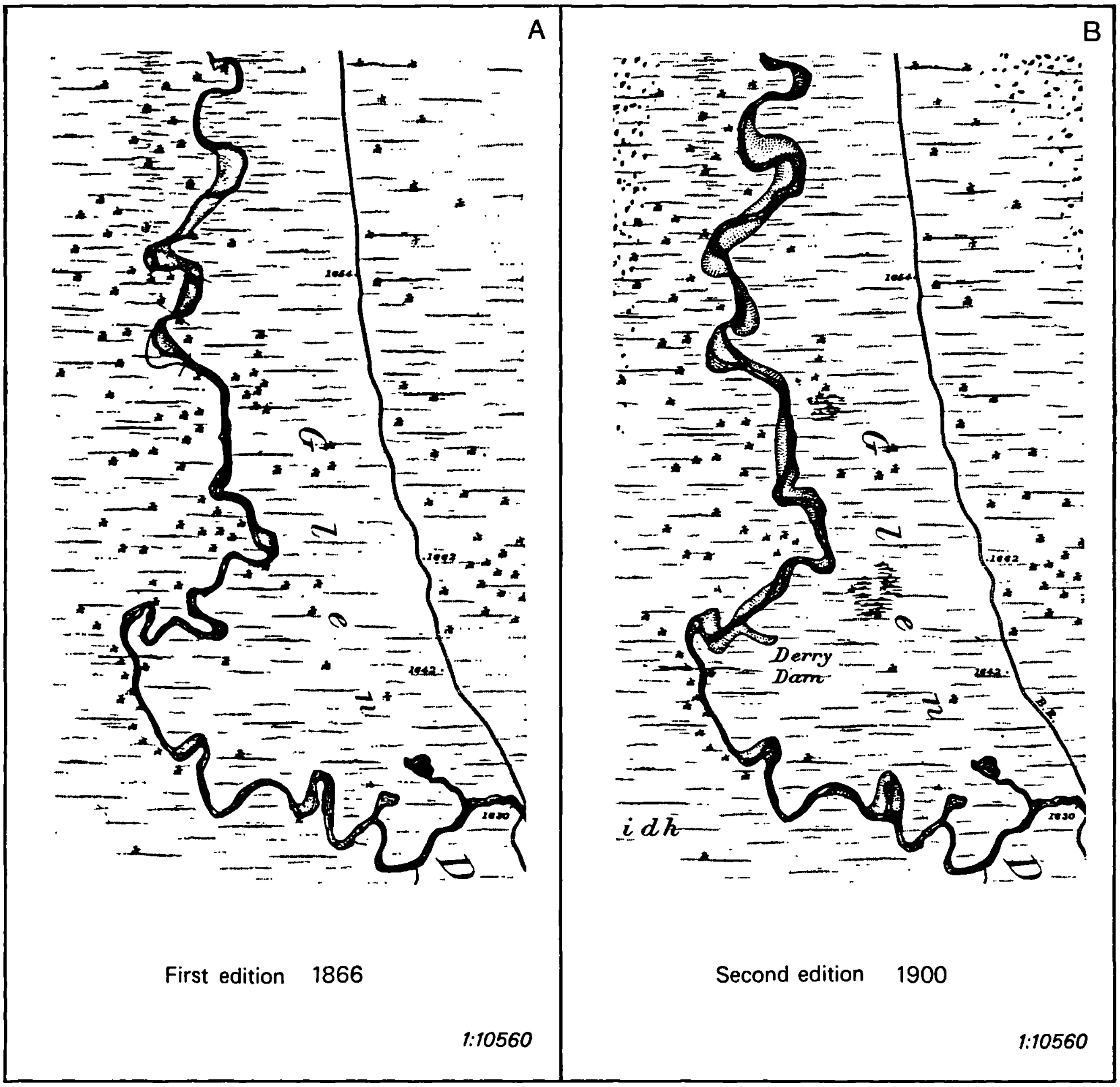
	1866	1900	1971
B (a) UPSEDMT:	2	2	2
(b) LOCSEDMT:	3	3	2
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	2	2	2
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	8	8	8

E MAXWID 52

F (a) CHANPATT:	6/8	6/8	6/8
(b) ISLANDS:	2	2	2
G (a) ACTIVITY:	8	8	8

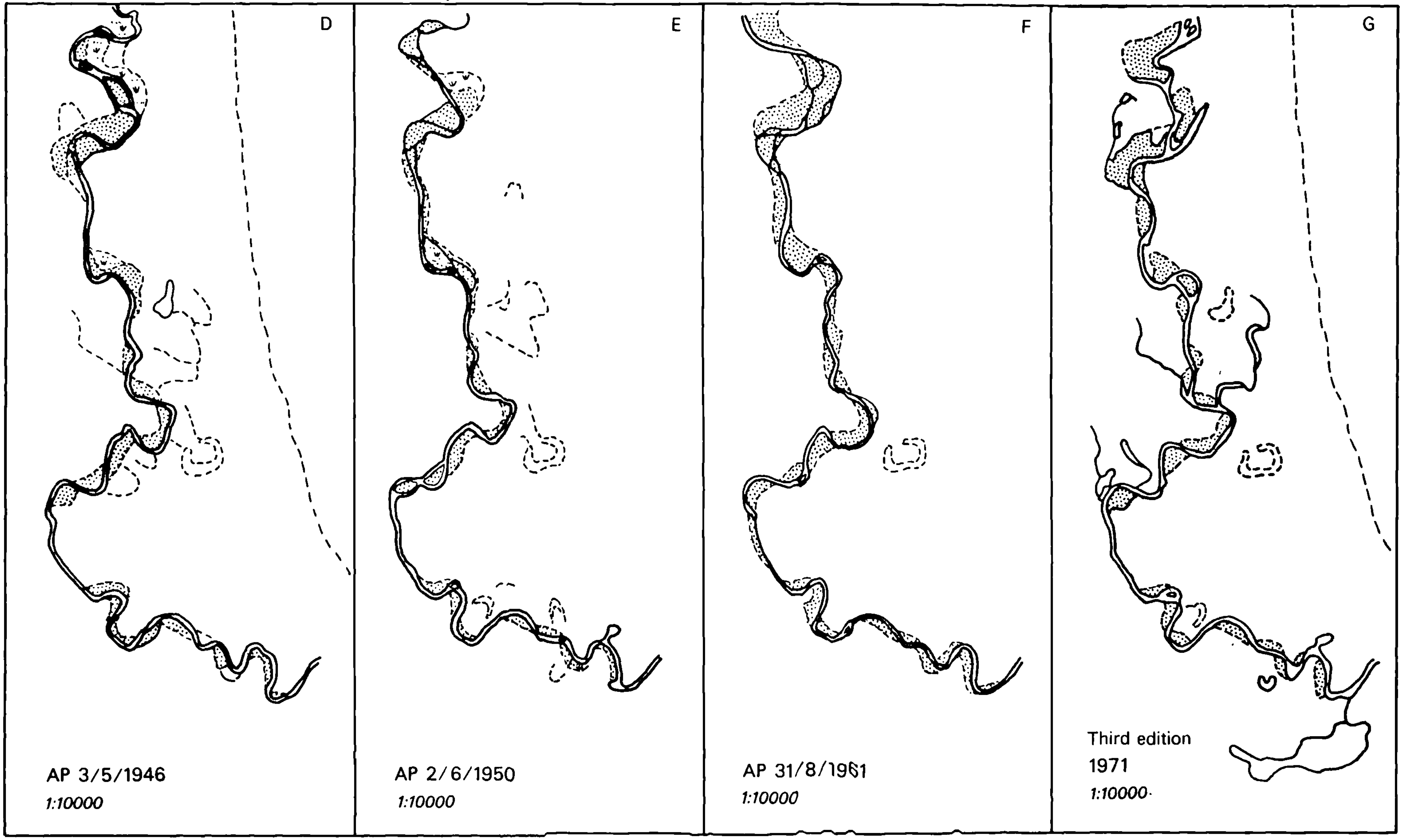
Figure 7.2.7.(i)

Dee study reach 7: Derry Burn



Dee study reach 7: Derry Water

Figure 7.2.7.(i) cont.



higher slopes, and downstream tortuous meanders, with fewer bars, where slope is lower and grain size smaller.

Between 1866 and 1900, there was a decrease in sinuosity from 1.75 to 1.63. Three meander necks, including one composite, have been breached since 1866, leaving areas of gravel distant from the channel, which have since been stabilised. By 1900, the tendency was for a single channel to develop as opposed to localised switches of two channels around a gravel bar. This coincides with the increased frequency of rainfall POT events recorded at Braemar and clearly the channel was highly active at that time. This activity was not in the sense of major planform disruption but rather large-scale reworking and accumulation of channel side material (see Figure 7.2.7.(i).B).

With the first aerial photograph (3/5/1946), the tortuous nature of the channel had become more subdued and the channel seemed to shift locally, through contained expansion and translation, within the active gravels between its banks rather than initiating new meander bends (Figure 7.2.7.(i).C). In the four years between 3/5/1946 and 2/6/1950, there had been localised switching between a divided and undivided channel, particularly in the upper reaches (Figure 7.2.7.(i).D). In fact, two divided reaches occurred in contrasting positions in 1946 and 1950. The positions of stream undercutting and point bars, in the process of building up, were however at similar positions. The channel thus appears to be in a quasi-equilibrium condition.

Between 2/6/1950 and 3/8/1961, the active area had widened in many places with lateral bars reworked, which formerly appeared to be stabilising (Figure 7.2.7.(i).E). No major changes in planform alignment had taken place despite the incidence of a major rainfall event (Figure 5.4.1.(ii)). However, the width of the active area had increased up to 3 times on some cross-sections and there was more unstabilised sediment by the channel. In Baird and Lewis's (1957) report on the localised cloudburst over the Cairngorms in Aug, 1956, Glen Derry was reported to have received less heavy precipitation:

> "But there was enough [stream power] for the burn to burst its banks on the flat north of Derry Lodge and to carve a new channel to the west, toppling pine trees in the process. After a lapse of six weeks, it had still not settled into a definite course..." (Baird and Lewis, 1957 p92).

Clearly, a major flood had occurred within this upper area and with similar source areas over Derry Cairngorm, rainfall must have been high in the upper limits of the Derry catchment. It is also recorded that an antecedent storm caused flooding that destroyed a bridge on the Derry (see Appendix 1.1). Two major floods in succession did not however precipitate any major cutoffs.

In 7/9/1968, the planform seemed to have altered little, the only apparent "recovery" being the gradual stabilisation of lateral and point bars. By 1971, the sinuosity had decreased from 1.63 to 1.57 since 1900, with a total reduction of 0.18 since 1869 (see Figure

Table 7.2.7.(i)

Tortuous palaeomeanders distant from the present channel

in Glen Derry

7.2.7.(i).F). It seemed the channel was not easily upset from what appears to be an equilibrium condition; although in the past (pre-1850) from the form of palaeochannel meanders, it was clearly more meandering. It is difficult to assess whether a major threshold has been crossed from map evidence alone but there may have been a shift in the nature of this equilibrium condition over time. This was caused by large increases in sediment within the channel, due to both the extreme Aug, 1829 event and increased instability of the floodplain associated with deforestation.

Field checking showed no major obstacles to prevent this meandering except the steep sides of the "U" shaped valley and locally low-level terrace fragments. Since 1869, it was interesting to note that though changes have taken place, the basic positioning of the channel within its floodplain is similar. This makes the timescale of past floodplain reworking interesting to contemplate.

7.2.8 Dee study reach 8: The River Dee by Clunie Cottage

This study reach on the mainstream Dee (draining 481.2 km^2) was chosen because it has features both braiding and meandering planforms, distinctly separate but in close proximity. Upstream there is a wide but localised braided reach, while downstream there is a regular meander bend. Both have evolved post-1750 but at different rates. Position within the channel system typology is outlined in Table 7.2.8.(i).

Table 7.2.8.(i)

Position of Dee study reach 8: The River Dee near Clunie Cottage within the map-based channel system typology

A (a) Basin area: 481.2 km^2

(b) Average height: 315 m

	1869	1903	1971
B (a) UPSEDMT:	1	1	1
(b) LOCSEDMT:	2	1	1
C FLOOD:	3	3	0
D (a) FLOODPLN VEGETATION:	3	3	3
(b) BANK VEGETATION:	3	3	3
(c) BAR VEGETATION:	0	2	3

E MAXWID 11

	1869	1903	1971
F (a) CHANPATT:	6	6	6
(b) ISLANDS:	1	3	2
G (a) ACTIVITY:	8	8	8

Figure 7.2.8.(i)

Dee study reach 8: The River Dee by Clunie Cottage

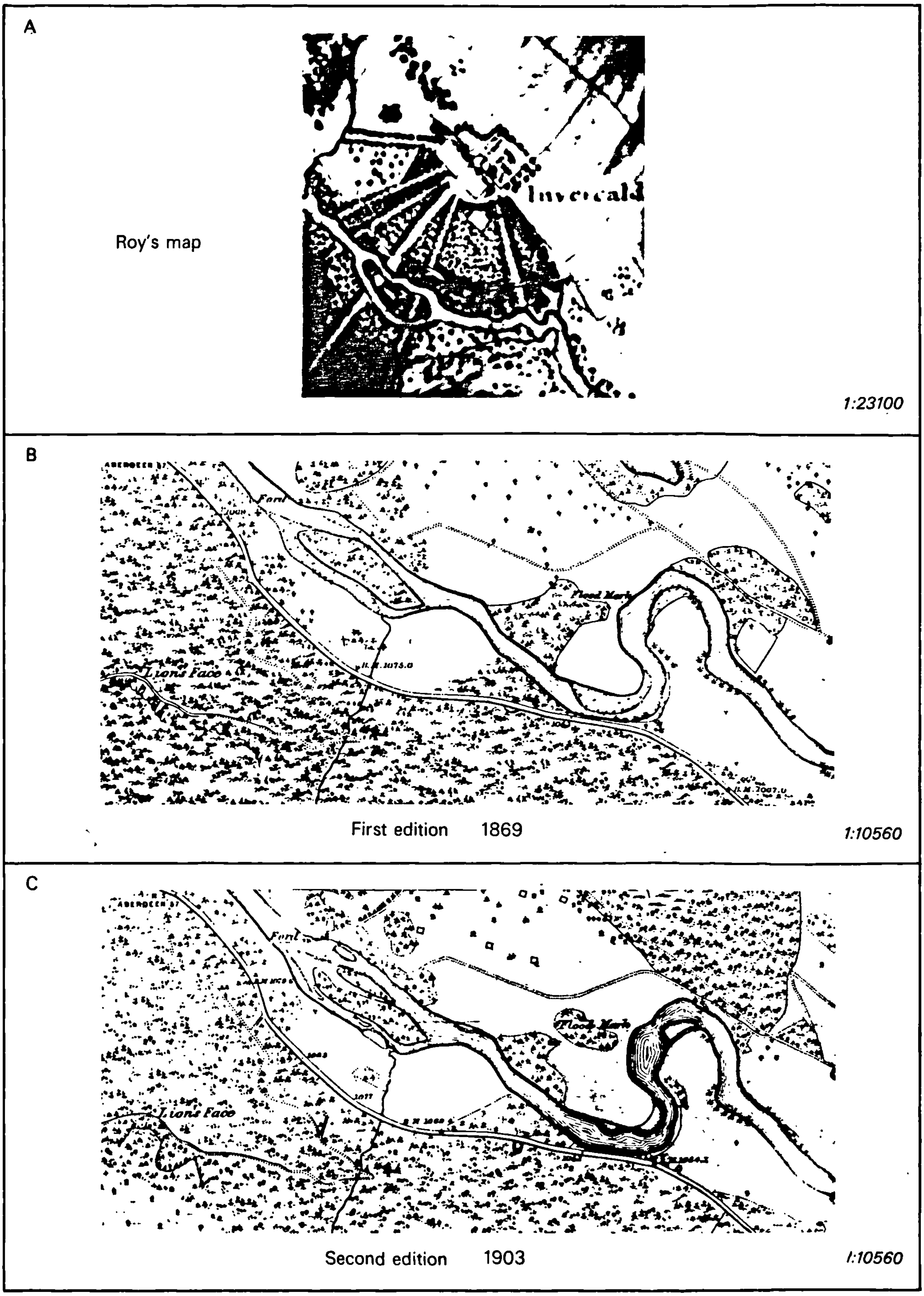
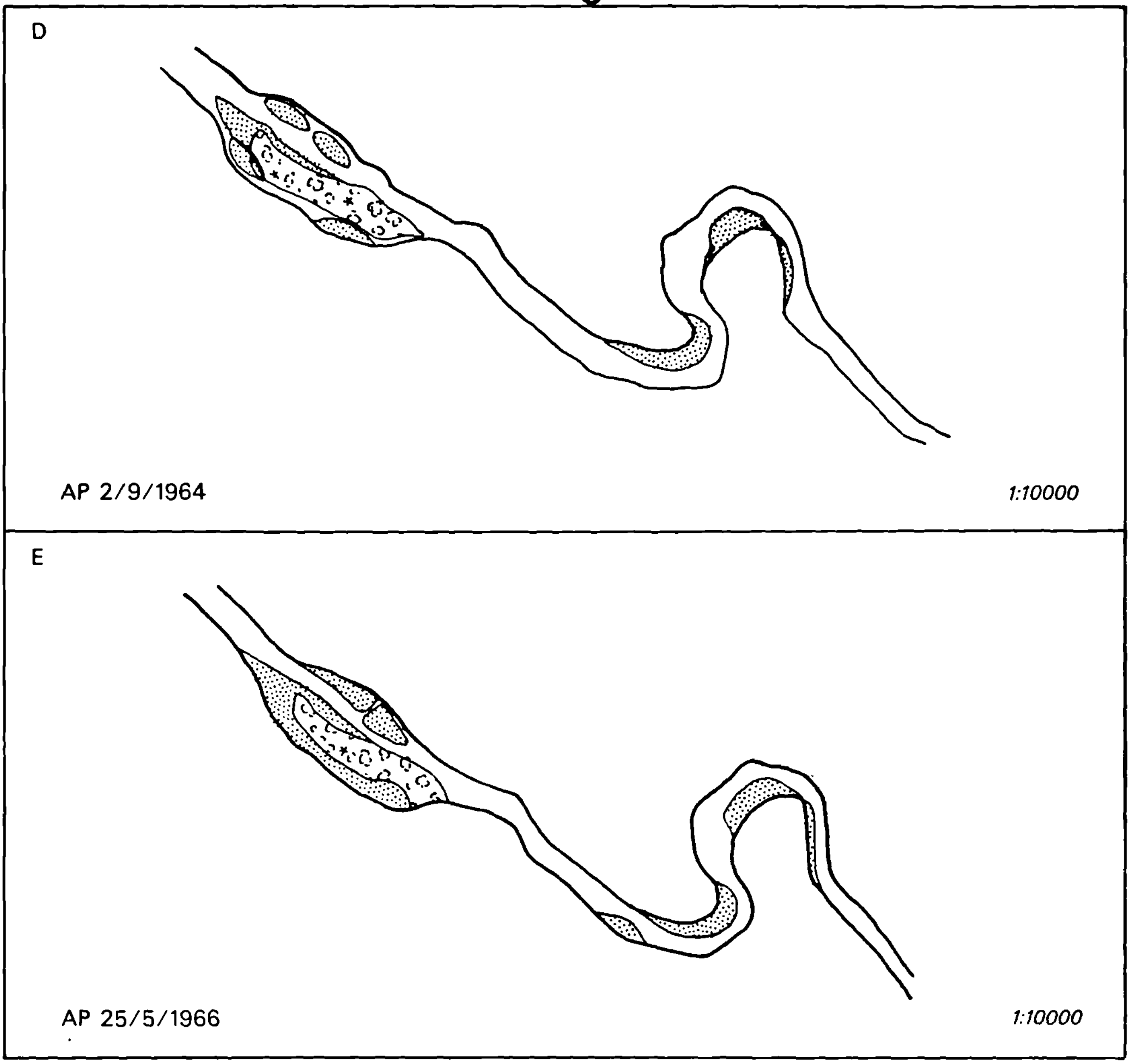


Figure 7.2.8.(i) cont.

Dee study reach 8: The River Dee near Clunie Cottage



On Roy's map (1750), the large meander bend did not exist, but upstream a stable, tree covered bar occurred around that place in the former Invercauld gardens where the present day anabranch exists. Apart from the break around this bar, the channel was sinuous. The banks form part of the Invercauld castle gardens and since these gardens continue on to the island, it may be suggested that at one time (perhaps before the 1768 event), this island formed part of the river bank ie. an undivided channel (Figure 7.2.8.(i).A). Thus, between Roy's map and the first edition, considerable change took taken place which must be attributed to the geomorphic effectiveness of the 1768 or 1829 floods. The general form may have developed post-1768, as the 1808 estate plan (RHP 3645) indicated both upstream gravels and a downstream meander feature. Lauder (1830) reports that:

> "In its progress through the park of Invercauld, the Dee was about 400 yards wide [366 m] and 14.5 feet [4.4 m] above its usual level". (Lauder, 1830 p297)

On the 1869 map, there is a flood mark probably recording the height of this flood event (Figure 7.2.8.(i).B). The 1768 event was not nearly as destructive at this reach; drawings of Invercauld House grounds in 1784 indicated that the gardens were intact (Michie, 1901).

By 1869, only one anabranch of the previously divided channel was being used and further downstream on the meander bend, large unvegetated point bars existed. The inside neck of the meander was stabilised by trees, though the top had a gravel point bar (Figure 7.2.8.(i).B). In contrast by 1903, the anabranch sub-reach had become disrupted with at least two channels being utilised along any one cross-section (Figure 7.2.8.(i).C). Small sandy bars occurred and obviously a stress had been competent enough to rip through the major 1869 bar form and redistribute the resulting mobilised sediment. Overall BI increased from 1.00 to 1.34 and the average shift in the mid-channel was 27 metres. The whole active area at this point had thus been considerably widened over this 34 year period. Similarly at the meander bend, the channel had widened and the point bar had been detached by intra-channel avulsion to form a separate medial bar. It is known from Appendix 1.1, that several moderate flood events occurred between 1869-1903, especially in the 1870s. Although not as large as in 1829 or 1937, they were of greater frequency and clearly caused considerable channel disruption within the braided area.

The planform in 2/9/1964 was even more subdivided and unstable than in 1903 while the meander point bar was slowly increasing in size and sediment was building up on the east-ward side of the bend (Figure 7.2.8.(i).D). It is known from Figure 7.2.8.(ii) that several major flood events, as evidenced by the flood plaques at Braemar, must have widened and reworked the disrupted area.

By 25/8/1966, however the braided area was only using the one channel, aligned similarly to 1903 (Figure 7.2.8.(i).E). There was a large amount of sand and gravel storage in this reach, which to a large degree seemed to be a sediment trap from sources in the upper tributaries eg. Quoich Water, and therefore regulated sediment input to the meander sub-reach. The main tree-covered island core seemed persistent through time, while on the meander bend, the point bar was gradually building up. No major flood event had occurred between 1964 and 1966 and thus more moderate flows must have the competence to rework medial bars to return the divided planform to a more simple pattern. In 1971, the river was again using only the one channel of the 1966 anabranched reach and the point bar on the meander bend was continuing to accrete. There had been minor erosion of the meander neck since 1903.

Field checking in 1984 showed further erosion through bank slumping at the meander neck. However, despite its regular appearance, the meander is partially confined, spanning the limits of the floodplain deposits, as seen in Figure 3.2.2.(ii). This explains its relative inactivity. Point bars may build up and subsequently be reworked but the thresholds for meander cutoff are high and rates of meander migration slow. The upper braided area still seems to have large reserves of unstable material. In general, rates of activity on the meander bend are much lower than on the braided reach though presumably, both reaches have undergone a similar history of magnitude/ frequency flooding relationships. The meander seems relatively stable having attained some kind of equilibrium condition while the braided area has both expanded and contacted its active area over the 200 year timespan.

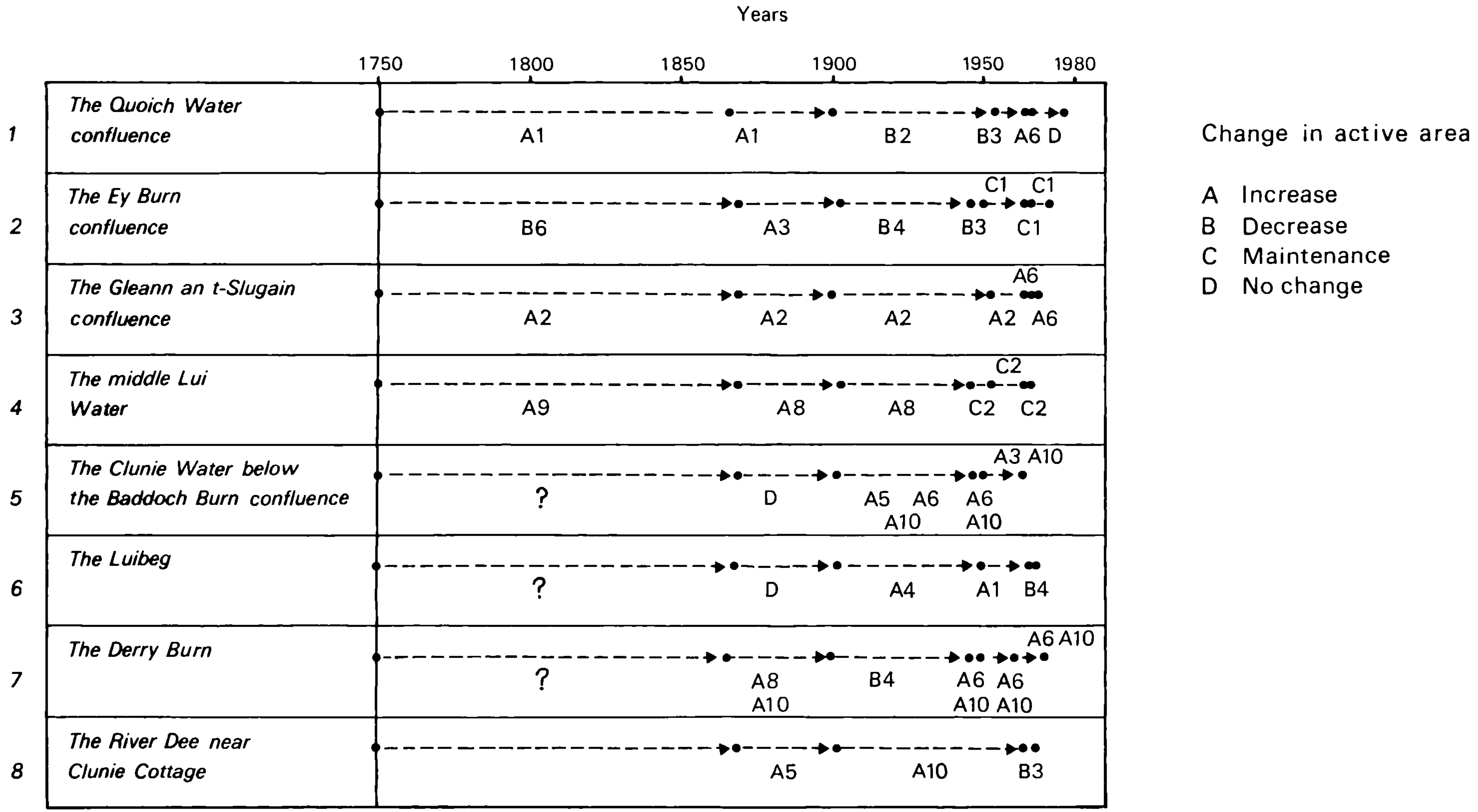
7.2.9 Summary

A summary table showing the dominant modes of channel adjustment for the Dee study reaches occurs in Figure 7.2.9.(i). Channel response to discharge events of similar magnitude can be very different depending on the position within the channel description classification, degree of confinement, channel slope, sediment size and distance of channel planform from an equilibrium condition. Within potentially active sites, extreme events are important in triggering several modes of channel expansion, for example channel switches across fans (Gleann an t-Slugain), extra-channel avulsions (Clunie) and cleaning out of former flood channels (Luibeg), thus causing in some cases large increases in width of the active area. Extreme events are also important in terms of injecting large quantities of sediment into the system over a very short timeperiod (eg. as occurred in Glen Derry or within the Quoich fan).

The most extreme runoff event was the 1829 flood that caused transient channel metamorphosis on the lower Quoich Water, and which in a few hours caused catastrophic disruption to the system. The channel is still undergoing a complex response to that extreme stress. More confined reaches eg. on the irregular meandering middle Lui Water and the mainstream Dee meander bend have a more restricted response to extreme runoff, due to much higher thresholds for change through neck cutoffs. At these sites, even such extreme events have little impact. However, the location of local base-levels is crucial; frequently upstream braiding and tortuous meanders are found in close proximity and are associated with different modes and rates of response to similar magnitude extreme runoff events eg. on the upper Derry and on the Dee

Figure 7.2.9.(i)

Modes of channel planform change recorded within the Dee study reaches (for key, see Table 4.6.3.(i))



at Clunie Cottage.

The impact of more moderate events (especially the increased frequency in the 1870s and 1880s) differs considerably depending on planform type. This mainly involves the reworking of material within the channel and bank erosion, with associated channel widening, rather than major planform disruption. However, minor extra-channel avulsions may occur or former avulsions may become gradually plugged with sediment. This depends on local conditions and may lead to small-scale increases or decreases in the active area. The inter-arrival time of such moderate floods in relation to more extreme events is crucial, but where sediment size is smaller, moderate discharges can play an important role in regaining a quasi-equilibrium condition. The importance of high winter flows in relation to bank erosion may also be geomorphically significant. However, the cumulative impact of these is small in comparison with the geomorphic work done and effectiveness of more extreme events.

7.3 Selected reaches within the Spey study area

The reaches studied within the Spey study area are as follows:

(1) The River Feshie confluence

(2) The River Nethy confluence

(3) The River Druie at Inverdruie

(4) The River Feshie at Lagganlia

(5) The River Tromie near Tromie Lodge

(6) The River Avon near Tomintoul

(7) The River Avon near Foals Craig

(8) The Dorback Burn near Aittenlia

(9) The River Spey near Loch Alvie

The location of these reaches within the Spey study area is shown in Figure 7.3.(i).

7.3.1 Spey study reach 1: The River Feshie confluence

The Feshie confluence site is a large, highly active, low-level, gravel fan, draining an area of 234 km^2. It debouches from a rock controlled meltwater gorge at Feshiebridge and has an abundance of both upstream and local fluvioglacial material to rework (see Figure 3.3.3.(i)). Channel pattern is sinuous to wandering, depending on date of observation. Position within the channel system typology is outlined in Table 7.3.1.(i).

Figure 7.3.(1)

Location of study reaches within the Spey study area

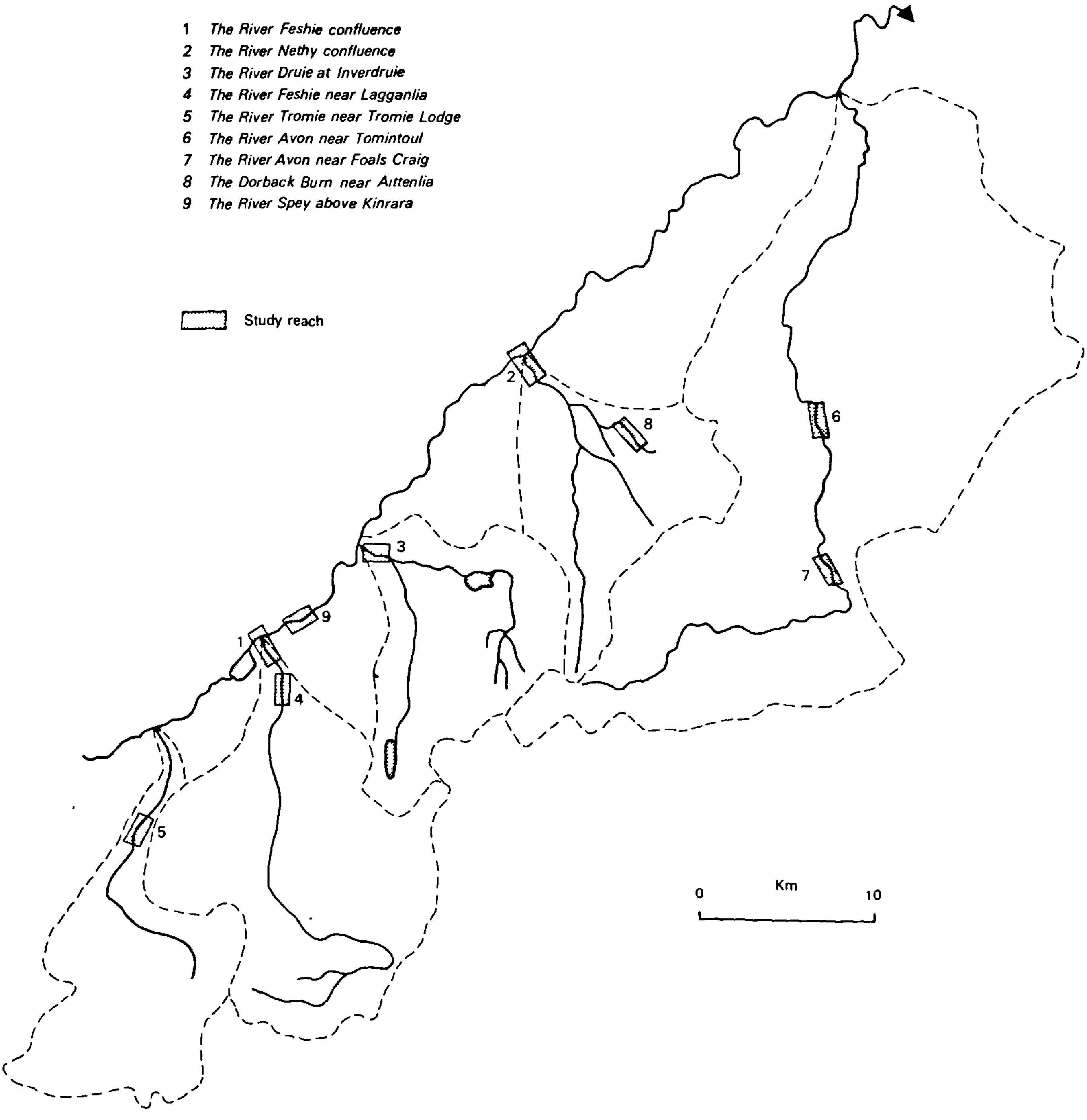


Table 7.3.1.(i)

Position of Spey study reach 1: The River Feshie confluence within the map-based channel system typology

A (a) Basin area: 230 km^2

(b) Average height: 340 m

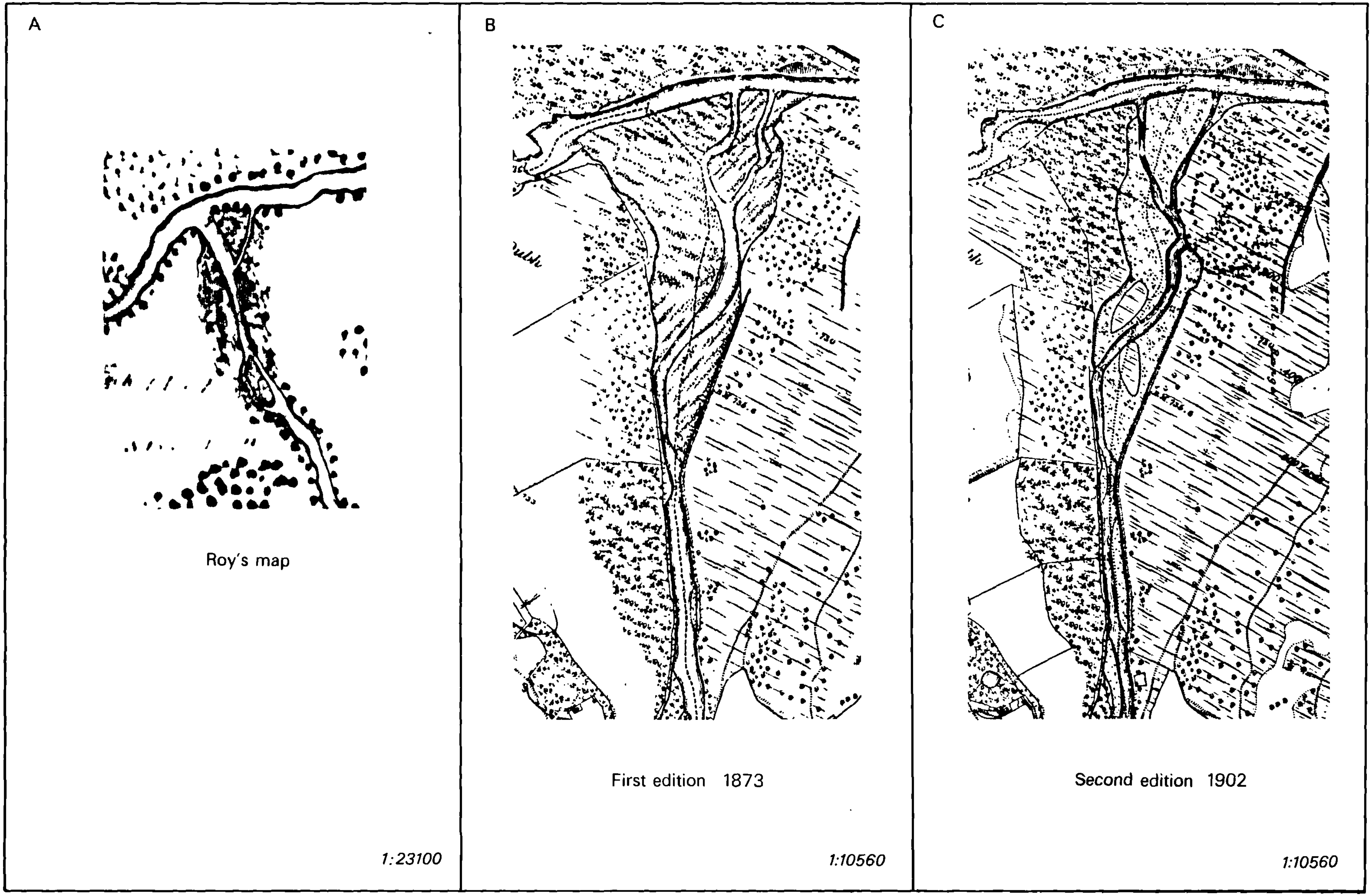
	1873	1902	1969
B (a) UPSEDMT:	1	1	1
(b) LOCSEDMT:	1	3	3
C FLOOD:	0	3	3
D (a) FLOODPLN VEGETATION:	2	2	2
(b) BANK VEGETATION:	2	2	2
(c) BAR VEGETATION:	3	0	0

E MAXWID 64

	1873	1902	1969
F (a) CHANPATT:	4	2	2
(b) ISLANDS:	3	3	1
G (a) ACTIVITY:	8	8	8

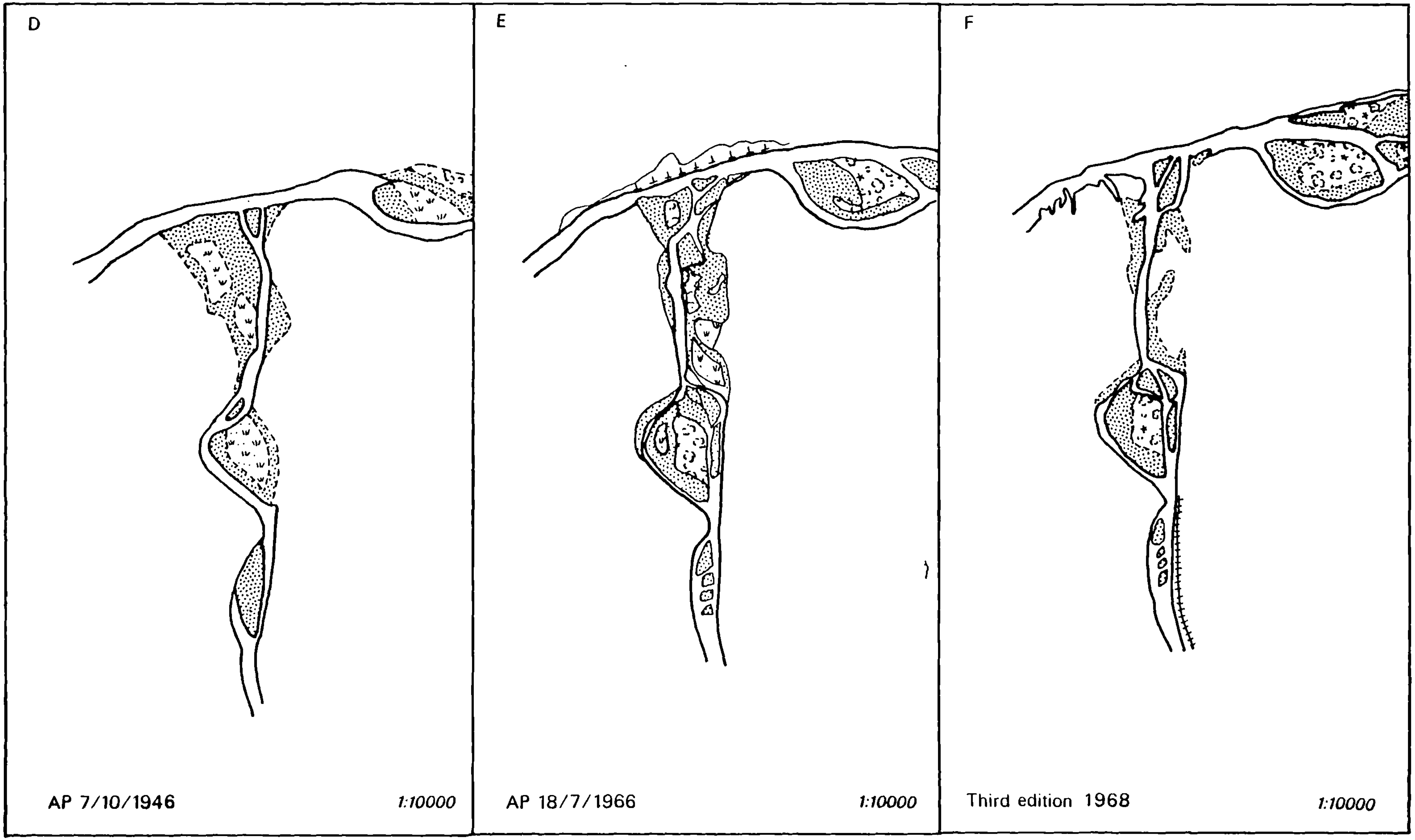
Spey study reach 1: The River Feshie confluence

Figure 7.3.1.(i)



Spey study reach 1: The River Feshie confluence

Figure 7.3.1.(i)



Roy's map (1750's) indicated that the reach above the confluence was highly subdivided, with a large number of gravel bars and with little stabilising vegetation apart from the occasional tree (Figure 7.3.1.(i).A). Between 1750 and the first edition (1873) ie. over approximately 120 years later, it is known that at least two major flood events had occurred within the Feshie catchment (Figure 5.5.1.(vii)), affecting its lower reaches. The 4th Aug, 1829 flood must have had a considerable geomorphic effect on this area and some idea of the competence involved was provided by Lauder (1830):

> "The .... bridge at Invereshie is of two arches, of 34 feet [10.4 m] and 12 feet [3.7 m] span. The larger of these is 22 feet [6.7 m] above the river in its ordinary state, yet the flood was 3 feet [0.9 m] above the keystone, which would make its height here above ordinary level about 25 feet [7.6 m]. The force pressing on this bridge must have been immense. Masses of the micaceous rock below the bridge, of several tons weight, were rent away, carried down and buried under heaps of gravel at the lower end of the pool, 50 to 60 yards [46-55 m] from the spot whence they were taken.... The Feshie carried off a strong stone bulwark, a little further down- overflowed and destroyed the whole low ground of Dalnavert- excavated a new channel for itself- and left an island between it and the Spey of at least 200 acres [81 ha]."
> (Lauder, 1830 p145)

Nairne (1895) also stated that during 24-26th Jan, 1849, the area in the vicinity of the Feshie confluence was heavily flooded, with the water level exceeding that of 1829 by 18 inches [0.48 m]. The estate plan of 1862 (RHP 2200), proposing a straightening of the channel, showed the Feshie as a single wide channel with occasional, unvegetated bars (see Figure 6.3.(ix)). Its existence also suggested that over this period, the problems of the reworking of agricultural land must have been acute. It is not known whether this plan was implemented but if so, the channel had already reworked the artificial planform by 1873.

It was clear from the first edition map (1873), that there had been a shift in the main channel since the parish boundary was drawn since the Feshie now entered the Spey to the left (see Figure 7.3.1.(i).B). By 1873 however, there was an extensive unvegetated gravel area with a sinuous channel, culminating in an anabranch to the right of the confluence. The 1829 event must have completely reworked the bars and neighbouring floodplain, as indicated on Roy's map.

In 1902, the size of the active area had been reduced, with flood flow reworking concentrated to the east. Some areas distant from the channel had stabilised, with a channel sinuosity of 1.06 and a BI of 1.60 (Figure 7.3.1.(i).C). However, large amounts of gravels remained unvegetated and the pattern was fairly similar to 1873, though the separation between the two confluence channels had increased. Clearly no major flood event had totally disrupted the channel pattern and the only channel response to the known flood events that did occur (Figure 5.5.1.(vii)) was through channel shift across the unvegetated sediment of the lower fan. This was not to say that flooding did not frequently occur on the Feshie:

> "It has in early ages scooped out a deep glen, of the most wild and picturesque sort and poured vast quantities of detritus into the Spey valley, levelling up the natural gradient and damming back the upper waters. The Feshie is still subject to the most violent floods and is still carrying down its talus of gravel" (Calderwood, 1909 p142).

Thus, a period of slight shrinkage of the active area, with stabilisation and general recovery, seemed to have taken place but this was only relative to the 1873 situation. Presumably post-1829, an even more extensive active area must have existed and the channel by 1902 was still undergoing post-flood recovery. Again the inter-arrival times of extreme floods as opposed to more moderate events is very important (cf. Dee study reach 1: the Quoich Water confluence).

A further 44 years later (7/10/1946), and after at least another major disruptive flood event had affected the Feshie (Figure 5.5.1.(vii)), the channel had become more irregular and now entered the Spey to the extreme east. Localised bank erosion had occurred with the shift of the channel across the fan. This was accompanied by a reduction in BI and a stabilising of areas then more distant from the flow. However, upstream extra-channel avulsion had taken place, causing an increase in sinuosity. This change was clearly recent as can be seen from the sparse colonisation of the gravels, which represented the former active area. Perhaps this change can be attributed to the 24th

Jan, 1937 flood event, though it is known that at least another three large events occurred in that intervening period (1902-1946) (Figure 5.5.1.(vii)). Considerable change had occurred both in terms of planform change and increased sedimentation.

By 18/7/1966, a large and complex anabranch had developed by extra-channel avulsion just upstream of the confluence and the Feshie then entered the Spey by a fragmented channel to the east (Figure 7.3.1.(i).D). Clearly over this period, a large proportion of the previously stabilising floodplain had been reworked and the active area enlargened, though not to the extent of 1873. The river clearly inundates and reworks its neighbouring floodplain regularly. The actual channel planform was more fragmented and a major new channel had been cut within the mainstream Spey, just downstream of the Feshie confluence. This is very interesting as a perturbation in the mainstream Spey was directly related to the Feshie. It is known from the gauged record that in 28th Sept, 1961, a major flood event of around 200 $m^3 s^{-1}$ occurred and also another event of a just slightly lesser magnitude on 30th July, 1956. The 1961 event had a recurrence interval of over 30 years and is known to have had a significant landforming capacity, with subsequent erosion being focussed in new areas of the floodplain. However, its effectiveness over a longer timespan will depend on the magnitude and frequency of subsequent events.

On the third edition map (1968; Figure 7.3.1.(i).F), as can be seen from the 1983 photographs (Plate 7.3.1.(i)), change occurred with the excavation of new channels at the confluence. The anabranch feature upstream seemed to remain similar, becoming a relatively more persistent feature of the landscape. The braiding index had increased from 1.00 to 1.87 since 1869. The 1983 photographs were oblique and the channels appeared chaotic, with the Feshie having excavated a channel even further to the east and another through the trees to the extreme west. Upstream of these two channels, and in contrast to 1966, the river seemed much more highly braided, working its way through unstabilised gravel bars and more stable bar features. These have been left isolated when flood channels were excavated through formerly stable floodplain areas. For example, a new channel cut through the trees was still flowing on grass. Recent flood disruption must have occurred (possibly in Sept, 1981 or Sept/Oct, 1982).

The landowner (pers. comm. Brigidier Curtis) confirmed that the pools below Feshie Bridge were gradually filling up with sediment, brought down by flooding and could be dredged to at least 20 ft [6 m]. The bar downstream of the rock-controlled section is known to have gradually built up and stabilised with trees over the past 10 years. Brigidier Curtis also observed that within that period, the Feshie had changed its course at the Spey confluence, formerly entering at right angles but now with a channel cut through to the east. Clearly, coarse material within the fan is accumulating more rapidly than it can be transported by the Spey (see also Hinxman and Anderson, 1915) and thus the fan is constantly pushing out into the lower gradient mainstream channel. Since 1902, the actual fan has had periodic increases in size, associated with large disruptive flood events, though none as substantial as in 1829. Shifting of unstabilised gravels proximal to the channel must occur in more moderate flows. Thus, rather than being an equilibrium channel form, both the active area and the channel

Plate 7.3.1.(i)

The Feshie confluence fan

planform undergo periods of expansion and contraction, depending on the interspacing of high competence floods. These events reoccupy palaeochannels and reactivate stabilising areas of floodplain.

7.3.2 Spey study reach 2: The River Nethy confluence

This study reach is a low-level fan at the confluence of the Nethy with the Spey, on a smaller scale to that of the River Feshie and with a contributing catchment area of 125 km^2. Position within the channel system typology is outlined in Table 7.3.2.(i).

A record of the pre-1829 situation on the Nethy existed from both on Roy's map (1750s) and Peter May's (1771) plan of Coulnakyle (RHP 8893), Figures 7.3.2.(i).A and 7.3.2.(ii) respectively. Roy's map indicated a single, sinuous, tree-lined channel at the confluence, entering the River Spey to the west. However, Peter May (1771) showed the channel to be irregular with major splits and anabranches upstream, but with no indication of palaeochannels at the confluence. Bank erosion problems, especially associated with river bends, were annotated. This may suggest a lack of detail on Roy's map. In Brown's (1811) plan of Coulnakyle (RHP 13936), a similar channel pattern was shown but with the widening and development of a bar at the confluence. In complete contrast to Figure 7.3.2.(ii), the estate plan of the Forest of Abernethy in 1858 showed large-scale change in the lower Nethy, with a single, wide sinuous channel (Figure 7.3.2.(iii)). Evidence of earlier channel activity was provided by Lauder (1830), with description of channel shift and extensive floodplain reworking (see Appendix

1.5.1).

The considerable change since 1811 was confirmed by the first edition (1867-1871) when the channel entered the Spey to the east, as shown in Figure 7.3.2.(i).B. Upstream of the confluence, the channel was split with unvegetated medial bars and still further upstream, there were extensive gravels by the channel side above Coulnakyle. The date of a large proportion of the major sediment input was documented as 4th Aug, 1829, though there was another major flood event in 1799 (Figure 5.5.1.(ix)). The floodstone of 1829 indicated that the Nethy flood waters spread out far beyond the channel's active area, and Lauder (1830) described the Nethy/Spey confluence area as "a lake several miles in extent" (Lauder, 1830 p153). The margins of this lake are reconstructed in Figure 7.3.1.(v). Upstream at Nethybridge, there was large scale destruction again reported:

> "The work of destruction went on with fearful rapidity...in 15 mins the road leading up the left bank was swept away and a large breach made in the road beyond it....large masses of bank tumbling every now and then into the torrent." (Lauder, 1830 p154)
>
> "The flood having swept away about 20 yards [18.3 m] of a green bank opposite the house of Coulnakyle." (Lauder, 1830 p164)

Figure 7.3.2.(ii) Peter May's (1771) plan of Coulnakyle (RHP 8893)

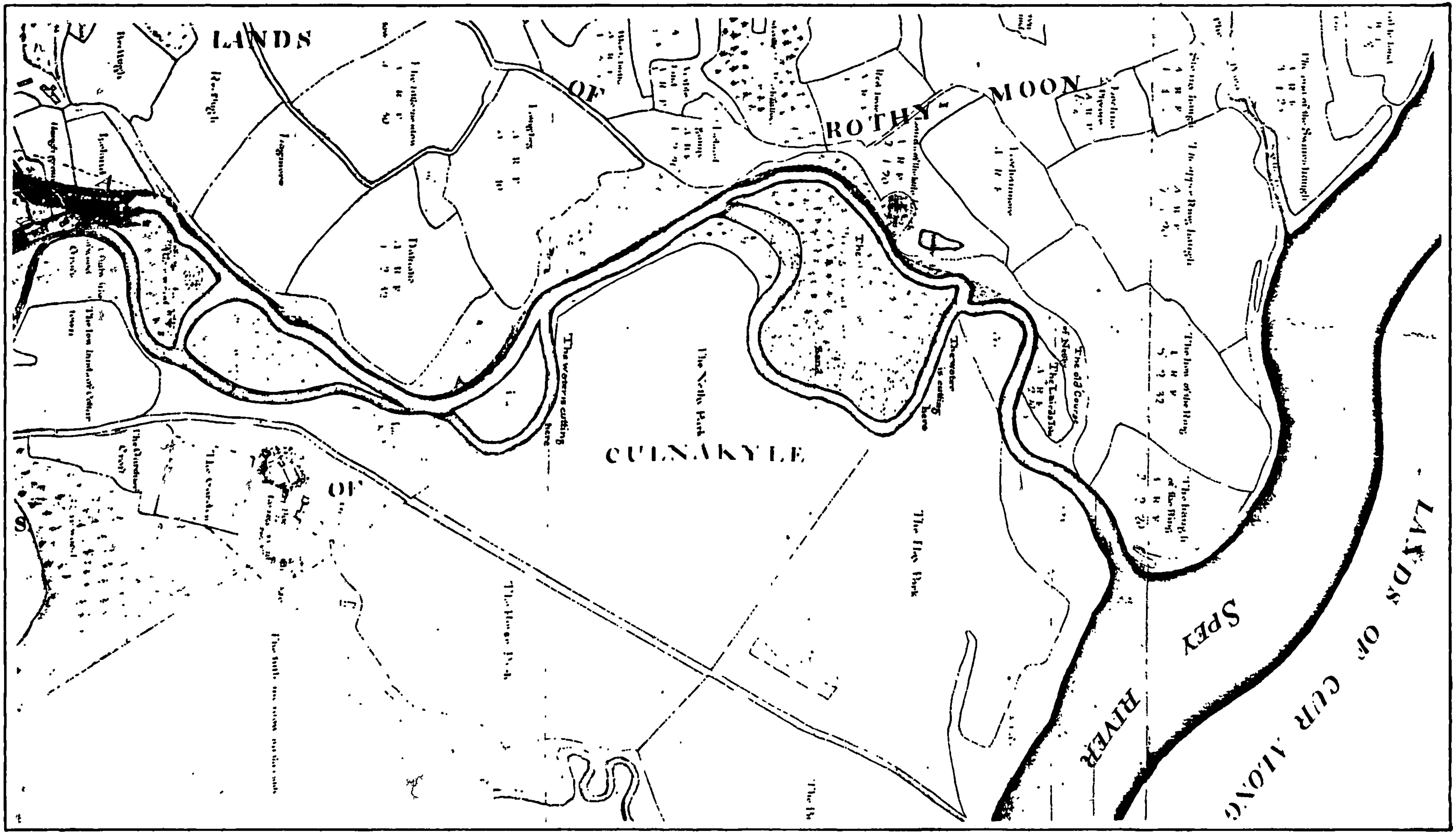


Figure 7.3.2.(iii) Plan of the Forest of Abernethy (1858; RHP 13995)

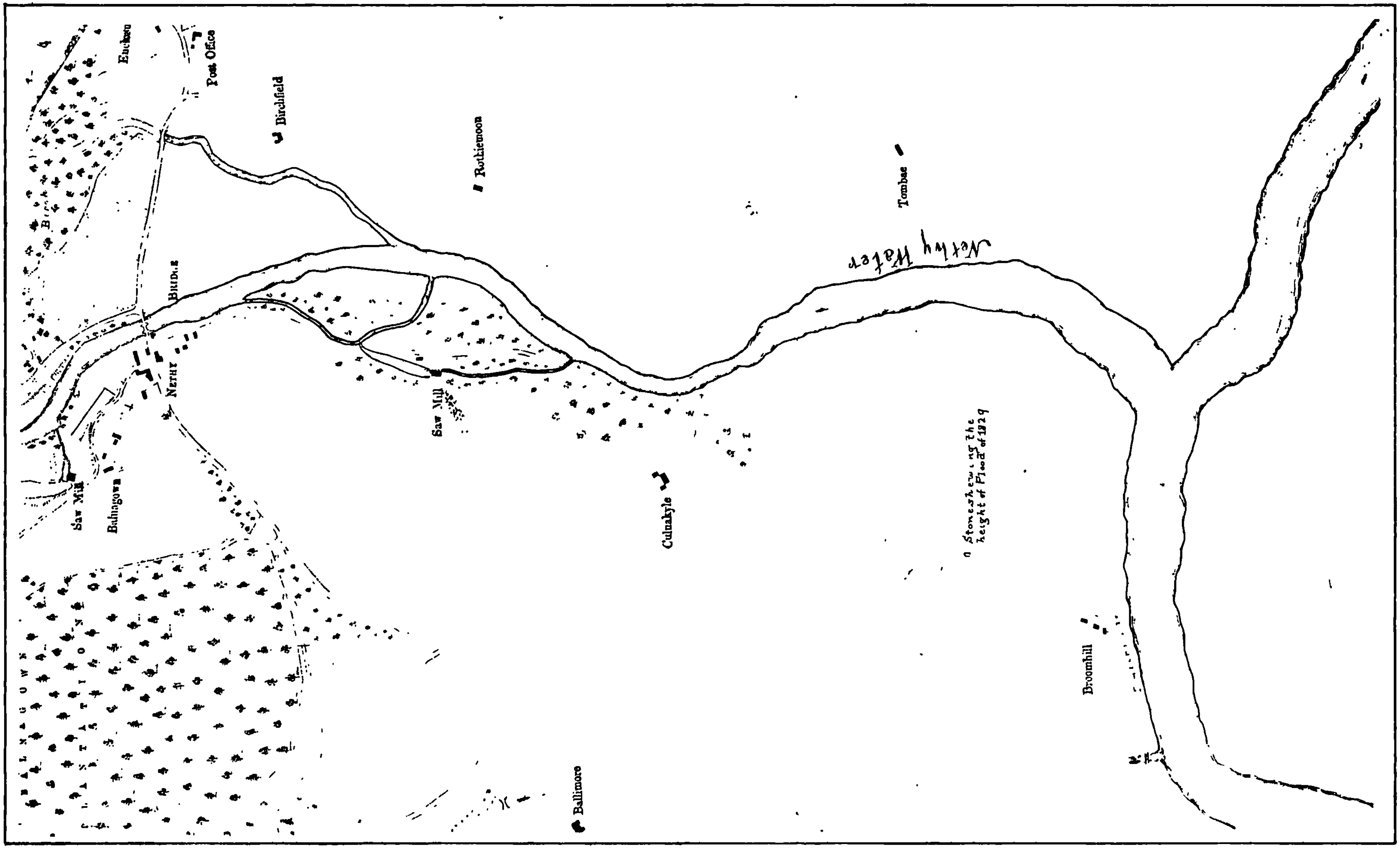


Table 7.3.2.(i)

Position of Spey study reach 2: The River Nethy confluence within the map-based channel system typology

A (a) Basin area: 121.4 km^2

(b) Average height: 202 m

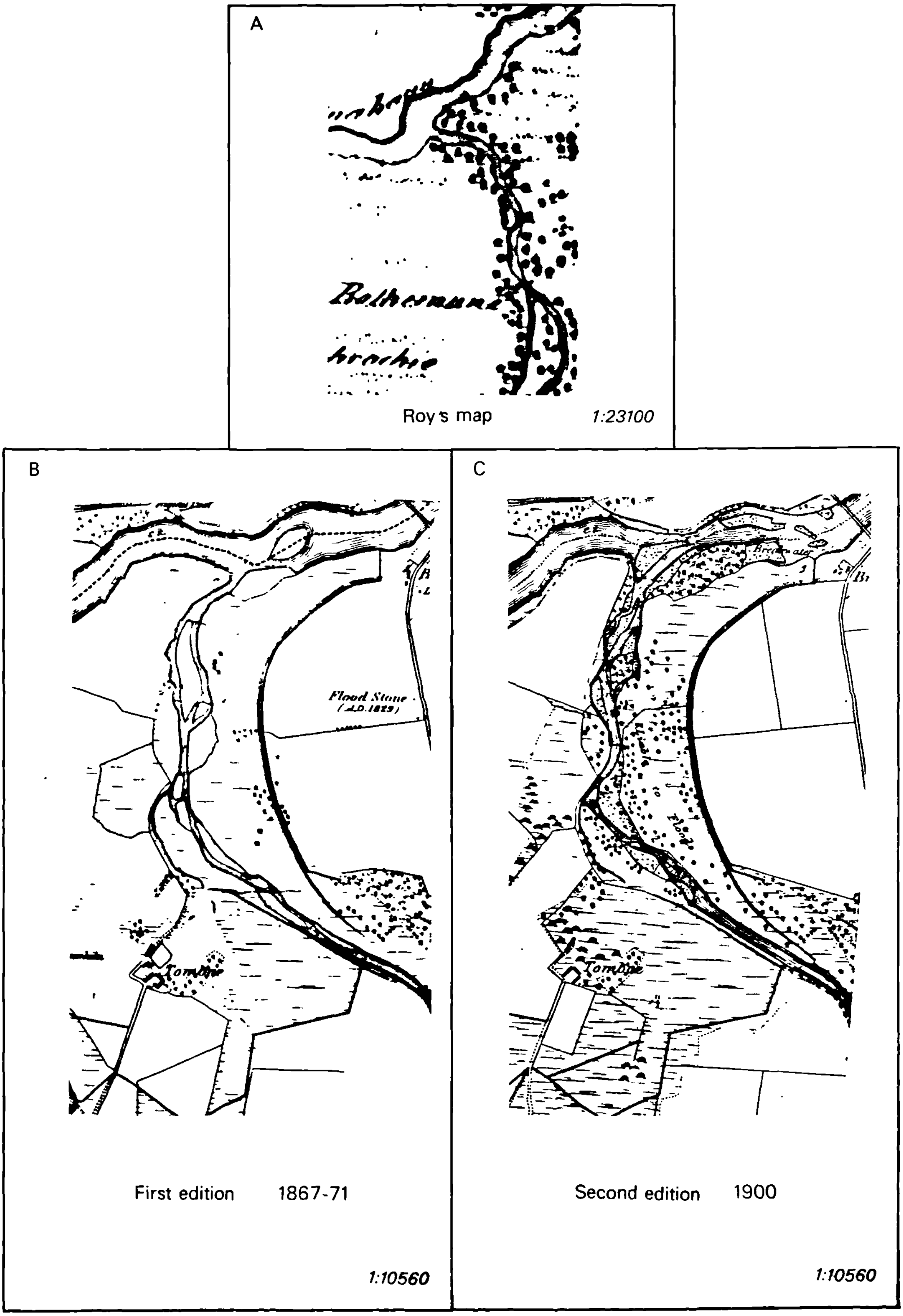
	1871	1900	1976
B (a) UPSEDMT:	2	2	1
(b) LOCSEDMT:	2	2	0
C FLOOD:	0	3	0
D (a) FLOODPLN VEGETATION:	3	4	5
(b) BANK VEGETATION:	3	3	5
(c) BAR VEGETATION:	8	3	1

E MAXWID 100

	1871	1900	1976
F (a) CHANPATT:	3	3	3
(b) ISLANDS:	2	3	2
G (a) ACTIVITY:	2	8	1

Figure 7.3.2.(i)

Spey study reach 2: The River Nethy confluence



A: Roy's map 1:23100

B: First edition 1867-71 1:10560

C: Second edition 1900 1:10560

Figure 7.3.2.(i)

Spey study reach 2: The River Nethy confluence

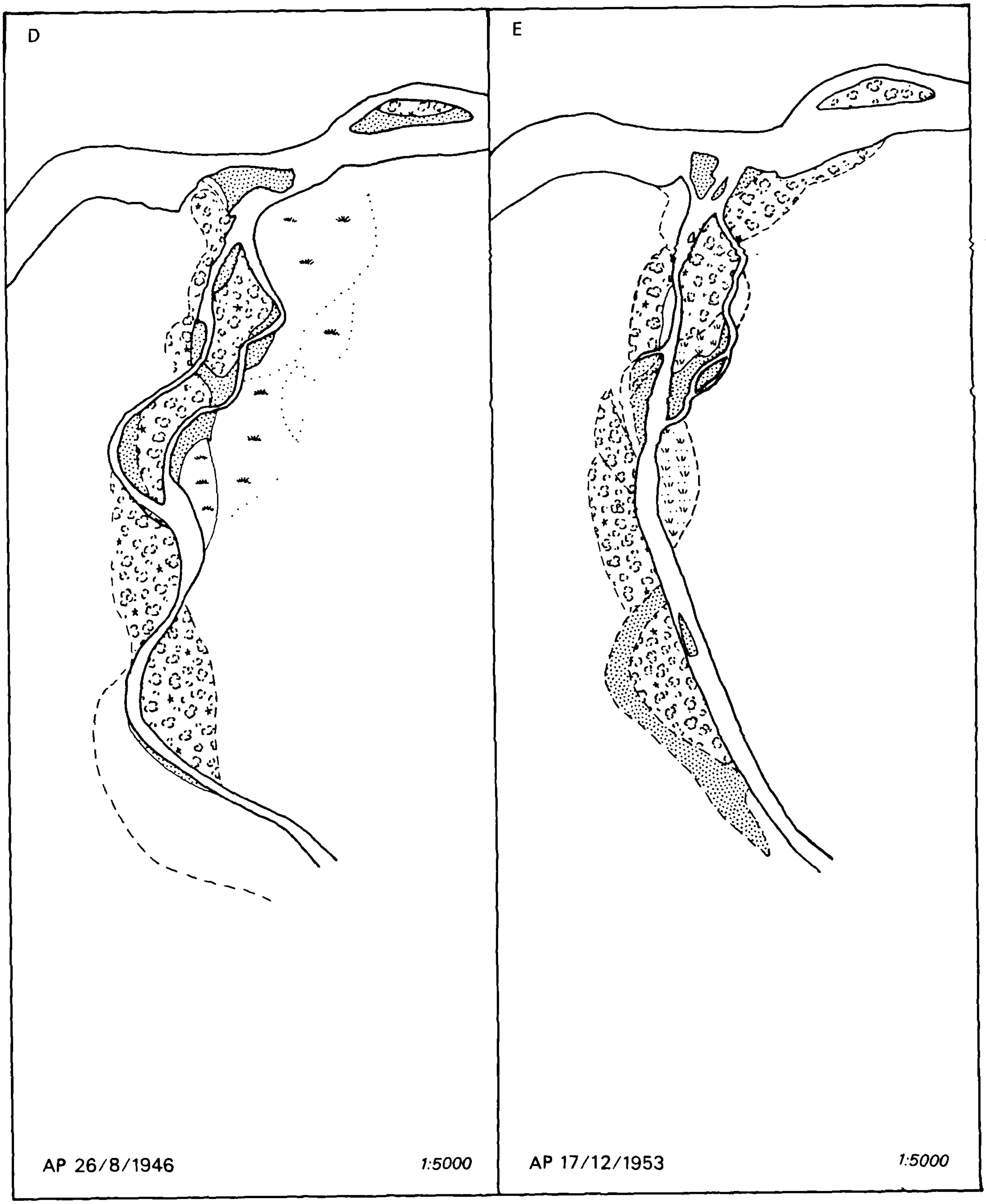


Figure 7.3.2.(i)

Spey study reach 2: The River Nethy confluence

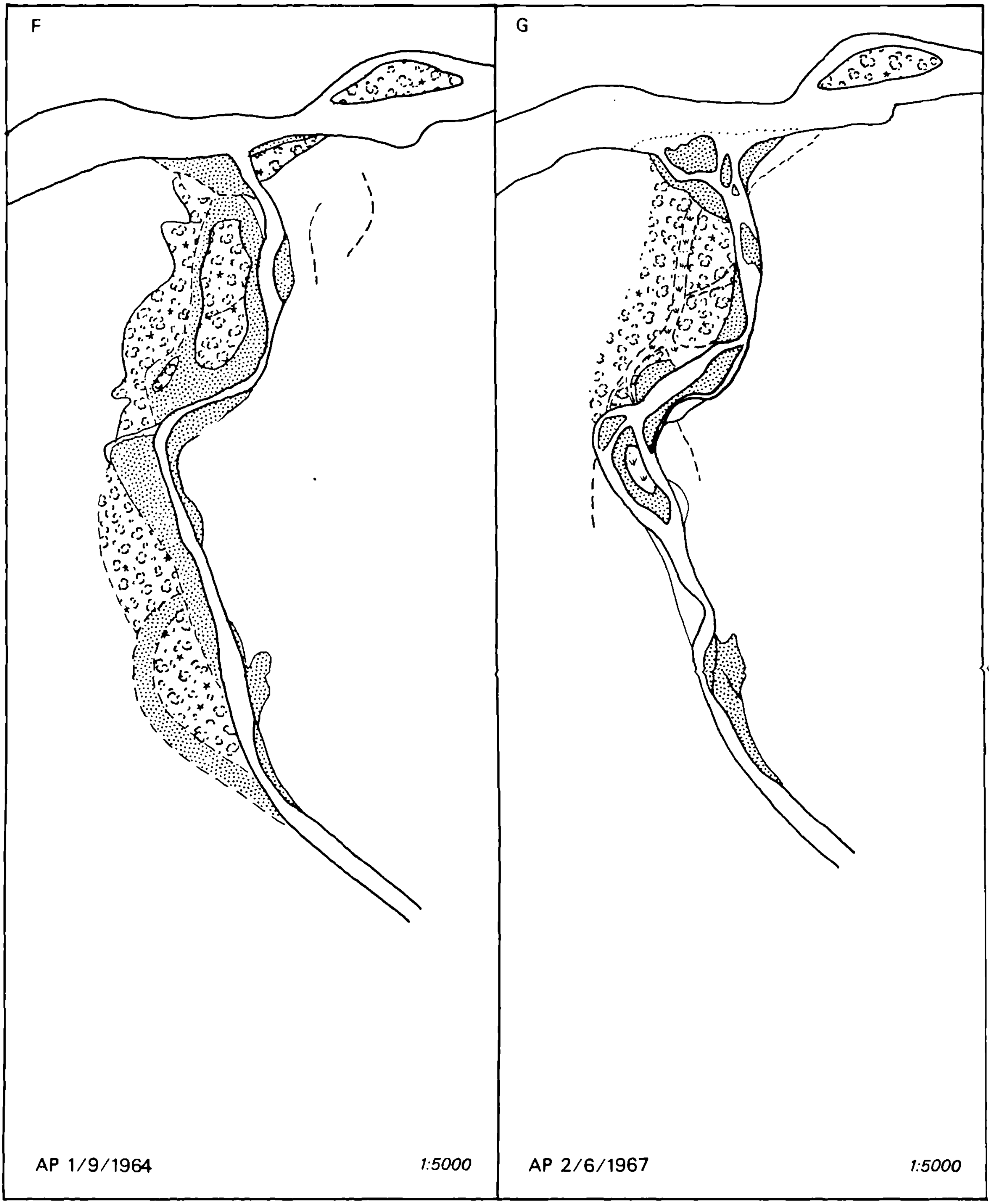
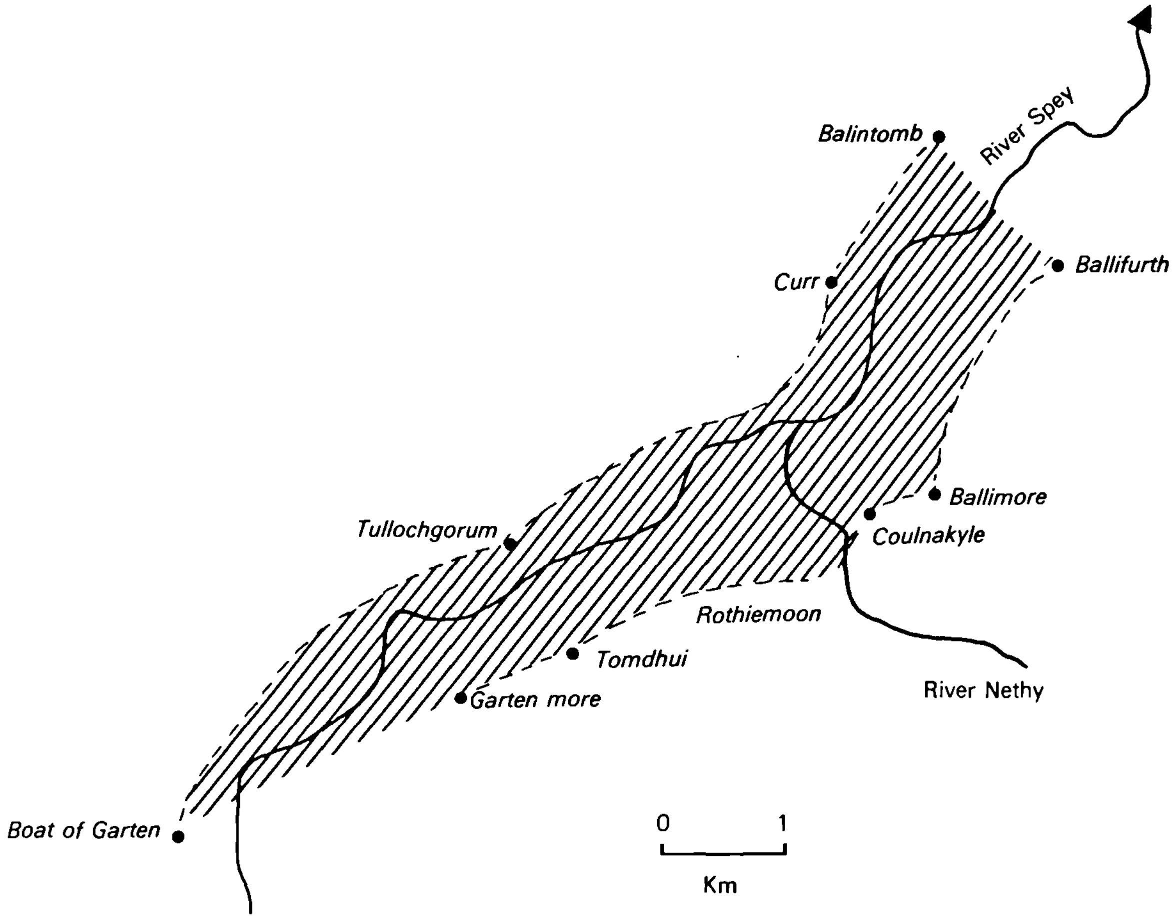


Figure 7.3.2.(v)

A flood zone map for the Nethy confluence during the 4th August, 1829 flood event



By the second edition (1900), there had been an increase in BI from 1.55 to 2.23; the whole area was considerably more fragmented and the width of the active area had been increased (Figure 7.3.2.(i).C). Again, there were large quantities of unvegetated gravels beside the channel and frequent inundation was indicated by "liable to flooding", perhaps due to an increase in the level of the bed post-1829. Obviously, this area had been reworked at least once since 1871, possibly on 30/1/1892. No major extra-channel avulsion had taken place, rather a reworking of bars within the channel and an erosion of banks.

When the second edition (1900) was compared with the first aerial photograph on 26/8/1946, the confluence channel was still to the east and above this, the channel was split around a large stable bar, which had been cut through the former bank in an extra-channel avulsion (Figure 7.3.2.(i).D). Upstream of this bar however, the channel had less unvegetated sediment, with a reduced active area, and thus seemed generally more stable than in 1900. In contrast by 17/12/1953, a major change had occurred, which appeared to have been man-made as a response to increasing sedimentation. A channel had been cut through the sinuous upstream bends creating a single, undivided channel. Large amounts of sediment had been dredged from the main channel and the anabranch channels still retained flow, although they were of secondary importance.

By 1/9/1964, there had been a large switch of flow from the major channel of 1953 to the former secondary channels to the east, with the Nethy entering the Spey almost at right angles. The channel was more sinuous with large quantities of unvegetated active gravels by the channel side. Obviously with such a large switch, a major geomorphic stress must have been applied to the system. This was unrecorded but may have been the 1956 or 1961 events that affected neighbouring catchments (RI of over 30 years at Feshiebridge). By 2/6/1967, a similar channel was followed although within the active area, the BI had increased (see Figure 7.3.1.(i).G), with a widening and reworking of channel side gravels. The geomorphic disruption (pre-1964) appears to have caused a subsequent pattern of instability. However, by 7/9/1968, the channel had again simplified with most of the flow returning to one channel. Thus, overall between 1900-1971, there had been a decrease in sinuosity from 1.15 to 1.11 and the braiding index has reduced dramatically from 2.23 to 1.00. But this pattern was broken by at least one major phase of disruption and subsequent recovery.

Most recent flood activity within this area has been followed by a man-induced response. During the Sept, 1981 storms when 2 discharge POT were recorded in one month, a major channel switch occurred on the Nethy, back to its western channel alignment and large amounts of sedimentation occurred. Both these POT were less than the mean annual flood (68.7 $m^3 s^{-1}$) and the accumulated build up of sediment must have exceeded an intrinsic threshold. It is interesting to note that the switch did not occur during the 6th June, 1980 event, which was over 4 times larger in discharge than the 20th Sept, 1982 event. Undoubtably,

Plate 7.3.2.(i)

The lower Nethy fan before its confluence with the River Spey. A wide area of unvegetated flood sedimentation exists, relating to the flooding of Sept, 1981.

this earlier flood had a major role in the accumulation of sediment so that an incipient threshold condition could be attained. Since this channel change, the lower fan area has been bulldozed and this deepening of the channel bed and removal of sands and gravels cost 20,000 pounds of estate grant to clear. Two years later, some of this sediment has already been washed back into the channel during the floods of Oct, 1982 (see Plate 7.3.2.(i)). There has been a suggestion of spending even more but it is now considered that enough has been done to keep sediment out of the main channel. Upstream, large angular boulders or "rip-rap" have been placed at the base of the banks as protection from further undermining. According to the farmer at Rothiemoon, the area immediately above the confluence is frequently flooded and reaches bankfull stage on average 1-2 times a year. Upstream however, the height of the channel increased and here it had overflown only once in the farmer's memory (but he looked a young farmer!). This was under atypical circumstances when 6 inches [15 cm] of ice formed and flooding underneath forced the ice and water up.

7.3.3 Spey study reach 3: The River Druie near Inverdruie

The Druie study reach, draining 122.9 km^2, falls into the wide shallow frequent bars to braided/ anabranching categories of channel pattern, and has a known history of high activity. Position within the channel system typology is outlined in Table 7.3.3.(i). Unfortunately, there is no discharge gauge due to bed mobility and the flood record was thus entirely based on alternative sources. It was reported by Mr. Lawrie Wedderburn (the Rothiemurchus ranger) that frequently two flood

Table 7.3.3.(i)

Position of Spey study reach 3: The River Druie near Inverdruie within the map-based channel system typology

A (a) Basin area: 124.2 km^2

(b) Average height: 217 m

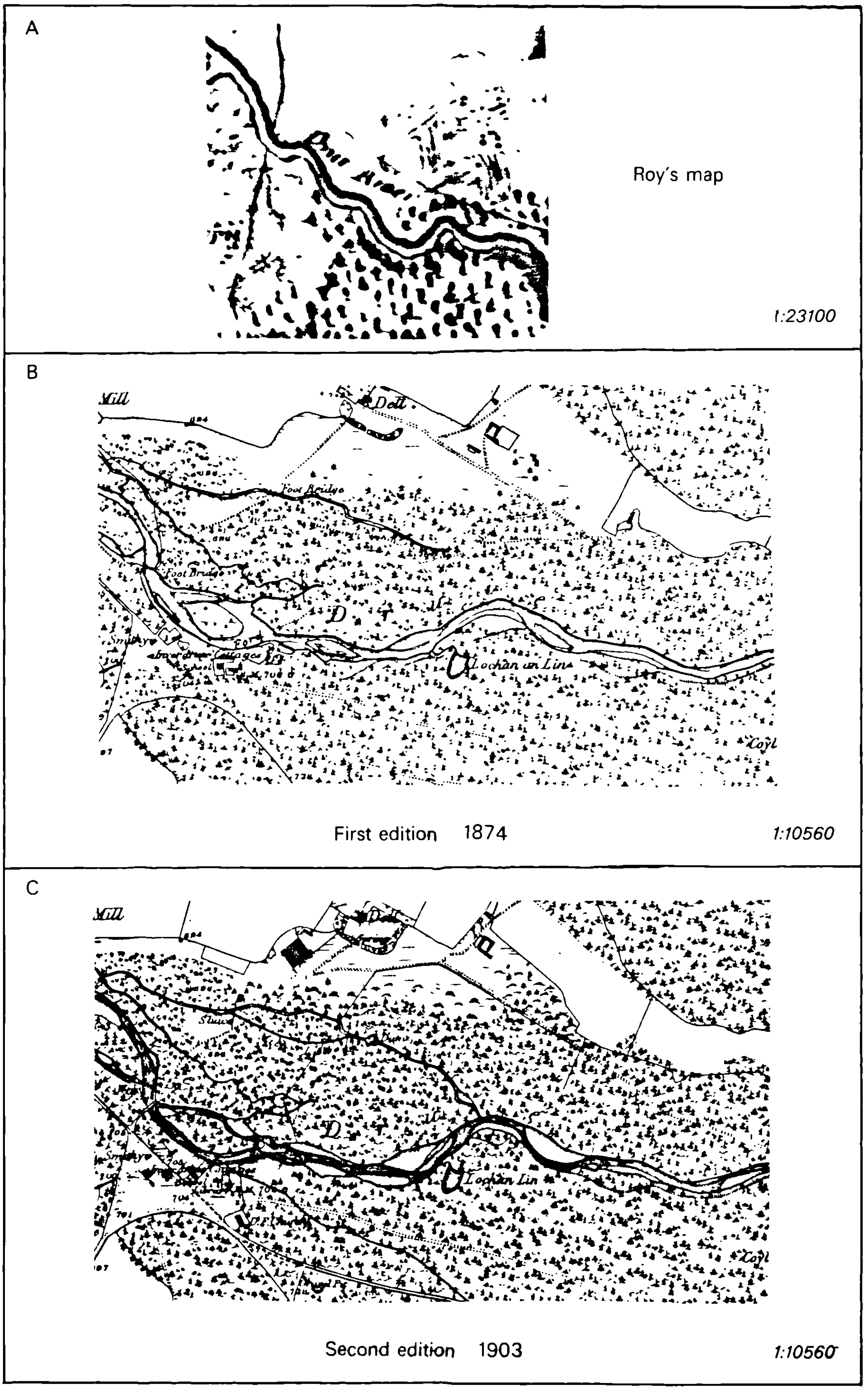
	1874	1903	1973
B (a) UPSEDMT:	1	1	1
(b) LOCSEDMT:	1	2	1
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	2	2	2
(b) BANK VEGETATION:	2	2	2
(c) BAR VEGETATION:	2	2	2

E MAXWID 50

F (a) CHANPATT:	4	4	4
(b) ISLANDS:	3/6	3/6	7
G (a) ACTIVITY:	8	8	8

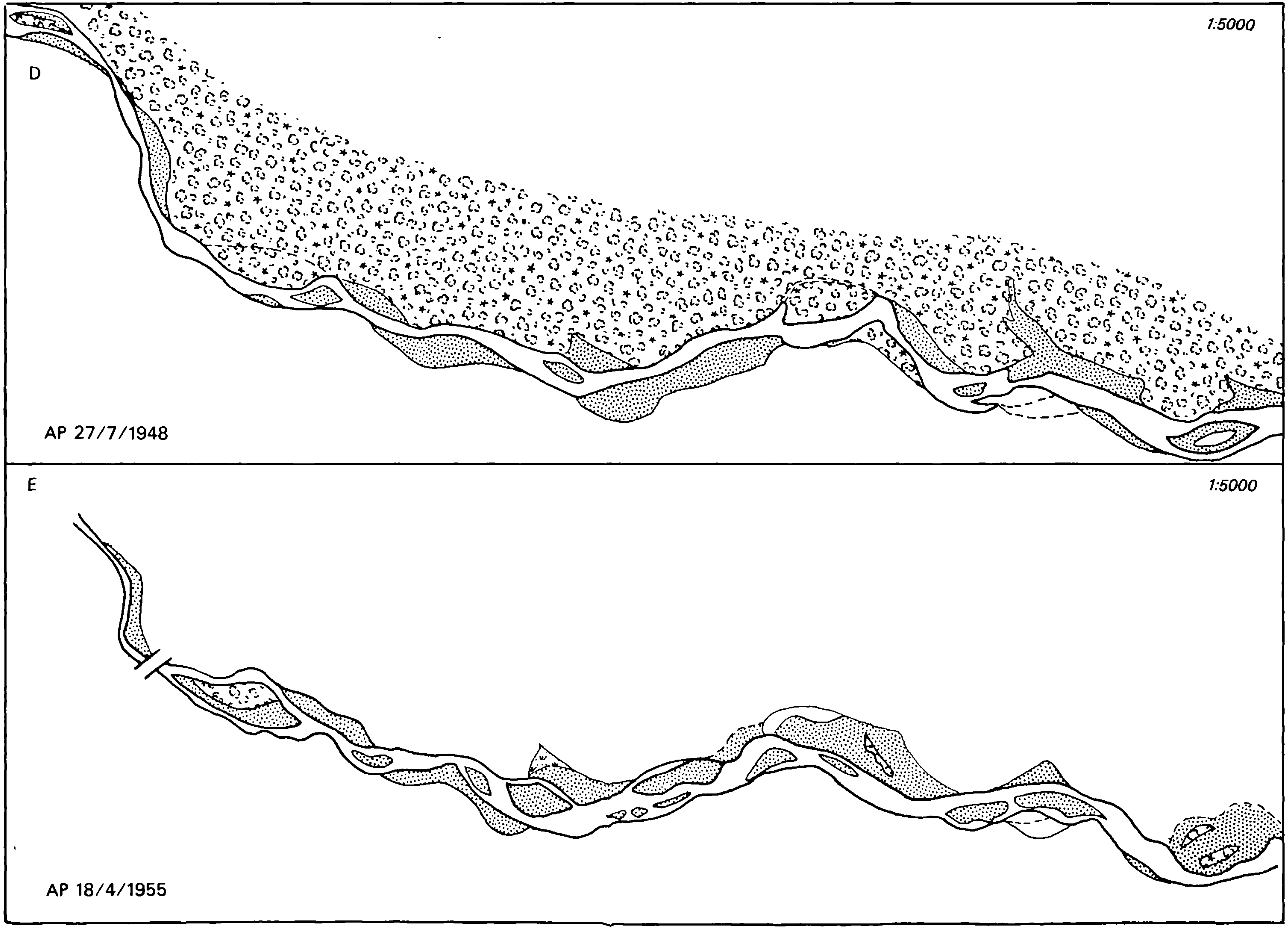
Figure 7.3.3.(i)

Spey study reach 3: The River Druie by Inverdruie



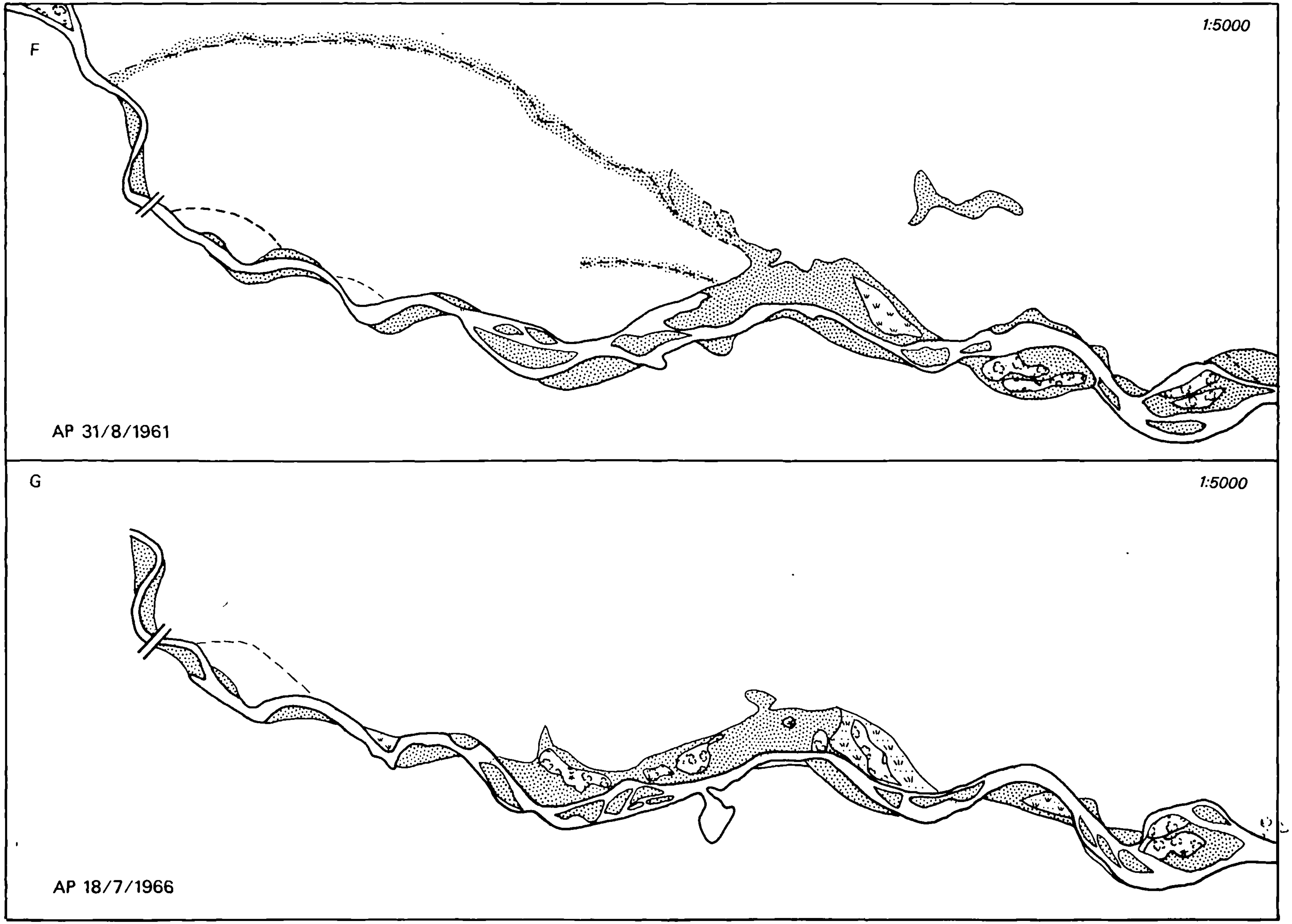
Spey study reach 3: The River Druie at Inverdruie

Figure 7.3.3.(i)



Spey study reach 3: The River Druie at Inverdruie

Figure 7.3.3.(i)



peaks occurred; the first from the Am Beanaidh and the second slowed down by Loch Morlich. This may reduce or exacerbate the flood effects depending on the magnitude and regional extent of the storm.

When Roy's map (1750) was studied for this reach (Figure 7.3.3.(i).A), the Druie was shown as a single channel; multiple braids beside Inverdruie were not indicated. This however was not confirmed by the literature:

"The Druie is a capricious river that often shifts its channel and converts much fertile land into a wilderness of sand and gravel. With its vagaries have been connected the fortunes of the House of Rothiemurchus, which were to be prosperous so long as the course of the river continued the same but disastrous should it change its bed and work out a new channel for itself. Twice at least, this change has happened, when the property passed from the Shaws to the Grants [1570] and during the great Moray floods [1829] that devastated the whole district." (MacMillan, 1907 p14)

However, Roy's map does not indicate former flood channels, just the occupied channel at the time of surveying and this explains the discrepancy.

Palaeochannels and tonal changes in vegetation, evident from the aerial photographs, confirmed this historic planform alteration. During the 4th Aug, 1829 floods in Speyside, the Druie was reported to have undergone considerable change in planform.

"The Druie entering from the right bank swept away a house at Upper Dell. The river broke from its channel and running in a parallel at a distance of 200 yards [183 m], it bore down every object natural or artificial that presented itself and surrounded the house of the Dell of Rothiemurchus with an immense body of water, though its side was 500 yards [458 m] from its bed.... The whole place was cut up and ruined, and the sawmills which were much damaged, escaped utter destruction only by the breaking of the embankment higher up." (Lauder, 1830 p147)

Large amounts of both upstream and local sediment must thus have been mobilised. By 1874, the Druie had a highly split channel downstream around vegetated bars of varying size, which suggested planform adjustment had occurred principally by extra-channel avulsion (Figure 7.3.3.(i).B). Upstream bars were fewer and change seemed to occur by intra-channel avulsion. Throughout, the active area was wide and the 1829 flood channel was still very evident. Sinuosity of the main channel was 1.15 and the braiding index 2.96. By 1903, while channel widening and bank erosion had taken place upstream with more unvegetated sediment by the channel side and medial bars reworked, downstream other areas had become well-stabilised by trees (Figure 7.3.3.(i).C). Overall BI in fact decreased slightly from 2.96 to 2.87. Water also had been diverted to power a sawmill and thus downstream discharge will have been reduced.

The first available aerial photograph was 27/7/1948 and the channel's active area widening had continued upstream; the previously embanked area, as shown in 1903, had been heavily eroded with a sinuous channel making its way through large amounts of available gravel. In some areas (Figure 7.3.3.(i).D), banks had been substantially eroded in a 45 year time-interval, and it was principally the west bank being reduced. By Inverdruie, the channel had switched its course to an alignment away from the settlement, a change that has persisted to 1984. Between 1903 and 1948, it is known that at least one major event affected this catchment (eg. 25-26/9/1915), as seen in Figure 5.5.1.(viii). Again, the 18/4/1955 photograph showed that some further changes had taken place, with localised bank erosion, channel widening, and shifting around bars within the active area but no major avulsions had occurred (Figure 7.3.3.(i).E). It was not known of any major flood events which took place at this time, so perhaps this shifting can be attributed to more moderate events of bankfull stage.

In contrast, the 31/8/1961 photograph showed that the 1829 flood channel had been reactivated, indicated by fresh sediment (Figure 7.3.3.(i).F). The main channel was much wider and much more chaotic than in 1955, having attained a more braided planform, with erosion and reworking of the previously stabilising channel side gravels. It is known that a major flood event occurred in the Druie catchment on 11th June, 1956 (see Section 7.3.2.(ii)) with a 24 hour rainfall RI at Glenmore Lodge of around 50 years, and it is likely that this was the principle cause of this disruption. Upstream, it is known that by Glenmore Lodge, channel changes and large scale mobilisation of sediment took place (see Appendix 1.6). By 18/7/1966, the channel planform was largely unchanged, though some bank erosion had occurred and there was some reworking of the occasional bars through intra-channel avulsion (Figure 7.3.3.(i).G), in response to moderate flows. A similar situation was found on 17/9/1968.

In 1973, the flow appeared to be split between the main channel and the previous flood channel beside the Dell suggesting expansion of the channel planform in response to a large discharge. The western channel planform did not seem to have suffered large scale disruption as the channel had already been enlarged by an event of 1956 magnitude. Overall BI at this map-date was increased to 3.14 and this major change was dated to 1970 when two major flood events of high RI (6th June and 16-17th Aug) were known to have affected the Druie catchment (see Figure 5.5.1.(viii)).

Unfortunately, the Druie was bulldozed in 1982 after extensive flooding and sedimentation, when the fish tanks at the Inverdruie fish farm were washed away. Field checking of the area revealed a complex of deep, disused channels running through the trees, although the focus of present activity was clearly to the west. There was frequent evidence of log-jamming and diversion of flow, for example in one area, a large Scots Pine had collapsed into the stream causing considerable scour and localised bank erosion. Such obstructions could have considerable impact on the centres of subsequent erosional activity. It seems that the channel has two major stage dependent forms of adjustment. Firstly, it has the ability to expand its pattern to a more anabranching form, with reuse of its flood channels, to capacitate discharges well in excess of bankfull. Secondly, with more moderate flows, it will rework sediment within the channel and erode its banks.

7.3.4 Spey study reach 4: The River Feshie near Lagganlia

This wandering reach, draining 204.5 km^2, has the highest rates of activity within the entire Spey study area, with a continual shifting and abandonment of channels. This is associated with both intra- and extra-channel avulsion. Sediment supply is abundant, through upstream lateral channel migration into kame deposits and first terrace features. Position within the channel system typology is outlined in Table 7.3.4.(i).

On Roy's map (1750s), this reach was shown as both wandering and braided with extensive channel side gravels (Figure 7.3.4.(i).A). Upstream of the confluence with Allt na Mharcaidh, there were two large medial bars and above this there was a highly sinuous, wide and fragmented channel pattern. Palaeochannels extended well beyond the active area of the 1873 channel and can be seen accentuated by differential vegetation cover on the aerial photographs. Indeed many of these palaeofeatures must be pre-1750. In 1873, the channel split around occasional braid bars and had a braiding index of 1.54 but the active area of the channel could be 3-4 times the stream width. Upstream and locally, there were extensive reserves of sediment by and within the channel, indicating that the river had consistently shifted its channel. It was certain from Lauder's (1830) description of the extent of 1829 flooding in Glen Feshie, with the destruction of

Table 7.3.4.(i)

Position of Spey study reach 4: The River Feshie near Lagganlia within the map-based channel system typology

A (a) Basin area: 204.5 km^2

(b) Average height: 250 m

	1873	1902	1969
B (a) UPSEDMT:	3	3	3
(b) LOCSEDMT:	3	3	3
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	2	2	5
(b) BANK VEGETATION:	2	2	3
(c) BAR VEGETATION:	8	8	8

E MAXWID 64

F (a) CHANPATT:	4	4	4
(b) ISLANDS:	4	5	5
G (a) ACTIVITY:	2	2	2

Spey study reach 4: The River Feshie near Lagganlia

Figure 7.3.4.(i)

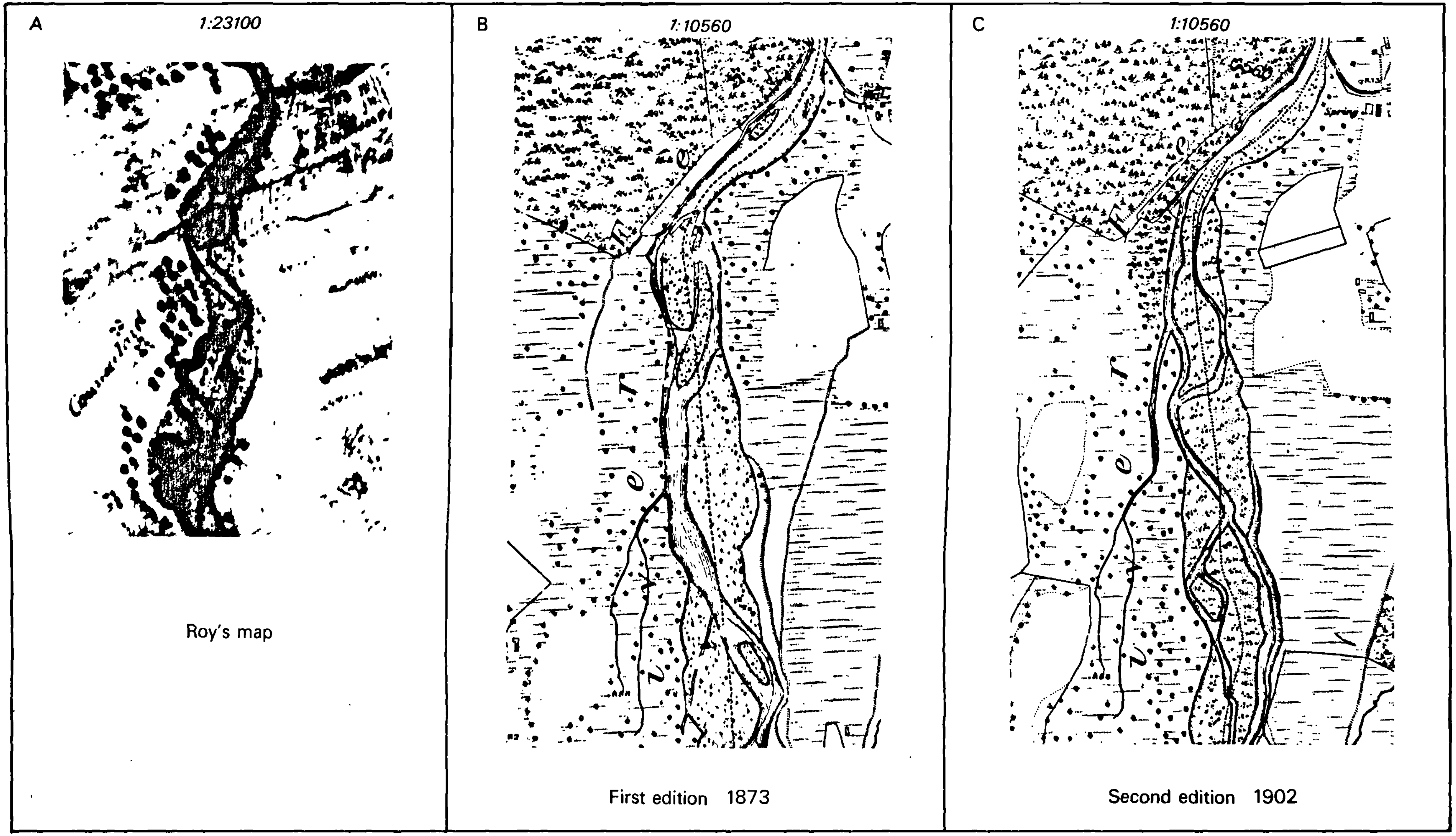


Figure 7.3.4.(i)

Spey study reach 4: The River Feshie near Lagganlia

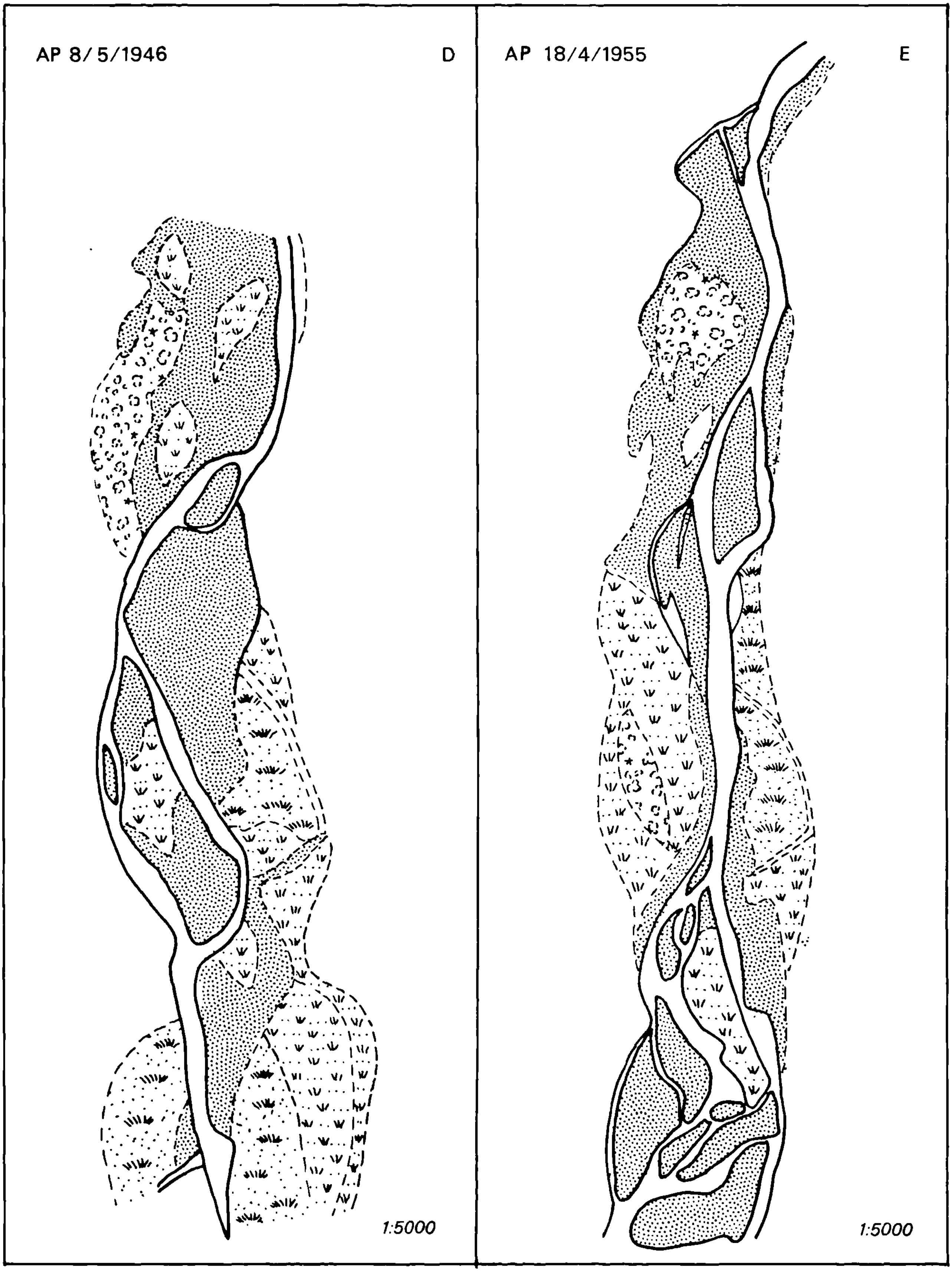
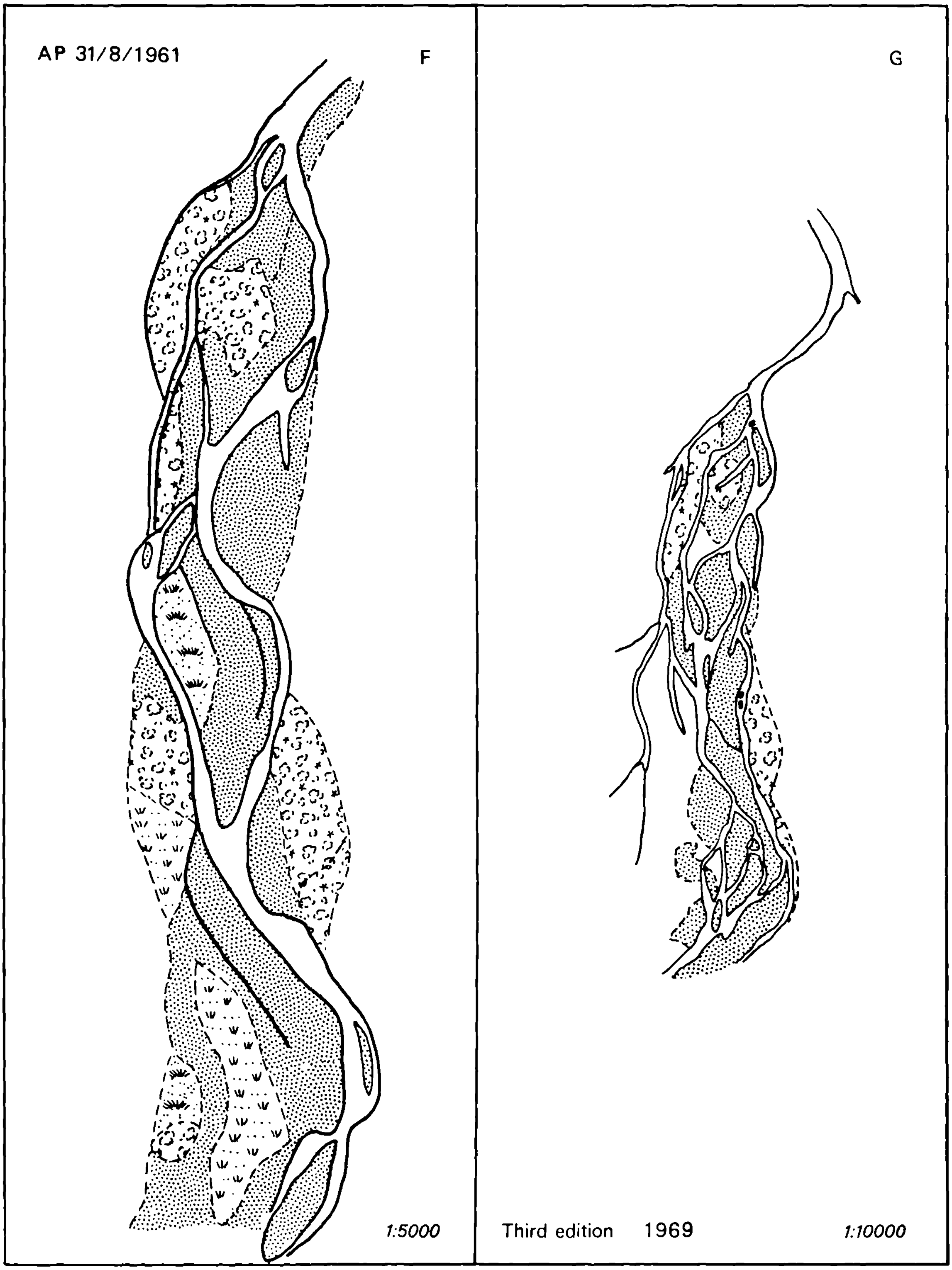


Figure 7.3.4.(i)

Spey study reach 4: The River Feshie near Lagganlia



channel-side trees, that major disruption and mobilisation of sediment must have taken place. It appeared that this flood flow had cut through the sinuous bends and reworked medial bars, indicated on Roy's map.

By 1902, the channel planform had become even more disrupted and the braiding index had increased to 1.87 upstream and 1.69 downstream. The channel was frequently braided around large, unvegetated, gravel bars principally through intra-channel avulsion and no stabilisation of channel-side sediment had taken place. Presumably, the high frequency of moderate to extreme flood events described by Calderwood (1909) must have reworked this area several times over, not allowing the channel to regain a quasi-equilibrium condition.

From the first available aerial photograph (8/5/1946), it could be seen that the active area had been further widened, with sub-sections of the floodplain at varying stages of stabilisation (Figure 7.3.4.(i).D). The channel pattern alternated between split and bar-less sections of the channel. There was one large highly braided area, with evidence of overbar flood flow channels. This large-scale widening may be related to the Jan, 1937 flood, which was a major event within the catchment. Between 8/5/1946 and 18/4/1955, again there had been major change with a more complex braiding pattern (Figure 7.3.4.(i).D and E) though no major flood event was known to have occurred. The channel must therefore be able to shift as a response to more moderate flows. Stabilised areas had been cut back and in certain areas, the Feshie had shifted completely across its present active area with the channel becoming fragmented around numerous small gravel bars. There seemed to be an alternation between brief single reaches and highly disrupted areas.

Even three months later in a subsequent aerial photograph, there has been some simplification of planform but basically the same pattern persisted.

By 31/8/1961 again there had been major changes in channel pattern, with a large expansion in use of the active area. It was not merely that old flood channels were being reused but rather that the Feshie seemed to rework its whole active area regularly. It is known that a major event occurred on 30th Jan, 1956 but the discharge RI was not in excess of 10 years though despite this, extensive reworking had taken place. The Feshie was however unpredictable as to which area of the floodplain it would rework next.

By the third edition (1972), there had been a large change to the system, clearly reflected in the change in BI (downstream 1.69-2.87 and upstream 1.87-2.98). The whole area had become highly braided, mainly through intra-active area avulsion and bank erosion, and with this massive disruption, a much increased unstabilised active area was being reworked. This planform change could probably be attributed to the 28th Sept, 1961 event (RI > 30 years), though subsequent more moderate events had already shifted and reworked sediment. An increasingly disrupted planform had occurred, especially since 1955. It appears that less extreme events (RI=30-50 years) can still cause major planform change and the active area is progressively expanding and not being allowed to stabilise.

Plate 7.3.4.(i)

The wide, braiding channel of the River Feshie near Lagganlia

Field study showed a highly unstable area, with a wide, braided channel (Plate 7.3.4.(i)). The landowner at Lagganlia claimed that at this reach, the Feshie changes "from day to day", with large scale cutting upstream on to agricultural land. Some unsuccessful attempts have been made to counter the erosion problem, with banks reinforced every 2 years; field survey indicated high rates of bank erosion. Rates of planform change contrast with those found by Werritty and Ferguson (1980; 1983) for the upper braided reach. Upstream, process-response involved a binary switch between two main channel alignments and an alternation between a braided and meandering main channel depending on the inter-arrival time of the last major event. Downstream, planform change appears more rapid and certainly much more complex.

7.3.5 Spey study reach 5: The River Tromie near Tromie Lodge

This study reach on the middle Tromie, with a catchment area of 119.5 km^2, has a sinuous planform with occasional bars. There are not the same reserves of local and upstream sediment characteristic of several other Spey study sites eg. on the Feshie. Position within the channel system typology is indicated in Table 7.3.5.(i).

Roy's map showed the Tromie valley floor to be densely tree-covered (Figure 7.3.5.(i).A). The actual channel was sinuous with no indication of any channel division. Unlike the other study catchments, the Tromie was relatively unaffected by the 4th August, 1829 event (Lauder, 1830) and thus large scale activity at the slope/ river interface and

Table 7.3.5.(i)

Position of Spey study reach 5: The River Tromie near Tromie Lodge within the map-based channel system typology

A (a) Basin area: 119.5 km^2

(b) Average height: 297 m

	1870	1903	1973
B (a) UPSEDMT:	1	1	1
(b) LOCSEDMT:	1	1	1
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	3	3	2
(b) BANK VEGETATION:	1	3	2
(c) BAR VEGETATION:	1	3	8

E MAXWID 19

	1870	1903	1973
F (a) CHANPATT:	3	3	3
(b) ISLANDS:	3	3	2
G (a) ACTIVITY:	2	9	8

Figure 7.3.5.(i)

Spey study reach 5: The River Tromie near Tromie Lodge

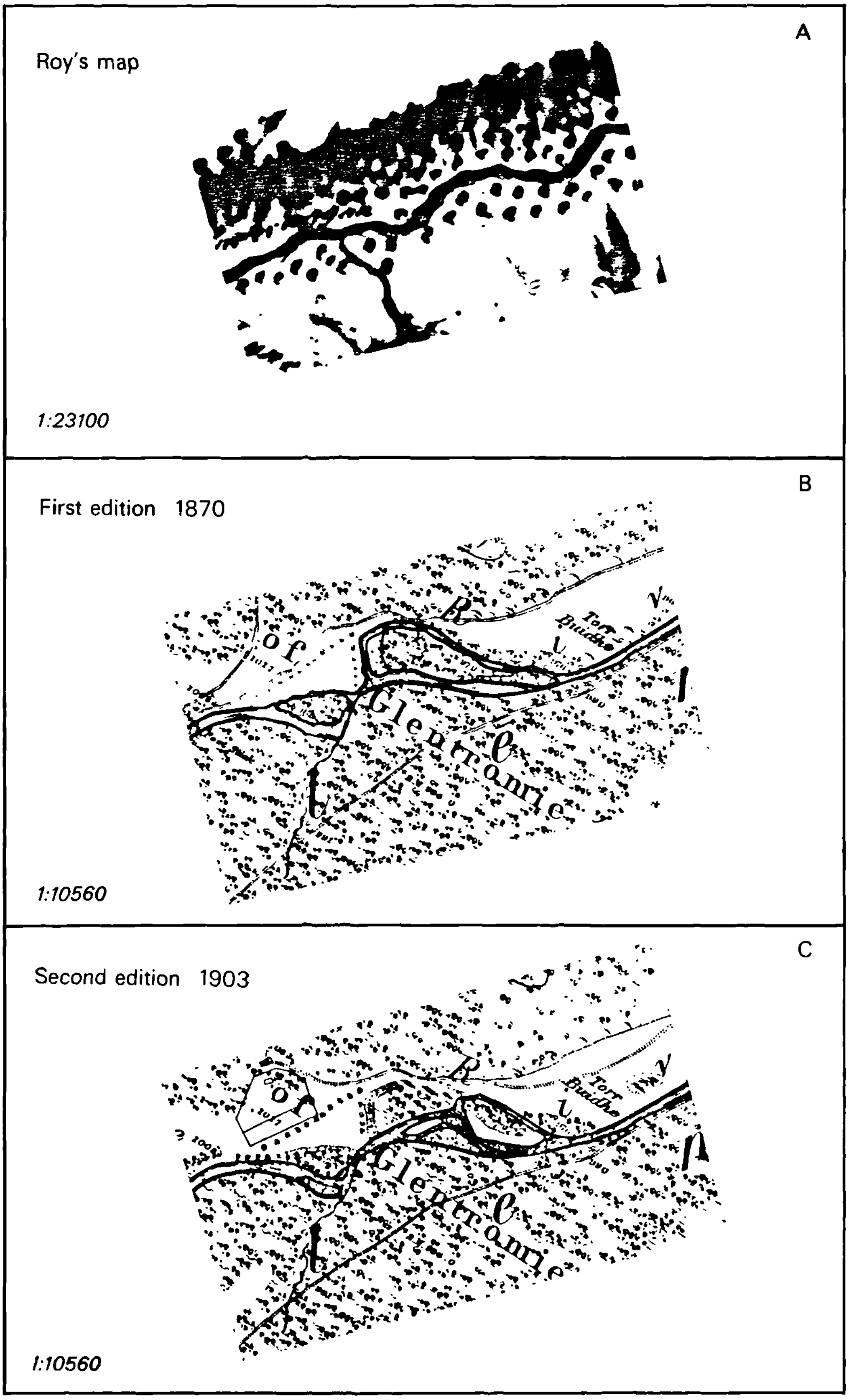
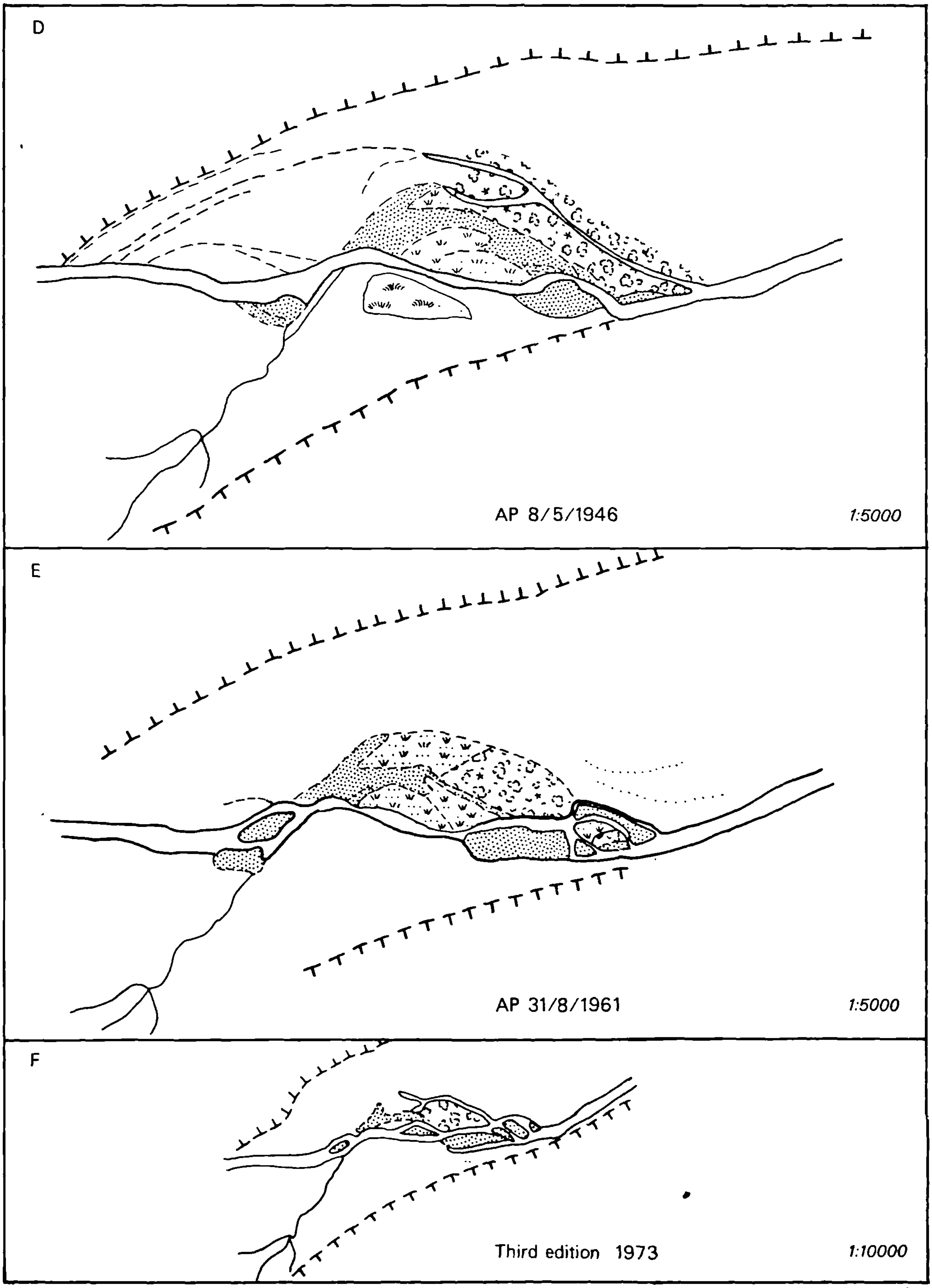


Figure 7.3.5.(i)

Spey study reach 5: The River Tromie near Tromie Lodge



consequent sedimentation did not seem to occur. In 1870, the study reach was split around two large, stable, tree-covered bars, with a BI of 1.48 (Figure 7.3.5.(i).B). There was no sign of recent disruption, no indication of channel-side sediment and only localised evidence of one tree-lined palaeochannel. The channel pattern thus appeared comparatively stable.

By 1903 however, there had been a major alteration of channel pattern (Figure 7.3.5.(i).C). One major bar had been cut through and upstream the Tromie had switched entirely to the eastward channel with unvegetated sediment remaining by the channel side. A considerable stress would have been necessary to disrupt and rework the bar surface and this most likely can be attributed to the major flood event reported in 1881, with a RI of over 50 years.

Between 1903 and the first aerial photograph in 8/5/46, it is known that two high RI flood events (3/11/1931 and 24/1/1937; RI of approximately 50 years) occurred (Figure 5.5.1.(vi)). During the same period, the channel had altered and simplified to a single channel with no bars, although several disused channels still continued to hold ponded water (Figure 7.3.5.(i).D). The planform had thus crossed a significant change threshold since 1870. Unfortunately, the next photograph was not until 31/8/1961 and localised change in planform had taken place with small scale widening of channel, reworking of bank material and the accumulation of both localised medial and lateral bars (Figure 7.3.5.(i).E). It is known from the Tromie bridge gauging record (commencing 8/9/1952) that between 1952 and 1961, only two flows of over 100 m^3 s^{-1} occurred, with RIs of 15 and 30 year respectively (in 1953 and 1958). However, the 1958 event was the higher with a specific runoff rate of 1.19 m^3 s^{-1}. This however was not of sufficient magnitude to cause major channel disruption. Either the earlier events were sufficiently larger in size to exceed a change threshold or the channel planform had become more resistant to change; the former is more likely. After such geomorphic thresholds have been exceeded, there may be a time-lag before such thresholds can be crossed again.

The next photograph was at 31/8/1964 and again the planform had altered little, even though another moderate runoff event had occurred (28th Sept, 1961). A similar situation was found in 1973, with ponded water still found within the former anabranch. Field checking in 1984 showed that despite localised widening and bank erosion, this basic planform was still maintained. Obviously sufficient competence thresholds have not been attained to remove the plugs of sediment from the old anabranch channels. In terms of channel planform change, the 1931 and 1937 events in close succession (with approximately 50 year RI) were the dominant land-forming stresses and present day planform is still an indication of their effectiveness. Features of more recent scouring and erosion were however evident by the channel margins as well as more recent flood channels (Plate 7.3.5.(i)).

Plate 7.3.5.(i)

A sinuous planform (formerly around occasional stable bars) on the middle Tromie

A more recent flood channel is evident in the foreground.

7.3.6 Spey study reach 6: The River Avon near Tomintoul

The study reach on the River Avon near Tomintoul, with a drainage area of 205.7 km^2, has a periodically split channel, which has changed its planform at all three map-dates. The reach is confined to the west by a conglomerate cliff and by first terraces to the east. Position within the channel system typology is outlined in Table 7.3.6.(i).

Roy's map did not indicate a split channel but rather a tree-lined sinuous planform (Figure 7.3.6.(i).A). Since 1750 and before the first edition (1869), the Aug, 1829 event occurred, which had particularly high discharge RI within the Avon catchment (250-500 years; Figure 5.5.1.(x)). From the Tomintoul rainfall estimates (Chapter 5.5.7), this event must have been even more extreme on higher ground. Discussing the flood impact near Tomintoul, Lauder (1830) states:

"The whole valley was covered by the flood, the river appearing like a vast moving lake, where it was impossible to distinguish the real channel except from the greater velocity of its current." (Lauder, 1830 p188)

The first edition (1869) showed a sinuous channel with occasional gravel islands and much sediment by the channel sides, resulting from a widening by a much larger discharge. There had been plenty of local and upstream change, with a possible weakening of banks. Despite this increase in active area, no major disruption of planform remains 40 years after the 1829 event. By 1903, a much larger change had taken

Table 7.3.6.(i)

Position of Spey study reach 6: The River Avon near Tomintoul within the map-based channel system typology

A (a) Basin area: 207.0 km2

(b) Average height: 301 m

	1869	1903	1973
B (a) UPSEDMT:	0	0	0
(b) LOCSEDMT:	1	1	1
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	3	3	3
(b) BANK VEGETATION:	3	3	3
(c) BAR VEGETATION:	8	8	0

E MAXWID 20

	1869	1903	1973
F (a) CHANPATT:	3	3	5
(b) ISLANDS:	2	4	2
G (a) ACTIVITY:	2	8	8

Figure 7.3.6.(i)

Spey study reach 6: River Avon near Tomintoul

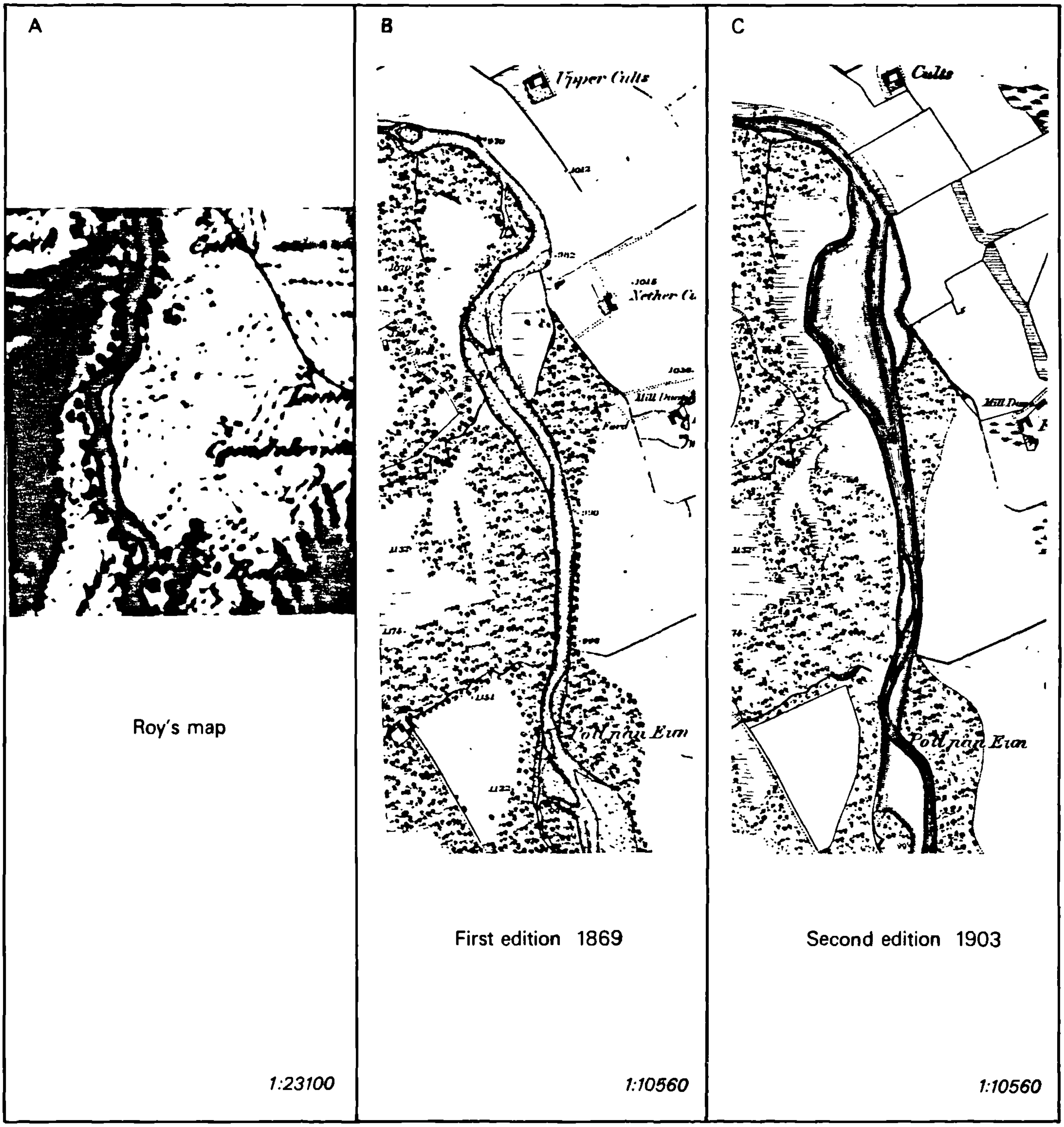
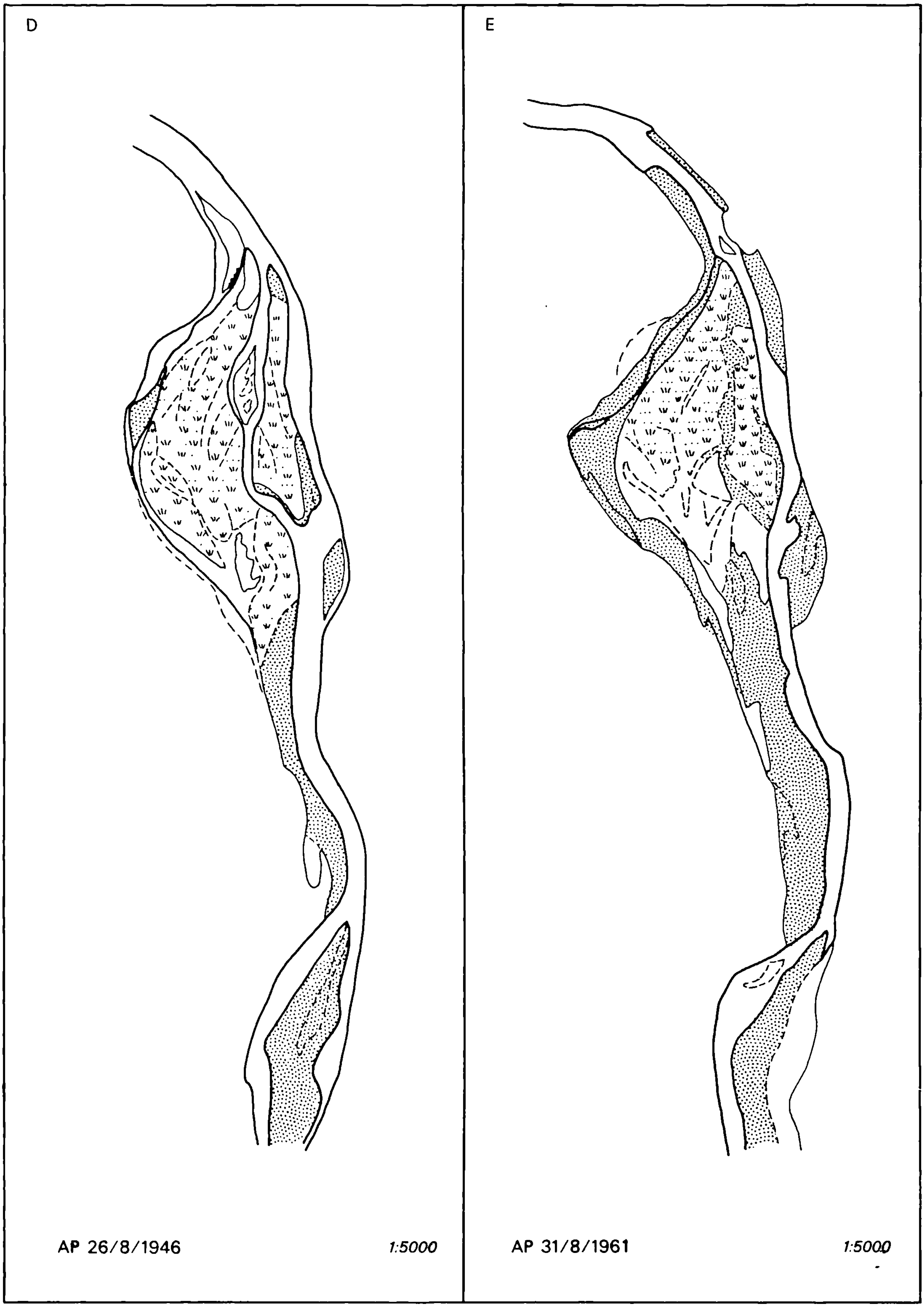


Figure 7.3.6.(i)

Spey study reach 6: The River Avon at Tomintoul



place, with the braided index increasing from 1.31 to 1.46 as a major new anabranch formed. This may have been associated with either the 1873 or more likely the 1892 flood events (Figure 5.5.1.(x)), the latter ranking second to the 1829 event within the Avon catchment. This planform change reworked a large amount of former agricultural land to the east and there were large amounts of local sediment incorporated into the channel, especially in the form of a large medial bar that split the flow near Lynachork. A major change threshold had thus been exceeded. However, the level of this threshold for change had probably already been lessened by the channel widening of the 1829 event and in subsequent more moderate flows associated with the increased rainfall/ discharge POT of 1870-1880.

By 26/8/1946, flow had switched almost entirely to the new channel cut pre-1900, though minor flow still persisted through the old channel (Figure 7.3.6.(i).D). Some of the new medial bar surface had been stabilised by vegetation but there were signs from the supra-bar channels on the surface that this feature was frequently flowed across during periods of higher stage. The bar form had also been reworked to the west with the formation of a smaller more local anabranch system cf. the major feature of 1900. There was no extreme flood event recorded over that period (though 22/9/1927 probably had a high flow with 111.5 mm rainfall in 96 hours at Ballindalloch). If this event did not disrupt the channel planform then it must therefore be assumed that the channel switch was a response to a more moderate flood.

By 31/8/1961, the flow had reverted entirely to a channel to the east and thus since 1869, the channel had reworked an extensive amount of its flood plain. This disruption must be attributed to the 25th Aug, 1966 (discharge RI of 35 years at Delnashaugh). A large proportion of the former channel was now distant from the main focus of channel activity (Figure 7.4.6.(i).E). By 1966 however, there had been little further change despite a shifting of flow east-wards, which eroded into a large medial bar. In 1973 (third edition), a similar pattern again persisted despite the occurrence of several major flood events on the Avon, especially that of 16/8/1970 with a rainfall RI of 100 years at Ballindalloch (see Figure 5.5.1.(x.)). The channel planform thus underwent more large-scale disruption with the increase in moderate to extreme flows pre-1900, than with isolated extreme events recorded within the gauged record. These have been important in more minor intra-channel avulsions, widening the channel to the east and reworking sediment within the channel.

Field survey showed that upstream of this large split area, the reach was much more constrained by a large conglomerate bank, thus explaining the lack of upstream movement. Downstream, the floodplain widens to provide a much larger potential active area, associated with a series of old flood channels and a relatively shallow braided channel (see Plate 7.3.6.(i)). The west flood channels are now disused and despite the consistency of channel pattern post 1961 and the revegetating of former channels to the west, bank erosion and widening are still very much a problem to the east. There is slumping at the side of the channel and a large scourpool at one point. To the east,

Plate 7.3.6.(i)

Widening of the Avon's potential active area near Tomintoul (looking north to south). Palaeochannels (dating 1869/1903) are evident to the right of the present channel.

there is embanking and other evidence of attempts to stop encroachment on to agricultural land upstream by reducing undercutting of the first terrace.

7.3.7 Spey study reach 7: The River Avon at Foals Craig

The Avon at Foals Craig, draining of 110 km^2, has changed its planform regularly in all three editions. It has several different sediment sources, namely upstream fluvioglacial material, local undercutting of terraces and also the basal undercutting of large, primarily fossil fans (see Figure 7.3.7.(i)). The channel's braided pattern is spatially isolated and immediately upstream and downstream, the planform is sinuous and without bars. Position within the channel system typology is outlined in Table 7.3.7.(i).

From Roy's map (1750), there was no indication of any braiding with a sinuous channel and scattered trees on the floodplain. Unfortunately, Lauder (1830) did not document in detail any change in this subreach of the Avon but a conservative estimate of discharge made at Poll-du-ess (Chapter 5) indicates that it was a highly extreme flood event. It was also reported that a large amount of sediment entered the Avon around the Inchory area. For example, in the Hill of Delnatit near Inchory, several openings appeared and a number of considerable landslips took place eg. a great landslip above Torbain. Lauder (1830) cited another example:

Table 7.3.7.(i)

Position of Spey study reach 7: The River Avon at Foals Craig within the map-based channel system typology

A (a) Basin area: 122.3 km^2

(b) Average height: 381 m

	1869	1902	1971
B (a) UPSEDMT:	1	1	0
(b) LOCSEDMT:	2	2	2
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	4	4	4
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	6	6	0

E MAXWID 6

	1869	1902	1971
F (a) CHANPATT:	4	4	4
(b) ISLANDS:	4	5	1
G (a) ACTIVITY:	8	8	8

Figure 7.3.7.(i)

Spey study reach 7: The River Avon at Foals Craig

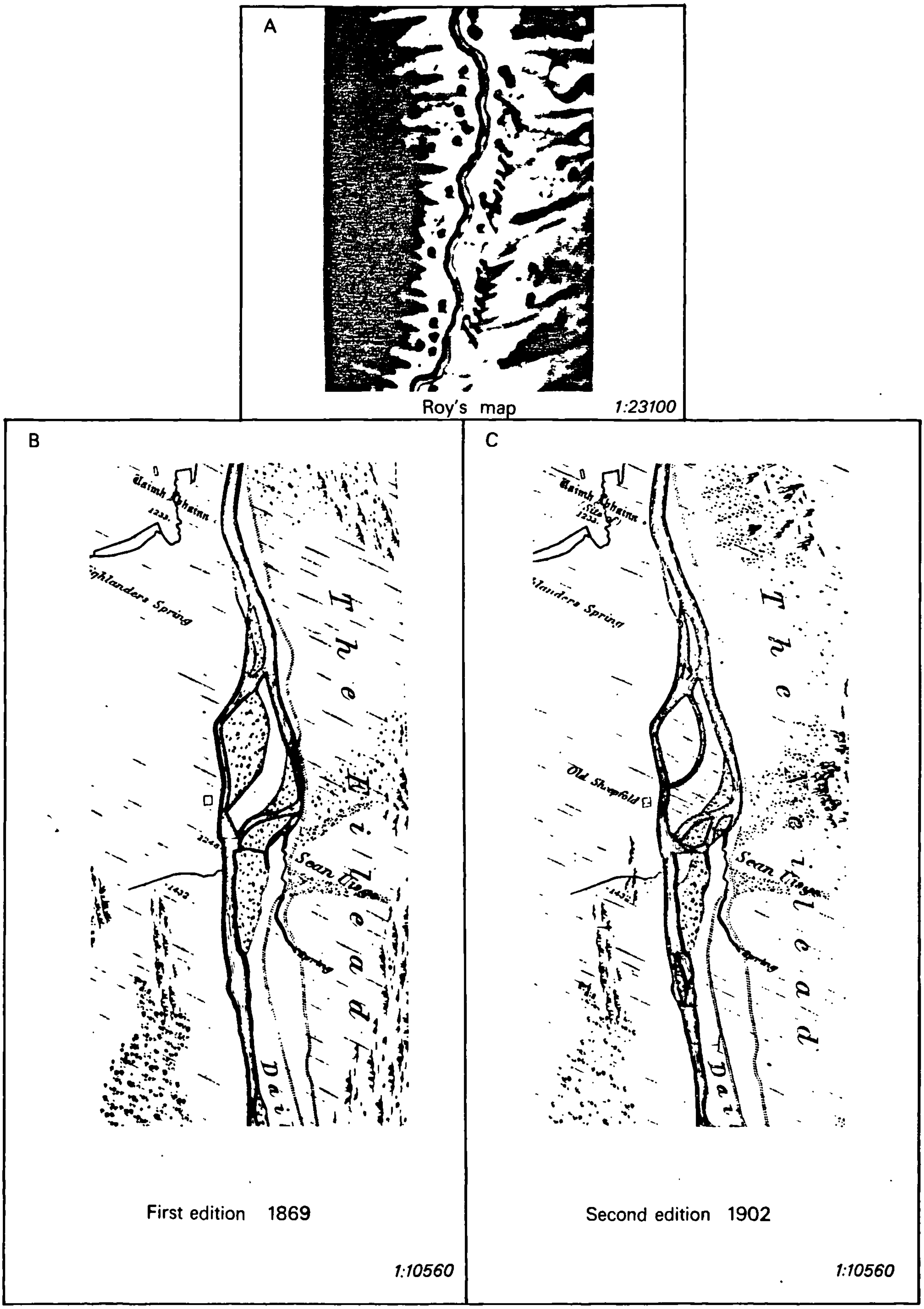


Figure 7.3.7.(i)

Spey study reach 7: The River Avon at Foals Craig

"...below Dalestie, which brought down about 500 yards [458 m] of hill, measuring from "above downwards", till it reached the haugh. No less than 15 acres [6 ha] of the haugh have been carried away or ruined by the river." (Lauder, 1830 p187)

A monument near Inchory, which had stood "for many ages", was also swept away, suggesting in terms of flow magnitude that the 1829 flood event was inundating and reworking floodplain areas that had been previously untouched for a considerable time. Thus in 1869, the channel was no longer sinuous in the Foals Craig reach and there were extensive reserves of unvegetated sediment, both within and by the channel. This area seemed to have acted as a sediment trap for material moving downstream; upstream, there was only localised sediment beside the channel. The BI was 1.71 and there was a major avulsion, which had obviously been ripped through the floodplain. The original path (pre-1829 ?) of the channel was impossible to discern. By 1902, the channel planform was more fragmented, with the major bars dissected (Figure 7.3.7.(i).C). It is known that two major flood flows occurred in 1873 and 1892 (Figure 5.5.1.(x)) and there must have been associated reworking of available sediment. Some of the 1869 active gravels had stabilised but in fact overall, there was a increase in BI to 1.94 for the whole reach.

In complete contrast, the first aerial photograph (3/7/1946) showed a very different sinuous channel, with no major bars. It appeared that some sort of stabilising work had taken place in response to an economically unacceptable degree of channel reworking, although the old braiding pattern of the river was clearly visible, as seen in Figure 7.3.6.(i).D. It is known that 1927 was an exceptional year on the Ballindalloch rainfall record with 5 POT of 24 hour duration >24.5 mm. Major flooding is likely to have occurred on the Avon, as a result of prolonged rainfall over 22-25th Aug, 1927 (Figure 5.5.1.(x)).

Two years later (14/5/1948), the planform had been contained by these steps taken to counter erosion and had not reverted to a braided form. Unfortunately, the next aerial photograph was not until 1/9/1964 but a major change had occurred in the location of the channel, which was now undercutting the banks to the east, with a minor split of flow along the former alignment. The stabilising floodplain of 1948 had obviously been reworked, with the removal of stabilising vegetative cover. Several events in excess of 300 m^3 s^{-1} occurred at Delnashaugh over this period eg. 25th Aug, 1960 (discharge RI of 35 years) but the disruption seemed recent, and during such high flows the 1902 braiding pattern had clearly been reactivated. There was some overbar flow and a minor increase in BIs (Figure 7.3.7.(i).E). Presumably, immediately post-flood, the channel was more disrupted in terms of medial bars but it had since recovered. By 21/7/1966, the planform had reverted to a single, low sinuosity channel, a modification that must be related to more moderate flows (Figure 7.3.7.(i).F). The 1971 map indicated that there was still some flow through the Foals Craig side channel, but basically that channel had retained its 1966 planform. Sinuosity was very low (1.03) and BI was 1.00.

Field checking confirmed that this reach has been prevented from returning to its old flood path by the bulldozing of former bed material to the side of the channel (since 1966). The whole area is however extensively covered with gravel. Stagnant water in the old braid channels suggests that with a high increase in flow, these were reused. However, the longer the flow remains constrained within the straightened channel, the larger is the discharge required to reoccupy these old channels and to rework the floodplain. The W:d ratio will decrease as the channel becomes more entrenched and an artificial first terrace will be induced. Banks, although wired up to protect against erosion, are already degrading. It is difficult to assess in what flow stages, these measures will last but an extreme event is still likely to reuse the former braided channel network.

Plate 7.3.7.(i)

The Avon at Foals Craig, showing former channels (1869 and 1900) and former basal erosion of tributary fan deposits

7.3.8 Spey study reach 8: The Dorback Burn near Aittenlia

The Dorback Burn reach, draining 20.4 km^2, is a wandering gravelly river, but at a smaller scale than for example the Feshie at Lagganlia. Upstream, the active area is partially constrained in width by kames, while downstream the channel planform is more stable and restricted by smaller mounds of fluvioglacial debris. The study reach thus has very highly available and accessible sediment. Present day floodplain and bank vegetation are heather and marsh, suggesting frequent floodplain inundation. Position within the channel system typology is outlined in Table 7.3.8.(i).

Estate plans (1811: RHP 13936) and Roy's map (1750) showed that the channel was sinuous but there was no indication of bars. However, Roy's map was too distorted to be included. From Lauder (1830), there was a report of the damage done on this river during the 1829 floods. The Dorback caused serious disruption along its banks, especially at Drum of Dorback, where a house some 12 ft [3.7 m] above the level of the water was swept away, as reported by the local fox hunter:

"It was a' we could do to get to the bank after the hoose was gane, standing as it did on a wee bit plain by the waterside. But that and my garden, field and cornyard are now gane to sea and the place is noo a bare claddoch (barren spot covered with stones)." (Lauder, 1830 p157)

Table 7.3.8.(i)

Position of Spey study reach 8: The Dorback Burn near Aittenlia within the map-based channel system typology

A (a) Basin area: 20.4 km^2

(b) Average height: 297 m

	1869	1900	1972
B (a) UPSEDMT:	2	2	2
(b) LOCSEDMT:	3	3	2
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	4	4	4
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	8	8	0

E MAXWID 50

	1869	1900	1972
F (a) CHANPATT:	3	4	4
(b) ISLANDS:	0	2	3
G (a) ACTIVITY:	8	8	8

Figure 7.3.8.(i)

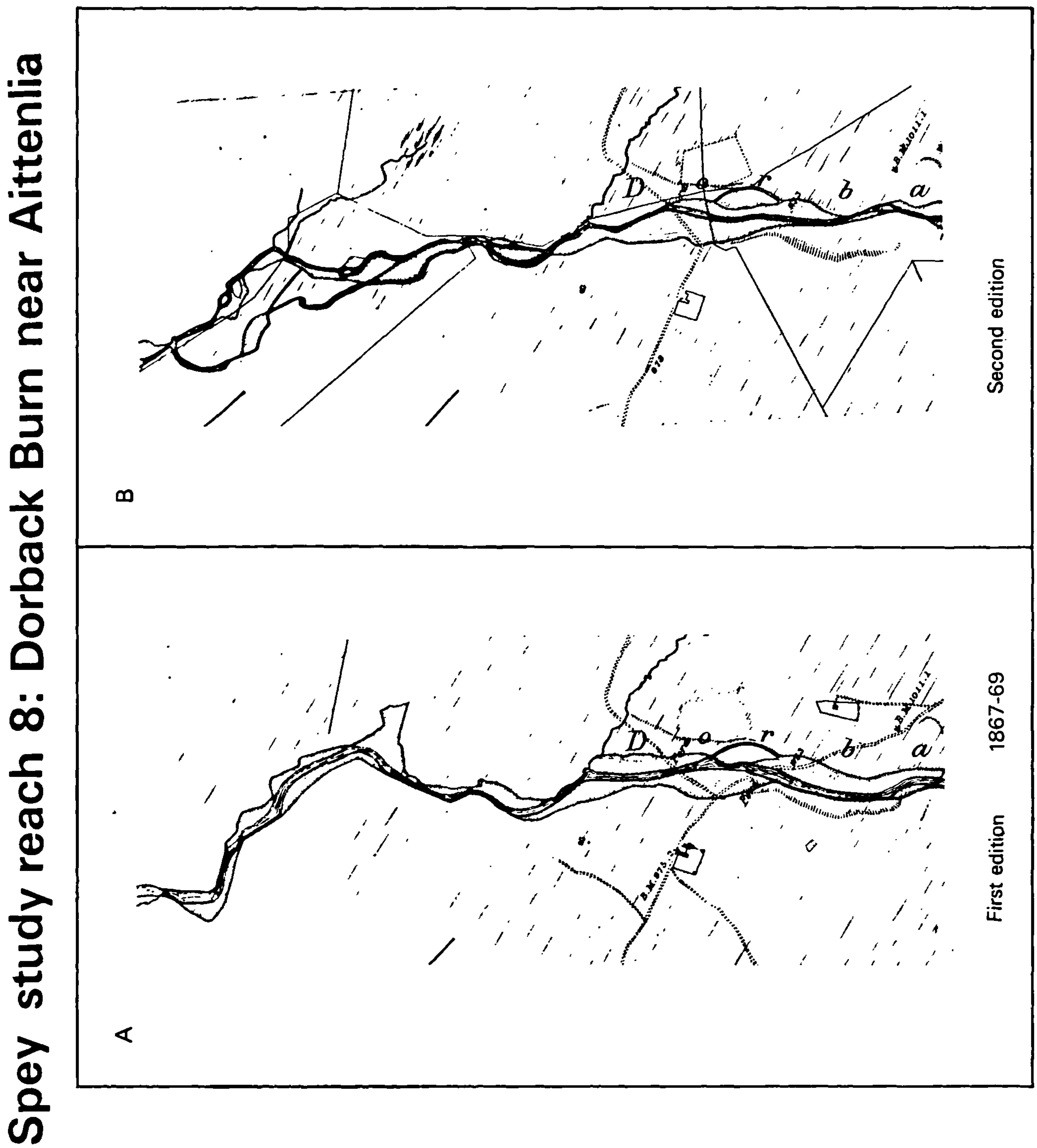

Spey study reach 8: Dorback Burn near Aittenlia
A
First edition
1867-69
B
Second edition
Dorback

Figure 7.3.8.(i)

Spey study reach 8: Dorback Burn near Aittenlia

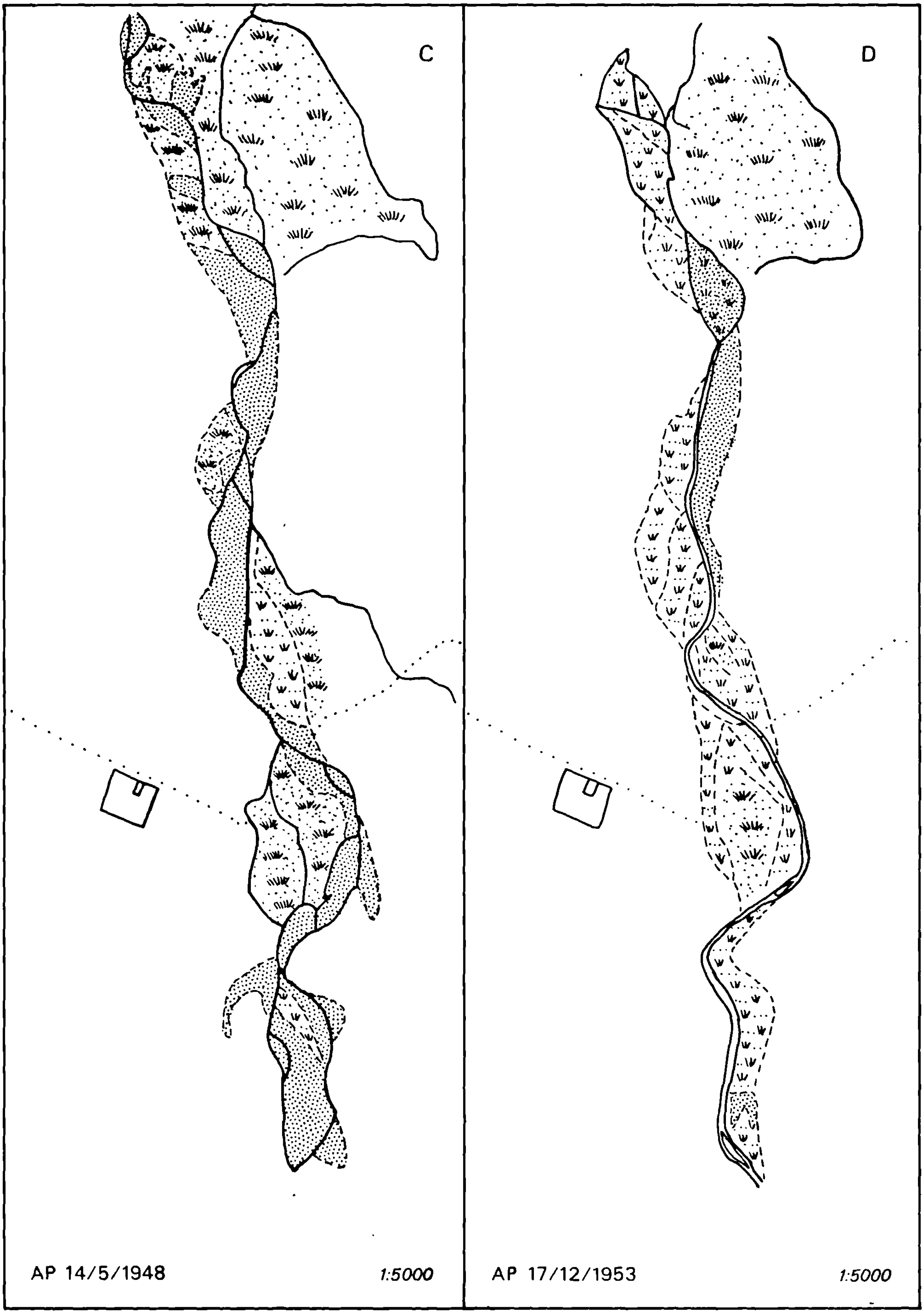
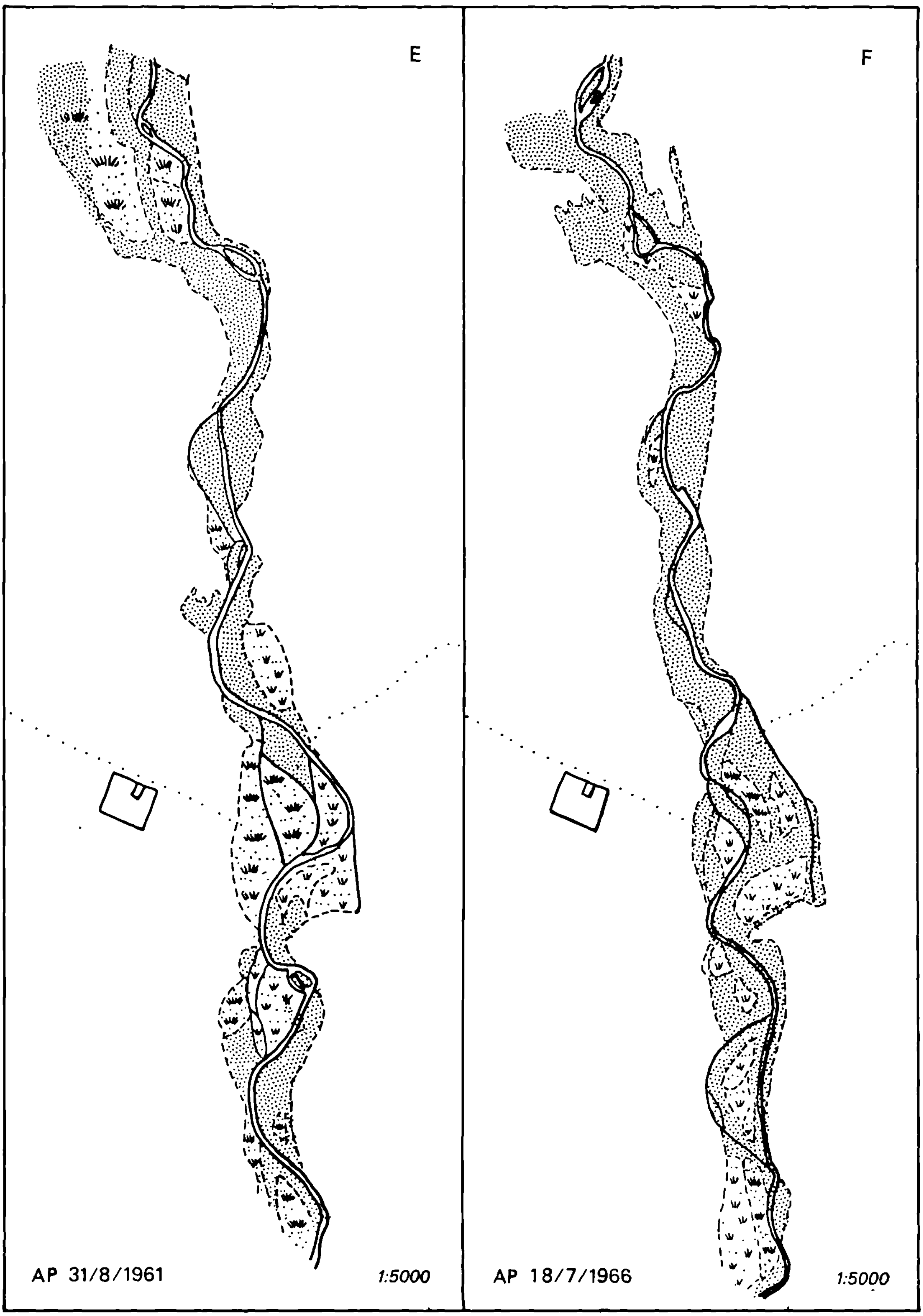


Figure 7.3.8.(i)

Spey study reach 8: Dorback Burn near Aittenlia



In the first edition (1867-1869), this reach followed a sinuous to wandering course with no bars, although there was localised evidence of former flood channels. There were however extensive amounts of channel-side sediment and the actual flow only utilised 0.5 to 0.25 of the available active area. The channel appeared to have been eroded by a much larger flow (1829 flood?; see Figure 7.3.8.(i).A). Between 1867/9 and 1900, a major change had taken place, with shifting of the main centres of erosion and a further widening of the active area (Figure 7.3.8.(i).B). A large extra-channel avulsion had also taken place and this suggested that a major geomorphic stress must have been applied over this period, eg. 1868 or 1892 (Figure 5.5.1.(ix)), to rip through the neighbouring floodplain. In terms of change in planform, the stresses between 1867/9 and 1900 appeared more destructive in terms of planform change rather than just channel widening.

The first available aerial photograph was from 14/5/1948 and the channel planform was highly fragmented and irregular (Figure 7.3.8.(i).C). There was evidence of fresh gravels by the channel side suggesting recent high flows. Clearly, further disruption had taken place post-1900 but the flood record is not detailed enough to state conclusively which events were the cause of this disruption. By 17/12/1953, some anabranches had stabilised from their 1948 planform while others had undergone considerable shift, despite the lack of a major flow within the reconstructed discharge record (Figure 7.3.8.(i).E). More moderate events must thus be important in reducing channel division within the less stable active area, returning the planform towards a more quasi-equilibrium form. Such an equilibrium appears however to be of a highly transient nature.

When the 31/8/1961 photograph was compared with that of 1953, it was clear that a major disruption to the system had taken place (Figure 7.3.8.(i).F). A large scale avulsion had occurred with extensive changes in channel planform, which tended towards a more sinuous and divided channel. The whole of the former active area had been reworked and flood flow distributary development was clearly evident from flood sedimentation. This planform change could perhaps be related to the 1956 flood event (RI in excess of 30 years), which from the reconstructed storm profile, was a major event over this catchment. By 18/7/1966, even more of the available active area had been reworked. Some of the divided channels had reverted back to a dominantly single channel, with occasional bars, but there were still extensive unvegetated areas. The planform had clearly been reworked during the 8th Sept, 1961 event, which affected the neighbouring Feshie catchment.

Field checking in 1984 showed that the whole area was a waterlogged area of marsh. There was evidence of frequent channel switching and a gradual downcutting into the fluvioglacial deposits, as seen by fairly recent flood channels above the height of present erosion. In one area, a new channel was being excavated quite a distance from the old channel where there was still flow. Suprabar flow over an extensive vegetated surface was also taking place, suggesting some recent planform disruption. This chaotic channel pattern suggested that Dorback Burn has been disrupted again since the 1956 event and has not yet been allowed to attain anything like a stable condition. It is known that a major flood occurred over this area in July, 1978 but many features appeared more recent than this (see Werritty, 1984). Thus, since the pre-1900 channel widening and destabilisation, the channel has been disrupted at least 3 times by discharges of RI (30-50) years and a period of high activity has been maintained. The channel seems to attain a temporally reduced braided form through subsequent events of lesser magnitude but is comparatively frequently disrupted. High winter flows may also be important in the redistribution of sediment.

7.3.9 Spey study reach 9: The River Spey near Loch Alvie

The Spey at this reach drains an area of 1011.9 km^2, just above the gauging station at Kinrara. Position within the channel system typology is outlined in Table 7.3.9.(i). The channel planform though at one time highly mobile, with a highly braided planform around large medial bars, has stabilised considerably since 1903.

Roy's map (1750s) defined the area as a sinuous to irregular reach (Figure 7.3.9.(i).A), with some localised trees on the banks; there was no indication of a divided channel. By the first edition (1869) however, the channel had widened with frequent medial bars and much unstabilised sediment in storage within the river channel. The remains of an old flood channel, excavated through the neighbouring floodplain, can be seen in Figure 7.3.9.(i).B. The sinuosity of the main channel was low (1.08). Unfortunately, this reach was not specifically mentioned in Lauder's (1830) account but it was clear that the channel had been disrupted by a major geomorphic force, with an area of

Table 7.3.9.(i)

Position of Spey study reach 9: The River Spey near Loch Alvie within map-based channel system typology

A (a) Basin area: 1011.9 km^2

(b) Average height: 210 m

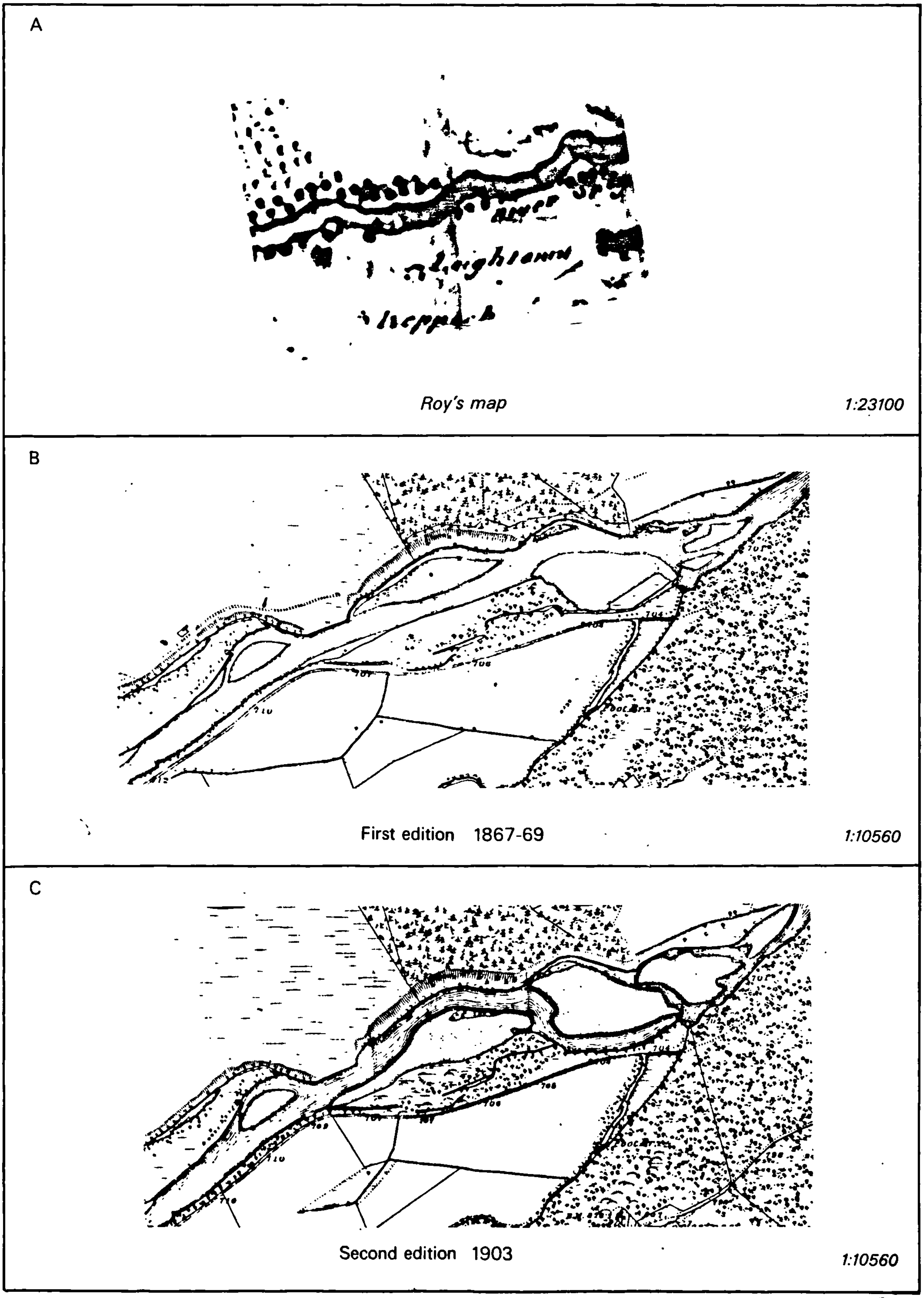
	1869	1903	1972
B (a) UPSEDMT:	1	0	1
(b) LOCSEDMT:	3	3	1
C FLOOD:	0	1	0
D (a) FLOODPLN VEGETATION:	3	3	3
(b) BANK VEGETATION:	3	3	3
(c) BAR VEGETATION:	8	8	3

E MAXWID 16

F (a) CHANPATT:	4	5	5
(b) ISLANDS:	5	5	7
G (a) ACTIVITY:	8	8	7

Figure 7.3.9.(i)

Spey study reach 9: The River Spey near Loch Alvie



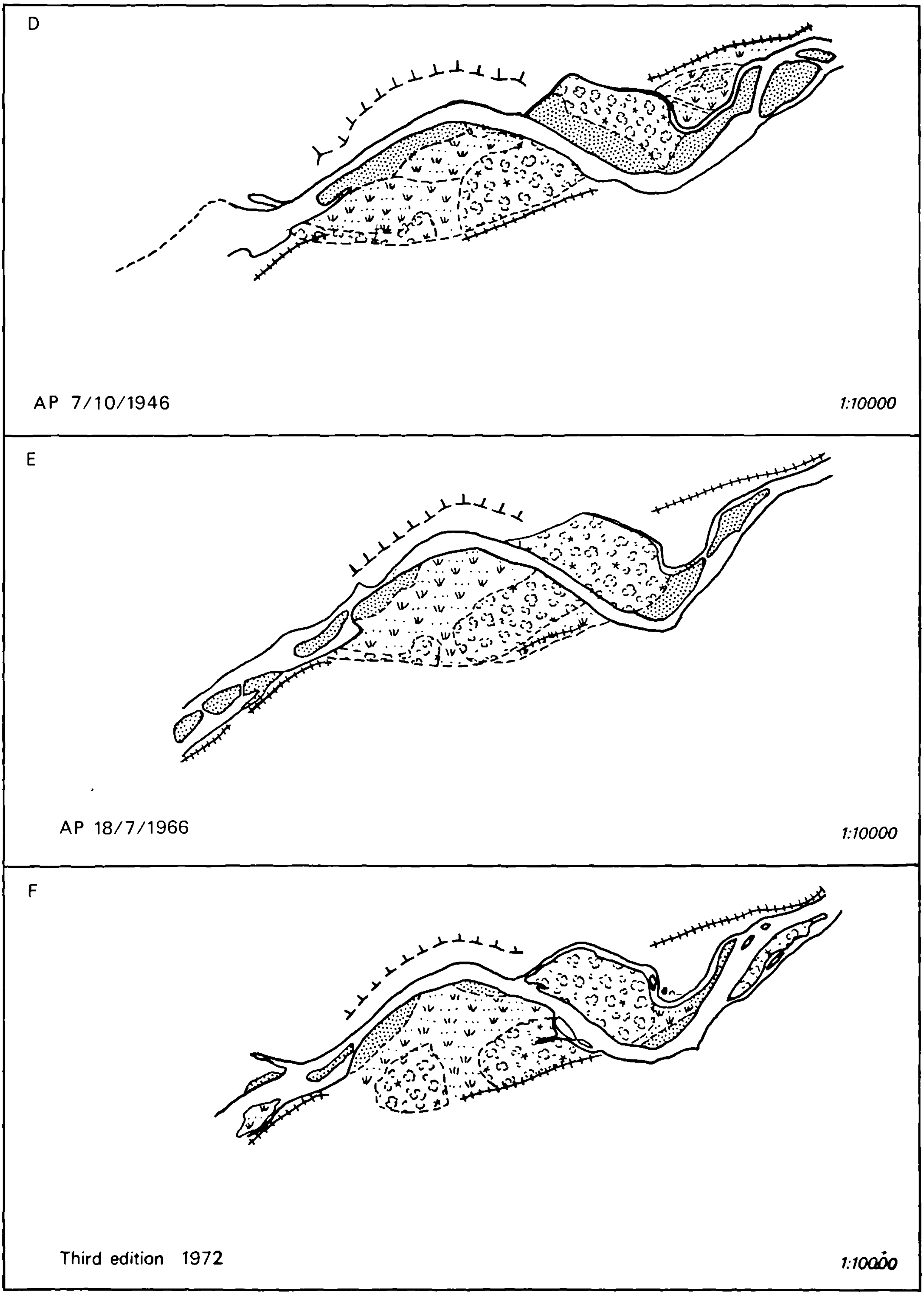
A — *Roy's map* *1:23100*

B — First edition 1867-69 *1:10560*

C — Second edition 1903 *1:10560*

Figure 7.3.9.(i)

Spey study reach 9: The River Spey near Loch Alvie



floodplain downstream indicated as "liable to floods". The 1829 flood is known to have had a major impact on this area of the Spey, in terms of both bank erosion and reworking of sediment. However, at this locality, the 1849 and 30/1/1868 events were also major floods of high RI (>50 years; Figure 5.5.1.(iv)). Thus, three major events had occurred along this reach, with an intervening period of approximately 20 years. This disruption was confirmed by the Kinrara estate plan of Ray (1838; RHP 1837), where this reach was shown to have three large unvegetated braid bars.

By 1903, major widening had again taken place on the southern bank, with two large unvegetated gravel bars increasing in size (Figure 7.3.9.(i).C). The area gave the impression of steadily undergoing sedimentation with the flow gradually having to rework larger amounts of sediment. This sediment was incorporated within the river system from both the undercut fluvioglacial exposures and upstream sources. These fluvioglacial materials had been trimmed back, leaving material stored "in situ" in the channel to be flushed out by larger flows. Coarser sediment inputs from steeper upstream tributaries were also important:

"The Feshie has poured vast quantities of detritus into the Spey valley, levelling up the natural gradient and damming up the upper waters." (Calderwood, 1909 p143)

Clearly, a large proportion of this sediment must be of Feshie origin.

From the later aerial photograph evidence (7/10/1946), palaeochannels were clearly evident (see Figure 7.3.9.(i).D) and these could have been flood channels, occupied with a large increase in discharge. Alternatively, they may indicate that a much more split planform must have occurred post-1750. Since 1903, a significant change in channel planform had taken place, resulting in a much more sinuous main channel. The southern bank of the river has also been heavily cut back, with a change in the focus of erosion. The major medial barforms were stabilising and had become progressively attached to opposite banks, with the minor channels still separating them from the banks, producing a more stable anabranching planform. If there had been a large input of sediment pre-1900, by 1946 there seemed to be a more stabilised planform developed, with well vegetated bar surfaces with trees. The river was still undercutting the fluvioglacial exposure, which was by 1946 unprotected at the base by any bar forms.

Between 1946 and 1955, little planform change had taken place except that stabilisation of some channel side sediment had occurred. This lack of activity took place despite several moderate flood events on the Spey (Figure 5.5.1.(iv)). In comparison to the estimated recurrence intervals of the pre-1900 events, these flows were of lesser magnitude. By 31/8/1961 and 18/7/1966 (Figure 7.3.9.(i).E), these minor channels were decreasing in size and flow appeared to be contained almost entirely within one major channel. This planform persisted in 1975 (third edition) without any major modification, again despite the occurrence of several flood events, as indicated by the Kinrara record. The channel thus appears to have gradually attained a quasi-equilibrium condition, which it had not previously attained since before 1829 and does not seem to be easily disrupted, even by events of moderate to high magnitude (30-50 years RI).

7.3.10 Summary

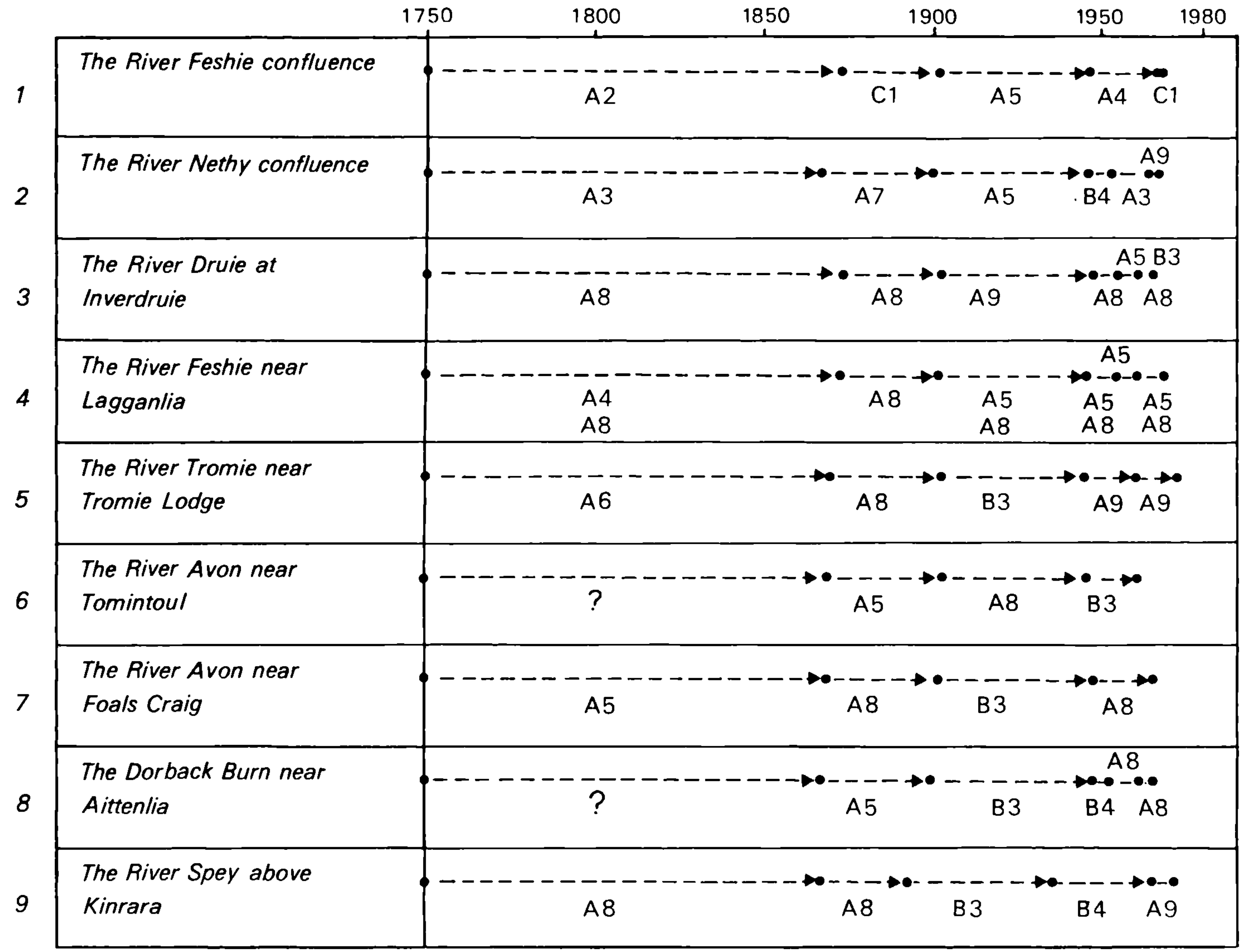
Within the Spey study reaches, there are a range of flows that are geomorphically important. Catastrophic discharges of high recurrence interval, such as occurred on 4th Aug, 1829, have a variety of impacts, depending on the balance of controls within the reach involved, the position of the planform in relation to process thresholds, and the inter-arrival times of subsequent less extreme events. Firstly, the channel can undergo major planform disruption associated with extensive reworking of the floodplain and destruction of former anabranching/ split planforms. This is particularly typical of fan areas, where there is room for large-scale channel reworking without exceeding major erosional thresholds for reoccupation of the floodplain. Associated with such change is the large-scale deposition downstream of fluvioglacial material and the erosion of upstream areas. A large number of these more active reaches are in fact large sediment stores, thus accounting for the ease with which sediment is reworked eg. the Feshie at Lagganlia and Dorback Burn near Aittenlia.

The second major impact is that of extensive channel widening of the pre-flood channel. This was especially typical of wandering channels, such as the Dorback Burn and the Feshie confluence, where large amounts of sediment were flushed through the system. Thirdly, where channel planform already has flood channels excavated by some earlier catastrophic event of similar proportions, then flow can be relieved from the main channel eg. as occurred on the lower Druie. Presumably in that case, there would have been more channel disruption

Modes of channel planform change recorded within the Spey study reaches

Figure 7.3.10.(i

(for key, see Table 4.7.3.(i))



Change in active area

A Increase
B Decrease
C Maintenance
D No change

within the main channel had this not occurred.

In more stable areas, the impact of extreme events is different. For example, in response to an extreme flood of over 50 year RI on the River Tromie, the split channel was locally dissected but there was no major mobilisation of sediment. Artificial strengthened reaches are more resistent to planform change, though where artificially heightened thresholds for change are exceeded, change will still occur eg. the Avon at Foals Craig. The lasting impact of extreme events is also highly variable. A major geomorphic stress may so disrupt the equilibrium of the channel that post flood, a period of disequilibrium continues, periodically enhanced by the disruption of subsequent more moderate floods eg. the Feshie at Lagganlia. It is notable that where major planform change (other than channel widening) did not occur in response to the 1829 event, more moderate floods occurring between 1869-1900 appeared to have a more major impact, in terms of larger-scale disruption. This is because the stress required to exceed erosional thresholds has been lessened. This may have occurred on the Avon near Tomintoul where the channel developed a much wider split planform or along Dorback Burn, where a major extra-channel avulsion occurred.

In relation to more moderate flows, these have a varying impact, dependent on the controls on the reach. Where such flows exceed important competence thresholds, they can be important in intra-channel avulsion and the reworking of medial bars. For example, the Feshie at Lagganlia undergoes regular shifting of its split/ braided channel in response to much more moderate flows (RI < 10 years). In comparison, the planform of the Spey near Loch Alvie is highly resistent to more moderate flows of moderately high recurrence interval (20-50 years).

7.4 Selected reaches within the Tweed study area

The reaches studied within the Tweed study area are as follows:

(1) The Bowmont Water near Attonburn

(2) The lower Boonreigh Water

(3) The Cleekhimin Burn

(4) The Monynut Water near Inner Law

(5) The Dye Water confluence

(6) The River Teviot below Falnash Burn

(7) The River Teviot near Nisbetmill

The location of these reaches within the Tweed study area are shown in Figure 7.4.(i).

7.4.1 Tweed study reach 1: The Bowmont Water near Attonburn

This complex irregular reach with occasional bars on Bowmont Water, with a contributing area of 42.5 km^2, from the map work showed itself to be highly active and disruptable in its channel pattern. Position within the channel system typology is outlined in Table 7.4.1.(i).

From Roy's map (1750's), though detail is limited, this area was shown as having a sinuous planform of large regular meanders, which had a tendency to straighten out downstream of the bridge at Attonburn (Figure 7.4.1.(i).A). There was no indication of trees or other stabilising vegetation but rather furrows indicating ploughed land on

Location of study reaches within the Tweed study area

Figure 7.4.(i)

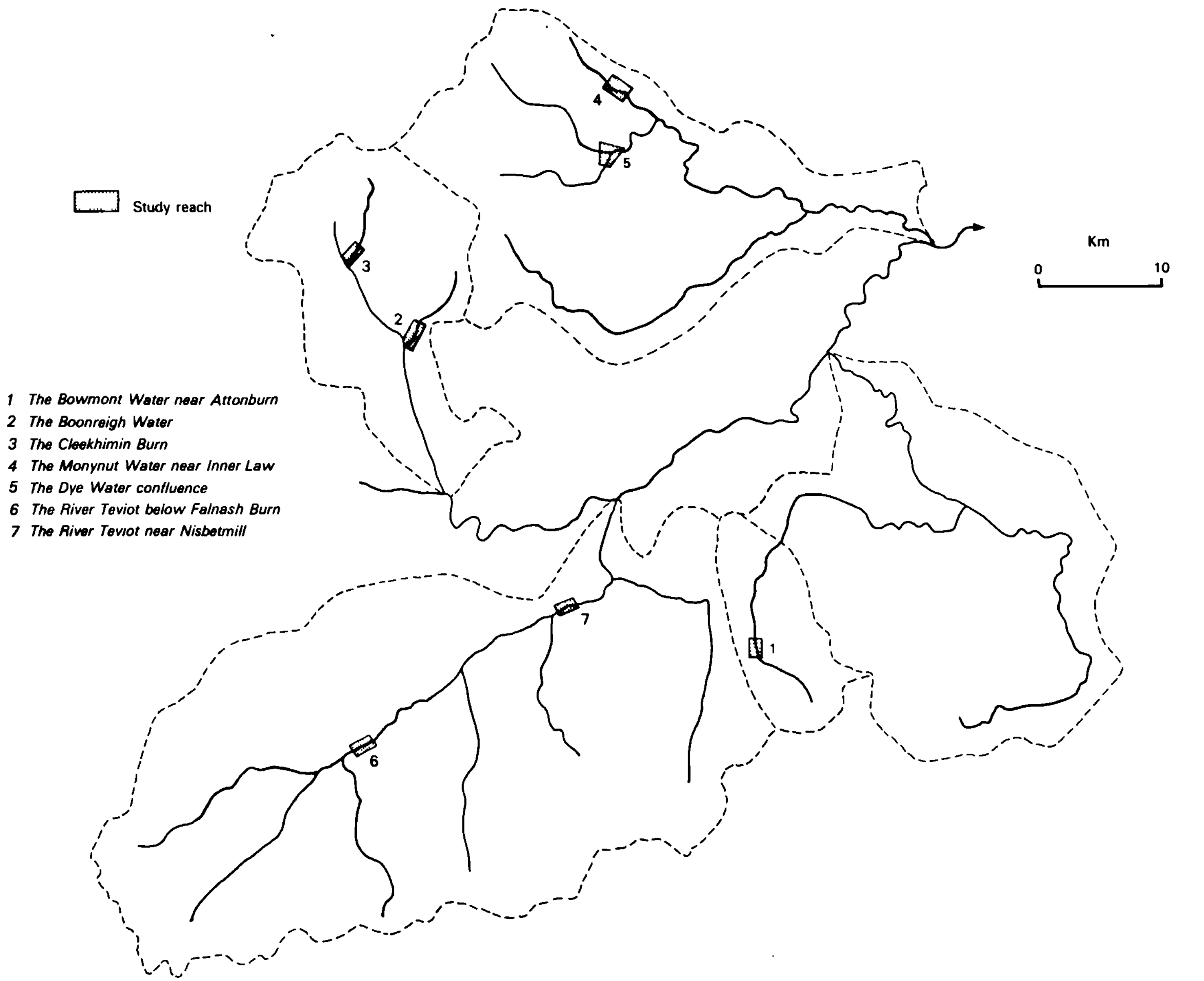


Table 7.4.1.(i)

Position of Tweed study reach 1: The Bowmont Water near Attonburn within the map-based channel system typology

A (a) Basin area: 42.5 km^2

(b) Average height: 150 m

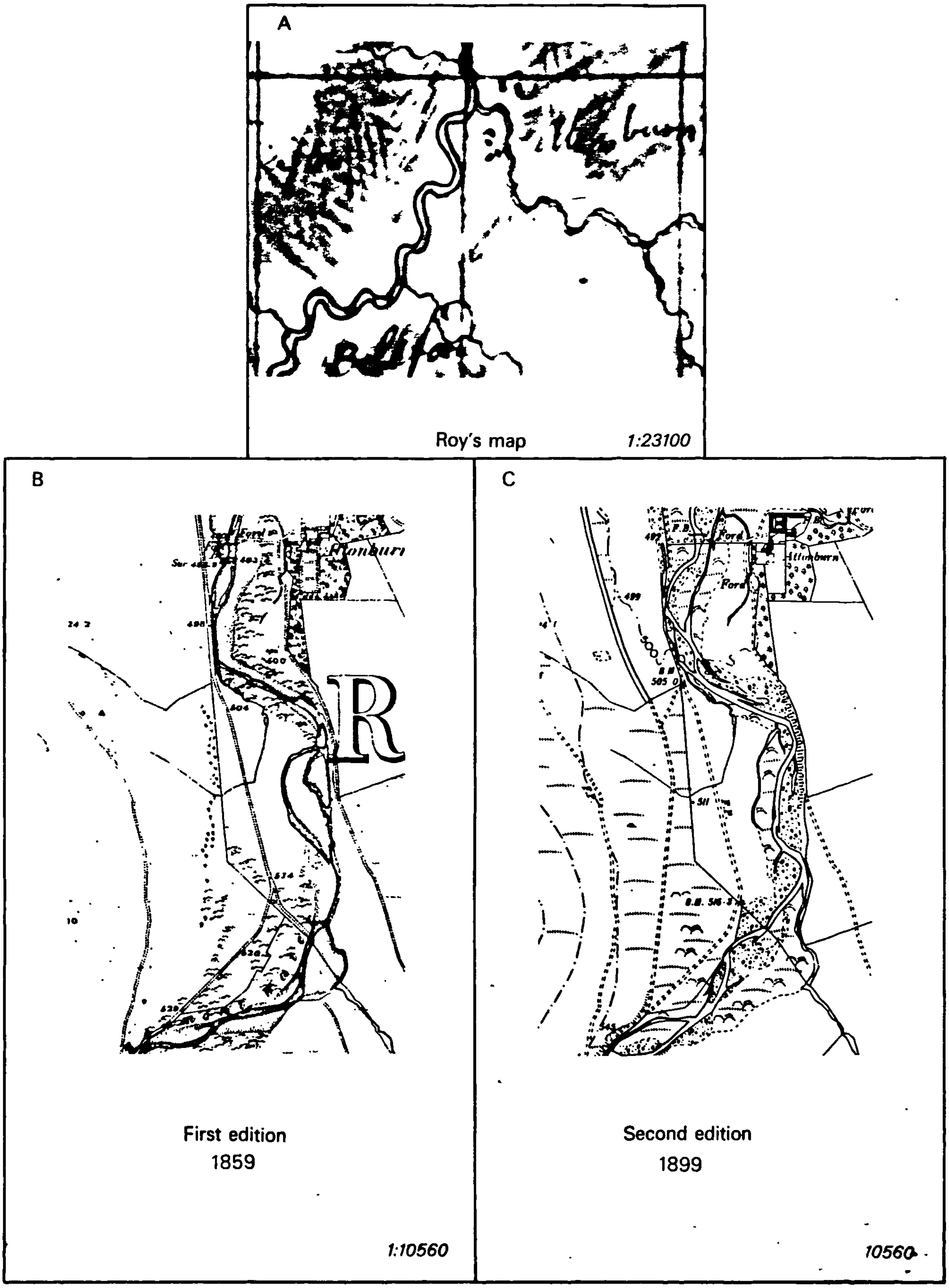
	1858	1896	1962
B (a) UPSEDMT:	2	2	1
(b) LOCSEDMT:	2	2	1
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	4	4	4
(b) BANK VEGETATION:	6	6	4
(c) BAR VEGETATION:	8	8	8

E MAXWID 30

F (a) CHANPATT:	5	5	6
(b) ISLANDS:	3	3	2
G (a) ACTIVITY:	9	9	8

Figure 7.4.1.(i)

Tweed study reach 1: The Bowmont Water near Attonburn



A: Roy's map 1:23100

B: First edition 1859 1:10560

C: Second edition 1899 10560

Figure 7.4.1.(i)

Tweed study reach 1: The Bowmont Water near Attonburn

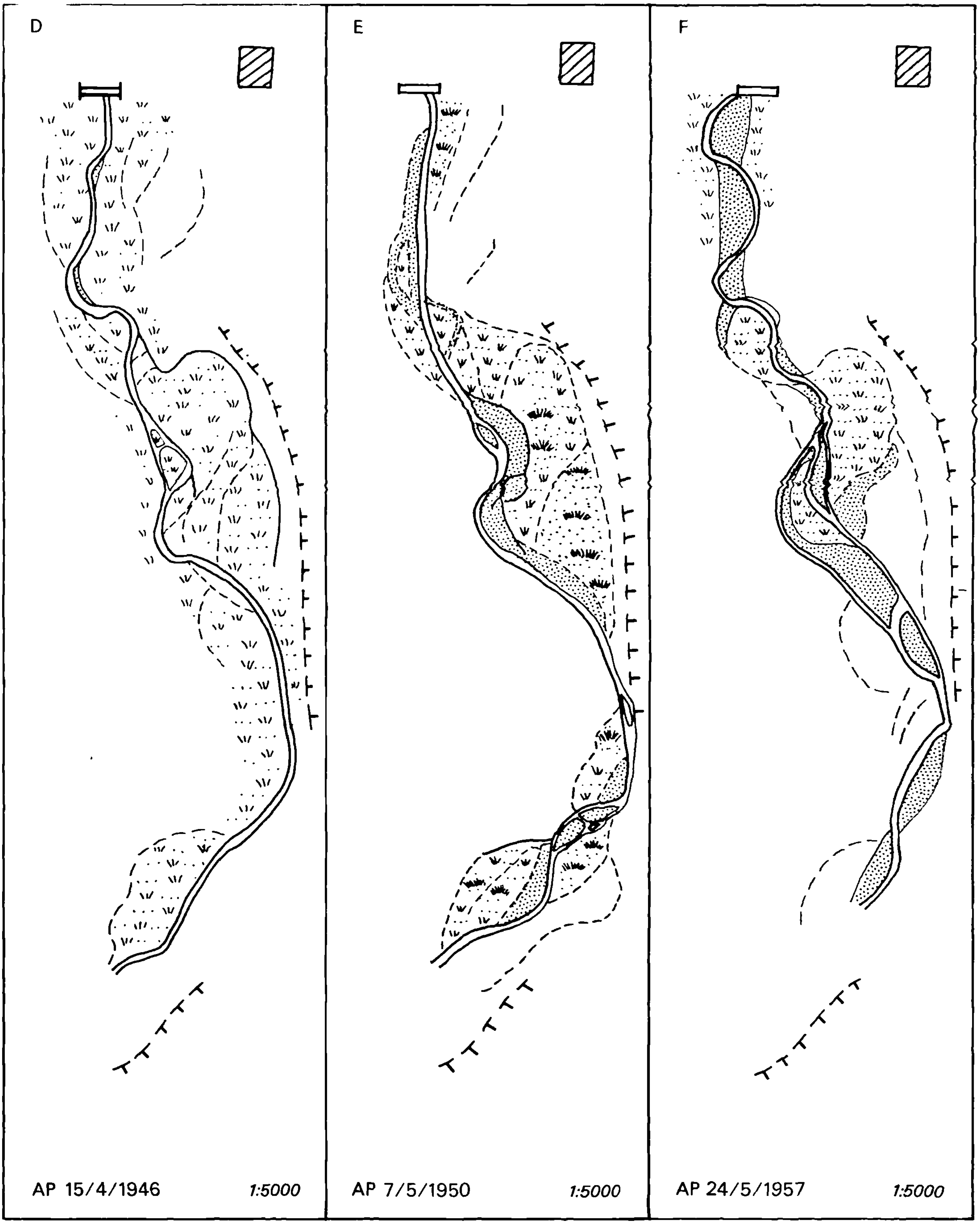
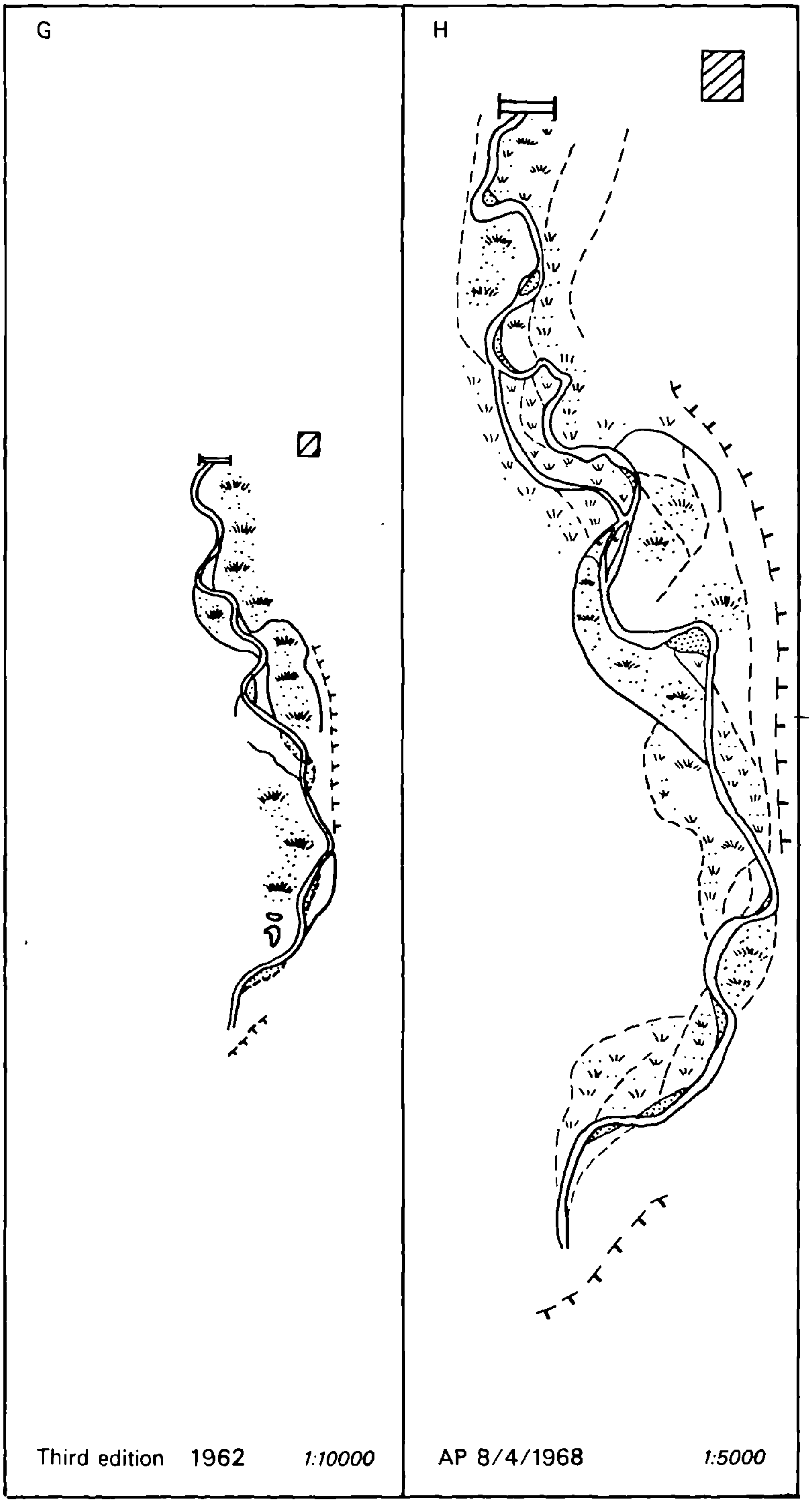


Figure 7.4.1.(i)

Tweed study reach 1: The Bowmont Water near Attonburn



the floodplain. Perhaps at that time, the river was not so destructive in its reworking of its floodplain.

Approximately 100 years later on the first edition map (1859), the channel seemed completely altered in character (Figure 7.4.1.(i).B). The channel planform was highly chaotic and irregular with extensive amounts of unvegetated gravel, both locally and upstream of the sample area. The channel frequently divided around unvegetated bars and appeared out of equilibrium with the present regime. There was much rough-grassland on the floodplain and lines of trees and other vegetative indicators existed, which showed the location of former flood or palaeochannels. It certainly seemed likely that some major geomorphic stress had disrupted this system but it was difficult to place a date on it, given the paucity of historical information available for this site. It was known, for example, that flooding occurred in 1782 (see Figure 5.6.1.(iv)).

By 1899, the channel had increased in braiding index, with extra-channel avulsion immediately above the bridge, but the planform also had more permanent features with the stabilisation of some bars (Figure 7.4.1.(i).C). Channel-side gravels were still very abundant but the main channel remained basically within the same area of the floodplain. Again anabranch cutoffs were indicated where the planform had expanded since 1858 but subsequently had been reduced in terms of its braiding index in response to more moderate events, in the intervening period. In this area, the braiding index increased from 1.20 to 1.62 between the first and second edition (1859-1899) although sinuosity did not record any significant change (1.20). The total maximum shift of any point on the main channel was large (68 m), while the total average value taken at cross-sections along the reach was 19 m. The only known major event was in Oct, 1864, so it is suggested that shifting may be related to more moderate events.

By the first aerial photograph (15/4/1946), the channel had stabilised considerably with fewer bars, and flow concentrated mainly in one channel with little evidence of unstable channel-side sediment (Figure 7.4.1.(i).D). Between 1899 and 1946, it was known that at least one major flood event occurred within the Till catchment on 14th Dec, 1914, but there was no record of any since that date. The channel had clearly stabilised since any disruption caused by that event. Between 15/4/1946 and 7/5/1950, it is known that a major flood occurred. The 26th Sept, 1949 flood event, which from the reconstructed storm profiles of Chapter 5, was a major event in this area (113.5 mm in 72 hours at Old Graden). This however seemed to have limited geomorphic effect in terms of planform change, except for localised reworking of the floodplain and considerable bare gravel (Figure 7.4.1.(i).D).

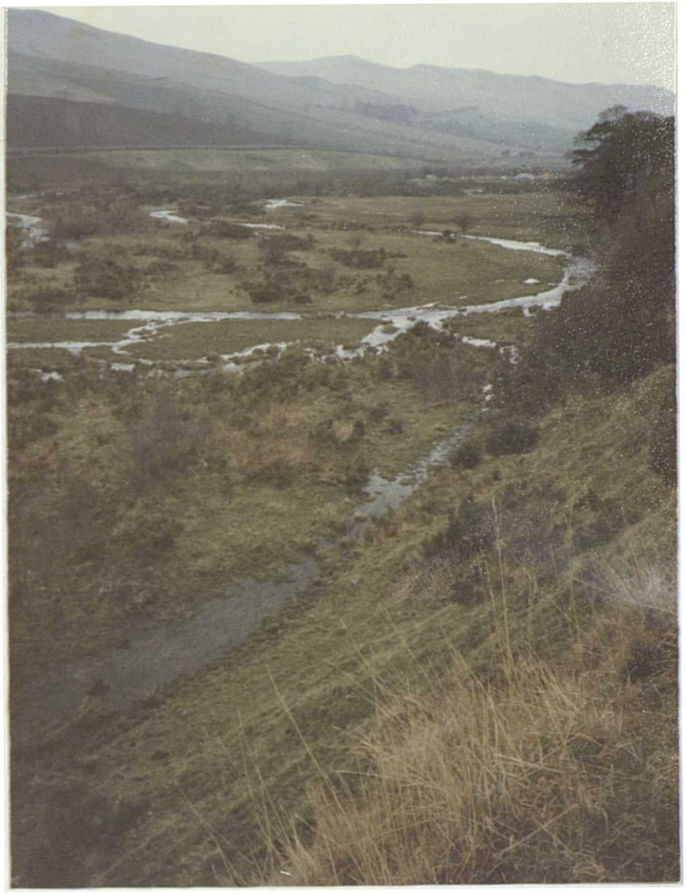
In contrast, by 24/5/1957, there had been a considerable shift in channel planform (Figure 7.4.1.(i).E). It was known for this period, that a major flood event had taken place (28th Aug, 1956; 65 year 24 hour rainfall RI at Jedburgh and higher still over the Bowmont catchment) and the unvegetated channel-side gravels suggested that the disruption had taken place recently. The channel was frequently split with large amounts of unvegetated sands and gravels by the channel side. The main mode of planform expansion was sweeping bypasses of the more accentuated bends, and these had been cut during periods of high flow and high stream power.

By 1962 (third edition), the gravel deposits were very much more localised but the dominant floodplain/bank vegetation was still rough-grassland indicating no major stabilisation. The main channel formed a series of irregular meanders with a series of anabranches with small channels, which increased to a braiding index value of 1.72 if these single line channels are included. Sinuosity was however increased only slightly to 1.23. The photograph taken in 8/4/1968 again showed a gradual stabilisation of that channel form and some further accentuation of meander bends. The splitting of the channel, rather than the reversion to a more simplified planform, seemed to have stabilised, with the secondary channels becoming more permanent features. These were small in width in comparison to the size of the islands and thus the resulting planform was pseudo-anastomosing.

Field checking of the site in April, 1984 showed that although below Attonburn the channel was well set into its banks, upstream it was a highly irregular, chaotic and multibranched channel pattern, which was clearly destroying what pastoral land the floodplain originally provided (Plate 7.4.1.(i)). The floodplain/bank vegetation was a mixture of rough grassland and heath but principally water-logged, marshy ground. Particle size was small but most of the ground was vegetated although localised gravel bars and shoals occurred. Upstream steep fluvioglacial faces of material were being under cut by the river so there was a ready supply of both local and upstream sediment. According to the farmer at Attonburn, inundation in excess of bankfull occurs on average 10-12 times a year but on an extreme case in May 1983, the floodplain was

Plate 7.4.1.(i)

The Bowmont Water near Attonburn, showing initial reoccupation of a former palaeochannel (foreground)



flooded for ten days. More recently, the river has split its channel to the east with a similar alignment to that of 1859. This involves much overbar and overfloodplain flow, especially to the righthand side of the floodplain. Clearly, one or more disruptive events have taken place since 1968 (eg. 1981). In the next flood event, presumably the vegetation will be ripped through and a new channel along an old channel line will be reactivated. The threshold for such a change does not seem very high in terms of past evidence. There have been some unsuccessful attempts to alter the channel pattern eg. by strengthening with larger clasts, but according to the farmer, all have been useless. Clearly, most of the floodplain has been reworked over the last 150 years. High flow erosion of banks revealed sequences of former bar surfaces interspaced with fine sedimentation, suggesting that this reach had a long history of channel shift.

7.4.2 Tweed study reach 2: The lower Boonreigh Water

The lower Boonreigh water, draining an area of 55 km^2, has an irregular planform with occasional bars. Sediment supply seems limited with most clasts derived from reworked conglomerate. Aerial photographs indicate a large number of palaeochannels (Figure 7.4.2.(i)), with a mixture of meander scrolls and braid features (see Plate 7.4.2.(i)). Position within the channel system typology is outlined in Table 7.4.2.(i).

Table 7.4.2.(i)

Position of Tweed study reach 2: The Boonreigh Water within the map-based channel system typology

A (a) Basin area: 51.9 km^2

(b) Average height: 160 m

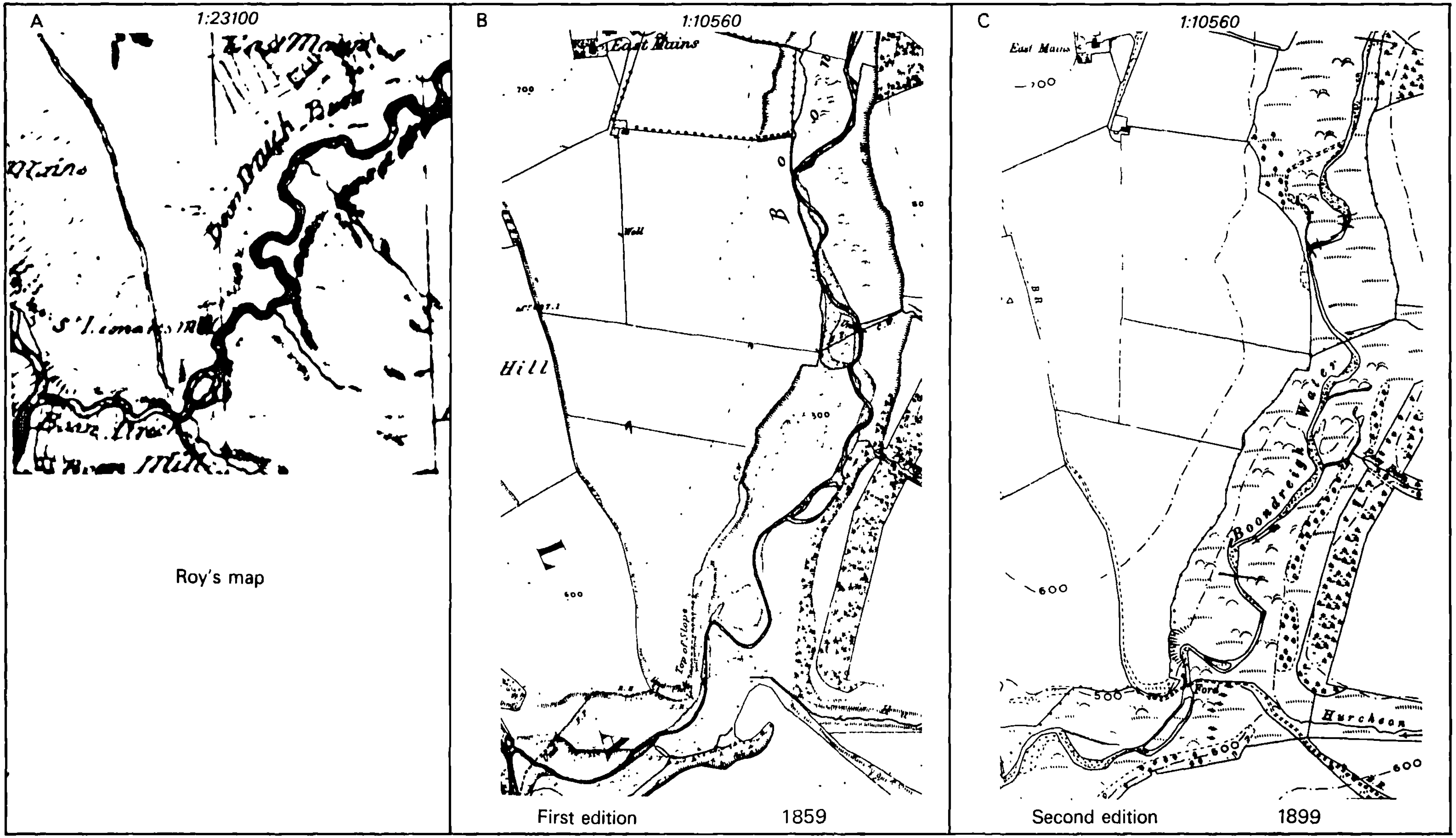
	1857	1897	1968
B (a) UPSEDMT:	1	1	1
(b) LOCSEDMT:	1	1	1
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	4	4	4
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	4	0	8

E MAXWID 37

	1857	1897	1968
F (a) CHANPATT:	3	5	3
(b) ISLANDS:	2	2	2
G (a) ACTIVITY:	8	8	2

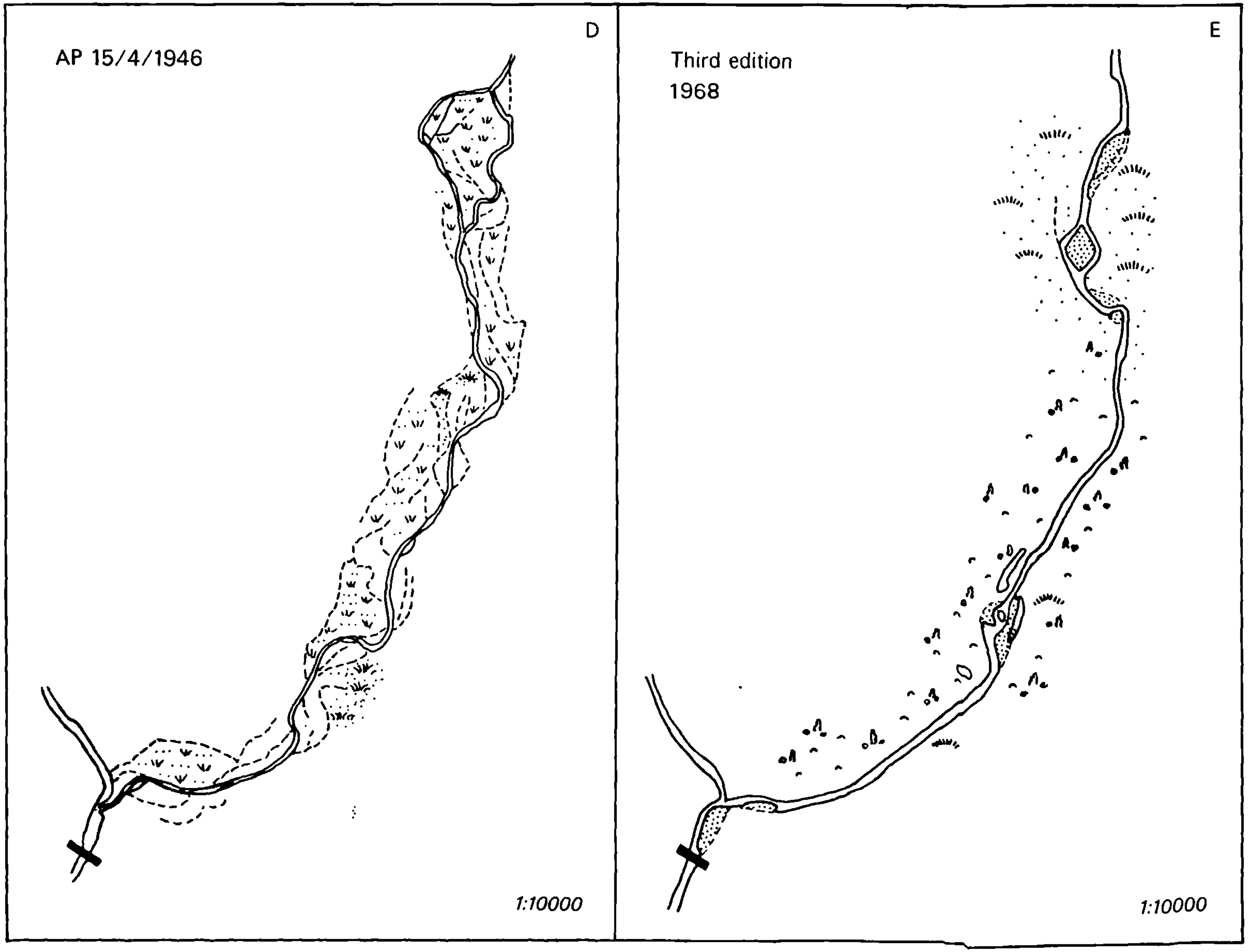
Tweed study reach 2: Boonreigh Water

Figure 7.4.2.(i)



Tweed study reach 2: Boonreigh Water

Figure 7.4.2.(i)



From Roy's map (1750), an irregular meandering planform was shown (Figure 7.4.2.(i).A), utilising a large proportion of the floodplain. In contrast by 1857, on Boonreigh Water, a large amount of sand and gravel was indicated beside the channel, especially at the confluence, suggesting an area of high mobility (Figure 7.4.2.(i).B). Upstream, a meander bend showed evidence of a formerly split channel, which corresponded to evidence from Roy's map, and the channel split around a fairly stable bar with grass cover. There were also unvegetated gravels indicating switches in channel, which have already taken place. Thus, a variety of features, indicating both recent and older changes in planform, were evident. Such changes may have taken place in response to the 9th Feb, 1831 event (ranked second within the Leader catchment; Figure 5.6.1.(i)).

Between the first (1857) and second (1900) edition maps, the Leader catchment had two major flood events. These occurred on 9th Mar, 1881 and 20/21st Sept, 1891 and were ranked fourth and third respectively by the TRPB. Years with heavy rain were also recorded (Figure 5.3.(iii)) and therefore an increase in more moderate flows would also be expected. It was obvious in studying the 1899 planform of the Boonreigh that extensive changes had occurred. Down at the confluence, the previously sinuous channel had increased considerably in sinuosity into a large irregular meander bend. Upstream of this point, a channel split had formed with an increase in sinuosity in the meander bend upstream; the change seemed to involve some rotation in a downstream direction. Further upstream still, the meander planform had become much more irregular and the channel was using a much higher proportion of its available floodplain area. The meander bend, which in the first edition looked as if it could potentially be cutoff, had widened considerably. Clearly, a large amount of spatially variable change has taken place in this 40 year period.

In 15/4/1946, the sinuosity of the channel had been decreased with a considerable reduction in meander bend amplitude (Figure 7.4.1.(i).D). There had also been some major lateral shifts in the channel across its floodplain. Upstream, there was a switch back to a 1857 channel but generally, there did not seem to be a reuse of past channels but rather a general reworking of the floodplain eg. as indicated by scroll features. The third edition planform (1968) was completely altered with a sinuous channel and little bare gravels indicating frequent reworking of the sediment peripheral to the channel. The 12th Aug, 1948 flood event, with high rainfalls in the Lammermuirs (Marchmont House, 101.6 mm in 24 hours with 300-500 year RI; Figure 5.6.1.(i)) must have caused very severe flooding on Boonreigh Water, perhaps of even higher RI than that on the mainstream Leader. It is known that the Leader beside the Boonreigh confluence was heavily channelised and it seemed likely that after disruption on the Boonreigh Water, a similar straightening process took place. This was in response to destruction of the neighbouring pastoral land and it is known that the channel underwent excessive sedimentation. Thus, the channel was artificially "recovered" from the 1948 event.

Field checking revealed that there were areas of standing water upstream where the tortuous meander-bend had cutoff, but the whole channel, whether naturally or artificially, had straightened out. It is known that the spatially isolated large meander was removed by the local farmer; and the 1:63360 O.S. map, revised in 1952, indicated a highly accentuated meander bend breaking an otherwise straight/ sinuous channel. This bend was bulldozed because it was destroying too much pastoral land and was bounding the limits of the active area on both sides of the floodplain so that eventually three bridges were going to be required to get access to the glen. Upstream too it was reported that gravel has been scooped out of the channel to stop the channel filling up with sediment. Despite the more restricted sediment sources, sediment is transferred from floodplain storage to within the channel during major events.

Field survey showed that some reaches are stable, cutting through the conglomerate very sharply in an unusual, square-shaped and presumably artificial cross-section. At one sub-reach, although the channel is less than 1 m across, it was over 1.2 m deep. Much of the available sediment were clasts that had been eroded free of the weak conglomerate cement, which holds the rock together and thus increase in available sediment supply must be regulated by the erosive power of the river ie. by the frequency of events competent enough to dislodge clasts.

Plate 7.4.2.(i)

Palaeomeanders indicated by differential vegetation on the lower Boonreigh Water

There was extensive evidence of palaeochannels (Plate 7.4.2.(i)); some are accountable from first and second edition map evidence but there are also features which are of indeterminate age. In terms of the vegetation cover of the floodplain and banks, while in 1857 and 1900, the vegetation was depicted as rough grassland, by 1984 some areas along the channel have been stabilised by coppice and the scrub. Thus, the floodplain seemed stable indicating that it has not been reworked for a period of time. The channel is also incised fairly deeply into its banks, so that now in certain areas along the reach, the river would require a high stage to overtop its banks and reoccupy its former channels. Moderate events may flush sediment through the system to the confluence but larger discharges may be required for significant planform alteration.

7.4.3 Tweed study reach 3: The Cleekhimin Burn

The Cleekhimin burn is an active tributary of the Leader, draining 23.3 km^2 of the Lammermuir hills. The study reach is on the lower part of the Burn and planform is wandering with occasional islands. Position within the channel system typology is outlined in Table 7.4.3.(i).

Roy's map (1750) depicted a sinuous to irregularly meandering reach (Figure 7.4.3.(i).A). The first edition (1857) showed the channel again as sinuous, but splitting around occasional bars, with large amounts of unvegetated sediment by the channel-side (Figure 7.4.3.(i).B). There is evidence of former anabranches, with sub-bar flow still occurring. The

Table 7.4.3.(i)

Position of Tweed study reach 3: The Cleekhimin Burn within the map-based channel system typology

A (a) Basin area: 23.3 km^2

(b) Average height: 197 m

	1869	1902	1971
B (a) UPSEDMT:	1	2	2
(b) LOCSEDMT:	2	2	2
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	4	4	4
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	8	8	8

E MAXWID 15

	1869	1902	1971
F (a) CHANPATT:	4	4	3
(b) ISLANDS:	4	3	2
G (a) ACTIVITY:	2	8	2

Figure 7.4.3.(i)

Tweed study reach 3: The Cleekhimin Burn

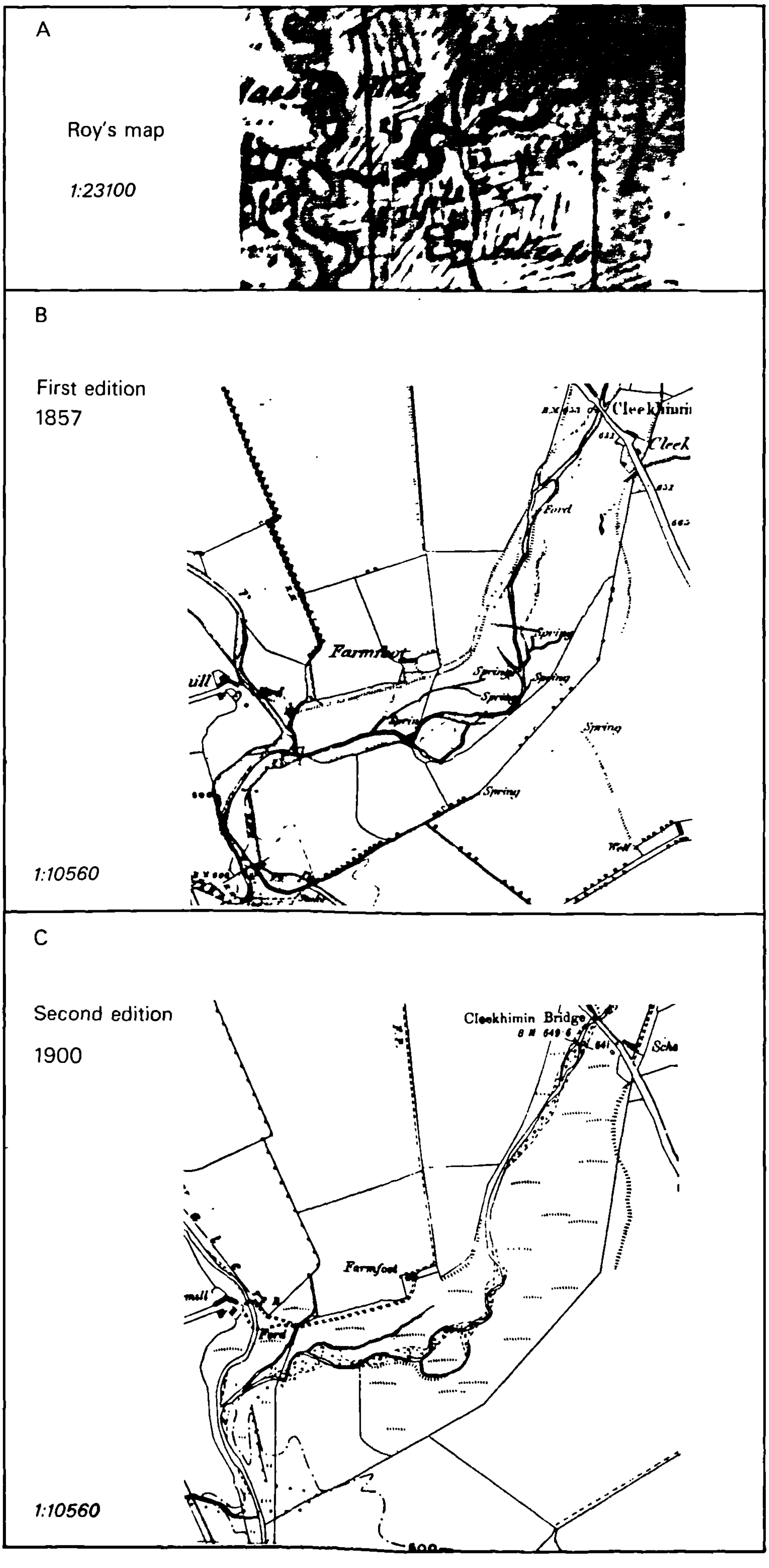
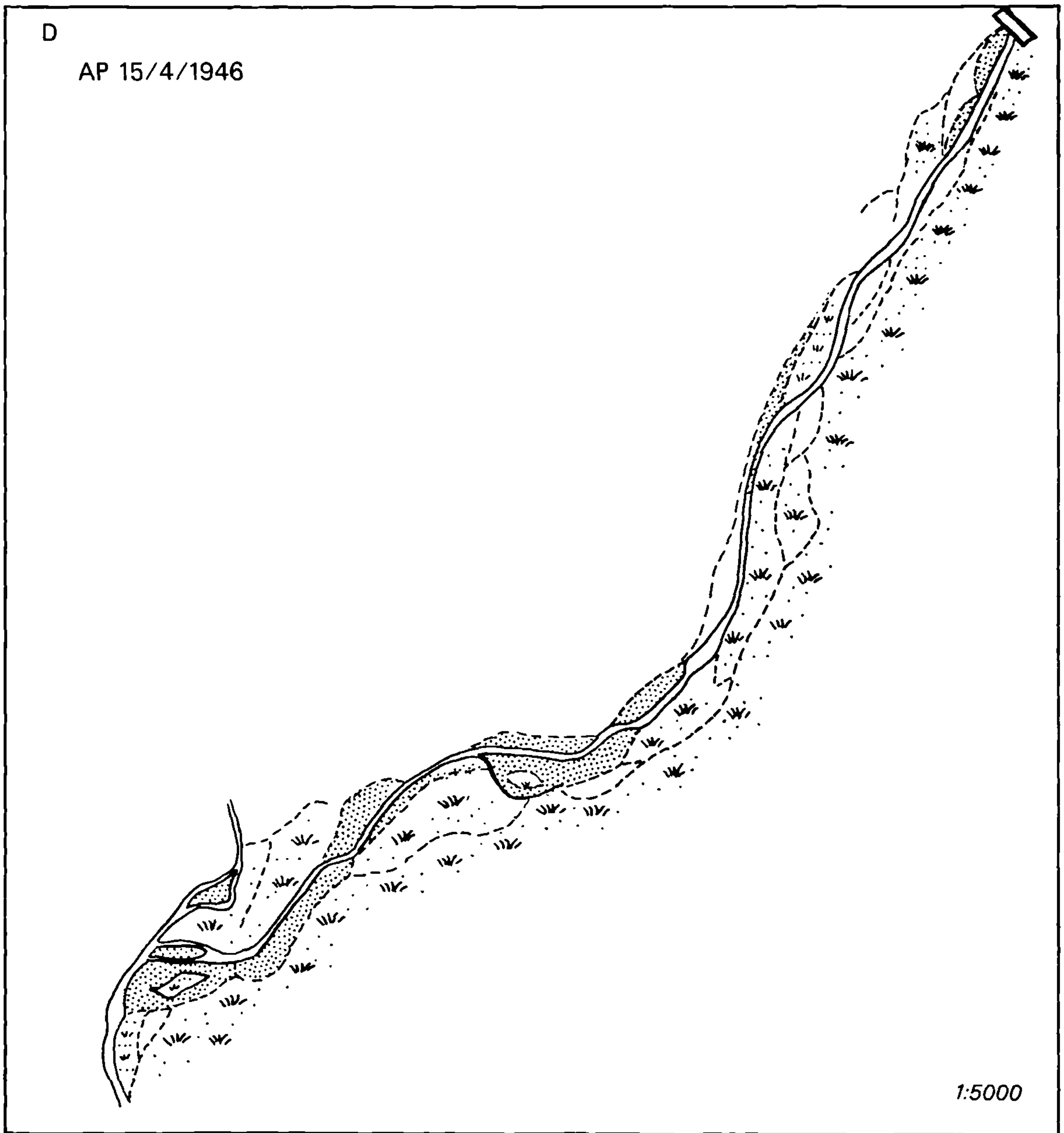
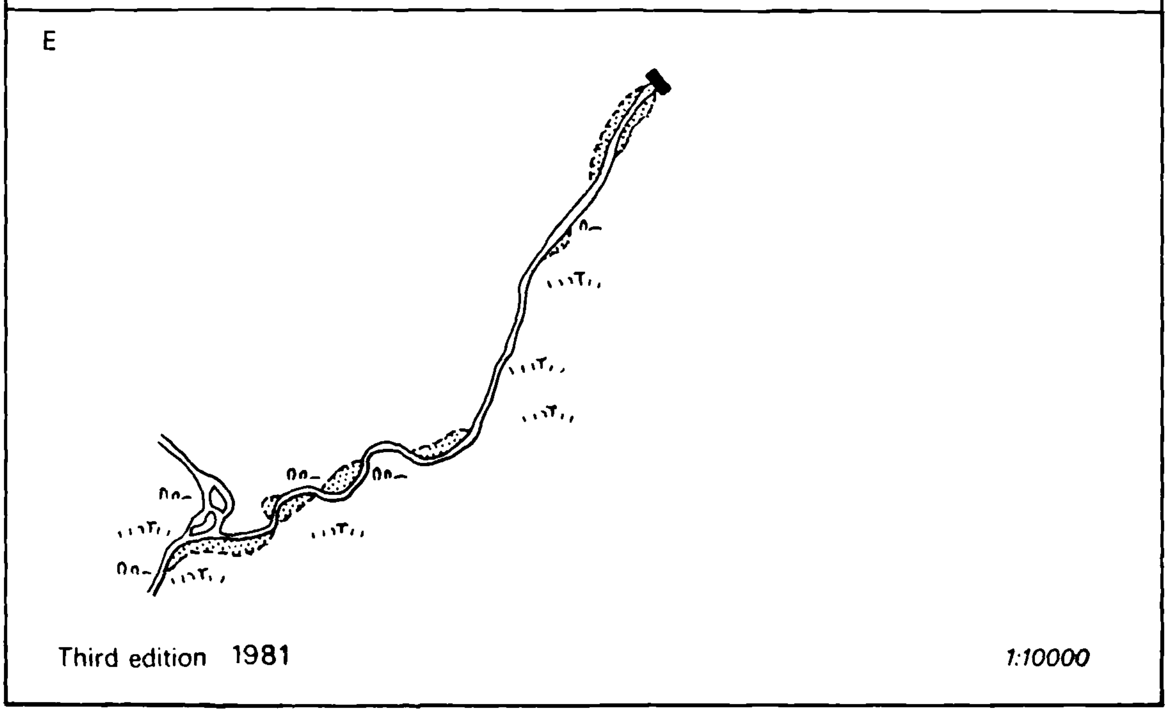


Figure 7.4.3.(i)

Tweed study reach 3: The Cleekhimin Burn





abundant sediment and the extended channel planform may be relict features from the 1831 event (Figure 5.6.1.(i)). Between 1857 and 1900, the channel had decreased its braiding index, with abandonment of old anabranches, but had increased amounts of unvegetated gravels by the channel-side (Figure 7.4.3.(i).C)). It was known that two major flood events took place in 1881 and 1891 but the overall impact in terms of planform change was small, though channel widening may have taken place.

Unfortunately, there was only one aerial photograph available for this site, in 15/4/1946. Between 1900 and 1946, there was considerable lateral shift across the floodplain; so that by 1946, the channel was entirely on the eastward side. The channel appeared fairly mobile, with revegetating gravels on the boundary, especially near the confluence. Perhaps this major channel shift can be related to the localised, convective flood event of 1909 (as shown on the Lauderdale estate plan (RHP 20739); Figure 7.4.3.(ii)). The flood flow attempted a major avulsion across the fan but the course of the flood water did not create a permanent new channel for the burn. Thus, although a convective event can attain considerable stream powers, the result was not a steady migration of the channel as the rest of the floodplain appeared quite undisrupted, and this suggested only small scale extra-channel avulsion. The former channel was not evident, indicating that change had not occurred recently. The third edition map (1981) despite the high RI 1948 flood event, showed the channel to be located in a similar area of the floodplain. Therefore, after the disruption, the channel must have reverted to a similar alignment.

Figure 7.4.3.(ii)

Estate plan showing the course of the flood waters during the 1909 flood on the Cleekhimin Burn (RHP 20739)

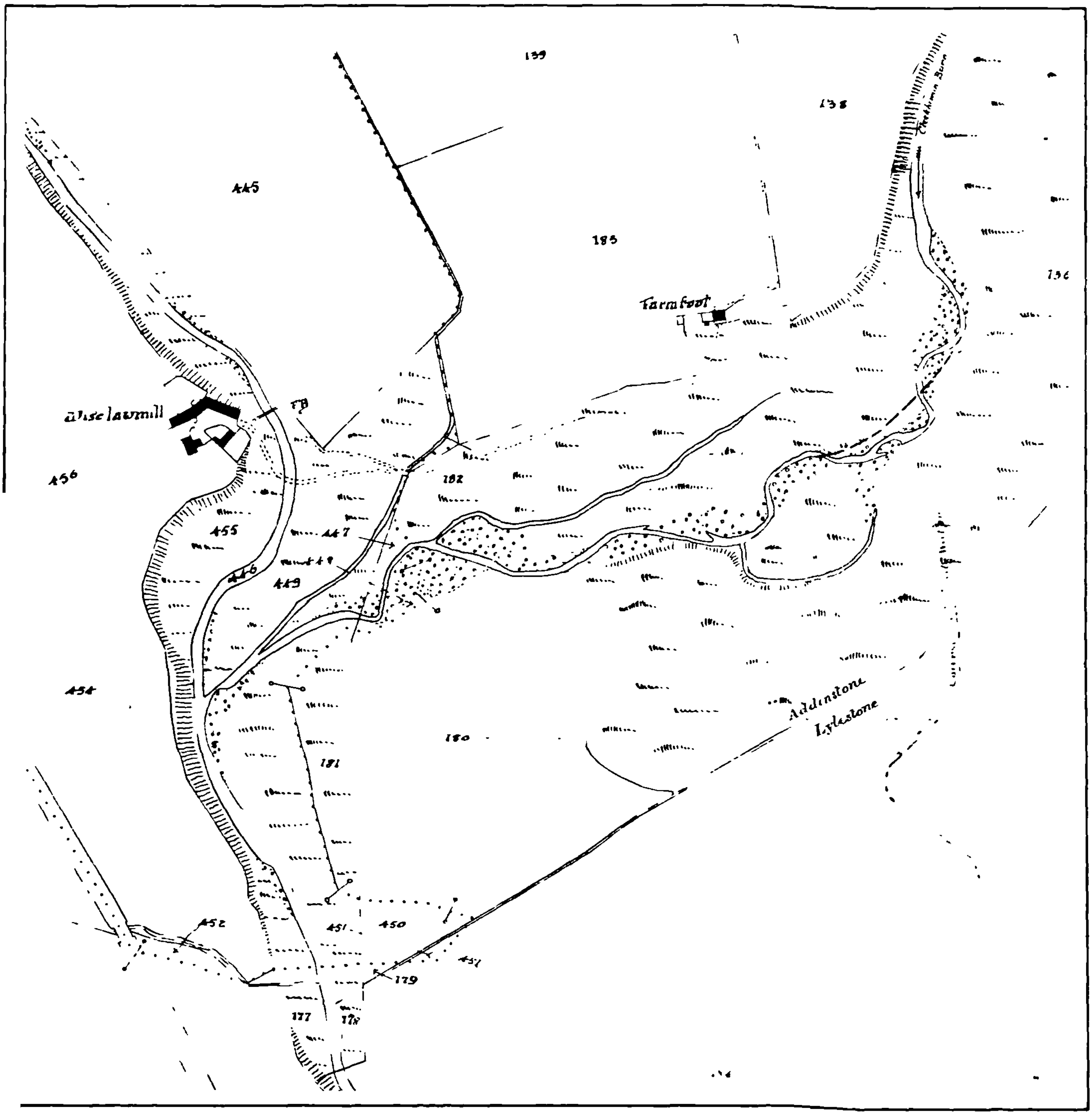


Plate 7.4.3.(i)

Restabilisation of both lateral and medial bars on the Cleekhimin Burn

Field checking revealed a wide shallow channel with several flood channels and former bar surfaces, probably reused in 1948 (Plate 7.4.(i)). The farmer at Wiselawmill said that at the confluence, the channel shifted regularly during flooding and they are continually having to shift a fence as it becomes undermined. This implies that more moderate floods have the competence to mobilise sediment.

7.4.4 Tweed study reach 4: Monynut Water near Inner Law

This irregularly meandering reach, draining 12.4 km^2, is located on an upper tributary of the Whiteadder, the Monynut Water. From the aerial photograph evidence, there are large numbers of old channels which indicate that however active this reach is at the present, it has been highly active in the past. Position within the channel system typology is outlined in Table 7.4.4.(i).

Unfortunately, Roy's map gave no detail about the channel. The first edition (1858) indicated a sinuous channel with little available reserves of sediment (Figure 7.4.4.(i).A). In contrast, by the second edition (1900), there was an irregularly meandering channel, with unvegetated sediment by the channel (Figures 7.4.4.(i).B). Upstream, increases in sinuosity must have occurred in response to the increased frequency of more moderate floods recorded within the upper Whiteadder catchment.

Table 7.4.4.(i)

Position of Tweed study reach 4: The Monynut Water within the map-based channel system typology

A (a) Basin area: 12.4 km^2

(b) Average height: 234 m

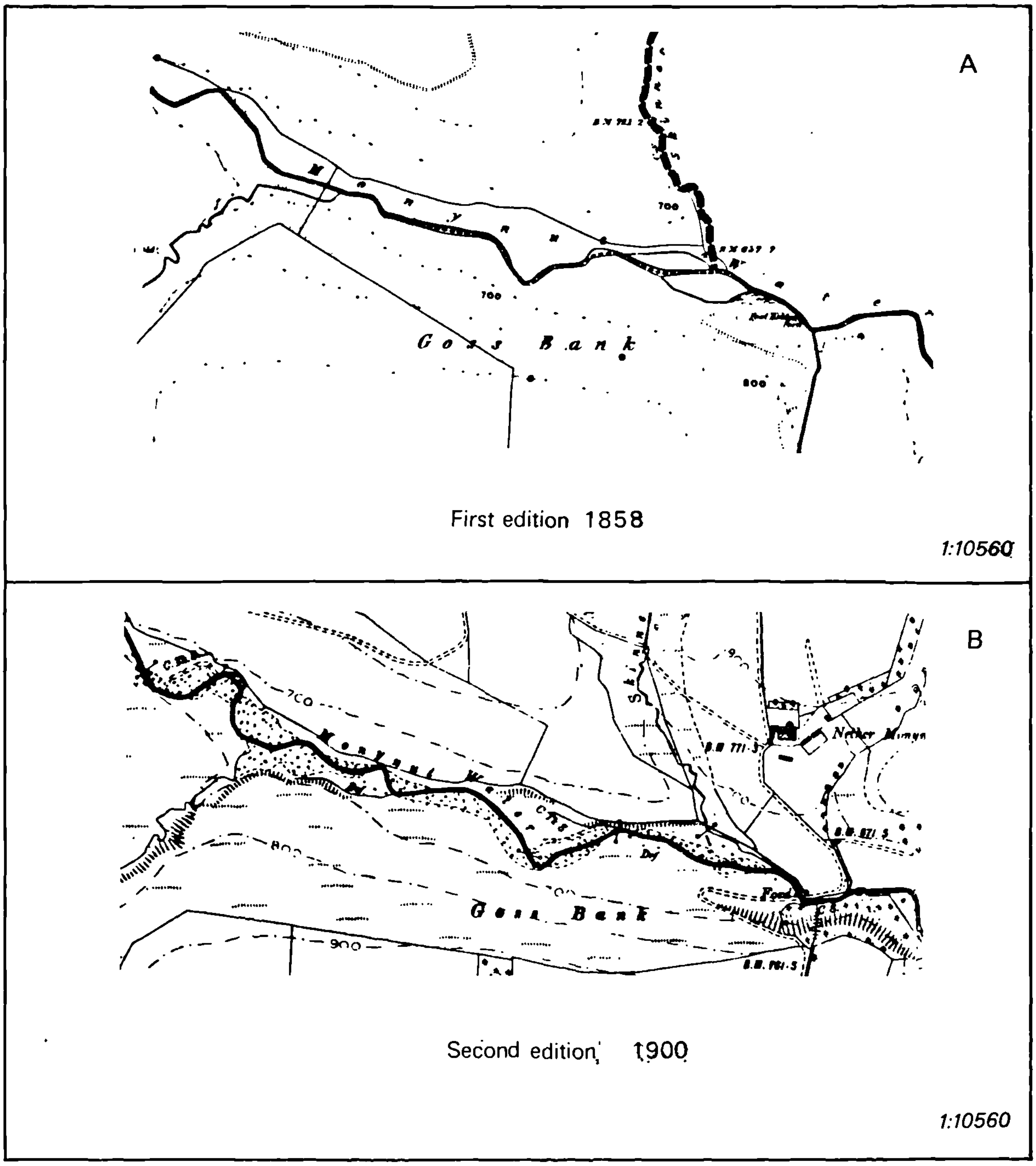
	1858	1900	1971
B (a) UPSEDMT:	0	1	1
(b) LOCSEDMT:	0	2	2
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	4	4	4
(b) BANK VEGETATION:	4	4	4
(c) BAR VEGETATION:	0	0	0

E MAXWID 20

	1858	1900	1971
F (a) CHANPATT:	3	5	5
(b) ISLANDS:	1	1	1
G (a) ACTIVITY:	1	2	8

Figure 7.4.4.(i)

Tweed study reach 4: Monynut Water near Inner Law



First edition 1858

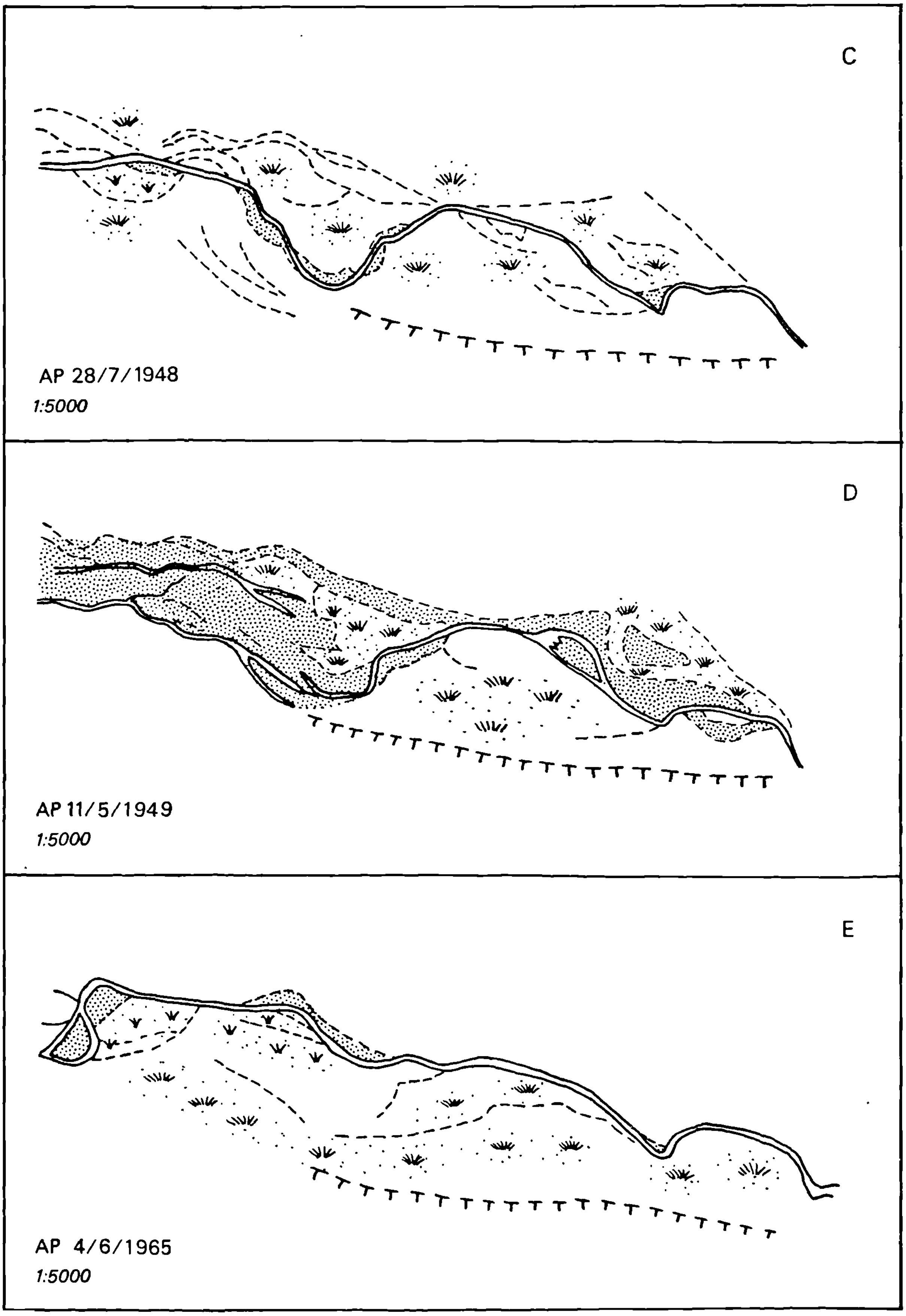
1:10560

Second edition 1900

1:10560

Figure 7.4.4.(i)

Tweed study reach:4 Monynut Water near Inner Law



The first aerial photograph (28/7/1948) fortuitously gave a pre-1948 flood planform. The channel was irregular with unvegetated gravels by the channel-side, but otherwise had a gradually stabilising floodplain. Clearly, there had been no major planform disruption since 1900, despite a high RI (> 100 year; 1910/1911?) event. The next aerial photograph on 11/5/1949, showed a completely different planform. The channel was frequently split (Figure 7.4.4.(i).D) and seemed highly out of equilibrium. Almost the entire floodplain had either been reworked or covered with extensive amounts of sand and gravel. It must be remembered that this was the situation over a year after the major 1948 event (24 hour RI of 300-500 years at Marchmont House), and the channel seemed highly unstable and fragmented. It was known that at Abbey St Bathans, the Whiteadder was 17 feet (5.2 m) above normal and thus, runoff rates within the Monynut Water catchment must have been very high. The next record was unfortunately not until 4/6/1965, and considerable stabilisation and simplification had already taken place, with most of the flow in a single channel. Much of the floodplain had also become stabilised by vegetation (Figure 7.4.4.(i).E). It would seem that although a runoff event with a possible 500 year return period had occurred, the recovery had been relatively rapid. The third edition map (1981) indicated that the channel was in basically a similar position.

However, between 1981 and 1984, field checking indicated some change in channel planform had taken place; while the main channel seemed relatively stable in location, one channel had been recently reactivated through the reeds to the west (Plate 7.4.5.(i)) and several

Plate 7.4.4.(i)

Evidence of palaeochannels extending over the entire available active area on the irregularly meandering Monynut Water minor anabranches existed. Clearly, there had not been large scale sedimentation over 1981-1984 but slumping of banks was widespread on the meander bends. Large areas of floodplain were marshy, suggesting frequent inundation.

7.4.5 Tweed study reach 5: The Dye Water confluence

The confluence site between Dye Water and the Whiteadder, draining a catchment of 51.6 km^2, has shifted regularly over the last 150 years. The Dye is a low-slope fan in its lower reaches (cf. the Quoich or the Nethy). However, after the Aug, 1948 event, some channelisation seems to have taken place. Aerial photographs and field survey identified palaeochannels, which indicated periodic avulsions across the fan. Older terrace fragments show a gradual downcutting into the fan surface.

When the confluence site was studied on Roy's map, it followed a straight course to join the Whiteadder Water at right angles, but no other detail is given. In the first edition map (1857), the confluence with the Whiteadder was to the east (Figure 7.4.5.(i).B). The main channel of the Dye was irregularly meandering (SIN=1.21) while the Whiteadder was sinuous. There were large localised amounts of unstabilised sands and gravels, both upstream on the Dye and on the mainstream Whiteadder. This would suggest that the channel had shifted either recently or regularly prior to 1857. It was known however that the most major recorded flood event pre-1900, occurred 14th Aug, 1846. This may be the cause of the channel-side sediment.

Table 7.4.5.(i)

Position of Tweed study reach 5: The Dye Water confluence within the map-based channel system typology

A (a) Basin area: 51.6 km^2

(b) Average height: 172 m

	1857	1900	1957
B (a) UPSEDMT:	1	1	0
(b) LOCSEDMT:	2	2	0
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	6	6	6
(b) BANK VEGETATION:	6	6	6
(c) BAR VEGETATION:	0	0	0

E MAXWID 6

	1857	1900	1957
F (a) CHANPATT:	6	6	6
(b) ISLANDS:	2	2	2
G (a) ACTIVITY:	2	2	2

Figure 7.4.5.(i)

Tweed study reach 5: The Dye Water confluence

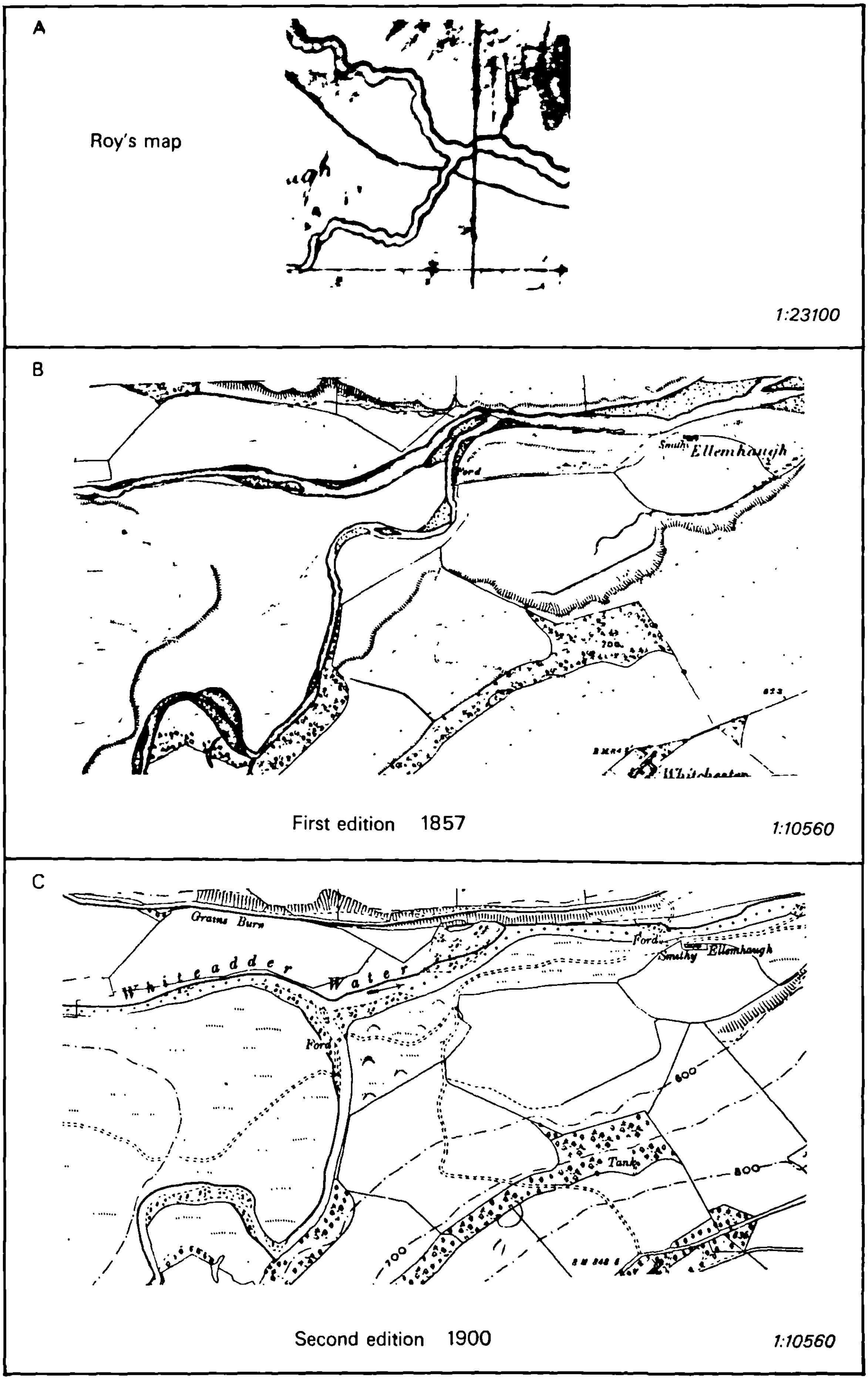
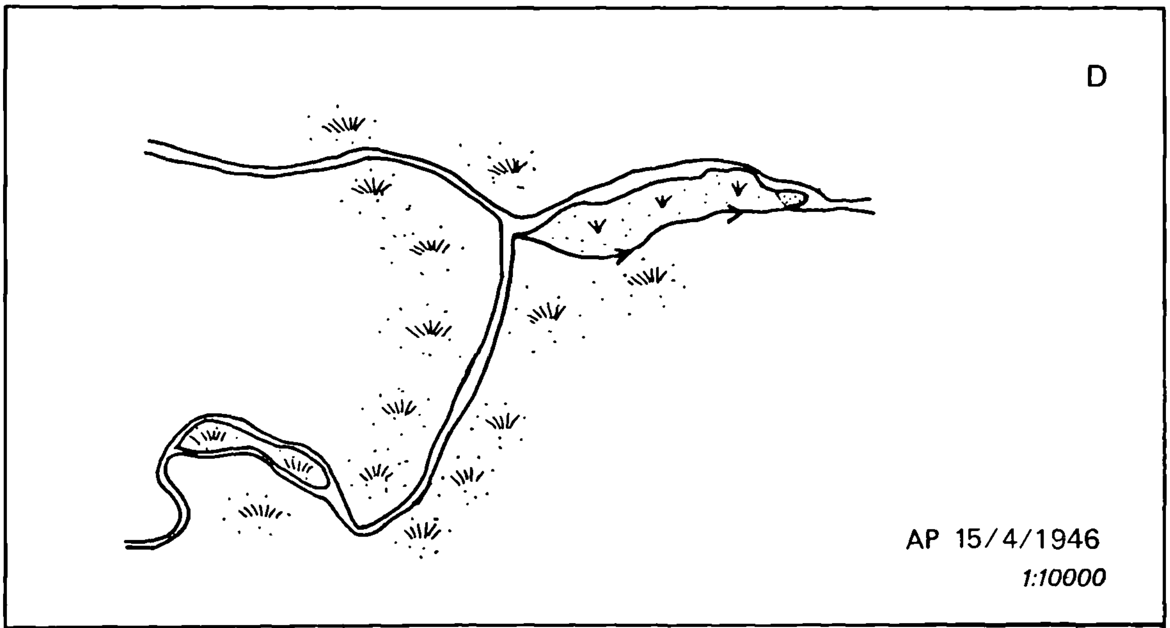
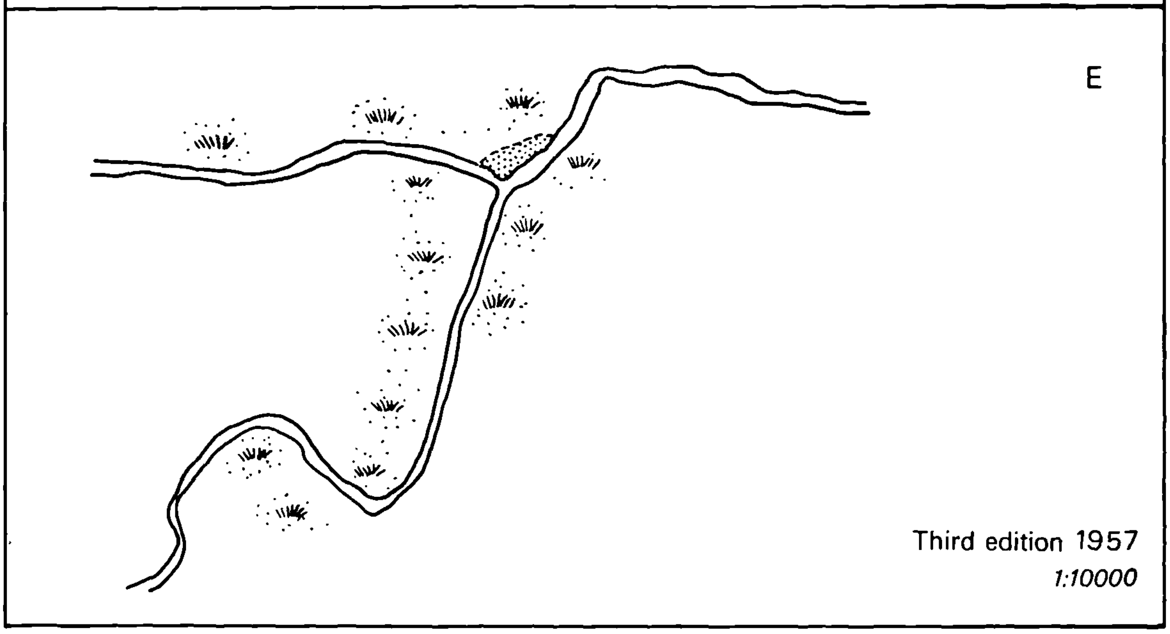


Figure 7.4.5.(i)

Tweed study reach 5: The Dye Water confluence





By 1900, (43 years later), the Dye had increased the size of its meander bend upstream (SIN=1.33), but downstream towards the confluence, a much shorter route had been excavated, breaking through the neck of rough-grassland covered fan deposits that remained in 1857 (Figure 7.4.5.(i).C). Since 1857, 27 floods had been recorded on the Whiteadder at the Abbey St Bathans record, however the magnitude of an event capable of eroding a new channel must have been high and possibly occurred in 1881 or 1891 (see Figure 5.6.2.(ii)).

By 15/4/1946, the Dye was entering the Whiteadder at right angles, with some flow through the 1857 channel (Figure 7.4.5.(i).D). There were no major changes on the Dye but the Whiteadder had become more sinuous. There was obviously no event large enough to exceed thresholds relating to the present more stable channel alignment. By 1957, the confluence had shifted slightly east and the mainstream Whiteadder had shifted back to an approximate alignment with 1857. Considerable widening had taken place on the Whiteadder, increasing its active area from 2-4 times that in 1946. Upstream, the Dye showed some alteration in terms of bar modification and considerable widening of its active area. It is known that the 1948 event was highly destructive within the Whiteadder catchment (Learmonth, 1950; Scott, 1950). This planform alignment within the fan persisted in 1959 and 1965 (Figure 7.4.5.(i)) and with some stabilisation of gravels. However, field checking showed that the Dye channel above the confluence had been embanked, most probably after the 1948 flood event. It had presumably switched its channel and this had been artificially deepened to prevent further shift. Upstream, the Dye channel had been more active with a reworking of the previously stabilised anabranched (1946) planform.

Field checking in 1983/84 showed that recently the gravels within the Whiteadder had been reworked. Scour around a bridge construction, extensive over-bar flow and scour holes all indicated reworking of the 1948 deposits. Trash-lines on the Dye also confirmed the occurrence of a recent high flow (perhaps that of Jan, 1982). Comparison of planforms between 1983 and 1984 showed that extensive reworking of medial and lateral bars has taken place over that timespan.

7.4.6 Tweed study reach 6: The River Teviot below Falnash Burn

This irregular meandering reach on the upper Teviot, with a contributing area of 67.2 km^2, occurs where there is localised widening of the floodplain. It has however, post-1945 undergone artificial straightening, post-1945. Position within the channel system typology is outlined in Table 7.4.6.(i).

On Roy's map (1750s), the channel was shown as sinuous (Figure 7.4.6.(i).A), though little detail is available. However, by 1858 (first edition) the channel planform had developed two large, fairly regular meander bends with an extensive amount of unvegetated sands and gravels bordering the channel. A large portion of the floodplain had thus been rendered unusable for agriculture. This situation was exacerbated by the Dovecot Burn which used to join the Teviot near the Falnash Burn, but now continued the whole length of the reach with an irregular channel pattern (Figure 7.4.6.(i).B). Both the mainstream Teviot and

Table 7.4.6.(i)

Position of Tweed study reach 6: The River Teviot near Falnash Burn within the map-based channel system typology

A (a) Basin area: 71.4 km^2

(b) Average height: 156 m

	1858	1897	1962
B (a) UPSEDMT:	1	1	0
(b) LOCSEDMT:	1	1	0
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	3	3	3
(b) BANK VEGETATION:	3	3	3
(c) BAR VEGETATION:	0	0	0

E MAXWID 20

	1858	1897	1962
F (a) CHANPATT:	6	5	2
(b) ISLANDS:	1	1	1
G (a) ACTIVITY:	6	1	1

Figure 7.4.6.(i)

Tweed study reach 6 : The River Teviot Falnash Burn

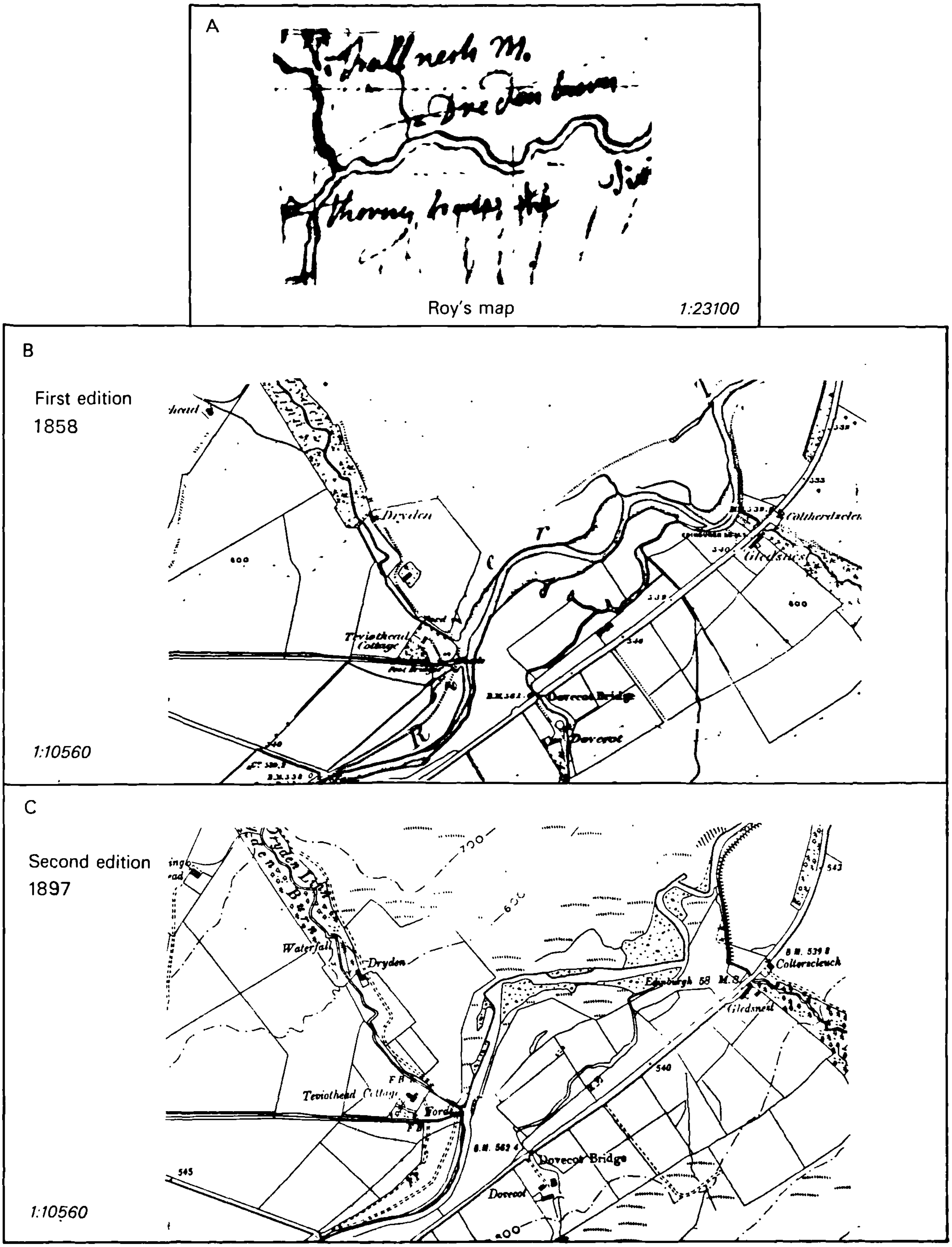
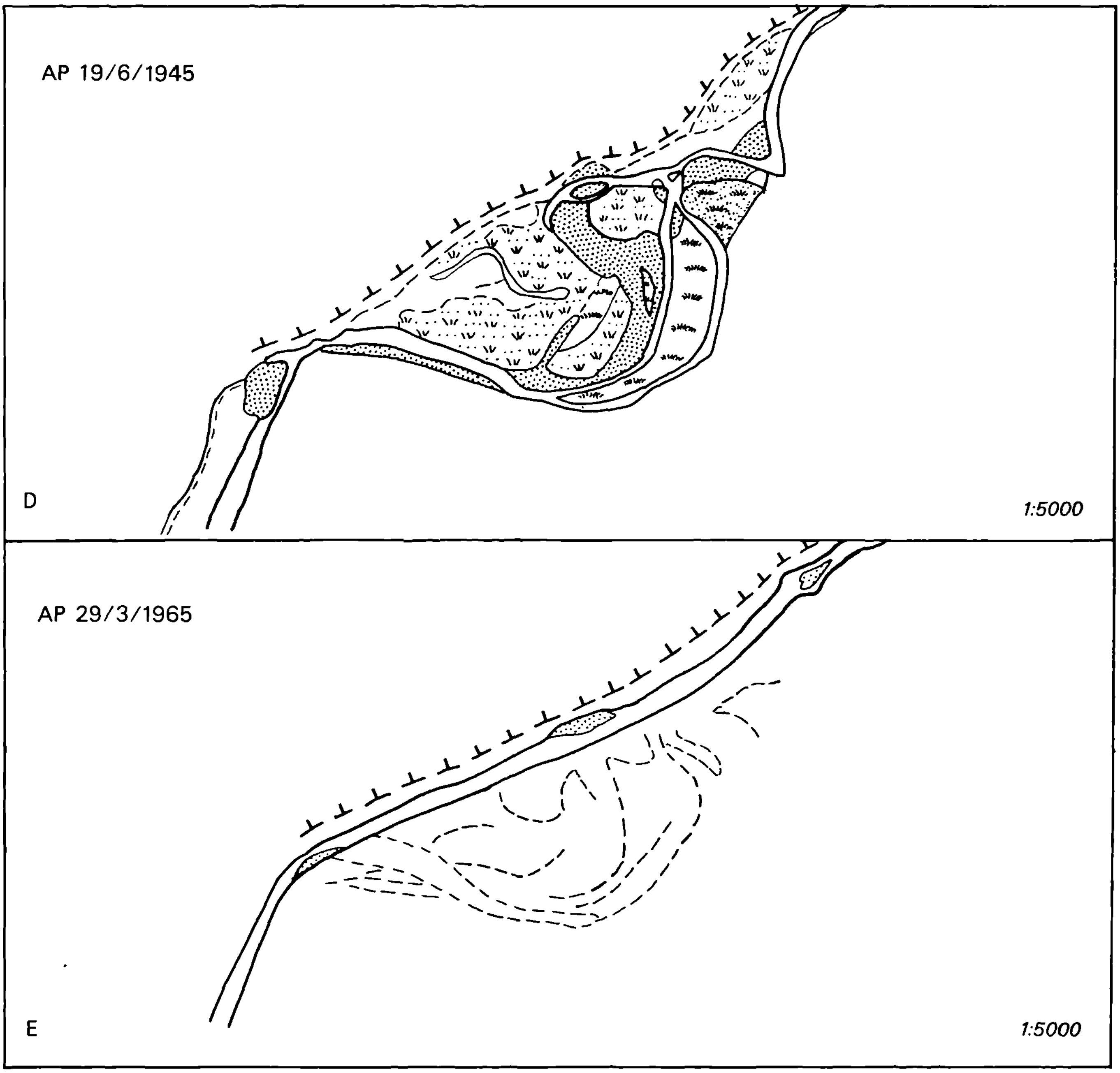


Figure 7.4.6.(i)

Tweed study reach 6: The River Teviot below Falnash Burn



the Dovecot Burn had evidence of anabranch cutoffs, perhaps caused by flood flows ripping through the floodplain, and this combined with the other mentioned characteristics suggested an area of channel which was both unstable and active.

Between Roy's map and 1858, two major flood events occurred on 9th Feb, 1831 and 3rd Aug, 1846, ranked joint third in magnitude in terms of the whole river, by the TRPB (Figure 5.6.1.(iii)). Clearly with floods of this magnitude, a certain amount of planform disruption would be expected but here the Teviot had plenty of room to increase its sinuosity with localised bank erosion and activation of sediment gravels on its floodplain cf. the more confined floodplain above and below this reach. The sinuosity of the channel was 1.33 and the braiding index 1.00 in 1858.

By the second edition (1899), there had been a reduction in sinuosity to 1.23; some of the active gravels seemed to have been stabilised and reused as agricultural land or rough-grassland (Figure 7.4.6.(i).C). The channel now had a more irregular rather than meandering planform and the Dovecot Burn now entered the Teviot one meander bend higher up. Downstream, there had been some new embanking to prevent inundation over agricultural land. Although the upper part of this study reach seemed to have only accentuated its meander bend, considerable change in the meandering planform downstream had taken place in the intervening 41 years. One meander bend had been cutoff along a diagonal chute cutoff, creating a new meander sequence so that by Glednest, the meander bend was reversed from the earlier date. It was of course difficult to attribute this change to any one flood event;

in the 41 intervening years British Rainfall records the Teviot in spate at least 16 times, with Oct, 1864 and Feb, 1881 the most major events (see Figure 5.6.1.(iii)). For a planform alteration of this magnitude however a large event in terms of geomorphic effectiveness must have occurred. Tentatively, it may be attributed to the 9/3/1881 flood, which again was ranked equal third by the TRPB. It may on the other hand be the accumulated effect of a large number of medium magnitude events, but with the threshold passed and the amount of material removed, this seemed improbable. It was however possible that one of the lesser events was more extreme and localised in the upper reaches of the Teviot, while only reaching more moderate levels downstream.

The first aerial photograph was in 19/6/1945 and clearly a major change had taken place since the second edition. Between 1899-1945, the irregular planform of 1899 had become more tortuous, by a combination of translation, rotation and enlargement (Figure 7.4.6.(i).D). However at some point, possibly 1938 when the largest flood on record on the Teviot occurred, this meander loop was truncated, leaving a meander of much reduced amplitude. By 1962, there had been a complete transformation of planform, which was obviously not natural (Figure 7.4.6.(i).E). Sinuosity was reduced to 1.06 and the whole length of the channel had been embanked to prevent further inundation of the surrounding agricultural land. Aerial photographs at 29/3/1965 and and ground survey (1983/4) indicated that these channelisation measures had been successful over that timespan.

Thus, field survey indicated that the channel was unnatural and the water depth too deep to survey. Old palaeochannels and former scour-hole features were easily identified to the north of the present channel well away from the present line of flow. The threshold stage for further erosion is presumably the overtopping of these embankments. Stabilising grasses appear to have been planted down the banks to reduce the chances of erosion.

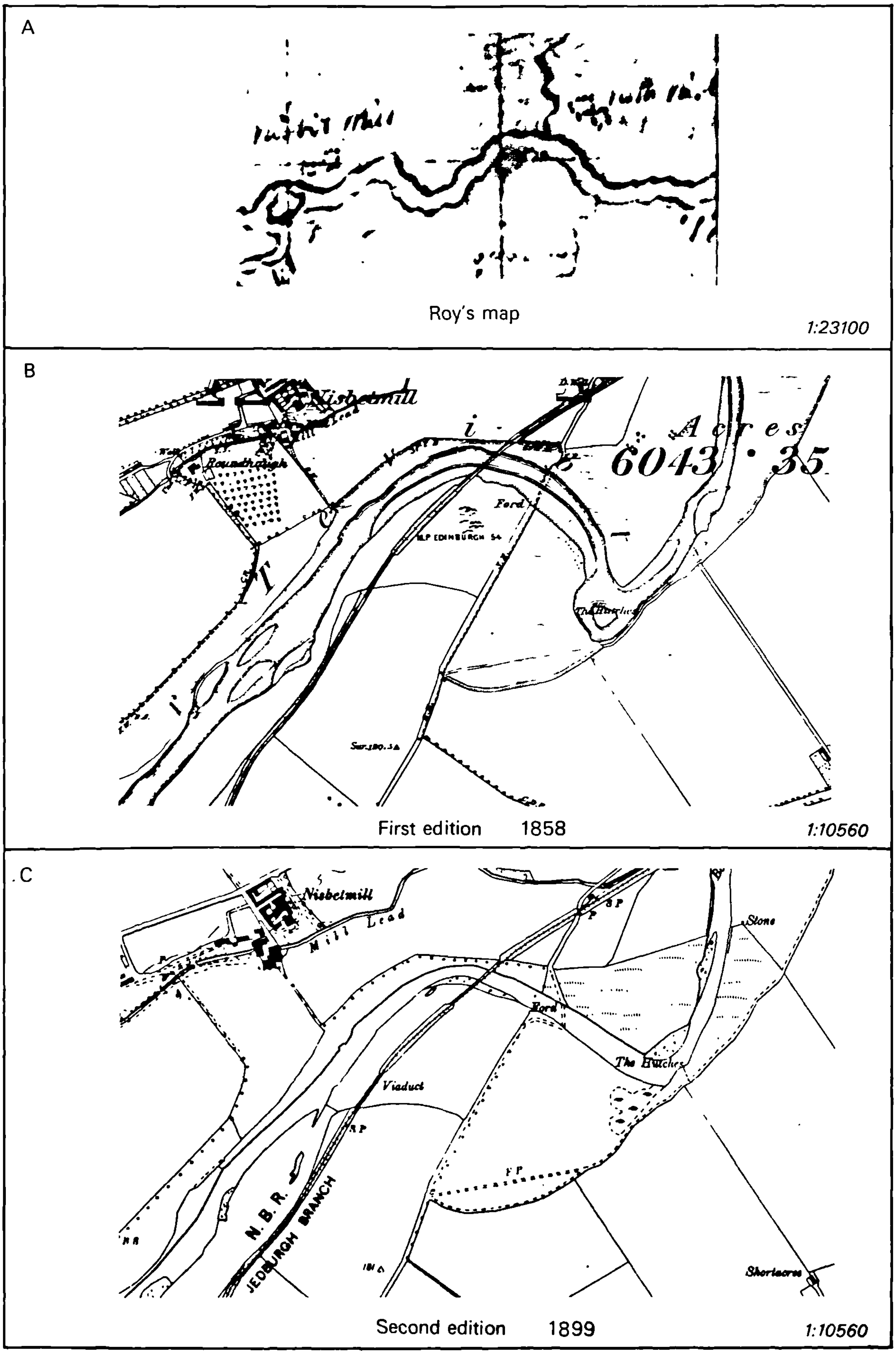
7.4.7 Tweed study reach 7: The River Teviot near Nisbetmill

The planform of the Teviot at this reach was a large irregular meander, which pre-1948 has undergone artificial strengthening of banks and embanking. A similar flood history to the Falnash Burn site had to be assumed. Catchment area above this reach is 844.7 km^2 and position within the channel system typology is outlined in Table 7.4.7.(i).

Roy's map (1750) showed the Jed entering the Teviot lower down than it does in 1984, with a large bar in the Teviot at the confluence and downstream irregular meanders were indicated (Figure 7.4.7.(i).A). On the aerial photograph, the outline of a former meandering channel in another area of floodplain suggested considerable movement at some time pre-1750. By 1858 however, the Jed seemed to have been embanked at the confluence and what remains of the large bar were only a few braid shoals. The sinuosity of the channel had increased to 1.40 with a braiding index of 1.16. The meander bend was almost tortuous in character, having eroded a channel to extend the meander bend even

Figure 7.4.7.(i)

Tweed study reach 7: The River Teviot near Nisbetmill



A: Roy's map 1:23100

B: First edition 1858 1:10560

C: Second edition 1899 1:10560

Figure 7.4.7.(i)

Tweed study reach 7 The River Teviot near Nisbetmill

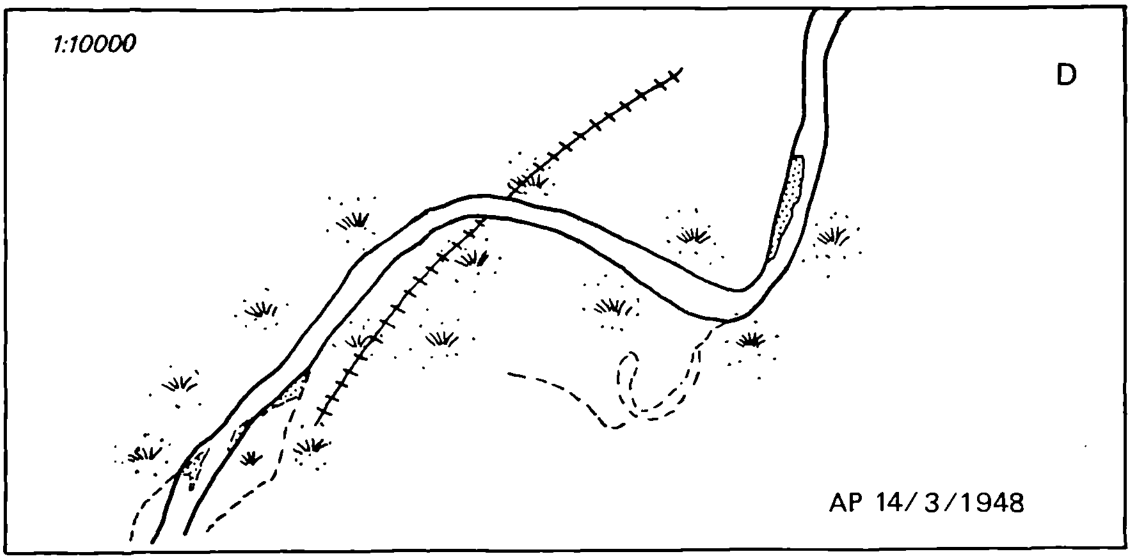


Table 7.4.7.(i)

Position of Tweed study reach 7: The River Teviot near Nisbetmill within the map-based channel system typology

A (a) Basin area: 844.7 km^2

(b) Average height: 52 m

	1858	1899	1972
B (a) UPSEDMT:	1	1	0
(b) LOCSEDMT:	2	1	0
C FLOOD:	0	0	0
D (a) FLOODPLN VEGETATION:	5	5	5
(b) BANK VEGETATION:	6	6	5
(c) BAR VEGETATION:	8	0	0

E MAXWID 34

	1858	1899	1972
F (a) CHANPATT:	8	6	6
(b) ISLANDS:	2	1	1
G (a) ACTIVITY:	2	7	6

further with "the Hutches", and there was plenty of channel-side sediment (Figure 7.4.7.(i).B).

By 1899, the channel had narrowed in several places; the braid shoals of sediment stored in mid-channel had been reworked and the channel shifted through a combination of rotation and translation to a single branch (Figure 7.4.7.(i).C). The amplitude of the meander bends had been reduced and the gravels by the channel side were more localised. Again as at the River Teviot below Falnash reach, the channel had undergone a diagonal cutoff leading to a reduced sinuosity of 1.18. Marshy ground indicated the former tip of the meander bend and the braiding index was reduced to 1.00. The first aerial photograph in 14/3/1948 showed the situation after the 1938 event and before the 1948 event, with a more stable meandering planform type (Figure 7.4.7.(i).D). It was clear that the discharge at this point had been large in 1938, as there was damage to the railway line between Jedfoot and Nisbet. Despite the 1948 flood event and the destruction of a bridge in a more recent event upstream, this pattern remained in 28/8/1968 basically unaltered. By the third edition (1972), the channel had reduced its sinuosity further but had undergone some embanking. Thus post 1900, there has been little change on the Teviot.

Unfortunately, field survey revealed the river too deep to survey. The river banks have been locally reinforced with wire although erosion is still taking place; at the tip of the meander bend, the bank is sheer, composed of fine sediment, and is gradually being scoured and deepened in to a pool.

Plate 7.4.7.(i)

A large irregular meander on the Teviot near Nisbetmill

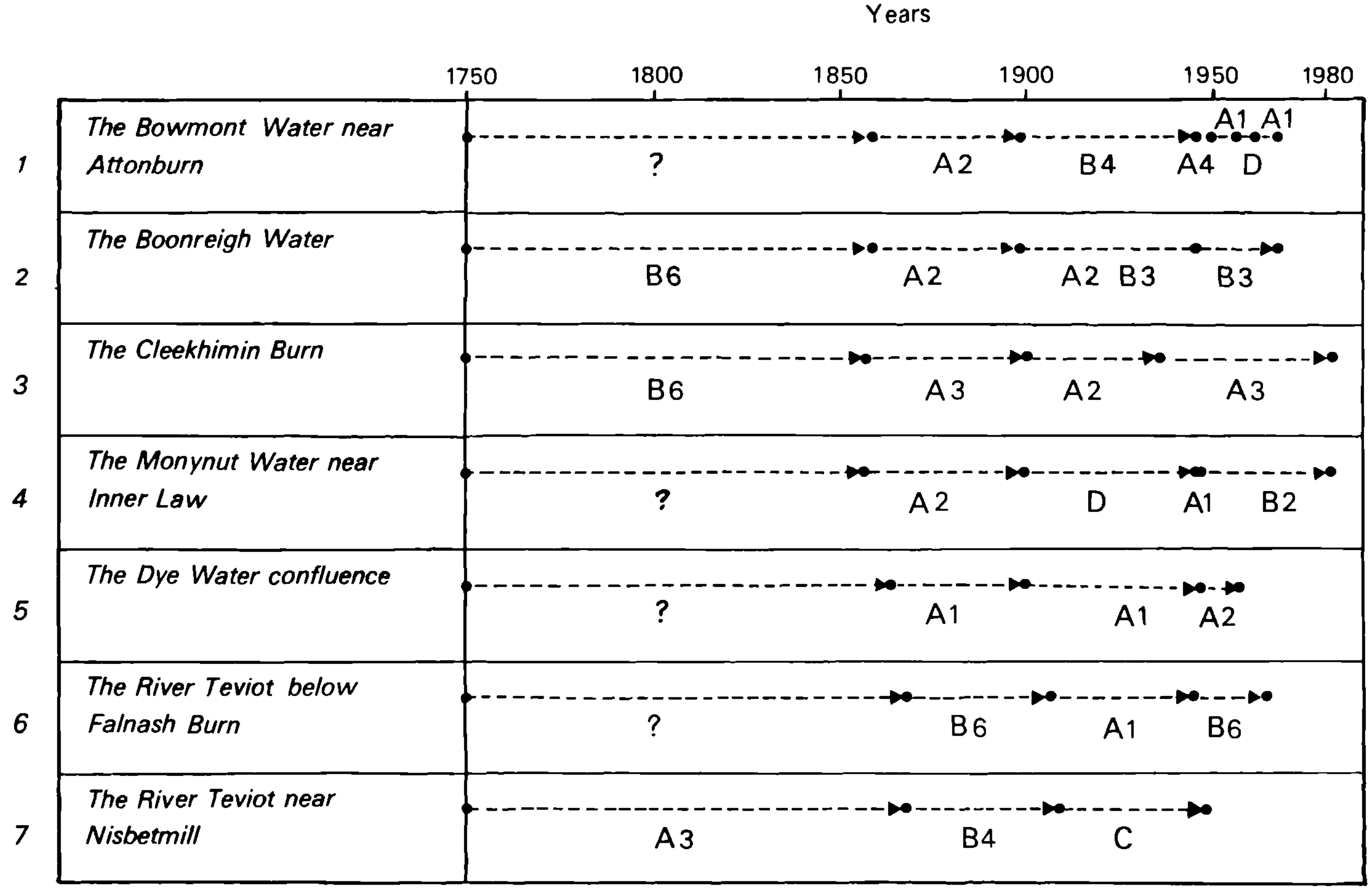
Evidence of slumping along the bank, which had previously been artificially reinforced.

7.4.8 Summary

The Tweed study reaches in general have a more restricted area for reworking and frequently the whole floodplain could undergo sedimentation during a major flood event (as occurred during the 1948 event on Monynut Water and Boonreigh Water). However, sediment sources are mainly derived from reworking of upstream and local floodplain areas. Modes of planform adjustment on tributaries near confluences are however rather different from the other two study areas. Low gravel fans were much less extensive and there was less frequent avulsion, probably due to the lower slopes involved. For example, the Dye water confluence clearly had to exceed high thresholds before major avulsion can occur. Frequent modes of adjustment are extra-channel avulsion, leaving the former bar surface intact,and chute cutoffs, depending on channel pattern type. Several reaches had artificial channel recovery after the major 1948 event and thus its geomorphic effectiveness was more limited than its high recurrence interval (300-500 year) would have suggested. Other channels, despite the occurrence of major flows, have a more limited planform response. For example, on the lower Teviot, the 1938 and 1948 events caused little disruption other than channel-side sedimentation. Stabilisation of unvegetated sediment distant from the channel margins takes place quickly, even after an extreme flood event has occurred. The interarrival times of major events are thus less important in terms of floodplain stability as flood deposits revegetate quickly.

Figure 7.4.8.(i)

Modes of channel planform change recorded within the Tweed study reaches (for key, see Table 4.8.3.(i))



Change in active area

A Increase
B Decrease
C Maintenance
D No change

However, more moderate flows in terms of sediment transport frequently keep the channel side gravels unstabilised and are often very important in quickly returning the channel to a quasi-equilibrium condition. Despite this, such flows are unable to access and mobilise large amounts of floodplain sediment and thus, sedimentation during more moderate flows has a more restricted sediment supply (cf. Speyside and Deeside). Thus, there was less intra-channel reworking of sediment.

CHAPTER 8

Stream power analysis of the active study reaches

8.1 Introduction

At the macro- and meso-scale, different rates and different types of channel pattern change were evident within the aerial photograph (API) case studies of active sites, examined in Chapter 7. Such changes can be compared both within the three study areas and by inter-region comparisons. It is therefore important to assess the stream power associated with such change ie. the rate of energy supply to overcome friction at the channel bed and transport sediment (Ferguson, 1981; see Section 2.6). Field survey and the study of channel hydraulics necessitate concentrating such comparative analyses at an even more localised scale than has hitherto been adopted in this thesis.

Although it would be ideal to study the shear stresses exerted by moving water of varying magnitudes and frequencies, few of the study sites were near gauges. Thus, bankfull discharge and associated stream power had to be estimated indirectly, as the criterion for comparative measurement. Unfortunately when making such measurements, it was necessary to concentrate on present channel dimensions; if channel dimensions are not in equilibrium and have altered over the last 250 years, then bankfull discharge and stream power may also have changed. If such stream power at bankfull level is insufficient to transport the available bedload and perhaps disrupt the channel pattern, even higher flows with associated higher stream powers must be important. The bankfull stream power values can then be compared with the results of Ferguson (1981) for other British sites (see Section 2.6 and Figure 2.6.(i)).

Within the time limitations of this study, analysis was concentrated on the selected sites of moderate to high activity. However where possible, to put such information in context, a few more stable sites were also studied. Here there is obviously room for future research, as the more representative values gained from a variety of different sites with different controls, the better. Unfortunately, within upland areas, measurement depended upon accessibility and permission to enter land. There were also limitations on which reaches could be analysed, imposed by the surveying method chosen, whether the cross-section could be waded and the density of the bank-side vegetation. Dense tree-lined banks were virtually impossible to survey. Finally, especially within the Tweed study area, many cross-sections at potential sites had to be rejected where man had induced an unnatural hydraulic geometry.

Where possible, for each of the study reaches, the following procedure was adopted. Each API site was checked in the field and then suitable cross-sections selected, in terms of ease of identification of bankfull stage (ie. the point of incipient overbank flow) and measurement of bankfull slope. Bankfull stage is recognised to be most successfully defined morphologically in straight reaches (Richards, 1982). Unfortunately, within other planform categories, the bankfull concept is much more easily defined theoretically than actually applied in the field. Because of the inherent nature of the more active areas, with banks locally eroding at different rates, bankfull stage was frequently ill-defined and the distinction between present bankfull and the first terrace could be small in height. Thus, representative cross-section sites for each study reach had to be selected with care.

8.2 Data collection and analysis

Each channel cross-section was surveyed, using a staff and automatic level, from bankfull stage on each bank to gain the basic hydraulic parameters of channel width, maximum and mean depth, wetted perimeter, cross-sectional area and hydraulic radius. Composite sediment size of the channel bed material was measured, using the Wolman (1954) sampling method, with a systematic random sampling of the intermediate axis of the bed material across the channel. A sediment template and sediment size comparator were used to measure the larger (-2 to -10 phi) and smaller (less than -2 phi) clast sizes, respectively. Sample size varied from 100 to 200 clasts, dependent on channel width. Although some channel cross-sections had roughness varying along the wetted perimeter, as discussed by Motayed and Krishnamurthy (1980), this was not considered large enough to cause a major discrepancy in D_{84} values.

Cross-section slope was measured along the bankfull stage over several channel widths to gain an accurate estimate of the water surface slope at bankfull. Three values were then calculated and compared to gain a representative value:

(1) the total average slope taken from the first and last slope value measured

(2) the average of all the slope increments measured between the first and last level readings

(3) the slope measured from the level measurements directly on either side of the cross-section

In terms of analysis of bank resistance, it was necessary to assess whether erosion occurred periodically or continually. Obviously, a more long term, field-based study, specifically on bank erosion, would map bank retreat rates over time with erosion pins; this study relied on simple field measurement and observation. The unreliability of soil strength measurements for predicting types and rates of retreat, led to the rejection of that sort of quantitative analysis in the present study (see Park, 1978). A sample core of bank material was removed from the bank to assess both the depth of the upper unit before contact with bedrock/ large clasts and the depth of the stabilising root layer. To provide a measurement of the silt-clay ratio and cohesiveness of banks, this sample was sieved for the percentage of the total sample below 63 microns (Schumm, 1960). Unfortunately, due to varying degrees of supra-bar sedimentation, flood deposition and past channel shift, banks did not have a uniform silt-clay ratio from base to surface and thus an average value had to be taken.

Bank vegetation was also noted within similar hydrologically significant categories as in the map-based typology. This was also comparable with the scheme adopted by Charlton et al. (1978) in their study of the hydraulic geometry of British gravel bed rivers. The categories were (1) trees (2) trees and heath (3) trees and grassland (4) heather (5) agricultural land (6) rough-grassland. More detail on definition of the vegetative categories is found in Section 4.3 (Table 4.3.(i)).

Bankfull discharge was calculated using Manning's (1891) open channel, slope-area method although most natural streams do not fulfil the uniform flow conditions. This was compared with discharge calculated using a variety of comparable methods, to gain a realistic value. Other methods used were those variants on the the slope-area method, proposed by Charlton et al. (1978), Bathurst (1982), Simons and Senturk (1977) and an alternative parameter describing resistance to steady uniform flow, the Darcy Wiesbach friction factor (F). Manning's slope-area method will be discussed here and the alternative methods are outlined in Table 8.2.(ii). The symbols used in the following equations are outlined in Table 8.2.(i).

To gain a representative Manning's roughness value for the channel bed, the cumulative size frequency of the sampled material was plotted on probability paper and the D_{84} value extracted (Limerinos, 1970). This percentile seems appropriate within most upland environments as the finer fraction will not constitute the major roughness element at bankfull stage. Limerinos (1970) found that the best relations fitting

Table 8.2.(i)

Symbols and definitions involved in the discharge and stream power equations

Parameter	Symbol	Units
Area of cross-section	A	m^2
Wetted perimeter	WP	m
Hydraulic radius	R	m
Width	W	m
Average depth	d	m
Maximum depth	d_m	m
Width: depth ratio	W:d	dimensionless
Average velocity	V	$m\ s^{-1}$
Discharge	Q	$m^3\ s^{-1}$
Bankfull discharge	Q_b	$m^3\ s^{-1}$
Critical discharge at which sediment movement is likely to begin	Q_c	$m^3\ s^{-1}$
Slope	S	dimensionless
Slope at bankfull	S_b	dimensionless
Size of particle for which x% of total particles are finer	D_x	m
Shields' competence at bankfull	D_s	m
Manning's roughness coefficient	n	dimensionless
Constant to be established empirically	K	dimensionless

Table 8.2.(i) cont.

Parameter	Symbol	Units
Chezy coefficient of roughness	C	dimensionless
Critical shear stress for initiating particle transport	τ_c	$N\ m^{-2}$
Darcy-Weisbach friction factor	F	dimensionless
Specific density of transporting fluid	ρ	$1000\ kg\ m^{-3}$
Specific weight of sediment	γ_s	$KN\ m^{-3}$
Specific weight of fluid	γ_f	$KN\ m^{-3}$
Gravity	g	$9.81\ m\ s^{-2}$
Gross stream power	Ω	$W\ m^{-1}$
Unit stream power	ω	$W\ m^{-2}$
Stream power index	Ω'	$m^3\ s^{-1}$
Du Boys' shear stress	τ	$N\ m^{-2}$
Specific gravity of bed material	s	2.65

Table 8.2.(ii)

Alternative discharge equations used for comparison with the Manning slope/ area method

(1) Charlton et al. (1978) p35, Equation (11.1)

(1) $$K = 5.60\ A\ (g\ d)^{0.5} \log \frac{(1.81\ d)}{D_{90}}$$

(2) $$Q = K\ S^{0.5}$$

(2) Bathurst (1982) p65, Equation (3)

Since slope > 0.005 and <0.05, Equation 3 was used:

(1) $$K = 5.62\ A\ (g\ R)^{0.5} \log \frac{(a\ R)}{(3.5\ D_{84})}$$

where

(2) $$a = 11.1\ (R/\ d_m)^{-0.314}$$

(3) $$Q = K\ S^{0.5}$$

Table 8.2.(ii) cont.

(3) Simons and Senturk (1977) pp 334-5, Equation (6.100)
(imperial units)

(1) $$\frac{C}{\sqrt{g}} = 7.4 \log \frac{d}{D_{85}}$$

(2) $$C = 7.4 \log (d/ D_{85}) * g$$

(3) $$V = C \sqrt{R S}$$

(N.B. $g = 32.17$ ft s^{-1})

(4) Darcy-Weisbach friction factor

(1) $$F = \frac{1}{1.14 + 2 \log ((A/W)/ D_{84})}$$

(2) $$C = (\sqrt{8\ g}/ F)$$
(3) $$V = C \sqrt{R S}$$

his field data were obtained using this characteristic particle size diameter. Leopold et al. (1964) also have stated that if a single flow resistance parameter is utilised, involving a bed particle percentile, a bed-size particle percentile in excess of D_{50} should be used. The obvious disadvantage is the implication that the bed-size distribution is irrelevant and a single value can be used with no indication of the potential variance. The equation (8.1) used to calculate roughness "n" was that recommended by Limerinos (1970).

$$n = \frac{0.113 * R^{1/6}}{1.16 + 2 \log (R/ D_{84})} \qquad (8.1)$$

Roughness values were expected to fall within the "mountain streams" category (D) of natural channels in Chow's (1959) range of roughness (Table 8.2.(iii)). Mean velocity of the bankfull cross-section can then be calculated (8.2).

$$V = \frac{R^{2/3} * S^{1/2}}{n} \qquad (8.2)$$

Then bankfull discharge was computed simply using Equation 8.3.

Table 8.2.(iii)

Manning's roughness coefficients for various boundaries

(extracted from Chow (1959) p7-25, Table 7-5)

Category D

(b) Mountain streams, no vegetation in channel, banks usually steep trees and brush along banks submerged at high stages.

	MIN	NORM	MAX
(1) Bottom: gravels, cobbles and a few boulders	0.030	0.040	0.050
(2) Bottom: cobbles with large boulders	0.040	0.050	0.060

$$Q = A V \qquad (8.3)$$

The calculation of bankfull stream power was then derived as follows. The critical mean shear stress for entrainment was calculated from DuBoys' equation (8.4) where γ is the specific weight of the transporting fluid. ($\gamma = \rho * g$)

$$\tau = \gamma R S \qquad (8.4)$$

Stream power per unit area of bed (standardised for comparative purposes) was then obtained using (8.5)

$$\omega = V \tau \qquad (8.5)$$

Shields competence at bankfull (D_s) was also calculated, using the Shields transport relation for the initiation of sediment transport (8.6). A Shield's value of 0.03-0.04 is now generally favoured for gravel-bed streams with high W:d ratios. (Specific gravity (s) represents the ratio of the specific weight of a fluid, solid or fluid/solid mixture to the specific weight of water at 4 ^{o}C.)

$$D_s = \frac{d\ S}{0.04 * (s - 1)} \qquad (8.6)$$

This allowed an estimate of the magnitude of clast size that could be entrained by a flow at bankfull slope and mean depth. This was compared with the D_{84} value of bed material sample for that cross-section. For comparison with the bankfull discharge, the Schoklitsch equation for critical discharge when sediment transport is likely to occur (Bathurst, 1982; Simons and Senturk, 1977) was also calculated (8.7).

$$Q_c = 0.26\ W * \frac{(\gamma s - \gamma f)^{5/3}}{\gamma f} \quad \frac{D_n^{3/2}}{S^{7/6}} \qquad (8.7)$$

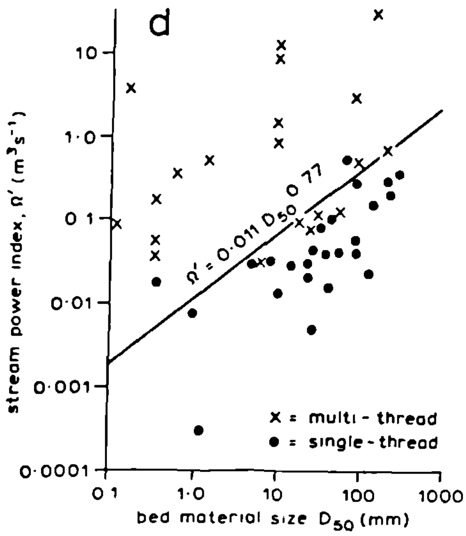
Before presenting the results, two important points should be understood. Firstly, the actual determination of the stochastic process of river transport and stream power is highly variable within a reach and thus the above equations may only provide a mean value. Specific considerations such as sediment packing, imbrication, shape and the impact of bank collapse are not considered. Secondly, because flow mechanics differ in contrasting fluvial environments, the shear stresses needed to entrain large clasts may diverge considerably from values based on flume experiments and theory (Komar, McCave and Miller, 1976). In fairly shallow rivers, for example, it would be expected that entrainment may occur at lower shear stresses than predicted by theory, as Benoulli type hydrodynamic lift and bank caving constitute additional transporting forces.

The results of this analysis for each study area will be presented as follows:

(1) The range of hydraulic parameters associated with the selected active reaches, analysed in Chapter 7
(2, The magnitude of bankfull discharge and associated specific runoff rates
(3) A comparison of events of bankfull stream power with the magnitude of discharge when sediment transport occurs
(4) The relationship between channel form (width and W:d; D_{84}) and unit stream power at bankfull
(5) The importance of different bank characteristics and associated modes of bank erosion

Finally, it is notable in relation to (4), that Richards (1982) distinguished between multithread and single streams on the basis of surrogate stream power index (Q_b* S)/ D_{50} relationships (see Figure 8.2.(i)).

Figure 8.2.(i)



Single-thread and multithread channels discriminated by a stream power index (Ω') and median bed material size (D_{50})

(Source: Richards, 1982 p215 Figure 7.12)

8.3.1 Dee study reaches: Limitations on study

Within the Dee study area, limitations depended principally on estate permission, accessibility and man's disruption of the natural channel geometry. For example, an interesting map site on the upper Geldie (Chapter 4.6.1.1) had to be left unmeasured because access to the site could not be obtained. The mainstream Dee was not wadable at the Clunie Cottage site and the more stable sites measured for comparison were thus only those on the tributaries. In several areas, estates had been bulldozing material out of the channel eg. lower Quoich Water and Gleann an t-Slugain, as described in Chapter 6.2, and thus selectivity in the choice of natural cross-sections was essential. It should be noted that several study reaches eg. the Ey confluence (Plate 8.3.1.(i)) frequently had well-defined trash lines around bankfull stage.

8.3.2 Dee study reaches: Results

The locations of the cross-sections measured at the study sites are shown in Figure 8.3.2.(i), with the basic hydraulic parameters at bankfull for each cross-section itemised in Table 8.3.2.(i). Examples of the cross-sections studied are shown in Figure 8.3.2.(ii). The different percentiles (D_{16}, D_{50}, D_{84} and D_{90}) of intermediate axis grain size composition for each cross-section are tabulated in Appendix 3.1 and selected cumulative frequency curves for channel bed material, to highlight size distribution differences between reaches, are shown in Figure 8.3.2.(iii). The bankfull discharge results are collated by

Figure 8.3.2.(i) Location of sampled cross-sections in relation to study reaches within the Dee study area

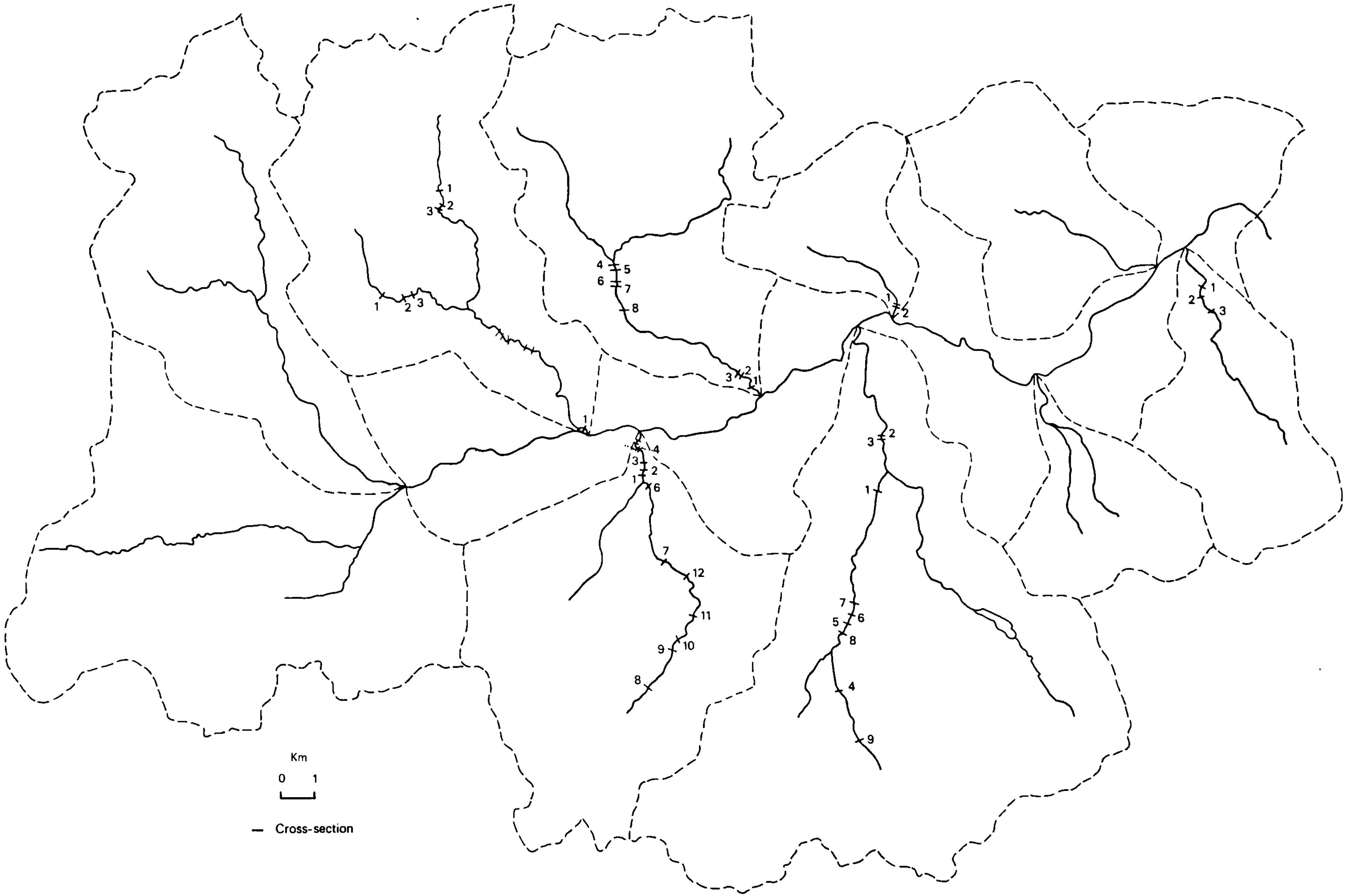
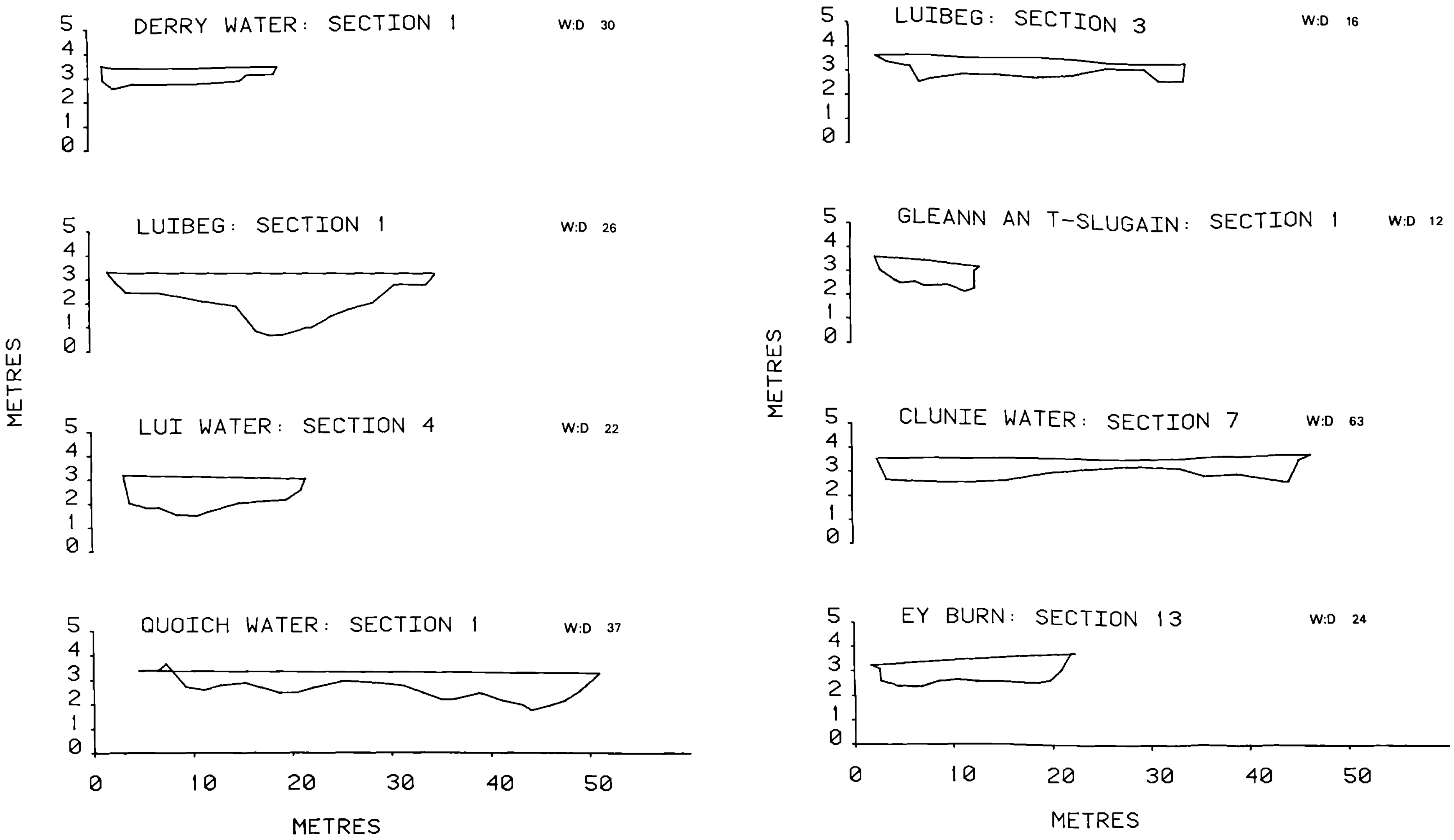


Figure 8.3.2.(ii)

EXAMPLES OF CROSS-SECTIONS USED IN STREAM POWER ANALYSIS WITHIN THE DEE STUDY REACHES.



Examples of cumulative frequency curves for channel bed material within the Dee study reaches

Figure 8.3.2.(iii)

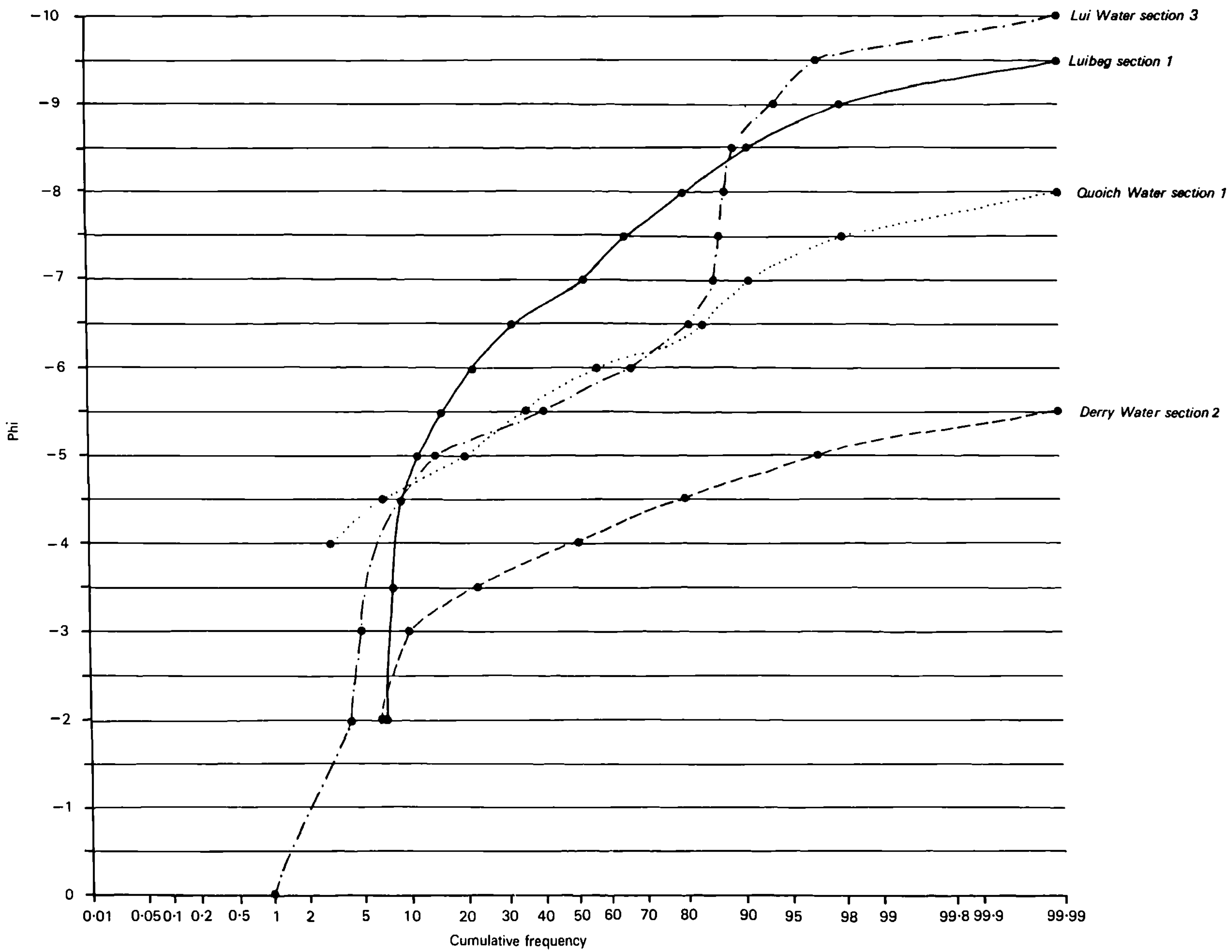


Table 8.3.2.(i)

Dee study reaches: Basic hydraulic parameters at bankfull stage

Reach	W (m)	d (m)	W:d	A (m^2)	R (m)	WP (m)	D84 (m)	Slope
1: Quoich confluence								
Section 1	44.5	1.21	37	53.8	1.18	45.6	0.128	0.016
Section 2	20.0	0.70	29	14.0	0.67	20.9	0.284	0.016
Section 3	18.9	0.72	26	13.6	0.69	19.6	0.187	0.016
2: Ey confluence								
Section 4	14.3	1.38	10	19.7	1.28	15.4	0.142	0.026
Section 5	13.2	1.53	9	20.3	1.39	14.6	0.142	0.022
Section 14	21.7	0.96	23	20.9	0.92	22.2	0.201	0.011
Section 13	20.2	0.85	24	17.1	0.82	20.9	0.169	0.011
3: Gleann an t-Slugain								
Section 1	10.8	0.87	12	09.1	0.78	11.6	0.169	0.055
Section 2	10.5	0.91	12	09.8	0.83	11.8	0.247	0.058
4: Lui Water								
Section 2	27.9	0.88	32	24.4	0.85	28.8	0.072	0.010
Section 3	15.5	0.95	16	14.7	0.90	16.3	0.108	0.019
Section 4	21.7	0.99	22	21.4	0.94	22.8	0.187	0.012
Section 5	33.9	0.57	59	19.2	0.55	34.6	0.082	0.004
5: Clunie Water								
Section 5	28.5	0.50	57	14.1	0.49	29.0	0.137	0.020
Section 6	28.2	0.47	60	13.2	0.46	28.9	0.106	0.013
Section 7	43.8	0.70	63	30.5	0.68	44.6	0.091	0.011
Section 8	39.4	0.81	49	31.9	0.80	40.2	0.152	0.015

Table 8.3.2.(i) cont.

Reach	W (m)	d (m)	W:d	A (m²)	R (m)	WP (m)	D84 (m)	Slope
6: Luibeg Burn								
Section 1	33.0	1.29	26	42.6	1.26	33.8	0.284	0.056
Section 2	45.3	0.78	58	35.4	0.76	46.6	0.181	0.031
Section 3	31.3	0.60	52	18.8	0.58	32.3	0.111	0.006
7: Derry Water								
Section 1	17.6	0.59	30	10.3	0.56	18.3	0.050	0.005
Section 2	12.4	0.64	19	07.9	0.61	13.1	0.024	0.007
Section 3	18.6	1.14	16	21.2	1.08	19.7	0.039	0.007
Other reaches								
(a) Ey Burn								
Section 1	19.1	1.49	13	28.4	1.38	20.6	0.175	0.028
Section 2	21.6	1.44	15	35.2	1.56	22.6	0.130	0.029
Section 3	17.8	1.16	15	20.7	1.12	18.5	0.239	0.029
Section 6	21.3	1.54	14	32.8	1.46	22.4	0.832	0.026
Section 7	16.8	0.77	22	13.0	0.74	17.5	0.256	0.017
Section 8	18.1	0.50	36	09.0	0.48	18.6	0.187	0.012
Section 9	11.4	0.78	15	08.7	0.72	12.1	0.069	0.005
Section 10	14.1	0.81	17	11.4	0.76	14.9	0.059	0.004
Section 11	16.0	1.04	15	16.8	0.99	17.9	0.060	0.003
Section 12	18.7	0.91	21	17.1	0.89	19.2	0.315	0.037

Table 8.3.2.(i) cont.

Reach	W (m)	d (m)	W:d	A (m^2)	R (m)	WP (m)	D84 (m)	Slope
(b) Quoich Water								
Section 4	21.0	0.57	37	12.1	0.57	21.3	0.187	0.016
Section 5	29.0	0.77	38	22.4	0.75	29.8	0.208	0.008
Section 6	28.4	0.41	69	11.7	0.40	28.9	0.223	0.022
Section 7	71.0	0.55	129	39.2	0.55	71.7	0.163	0.009
Section 8	33.4	0.51	65	17.1	0.50	34.0	0.152	0.017
(c) Clunie Water								
Section 1	21.7	1.29	17	28.0	1.23	22.7	0.338	0.006
Section 2	43.7	0.56	78	24.6	0.56	44.2	0.163	0.015
Section 3	30.0	0.92	33	27.5	0.90	30.4	0.175	0.010
Section 4	23.6	0.43	55	10.3	0.42	24.4	0.175	0.026
Section 9	12.5	0.67	19	08.4	0.65	13.0	0.128	0.023
(d) River Gelder								
Section 1	10.9	1.03	11	11.2	0.94	11.9	0.091	0.004
Section 2	16.3	0.70	23	12.9	0.77	16.8	0.235	0.033
Section 3	11.7	0.86	13	12.3	0.82	10.1	0.327	0.025
(e) Lui Water								
Section 1	16.2	0.95	17	15.4	0.90	17.1	0.320	0.025

Table 8.3.2.(ii)

Dee study reaches: Calculation of bankfull discharge

Study reach	n	A (m^2)	V ($m\ s^{-1}$)	Q ($m^3\ s^{-1}$)
1: Quoich confluence				
Section 1	0.038	52.2	3.9	202.1
Section 2	0.055	14.0	1.7	24.1
Section 3	0.053	13.6	2.1	28.6
2: Ey confluence				
Section 4	0.038	19.7	5.0	97.6
Section 5	0.038	20.3	4.9	99.4
Section 14	0.045	20.9	2.2	47.1
Section 13	0.043	17.4	2.1	36.5
3: Gleann an t-Slugain				
Section 1	0.049	9.1	4.7	42.9
Section 2	0.050	9.8	4.2	40.9
4: Lui Water				
Section 2	0.033	24.5	2.7	65.8
Section 3	0.037	14.7	3.5	50.9
Section 4	0.044	22.2	2.3	51.5
Section 5	0.036	19.2	1.2	22.6
5: Clunie Water				
Section 5	0.044	13.8	2.0	27.8
Section 6	0.041	13.1	1.7	21.7
Section 7	0.036	30.5	2.2	68.1
Section 8	0.042	31.9	2.5	80.2

Table 8.3.2.(ii) cont.

Study reach	n	A (m²)	V (m s⁻¹)	Q (m³ s⁻¹)
6: Luibeg Burn				
Section 1	0.048	42.6	5.8	245.8
Section 2	0.045	35.5	3.3	116.0
Section 3	0.040	18.8	1.4	25.5
7: Derry Water				
Section 1	0.031	10.3	1.5	15.8
Section 2	0.026	7.9	2.3	18.2
Section 3	0.028	21.3	3.1	65.9
Other reaches				
(a) Ey Burn				
Section 1	0.040	28.3	5.1	145.7
Section 2	0.037	35.3	6.2	220.1
Section 3	0.046	20.7	4.0	82.7
Section 6	0.073	32.7	2.9	93.9
Section 7	0.052	13.0	2.1	27.0
Section 8	0.050	9.0	1.3	12.0
Section 9	0.033	8.7	1.7	14.7
Section 10	0.032	11.4	1.7	18.9
Section 11	0.031	17.4	1.7	30.0
Section 12	0.054	17.1	3.3	56.6

Table 8.3.2.(ii) cont.

Study reach	n	A (m^2)	V ($m\ s^{-1}$)	Q ($m^3\ s^{-1}$)
(b) Quoich Water				
Section 4	0.048	12.1	1.8	21.6
Section 5	0.047	22.4	1.6	35.0
Section 6	0.058	11.7	1.4	16.4
Section 7	0.046	39.3	1.4	53.9
Section 8	0.046	17.2	1.8	30.9
(c) Clunie Water				
Section 1	0.051	28.1	1.7	47.4
Section 2	0.046	24.7	1.8	44.7
Section 3	0.043	27.5	2.2	59.6
Section 4	0.051	10.2	1.8	18.2
Section 9	0.041	8.4	2.8	23.2
(d) River Gelder				
Section 1	0.035	11.2	1.7	19.5
Section 2	0.049	12.9	3.1	39.6
Section 3	0.056	10.1	2.5	25.0
(e) Lui Water				
Section 1	0.054	15.4	2.7	42.3

Table 8.3.2.(iii)

Dee study reaches: Specific runoff rates associated with bankfull discharge

	Q_b (m^3 s^{-1})	Catchment area (km^2)	Specific runoff (m^3 s^{-1} km^{-2})
1: Quoich confluence			
Section 1	202.1	61.4	3.3
Section 2	24.1	61.1	0.4
Section 3	28.6	60.9	0.5
2: Ey confluence			
Section 4	97.6	60.2	1.6
Section 5	99.4	60.3	1.6
Section 13	36.5	60.4	0.6
Section 14	47.1	60.3	0.8
3: Gleann an t-Slugain			
Section 1	42.9	16.0	2.7
Section 2	40.9	16.4	2.5
4: Lui Water			
Section 2	65.8	54.5	1.2
Section 3	50.9	54.3	0.9
Section 4	51.5	52.5	1.0
Section 5	22.6	52.2	0.4
5: Clunie Water			
Section 5	27.8	27.7	1.0
Section 6	21.7	28.5	0.8
Section 7	68.1	29.8	2.3
Section 8	80.2	26.8	3.0

Table 8.3.2.(iii) cont.

	Q_b (m^3 s^{-1})	Catchment area (km^2)	Specific runoff (m^3 s^{-1} km^{-2})
6: Luibeg Burn			
Section 1	245.8	13.3	18.5
Section 2	116.0	20.6	5.6
Section 3	25.5	23.2	1.1
7: Derry Water			
Section 1	15.8	15.8	1.0
Section 2	18.2	17.2	1.1
Section 3	65.9	17.4	3.8
Other reaches			
(a) Ey Burn			
Section 1	145.7	59.3	2.5
Section 2	220.1	59.5	3.7
Section 3	82.7	59.7	1.4
Section 6	93.9	41.1	2.3
Section 7	27.0	33.0	0.8
Section 8	12.0	19.8	0.6
Section 9	14.7	21.5	0.7
Section 10	18.9	21.9	0.9
Section 11	30.0	22.7	1.3
Section 12	56.5	31.8	1.8

Table 8.3.2.(iii) cont.

	Q_b (m^3 s^{-1})	Catchment area (km^2)	Specific runoff (m^3 s^{-1} km^{-2})
(b) Quoich Water			
Section 4	21.6	44.1	0.5
Section 5	35.0	44.5	0.8
Section 6	16.4	45.2	0.4
Section 7	53.9	45.6	1.2
Section 8	30.9	48.3	0.6
(c) Clunie Water			
Section 1	47.4	60.2	0.8
Section 2	44.7	98.2	0.5
Section 3	59.6	97.5	0.6
Section 4	18.2	19.7	0.9
Section 9	23.2	16.8	1.4
(d) River Gelder			
Section 1	19.5	27.0	0.7
Section 2	39.6	26.5	1.5
Section 3	25.0	25.1	1.0
(e) Lui Water			
Section 1	42.3	60.8	0.7

Table 8.3.2.(iv)

Dee study reaches: Parameters used in stream power calculations

Study reach	Du Boys' ($N\ m^{-2}$)	Velocity ($m\ s^{-1}$)	Stream power ($W\ m^{-2}$)
1: Quoich confluence			
Section 1	196.7	3.9	761.2
Section 2	102.6	1.7	176.5
Section 3	105.7	2.1	222.0
2: Ey confluence			
Section 4	326.1	5.0	1614.2
Section 5	303.5	4.9	1484.1
Section 13	88.5	2.1	185.8
Section 14	101.7	2.3	228.8
3: Gleann an t-Slugain			
Section 1	447.3	4.7	2106.8
Section 2	447.3	4.2	1869.3
4: Lui Water			
Section 1	83.2	2.7	223.8
Section 2	54.6	3.5	189.5
Section 3	110.6	2.3	256.4
Section 4	21.8	1.2	25.7
5: Clunie Water			
Section 5	58.1	1.7	95.9
Section 6	73.8	2.2	164.6
Section 7	117.0	2.5	293.7
Section 8	100.2	2.0	202.4

Table 8.3.2.(iv) cont.

Study reach	Du Boys' ($N\ m^{-2}$)	Velocity ($m\ s^{-1}$)	Stream power ($W\ m^{-2}$)
6: Luibeg Burn			
Section 1	692.3	5.8	3994.6
Section 2	231.4	3.3	756.7
Section 3	34.2	1.4	46.5
7: Derry Water			
Section 1	27.7	1.5	42.4
Section 2	41.7	2.3	95.5
Section 3	73.9	3.1	229.1
Other reaches			
(a) Ey Burn			
Section 1	378.8	5.1	1947.0
Section 2	443.8	6.2	2769.3
Section 3	318.4	4.0	1270.4
Section 6	377.6	2.9	1083.7
Section 7	123.9	2.1	256.5
Section 8	56.9	1.3	76.2
Section 9	35.1	1.7	59.3
Section 10	30.0	1.7	49.8
Section 11	29.1	1.7	50.3
Section 12	322.9	3.3	1068.8

Table 8.3.2.(iv) cont.

Study reach	Du boys' ($N\ m^{-2}$)	Velocity ($m\ s^{-1}$)	Stream power ($W\ m^{-2}$)
(b) Quoich Water			
Section 4	88.9	1.8	159.1
Section 5	59.1	1.6	92.2
Section 6	87.3	1.4	122.2
Section 7	48.3	1.4	66.2
Section 8	84.1	1.8	151.4
(c) Clunie Water			
Section 1	68.9	1.7	116.4
Section 2	83.1	1.8	150.4
Section 3	87.8	2.2	190.5
Section 4	107.2	1.8	190.8
Section 9	145.9	2.8	404.1
(d) River Gelder			
Section 1	37.0	1.7	64.4
Section 2	248.0	3.1	763.8
Section 3	201.1	2.5	498.7
(e) Lui Water			
Section 1	221.4	2.7	604.4

Table 8.3.2.(v)

Dee study reaches: Shield's competence at bankfull and the sediment transport discharge

Reach	D_s (m)	% D	Q_b (m^3 s^{-1})	Q_c (m^3 s^{-1})
1: Quoich confluence				
Section 1	0.293	99.5	202.1	152.2
Section 2	0.165	77	24.1	232.9
Section 3	0.170	83	28.6	117.6
2: Ey confluence				
Section 4	0.543	100	97.6	32.4
Section 5	0.518	100	99.4	36.0
Section 13	0.141	78	36.5	162.3
Section 14	0.160	78	47.1	226.2
3: Gleann an t-Slugain				
Section 1	0.765	100	42.9	12.1
Section 2	0.755	100	40.9	23.4
4: Lui Water				
Section 2	0.133	100	65.8	69.7
Section 3	0.273	88	50.9	33.6
Section 4	0.179	84	51.5	183.3
Section 5	0.034	25	22.6	299.8
5: Clunie Water				
Section 5	0.150	87	27.8	83.2
Section 6	0.092	77	21.7	92.6
Section 7	0.116	97	68.1	139.1
Section 8	0.184	91	80.2	188.0

Table 8.3.2.(v) cont.

Reach	D_s (m)	% D	Q_b (m^3 s^{-1})	Q_c (m^3 s^{-1})
6: Luibeg Burn				
Section 1	1.095	100	245.8	86.5
Section 2	0.368	100	116.0	120.4
Section 3	0.054	24	25.5	271.6
7: Derry Water				
Section 1	0.044	76	15.8	57.1
Section 2	0.068	100	18.2	9.0
Section 3	0.225	100	65.9	28.1
Other reaches				
(a) Ey Burn				
Section 1	0.630	100	145.7	54.4
Section 2	0.717	100	220.1	37.8
Section 3	0.512	100	82.7	77.6
Section 6	0.613	72	93.9	676.0
Section 7	0.199	74	27.0	151.4
Section 8	0.090	64	12.0	152.9
Section 9	0.058	72	14.7	60.0
Section 10	0.049	70	18.9	76.1
Section 11	0.048	77	30.0	123.9
Section 12	0.512	97	56.6	92.8

Table 8.3.2.(v) cont.

Reach	D_s (m)	% D	Q_b ($m^3\ s^{-1}$)	Q_c ($m^3\ s^{-1}$)
(b) Quoich Water				
Section 4	0.139	74	21.6	126.8
Section 5	0.094	54	35.0	461.4
Section 6	0.137	68	16.4	154.0
Section 7	0.075	43	53.9	683.0
Section 8	0.132	79	30.9	137.7
(c) Clunie Water				
Section 1	0.111	68	47.4	1062.1
Section 2	0.130	78	44.7	228.0
Section 3	0.138	74	59.6	287.2
Section 4	0.171	84	18.2	73.2
Section 9	0.233	97	23.2	28.0
(d) River Gelder				
Section 1	0.062	70	19.5	112.7
Section 2	0.395	96	39.6	59.6
Section 3	0.325	84	25.0	97.1
(e) Lui Water				
Section 1	0.361	87	42.3	130.1

Plate 8.3.1.(i)

Trash line around bankfull stage on the upper Ey fan

Key for scattergrams within Chapter 8

Q	Quoich Wat
E	Ey Burn
S	Gleann an t-Slugain
L	Lui Water
C	Clunie Water
LB	Luibeg
D	Derry Water
G	River Gelder

F	River Feshie
N	River Nethy
D	River Druie
T	River Tromie
A	River Avon
FC	Foals Craig
DB	Dorback Burn
C	Conglass Water

B	Bowmont Water
BR	Boonreigh Water
C	Cleekhimin Burn
M	Monynut
D	Dye Water
W	Whiteadder Water
BO	Borthwick Water
J	Jed Water

Figure 8.3.3.(i)

Scattergram showing Shield's entrainment diameter at bankfull against D84 channel bed material within the Dee study reaches

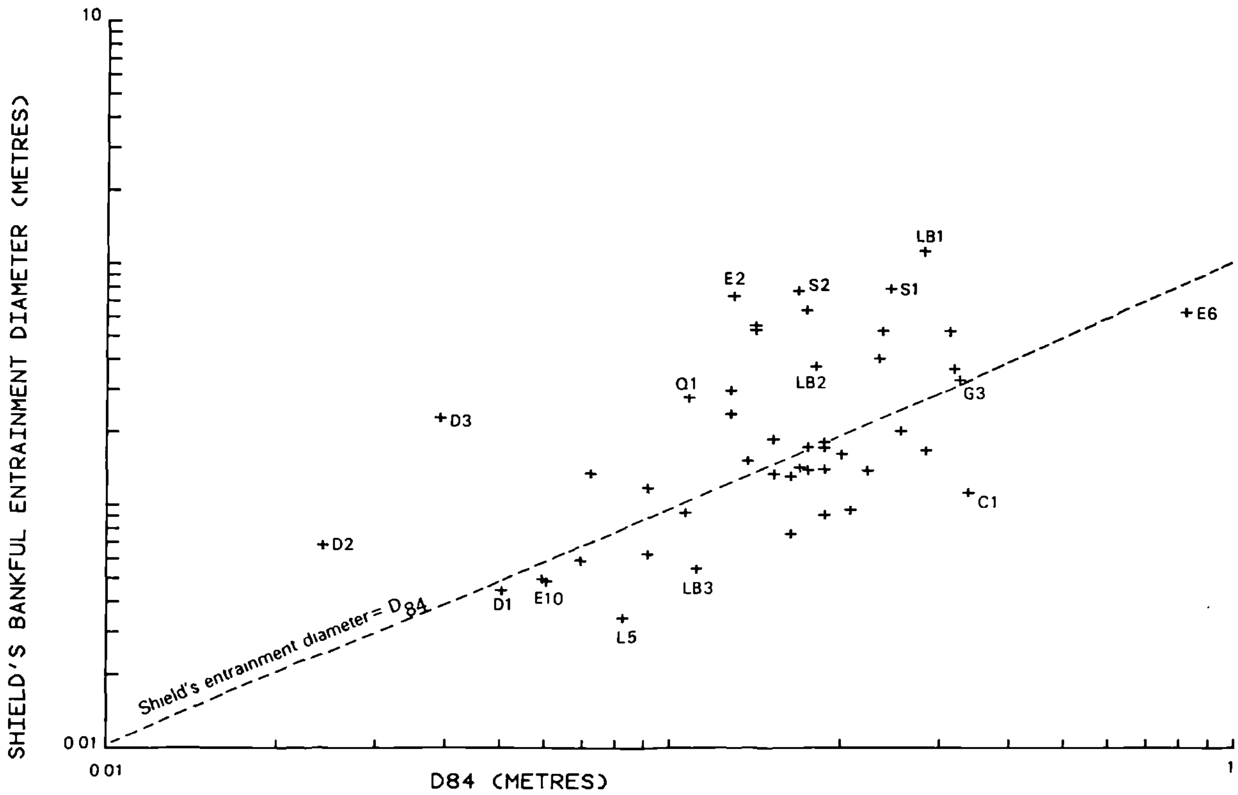


Figure 8.3.3.(ii)

Scattergram showing bankfull discharge against discharge at which sediment transport occurs within the Dee study reaches

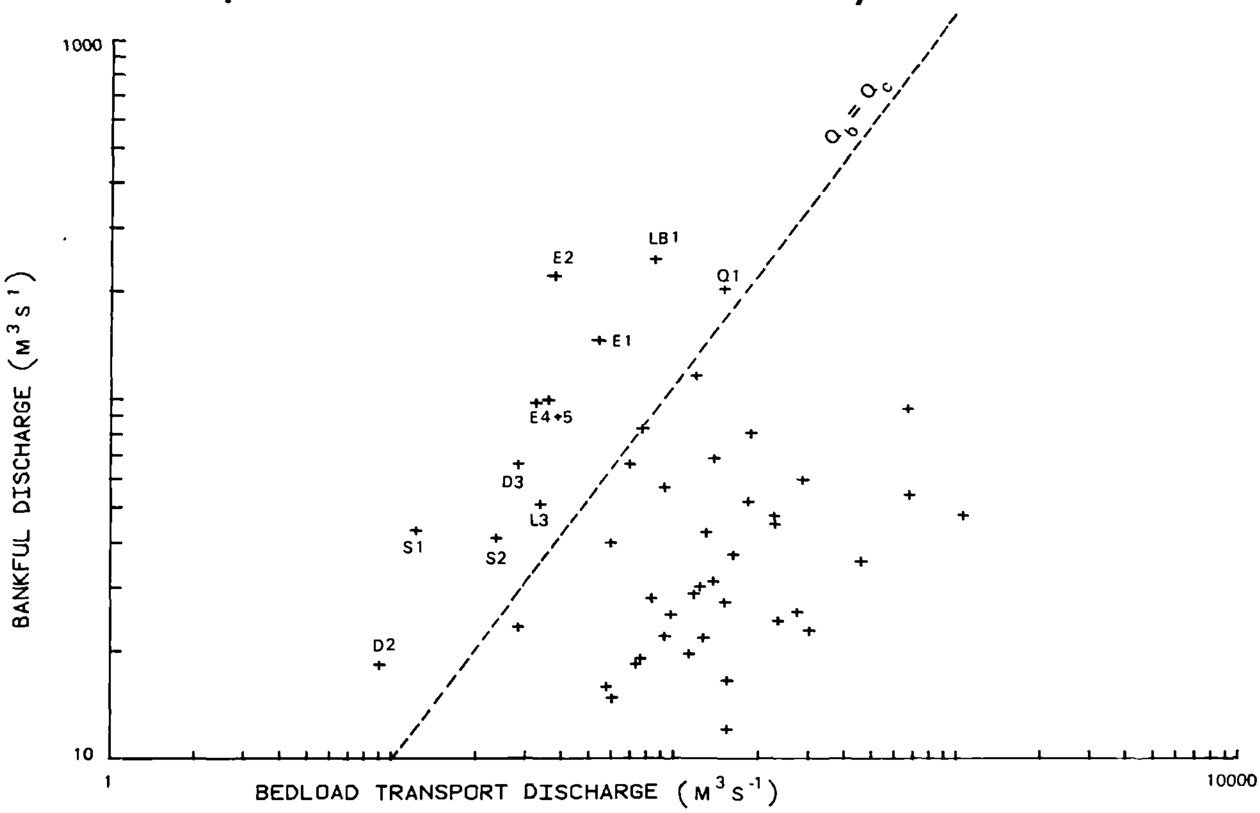


Figure 8.3.4.(i)

Scattergram showing bankfull stream power in relation to associated rates of catchment runoff within the Dee sample

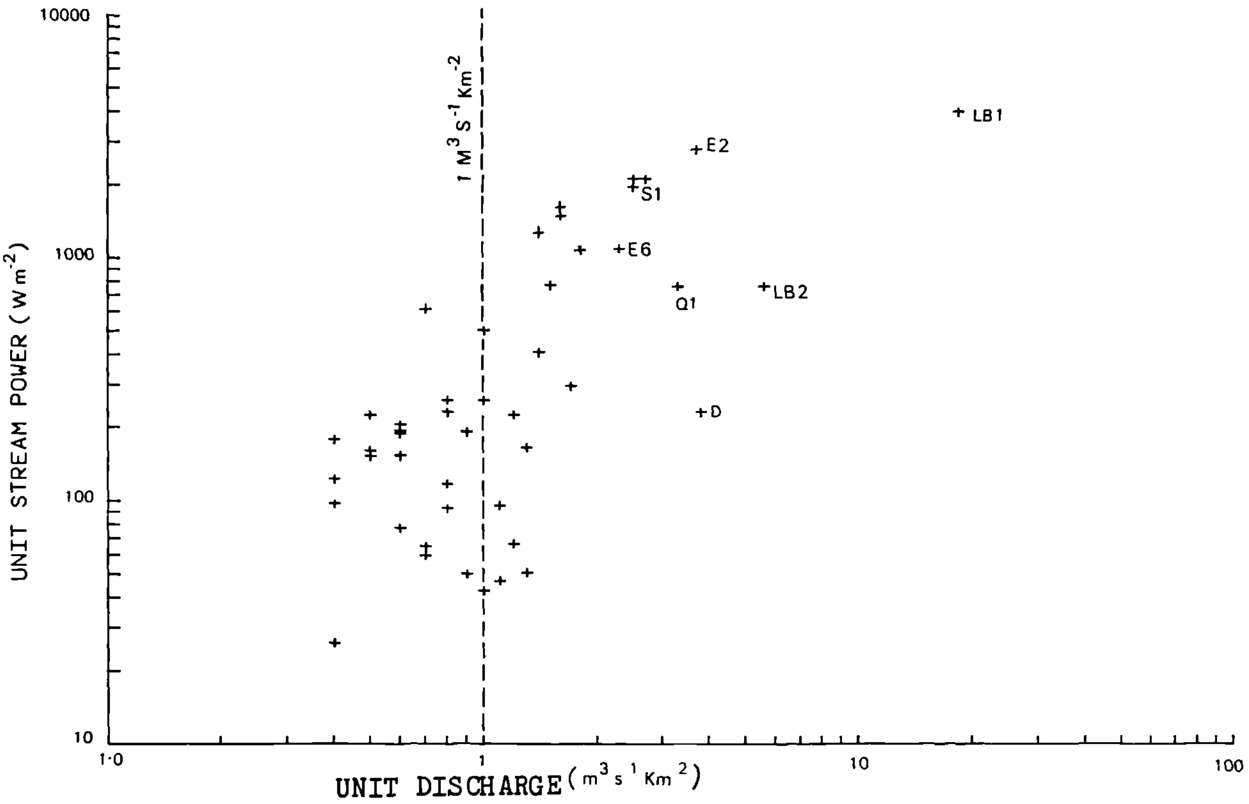


Figure 8.3.5.(i)

Scattergram showing W:d against unit stream power at bankfull within the Dee study reaches

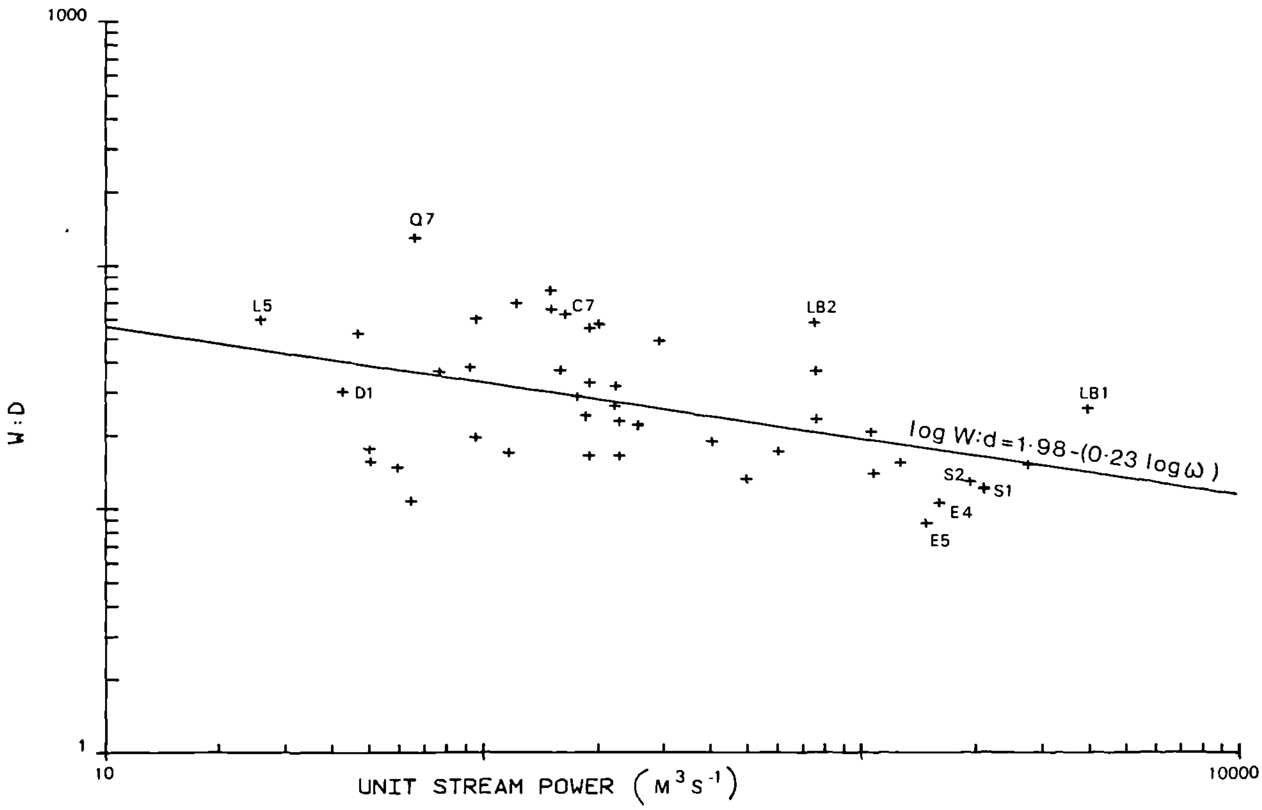
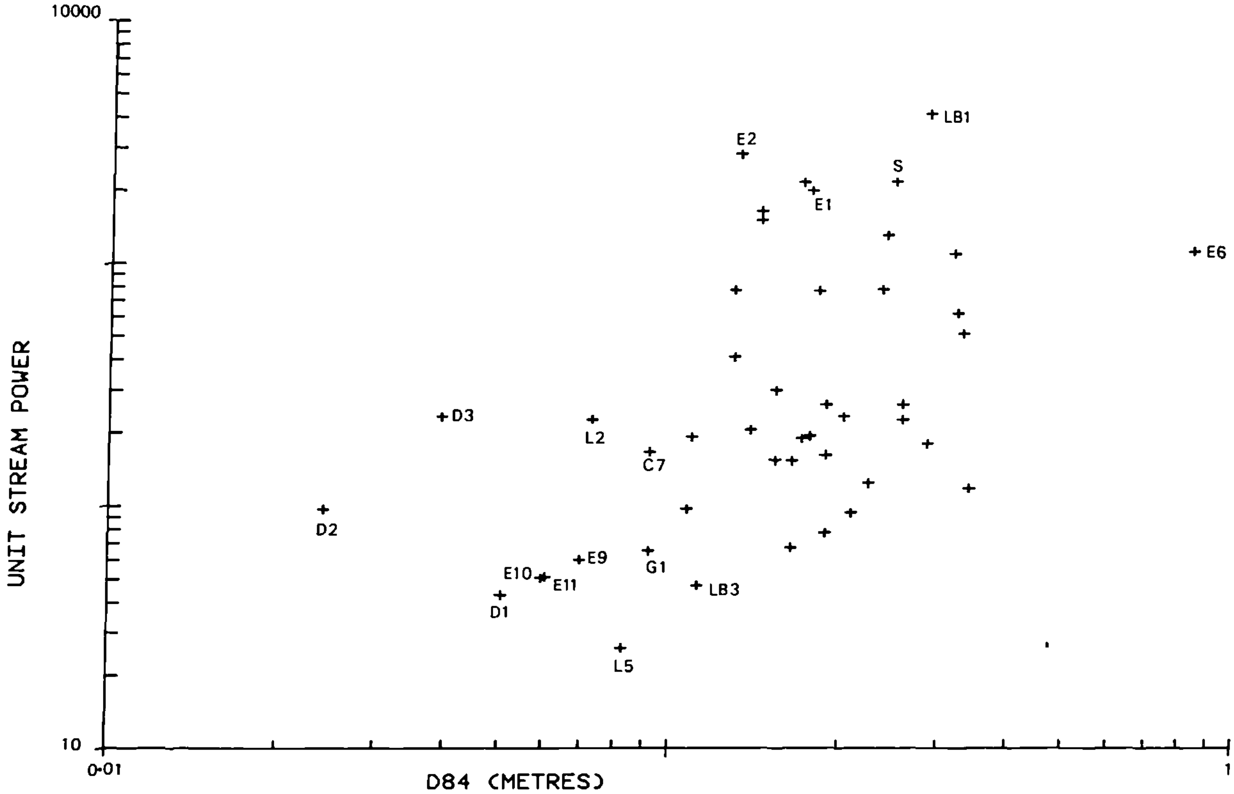


FIGURE 8.3.5.(ii)

Scattergram showing unit stream power at bankful against D_{84} channel bed material within the Dee study reaches



study reach in Table 8.3.2.(ii) and associated specific runoff rates in Table 8.3.2.(iii). Appendix 4.1 gives the comparative bankfull discharge values calculated by other methods. Unit stream power results are found in Table 8.3.2.(iv). Table 8.3.2.(v) shows Shields' limit of entrainment diameters and the percentile of channel bed material that this represents. The discharge at which sediment transport is likely to commence is also presented.

8.3.3 Dee study area: Analysis and implications of results

As can be seen from Table 8.3.2.(i), there was a considerable variation in hydraulic geometry parameters, such as W:d ratio, which varied from 9 at the apex of the Ey fan to 129 on the middle Quoich. Variation could occur even along a limited reach of channel; for example, on the irregular meandering middle Lui study reach (Chapter 7.2.4), W:d ratios varied spatially from 16 to 59 over a short reach length. D_{84} values also varied 10-fold between study reaches from 0.024 (upper Derry) to 0.284 (Luibeg) and thus, roughness values (n) were also highly variable, ranging from 0.026 again on the tortuous meanders of the upper Derry to 0.055 above the Quoich fan. The actual distribution of sediment size varied (Figure 8.3.2.(iii)) with a tendency towards a bimodal distribution, seen especially on the middle Lui. It would therefore be expected that different cross-sections will be modified by different ranges of flow, depending on the competence required to rework their bed and banks. Most exceptional in terms of slope (S_b) were the upper Gleann an t-Slugain fan and the upper Luibeg Burn (0.055-0.058). In contrast within the alluvial basins, slope was as low as

0.005-0.007.

Specific bankfull discharges were calculated by dividing bankfull discharge by the appropriate contributing area. This provided a standardised basis for assessing the large range of bankfull values (Table 8.3.2.(iii)). By far the largest with a specific runoff rate of 18.5 m^3 s^{-1} km^{-2} was the mountain torrent of the upper Luibeg. This value was obtained because the present channel form relates to a much larger discharge event than that associated with an expected bankfull frequency ie. the Aug, 1956 event (Section 7.2.6). This is not the runoff associated with $Q_{1.58}$, even in an upland Scottish context. Subsequent more moderate events will be well-contained within the post-flood channel, thus explaining the lack of modification post-1956. At the other extreme, cross-sections on the middle reaches of the Lui and lower Quoich (with irregularly meandering and sinuous planforms respectively) only required specific runoff rates of 0.4 m^3 s^{-1} km^{-2} to attain bankfull stage (Table 8.3.2.(iv)). This should be compared with specific runoff rates of at least 1.47 m^3 s^{-1} km^{-2} at Polhollick associated with the Q_{max} of the 4th Aug, 1829 flood event. Bankfull competence must therefore be expected much more frequently, though precise frequency analysis is impossible without a gauged record.

When the upper limit of bankfull transport according to Shields' entrainment function was compared with the D_{84} percentile of bed material (Figure 8.3.3.(i)), the following results were found. On some of the periodically more active channels, especially near fan apexes and on mountain torrents, the bankfull Shields' value was well in excess of the D_{84} value eg. on the upper Luibeg Burn. The lower Quoich fan also fell into this category, explaining the reworking of medial bars and channel margins during more moderate events. This implies that Q_bs play an important role in flushing sediment through the system. However, when specific runoff rates are considered, the frequency of such discharges is probably much lower than that normally associated with bankfull stage. When lower Shields' entrainment limits, eg. 0.068 m on the Derry, were coupled with lower D_{84} values (0.024), this explains why activity rates are still relatively high, with periodic shifts and avulsions. Specific runoff rates are also lower but a moderate discharge event is still required.

Studying sites which are periodically disrupted, eg. the Ey fan, Shields' value was less than D_{84} near the apex but downstream, D_{84} and Shields' were of comparable magnitude. Flows of bankfull stage and above must therefore be important in disruption of planform. Where Shields' threshold was considerably less than D_{84} eg. Lui (section 5) and Clunie (section 1), these are typically more stable sites. A high magnitude event is required for mobilisation of a large % of the bed material. However, there is considerable variation along the reach, and even within a limited length of channel, there was considerable spatial variation in specific runoff rates associated with high channel competence and stream power.

When Shields' entrainment diameter was studied in terms of percentile of bed-composition, this varied from D_{24} on the lower Luibeg to D_{100} at several sites eg. Derry Water, Lui Water (Table 8.3.(v)). Cross-sections on the upper Ey fan thus had a bankfull competence to transport 100% of the available load with specific runoff rates of only

1-2 $m^2 s^{-1} km^{-2}$. Q_bs therefore must be important in reworking sediment within the channel. However, events in excess of this stage reactivate old flood channels within the fan area (as occurred at least three times from the planform record; Section 7.2.2). One cross-section on the middle Lui also was competent to transport 96% of its load with specific runoff rates of 0.7 $m^2 s^{-1} km^{-2}$. Sediment must be flushed through the system, despite the apparent stability of channel form.

Critical sediment transport discharge (Q_c) had a 1000 fold range with very high values eg. 1062 $m^3 s^{-1}$ on the stable lower Clunie (lower slope, high D_{84}) to a mere 9 $m^3 s^{-1}$ on the upper Derry (low slope, low D_{84}). This value on the Clunie is thus far greater than the estimated discharge in Aug, 1829 ie. bed never mobilised in terms of present regime. When Q_b was compared with Q_c (Figure 8.3.3.(ii)), several cross-sections had Q_b well in excess of Q_c associated with a range of sediment size, from the upper Luibeg, Gleann an t-Slugain and upper Ey fan to selected locations on the Derry. However, the greater proportion of the sample had Q_b less than Q_c and thus flows greater than bankfull stage would be required to transport the D_{84} size fraction eg. on the upper Quoich apex and the sinuous/ wandering middle Clunie. This implies at these sites that events in excess of bankfull must be important in planform change. It is interesting to note for example on the Ey fan that on the upper two cross-sections, Q_b is approximately 3 times Q_c while further down, Q_b is 0.2-0.25 times Q_c. Thus, sediment is funnelled through the fan apex during events of bankfull stage and deposited further down the fan. However, discharges in excess of bankfull stage at the toe of the fan must rework a large proportion of the available bed material, explaining the periodic disruption and flushing through of sediment. This high Q_b (cf. Q_c) at the fan apex is confirmed by the Gleann an t-Slugain fan. In contrast, on the apex of the Quoich fan, Q_b is only 0.1-0.2 times Q_c whereas within the fan Q_b is 1.2 times Q_c. Thus, depending on controls (ie. sediment size and slope), higher flows may be important in flushing sediment to the fan. These results are broadly comparable with Shields': D_{84} (Figure 8.3.3.(i)).

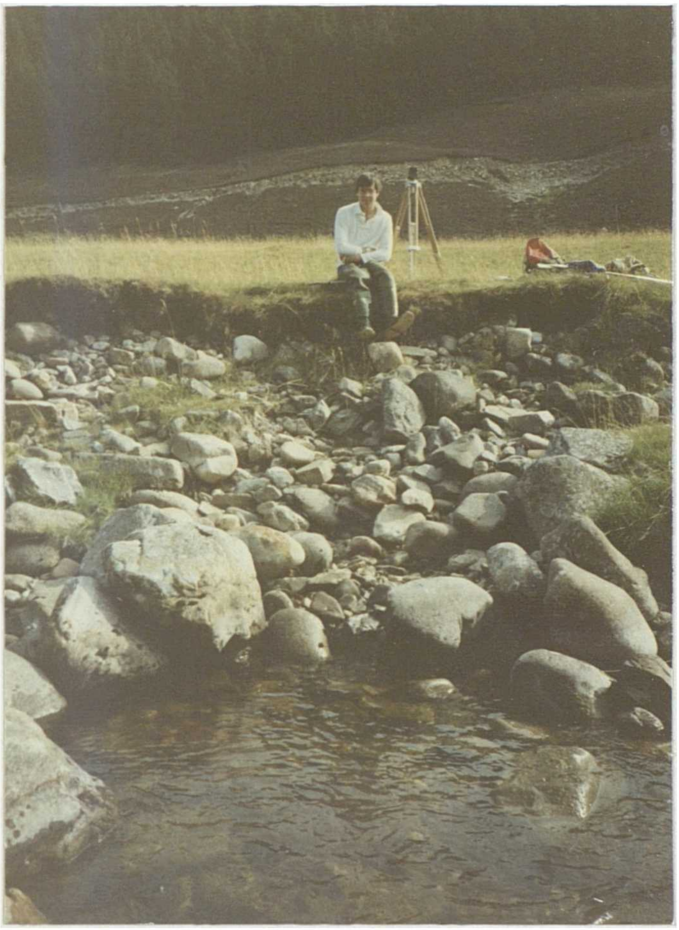
8.3.4 Dee study reaches: Stream power values

The unit stream power values (ω) are shown in Table 8.3.2.(iv), and even within this defined area, there was a considerable variation. The highest value was again obtained on the upper Luibeg, a sinuous mountain torrent (Dee study reach 6, Section 7.2.6) where average velocities at bankfull were calculated at 5.8 m s^{-1} and Du Boys' shear stress was 692.3 N m^{-2}. This was exceptional in comparison with other study reaches and was only maintained in the high energy upper subreach, associated with greatest slope (S_b=0.056). As can be seen from Table 8.3.2.(iv), unit stream power on this sinuous reach reduced dramatically downstream to 47 W m^{-2}. Other cross-sections with unit stream power in excess of 1000 W m^{-2} included those near the apex of the sinuous Gleann an t-Slugain gravel fan with 2107 W m^{-2}. Similarly above the Ey confluence (Section 7.2.2), high unit stream powers were consistently recorded with 1614 and 1484 W m^{-2} at the fan apex. Again, there was a considerable reduction to 107 W m^{-2} before the flow disrupted into a fragmented distributary system. It was interesting to note upstream of this site that below the rock controlled section (see Figure 8.3.2.(i)), despite the apparent stability of the channel, high values of stream power were maintained with little lateral activity. This was due to confinement of the first high terrace (Plate 8.3.4.(i)).

Those study reaches, which showed comparatively lower activity, seemed to have variations in power downstream, rather than having the dramatic stream power reduction down fan. For example, on the wandering planform of the middle reaches of the Clunie (Dee study reach 5), unit stream powers of 96-294 W m^{-2} were recorded while values of 42-96 W m^{-2} were recorded on the tortuous meanders of the upper Derry. In comparison to Ferguson's (1981) values for British rivers, the Deeside values are high for the equivalent category of channel planform (Section 2.6).

When unit stream power was correlated with runoff rates associated with bankfull stage, not unexpectedly a high correlation was found (Figure 8.3.4.(i)). Several sites required high runoff rates to attain high bankfull stream power eg. lower Quoich fan with 3.3 m^3 s^{-1} km^{-2} (Dee study reach 1). However on studying Figure 8.3.4.(i), it appears that there were some high unit stream powers at bankfull that do not require very high rates of specific runoff (< 1 m^3 s^{-1} km^{-2}) ie. given similar rainfall conditions, these represent potentially more active sites. For example, in terms of reduction of stream power and competence, the Gleann an t-Slugain confluence (Section 7.2.3) only required a peak runoff of 2.6 m^3 s^{-1} km^{-2} to have a bankfull stream power competent to transport 100% of the available bed material. Therefore the channel switches (evident from the map and API record) could have taken place at bankfull stage. Within such a small catchment

Plate 8.3.4.(i)



Reach confined by the first high terrace on the lower

Ey Burn

(16.7 km^2), the maintenance of higher peak runoff rates is more likely. At some other sites, eg. upper Quoich fan, even if specific runoff rates associated with Q_b are reduced further (0.4-0.5 m^3 s^{-1} km^{-2}), magnitude of unit stream powers were still maintained (Table 8.3.2.(iv)). Irregular and tortuous meander planforms in particular for a given runoff rate had lower unit stream powers eg. upper Ey and upper Derry.

8.3.5 Dee study reaches: Stream power- process and form

It was necessary then to assess in what ways, if any, such unit stream powers at bankfull and channel form were related. When $\log_{10}$ W:d ratio was correlated with $\log_{10}$ stream power, a highly significant negative correlation (r=-0.46) was found (Figure 8.3.5.(i)). The linear regression equation obtained was (8.8).

$$\log_{10} W{:}d = 1.98 - (0.23 \log_{10} W) \qquad (8.8)$$

Channels with lower W:d ratios were therefore associated with higher unit stream powers, though there was a large amount of scatter. This was in contrast with Ferguson's (1981) suggestion that W:d ratios of 7-25 are associated with mixed load channels (Schumm, 1963). This does however depend on whether these are mixed load channels in this situation. Ferguson found these had lower unit stream powers than bedload channels. Certain cross-sections stood out in Figure 8.3.5.(i) as having low W:d and high unit stream powers. Examples include both the upper Ey and upper Gleann an t-Slugain fans but also more stable reaches for example, on the Ey below the rock controlled section and on the stable Gelder. The reason for stability seemed to be either confinement by high terraces or by high, stable and well-vegetated banks. Higher W:d ratio and lower unit stream powers at bankfull were found in the middle reaches of the Quoich and Clunie. An extreme example was on the upper Quoich (section 7) with a W:d of 129 and a unit stream power of under 100 W m^{-2}.

When bankfull stream power values were correlated with D_{84} channel bed material, the general pattern, compared to Richards (1982), held but the situation was not so simple (Figure 8.3.5.(ii)). Several of those cross-sections with high D_{84} and high surrogate stream powers were at the head of gravel fans. At the apex, there are still high slopes, bed material size has not yet started to decrease, but the flow is still well contained within a single channel. Cross-sections with lower D_{84} and lower stream power surrogate values occurred on the tortuous meanders of the upper Ey and upper Derry, which again have an occasional tendency to split around bars.

8.3.6 Dee study area: Bank composition and vegetative cover

When width and W:d ratio were broken down by hydrologically significant bank vegetation category, neither produced groups that were significantly different. This implied that bank vegetation, in itself, was not an important control on hydraulic geometry along the measured Dee study reaches. Locally however trees were noted in the field to provide stability, but this was highly dependent on both maturity and density of the tree cover and unit composition of the bank. However, it should be noted that the mean and standard deviation of the width and W:d ratio were considerably less for trees with rough-grassland (3) than for heather (4) or rough-grassland (6) (Table 8.3.6.(i)), implying greater stability with less bank erosion.

In terms of bank stability, when W:d was correlated with the surficial depth on the bank with least upper unit depth ie. less stable, a low but significant correlation was gained (-0.29). Banks with a thicker upper unit of overbank fine sediments had lower W:d ratios than those with a small stabilising surface layer. High depths (> 36 cm), high % silt-clay and low W:d characterised the upper Ey and upper Derry (irregular meandering to tortuous meandering planforms). Throughout the study reaches, the % silt-clay was highly variable (eg. the middle Clunie). Thus, the tortuous meanders of the upper Ey and Derry had high values of 25-50 % while other sites, eg. on the upper Luibeg, had very low values and a small upper unit. For example, several sites had zero % silt-clay, and all occurred at highly active sites with high bankfull stream powers and banks that would therefore be easily eroded (eg. lower Quoich fan and upper Luibeg).

Table 8.3.6.(i)

Dee study reaches: Channel form broken down by bank vegetation

	Width		W:d	
Vegetation Category	Mean	SD	Mean	SD
3	17.8	3.7	17.5	7.1
4	26.3	14.1	39.1	29.4
6	24.3	11.8	33.7	19.7
	Sig = 0.18		Sig = 0.06	

3 = trees and rough-grassland

4 = heather

6 = rough-grassland

8.3.7 Dee study reaches: Main modes of bank erosion

Several different types of banks and associated modes of bank erosion were identified in the field and these could be subdivided into those which were inherently stable or unstable. Bank composition could be highly variable along a reach, especially along reaches of irregular/irregular meandering planform with periodic erosion of the first terraces. Thus, different modes of bank erosion were seen to occur in close proximity, and with different forms of bank stability. Banks ranged from the highly stable, undergoing only slow apparent modification under a range of flows, (eg. River Gelder and lower Clunie above Braemar; see Table 8.3.7.(i)), to those that were incohesive and very unstable. These were easily eroded and reworked but only at higher stages eg. Quoich fan and upper Luibeg. The proportion of the bank under water during both normal and high flow conditions was very important. Each of the categorised banks in Table 8.3.7.(i) may occur at a variety of scales, depending on the average depth of the cross-section.

The modes of erosion were identified as follows. In category 2(a), the initial sheer surface is basally eroded in flows of low to moderate magnitude, typically up to a layer with a change in sediment size (low silt-clay ratio; see Plate 8.3.7.(ii)). This may be a cohesive organic layer or imbricated clasts of pebble size so that the bank becomes cantilevered. Higher rates of such basal under cutting occurred on meander bends, where flow was concentrated eg. upper Derry and upper Ey. The threshold of incipient slumping is exceeded when the bank suffers excessive cantilevering and the bank retreats to maintain its

Table 8.3.7.(i)

Categories of bank composition found within the Dee study reaches

(1) Stable banks (associated with slow or little apparent erosion)

(a) Rock controlled

(i) associated with meltwater gorges

eg. lower reaches of Quoich, Lui, Clunie and mainstream Dee at Linn of Dee (see Plate 8.3.7.(i)).

(b) Partially rock controlled

(i) bedrock locally outcropping at or near surface within the channel and/or banks.

eg. middle to lower Clunie

(c) Low banks associated with low first terrace.

(i) medium width: depth ratio at bankfull

(ii) stable/ imbricated bed

(iii) banks composed of medium sized clasts with medium silt:clay supporting matrix

(iv) well vegetated (frequently rough-grassland)

eg. upper Clunie and middle Ey

(d) Incised channel with high banks

(i) low width:depth ratio at bankfull

(ii) well vegetated banks giving protection even in higher stages up to bankfull

eg. Gelder and Callater

(2) Unstable banks (associated with higher rates of erosion).

(a) Deep sheer banks with high silt-clay ratio, continuous down depth.

(i) silt-clay ratio varied from 20-50% on banks sampled

(ii) continuous high silt-clay ratio down bank

(iii) a high organic content

(iv) possible peat basal layer

(iv) frequently associated with meandering (irregular to tortuous) planforms

(v) normal flow stage has greater percentage of bank depth under water

eg. Glen Derry and upper Glen Ey (see Plate 8.3.7.(ii))

(b) Banks with larger clast sizes and low surficial layer depths

(i) Low amount of silt-clay in the matrix

(ii) sloping angle of repose, dependent on size structure of the bank

(iii) low banks

(iv) normal flow stages do not cover a large % of the bank.

(v) vegetative cover has very low root layer

eg. Gleann an-t Slugain (see Plate 8.3.7.(iii))

(c) Highly variable intermediate bank composition

(i) lower unit composed of large clasts

(ii) variable depth of finer material within upper unit

(iii) medium range silt-clay content

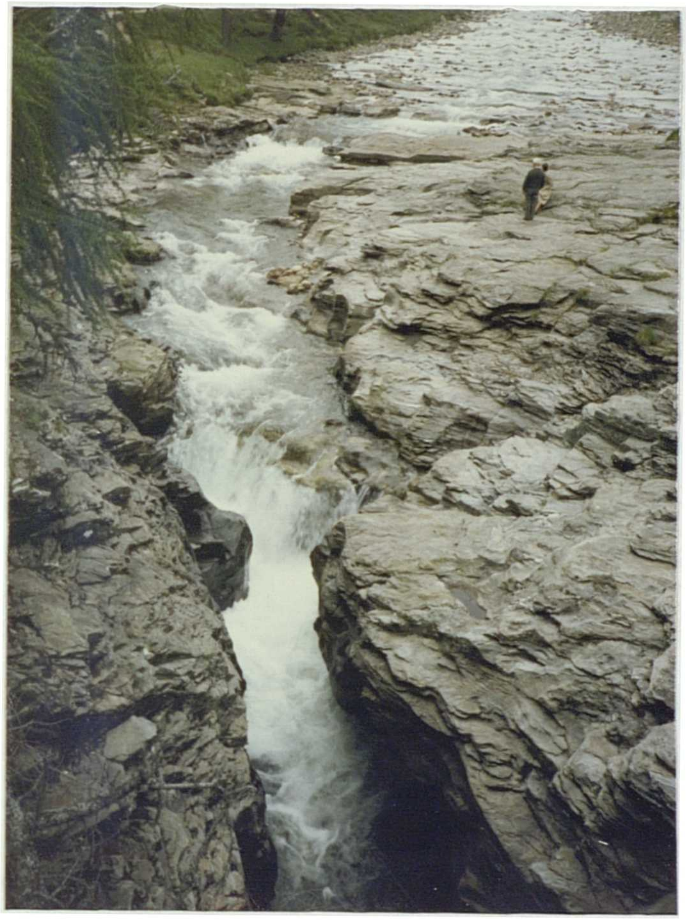
(iv) medium root depth associated with vegetative cover

eg. Ey confluence (see Plate 8.3.7.(iv)) initial profile. Slumped blocks must lie in situ at the base of the bank until broken down by the turbulence of higher flows, eventually leaving a base unprotected against further erosive stresses. Higher flows will differentially erode the bank's weaker beds, accentuating the structure of the bank. The location of different beds within the bank may also influence its rate of slumping.

In contrast in category 2(b), banks will be eroded at higher flows when a protective base of larger clasts can be transported eg. the Quoich and Gleann an t-Slugain fans (see Plate 8.3.7.(ii)). Flows in excess of bankfull may rip through the shallow upper unit, incorporating large amounts of sediment into the channel system. Removal of the basal fines may take place at lower stages, thus lessening the threshold of subsequent erosion and dislodging clasts to the base of the bank. Heavy rainfall may also weaken the cohesiveness of the bank matrix, with flushing out of this finer fraction. Larger clasts may however remain in situ at the base of the bank over a longer time-period, until a flow competent enough to transport them occurs. In the case of larger clasts, the stream power required may only be associated with very extreme events.

In terms of intermediate banks (Category 2(c)), these have variable rates and modes of bank erosion, depending on the precise bank structure, height, clast size composition and vegetative cover. Modes of retreat witnessed in the field generally were a combination of cantilevering and slumping, though different from Category 2(a), with considerable overhang possible before the slump occurs. The rates of erosion are typically much less than in Category 2(b), requiring greater

Plate 8.3.7.(i)



Rock-controlled reach associated with former meltwater gorge at Linn of Dee (mainstream Dee). The dramatic change in controls (slope, channel confinement) along a short distance of channel should be noted.

Plate 8.3.7.(ii)

Shear banks with high silt-clay ratio on the upper Ey

Plate 8.3.7.(iii)

Easily eroded, low banks with a "carpet" layer of vegetation, overlying boulders with a sandy matrix (on the lower Gleann an t-Slugain)

Plate 8.3.7.(iv)

Intermediate bank composition (medium depth of upper unit; medium silt:clay) associated with slower average rates of erosion. Such banks were however ripped through during more extreme events.

stream powers to disrupt the bank.

8.4.1 Spey study reaches: Limitations on study

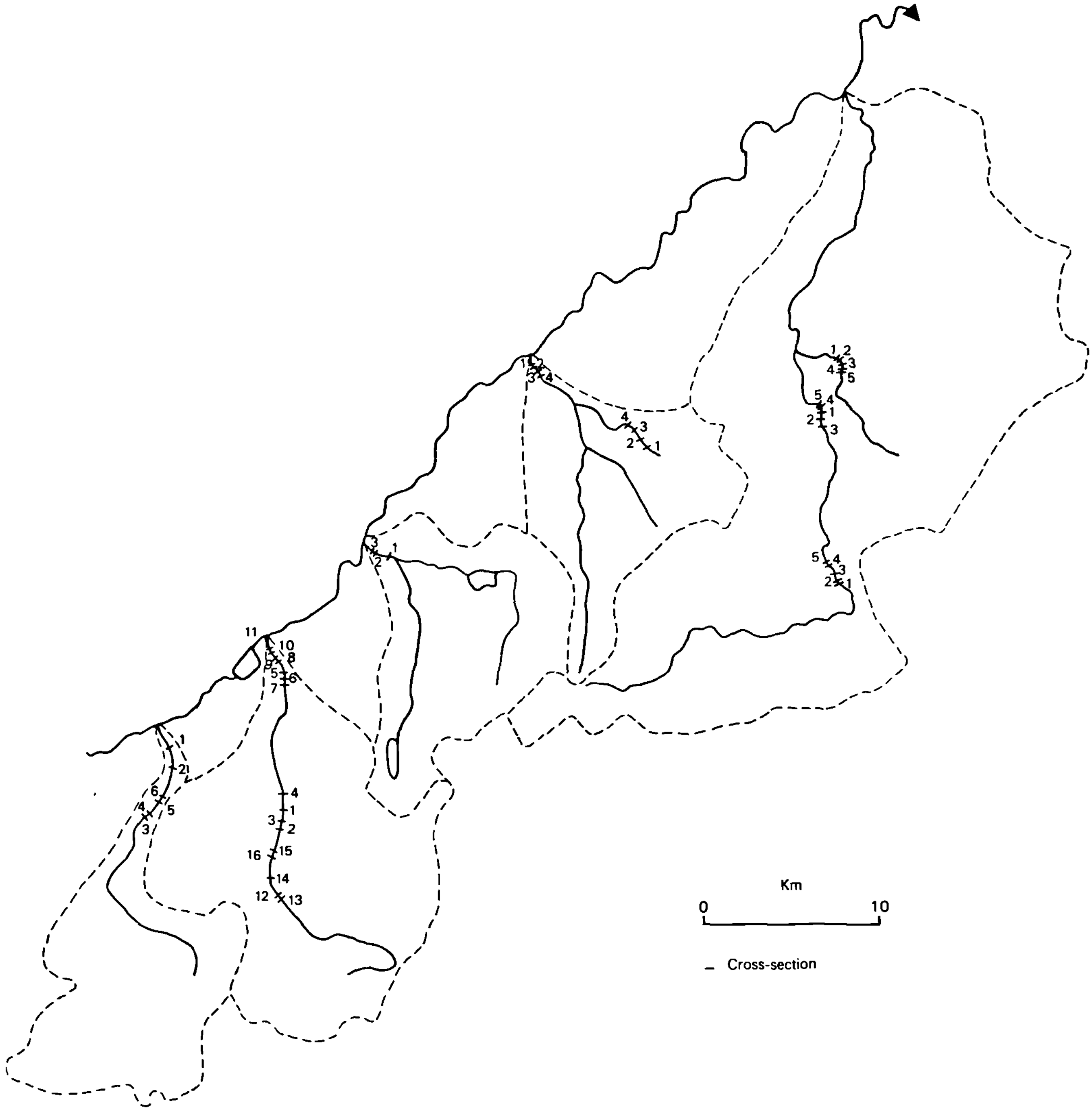
As with the Dee study area, the main problems were accessibility of estate land and finding natural cross-sections, free from bull-dozing. Both the Nethy confluence (Spey study reach 2) and the River Avon at Foals Craig (Spey study reach 7) were sites which had been locally artificially disturbed and thus the choice of representative cross-sections had to be done with care.

8.4.2 Spey study reaches: Results

The locations of the cross-sections surveyed and selected cross-sections are shown in Figures 8.4.2.(i) and (ii). The basic hydraulic geometry parameters are tabulated in Table 8.4.2.(i) and selected sediment size cumulative frequency curves are shown in Figure 8.4.2.(iii). D_{16}, D_{50}, D_{84} and D_{90} values of bed-size composition are tabulated in Appendix 3.2. The Q_b results are collated by study reach in Table 8.4.2.(ii) and associated specific runoff rates in Table 8.4.2.(iii). Appendix 4.2 gives the comparative discharge results computed by alternative methods. Stream power results are tabulated in Table 8.4.2.(v) and Shields' limits of entrainment and the sediment transport discharge are found in Table 8.4.2.(vi).

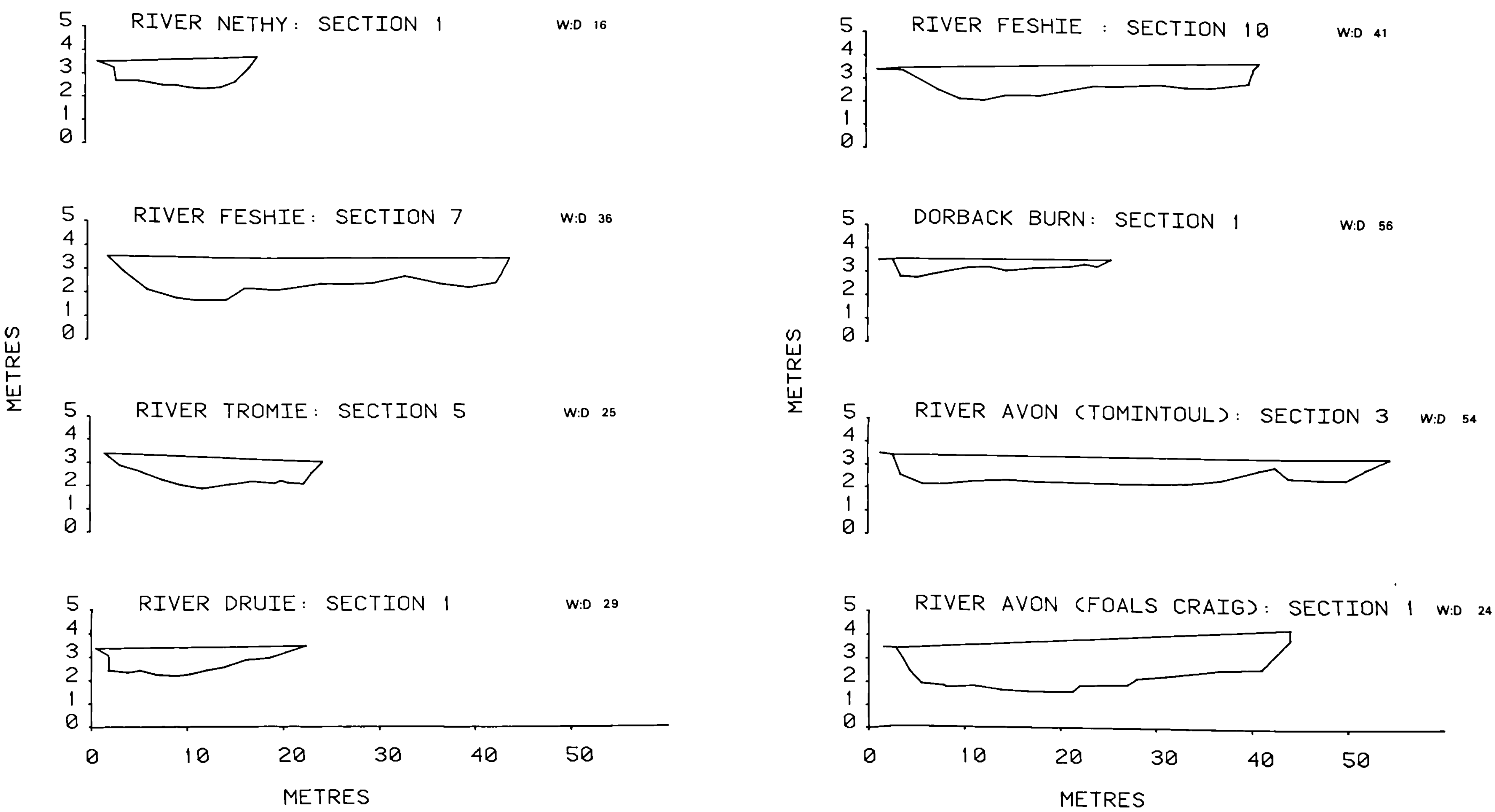
Figure 8.4.2.(i)

Location of sampled cross-sections in relation to study reaches within the Spey study area



EXAMPLES OF CROSS-SECTIONS USED IN STREAM POWER ANALYSIS WITHIN THE SPEY STUDY REACHES.

Figure 8.4.2.(ii)



Examples of cumulative frequency curves for channel bed material within the Spey study reaches

Figure 8.4.2.(iii)

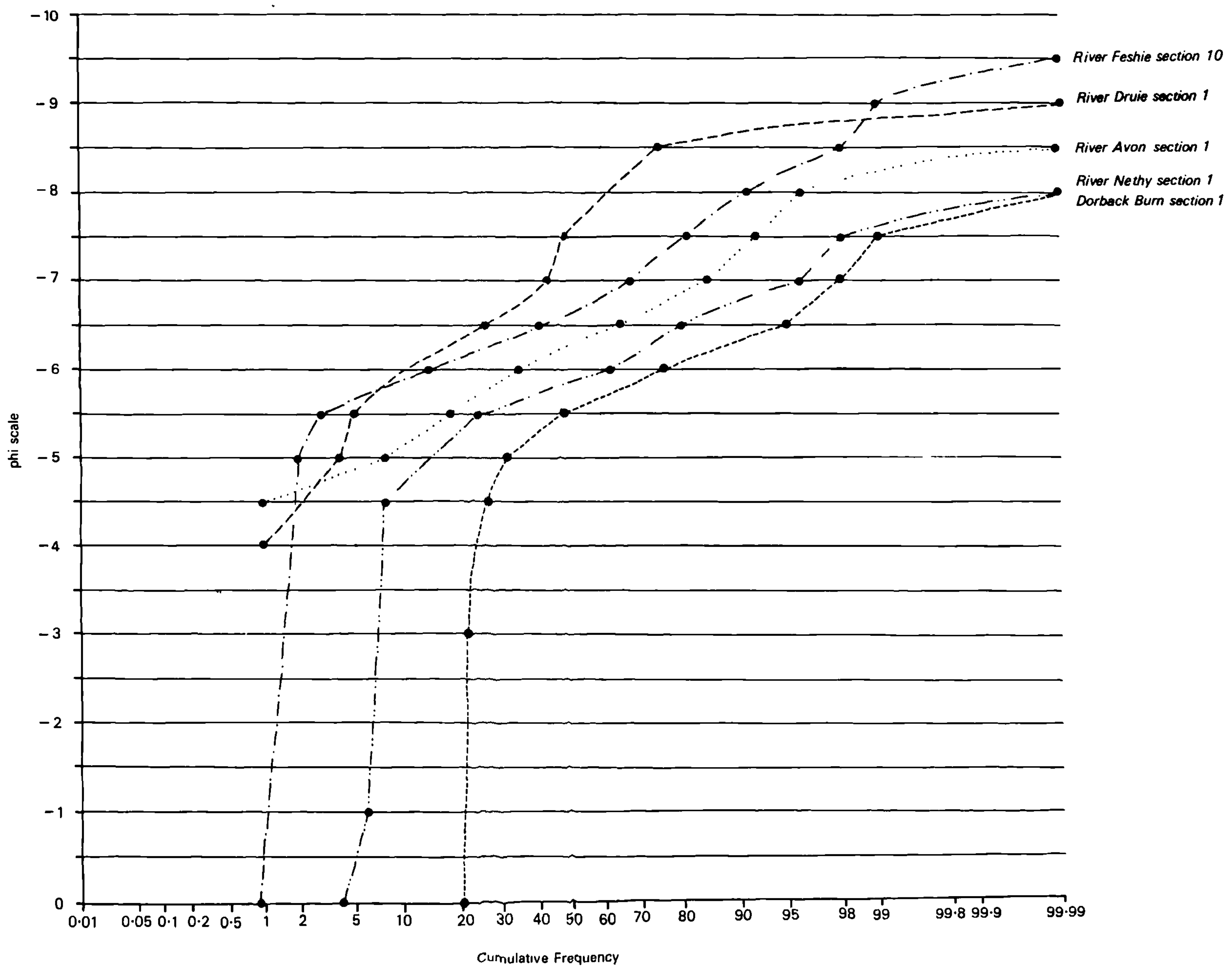


Table 8.4.2.(i)

Spey study reaches: Basic hydraulic parameters at bankfull stage

Reach	W (m)	d (m)	W:d	A (m^2)	R (m)	WP (m)	D84 (m)	Slope
1: Feshie confluence								
Section 8	23.0	1.48	16	34.0	1.39	24.5	0.119	0.021
Section 9	34.0	0.98	35	33.3	0.95	35.0	0.265	0.007
Section 10	39.9	0.97	41	38.6	0.95	40.4	0.194	0.007
Section 11	26.2	1.43	18	37.6	1.36	27.7	0.113	0.007
2: Nethy confluence								
Section 1	14.9	0.92	16	12.8	0.82	15.5	0.097	0.002
Section 2	19.6	0.86	23	16.9	0.84	20.0	0.097	0.002
Section 3	23.0	0.97	24	22.3	0.92	24.3	0.090	0.006
Section 4	21.1	1.39	15	29.3	1.31	22.3	0.086	0.011
3: Druie at Inverdruie								
Section 1	21.8	0.75	29	16.5	0.73	22.6	0.395	0.018
Section 2	18.0	0.73	25	18.6	0.70	13.1	0.117	0.023
Section 3	15.9	0.63	25	10.0	0.62	16.3	0.095	0.015
4: Feshie at Lagganlia								
Section 5	29.4	1.30	23	38.3	1.28	29.9	0.197	0.010
Section 6	41.5	1.07	39	44.3	1.05	42.2	0.274	0.014
Section 7	41.9	1.17	36	49.2	1.15	42.7	0.223	0.019

Table 8.4.2.(i) cont.

Reach	W (m)	d (m)	W:d	A (m^2)	R (m)	WP (m)	D84 (m)	Slope
5: River Tromie								
Section 3	24.0	1.05	23	19.4	0.79	24.5	0.187	0.010
Section 4	21.9	0.74	30	22.4	0.73	16.3	0.155	0.010
Section 5	22.7	0.92	25	20.9	0.91	23.1	0.187	0.008
Section 6	26.9	1.07	25	28.7	1.03	27.8	0.155	0.007
6: Avon at Tomintoul								
Section 1	46.9	1.10	43	51.7	1.09	47.6	0.124	0.017
Section 2	32.1	1.47	22	47.2	1.40	33.8	0.137	0.019
Section 3	51.9	0.96	54	49.1	0.93	52.5	0.204	0.013
Section 4	39.7	1.64	24	53.5	1.32	40.3	0.239	0.011
7: Avon at Foals Craig								
Section 1	41.1	1.73	24	71.2	1.68	42.3	0.197	0.003
Section 2	32.6	1.33	25	43.5	1.31	33.3	0.265	0.008
Section 3	35.5	1.16	31	41.0	1.14	35.8	0.215	0.012
Section 4	35.9	1.12	32	40.3	1.10	36.6	0.194	0.012
Section 5	32.9	0.82	40	27.1	0.81	33.4	0.169	0.009
8: Dorback Burn								
Section 1	22.8	0.41	56	09.3	0.40	23.2	0.075	0.012
Section 2	23.4	0.44	53	10.3	0.43	23.8	0.094	0.016
Section 3	28.2	0.45	63	12.8	0.45	28.5	0.071	0.033
Section 4	11.9	0.80	15	09.5	0.76	12.5	0.075	0.011

Table 8.4.2.(i) cont.

Reach	W (m)	d (m)	W:d	A (m^2)	R (m)	WP (m)	D84 (m)	Slope
Other reaches								
(a) River Feshie								
Section 1	27.4	0.80	34	28.1	0.78	21.8	0.256	0.012
Section 2	23.1	1.00	23	23.2	0.98	23.6	0.181	0.014
Section 3	20.8	1.94	11	40.4	1.80	22.4	0.181	0.026
Section 4	22.0	1.81	12	39.9	1.73	23.1	0.215	0.012
Section 12	69.5	1.00	70	69.6	0.99	70.6	0.137	0.008
Section 13	43.4	0.78	56	34.0	0.77	44.1	0.181	0.012
Section 14	118.0	0.55	215	65.5	0.55	118.8	0.111	0.011
Section 15	55.5	0.53	105	29.2	0.52	56.6	0.169	0.010
Section 16	54.0	0.52	104	28.0	0.51	54.7	0.097	0.010
(b) River Tromie								
Section 1	16.7	0.67	25	11.0	0.65	17.0	0.097	0.021
Section 2	18.7	0.88	21	16.4	0.80	20.4	0.388	0.021
(c) Conglass Water								
Section 1	8.2	1.04	8	08.6	0.92	09.4	0.201	0.015
Section 2	8.2	0.69	12	05.7	0.65	08.7	0.194	0.005
Section 3	11.3	0.67	17	07.6	0.63	12.2	0.090	0.009
Section 4	15.4	0.75	21	11.5	0.72	16.1	0.119	0.007
Section 5	11.2	0.78	14	08.8	0.75	11.7	0.090	0.014

Table 8.4.2.(ii)

Spey study reaches: Calculation of bankfull discharge

Study reach	n	A (m^2)	V ($m\ s^{-1}$)	Q ($m^3\ s^{-1}$)
1: Feshie confluence				
Section 8	0.036	60.2	5.0	299.1
Section 9	0.049	33.2	1.6	54.5
Section 10	0.044	38.5	1.8	70.9
Section 11	0.036	37.6	2.9	107.5
2: Nethy confluence				
Section 1	0.036	12.2	1.1	13.9
Section 2	0.036	16.9	1.1	18.7
Section 3	0.035	22.4	2.1	46.5
Section 4	0.034	29.3	3.8	110.0
3: Druie at Inverdruie				
Section 1	0.063	16.5	1.7	28.2
Section 2	0.039	13.1	3.1	40.0
Section 3	0.037	10.0	2.4	23.7
4: Feshie at Lagganlia				
Section 5	0.042	38.2	2.8	106.7
Section 6	0.049	44.4	2.5	110.5
Section 7	0.045	49.1	3.4	166.6

Table 8.4.2.(ii) cont.

Study reach	n	A (m^2)	V ($m\ s^{-1}$)	Q ($m^3\ s^{-1}$)
5: Tromie				
Section 3	0.045	19.4	1.9	36.9
Section 4	0.043	16.3	1.9	30.8
Section 5	0.044	20.9	1.9	39.9
Section 6	0.040	28.8	2.1	60.7
6: Avon at Tomintoul				
Section 1	0.038	51.2	3.7	189.4
Section 2	0.036	47.2	4.6	216.1
Section 3	0.045	49.1	2.4	118.8
Section 4	0.045	53.6	2.8	151.6
7: Avon at Foals Craig				
Section 1	0.041	71.2	1.9	135.4
Section 2	0.046	43.6	2.3	100.2
Section 3	0.044	40.9	2.7	110.8
Section 4	0.043	40.3	2.7	109.1
Section 5	0.043	40.5	1.3	51.5
8: Dorback burn				
Section 1	0.037	8.3	1.8	14.8
Section 2	0.040	10.3	1.8	18.9
Section 3	0.036	12.7	2.5	31.6
Section 4	0.034	9.5	2.6	24.6

Table 8.4.2.(ii) cont.

Study reach	n	A (m^2)	V ($m\ s^{-1}$)	Q ($m^3\ s^{-1}$)
Other reaches				
(a) River Feshie				
Section 1	0.051	28.1	1.8	39.6
Section 2	0.043	23.2	2.7	63.3
Section 3	0.040	40.4	6.0	243.8
Section 4	0.042	39.9	3.8	151.1
Section 12	0.036	69.6	3.9	268.0
Section 13	0.045	34.0	2.1	70.1
Section 14	0.040	65.5	1.8	115.1
Section 15	0.047	29.1	1.4	39.6
Section 16	0.038	27.9	1.5	42.2
(b) River Tromie				
Section 1	0.037	11.0	2.9	31.8
Section 2	0.061	16.4	2.1	33.8
(c) Conglass Water				
Section 1	0.045	8.6	2.6	22.0
Section 2	0.048	5.0	1.1	5.6
Section 3	0.037	7.6	1.9	14.4
Section 4	0.039	12.5	1.6	19.7
Section 5	0.036	8.8	2.7	23.9

Table 8.4.2.(iii)

Spey study reaches: Specific runoff rates associated with bankfull discharge

	Q_b ($m^3\ s^{-1}$)	Catchment area (km^2)	Specific runoff ($m^3\ s^{-1}\ km^{-2}$)
1: Feshie confluence			
Section 8	299.1	233.1	1.3
Section 9	54.5	233.6	0.2
Section 10	70.9	233.9	0.3
Section 11	107.5	234.2	0.5
2: Nethy confluence			
Section 1	13.9	124.1	0.1
Section 2	18.7	124.0	0.2
Section 3	46.5	123.8	0.4
Section 4	110.0	123.6	0.9
3: Druie at Inverdruie			
Section 1	28.2	122.9	0.2
Section 2	40.0	125.4	0.3
Section 3	23.7	125.6	0.2
4: River Feshie at Lagganlia			
Section 5	106.7	210.5	0.5
Section 6	110.5	208.8	0.5
Section 7	166.6	207.3	0.8

Table 8.4.2.(iii) cont.

	Q_b ($m^3\ s^{-1}$)	Catchment area (km^2)	Specific runoff ($m^3\ s^{-1}\ km^{-2}$)
5: River Tromie			
Section 3	36.9	117.4	0.3
Section 4	30.8	117.0	0.3
Section 5	39.9	120.3	0.3
Section 6	60.7	124.8	0.5
6: Avon at Tomintoul			
Section 1	189.4	205.7	0.9
Section 2	216.1	206.2	1.0
Section 3	118.8	207.4	0.6
Section 4	151.6	209.3	0.7
7: Avon at Foals Craig			
Section 1	135.4	112.0	1.2
Section 2	100.2	112.3	0.9
Section 3	110.8	112.9	1.0
Section 4	109.1	113.4	1.0
Section 5	51.5	113.7	0.5
8: Dorback Burn			
Section 1	14.8	23.3	0.6
Section 2	18.9	20.7	0.9
Section 3	31.6	25.0	1.3
Section 4	24.6	27.3	0.9

Table 8.4.2.(iii) cont.

	Q_b ($m^3\ s^{-1}$)	Catchment area (km^2)	Specific runoff ($m^3\ s^{-1}\ km^{-2}$)
Other reaches			
(a) River Feshie			
Section 1	39.6	127.4	0.3
Section 2	63.3	119.0	0.5
Section 3	243.8	125.3	1.9
Section 4	151.1	130.4	1.2
Section 12	534.5	93.2	0.0
Section 13	70.1	92.8	0.8
Section 14	115.1	106.8	1.1
Section 15	39.6	115.4	0.3
Section 16	42.2	234.2	0.2
(b) River Tromie			
Section 1	31.8	125.2	0.3
Section 2	33.8	124.8	0.3
(c) Conglass Water			
Section 1	22.0	45.7	0.5
Section 2	5.6	45.6	0.1
Section 3	14.4	45.4	0.3
Section 4	19.7	45.2	0.4
Section 5	23.9	44.9	0.5

Table 8.4.2.(iv)

Spey study reaches: Parameters used in stream power calculations

Study reach	Du Boys' ($N m^{-2}$)	Velocity ($m s^{-1}$)	Stream power ($W m^{-2}$)
1: Feshie confluence			
Section 8	285.3	5.0	1417.9
Section 9	65.2	1.6	106.9
Section 10	65.5	1.8	120.5
Section 11	93.1	2.9	266.3
2: Nethy confluence			
Section 1	17.3	1.1	19.7
Section 2	16.6	1.1	18.4
Section 3	54.0	2.1	112.3
Section 4	141.7	3.8	531.4
3: Druie near Inverdruie			
Section 1	128.6	1.7	219.9
Section 2	158.8	3.1	485.9
Section 3	90.6	2.4	214.7
4: River Feshie at Lagganlia			
Section 5	125.5	2.8	351.4
Section 6	144.1	2.5	358.8
Section 7	214.8	3.4	728.2

Table 8.4.2.(iv) cont.

Study reach	Du Boys' ($N m^{-2}$)	Velocity ($m s^{-1}$)	Stream power ($W m^{-2}$)
5: River Tromie			
Section 3	77.7	1.9	147.6
Section 4	71.3	1.9	134.8
Section 5	54.7	1.9	104.5
Section 6	71.0	2.1	149.8
6: Avon at Tomintoul			
Section 1	181.1	3.7	670.1
Section 2	260.3	4.6	1192.2
Section 3	119.1	2.4	288.2
Section 4	143.3	2.8	405.5
7: Avon near Foals Craig			
Section 1	49.5	1.9	94.1
Section 2	102.6	2.3	236.0
Section 3	134.5	2.7	364.5
Section 4	129.4	2.7	350.7
Section 5	31.8	1.3	40.4
8: Dorback Burn			
Section 1	58.8	1.8	105.3
Section 2	68.0	1.8	124.4
Section 3	100.9	2.5	250.2
Section 4	82.5	2.6	212.9

Table 8.4.2.(iv) cont.

Study reach	Du Boys' ($N\ m^{-2}$)	Velocity ($m\ s^{-1}$)	Stream power ($W\ m^{-2}$)
Other reaches			
(a) River Feshie			
Section 1	91.4	1.8	165.4
Section 2	135.1	2.7	364.8
Section 3	459.0	6.0	2754.0
Section 4	203.4	3.8	768.8
Section 12	154.2	3.9	593.7
Section 13	90.9	2.1	187.3
Section 14	59.5	1.8	104.7
Section 15	50.7	1.4	69.0
Section 16	50.2	1.5	75.8
(b) River Tromie			
Section 1	132.9	2.9	384.1
Section 2	165.7	2.1	341.3
(c) Conglass Water			
Section 1	134.7	2.6	346.2
Section 2	31.8	1.1	35.3
Section 3	55.3	1.9	104.5
Section 4	42.2	1.6	66.7
Section 5	103.1	2.7	280.4

Table 8.4.2.(v)

Spey study reaches: Shield's competence at bankfull and the sediment transport discharge

Reach	D_s (m)	% D	Q_b (m^3 s^{-1})	Q_c (m^3 s^{-1})
1: Feshie confluence				
Section 8	1.477	100	299.1	51.3
Section 9	0.104	42	54.5	909.0
Section 10	0.102	54	70.9	668.2
Section 11	0.152	94	107.5	195.0
2: Nethy confluence				
Section 1	0.026	3	13.9	424.1
Section 2	0.026	10	18.7	500.7
Section 3	0.088	84	46.5	145.7
Section 4	0.231	100	110.0	61.5
3: Druie at Inverdruie				
Section 1	0.206	52	28.2	352.3
Section 2	0.253	100	40.0	35.2
Section 3	0.143	98	23.7	37.5
4: River Feshie at Lagganlia				
Section 5	0.197	84	106.7	332.3
Section 6	0.226	78	110.5	519.5
Section 7	0.337	89	166.6	269.7

Table 8.4.2.(v) cont.

Reach	D_s (m)	% D	Q_b (m^3 s^{-1})	Q_c (m^3 s^{-1})
5: River Tromie				
Section 3	0.123	61	36.9	250.9
Section 4	0.113	57	30.8	172.7
Section 5	0.112	56	39.9	307.8
Section 6	0.113	55	60.7	321.7
6: River Avon near Tomintoul				
Section 1	0.284	99	189.4	142.5
Section 2	0.423	100	216.1	99.5
Section 3	0.186	78	118.8	455.1
Section 4	0.225	82	151.6	536.5
7: Avon at Foals Craig				
Section 1	0.079	24	135.4	1893.2
Section 2	0.162	65	100.2	745.8
Section 3	0.211	83	110.8	367.7
Section 4	0.204	88	109.1	320.5
Section 5	0.112	58	51.5	860.8
8: Dorback Burn				
Section 1	0.074	83	14.8	48.9
Section 2	0.107	86	18.9	50.4
Section 3	0.158	98	31.6	26.1
Section 4	0.134	100	24.6	28.3

Table 8.4.2.(v) cont.

Reach	D_s (m)	% D	Q_b (m^3 s^{-1})	Q_c (m^3 s^{-1})
Other reaches				
(a) River Feshie				
Section 1	0.145	76	39.6	370.8
Section 2	0.213	87	63.3	155.3
Section 3	0.765	100	243.8	67.9
Section 4	0.330	95	151.1	229.2
Section 12	0.242	95	534.5	591.0
Section 13	0.143	77	70.1	349.2
Section 14	0.092	75	115.1	504.7
Section 15	0.080	27	39.6	498.4
Section 16	0.079	0	42.2	312.2
(b) River Tromie				
Section 1	0.209	95	31.8	27.4
Section 2	0.279	77	33.8	245.8
(c) Conglass Water				
Section 1	0.237	89	22.0	59.5
Section 2	0.042	11	5.6	203.4
Section 3	0.092	84	14.4	44.6
Section 4	0.079	65	19.7	123.9
Section 5	0.166	100	23.9	26.4

Figure 8.4.3.(i)

Scattergram showing Shield's entrainment diameter at bankfull against D_{84} channel bed material within the Spey study reaches

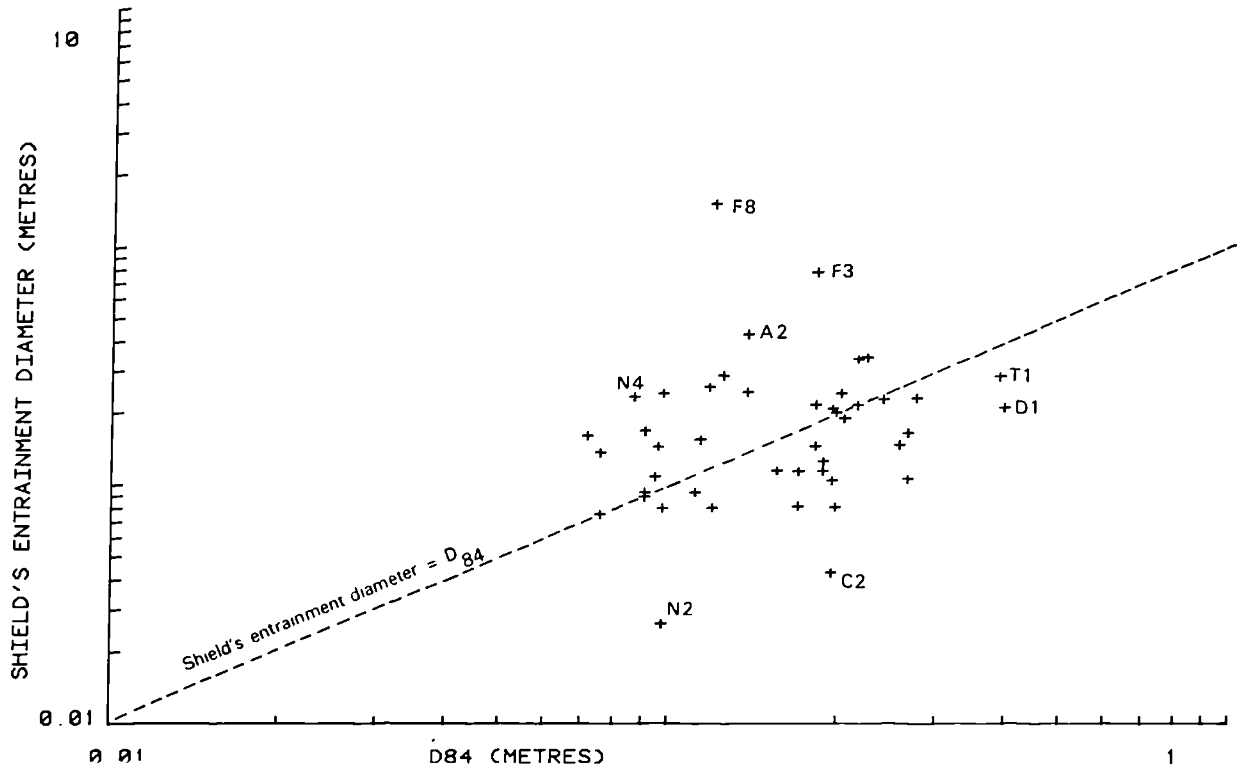


Figure 8.4.3.(ii)

Scattergram showing bankfull discharge against discharge at which sediment transport occurs within the Spey study reaches

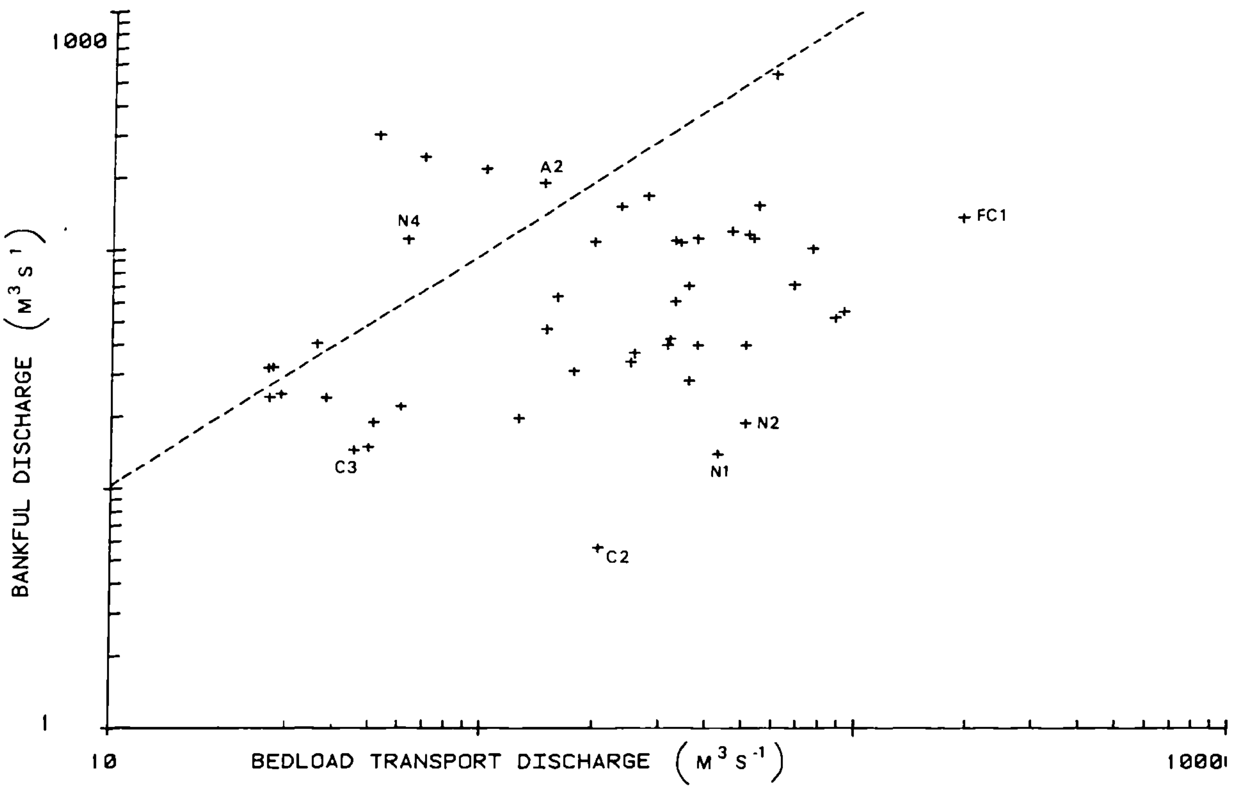


Figure 8.4.4.(i)

Scattergram showing bankfull stream power in relation to associated rates of catchment runoff within the Spey study

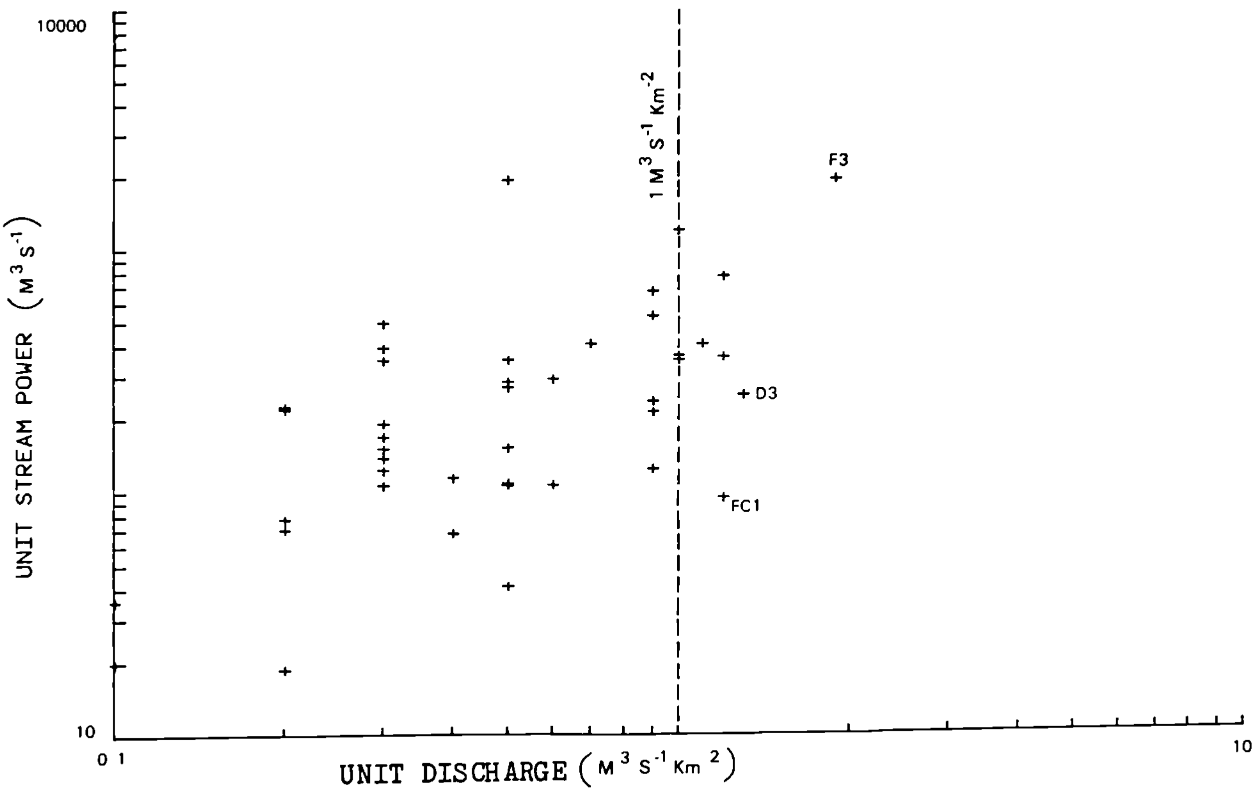


Figure 8.4.5.(i)

Scattergram showing W:d against unit stream power at bankfull within the Spey study reaches

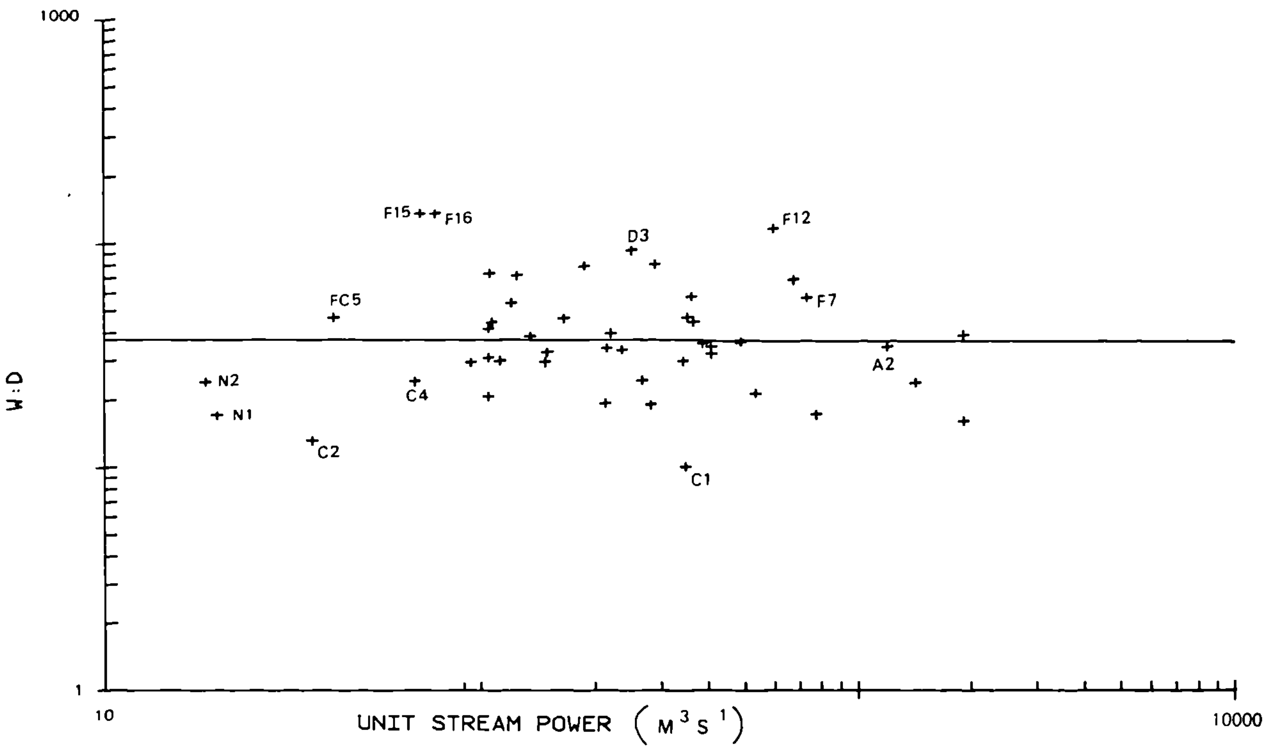
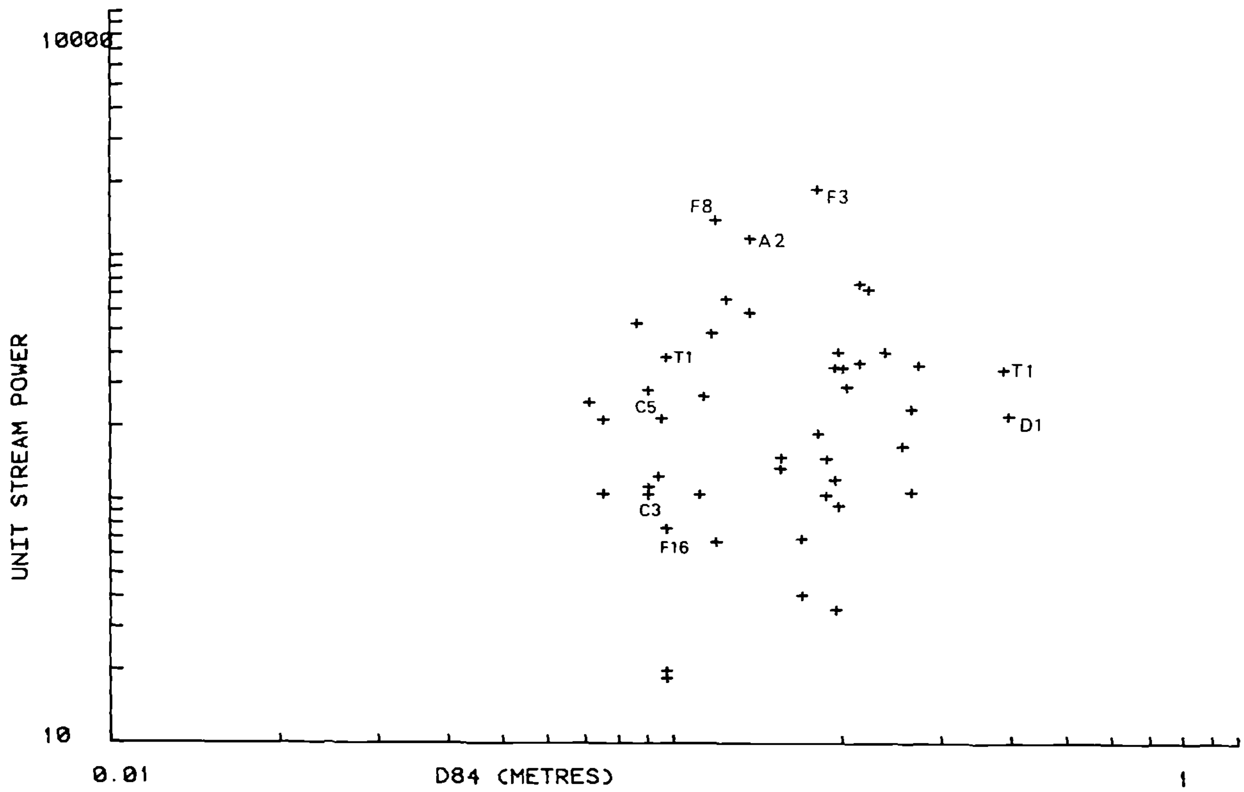


Figure 8.4.5.(ii)

Scattergram showing unit stream power at bankful against D84 channel bed material within the Spey study reaches



8.4.3 Spey study reaches: Analysis and implications of results

The large range of form parameters associated with moderate to highly active sites, can be seen in Table 8.4.2.(i). W:d ratios varied from 8-21 on the more stable regular meanders of the Conglass Water site to 215 on the extensive braiding reaches of the upper Feshie. In fact, the maximum values on the Feshie were considerably higher than those on any of the other study reaches, suggesting atypical controls. The cumulative sediment size frequency curves frequently indicated a smaller IQR than the Dee study reaches but a bimodal distribution still exists, with a fine fraction (sand) and much coarser clasts (see Figure 8.4.2.(iii)). Thus, it is likely that transport of different size fractions will be associated with a range of flows. Roughness values (n) ranged from 0.034-0.036 on the pebble bed of the Nethy confluence (with occasional bars; Spey study reach 2) to 0.063 on the bouldery bed of the Druie, below Coylumbridge (anabranching channel; Spey study reach 3). Slopes too varied 10-fold from 0.002 at the toe of the Nethy fan to 0.026 locally on the middle Feshie. Thus, there were considerable variations in all parameters between different active study sites.

When calculated Q_b values were subdivided by contributing drainage basin area, there was a much smaller range than in Deeside. The highest specific runoff rate required was at the stable Feshie bedrock reach with 1.9 $m^3\ s^{-1}\ km^{-2}$ but there was nothing to compare with the extreme runoff rates of the upper Luibeg. Higher specific runoff rates (in excess of 1 $m^3\ s^{-1}\ km^2$) included the upper Feshie fan (Table 8.4.3.(iii) with 1.3 $m^3\ s^{-1}\ km^{-2}$ and Foals Craig with 1.2 $m^3\ s^{-1}\ km^{-2}$. However, the majority of cross-sections had values of below 1 $m^3\ s^{-1}\ km^{-2}$ ie. they do not require extreme runoff rates to attain Q_b.

When the upper limits of bankfull transport according to Shields' were compared with the D_{84} percentile of bed material at bankfull stage (Figure 8.4.3.(i)), the bankfull Shields' value was well in excess of the D_{84} value on some of the more active channels eg. on the upper Feshie fan, Dorback Burn and the Avon at Tomintoul and thus bankfull flows must be important in terms of sediment transport. Others however were considerably less than the D_{84} value eg. the Druie site below Coylumbridge and the middle Tromie reach and these are sites where only more extreme floods transport D_{84} percentile bed material. Thus, the Shields' diameter as a percentile of bed material varies considerably (Table 8.4.2.(vi)). On the Nethy confluence, bankfull Q was able to transport only 3-10% of the bed material, while upstream nearer the apex, this value increased to 84-100%. In contrast, the Avon near Tomintoul (Spey study reach 6) and Dorback Burn (Spey study reach 8) at bankfull stage had the competence to transport 78-100% and 83-100% (respectively) of their bed material.

When Q_b was compared with the Q_c value, the majority of reaches had Q_b less than Q_c, as annotated in Figure 8.4.3.(ii). Sediment transport discharge however varied considerably; where Q_c was well in excess of Q_b, then clearly the more extreme floods must be important at these sites. Such sites included the Feshie at Lagganlia and the River Tromie. Only a few cross-sections had bankfull discharge well in excess of Q_c eg. the Avon at Tomintoul and the upper Nethy fan, and thus flows of bankfull stage must have an important role in sediment transport and channel form. The majority of cross-sections had Q_b below Q_c, an extreme example being at Foal's Craig section 1 (where Q_b was 135.4 m^3 s^{-1} whereas the required Q_c was 1893.2 m^3 s^{-1}). The moderate to extreme events in excess of bankfull must be very important in terms of mobilising bed material. This corresponds well with the aerial photograph record. Unfortunately, there was no indication of how frequently bankfull conditions occur.

8.4.4 Spey study reaches: Stream power

The results for each individual study reach are shown in Table 8.4.2.(iv). The number of study reaches with cross-sections recording a unit stream power in excess of 1000 W m^{-2} was less than on upper Deeside. However, the Avon at Tomintoul (Spey study reach 6) recorded stream powers ranging from 288-1192 W m^{-2}. But unlike on the Dee study reaches, only two other values in excess of 1000 W m^{-2} occurred and these were on the Feshie, associated with local increases in slope and channel confinement. These were section 8 on the upper Feshie fan and section 3 on the incised stable site in the middle reaches. This high bankfull stream power near the apex of the Feshie fan must account for the frequent fan disruption; downstream vast amounts of material will be deposited as bankfull stream powers reduce 10 fold, thus building up the fan. The dramatic decreases in stream power associated with progression down gravel fans as seen in Deeside also occurred on gravel fan confluence sites in Speyside. Thus, the Feshie fan had bankfull stream powers of 1417.9 W m^{-2} below Feshiebridge and 266.3 W m^{-2} down nearer the confluence. A similar pattern was found on the Nethy, where bankfull stream power decreased from 531.4 W m^{-2} with a catchment area of 123.6 km^2 to 18.4 W m^{-2} with an increase in catchment area to 124.0 km^2. As can be seen in Table 8.4.2.(iv), maximum rates of stream power at the API sites within the Spey study region are lower than those of the Dee. The assumption is of course that, in terms of controls, the sites selected here are necessarily typical of the range of high activity areas with the study area.

When bankfull stream power was studied in relation to specific runoff rates, certain reaches stand out (Figure 8.4.4.(i)); the Druie for example, for specific runoff rates of only 0.3 m^3 s^{-1} km^{-2} could produce stream powers of 486 W m^{-2} and was able to transport 100% load. The upper Nethy fan could too *transport 100%* load with only 0.9 m^3 s^{-1}. In contrast, other *reaches with similar* specific runoff rates were associated with lower stream powers eg. the Tromie and Dorback. It is clear that similar specific runoff rates can produce very different stream powers, dependent on other controls, such as slope and hydraulic geometry.

8.4.5 Spey study reaches: Stream power and channel form

Within the Spey study area, there was no significant correlation between W:d ratio and unit stream power, though the relationship continued to be an inverse one (Figure 8.4.5.(i)). Only the Feshie, sections 15,16 and 12 had W:d greater than 100. Sections 15 and 16 however had relatively lower bankfull unit stream powers, explaining their relative stability. The most active sites, associated with divided sites on the Feshie fan and the wandering planform above

Lagganlia, generally had relatively lower W:d ratios (20-40) and higher stream powers. This also applied to the range of lower W:d ratios, eg. on the upper Nethy confluence, which tended to have higher stream powers. When D_{84} value was plotted against bankfull stream power (see Figure 8.4.5.(ii); cf. Richards, 1982), reaches with a split/braided/anabranching tendency plotted above those which remained consistently within a single channel.

8.4.6 Spey study area: Bank composition and vegetative cover

When channel width was broken down by category of bank vegetation, there was a significant difference between category means, as seen in Table 8.4.6.(i). Although the highest mean W:d ratios (and standard deviations) were in heather and rough-grassland channels, those with trees were lower as shown in Table 8.4.6.(i). However, a similar breakdown with W:d ratio revealed no significant difference between means, though the tree-lined cross-sections again had the lowest mean W:d and standard deviation. Like Deeside, there was considerable variation in bank stability. Most stable banks possessed at least one of the characteristics in Table 8.4.7.(i). The range of bank characteristics on the Speyside reaches was however consistently different from Deeside. Generally the silt-clay ratio was not as high, with values in excess of 20% occurring rather rarely eg. on the Nethy confluence and the Avon at Tomintoul. In contrast, the meanders of Conglass water locally had 70% silt-clay, thus explaining their relative stability. Frequently, there was a considerable disparity between banks on either side of a reach eg. Foals Craig where one bank had the

Table 8.4.6.(i)

Spey study reaches: Channel form "broken down" by bank vegetation

	width		width:depth	
vegetation	mean	S.D.	mean	S.D
3	23.5	9.3	24.4	7.8
4	38.7	15.4	41.9	29.2
5	21.6	16.9	46.6	21.5
6	30.5	15.4	33.5	25.2
	Sig = 0.02		Sig = 0.07	

3 = trees and rough-grassland

4 = heather

5 = agricultural land

6 = rough-grassland

tendency to be reworked while the other was much more stable. In terms of bank composition characteristics, both depth of surficial layer and silt-clay ratio had no significant correlation with W:d.

8.4.7 Spey study reaches: Main modes of bank erosion

Certain categories of banks typified the study sites and like Deeside, there were both stable and inherently unstable reaches (see Table 8.4.7.(i)).

In terms of modes of bank erosion, the various categories were highly variable spatially, with local bank stratigraphy important in defining areas of weakness or strength. Category 2(a) bank's rate of erosion was stage controlled at the base, but weathering of the upper bank and failure was probably due to rainfall stress and the incohesiveness of the banks. Category 2(b) banks were susceptible to slumping, though the banks were generally not as high as in Deeside. These had the highest values of silt-clay content. Again, blocks lay in situ at the base of the bank until they were transported by higher flows. Category 2(c) banks are winnowed away by more moderate flows but major transport of large boulders must only take place during more extreme events eg. on the lower Tromie and Avon. The percentage matrix varied but in some cases it was negligible (eg. Foals Craig).

Table 8.4.7.(i)

Categories of bank composition found within the Spey study reaches

1: Stable banks (associated with slow or little apparent erosion)

(a) Rock controlled

(i) associated with both meltwater gorges and erosion of fluvioglacial deposits down to bedrock

eg. locally on the middle Feshie, lower Tromie

(b) Partially rock controlled

(i) bedrock locally outcropping within the channel bed and (or) banks

eg. lower Tromie

(c) Low bank with large clasts

(i) fine cohesive matrix

(ii) overhanging protective vegetation

(iii) large clasts well embedded within matrix

eg. on the lower Tromie (see Plate 8.4.7.(i)).

Table 8.4.7.(i) cont.

2: Unstable banks (associated with higher rates of erosion)

(a) High bank with medium sized clast/fine matrix

(i) basal layers represent former bar surfaces

(ii) low % of bank covered under normal flow conditions.

(iii) sheer face

(iv) vegetative cover stabilises only the upper unit

eg. lower Feshie (see Plate 8.4.7.(ii))

(b) High bank with high sand fraction

(i) large overhanging surficial layer of clasts and vegetation

(ii) clasts accumulate at base of bank

(iii) medium silt-clay ratio of 10-30 %

(iv) medium depth of upper unit

eg. Dorback Burn, middle Tromie

(c) Similar characteristics to category 2(b) on Deeside

(but frequently larger scale)

(i) highly incohesive

(ii) very low percentage of sandy matrix

(iii) very low silt-clay ratio (3-8 %)

(iv) large range of clast sizes

(v) sloping angle of repose

(vi) carpet of vegetation

eg. Feshie confluence, Avon near Foals Craig (see Plate 8.4.7.(iii))

Plate 8.4.7.(i)

Stable, cohesive banks on the Tromie below Tromiebridge

Plate 8.4.7.(ii)

High bank with inter-layering of medium sized clasts and fine matrix on the lower River Feshie

Plate 8.4.7.(iii)

High, incohesive, easily eroded banks with very little matrix

(on the Avon at Foals Craig)

8.5.1 Tweed study area: Limitations on study

Unfortunately, when studying stream power in the Tweed study reaches, many potential sections had undergone straightening and embanking since the 1948 flood eg. on the mainstream Leader and Teviot. This prohibited any meaningful measurement at several study sites and therefore the Tweed data set is comparatively small when compared with those of Deeside and Speyside. The other major problem was accessibility due to vegetation cover, and several cross-sections had to be rejected due to excessive trees on banks eg. on mainstream Whiteadder. The Teviot even after the drought summer of 1984 was still too deep to survey at the Nisbetmill study site. Finally, Charlton et al. (1978) included the river Glen at Kirknewton (see Figure 3.4.5(i)) in their study of discharge and geometry of rivers at bankfull and thus some detail is available further downstream on the Bowmont.

8.5.2 Tweed study reaches: Results

The locations of the cross-sections and the actual cross-sections are shown in Figure 8.5.2.(i) and the basic hydraulic parameters are tabulated in Table 8.5.2.(i). Selected sediment size cumulative frequency curves are shown in Figure 8.5.2.(i). D_{16}, D_{30}, D_{84} and D_{90} percentiles of bed-size composition are tabulated in Appendix 3.3. The Q_b results are collated by study reach in Table 8.5.2.(ii) and associated specific runoff rates in Table 8.5.2.(iii). Appendix 4.3 gives the comparative discharge results computed by alternative methods. Stream power results are tabulated in Table 8.5.2.(iv).

Figure 8.5.2.(i) Location of sampled cross-sections within the Tweed study area

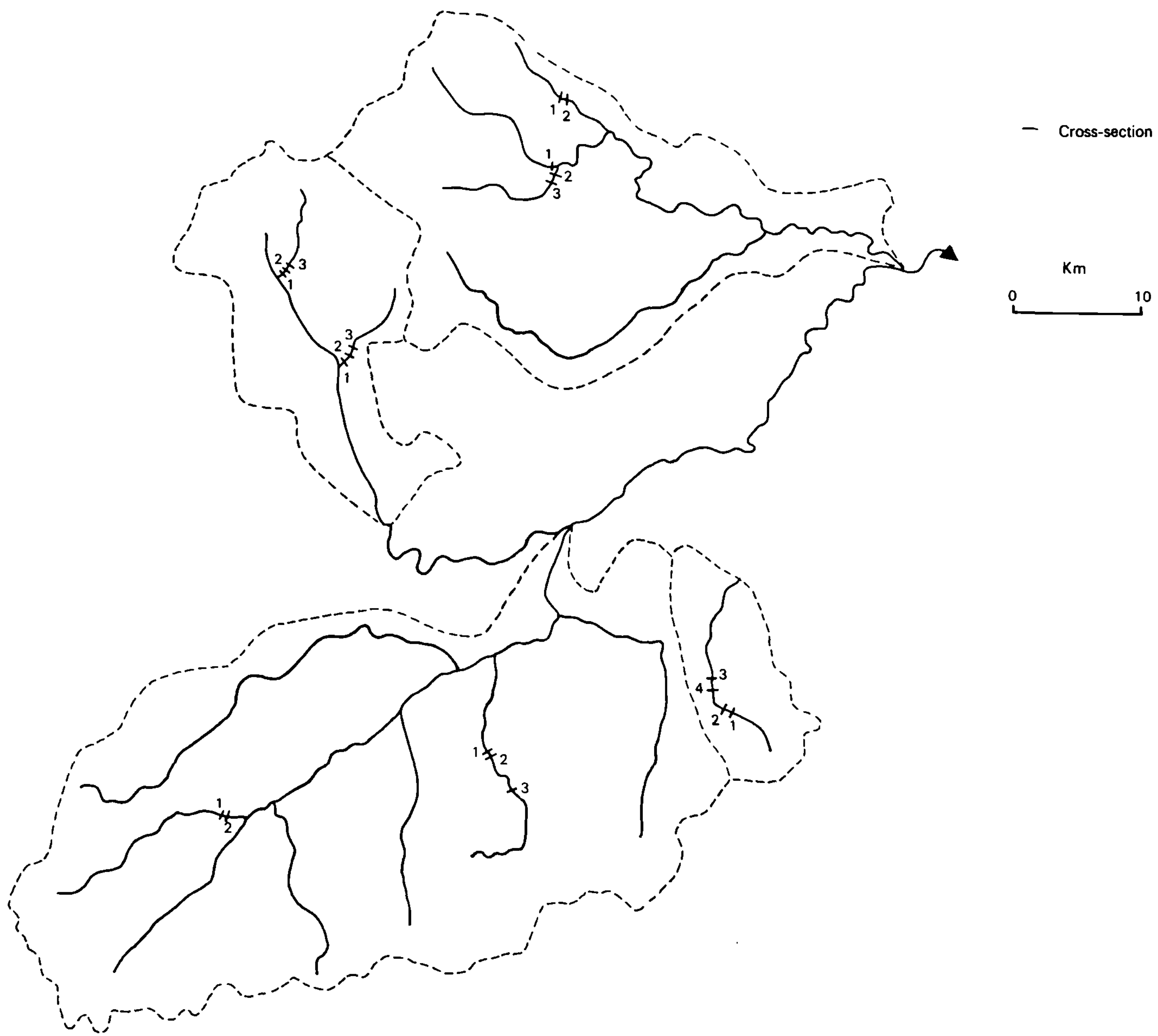
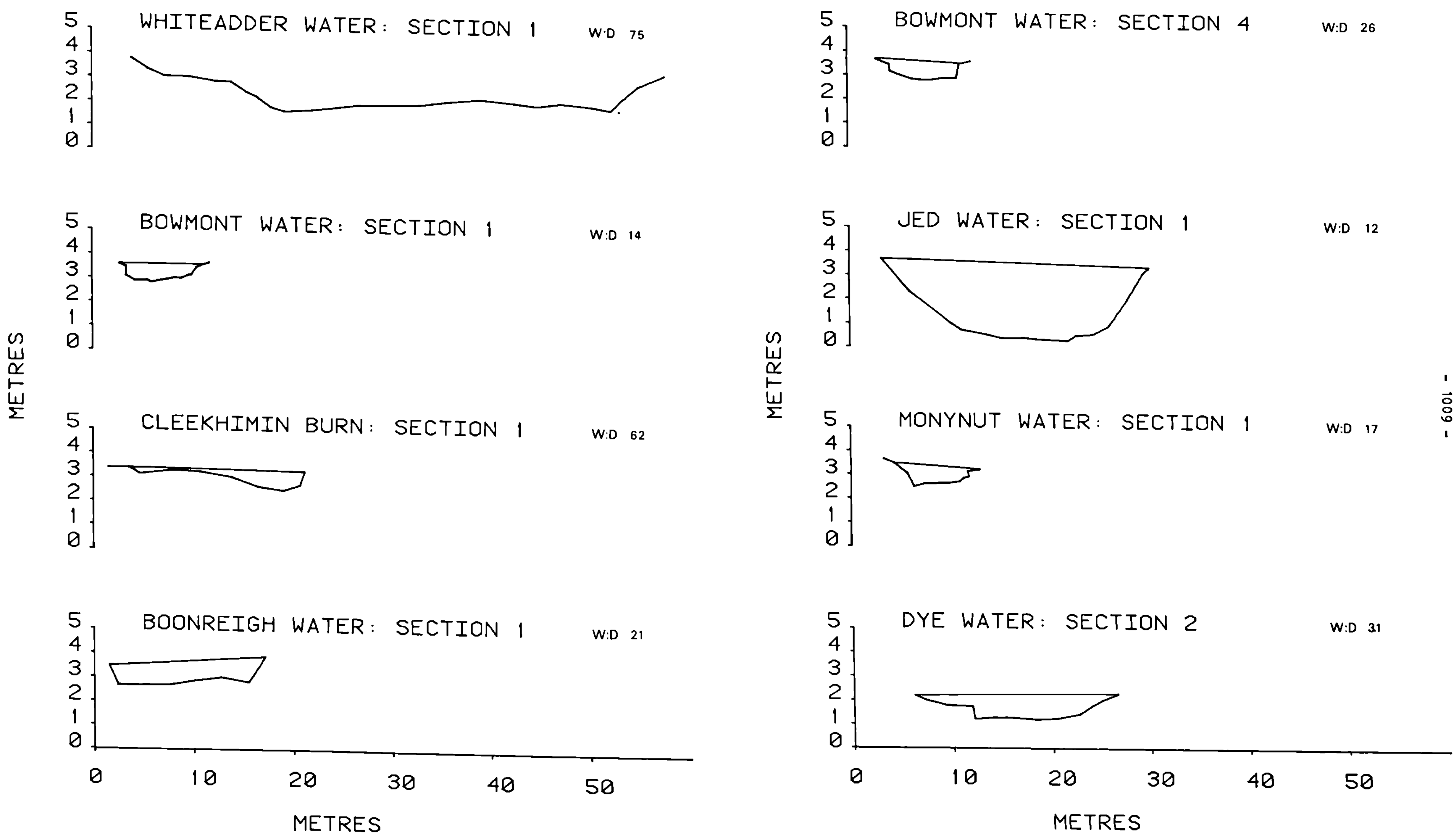


Figure 8.5.2.(ii)

EXAMPLES OF CROSS-SECTIONS USED IN STREAM POWER ANALYSIS WITHIN THE TWEED STUDY REACHES



Examples of cumulative frequency curves for channel bed material within the Tweed study area

Figure 8.5.2.(iii)

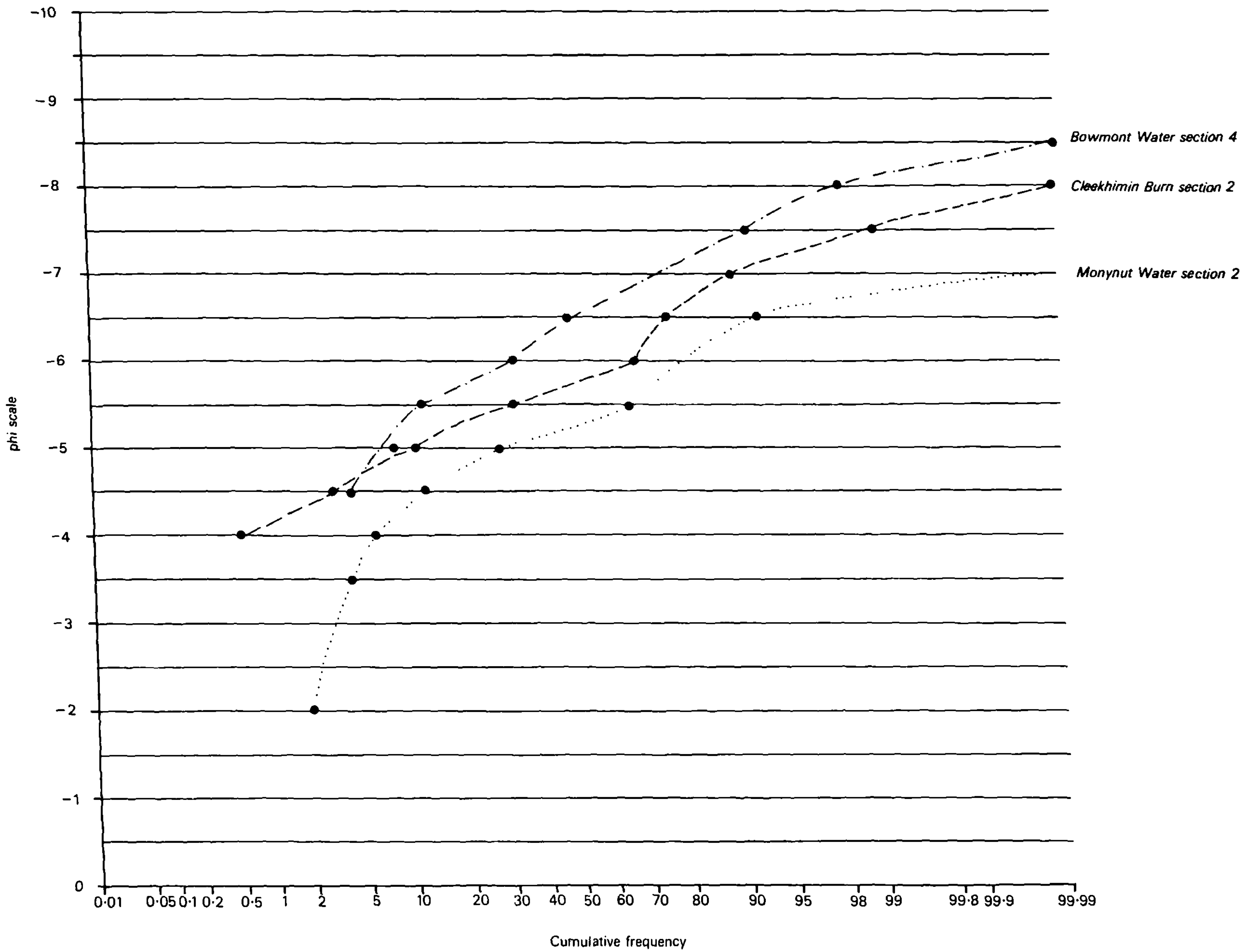


Table 8.5.2.(i)

Tweed study reaches: Basic hydraulic parameters at bankfull stage

Reach	W (m)	d (m)	W:d	A (m^2)	R (m)	WP (m)	D84 (m)	Slope
1: Bowmont Water								
Section 3	9.4	0.71	13	4.2	0.48	8.8	0.128	0.006
Section 4	8.4	0.55	15	6.7	0.49	13.8	0.152	0.013
Section 1	8.3	0.51	16	6.7	0.61	11.0	0.181	0.010
Section 2	13.3	0.51	26	4.6	0.51	9.0	0.128	0.012
2: Boonreigh Water								
Section 1	15.7	0.75	21	11.8	0.72	16.3	0.084	0.012
Section 2	10.3	0.67	15	6.9	0.64	10.8	0.150	0.012
Section 3	11.3	0.64	18	7.2	0.61	11.7	0.128	0.018
3: Cleekhimin Burn								
Section 1	33.6	0.54	62	18.2	0.53	34.2	0.100	0.017
Section 2	5.7	0.32	80	8.3	0.32	26.3	0.069	0.014
Section 3	17.6	0.35	50	6.2	0.34	18.0	0.100	0.014
4: Monynut Water								
Section 1	8.6	0.52	15	4.5	0.48	9.2	0.074	0.010
Section 2	7.6	0.80	10	6.1	0.51	9.0	0.066	0.010
5: Dye Water confluence								
Section 1	39.1	0.52	75	20.5	0.52	39.3	0.100	0.007
Section 2	20.5	0.66	31	13.6	0.65	21.0	0.084	0.009
Section 3	18.6	0.64	29	11.9	0.63	18.8	0.097	0.007

Table 8.5.2.(i)

Reach	W (m)	d (m)	W:d	A (m^2)	R (m)	WP (m)	D84 (m)	Slope
Other reaches								
(a) Jed Water								
Section 1	27.0	2.32	12	62.6	2.21	28.3	0.104	0.004
Section 2	24.8	1.43	17	35.5	1.38	25.7	0.128	0.007
Section 3	21.1	1.98	11	41.7	1.79	23.4	0.087	0.004
(b) Borthwick Water								
Section 2	18.5	1.16	16	16.6	0.93	17.8	0.123	0.011
Section 1	16.9	0.98	17	21.4	1.12	19.2	0.142	0.014

Table 8.5.2.(ii)

Tweed study reaches: Calculation of bankfull discharge

Study reach	n	A (m^2)	V ($m\ s^{-1}$)	Q ($m^3\ s^{-1}$)
1: Bowmont Water				
Section 3	0.041	6.7	1.3	9.0
Section 4	0.046	4.6	1.6	7.4
Section 1	0.050	4.4	1.2	5.2
Section 2	0.043	6.7	1.6	10.5
2: Boonreigh Water				
Section 1	0.035	11.8	2.5	29.5
Section 2	0.045	6.8	1.9	12.8
Section 3	0.032	7.2	2.3	16.9
3: Cleekhimin Burn				
Section 1	0.039	18.2	2.2	39.9
Section 2	0.045	8.3	1.2	10.2
Section 3	0.032	6.2	1.4	8.5
4: Monynut Water				
Section 1	0.036	4.4	1.7	7.6
Section 2	0.033	6.1	2.3	14.0
5: Dye Water confluence				
Section 1	0.039	20.5	1.4	28.3
Section 2	0.036	13.6	2.0	27.0
Section 3	0.038	11.9	1.7	19.6

Table 8.5.2.(ii) cont.

Study reach	n	A (m^2)	V ($m\ s^{-1}$)	Q ($m^3\ s^{-1}$)
Other reaches				
(a) Jed Water				
Section 1	0.034	62.6	3.2	198.9
Section 2	0.037	35.4	2.8	99.5
Section 3	0.033	41.8	2.8	118.2
(b) Borthwick Water				
Section 1	0.040	27.8	2.3	63.9
Section 2	0.038	16.6	2.8	46.8

Table 8.5.2.(iii)

Tweed study reaches: Specific runoff rates associated with bankfull discharge

	Q_b (m^3 s^{-1})	Catchment area (km^2)	Specific runoff (m^3 s^{-1} km^{-2})
1: Bowmont Water			
Section 3	9.0	49.4	0.2
Section 4	7.4	42.1	0.2
Section 1	5.2	39.2	0.1
Section 2	10.5	39.6	0.3
2: Boonreigh Water			
Section 1	29.5	54.6	0.5
Section 2	12.8	52.9	0.2
Section 3	16.9	51.8	0.3
3: Cleekhimin Burn			
Section 1	39.9	26.4	1.5
Section 2	10.2	25.4	0.4
Section 3	8.5	25.2	0.3
4: Monynut Water			
Section 1	7.6	12.8	0.6
Section 2	14.0	13.4	1.0
5: Dye Water			
Section 1	28.3	95.3	0.3
Section 2	27.0	80.2	0.3
Section 3	19.6	80.0	0.2

Table 8.5.2.(iii) cont.

	Q_b ($m^3\ s^{-1}$)	Catchment area (km^2)	Specific runoff ($m^3\ s^{-1}\ km^{-2}$)
Other reaches			
(a) Jed Water			
Section 1	198.9	125.9	1.6
Section 2	99.5	126.7	0.8
Section 3	118.2	101.4	1.2
(b) Borthwick Water			
Section 1	63.9	85.3	0.7
Section 2	46.8	87.0	0.5

Table 8.5.2.(iv)

Tweed study reaches: Parameters used in stream power calculations

Study reach	Du Boys' ($N\ m^{-2}$)	Velocity ($m\ s^{-1}$)	Stream power ($W\ m^{-2}$)
1: Bowmont Water			
Section 1	35.8	1.3	48.0
Section 2	65.3	1.6	104.5
Section 3	48.8	1.2	57.1
Section 4	57.2	1.6	89.8
2: Boonreigh Water			
Section 1	85.1	2.5	212.8
Section 2	74.8	1.9	139.9
Section 3	108.4	2.3	254.7
3: Cleekhimin Burn			
Section 1	88.5	2.2	193.8
Section 2	43.4	1.2	53.4
Section 3	47.3	1.4	64.8
4: Monynut Water			
Section 1	47.2	1.7	80.7
Section 2	65.9	2.3	151.6
5: Dye Water confluence			
Section 1	35.7	1.4	49.3
Section 2	86.8	3.2	276.0
Section 3	94.8	2.8	266.4

Table 8.5.2.(iv) cont.

Study reach	du Boys' ($N\ m^{-2}$)	Velocity ($m\ s^{-1}$)	Stream power ($W\ m^{-2}$)
Other reaches			
(a) Jed Water			
Section 1	70.1	2.8	198.4
Section 2	65.9	2.3	151.6
Section 3	127.8	2.8	360.4
(b) Borthwick Water			
Section 1	57.3	2.0	114.0
Section 2	43.5	1.7	71.8

Table 8.5.2.(v)

Tweed study reaches: Shields' competence at bankfull and the sediment transport discharge

Reach	D_s (m)	% D	Q_b (m^3 s^{-1})	Q_c (m^3 s^{-1})
1: Bowmont Water				
Section 3	0.065	58	9.0	101.0
Section 4	0.108	62	7.4	47.4
Section 1	0.077	91	5.2	93.4
Section 2	0.092	62	10.5	63.6
2: Boonreigh Water				
Section 1	0.137	97	29.5	39.9
Section 2	0.122	76	12.8	62.5
Section 3	0.174	97	16.9	33.7
3: Cleekhimin Burn				
Section 1	0.139	97	39.9	73.9
Section 2	0.069	70	10.2	79.6
Section 3	0.075	77	8.5	48.6
4: Monynut Water				
Section 1	0.078	86	7.6	22.4
Section 2	0.121	99	14.0	16.7
5: Dye Water confluence				
Section 1	0.055	50	28.3	242.3
Section 2	0.091	88	27.0	73.0
Section 3	0.068	51	19.6	110.1

Table 8.5.2.(v)

Reach	D_s (m)	% D	Q_b ($m^3\ s^{-1}$)	Q_c ($m^3\ s^{-1}$)
Other reaches				
(a) Jed Water				
Section 1	0.141	97	198.9	341.0
Section 2	0.151	76	99.5	222.6
Section 3	0.120	91	118.2	203.9
(b) Borthwick Water				
Section 1	0.193	92	63.9	78.9
Section 2	0.208	94	46.8	98.0

Figure 8.5.3.(i)

Scattergram showing Shield's entrainment diameter at bankfull against D_{84} channel bed material within the Tweed study reaches

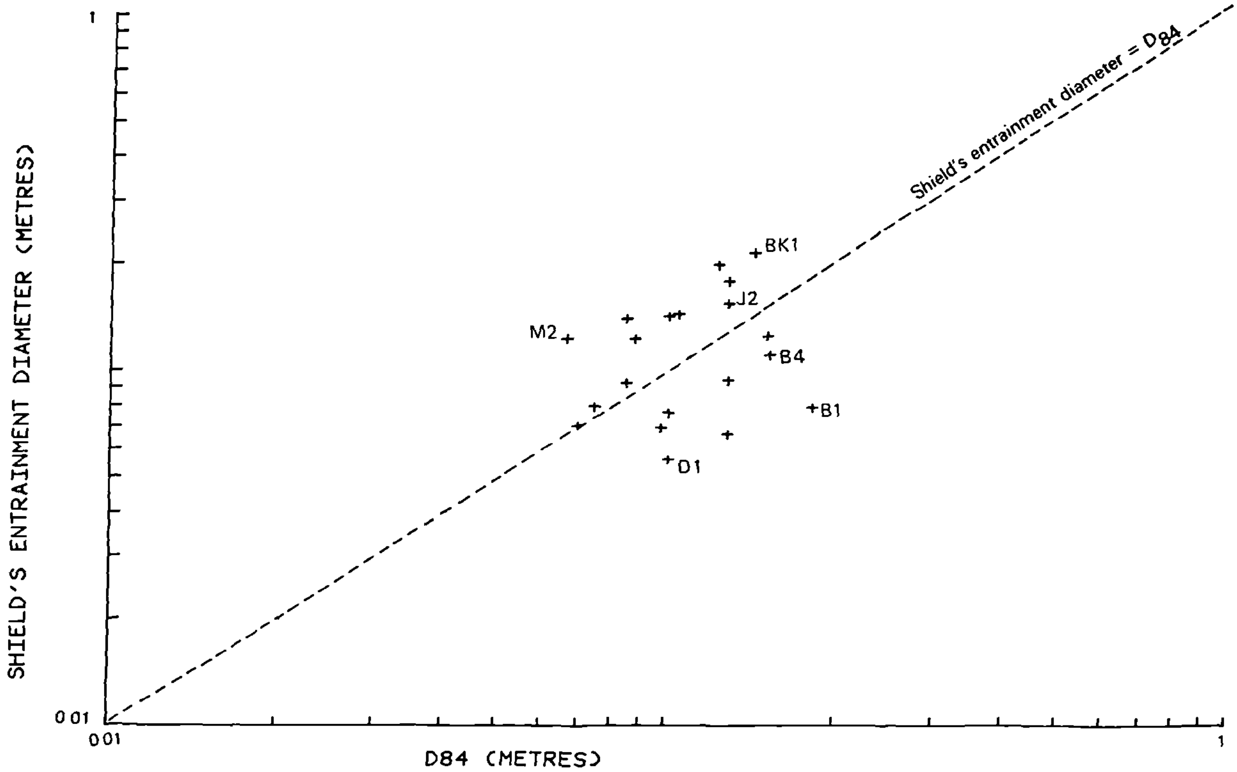


Figure 8.5.3.(ii)

Scattergram showing bankfull discharge against discharge at which sediment transport occurs within the Tweed study reaches

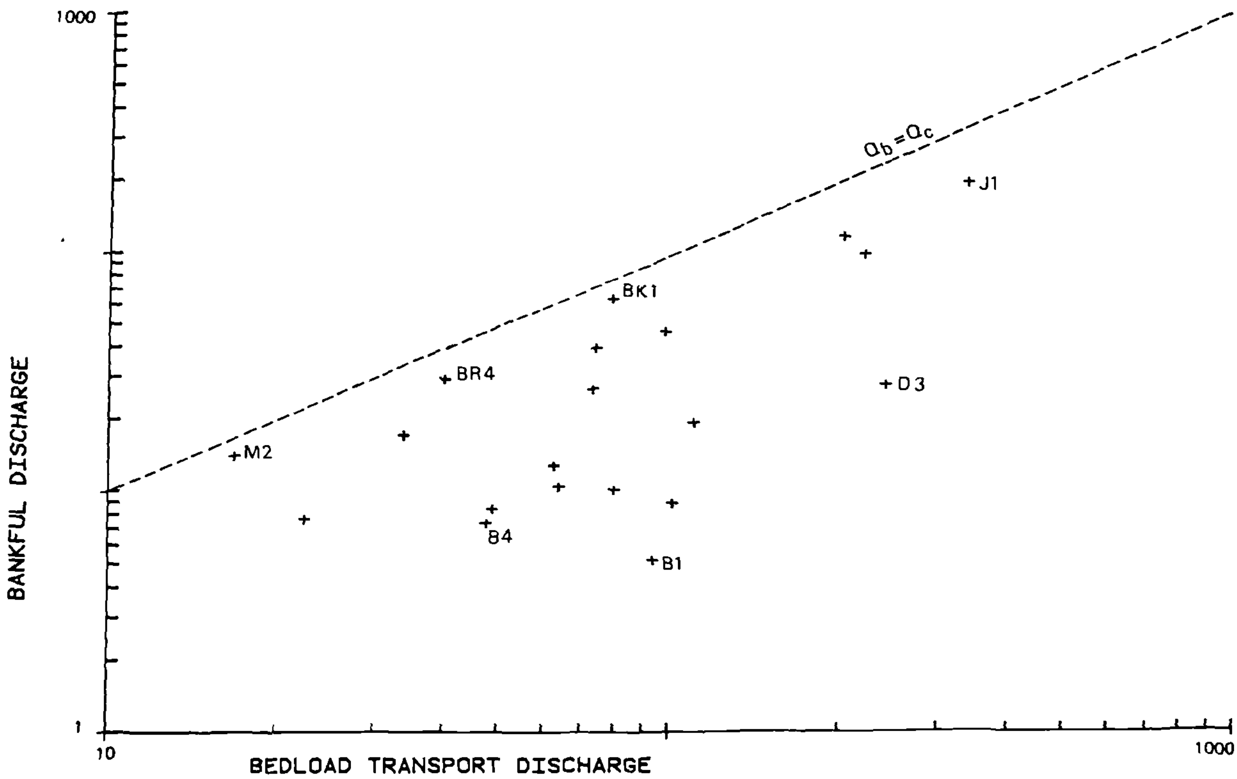


Figure 8.5.4.(i)

Scattergram showing unit stream power at bankful in relation to associated rates of catchment runoff within the Tweed study reaches

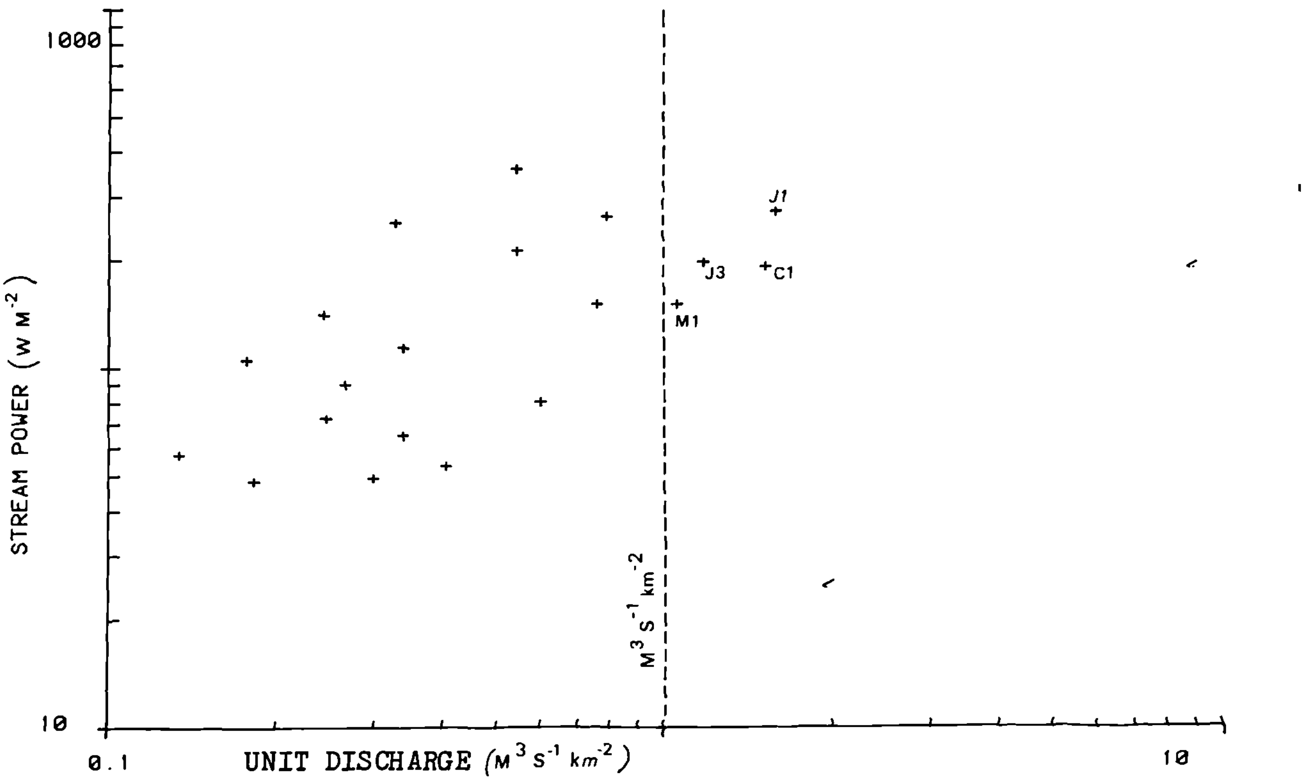


Figure 8.5.5.(i)

Scattergram showing W:d against unit stream power at bankfull within the Tweed study reaches

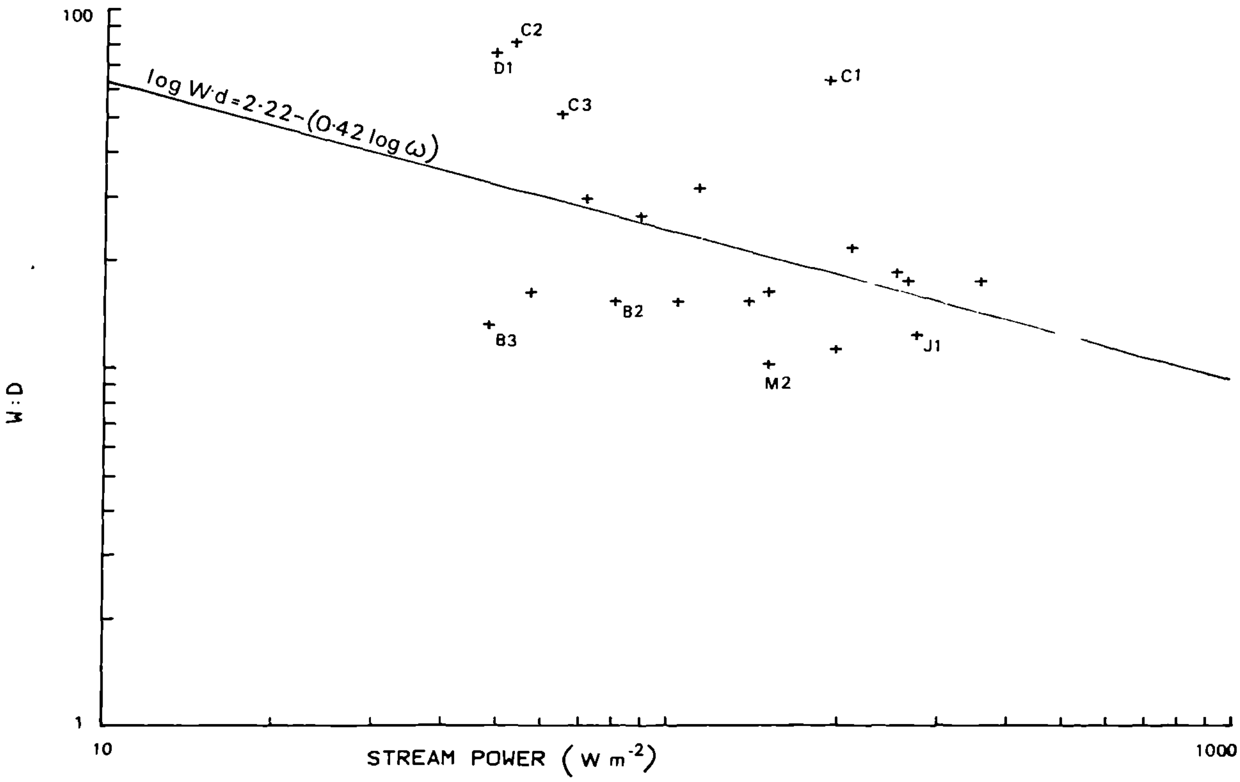
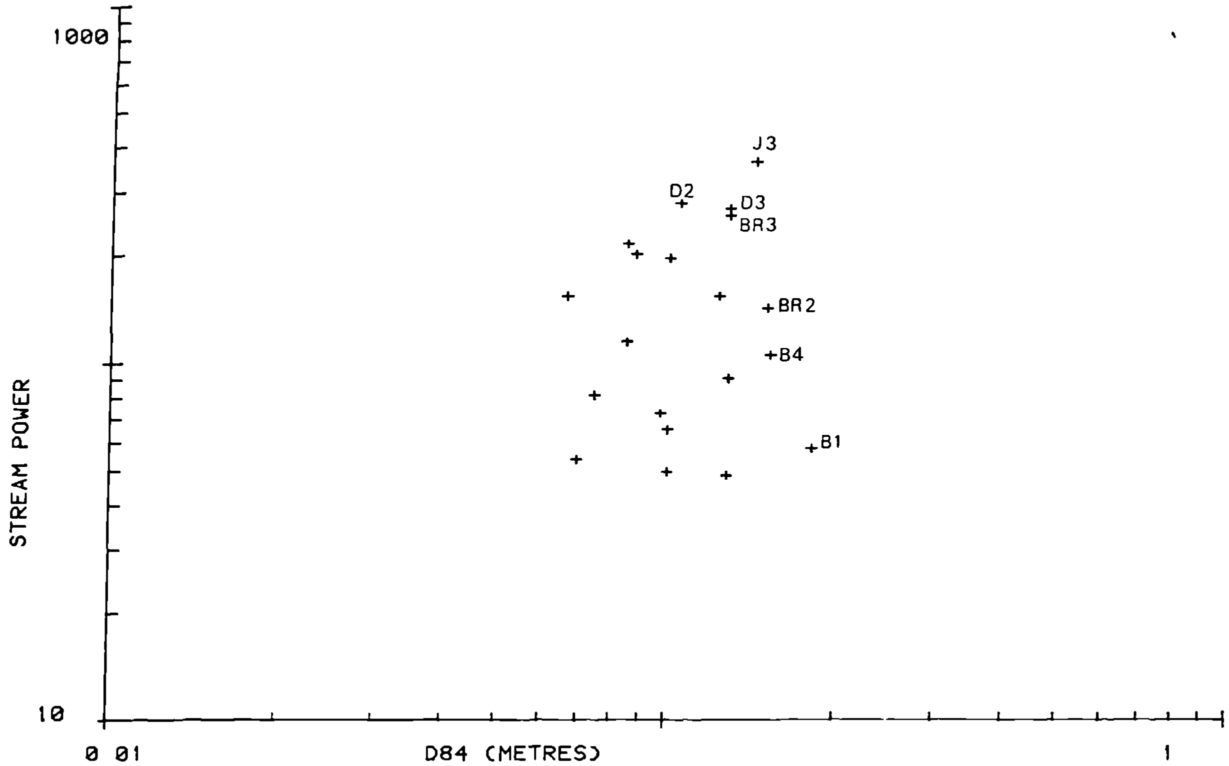


Figure 8.5.5.(ii)

Scattergram showing unit stream power at bankfull against D_{84} channel bed material within the Tweed study reaches



Finally, Shields' limit of entrainment and sediment transport discharge are found in Figure 8.5.2.(v).

8.5.3 Tweed study area: Analysis and implications of results

W:d ratios varied from 10 on the irregular meandering channel of Monynut water (Tweed study reach 7.4.3) to 80 on the lower Cleekhimin burn (Tweed study reach 7.4.3). Roughness values were generally lower than on the Dee and Spey study areas with values of 0.033-0.050 (Table 8.4.2.(i)). Slopes too were lower than the Deeside/Speyside equivalents, ranging from 0.004 on the lower Jed to 0.018 on Boonreigh Water. Bankfull discharges were lower than within the Spey and Dee study areas for catchments draining a comparable area. Specific runoff rates associated with bankfull stage ranged from 0.13 $m^2\ s^{-1}\ km^{-2}$ on Bowmont Water to 1.58 $m^2\ s^{-1}\ km^{-2}$ on the Jed. Obviously, this is why the Bowmont reach was reported to attain bankfull 10-12 times per year. Only two other reaches had bankfull runoff rates in excess of 1 $m^3\ s^{-1}\ km^{-2}$; on the Monynut Water and the lower Cleekhimin Burn and the general trend for the study reaches was low. Perhaps bankfull stage is a more meaningful measure in terms of frequency within these sample sites cf. the Dee and Spey study reaches.

When Shields' competence at bankfull was studied, the highest values of 0.193 and 0.208 m were found on the relatively stable site on the lower Borthwick. It is known that this reach overflows frequently and thus large clasts must be frequently flushed through the system. At the other extreme, low bankfull Shields' values of 0.055 and 0.091 were found at the Dye/ Whiteadder confluence (51-88% channel bed material). Larger events must be required to rework sediment and this suggests the stream powers involved in major channel avulsions found in the planform record must be much higher. When Shields' entrainment function was plotted against D_{84}, the sites were clustered around the Shields' value=D_{84} line with no really extreme outliers (Figure 8.5.3.(i)). Some sites had Shields' value in excess of D_{84} ie. bankfull competence capable of transporting D_{84}+ and these included the Monynut Water and Boonreigh Water. These sites must be modified by more frequent flows around bankfull. In contrast, Bowmont Water and the Dye Water confluence sites both required events in excess of bankfull to transport D_{84}+ bed material. The disparity between Shields' and D_{84} however was not nearly as great as for certain Deeside and Speyside sites. In contrast, when Q_b was compared with Q_c, there was much more variation but below the threshold line (Figure 8.5.3.(ii)) ie. all cross-sections had Q_c greater than Q_b. However, although Q_b can transport the D_{84} at many cross-sections, flows in excess of bankfull must be important in transporting the larger bedload fraction and in accessing sediment from the floodplain.

8.5.4 Tweed study area: Stream power

Values for bankfull stream power per unit area of bed were considerably smaller within the study sites recorded in the Tweed study area, with values ranging from 48 W m^{-2} on the complex anabranching channel of Bowmont Water to 360 W m^{-2} on the more stable reach of Borthwick Water (Table 8.5.2.(iv)). The Jed had values of 198-276 W m^{-2}

but was highly stable; here other factors such as cliff confinement, bedrock control, tree-lined banks and cohesive bank material were important. When stream power is compared with associated runoff rates (Figure 8.5.4.(i)), both had a lower range of values than the Dee or Spey samples. There were however certain patterns; for example, Bowmont Water had lower stream powers (48.0-104.5 W m^{-2}) associated with low rates of runoff (0.13-0.27 m^3 s^{-1} km^{-2}). Monynut Water in contrast, had higher runoff rates (0.59-1.04 m^3 s^{-1} km^{-2}) associated with higher stream powers (80.7-151.6 W m^{-2}). The Jed and the Borthwick, the more stable sites, also had higher bankfull unit stream powers, associated with higher runoff rates.

8.5.5 Tweed study reaches: Stream power- process and form

When W:d ratio was correlated with stream power, a significant negative correlation was found (r=-0.49; see Figure 8.5.5.(i)). Again unit stream power decreased as W:d increased. Sites with high W:d ratios and lower stream powers included the gravel fan of the Cleekhimin Burn (wandering planform) and the Dye/ Whiteadder confluence (irregular meanders), while sites with lower W:d and higher stream power included the Boonreigh, Jed and Borthwick. These were associated with sinuous to irregular planforms. However, when stream power was plotted against D_{84} (Figure 8.5.5.(i)), for this limited sample, there was a reverse pattern to that found by Richards (1982). Single channels like the Jed plotted high above split to braided channels eg. the Cleekhimin Burn and Monynut Water. Confinement must therefore be very important, in terms of containing lateral activity.

8.5.6 Tweed study reach: Bank composition and vegetative cover

Banks within the Tweed study area had high silt:clay ratios eg. banks on the Boonreigh, Cleekhimin burn, Jed and Borthwick water all exceeded 30%. Lowest values were gained on Bowmont Water with 3-20%. When the depth of the minimum upper unit was correlated with W:d for this rather limited data set, no significant correlation was found. However, the 4 cross-sections with W:d of 50 or above were all associated with surficial layers of under 0.13 m cf. on the stable Jed with depths of over 0.350 m.

8.5.7 Tweed study reaches: Modes of bank erosion

Bank composition on the sites studied was categorised as follows. Some reaches were inherently stable due to bedrock confinement or compact, cohesive banks, well covered by vegetation with a deep rooting layer (see Table 8.5.7.(i). In contrast, other banks were characterised by much higher rates of erosion. Frequently, the successive shifts of the channel through time have built up layers of sands and gravels, though the actual nature of the bank varied with both glacial deposits and underlying bedrock type. In terms of types of bank and modes of erosion, where the silt-clay ratios were highest (20-40%; category (a)), the dominant mode of erosion was slumping (as in Deeside), with blocks lying in situ for higher flows to breakdown. Other dominant forms of erosion were sub-aqueous winnowing of fines and the subsequent failure of the upper bank, as discussed in Section 8.3.7.(i).

Table 8.5.7.(i)

Categories of bank composition found within the Tweed study reaches

(1) Stable banks (associated with slow or little apparent erosion)

(a) Rock controlled or confined by a rock face

eg. lower Jed Water, lower Whiteadder (see Plate 8.5.7.(i))

(b) Low grass-covered banks, vegetated down to normal water level

(i) medium silt-clay ratio (10-20 %)

(ii) large % of banks under water during normal flows

eg. Monynut Water

(c) Compact, cohesive banks

(i) high silt-clay ratio (over 40%)

(ii) cohesive vegetation, deep root layer

(iii) low width:depth ratio

eg. Jed Water

Table 8.5.7.(i) cont.

(2) Unstable banks (associated with higher rates of erosion)

(a) Deep sheer banks

(i) high silt-clay ratio (20-40 %)

eg. Monynut Water, Tweed near Nisbetmill

(ii) large proportion of bank covered under normal flow conditions

(b) Banks consisting of medium sized clasts with fine matrix

(i) compact with clasts well embedded in matrix

(ii) high silt-clay content (25-37 %)

(iii) sheer banks

(iv) reworked conglomerate

eg. Boonreigh Water, Borthwick Water (see Plate 8.5.7.(ii))

(c) Banks with reworked till deposits

(i) stratified layers of coarse clasts

(ii) interspaced sequences of finer flood sedimentation

(iii) low silt-clay ratio (< 20 %)

(iv) more friable than (b)

(v) easily reworked vegetative cover

eg. Bowmont Water (see Plate 8.5.7.(iii))

Plate 8.5.7.(i)

Jed Water confined by a sandstone cliff

Plate 8.5.7.(ii)

Compact banks derived from reworked till, with clasts mainly derived from conglomerate (on Boonreigh Water)

Plate 8.5.7.(iii)

Unstable bank composed of layers of reworked till deposits, inter-layered with finer flood sedimentation.

With category (b), the whole resulting profile, though compact, was highly erodible and friable and even a small amount of undercutting could input a new plug of sediment into the stream. The actual root depth and soil profile was not found to be deep, especially along the banks although presumably it must locally deepen in some areas of the floodplains. This would depend on whether the area represents, for example, a former point bar or palaeochannel before the major channel switch took place. In contrast, within category (c), the layers of fine and coarse deposits were much more distinct. Basal erosion and subsequent bank failure were the dominant modes of erosion leading to sediment transfer. Unlike within some Dee and Spey study reaches, sediment was not left in situ to protect the bank from subsequent flows as maximum clast size is much smaller.

8.6 Summary

In terms of hydraulic parameters, roughness values were higher within the Dee and Spey study reaches (cf. the Tweed reaches), while bankfull slopes were highly variable. Both highest and lowest values were recorded within the Dee study area, however slopes were generally lower within the Tweed study reaches.

Highest unit stream powers at bankfull were associated with mountain torrents, apexes of tributary fans and wandering channels. The fans within the Tweed study area were characterised by lower values due to lower slopes, not debouching from rock controlled gorges as on Speyside and Deeside. Dramatic decreases in bankfull stream power down such fans were also more characteristic of the latter two areas. Generally lower stream power and lower specific runoff rates were found within the Tweed study reaches.
Only one sample showed an inverse relationship to that found by Richards (1982), with single channels tending to plot above multiple channels within the Tweed reaches. In contrast, within the Dee and Spey samples, the multiple/ single channel distinction held but there were several exceptions eg. at confined fan apexes.

Within the Spey and Dee reaches, Shields' entrainment diameter at bankfull was frequently less than D_{84} and thus more extreme flows were important in sediment transport (cf. the Tweed reaches). The frequency of bankfull discharge and associated stream powers was highly varied. Within the Spey and Dee reaches, hydraulic geometry was frequently related to larger events. In contrast, within the Tweed reaches it seemed that bankfull stage could be expected at least once a year.

CHAPTER 9

Discussion of results

Having analysed the macro-scale rates of river planform change, with subsequent detailed meso- and micro-scale study of selected more active reaches, a large variety of river systems and rates of adjustment have been found both within and between the three study areas. Returning to the questions posed in Chapter 1, it is now necessary to assess the magnitudes and frequencies of discharge events *that are the* dominant agents shaping the alluvial landforms on the present-day valley floors. With knowledge of fluctuations in the magnitude, frequency and duration of climatic inputs, the occurrence of *random* extreme events and the timing and extent of major landuse change, it is essential to evaluate the relative effects of each, as far as this reconstruction will allow.

9.1 The impact of climatic fluctuation

There was no evidence for highly significant periodicities within the annual rainfall data set, within any of the study areas. The largest climatic fluctuation, within the post-1850 gauged rainfall records, involved the increase in rainfall POT of both 24 and 48 hour duration (>25.4 mm and >38.1 mm respectively), which occurred during the 1870s and 1880s. This was reflected within both the Braemar and Marchmont House rainfall records and the reconstructed flood histories for all three study areas. This was clearly a regional event and not just the pecularity of a single basin. These POT were mainly associated with summer frontal storms, seen especially within the Deeside record. It should be noted that this climatic fluctuation was also associated with annual rainfall totals above the longterm average and thus both soil moisture deficit and winter rainfall acceptance potential would have been reduced over this period. This would have caused an increase in the catchment response to large rainfalls amounts, especially during summer months. The 1850-1900 period also contained several severe winters associated with the latter stages of the Little Ice Age and thus more moderate winter rainfall POT were sometimes exacerbated by a major snowmelt contribution (eg. the 1881 and 1891 floods within the Tweed catchment and the 1892 event within upper Deeside). It is interesting to compare how the different channel systems responded, within the three study areas.

This alteration in climatic inputs was associated with an increase in moderate to extreme runoff events within the Dee study area, though these did not rank as the most extreme events on record. Over a similar period, there were significant increases in braiding index within the total sample between the 1st and 2nd editions (1869-1900). This involved an increased utilisation of the floodplain area, where available, and a shift to higher categories within the "islands" classification of the typology. This suggested that some disruption to the system had occurred since the 1850s, with process thresholds crossed to more divided planforms. Several moderate discharge events in succession would explain the lack of stabilised gravels within a large percentage of the sample, the reworking of islands and frequent occurrence of avulsion. Where more moderate events had the stream power to transport large amounts of available sediment, intrinsic thresholds were perhaps more likely to be exceeded after a sequence of floods rather than in response to one high RI event. Different catchments varied in their response, from the Clunie (with its lower "islands" categories and more restricted sediment availability) which remained relatively stable, to the Quoich and Lui (with more frequent channel division and greater sediment availability) which underwent several disruptions along their courses.

Assuming the regional fluctuation in rainfall POT extended to the Spey study area (there certainly was an increase in discharge POT), there was considerable spatial variation in the response to this fluctuation in rainfall inputs. There was no statistical change within the total population as the Spey reaches had a greater tendency for higher BI under quasi-equilibrium conditions. However, the Nethy catchment increased its BI from the first to second edition (1871-1902) and dramatically decreased to the third (1971). In contrast, within the Feshie catchment there was an increase in BI between 1902-1969. To a greater extent than upper Deeside, many reaches were characterised by large to extensive amounts of unvegetated sediment due to increased bank erosion and channel widening eg. within the Feshie catchment and locally on the mainstream Spey. These reaches were particularly susceptible to intra-channel avulsion between the first and second editions, due to the non-stabilised and easily reworkable nature of the sediments.

The Tweed in contrast had a much more subdued planform response to the pre-1900 increase in discharge POT, due to restrictions in sediment availability. While the interquartile ranges for BI were generally higher for the first edition, median values were higher for the second. In fact, palaeochannel evidence of former anabranches at several samples suggests that channels were considerably more active at some time pre-1850. There was more sediment stored within the channel as medial bars and more use of the available floodplain area. It is known from the Lauder estate records (Thomson, 1903) that a series of very wet years occurred during the late 18th century, coincident with the short, wet summers associated with the Little Ice Age. There may also have been a lagged response due to increased incision associated with the onset of the Little Ice Age, as discussed by Brakenbridge (1980) for Alpine catchments. The increase of more moderate rainfall events, associated with significant increases in meridional upper circulation, may have caused increased stream power to transport material stored within the channel. After such a change, channels could take over a 100 years to regain their former equilibrium form. The occurrence of climatic fluctuations involving wet years and flooding in the latter years of both the 18th and 19th centuries may thus have implications in terms of the concept of episodic erosion. Episodes of increased channel division and reworking of channel bars and banks may be followed by periods of relative stability and relaxation to the system. Similar fluctuations associated with short wet summers were reported within the late 16th and 17th centuries and may explain some of the frequent palaeochannels found within all three study areas.

9.2 The impact of random extreme runoff events

The geomorphic importance of random magnitude/ frequency variations showed both similarities and dissimilarities between the three study areas. Within all three study areas, the most extreme discharge events were associated with high recurrence interval, summer frontal storms (>100 year RI for 24-48 hour rainfall; especially in August), which provided enough intense, long duration rainfall to exceed the soil moisture deficits and generate catastrophic runoff rates. Absolute rainfall amounts as an annual maximum for a set recurrence interval were similar for a 24 hour event within the Dee and Tweed study areas, but when duration was increased (48 and 72 hour durations), the Tweed study area seemed to have a lower depletion effect, especially for a 50-100 year return period storm. For example, the difference between Braemar and Marchmont House for a 72 hour event of 100 year RI was 10.1 mm (EV1 distribution) and 34.5 mm (GEV distribution).

There is no doubt that within the upper Dee catchment and especially the north to south flowing tributaries, that the major landforming event was the regional summer frontal storm of 4th August, 1829. The sediment inputs to the system and the extensive disruption of formerly stable floodplain areas completely altered the controls on channel planform along change susceptible reaches, with the exceedence of major extrinsic thresholds eg. at the Quoich confluence (Chapter 7.2.1). Different planform types responded in different ways, with meander cutoffs on some irregularly meandering to tortuous reaches while extra-channel avulsions were more frequent along sinuous, wandering and irregular channels. The relaxation time after an event of this high recurrence interval was well over 150 years. In fact in extreme examples such as tributary fans, a shift in equilibrium state may have occurred. In comparison, high recurrence interval winter events that occurred in 1920 and 1937 (>100 year discharge RI) had much lesser geomorphic impact suggesting that after major thresholds have been exceeded, there is a period of a lesser response to events of high magnitude until incipient thresholds are re-established. However, these were winter frontal storms of longer duration and thus may not have had such high instantaneous discharges within the upper catchment. There have been no high RI summer frontal storms within upper Deeside, post-1900. Thus, the channel systems have been allowed to relax after extensive disruption except where more localised events have caused further disruption to a quasi-equilibrium form eg. Luibeg, 1956. Lesser rainfall is required in the winter months to generate a flood event, especially within the middle to upper catchments where there is a very low winter rainfall acceptance potential.

As well as extreme summer frontal events, much more localised summer convective storm events generating high stream powers can have a major and lasting geomorphic impact. These are however only important in smaller catchments where high specific runoff rates can be generated, especially where the thresholds of sediment entrainment are high eg. the upper Luibeg burn and the Aug, 1956 storm. Although such events are of high RI within an individual catchment, their frequency increases within the larger catchment. As the sampling interval is extended over a larger area, time is substituted for space in identifying these rare but highly localised events. The geomorphic impact of such storms on the mainstream Dee is however negligible.

is in contrast to the Dee study area, where random high magnitude events post 1900 were amongst the highest on record. There has been no instance when similar regionally high rainfall intensities have been maintained over the upper Spey catchment. The 1956 and 1970 events did not cause major planform disruption on the mainstream Spey, though tributaries were more affected.

Nevertheless, more localised storms of a convective nature have had a greater geomorphic impact within the tributaries eg. June, 1956 within the Druie catchment. Planforms most susceptible to change during such events were wandering channels, with their high associated stream powers and with extensive amounts of channel-side sediment. These were frequently associated with a high frequency of both extra- and intra-channel avulsion and reworking of a large proportion of the available active area width over short time periods. The more sinuous planforms associated with confluence fans also frequently underwent extensive disruption and division of channel during convective storms.

Another major summer frontal storm, with similarly high RI (estimated 24 hour rainfall RI of 200-500 years), occurred in Aug, 1948 within the Tweed study area. This was associated with high estimated runoff rates, despite the higher SMDs recorded in the Tweed study area (up to 11.0 mm). Planform response was not generally a large scale disruption due to the more limited sediment supply (cf. Dee and Spey), nevertheless some more localised avulsions occurred, with channel sedimentation through reworking of floodplain deposits. It seemed that a rough-grass covered floodplain frequently produced a boundary that under overbank conditions acted as an extension of the channel's normal hydraulic geometry and thus, had a resistence to disruption. The thresholds for change could be high eg. for channel switches across the Dye confluence fan. However, extreme discharges (well over bank) reworked reserves of sediment formerly stored within the channel margins and stable floodplain areas. Such large amounts of sediment transfer over such a brief timespan must be important in terms of total Holocene sediment reworking. Within the Tweed study area, planform recovery was much more rapid but principally artificial because of post-flood engineering works. This therefore could be a significant element in the formation of floodplains in this area. Frequently, the flow reverted back to its original channel leaving a disrupted floodplain and/or extensive flood sedimentation. Sediment is less accessible in terms of reserves of fluvioglacial outwash with more localised stores and thus erosion and reworking of floodplain material was the major source of sediment during a such a catastrophic event (cf. Dee and Spey study areas with large-scale erosion of fluvioglacial deposits).

It was notable, especially from the aerial photograph analysis, how much more quickly the channel-side sediment became restabilised by vegetation after major disruption (due to the increased, finer size fraction of available sediment within the banks). Thus, recovery after such a major disruption was considerably quicker, even where there did not appear to be artificial intervention eg. on upper Bowmont Water (Chapter 7.4.1). Considering the extreme recurrence interval of both rainfall and discharge, the resulting effectiveness in terms of planform change was low. It is notable that major winter frontal events would require more rainfall to induce saturation overland flow, as the winter rainfall acceptance potential is much higher (categories 2-4 in Figure

3.2.5.(ii)) than within either the Spey or Dee study areas.

The distinction must therefore be made in all three study areas between extreme regional events (winter cyclonic and summer frontal) that affect all tributaries and more localised storms that may place a tributary geomorphically "out of step" with its neighbours (accounting for some of the variation in activity indices within the Spey sample). The difference in geomorphic activity resulting within catchments over which a storm is centred as opposed to those nearer the storm margins can be large, especially where stream power thresholds for sediment movement are high (Spey and Dee study areas). This is however also highly dependent on the strength of local catchment controls eg. sediment size and channel confinement. Thus, there are problems of generalisation with various deviations from a quasi-equilibrium form, even within neighbouring catchments. This has implications for the impact of "flood years" (which were especially common within the Spey study area), where more than one high recurrence interval event occurs in close succession, especially during July and August (see Chapter 5.5.1). The recovery of the channel may be speeded up or hindered depending on the subsequent discharge recurrence intervals, associated stream powers in relation to sediment entrainment thresholds and extent of overlapping catchment areas affected by such consecutive, high recurrence interval storm events.

Extending the timescale of the inter-arrival times of flood events to years rather than months, more moderate events may have differing effects depending on whether they supersede or precede a more extreme event. For example, extra-channel avulsion caused by extreme overbank flows on the Feshie or Avon may shift the focus of activity to a previously stable area of the floodplain and thus, new areas will be modified in subsequent lesser discharge events. Had the first events not occurred, the geomorphic effectiveness of the more moderate events would have been different. In the extreme case, channel metamorphosis may occur and subsequent events are attempting to rework a highly disrupted system, which has undergone a shift in controls eg. the Quoich confluence and upper Feshie.

The implication is therefore that neighbouring catchments may be at different distances from a quasi-equilibrium condition, depending not only on their differing responses to their individual history of extreme events but also whether these events are summer frontal or winter cyclonic (regional) or convective (more localised) ie. affecting different catchments to different extents.

In terms of maximum probable precipitation and its implications for maximum probable flood and maximum possible stream power, in none of the studied rainfall records has this value been nearly attained in either regional frontal events or localised convective events. The 1948 and 1829 summer frontal storms however attained closest values (eg. 24 hour rainfall of 6.21 inches [157.7 mm] on 12th Aug, 1948 at Floors, Kelso for the Tweed storm; the 1829 rainfall is by inference only). However, recorded values are well below the maximum envelope for Scotland and thus much lower than the maximum probable precipitation. In terms of the maximum probable flood, the areal extent of the highest precipitation is crucial as is the SMD at the time of occurrence. Theoretically, if the high rainfall intensities associated with a summer frontal storm could be maintained during a low frequency winter cyclonic event then greater flooding would occur in winter due to low winter rainfall acceptance potentials. This occurred to a certain extent within the pre-1900 discharge record in Speyside, where discharges were locally comparable or in excess of the 1829 event on the upper river. Thus, extreme discharges are much more likely to be generated by convective events in much smaller catchments, eg. on the Slitrig within the Tweed study area, or by intense regional rainfall centred over larger drainage basins.

Within high energy environments, such as mountain torrents, unit stream powers associated with extreme events can be in excess of 3000 W m^{-2} at selected sites, such as the upper Luibeg and upper fan apexes within the Dee study area. Within lower energy environments (eg. the Tweed study area), the magnitude of stream power reduced over 10 fold. The heterogeneous nature of the bed at many of the more active study reaches (especially within the Dee and Spey study reaches) implies that a range of flows must be important for transporting different clast sizes. At sites with a dominance of large bed elements, such extreme events are highly important as effective landforming agents. Bankfull discharge can therefore be misleading in frequency terms. Within upper Deeside, this frequency may be well over 50 years at some sites while within the Tweed study reaches, bankfull stage can be expected more often, associated with lower specific runoff rates and stream powers. An extreme event may frequently initiate or reactivate a channel, leaving no indication of its earlier form and thus the hydraulic geometry relates predominantly to this high RI event. This form however may be later retrograded depending on the magnitude and frequency of subsequent events and the size distribution of the bed material. In fact, in terms of channel form, channels with lower W:d ratios were found to have higher unit stream powers, especially within the Tweed study reaches.

However, many sites in all three areas, with more moderate unit stream powers at bankfull and above, were able to transport a large percentage of available bed material and thus planform change could take place both as disruption through an external stress but also through the progressive build up and crossing of internal thresholds, as channels became plugged up with sediment.

9.3 The impact of landuse change

While climatic fluctuation and to a lesser extent random magnitude/frequency variation cause a regional alteration in controls governing climatic input, landuse changes are more catchment specific and thus there are problems of generalisation within each study area. The major landuse change within both the Dee and Spey study areas, over this 250 year timespan, has been widespread deforestation. Major deforestation due to commercial forestry occurred within the Quoich and Lui catchments within the Dee study area before 1850, and therefore even the 1829 event would have been applying stresses to slopes that were previously more stable. However, there was no total catchment deforestation (ie. not comparable to the landuse changes experimented within catchments such as Plynlimon); a large proportion of the total catchment areas had already undergone bioclimatic treeline lowering over a much longer timescale.

There is no doubt that in specific runoff rate terms (estimated 1.4 m^3 s^{-1} km^2 at Polhollick), the 1829 event would have been catastrophic independent of landuse. However, the probably increased rates of saturation overland flow may have quickened hydrograph response to the increased incidence of more moderate rainfall events pre-1900. Post-1900 deforestation has generally been small scale in terms of catchment area. Apart from intensive felling during the World Wars, which may have caused minor changes in inputs, the overall effects are considered comparatively small.

More important is the impact of landuse change on sediment mobility, due to increased sediment accessibility after slopes are cleared. Had a 1829 event occurred in the early 18th century, when the middle to lower slopes were much more extensively forested, the impact may have been less disruptive, in terms of sediment available for transport. It must be remembered that a catchment's lagged response to such deforestation may take decades to work through the system. It is therefore also possible that the increased braiding pre-1900 was due to the increased sediment inputs to the channel at that time, as a result of an earlier destabilisation of fluvioglacial deposits.

Within Speyside, extensive man-induced landuse changes had also occurred pre-1800, especially within the Nethy and Druie catchments. There are problems however of generalisation within the study area, as the Avon catchment had undergone much earlier depletion of pine forests within the 17th century and thus the lower slopes may have had a longer period to attain a more stable condition. It is also difficult to assess whether major slope failures would have directly contributed to the channel. Again the Aug, 1829 event was acting on a system that was less stable than had the same event taken place 150 years earlier when, especially within the Feshie catchment, the lower slopes were still largely forested. There was however a difference in catchment response; the Avon was typified by restricted reworking of floodplain areas associated with periodic channel avulsions or low amplitude chute cutoffs, in comparison to the extensive braiding of the wandering Feshie.

In sediment mobility terms, more important than the actual deforestation of the catchment, which in percentage terms was small, were periods associated with the removal of trees from the floodplain and channel banks. Such removal could be either naturally through flood destruction or through commercial felling. Destabilisation of the floodplain, eg. on the Nethy and Feshie, must have made the floodplain more erodible, particularly where banks had a small upper unit overlying incohesive large clasts. The Feshie especially, within the braided reaches, tended towards progressively increased braiding index and active area since 1829 and along certain reaches seemed to have had a shift in equilibrium conditions.

It should be noted that both extensive bioclimatic tree-line reduction during the Holocene and man-induced change pre-1750 had already caused a much larger reduction in the forested catchment area. Thus, changes in runoff regime are perhaps smaller over the studied 250 year period, in comparison to a possible lagged response to changes which occurred much earlier.

The Tweed study area has a rather different landuse history, with a deforested landscape existing over a much longer timespan (since the 12th and 13th centuries), though there may have been increased runoff rates and inputs of sediment at that time. Again, the Aug, 1948 event was so extreme in 24 hour rainfall terms that a major discharge event would have occurred independent of landuse. The major summer flood of August, 1294 occurred when much of the area was still wooded. This again indicates that with extreme specific runoff rates, vegetation cover becomes of diminishing importance. Within the 250 year period studied, the major impact was drainage ditching due both to localised afforestation and extensive agricultural improvement. In comparison to Acreman's (1985) study on the neighbouring Ettrick catchment, the percentage of the catchment area undergoing afforestation was small and thus its implications for increased surface runoff were probably not significant. However, increased agricultural drainage post-1860 coincided with the pre-1900 increase in rainfall POT and is likely to have exacerbated the impact of the climatic fluctuation. Unfortunately, the percentage areas of catchment affected are not known.

The second major man-induced alteration within all three study areas was due to modification of channel planform and cross-sectional geometry of the channels. Disparities between sites, where similar patterns of response might have been expected, were frequently related to man's intervention eg. the relative stability of the Tromie confluence (Spey study area). Again, there was considerable variation between study areas and catchments within each study area. Within the Dee study area, man's impact was most limited and generally localised within the lower reaches of the tributaries. Mill lades were destroyed during the 1829 event and thus after this period, the channels were also readapting to increased flow and greater stream power within a single channel, such as occurred above the Quoich and Gelder confluences. This may also have enhanced the geomorphic impact of the subsequent increased frequency of moderate to extreme runoff events in the 1870s and 1880s.

Sawmilling, with associated lades, occurred to a much greater extent within the middle to lower reaches of the Spey tributaries. The Nethy was particularly prone to channel straightening thus explaining the changes in sinuosity found between editions. Major changes involving reduction of anabranching had however occurred before the 1850s.

Only within the uppermost reaches of the Tweed tributaries can reaches be described as natural. Periodic straightening, realigning, training and removal of sediment, in response to both commercial needs and flood-induced planform and floodplain disruption, occurred throughout all the catchments eg. on the middle Leader. It was difficult to evaluate the complex upstream and downstream effects that must send changes throughout the system. Clearly unit stream powers within the natural channel must be reduced during flood flows, due to division of flow through lades. This may partially explain the reduction in activity along the middle reaches of the Teviot in comparison to those in the past indicated by palaeochannels. It may also account for periodic sediment stores associated with reaches of lower competence.

9.4 The relative importance of the three changes in controls

In none of the three study areas can the effects of either climatic or landuse change on controls be completely separated. The increased ditching (greatest on the Tweed post-1860) and the lagged response of the system to deforestation (Dee/Spey) were coincident with the climatic fluctuation involving increased rainfall/ discharge POT and thus it is difficult to separate their relative effects. However, the Deeside catchments (eg. Gelder and Ey) that underwent least deforestation still possessed increased channel activity over that period but not to the same extent as those which underwent much larger scale forest depletion (within the Spey study area). Similarly, the Tromie catchment underwent increased activity pre-1900 despite considerably less deforestation. This would favour the importance of climatic inputs, but it is known that a major random high frequency event occurred in 1881 and thus change can not be attributed entirely to climatic fluctuation. In contrast, the post-1860 ditching within the Tweed catchment was highly important in speeding rates of catchment runoff and time to peak of the unit hydrograph. Reports suggest (Chapter 6; Appendix 1.8.1) that this increased both the effects of the pre-1900 climatic fluctuation and of subsequent random high magnitude/ low frequency events.

Similarly complex is the inter-relationship between climatic inputs. The inter-arrival times of both climatic fluctuations and random high magnitude events is very important. For example, within Deeside, the 1829 flood with its legacy of much greater sediment within the channel provided the subsequent increase in more moderate flows with additional material to rework. The Spey in contrast had both extreme high RI winter storms and increased events of more moderate frequency post-1829, and their relative impact is difficult to separate.

9.5 <u>Timescale of inquiry</u>

In studying process/ response within each of these three study areas, the timescale of enquiry is clearly very important. In paraglacial terms, all three areas are still undergoing a response over cyclic and graded timescales to their differing glacial legacies. For example, bedrock controls at varying scales provide an inherent stability over a graded timescale. Furthermore, constraints on width imposed by terraces of different levels and erodibility and fluvioglacial deposits are also very important planform controls over graded timescales. Present channel responses may be thus strongly influenced by both site specific and upstream characteristics, which exert controls over much longer periods. For example meltwater gorges have implications for the flushing of large amounts of sediment downstream although their actual planform is highly stable.

It can therefore be misleading to study channel planform totally within a steady timescale, as planform is a response to the work done by the interlocking series of various magnitudes and frequencies of discharge. Frequently process rates do not merely represent a direct response to immediate planform controls, due to the frequent transitory nature of the system. Similarly, it is wrong to classify a reach within a typology which does not possess a temporal dimension. Numerous examples can be cited, especially from the Dee and Spey study areas, where the legacy of process-response over a much longer period, in excess of 250 years, is important in assessing planform adjustment over a 10-30 year period eg. the Quoich confluence or the Dye fan. The occurrence of a random high magnitude event may show completely different modes of process-response with a much greater utilisation of available active area. Similarly, study over a shorter timespan may only reveal a fraction of the range of channel behaviour and possible stream powers.

In contrast with glacial controls, change in both climatic and landuse controls may initiate responses to an alteration in equilibrium condition that are effective over years,decades and possibly centuries, depending on the scale of the shock to the system and the magnitude of the thresholds exceeded. Where planform constraints enforced over cyclic and graded timescales are spatially relaxed, the impact of climatic fluctuation, landuse change and random magnitude/frequency variations are greatest. Different reaches may thus be responding principally to controls acting over very different timeperiods, thus explaining some of the spatial variation in channel form.

Finally, it should be asked whether with this knowledge of past and present process rates, it is possible to predict the likelihood of future change. Past rates of change have been highly variable and prediction must rely on the known range of planform response over that longer timespan. This is hindered by the fact that channel pattern may be totally disrupted over a 24 hour period. Within the early 1980s, there have been increased sequences of rainfall POT (see Braemar record) similar to those of the 1870s and 1880s. It is possible that another period of increased activity may be occurring, with associated increase in channel widths and available unstabilised sediment. It is however too early to judge. In terms of the estimated impact of a random high magnitude event, the discharge stages which could lead to the reoccupation of former channels may be estimated. However, establishing the likelihood of that stage occurring is much more difficult. Knowledge of channel response to rare events through application of the ergodic hypothesis is limited as the spatial variation in planform response to such an extreme stress is high. Temporal variations in response to a 500 year event within an individual catchment may also be great and as such our sample is too small to predict.

CHAPTER 10

Conclusions

Returning to the six questions posed in chapter 1, the following conclusions can be drawn. In terms of the spatial range of channel planform types (Question 1), there clearly was a large range of channel forms within all three study areas, with the middle of the range (sinuous to irregularly meandering channel pattern) encompassing the largest % of the sample. Individual study areas however had different frequencies throughout the range of channel pattern types. For example, wandering planforms were particularly typical of the Spey study area whereas large confined meanders were more frequently found within the Tweed study area. While highest sinuosities were attained within the Tweed study area, highest braiding index values were found in the Spey and Dee study areas. The dominant controls were glacial legacy, sediment availability, channel confinement and the positioning of local baselevels. The rates of planform change (Question 2) recorded at the most active sites within the three study areas are comparable with the highest documented values in the U.K. (see Table 2.4.(ii)), but other sites were relatively stable and display minimal planform change. The relative proportions within these two large categories varied between the three study areas, with the Dee and Spey study areas generally possessing higher maximum rates of change compared with the Tweed. In terms of modes of planform adjustment, more sinuous channels tended to have chute rather than neck cutoffs whereas less sinuous channels adjusted through avulsion.

The planform response is now considered in relation to runoff events of varying magnitude and frequency (Question 3). Within a global context, the channel planforms within the three study areas exhibited a small range in their response to changes in controls. However, these controls were highly varied both spatially and temporally. Thus, a site's response to discharges of varying magnitude and frequency depended upon the precise nature of these controlling factors, the site's position in terms of process thresholds and whether it was in a quasi-equilibrium condition. The size of the threshold, which must be exceeded for change to occur, was also highly variable.

Within individual study areas, generalisation is difficult when assessing the circumstances that allowed rare floods to be geomorphically significant (Question 4). Nevertheless, certain overall trends can be identified. An extreme event of high RI (> 100 years) will have a major initially disruptive impact providing that room is available for expansion of the active area and that the thresholds for such inundation are not too high. Competence thresholds must thus be exceeded by the associated stream powers. It is also important that neither internal nor external thresholds for channel disruption have recently been exceeded as there may be a time-lag before incipient threshold conditions can be attained again. However, modes of planform expansion in response to such geomorphic stresses are highly dependent on the type of channel planform involved and the specific controls operating at the site. Moderate discharges (10-50 years) will be more important in returning the channel to a quasi-equilibrium form than disrupting it. However, this is not always the case and this is very much dependent on the size distribution of the bed material. Thus, in reaches with medium sized clasts and high bankfull stream powers, internal thresholds for a channel switch may be exceeded by one or more moderate events, as well as in response to more extreme floods.

In terms of evidence indicative of change in the magnitude, frequency or duration of rainfall and runoff over the last 250 years (Question 5), certain features should be noted. Climatic fluctuations, involving increased or decreased frequency of extreme rainfall and runoff, have affected all three study areas. The most notable of these was the increase in rainfall POT in the 1870s and 1880s and periods of low POT frequency eg. in the 1960s and 1970s. The former period affected all three study areas and was generally associated with increased channel activity although the extent of this varied with sediment availability and room for channel expansion. Hence, planform adjustment was more marked within the Spey and Dee study areas than within the Tweed. In extreme contrast, the period between 1948 and 1956 was remarkable in that three high magnitude floods occurred within the Tweed study area. Although several sites underwent channel disruption, the response was less dramatic in terms of planform change than had similar conditions occurred within the Spey or Dee study areas.

Landuse changes affecting both speed of runoff and sediment supply (Question 6) affected all three study areas but to varying extents and over differing timeperiods. The Dee and Spey had both undergone extensive deforestation pre-1850 but subsequent changes were more limited. Lagged effects are considered more important in terms of differential sediment mobilisation on lower slopes and floodplains rather than deforestation causing major changes in runoff rates. In contrast, within the Tweed study area, artificial drainage was more important post-1845 and there is evidence to support the assertion of a more flashy runoff response over the past 150 years. Actual channel adjustments were also important but in varying degrees. While within the Dee study area the reaches affected were more isolated, within the Tweed basin large reaches were affected. The concept of a totally natural channel was thus hard to define, even within these upland areas.

It is also clear that it is not possible to give a detailed account of magnitude frequency relationships at a site without a reconstruction of its flood history and the associated channel's response. Whilst a map-based typology can only give a partial picture of a channel's response to a particular flood history, it nevertheless provides an essential framework for the interpretation of higher resolution data. These data involve such crucial variables as slope, sediment size, W:d ratio and bank composition; all of which require field survey. Such data may only relate to the present channel form; map-based studies provide the essential historic dimension.

In terms of explanation, the method of multiple working hypotheses provides a stepping stone for further studies on the rates and modes of planform response. It must be appreciated however that there are limits to this type of enquiry as history can never be completely reconstructed. Thus, without controlled catchment inputs and outputs, it is difficult to identify conclusively the hydrologic impact of historic deforestation. The spatial extrapolation of results from gauged catchment studies is also problematic. Nevertheless, there is no other method which can provide greater insight into the rates of planform change and the spatial and temporal variations in controlling factors over a 250 year timespan. More sophisticated dating of planform change at individual sites in the field, eg. through lichenometry or dendrochronology, may give greater detail on the periodicity of planform response. However, the variation in response even among reaches with similar positions within neighbouring catchments can be large and the extrapolation of such results must proceed with caution.

There are several important avenues for further research. In terms of sampling the population of stream channels at a macro-scale, the spatial and temporal variation of reaches within a single drainage basin must be studied. This would involve the analysis of the total population of river channel segments within a catchment unit, as opposed to a random sample. Only then can the inter-relationships between reaches with different planforms at different locations be studied, and the modes of sediment transfer and storage be further illuminated.

At a meso-scale, the runoff regime can be more reliably analysed in terms of its magnitude and frequency as the length of the gauged record increases. Better estimates of the temporal and spatial variation in the recurrence intervals of both moderate and extreme events may be gained through the fitting of more sophisticated distribution functions (Acreman, 1985). The presence or absence of planform response to a known stress can then be studied in more detail, possibly resulting in better predictions of likely modes of adjustment. It is unfortunate that neither of the high RI (200-500 year) regional storms were directly gauged and thus extreme runoff rates can only be estimated. Limits to maximum possible stream powers can thus only be approximations. It is also essential to compare the sediment transport during such events with the accumulated work of floods of much more moderate RI, over much longer timescales.

The possibility of rainfall/ runoff reconstruction and modelling within the three study areas, using either the Thom and Ledger (1977) approach or the Jones (1983)/ Wright (1978) CWPU model, should be considered. This would allow a detailed assessment of any changes in the runoff regime over time. In order that such work be undertaken, further data such as mean monthly evaporation and soil moisture levels would have to be collected and a snowmelt term would have to be incorporated for upland Scotland. However, this would only give a reconstructed flow history corresponding to relatively constant catchment controls over the calibration period. There would be no record of the hydrological impact of landuse changes. Disparities between the model's results and those from the qualitatively reconstructed discharge record developed in this study could be noted in an attempt to validate the model.

In terms of further analysis at the micro-scale, more data on the temporal variations in stream power for different planform types and activity rates is required. This would involve measuring stream power at a range of flows rather than just at bankfull stage, which in upland Scotland was found to have a highly variable frequency. Both the magnitude and frequency of competent flows must be studied at a range of sites. Regrettably, the currently available data sets are highly restricted since gauging stations are generally located on stable, straight reaches. More detailed work on the rates and modes of bank retreat in response to discharges of varying frequency and stream power would also be useful as very little work on this topic has been undertaken in Scotland.

Finally, this dissertation demonstrates the valuable contribution that can be made by the geographically-trained geomorphologist in studying rates of change in fluvial landforms. It is only by this wide-based and integrated approach that the analysis of present-day processes can begin to be integrated into the broader study of the long term evolution of fluvially-based landforms. By concentrating on the development of landforms over centuries rather than years and by integrating information from a great variety of sources, the work of other earth scientists and civil engineers can be placed in their proper geomorphic perspective.

APPENDIX 1

Additional information about the flood histories within the three study areas

The following abbreviations have been used to indicate the information sources within the subsequent flood history chronologies.

BR	British Rainfall
MM	Symon's Meteorological Magazine, later Meteorological Magazine
SA	Statistical Account for Scotland (Sinclair, 1791-1799)
EP	Estate plan
OS	Old Spalding (cited Lauder, 1830)
Sfld.	Seafield estate papers
Lauder	Lauder (1830)
Michie	Michie (1901)
Watt	Watt (1917)
Rob.	Roberts (1919)
Brem.	Bremner (1922)
Edgar	Edgar (1913)
Reid	Reid (1882)
Max.	Maxwell (1909)
Pring.	Pringle (1914)
Brown	Brown (1866)
Nairne	Nairne (1895)
Hald.	Haldane (1973)
Paul	Paul (1881)

Oliver	Oliver (1887)
B & G	Brooks and Glasspoole (1928)
Scalac.	Scalacronica of Sir Thomas Gray (translated by Maxwell, 1907)
Short	Short (1749)
Britt.	Britton (1937)
Chron.	Chronicle of Lauercost (1272-1346) (translated by Maxwell (1913))
Doug.	Gawain Douglas (15th century Scottish poet)
HI	Hammond Innes (photographer, Kelso)
McCL.	McClean
B & L	Baird and Lewis (1957)
Green	Green (1958; 1971)
Werr.	Werritty (1984)
Learm.	Learmonth (1950)
G & D	Glasspoole and Douglas (1949)
Common	Common (1954; 1958)
McEwen	McEwen (1981)
Hudson	Hudson (1978)
Whyte	Whyte (1980)
Haw. Ex	Hawick Express
Haw. Ad	Hawick Advertiser
Scots.	Scotsman newspaper
KM	Kelso Mail
NE	Northern Echo
Elg. C	Elgin Courant
Inv. C	Inverness Courier
Strath.	Strathspey and Badenoch Herald

ABE	_Aberdeen Evening Gazette_
HBNC	_History of Berwickshire Naturalists Club_
THAS	_Transactions of Hawick Archeological Society_
RCHRB	_Reports of the Commissioners for Highland Roads and Bridges_ (1802-1856)
FSR	_Flood Studies Report_ (NERC, 1975)
TRPB	Incidence of flooding according to Tweed River Purification Board.
BP	Series of flood plaques on Balmoral Castle lawn
ASB	Series of flood marks on Abbey St Bathans church steps
**	Indicates a flood event documented in detail in Chapter 5.
!!	Event which can be traced back to Short (1749) but which has no earlier confirmation
BB	Inscription on Ballater Bridge
SDD	Reported in Appendix of the _Speyside Drainage Report_ (1952-1958)
[TS	Thunderstorm]

Note on units used in Appendix 1

Where values are given in imperial units within the original source, this has been retained within Appendix 1. The conversion factors are as follows:

1 in = 25.4 mm

1 ft = 0.305 m

Methods of referencing dates (after Potter, 1978)

It should be noted that before the change from the Gregorian to Julian Calendar, years did not necessarily begin on the 1st of January.

Eg. from 1153 to 1750, the year began on 25th March and therefore 24th March, 1657 was followed by 25th March, 1658.

APPENDIX 1.1

Documented flood events within the Dee catchment

Date	Information	Source
2/2/1642	"On the 2d of February, 1642 at midnight, there arose an extraordinary high wind in Aberdeen, with fire-flaught and rain. The rivers Dee and Ythan, through high flood, overflowed their wonted limits, both in this month and January. Dee surpassed in speat the Key-head, and Ythan grew so great that it drowned out the fires in some men's houses in Ellen and Newburgh, far beyond the wonted course." (Lauder, 1830 p298)	OS Lauder
9/1768	Affected Deeside, especially the Invercauld Estate. The 1829 flood exceeded this by 2 ft near Kiloch	Lauder
8/1782	"Monaltrie wrote....of misfortune of the [first] bridge [Ballater]; luckily no damage was done to the stone work and I am hopeful of a great deal of the timber will be recovered". (Michie, 1901 p190) Letter to Mr Gordon to Charles Farquharson (24/8/1782). The accident was caused by a spate in the river which carried away most of the service work.	Michie
30/8/1799	Destroyed Ballater Bridge- inscription "A bridge of stone was built about 100 yds east of site in 1783 & was swept away by the flood of 1799" "an uncommon flood"	BB RCHRB Hald.
1814-1816	Repairs to Ballater Bridge- 20 pounds expended annually. "Foundation of piers have been somewhat injured by the rapidity and occasional violence of the river floods". (RCHRB, 8th report p28)	RCHRB
4/8/1829	** Most major flood event on record "For some time previous, there had been more than a common downfall of rain and in especially the day before, the rain had been pouring down in one incessant torrent; but the rise of the river was nothing to speak of. Up among the glens too, there had been heard rumblings of many fierce thunderclaps.. quick rise of the river....the river continued to rise higher and higher still; greater lots of trees, bushes and other wood began to gather about the arches of the bridge [Ballater]....blocking up the watercourse". (Brown, 1866 p52)	Lauder Nairne Brown
16/2/1865	"In the Dee, the breakup of the ice is said to have been a grand spectacle, but no material damage has been done along the banks of the river."	BR1865

Date	Information	Source
?/3/1866	Ballater- "during the last week, the weather became much milder and the snow melting on the hills caused the streams in the neighbourhood to be much flooded."	MM1866
31/1/1868	Dee down in spate on 1st Feb, 6 feet above the average depth, probably heavy rain in the hilly country on 31st, Jan.	MM1868
?/10/1869	Aberdeen- a month of extra-ordinary weather; not so severe a storm in October for many years. From 16th to end of month, the weather was terribly severe. Great floods on the 16th.	MM1869
1/2/1872	Stormy in Scotland with heavy rain. Flooding on the Dee.	BR1865 BP
26/2/1872	The rains ceased in Aberdeenshire early on 25th. Rivers flowing eastward were greatly swollen, but the Dee owing to its rapid course did not overflow its banks to an alarming extent, though its tributaries did much mischief. In Aberdeenshire, land was thoroughly saturated by the super abundance of rain falling during the last fortnight.	Scots.
25/10/1872	More than 2.00 in of rain fell on the 25th & streams were much flooded.	MM1872
28/12/1872	Flooding on the Dee. "Heavy rainfall previous week remarkable. The floods reached their height on 28th but now (30th) have fallen greatly." (Scotsman, 12/1872)	BP Scots.
15/9/1873	On 15th, there were unusually heavy floods in the Dee and Don, which were said to have been the highest since 1829. At Bridge of Dee, Aberdeen the water marked 10 feet on the piers and reached the spring of the arches. Large quantities of corn swept from the haughs.	BR1873
7/11/1873	** heavy floods in Aberdeenshire, especially in smaller streams near the coast. Fall of 2.73 inches of rain on previous day (Aberdeen) and snow on the hills.	MM1873
12-13/8/1874	Floods near Braemar. Thunder on 12th and flooded rivers on the 13th from a fall of 2.67 in.	MM1874
1877	"phenomenal flood on Dee"	Rob.
1881	"phenomenal flood on Dee"	Rob.
11/8/1884	** Waterspout at Braemar. Linn of Dee mentioned	MM1884
12/8/1885	** A rainfall of unprecedented severity. Dee has not been so swollen for many years. Quoich and Milton Burn affected.	BR1885

Date	Information	Source
8/6/1893	"Braemar had 0.82 in in half an hour and considerable flooding thereby."	BR1893
2/8/1894	Several bridges carried away in Aberdeenshire, the Dee at Cults bridge rose 12 ft above its usual level. Most violent TS experienced for many years. Dun Echt observatory (Midmar) had a fall of 2.79 inches.	BR1894 Scots.
27/10/1903	"Aberdeen (Cranford)- low lying grounds both on the Dee and Don were covered with water 12-14 ft deep and cornsheaves were washed out to sea."	BR1902
18/12/1911	Flooding on the upper Dee. Rain continued to fall almost incessantly yesterday and rivers Dee and Don are again in full flood.	BP Scots.
7-10/5/ 1913	** Great floods on the lower reaches of Don and Dee	BR1913 McCl.
2/12/1914	** Upper Dee in flood	BP Brem.
?/5/1915	Dee in flood	MM1915
28/10/1915	At Crathes, 5.14 inches fell in 42 hours. River Dee in high flood but not so high by several feet as it as it was in May, 1915	MM1915
10/10/1920	** Dee in flood; falls of 4" or more occurred along River Dee from Braemar to Drum. Height at Bridge of Dee (Aberdeen) said to have been 2 ft above that in famous floods of 1829. At Danzig Bridge- 1 ft lower than in December, 1914. On Balmoral Castle lawn, the flood mark of 10/1920 fall short of 2/12/1914 by 6 ft 7 in on the slope or 7 ft 25 in on the perpendicular. "The floods have wrought enormous havoc on Deeside and Donside- indeed, all over north of Scotland. In certain districts, the older floodmarks have scarcely been touched and on lower Deeside, the submerged area was probably more extensive in 1913, but all the reports seem to indicate that the damage done in Aberdeenshire was greater than it has been on any former occasion in living memory. Indeed it is doubtful whether at any time since the big spate of 1829, the destruction has been so extensive as during the past few days.... the floods could scarcely have come at a less opportune moment as many thousands sheaves of grain have been swept out to sea as well as ricks of hay and straw. Hundreds of acres on Deeside and Donside have been inundated ...... But serious though the rainstorm has been, the great Morays flood of 1829 were more extensive as well as more disastrous. They are still the high water mark of Scottish deluges." (British Rainfall 1920)	BP Brem. BR1920 AEG

Date	Information	Source
21/1/1928	Dee in flood	BP
24/12/1937	** Largest flow on Woodend record. "Following a day of torrential rain, the Dee at Ballater reached an alarming height. The water was higher than the piers at Ballater Bridge, streets and roads and Ballater golf course were all under water. The river was still rising last night with no signs of an improvement." (Scotsman, 12/1937)	BP Scots.
25/6/1951	Aberdeen- "among places where storms and flooding occurred during the 1st and 2nd weeks of month."	BR1951
6/11/1951	Largest flow at Woodend since 1937. Worst rain and wind storm in central Aberdeenshire for many years. Both the Dee and Don overflowed at many points and hundreds of acres of farm land are under water.	Scots.
28-30/7/ 1956	Storm centred on the Inverness-Nairn-Forres region At Derry Lodge, 1.75 in of rain in 24 hours was recorded and the Derry Burn rose high enough to carry away the footbridge 1.5 miles north of Derry Lodge.	B & L
13/8/1956	Isolated event within the upper Lui catchment	B & L

---------------------gauged records commence--------------------------

APPENDIX 1.1.1

Extracted from Barrow et al. (1913) p108.

"During the great flood of 1829 some remarkable accumulations of alluvial origin were formed and have become permanent features in the landscape. The most striking of these is seen where the Luibeg debouches on to the level ground of what was formerly a small lake; in the flood of 1829 this burn, swollen to vast proportions, cut into and carried with it a mass of moraine from its upper reaches and spread the detritus out upon the level ground where the burn turns eastward. The material brought down consists of granite, sand and large blocks of granite which blocked the normal channel of the stream and caused it to change its course. This mass of sand and blocks, about a quarter of a mile in length, reaches a breadth of 150 yards at its broadest part: it remains as a striking evidence of the transporting power of these highland streams during times of sudden flood."

APPENDIX 1.2

Documented flood history within the Clunie Water catchment

Date	Information	Source
4/8/1829	Clunie not swollen to any extraordinary degree	Lauder
?/2/1865	In Glen Clunie, the waters of the Clunie have made considerable havoc, the broken ice sweeping away several bridges.	BR1865
2/8/1894	Clunie believed to be higher than for 15 years	BR1894
4/10/1920	"The Cluny ... was in very high spate, and the rainfall in the upper part of its basin must have been extra-ordinarily heavy. At its highest, the stream rose to the spring arch of the bridge at Braemar, and was probably higher than it had ever been before. Between Braemar and Ballater, the rise in the mainstream Dee to all observers was chiefly due to the great volume of water contributed by the Cluny. (Bremner, 1922 p31)	Brem.

APPENDIX 1.3

Documented flood history within the Spey study area

Date	Information	Source
9/1768	Flooding on the Spey	SA Lauder SDD
10/1771	Flooding on the Spey	sfld.
28/7/1779	Flooding on Burn of Dalvey. "Dalvey of Sheradvie much hurt is done by a speat in the burns on yesterday....8 days the road at Dalvey was quite impassible with carriage or cart. The burn of Dalvey has thrown down much earth on the west side and dug pits in the road 7 or 8 feet deep. The Burn of Dalvey Dalvey has destroyed much of the corn on the haugh.....terrible claps of thunder and greatest falls of rain. Repairs to the road to the north of Lady Ballindalloch's house, where the burn had cut a gutter of 60 yds wide, carried off all the earth and left a beach of great stones, many needed 12 men to remove them." (Letter from James McGregor to Sir James Grant) (GD/248/56/4)	sfld.
1783	Flooding on Spey	Lauder SDD
30/8/1799	Flooding on the Spey	Lauder SDD RRB
13/5/1808	Spey flood	sfld.
5/5/1815	Flooding on the Dulnain	sfld.
1827	"Seldom a year passed without reports of floods and damage to roads and bridges...the Spey appears determined not to let you rest." (Hope to Telford) [written two years before the major flood of 1829] (Haldane, 1973 p174)	Hald.
29/6/1828	Flooding on the Spey	sfld.
4/8/1829	** Major flooding on the Spey "Since the great storms of 1799 and 1812, no similar visitation has happened in this quarter that could at all be compared with the deluge of the 4th August, 1829". (<u>Scotsman</u>, 8/1829)	sfld. Lauder Scots. Paul
13/8/1829	Flooding on the Spey	sfld.
18/8/1829	Flooding on the Spey	sfld.
9/12/1829	Flooding on the Spey	sfld.

Date	Information	Source
8/7/1830	Cullen House: "Flooding here was considerably greater yesterday than the memorable one of August last year and has done more damage. (GD/248/1564)	sfld.
22/5/1831	** Flooding on the Spey	sfld.
5/8/1846	Inverness district- visited by most terrific TS experienced for at least half a century. From 7am to 4pm- thunder. Rain mixed with hail occasionally fell very heavily but the quantity was only 0.85 inches. Damage was considerable in this unprecedented storm, arising almost wholly from torrents of rain that fell. In Strath-Spey, several fields were flooded and tracts of arable land swept away. Several bridges in the neighbourhood of Grantown were destroyed.	Scots. Inv.C.
24-26/12 1849	Great floods in the early spring of 1849 raised the Spey to a level 18-24 inches higher than it had been during the Moray floods, 20 years earlier (Mitchell to Smith 7/2/1849). Widespread damage done to roads and bridges throughout the highlands. "Writing from Belleville and Kinrara, correspondants of the Elgin Courant stated that this flood exceeded that of 1829 as regards the height of the river Spey; but if that really was the case, there certainly was not the faintest comparison between the damage done by the two floods. The river broke its banks at several places, submerged lands and houses, and seems to have attained a volume described as "sublime and terrific," but the chroniclers of the occurrence write briefly, and have little to say about serious loss of property or danger to life. At Belleville, where the flooding of the Spey always makes itself felt, the water stood between six and seven feet on the road-way; Lynehalt village was flooded to a depth of 18 inches; embankments were carried away between Loch Insch and the Tromie, and elsewhere.... At Kinrara, the Spey was on Thursday considered to have reached 18 inches higher than the memorable flood of 1829. The farmhouse and square of Kinrara were inundated to the height of four feet, and the farm of South Kinrara sustained great damage by scouring, while the Doune of Rothiemurchus was inundated to the extent of three feet. 'When the flood was at its height,' says one report,'the whole of the farms of Dalnavert, South and North Kinrara, and the low parks about the Doune had the appearance of one vast lake; but the damage, on the whole was not as great as might have been expected, and no loss of life or cattle occurred.'" (Nairne, 1895 pp 65-66.)	Hald. Nairne

Date	Information	Source
19-21/11 1864	"One of the most severe hurricanes that has visited this part for many years. Rain began to fall on 19th about 4 o'clock with a strong wind from the north-ward; as the afternoon advanced, a strong breeze became a hurricane with an incessant torrent of rain. This continued without intermission all night with the exception of a fair hour on 20th morning, the storm has continued to the present moment. The rivers in higher flood than they have been since 1829. The Spey, the Findhorn the Lossie and smaller streams are roaring from bank to brae and in many instances are over their banks and flood the haugh lands along their courses. Much damage has been done....." (Elgin Courant, 11/1864)	Elg.C. BR1864
?/2/1865	The Spey is in full flood and is a most magnificent sight.	BR1865
30/1-1/2 1868	** Heavy flooding on the Spey Heavy rain preceded by a stiff breeze from west which melted the snow on the Cairngorm range. "At Grantown the Spey rose to within 2 ft of the 1849 flood. The quantity of rain which fell in the lower grounds was 2.02 in. in 30 hours and the fall must have been greater on the neighbouring mountains where there was also snow to melt and add to the fury of the torrent. On Friday morning [31/1/1868] the noise made by stones and debris tumbling down the water courses of the streams on the Cairngorm range resembled distant thunder.... On Saturday [1/2/1868] the waters at Grantown reached within 3 ft [0.9 m] of the 1829 flood, at other places it attained to within 2 ft of that historic work." (Nairne, 1895 p83; see also Appendix 1.3.2)	MM1868 B & G
30/1/1892	During first days of Jan, weather had been extremely boisterous...throughout the north, with frost and intermittent snow showers. Storm culminated on the 7th and 8th with fall of alarming magnitude. Around Kingussie, 3 feet of solid snow where no drifting. Absence of contributary rainfall. "The flood overtook Strathspey with impressive suddeness and the rising of the river was phenomenally rapid being calculated in some localities at the rate of a foot per hour." (Nairne, 1895 p156) From Laggan to Doune of Rothiemurchus the country was submerged, with fields, houses and roads covered. The river embankment on the Belleville estate was overtopped by the flood and two large breaches were made in it.	Nairne B & G
5/2/1894	At Kingussie, it was reported that the Spey was even higher than in the Moray floods of 1829.	BR1894

Date	Information	Source
14/8/1894	Kingussie- Rain began at 9 pm and heavy at 4 am great floods.	BR1894
18/3/1906	Kingussie- highest flood in the Spey for 30 years.	BR1906
19/10/1906	Extra-ordinary heavy rainfall was experienced in NE of Scotland, especially in the upper valleys of the Spey and Findhorn. The precipitation took the form of snow on the higher hills, but even so the rivers were rapidly raised to high flood.	BR1906
11/9/1908	"The Spey is a wild waste of waters and it rose from 9 inches to a foot/ hour. It coloured the sea for 10 miles. 3 miles from its mouth, the river burst its banks and swept through Gordon Castle grounds in a current 15 ft deep and a 1/4 mile wide. Trees were uprooted and bridges and corn sheaves swept away to the sea."	BR1908
6/1914	Flooding on the Dulnain near Carrbridge. Special measures taken to guard against subsequent rushes of flood water.	B & G BR1914
24-26/9 1915	** Great rainstorm- caused by depression centred off N.E. Scotland moving abruptly eastward. Certainly surpassed any experienced in destruction since 1829. A large portion of the precipitation found its way into the Findhorn valley and Spey was also seriously affected. The most extensive floods seem to have occurred in the lower reaches of these rivers..... further inland, severe loss was sustained at Grantown and in all parts of the district, the damage was accentuated by the violent gales which accompanied the downpour. "a wild north-easterly storm, accompanied by heavy and continuous rainfall which had fallen for upwards of 40 hours. Near Aviemore, the highland line is covered with water at several points. The Spey came down in high flood with valuable agricultural land inundated. (<u>Scotsman</u>, 9/1915)	BR1915 Scots. Watt FSR
7/7/1923	Remarkable downpour on Grampians near Carrbridge. Bridges and embankments on the highland railway were severely damaged by the torrents. "On 8th July, the most sudden and violent floods within memory in the district wrecked 4 substantially built bridges, nearly 600 yds of permanent way of high embankments disappeared into the torrent of water and a stretch of 2 miles between Aviemore and Inverness has been so damaged that traffic cannot be resumed for at least a month." (<u>Times</u>, 10/7/1923)	BR1923

Date	Information	Source
28-30/7 1956	** Flooding within the Spey catchment Heavy rain associated with an occluded front of a small depression which moved N.N.E. between 28th and 30th July. Burns draining towards Spey affected.	Green B & L
13-14/8 1956	Well in excess of 3 in on the right bank tributaries of the Spey above Aviemore in 4 days. Flood added water to rivers which had not returned to normal level since flooding in July. Affected almost similar areas.	B & L
19/22/1966	In Badenoch- Spey swollen by rain and melting snow burst its banks and flooded miles of floor from Laggan to beyond Aviemore. With 1000s of acres of the Spey valley grazings almost ruined by weekend flooding....at Aviemore cost of damage to property will not be known until the flood has completely receded.	Scots.
18/8/1970	** Heavy rain in western Cairngorms in period 16-18th August, and caused flooding and damage on the right bank tributaries of the Spey and on low lying ground adjoining the Spey itself, as at Insh *Meadows, below Kingussie.*	Green

Appendix 1.3.2

Flood on the Spey, February 1st, 1868.

(To the editor of Meteorological Magazine)

"Sir- During the latter part of January, there had been hard frost, and much snow collected on the mountains. Between 9 pm., January 30th and 9 am. 31st., 0.48 inches [12.2 mm] of rain fell; 1.00 inch [25.4 mm] followed in the next 12 hours and 0.44 in the next: so that the total in 36 hours was 1.92 inches [48.8 mm]. This rainfall was preceded by a stiff breeze from the west, which melted the snow on the Cairngorm range, and on Friday Jan 31st, the Spey came down with all the suddeness of a dam let off and with the speed of a race-horse, spreading far beyond her usual flood marks.

The embankments gave way in many places, and from Balliefurth to Boat of Garten, a distance of 6 miles, a fleet of steamers may have plied, without once entering the channel of the river. Looking west-ward from Balliefurth (where the valley of the Spey is about a mile in breadth) was all one unbroken sea, and appeared as navigable as the Firth of Forth. On Saturday, February 1st, the river rose to within 19 inches [0.48 metre] of the memorable flood of August, 1829 so graphically described by the late Sir T. D. Lauder of Fountainhall. The rainfall on that occasion (as registered by the gardener at Huntly Lodge) was however, 3.75 inches [95.3 mm] in 24 hours. Since the spate of February, 1st, we have had heavy rainfalls: 0.89 inches [22.6 mm]was registered on the morning of February 28th, and the river has several times overflowed the injured embankment. While I write, several hundred acres are under water, and fears are entertained lest the ground must remain fallow during the ensuing season.

William Duncan, Granton, Speyside.

APPENDIX 1.4

Documented history of flooding on the River Avon

Date	Information	Source
9/1768	Flood of 1829 exceeded this flood by 6 feet at Ballindalloch. 4-5 ft flood deposition of enormous stones and gravel near Tomore.	Lauder
1783	Three or four inundations between 1768 and 1829 with 1783 being the greatest flood.	Lauder
4/8/1829	Major flooding on the Avon At the Bridge of Avon, where the water-way of the arches is 105 ft, the rise of the river was 23 ft; and at the upper end of the lawn, where it first escapes from the rocks, the rise was 10 ft on a water-way of 222 ft.	Lauder
?/9/1872	Tomintoul- month extremely wet and unseasonable. Rivers are in continual state of flood and hills and fields are disfigured by the incessant rains swelling the mountain streams.	BR1872
?/9/1873	very wet and cold month. Tomintoul- the rivers in the south of Banff and in Aberdeenshire have been more highly flooded than for many years, causing great damage to farmers.	BR1873
30/1/1892	"At Ballindalloch, where the Avon rushing down from mountain fastness of Tomintoul and Glen Livet joins the Spey, meeting of the waters was grand to witness; then on swept the combined current, sweeping away trees clearing fields of valuable soil and crops". (Nairne, 1895 p160.)	Nairne
2/8/1894	Great floods on the Avon and Conglass, near Tomintoul.	BR1894

Appendix 1.5

Documented history of flooding on the River Nethy

Date	Information	Source
30/8/1799	Bridge built 1768, was destroyed by a flood in 1799 "carried off by the extraordinary and memorable flood that did such damage at that time over the northern part of the kingdom." Reports also that the Nethy was susceptible to sudden rises "by sudden thaws or falls of rain and by the gorging of ice and snow in winter". (RCHRB, 4th Report, 1809)	RCHRB
4/8/1829	Extreme flooding on the Nethy	Lauder
27/8/1829	"Appendix" flood on the Nethy	Lauder
3/7/1978	Flash flood on Dorback burn	Werr.
6/6/1980	Flash flood on Dorback burn "Cloudburst in the hills above Dorback on the 6th June turned the Dorback and Faeschelach burns into raging torrents which spilled over their banks and caused what has been described as the worst flooding since 1939. Many farm fields were inundated, some up to four feet in depth." (Strathspey and Badenoch Herald, 6/1980) Nethy swollen to 7 feet above its normal level for a spell.	Werr. Strath

Appendix 1.5.1

Extracted from Lauder (1830), pp 161-162.

"The excavations of the River Nethy, on the Iron Mill Croft, are extremely interesting to the geologist. We have here the history of the operations of the river for exactly a century. At this time, 100 years ago, the English company were pounding iron ore...in the bed of the river Nethy. .... the river in some of its floods, obliterates all traces of them or of their works, by filling up its bed with rounded masses of stone, mingled with gravel, and so, by shutting itself out of one channel, compelling its stream to seek another, considerably to the westward. But floods succeed floods; and the quieter portions of each successive inundation, spread over the ground, where by degrees, they deposit a rich and fertile soil, forming a rich haugh of land, the surface of which is 6 or 8 feet above the level of the ground the works stood on....when comes the flood of 3rd and 4th of August last, tears off the shroud that covered it, and brings all back again to light...The river, previous to the flood, had a meandering course down towards the Bridge of Nethy; but, after making its burst on the 4th of August, it cut out a new bed for itself, in one broad, straight line of destruction, annihilating the haughs on both sides".

APPENDIX 1.6

Documented history of flooding on the River Druie

Date	Information	Source
4/8/1829	Druie in flood	Lauder
11/6/1956	Major storm affected the Allt Mor. Loch Morlich area suffered flooding. "A heavy thunderstorm developed and the full fury of its rain and hail fall descended on the northern slopes of Cairn Lochan, Cairngorm and the region around Glenmore Lodge. Over 3 in of precipitation caused flooding which washed out footbridges...... scarred the hillsides in this locality." (Baird and Lewis, 1957 p91) "Very rare rainfall..Mr Murray Scott of Glenmore Lodge wrote that small bridges normally 2 to 4 feet above water level were washed away and the burn in front of the lodge was filled with large and small boulders such that the water was compelled to find a new course. The burn flowing into the Allt Mor just to the south of the lodge also changed its course and flowed along the rough road parallel with it. One pothole in the road, left after the water subsided, was about 5 feet deep and 9 feet in diameter. The dam which supplies the lodge with water was blocked with sand and took 4 days to clear." (British Rainfall, 1956)	BR1956 B & L
27/2/1967	Gales made conditions dangerous on ski-roads in the Cairngorms. Burns and rivers are in spate.	Scots.
4/8/1978	Flash flood on the Allt Mor "In the worst flood in the area for 17 years, heavy rain turned the Allt Mhor burn into a raging torrent". (Strathspey and Badenoch Herald, 8/1978)	McEwen Hudson Strath.

APPENDIX 1.7

Documented Flood Events in the Tweed Valley

Pre-1800 flood events in the Tweed district and surrounding region

Date	Information	Source
218 AD	Floods in the Tweed: many people drowned !! (no mention before Short)	Britt.
336 AD	Floods in the Tweed Valley !! (no mention before Short)	Britt.
536 AD	Floods in the Tweed with heavy casualities !! (no mention before Short)	Britt.
834/836 AD	Inundations of the Tweed with great damage !! (no earlier record)	Britt.
1200	In the year 1200, Berwick bridge was carried away by a flood.	Max.
1/8/1294	"About this time, the Bridge of Berwick across the Tweed fell in a great flood, because the arches were too low, which bridge had lasted only 9 years since it was erected." (<u>Scalacronica</u>, p9) "The flood broke down the Bridge of Berwick and threw down a tower, even overthrowing all the piers of masonary and many of the people who were crossing the bridge were washed away to sea."	Britt. HBNC Scalac.
28/3/1296	Floods in Tweed Walter Hemingburgh: "On Wednesday in that same Easter week...our king with his army entered into the territory of the enemy by crossing the waters of the Tweed under the monastry of nuns at Coldstream and the waters were marvellously swollen". (Britton, 1937 p97) <u>Lauercost Chronicle</u> also refers to the same floods.	Britt.
1523	"Duke of Albany lay upon the Scottish side of the Tweed....raining heavily, the Tweed was waxing; the coming spate threatened to cut off Ker's column from the main body." (Maxwell, 1909 p259)	Max.
1734	Flooding on the Yarrow	HBNC
5/8/1767	Flooding on Slitrig and Teviot (see Appendix 1.9)	Max. THAS1867 Edgar
1771	Tremendous flooding on the Tyne. Only one bridge on Tyne below Hexham withstood flood.	HBNC

Date	Information	Source
31/10/1772	Flooding on Bowmont Water, from great fall of rain.	HBNC
?/10/1775	Flooding on Tyne	HBNC
1777	Flooding demolishes first bridge over Ettrick	Pring.
1782	Flooding on Bowmont Water	HBNC
26/10/1797	Flooding on Teviot and Tweed "Noble bridge of 5 arches spanning the united waters of the Tweed and Teviot was finished in 1803 by young J. Rennie, to replace the one built in 1754, which was swept away by the great flood of 26/10/1797." (Maxwell, 1909 p140)	Max.

APPENDIX 1.8

Documented history of floods on the Tweed (post-1800)

Date	Information	Source
10/8/1829	Tweed in flood. "tempest was equally dreadful and destructive from Berwick up the Tweed and along the Gala Water." (Scotsman, 8/1829)	KM Scots.
9/2/1831	Tweed in flood. Heavy snow- great storm Flood stone in Floor castle grounds (O.S. 1:10560) marking the height of flood waters at 2 pm.	KM
1839	Tweed in flood	
1845	From the beginning of July to the last week in August, rain fell almost daily, causing the rivers to overflow their banks to an extent not witnessed for the last 30 years, even in the floods of winter. The heavy crops of grain were in many places laid low.	Scots.
3/8/1846	"Had the Tweed risen proportionally with the Teviot we should have had a flood as great as the celebrated one in Feb, 1831, which exceeded all those within the memories of the oldest inhabitants."	KM THAS
14/8/1846	Tweed in flood	BR1881 Max. THAS HBNC
23-24/10 1864	"At Kelso, on the 24th, the Tweed was 9.5 feet above its ordinary level, great trees and vast quantities of farm produce being floated down. In many instances, the haughlands are flooded, mills damaged and one or more bridges carries away. At Haddington the Tyne rose 12 feet, being higher than it had been for 18 years. In the Pentland hills.... rainfall for the week ending 23rd was 6.5 inches while the previous 6 months had only given about 10 inches.... neither the previous drought, nor the present floods have been paralleled for many years." (BR 1864)	BR1864
25/9/1872	"Rivers are in a continual state of flood and rills and fields are disfigured by the incessant rains swelling the mountain streams."	HBNC
3/4/1874	"Beginning of April, 1874, Tweed rose to 9 feet during the night. For some years prior to 1874, there has been no great rise of the rivers during this time of year."	HBNC
29/4/1876	Flooding on the Tweed (see Appendix 1.8.2)	HBNC

Date	Information	Source
5/3/1879	"Melrose- westerly gale- Tweed flooded 1.11 inches fell in 3.5 hours. Good deal of snow fell at beginning of month followed by rain, which with the melting snow caused the Tweed to rise higher than at other time since 1846, destroying much property." (Scotsman, 3/1879)	BR1879 Scots.
22/4/1880	Melrose- Tweed and tributaries in high flood Tweedometer at Kelso Bridge marking a rise of 6 ft.	BR1880
24/11/1880	Melrose abbey gate- Tweed in high flood remarkable quantity of snow, nearly 8 inches, having fallen on 18th, 19th and 20th. Rainfall 1 inch above average and consequently floods.	BR1880
9/3/1881	One of the highest floods on record. Flood took place immediately after breakup of winter- hills are covered with several feet of snow. Rapid thaw set in, accompanied by rain and therefore with melt of snow, the flood was more intense than would occur with any ordinary rainfall. Area of land damaged by actual flooding was limited, but owing to the great velocity of the current, the destruction of river banks and of mills and other properties along the river was unprecedented. Tweed rose higher than at any other time since 1846, destroying much property.	Reid BR1881
30/3/1883	Melrose abbey gate- Tweed in high flood	BR1883
27/3/1886	Tweed in flood- stormy	BR1886
20-21/9 1891	** "R (1.6 inches) followed by heavy floods, crops sheep and bridges being swept away. Tweed has been known 4 feet higher. Peebles (Kailzie)- severe gale of wind and rain from NNE, 3.40 inches of rain falling in 36 hrs. Tweed itself did not come down in flood until it was swollen by its tributaries, the Lyne, Eddlestone, Leithen and Gala Waters. These were all perfect torrents, washing away roads and bridges and raising the Tweed to a height that no-one remembers before. These streams are all on the left bank of the Tweed; the station here (Peebles), although on the right bank appears to have been just on the edge of the heavy rain."	BR1891
25/10/1894	Melrose abbey gate- Tweed in flood	BR1894
14/12/1914	"The heavy rainfall of the past 3 days has caused a good deal of flooding and in Berwickshire and along Tweedside, a number of fields are under water... Tweed in high flood. At Berwick considerable damage was done by the great volume of water overflowing the banks." (Northern Echo, 12/1914)	NE1914

Date	Information	Source
18/8/1920	"River Tweed a racing flood". Incessant downpour of 16th and 17th caused considerable flooding in Melrose district. The Tweed rose rapidly and yesterday was a raging flood, while many adjoining fields were submerged. Over 8 feet flood water at Kelso.	Scots.
23/9/1927	Considerable trouble and some damage had been caused by the flood of 23/9/1927 when many trees and other wreckage were brought down by the river.	HBNC
13/11/1938	Torrential rain at the weekend caused extensive flooding in the Border districts. River Tweed and its tributaries reached highest level for many years, in some sections being 15 feet above normal. At Kelso, the Tweed was running 15 feet above normal in the afternoon and although it had subsided a little before nightfall, further rain threatened to swell the waters to even greater proportions.	Scots.
12/8/1948	** Most major flood on record on Tweed. At Floors Castle, Tweed rose 6.5 feet higher than highest previous flood mark recorded Feb, 1831	Learm. G & D
6/11/1951	"All the border rivers and their tributaries were in spate. The river Tweed, which had been running below normal level, rose about 6 feet and was still rising last night. Several fields in the low-lying parts of the Tweed were flooded." (Scotsman, 11/1951)	Scots.
1953	Tweed in spate at Kelso	HI
28/8/1956	At Berwick, the Tweed rose 16 ft [4.9m] over peak discharge period. Tweed/ Teviot confluence inundated with localised flooding of low-lying haughland above Kelso. Tweed carried greatly increased suspension loads during and after the flood period with discolouration of water 1-2 miles out to sea.	Common
21/11/1963	36 hours of heavy continued rain. Tweed at Peebles almost 7.5 feet above normal.	Scots.
4/1/1982	Ice breaking caused a huge flood on Tweed below Kelso, it was the highest level since the disastrous flood of 1948 although levels generally appear to have been around a metre below that event.	TRPB

APPENDIX 1.8.1

Extracted from Young (1879) p263.

"In proof of the remarkable effects of land drainage in shortening the duration of floods, I may quote the following evidence given by Mr. Paulin, Secretary to the Berwick Salmon Fisheries Company, when examined by me as Special Commissioner to inquire into the operation of the Tweed Fisheries Acts. Mr. Paulin said:

> 'To prove what has been said as to the land drainage, and also as to the rapidity with which water runs off, I have here a report by one of our foreman, from which it appears that on the 28th March 1872 there was 1 foot 2 inches of water; on the 29th, 4 feet 6 inches; on the next day it had risen to 8 feet 10 inches; but the next day it fell to 3 feet 5 inches. It fell 5 feet in a day. The same thing happened this year (1874) on the 3rd April. On 1st April there was 1 foot recorded, on 3rd April 8 feet 6 inches; and on 4th April it was back to 3 feet. In 1814 or 1816, it would have taken a week to fall as much.'"

APPENDIX 1.8.2

Extracted from the History of Berwickshire Naturalists Club Vol VIII, p113.

Fishing season on the Tweed

Season	No. of days on on which river was: *	+	Largest spate feet	date	No of days on which river flooded to depth of 3 ft or more
1874	77	104	9.6	3/4	4
1875	60	122	7.0	9/3	4
1876	110	73	11.0	29/4	15

* above ordinary summer level

+ at or below ordinary summer level

3 ft = 0.9 m

APPENDIX 1.9

Documented history of flooding on the River Teviot

Date	Information	Source
1/8/1294	Flooding on the Teviot. "Then after the feast of St. Peter ad Vincula (1st August, 1294) there happened a sudden stupendous flood in the river in Scotland called the Teviot, prognosticating future events at hand, such as we have witnessed before our eyes. For the waters of the Teviot suddenly waxed without much rain, overflowing bridges and lofty rocks, sweeping away the mill below Roxburgh Castle and others, besides everything else that was in their way." (Scalacronica, p108)	Britt. Chron. HBNC Max.
1410s	Flooding on the Slitrig? Gawain Douglas is supposed to have witnessed a flood similar to that of 5/8/1767, 350 years earlier.	Doug. Oliver
?/1689	Heavy rain caused flood damage to hayfields and arable land in Ettrick Forest, Eskdale, Liddlesdale and Teviotdale.	Whyte
5/8/1767	** Flooding on the Teviot and the Slitrig "One of the most sudden and disastrous of the many floods that have for centuries characterised the wild impetus Slitrig." (THAS 1867, p30.) Caused by the bursting of a waterspout on Windburgh hill. Waters began to flow deep and strong along each side of the Auld Brig bridge. "The stream began to rise about 4 o'clock, and by 6 it had risen 22 ft above its ordinary level." (Oliver, 1887 p374.)	Max. THAS1867 Edgar
1795	"a great ice flood". Completed the destruction of the old kirk and yard of Hassendean.	THAS
26/10/1797	Tweed and Teviot in flood. "Noble bridge of 5 arches spanning the united waters of the Tweed and Teviot was finished in 1803...to replace the one built in 1754 which was swept away by the great flood of 26th Oct, 1797." (Maxwell, 1909 p140)	Max.
9/8/1806	Flooding on the Teviot. "St. James's flood, which happened on 9th August, 1806 wrought much havoc through Teviotdale and nowhere was the flood more severely felt than at Bridgend....much of their property was swept away. the haugh which had cost them so much labour and charge to improve, was again rendered a waste of gravel." (HBNC, Vol XXII p98)	HBNC
9/2/1831	Teviot in flood	KM

Date	Information	Source
3/8/1846	"On 29th July, 1846, exactly 40 years after the 1806 flood, an immense deluge accompanied by fearful lightenings and thunder swept down the Rule valley. The river rose from 10-12 feet above its ordinary level and according to the testimony of the older inhabitants, the Rule was higher than the flood of 1806. Large trees were floated past. Much damage was done at Bridgend as the water rose to a height of 5 ft...the flood was at its greatest height at midnight.....Hobsburn bridge was entirely swept away, as were many others in the district." (HBNC, Vol XXII p98)	KM HBNC
1862	Teviot in flood "On the Tuesday preceding the Common Riding, there were several heavy showers and up till Tuesday night the weather remained unbroken....the rain came down in torrents... the rain continued for the entire evening and the haugh became a quagmire. During the night the wind rose and increased in violence until it blew a perfect gale. The river overflowed its banks and for a while, a large part of the haugh was under water". (Edgar, 1913 pp122-123.)	Edgar
23-24/10 1864	Teviot in flood. Tweed and Teviot have again been brought down in high flood, the Teviot being particularly red and swollen. Jedburgh- rain fell heavily .... Jed rose to a considerable height Trees and great quantities of debris were borne down by the current.	BR Scots.
22/5/1865	Swollen state of the Teviot, which was in greater flood than for many years, attested the heaviness the fall in its upper districts almost as well as the ample rain records of Cumberland. Jedburgh- most severe TS ever experienced in this quarter. Rain fell in torrents, more resembling the bursting of a waterspout than anything else. Rain continued for approximately 3.5 hours.	BR1865 Scots.
15/11/1866	Silverbut Hall, Hawick- Rivers full on the 15th and overflowing the next day, 1.03 inches of rain having fallen in those 2 days.	MM1866
31/1/1868	Silverbut Hall- rivers overflowing	MM1868
24-25/2 1872	Hawick (Silverbut Hall)- rivers flooded	MM1872 Scots.
10/7/1872	1.20" rain fell in an hour on the night of the 10th, which flooded many houses in Hawick	MM1872
26/7/1872	A severe TS on 26th, when 1.52 inches of rain was registered at Silverbut Hall, which brought the rivers down in full flood.	MM1872

Date	Information	Source
2/4/1874	Silverbut Hall- the rainfall on the 2nd was 1.08 in, which brought out the Teviot in full flood.	MM1874
3/9/1875	Heavy rains at Hawick. Teviot flooded	MM1875
21/12/1875	Hawick (Silverbut Hall)- Teviot in high flood on the 21st on which day 1.15" of rain fell	MM1875
28/12/1878	Snow fell on 12 days & amounted to 1.24 in and 1.03 in rain fell on 7 days. The thaw on the 28th and the heavy rain which accompanied it caused a high flood on the Teviot. The snowfall has been the severest and longest in duration experienced here for many years.	MM1878
10/7/1880	Hawick- severe thunderstorm on the afternoon of the 10th, 0.86" rain fell in 25 mins, the ground was white with hail and the low-lying parts of Hawick were flooded.	MM1880
27-28/10 1880	Terrible storm of snow, sleet, rain and wind causing a high flood on the Teviot.	MM1880
9/3/1881	Flooding in the Teviot basin	TRPB
27/11/1881	Snow storm with high wind on 1st, gales on 15th,16th 21st,25th,26th and 27th. The river Teviot in higher flood on the 27th than it has been since 1846, causing from 2000-3000 pounds worth damage to factory property.	MM1881 THAS Scots
3/12/1881	Hawick flood- "mightier even than that of the 5th, Aug, 1767....much larger than that awful occasion in 1846".	Haw.Ex Haw.Ad
25/9/1883	"last nine days were cold and wet, very stormy on 25th, causing high flood on the Teviot.	MM1883
10/8/1901	Lilliesleaf, Riddel -"excessive heavy thunderstorm with 2.79 inches of rain; all rain fell in about 2 hours. Ale water rose to the height of a winter flood".	MM1901
27/8/1905	Hawick- TS with heavy rain, causing a flood in the Slitrig valley.	MM1901
24/6/1911	"This weeks rain has flushed the waters and the Jed and other Cheviot streams were discoloured." (Scotsman, 6/1911)	Scots.
18/8/1920	Teviot running in heavy flood	Scots. TRPB
27/12/1924	Teviot in flood	TRPB
5/11/1926	Teviot in flood	TRPB

Date	Information	Source
5/1/1933	Teviot in flood	KM
13/11/1938	Teviot in flood. Hawick's worst flood in living memory- 2 bridges swept away. Considerable flooding in Jedburgh and district. Damage was caused to the railway line between Jedfoot and Nisbet.	TRPB Scots.
13/8/1948	Teviot in flood	Learm.
28/8/1956	Flooding in Tweed basin; Teviot affected Middle to lower tracts of Teviot suffered local inundation.	TRPB Common
19/1/1962	Flooding in Tweed basin; Teviot affected. Gale force winds up to 100 mph across Scotland and heavy rain In Borders, Teviot burst its banks in many places.	TRPB
27/2/1967	Teviot burst banks	Scots.
13/?/1968	Flooding at Jedburgh	TRPB
30/10/1977	Largest flood at Hawick on the gauged record- 310.4 $m^3 s^{-1}$.	S.R.
27/12/1979	Jed Water in flood	Scots.
4/1/1982	Ale Water in flood	Scots.

APPENDIX 1.10

Documented history of flooding on the Whiteadder Catchment

Date	Information	Source
3/7/1830	Abbey St. Bathans- TS more severe and destructive than any ever known. Very localised.	Scots.
14/8/1846	Whiteadder in high flood.	HBNC
25/9/1872	Flood height marked at Abbey St Bathans. "a furious storm of wind and rain, which was very disastrous to the crops. The Whiteadder was in higher flood than since 1846 and caused great damage by overflowing the fields and carrying down the corn yet exposed." (HBNC, Vol VII p3) "On the 25th September, 1872 is said to have occurred the highest flood on Whiteadder since 1846."	THAS HBNC
17/11/1872	Flood height marked at Abbey St Bathans (6 ft 2.5 in)	HBNC
1873	Whiteadder in flood	HBNC
31/8/1876	Flood height marked at Abbey St Bathans (6 ft 10 in)	HBNC
29/9/1876	Flood height marked at Abbey St Bathans (6 ft 4 in)	HBNC
1/1/1877	Flood height marked at Abbey St Bathans (6 ft 3.5 in)	HBNC
20/8/1877	Flood height marked at Abbey St Bathans (6 ft 6 in)	HBNC
20/8/1878	Flood on the Whiteadder	HBNC
31/12/1878	Flood height marked at Abbey St Bathans (5 ft 8 in)	HBNC
1/3/1879	Flood height marked at Abbey St Bathans (5 ft 1 in)	HBNC
1/7/1879	Flood height marked at Abbey St Bathans (7 ft 5.5 in)	HBNC
15/9/1880	Flood height marked at Abbey St Bathans (7 ft 4.5 in)	HBNC
25/11/1880	Flood height marked at Abbey St Bathans (6 ft 0.5 in)	HBNC
9/3/1881	Flood height marked at Abbey St Bathans (6 ft 6.5 in)	HBNC
22/9/1881	Flood height marked at Abbey St Bathans (7 ft 0 in)	HBNC
9/10/1882	Flood height marked at Abbey St Bathans (5 ft 11.5 in)	HBNC
7/9/1884	Flood height marked at Abbey St Bathans (6 ft 8.5 in)	HBNC
27/5/1886	Flood height marked at Abbey St Bathans (5 ft 10.5 in)	HBNC

Date	Information	Source
6/11/1886	Flood height marked at Abbey St Bathans (5 ft 4.5 in)	HBNC
7/11/1887	Flood height marked at Abbey St Bathans (5 ft 11 in)	HBNC
3/11/1888	Flood height marked at Abbey St Bathans (6 ft 0 in)	HBNC
3/12/1890	Flood height marked at Abbey St Bathans (5 ft 1.5 in)	HBNC
22/8/1891	Flood height marked at Abbey St Bathans (8 ft 3 in)	HBNC
21/9/1891	Flood height marked at Abbey St Bathans (8 ft 6.5 in)	HBNC
?/8-9/1891	Marchmont House- August and September were extremely wet, 13 inches of rain falling in 2 months. Destructive floods occurred injuring roads and bridges and carrying away sheep.	BR1891
10/10/1896	Flood height marked at Abbey St Bathans (5 ft 7 in)	HBNC
16/6/1897	Flood height marked at Abbey St Bathans (7 ft 1 in)	HBNC
18/10/1898	Flood height marked at Abbey St Bathans (8 ft 2 in)	HBNC
19/5/1900	Flood height marked at Abbey St Bathans (5 ft 3 in)	HBNC
2/9/1903	Flood height marked at Abbey St Bathans (5 ft 10.75in)	HBNC
6/10/1903	Flood height marked at Abbey St Bathans (6 ft 5 in)	HBNC
9/10/1903	Flood height marked at Abbey St Bathans (5 ft 10 in)	HBNC
1910	Flooding on the Whiteadder	TRPB
14/12/1914	Whiteadder in high flood	BR1914
19/8/1920	Heavy rain fell at Duns from mid-day on Tuesday till Wednesday morning without ceasing. Local streams are all still in top flood and considerable damage to crops.	Scots.
13/8/1948	Major flood event on the Whiteadder	Learm.
28/8/1956	The Whiteadder and Blackadder followed the pattern of the 1948 floods but on a smaller scale.	Common

------------------Gauged Records Commence------------------------------

APPENDIX 1.11

Documented Flood history in the Leader catchment

Date	Information	Source
9/9/1831	Flooding on the Leader	TRPB
14/8/1846	Flooding on the Leader	TRPB
23-24/10/ 1864	"Until the last few days, the Leader and its tributaries have not been in a state of flood since early spring, the former never having risen a foot during the whole summer. On Saturday morning, and during all the day a very heavy rain and at night, it was accompanied by a stiffish wind. By night fall, the Leader was running wild and high and it continued to increase in volume until a little past midnight when it began to recede. On Sunday, it still continues in high flood. The river has not been so large since the great flood of 1846 and by midnight on Saturday it continued to rise so fast that a number of persons, inhabiting houses on the haughs, removed to safer quarters.	BR1864
9/3/1881	Flooding on the Leader	BR1881
20-21/9 1891	The Gala and Leader have not been so high in living memory.	BR1891
9/1909	Flood event on the Cleekhimin Burn	EP
12/8/1948	Flooding on the Leader	Learm.
28/8/1956	Flooding on the Leader	Common
----------------------Gauging records commence-------------------------		
31/10/1977	Lauder high street flooded	Scots.

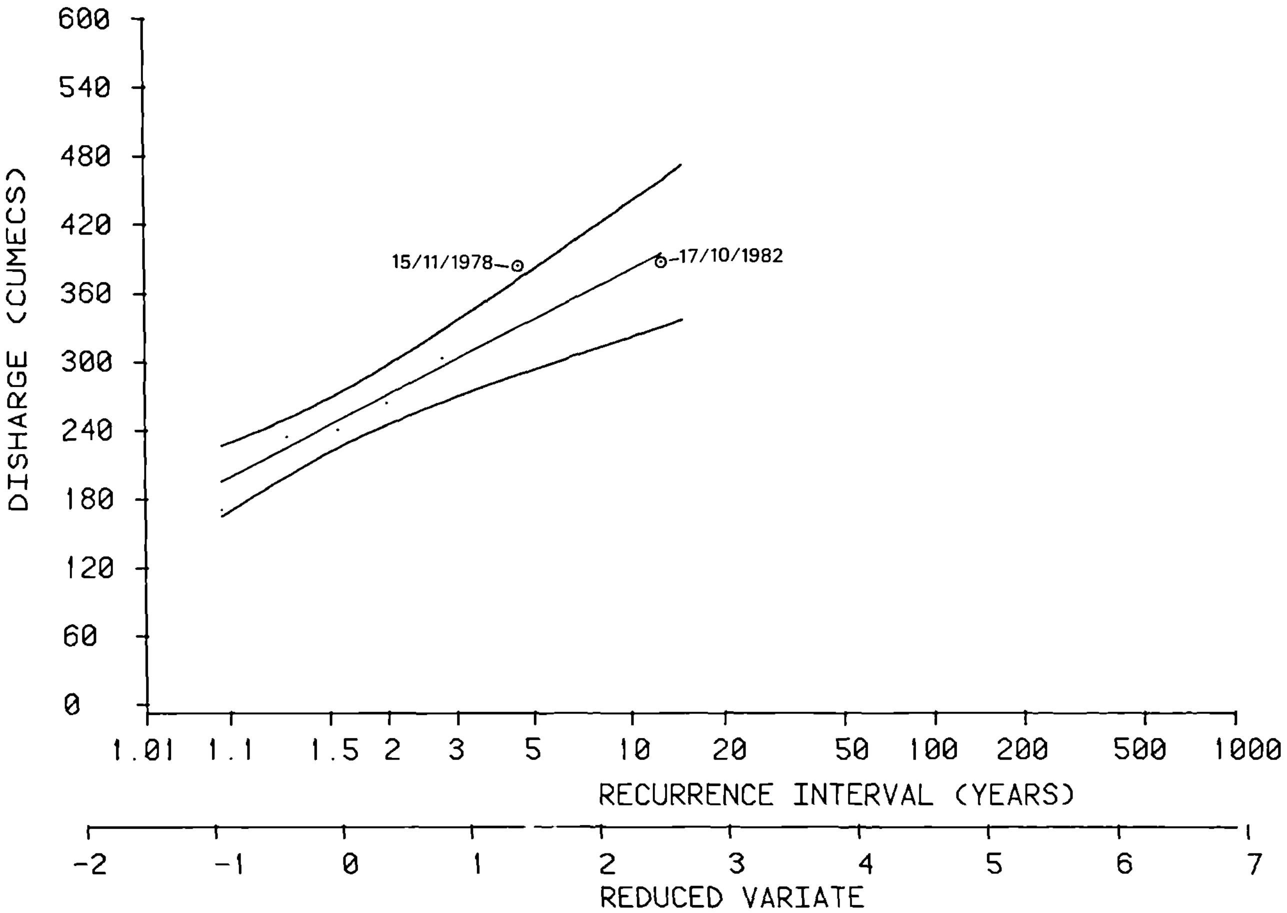
APPENDIX 1.12

Documented flood history on Bowmont Water

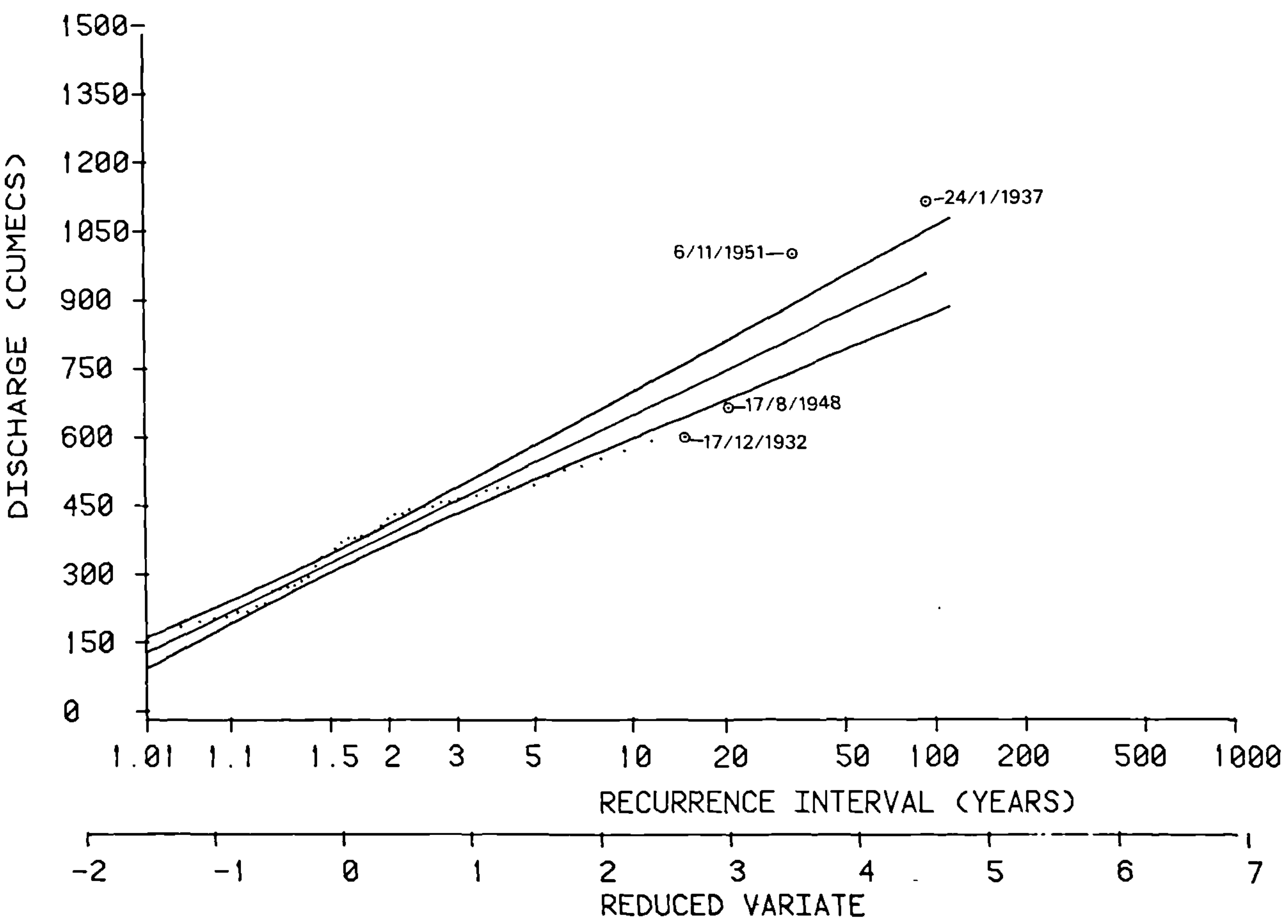
Date	Information	Source
31/10/1772	"From great fall of rain, one of the horses from Kelso coach drowned crossing the Ford at Mindrum (on Bowmont Water).	TBNC
2/2/1831	Flooding recorded near the Hermitage, Coquet. Flooding likely on the Bowmont Water.	HBNC
14/12/1914	Till in high flood	BR1914
26/9/1949	Gauge at Linhope in the Cheviots registered 4.80 inches. "This indicates the rainfall on the upper watershed of R. Breamish, the Wooler Water and College Burn. On the 26th, floods occurred on these 3 rivers, which in volume were in exceedence of the floods on Aug, 1948. Phenomenal rainfall on the Cheviot."	BR1949
28/8/1956	Flooding on the Till	Common

APPENDIX 2.1

DEE CATCHMENT AT POLHOLLICK 1976-1982

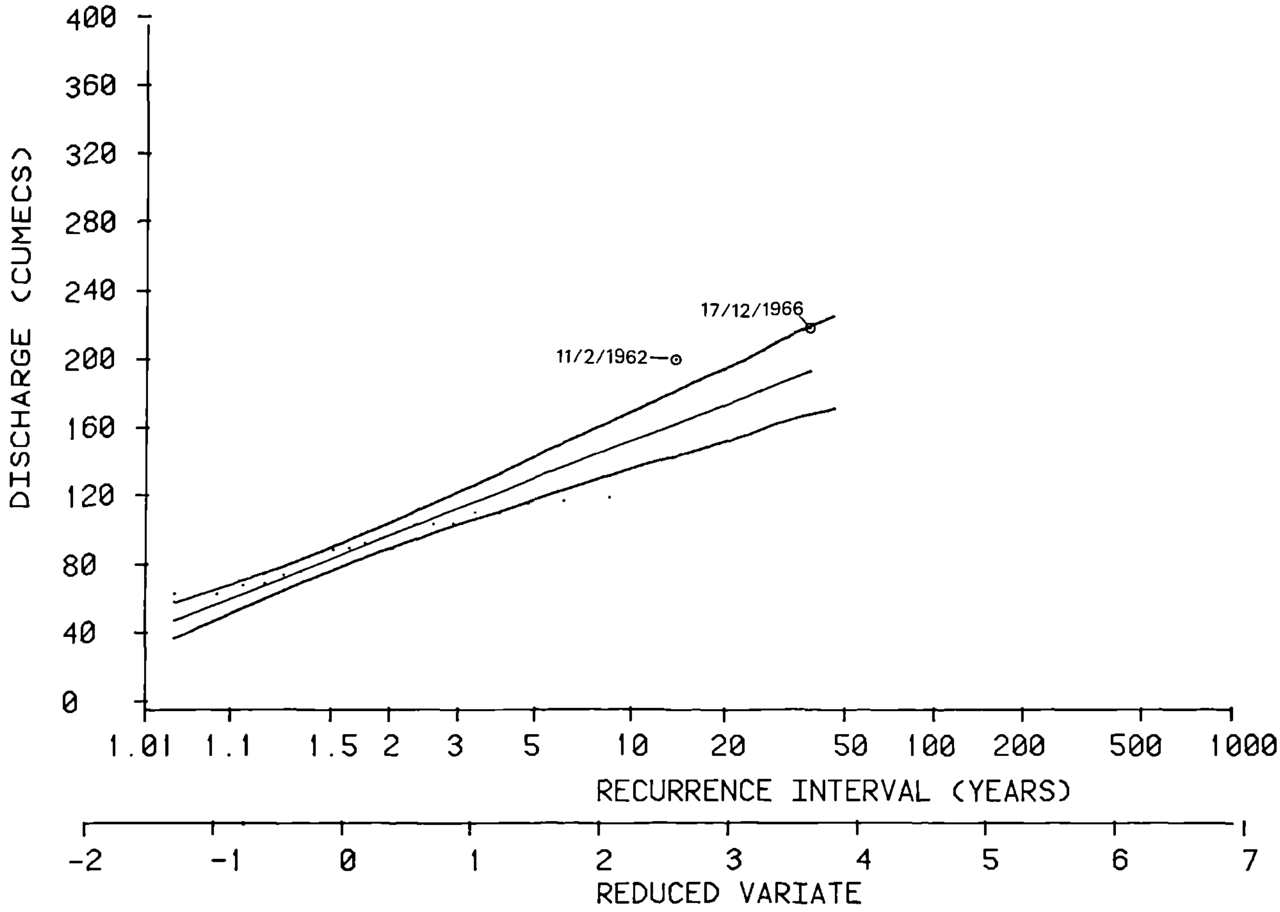


DEE CATCHMENT AT WOODEND 1930-1982

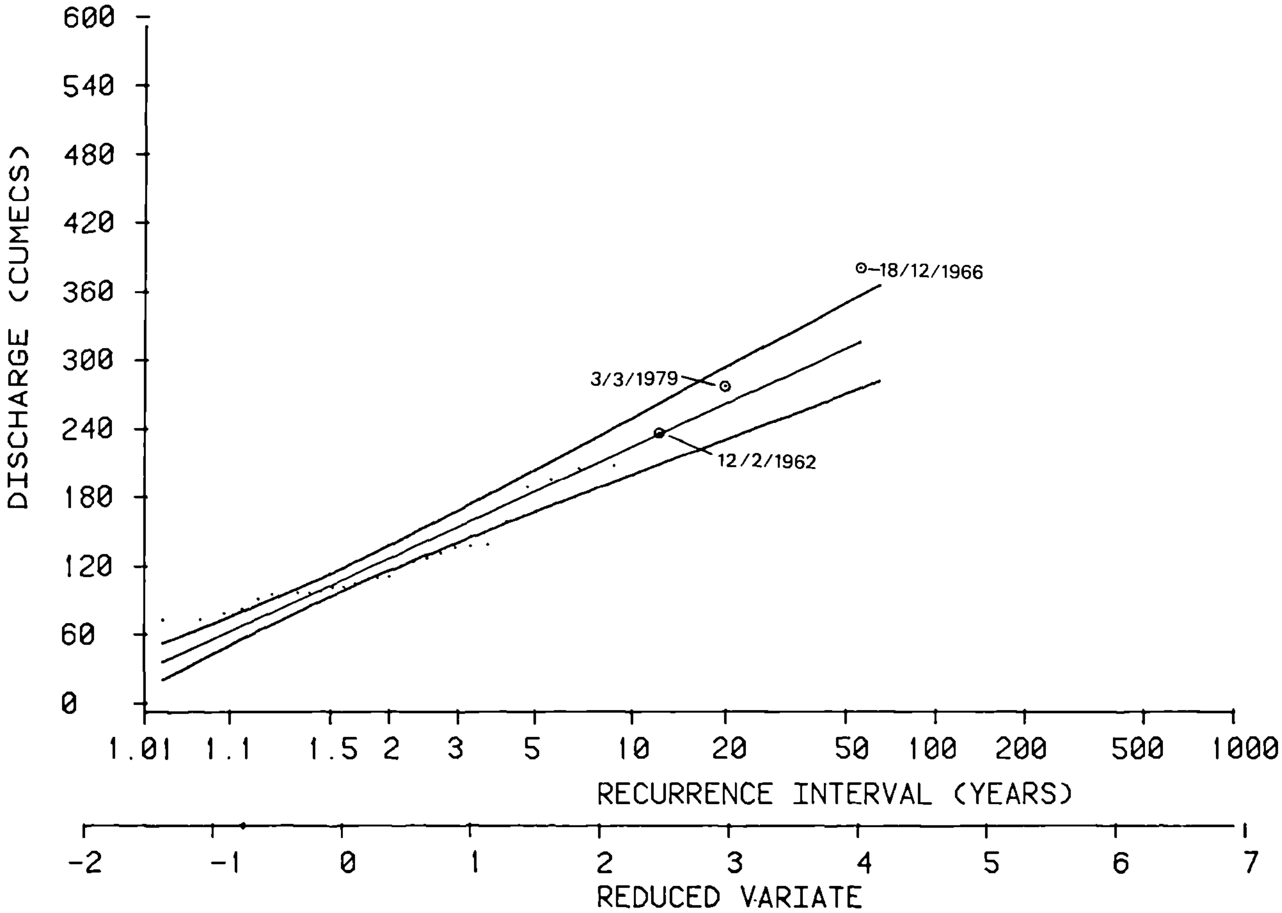


APPENDIX 2.2

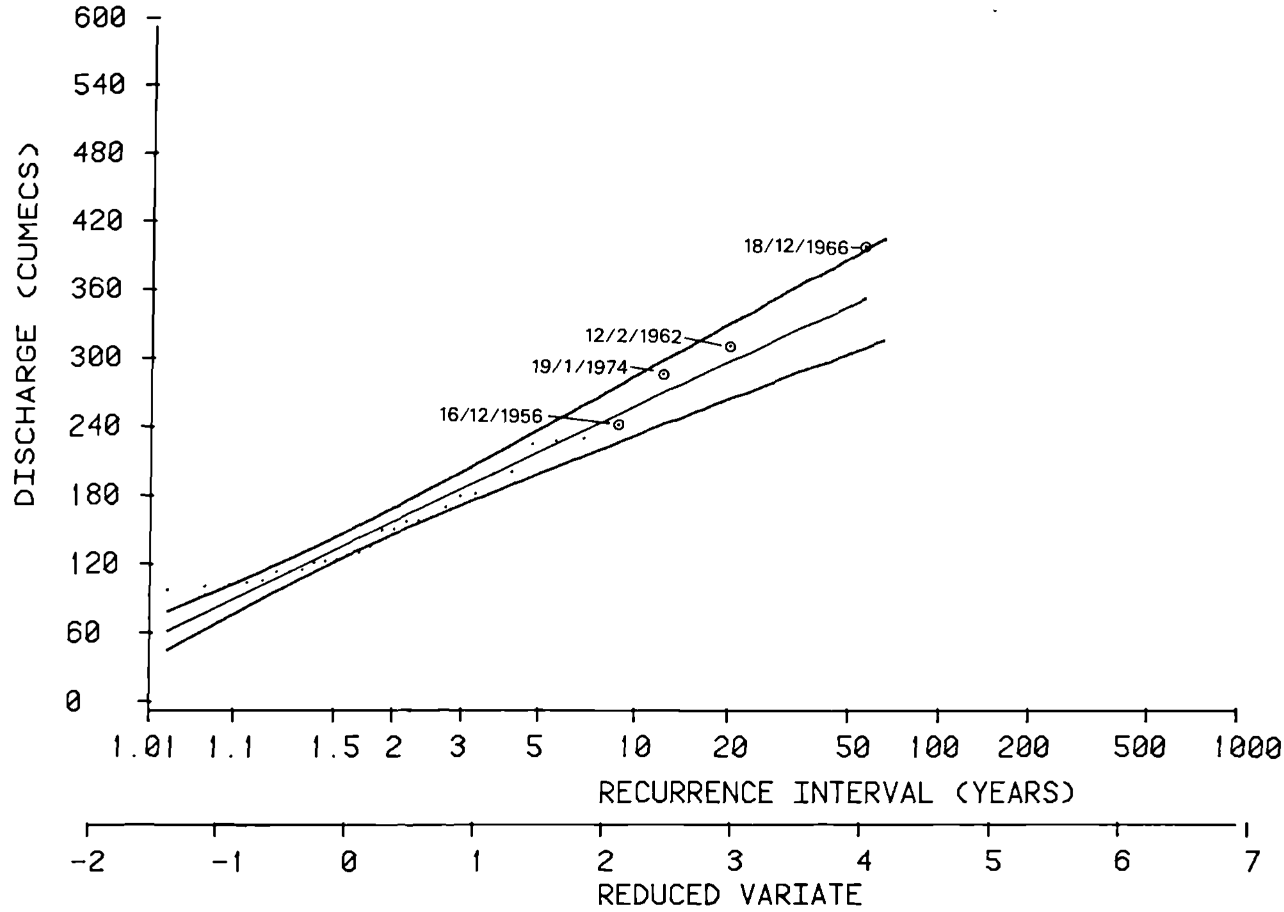
SPEY CATCHMENT AT RUTHVEN BRIDGE 1952-1973



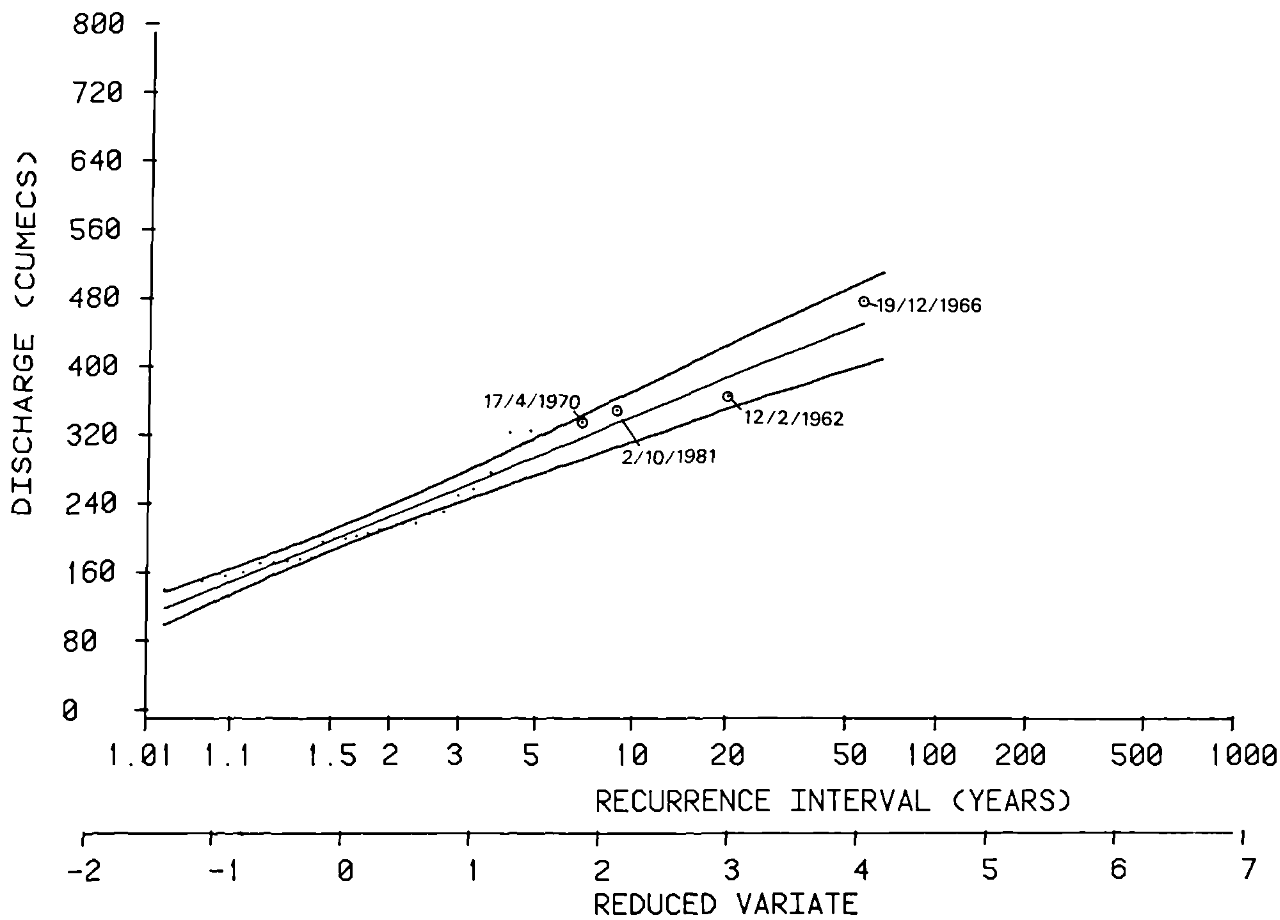
SPEY CATCHMENT AT KINRARA 1952-1982



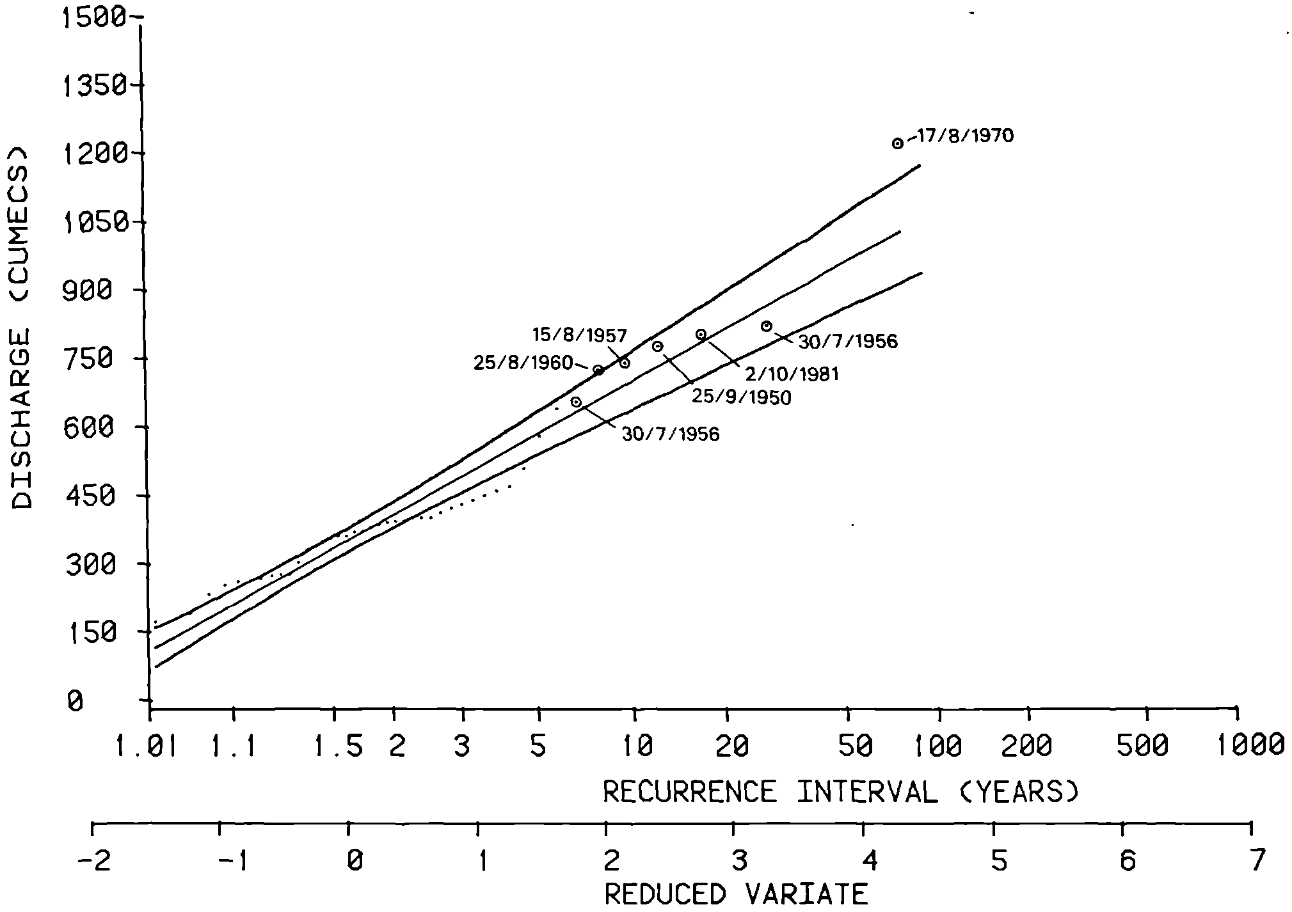
SPEY CATCHMENT AT BOAT OF GARTEN 1952-1982



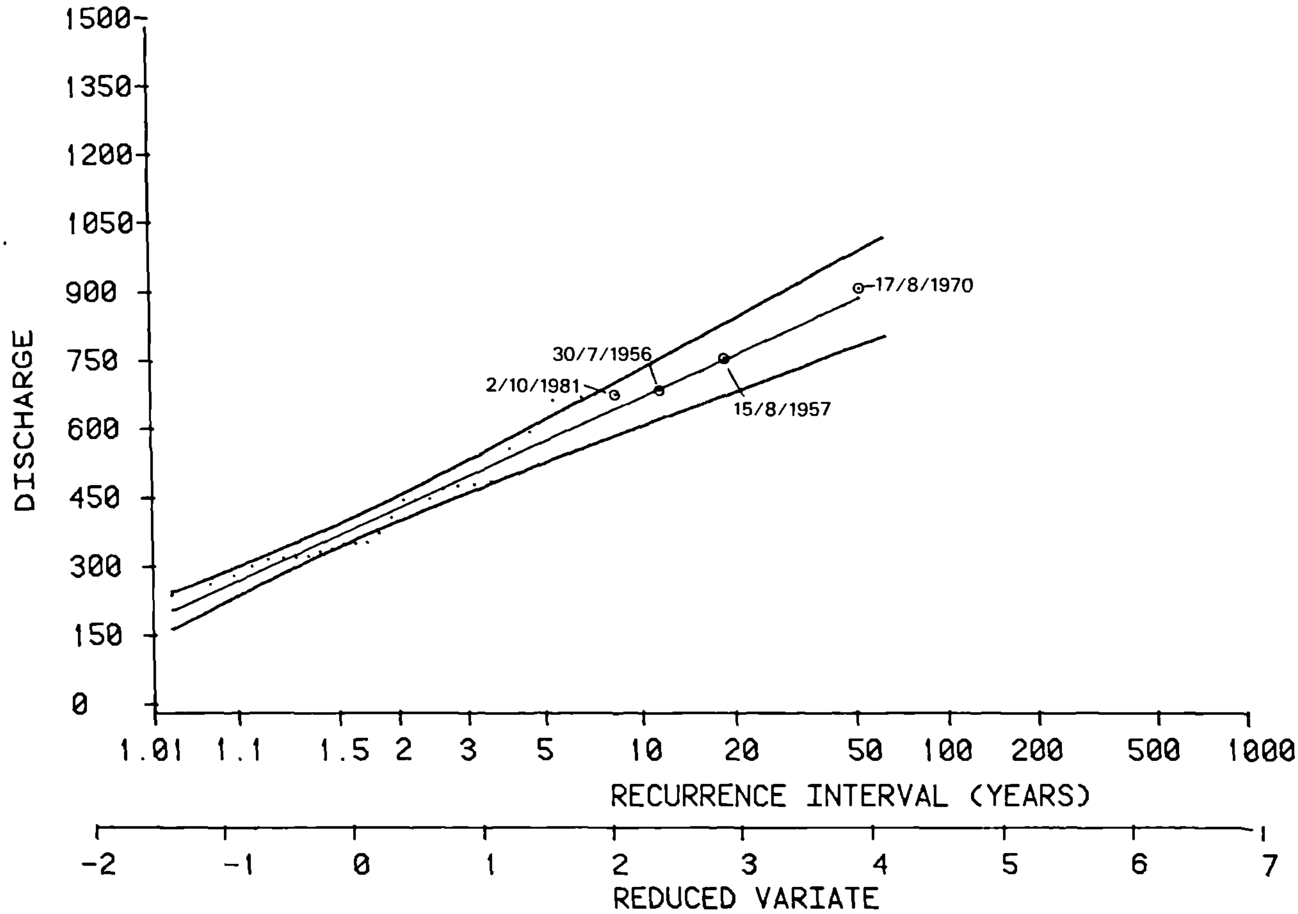
SPEY CATCHMENT AT GRANTOWN 1952-1982



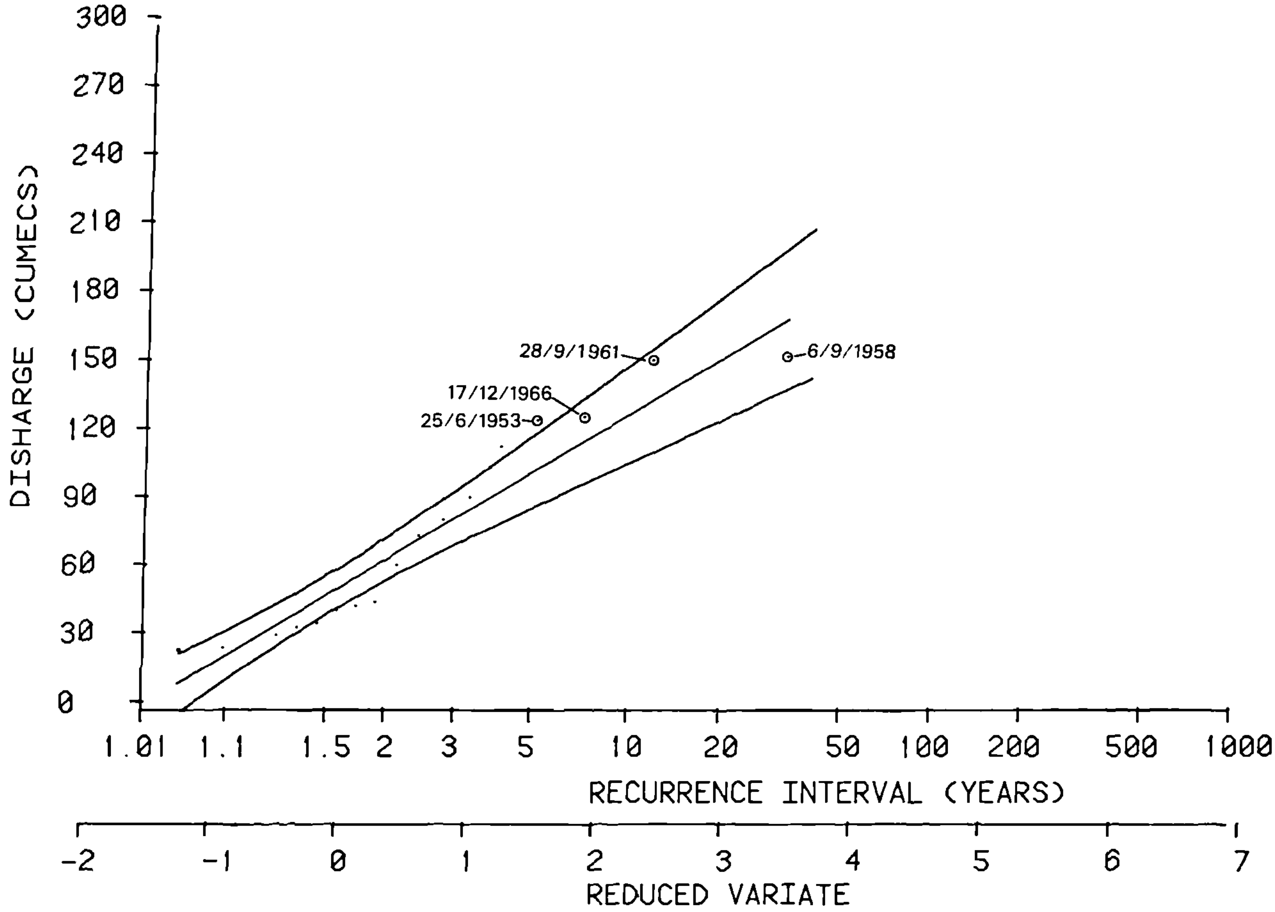
SPEY CATCHMENT AT ABERLOUR 1939-1982



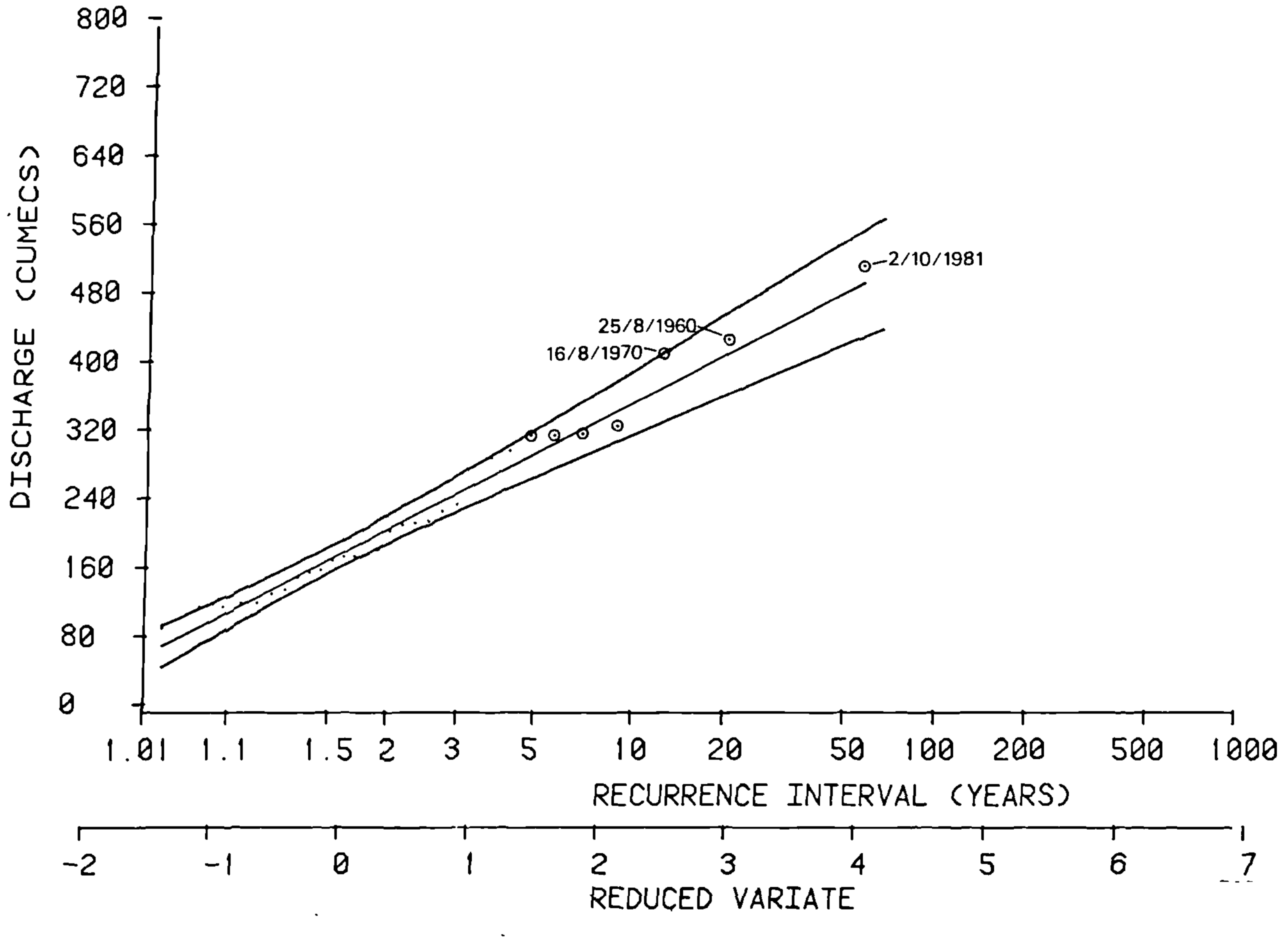
SPEY CATCHMENT AT BOAT O BRIG 1953-1982



TROMIE CATCHMENT AT TROMIE BRIDGE 1953-1970

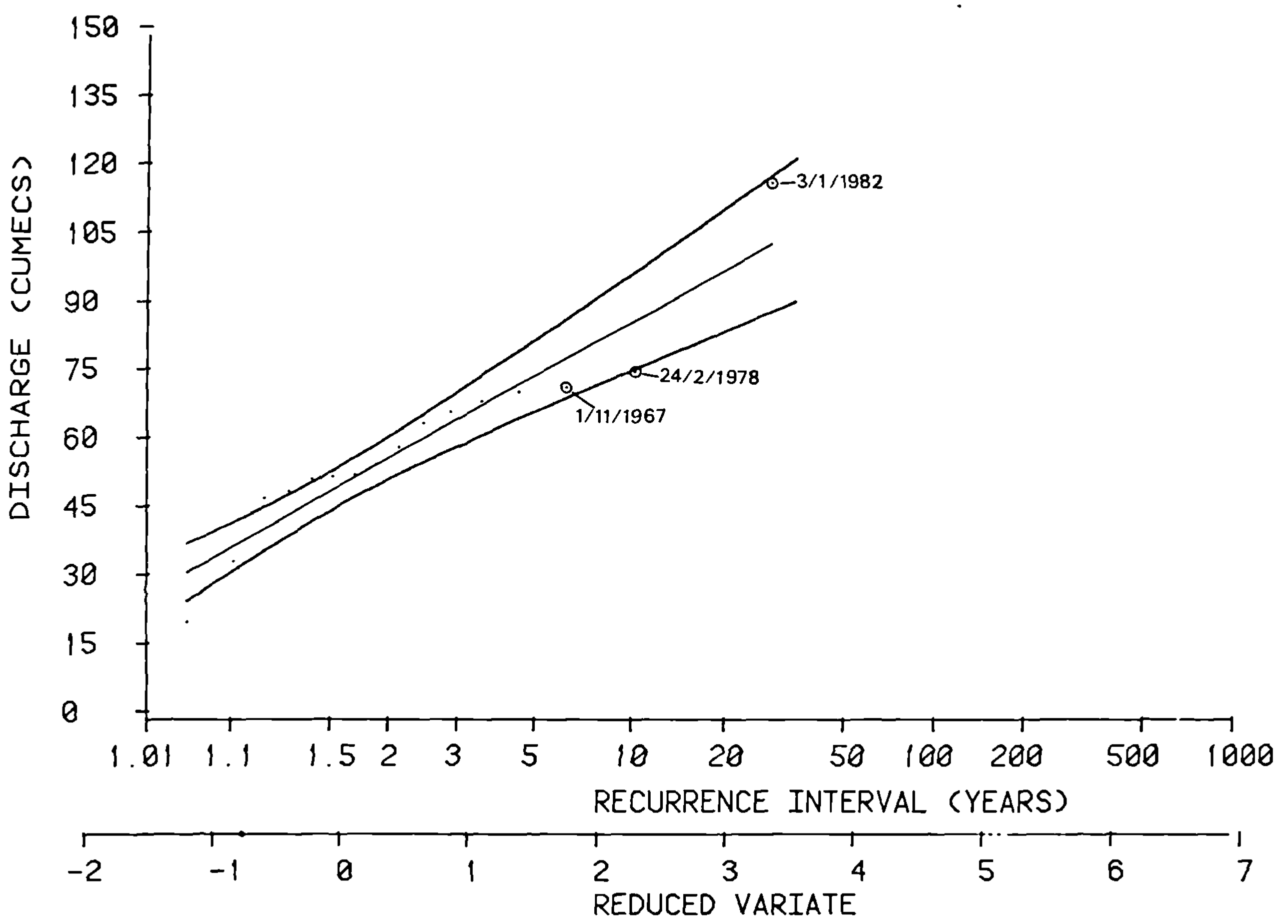


AVON CATCHMENT AT DELNASHAUGH 1952-1982

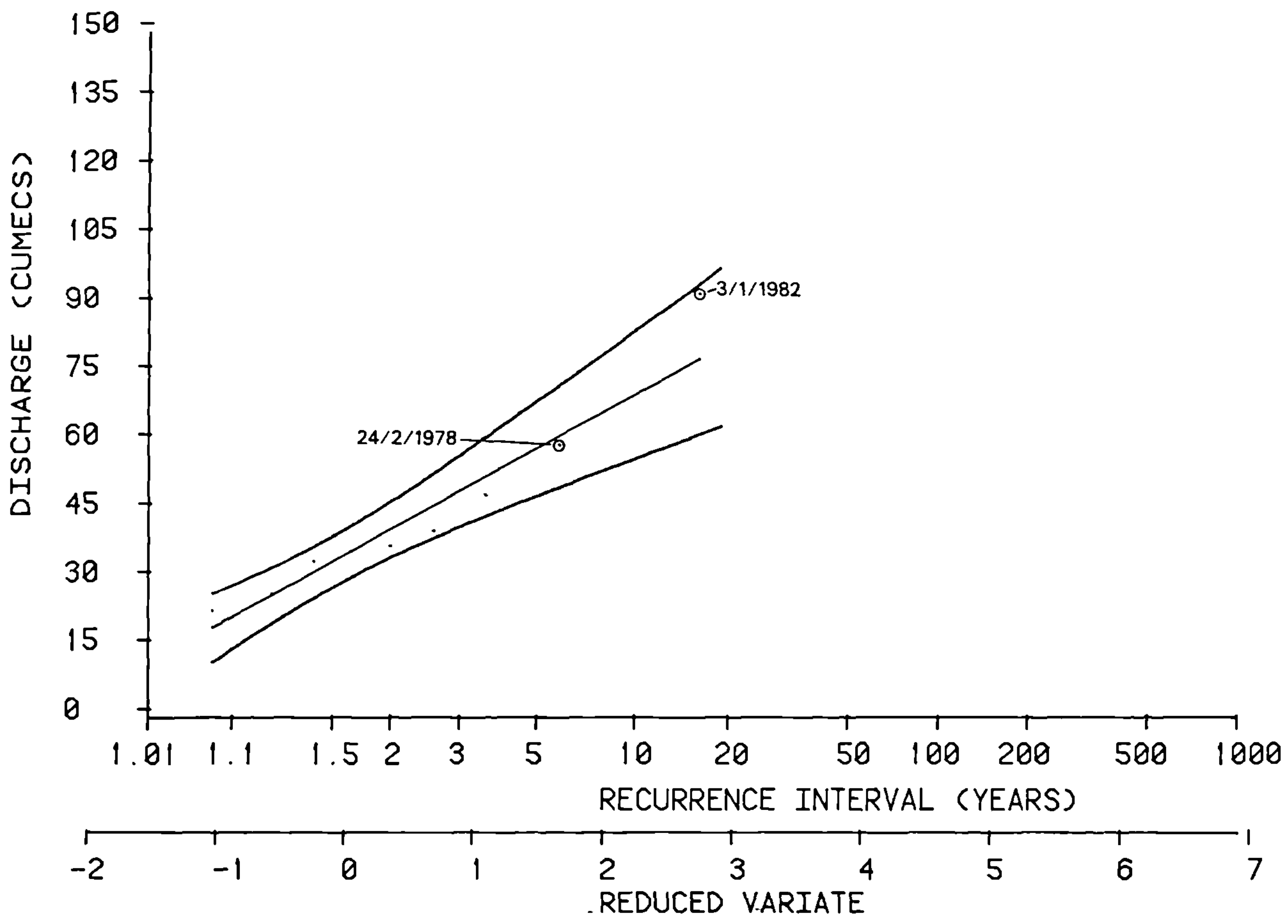


APPENDIX 2.3

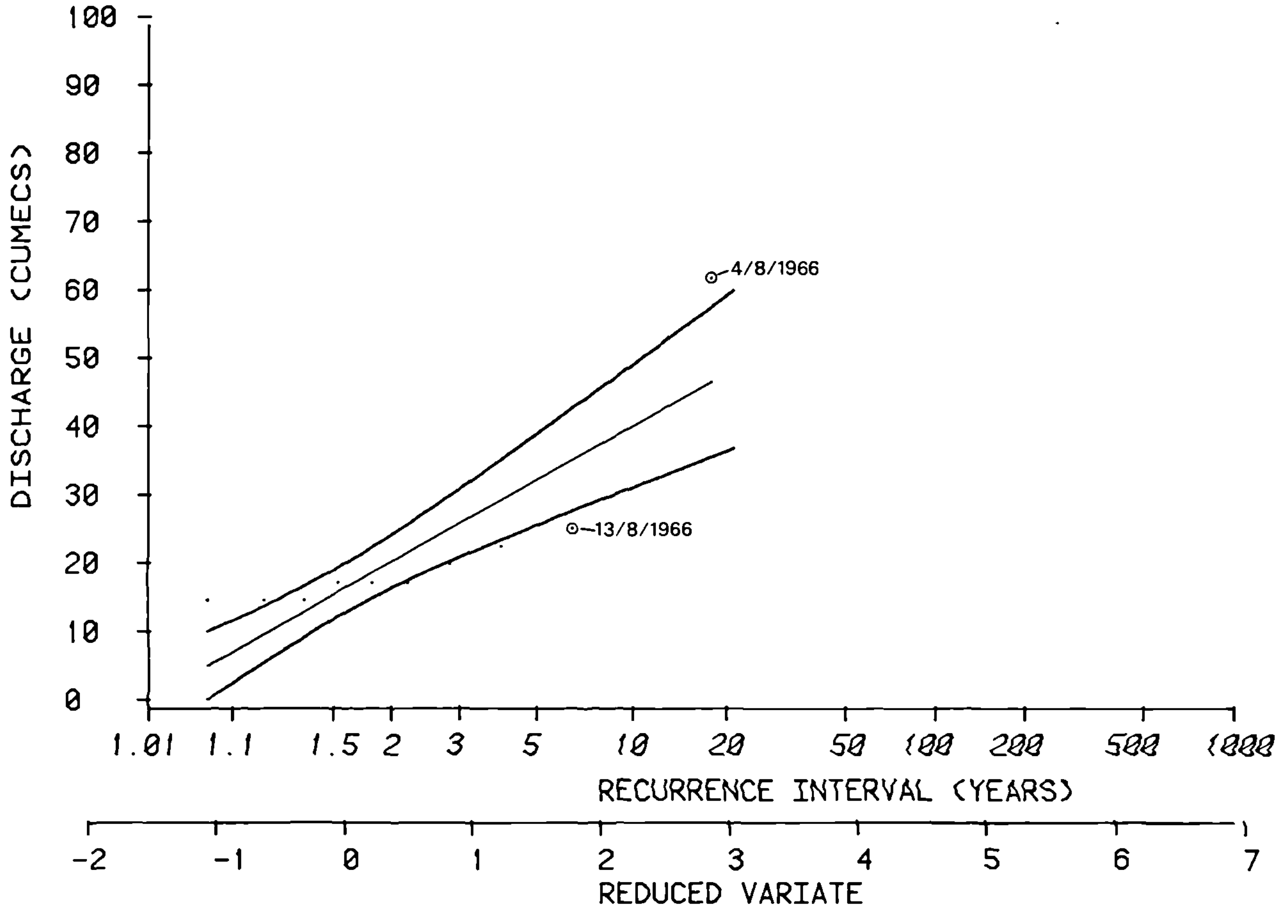
LEADER CATCHMENT AT EARLSTON 1967-1982



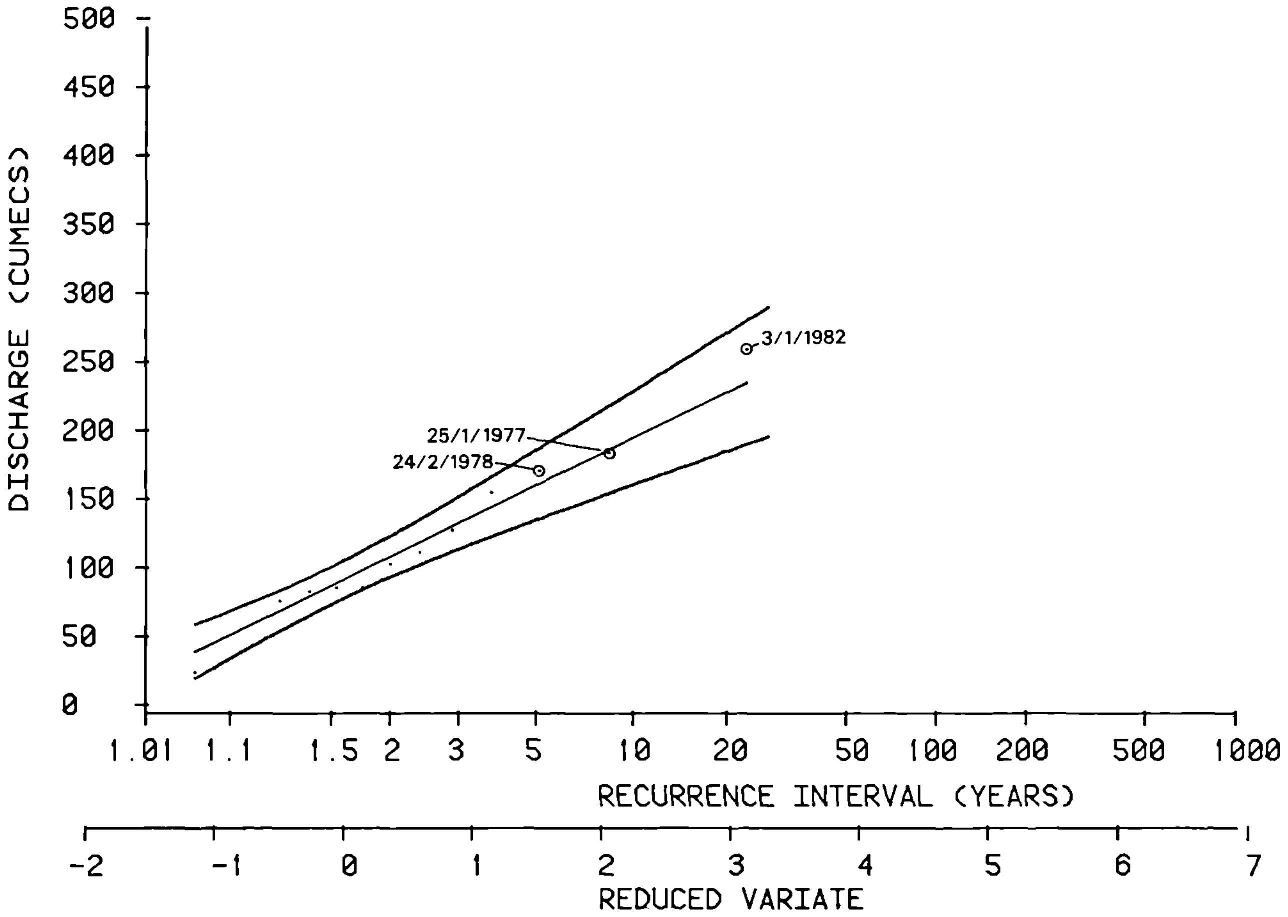
BLACKADDER CATCHMENT AT MOUTHBRIDGE 1974-1982



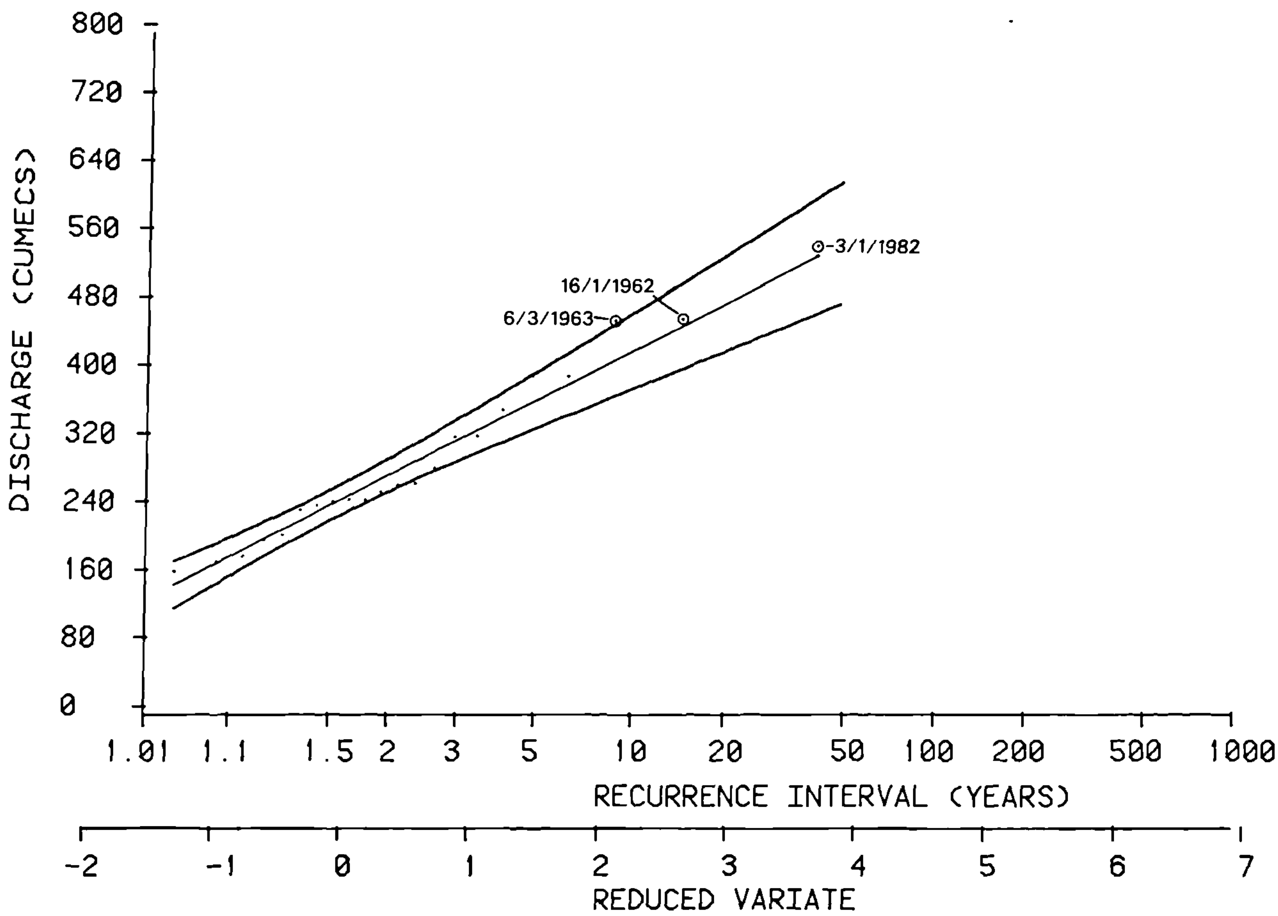
WHITEADDER CATCHMENT AT HUNGRY SNOUT 1958-1967



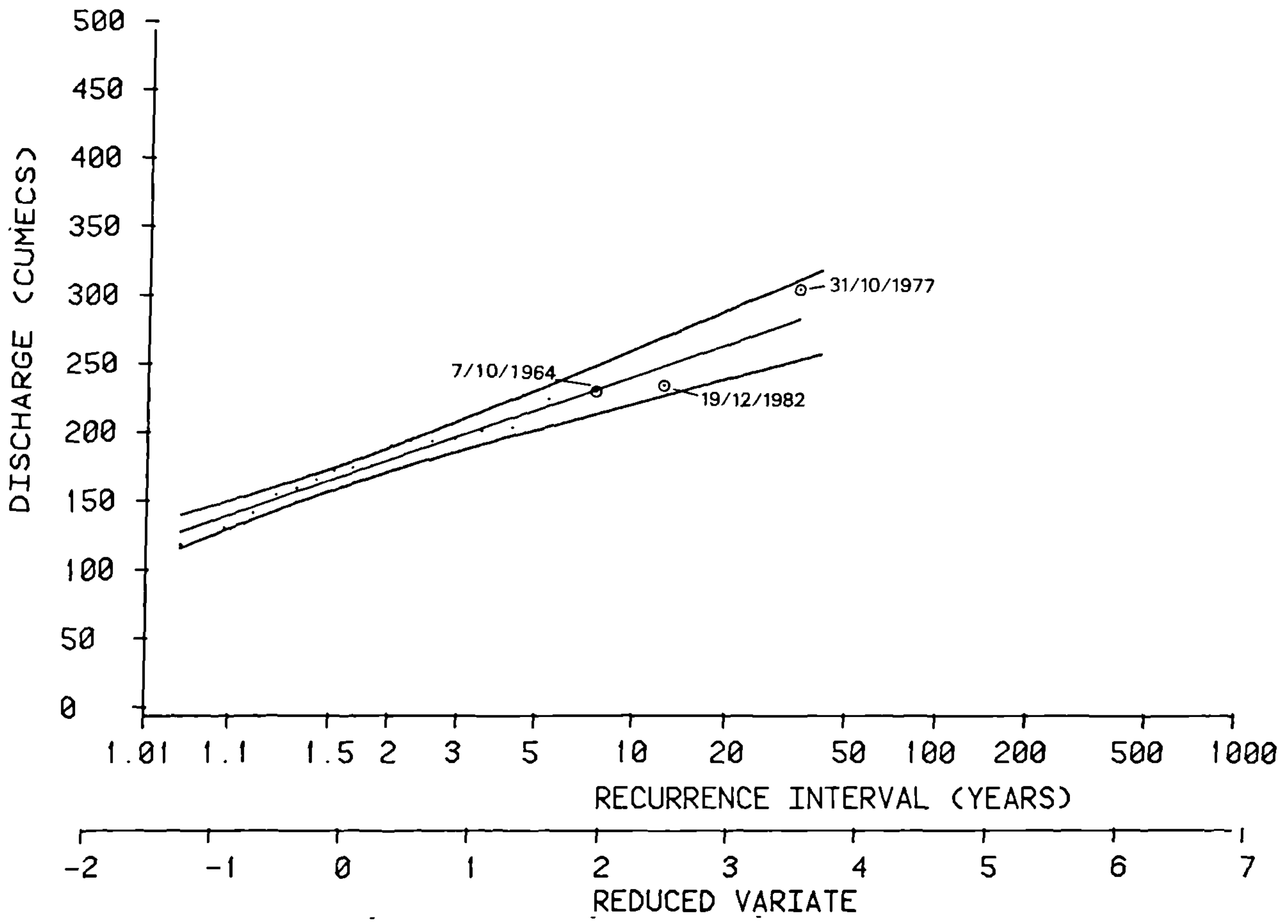
WHITEADDER CATCHMENT AT HUTTON CASTLE 1970-1982



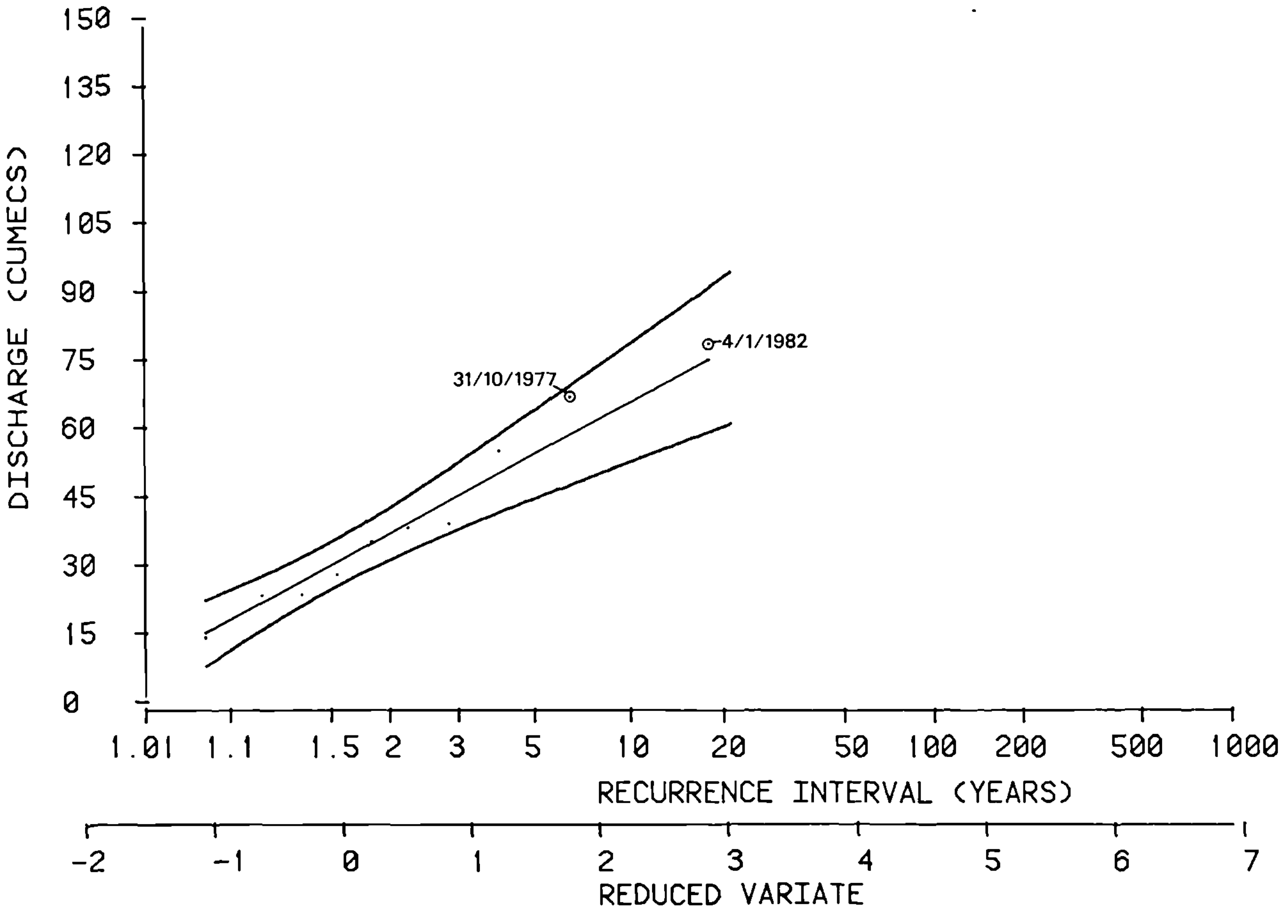
TEVIOT CATCHMENT AT ORMISTONMILL 1961-1982



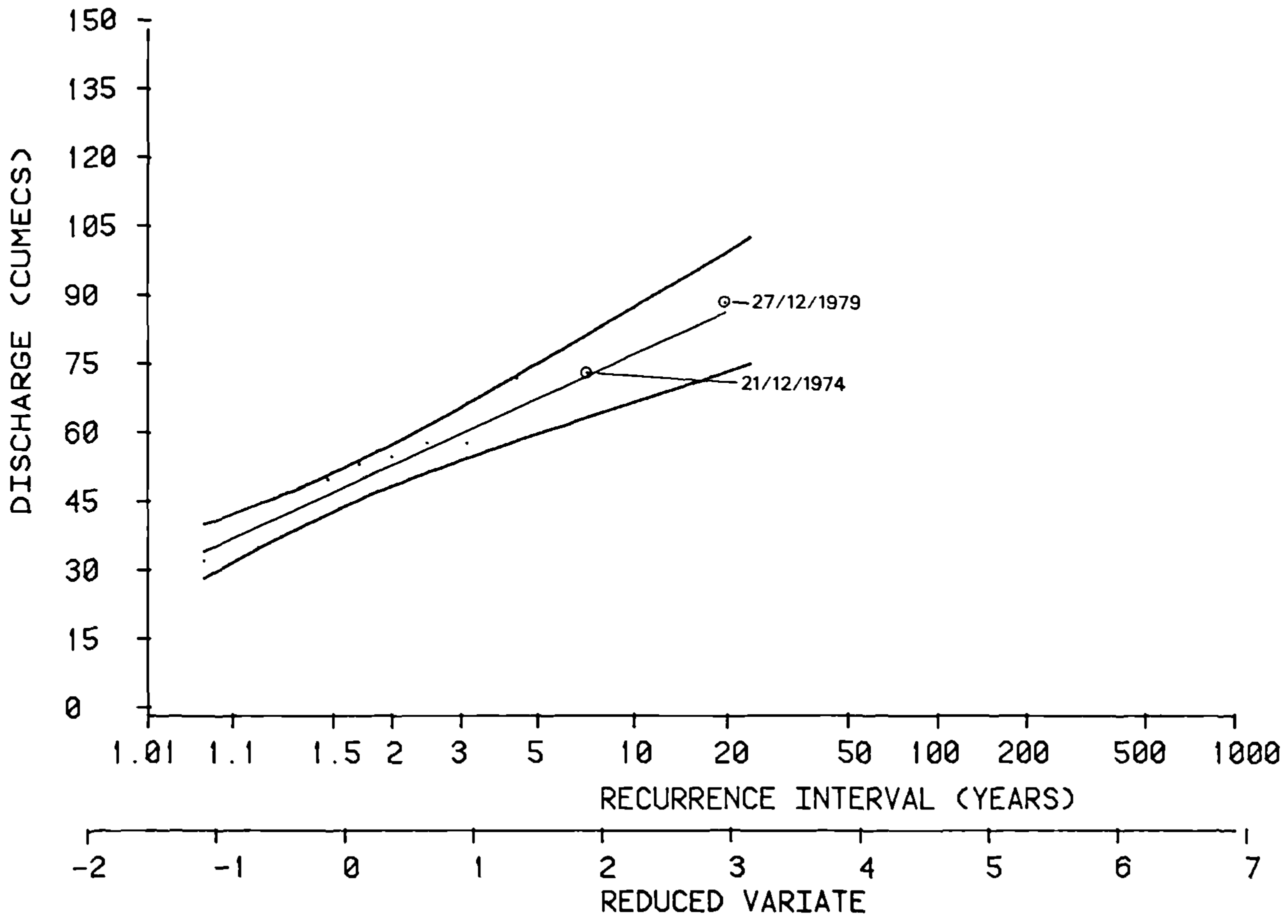
TEVIOT CATCHMENT AT HAWICK 1964-1982



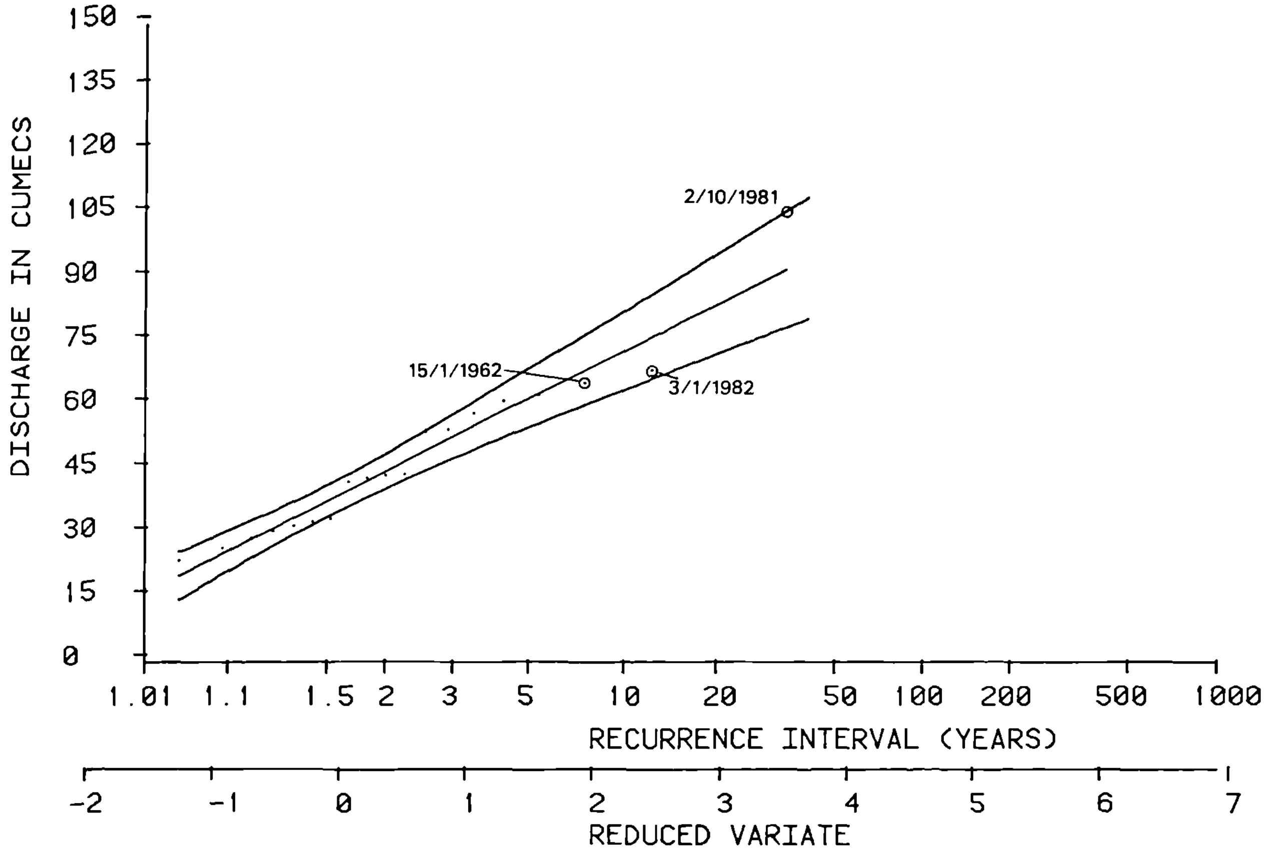
ALE CATCHMENT AT ANCRUM 1973-1982



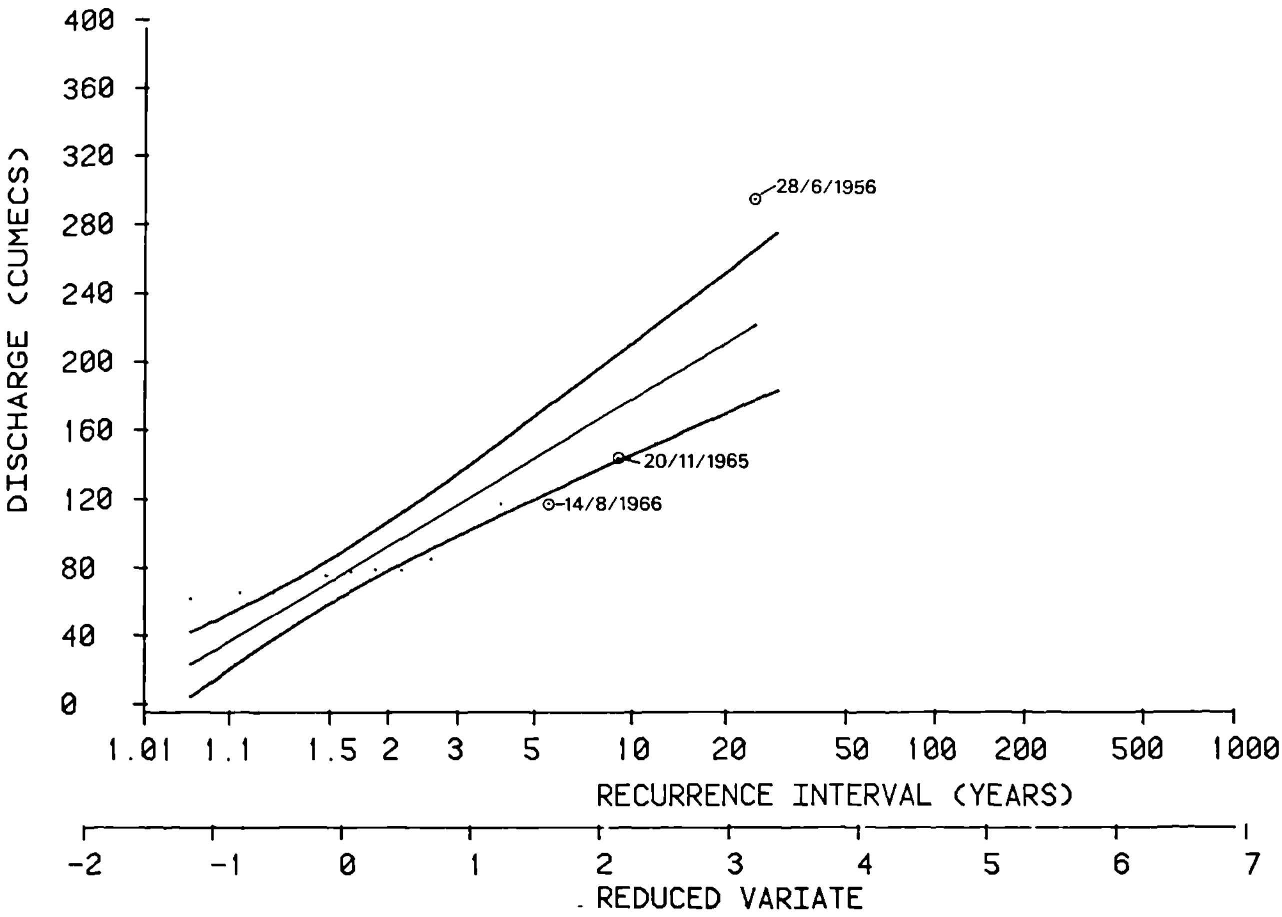
JED CATCHMENT AT JEDBURGH 1972-1982



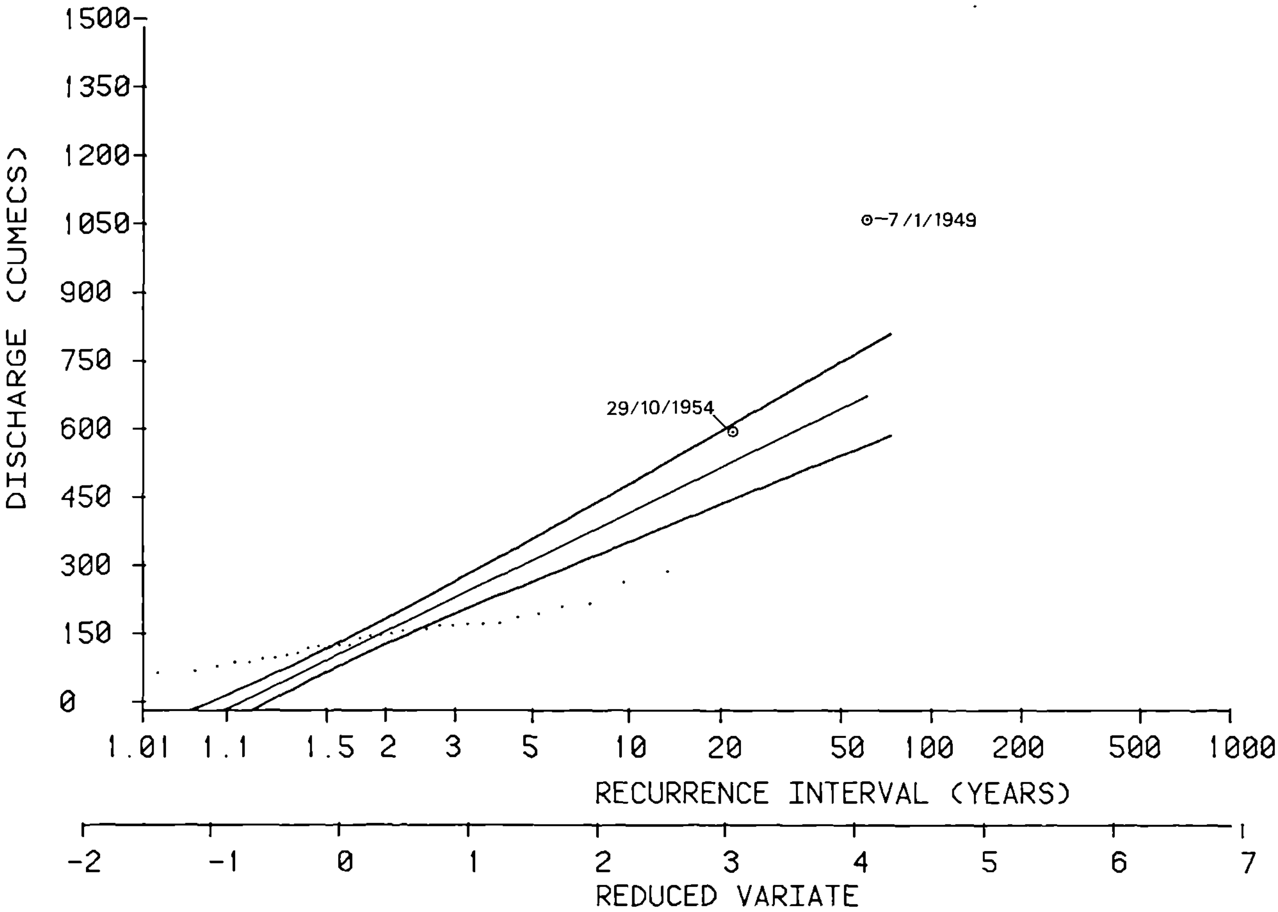
GLEN CATCHMENT AT KIRKNEWTON 1961-1982



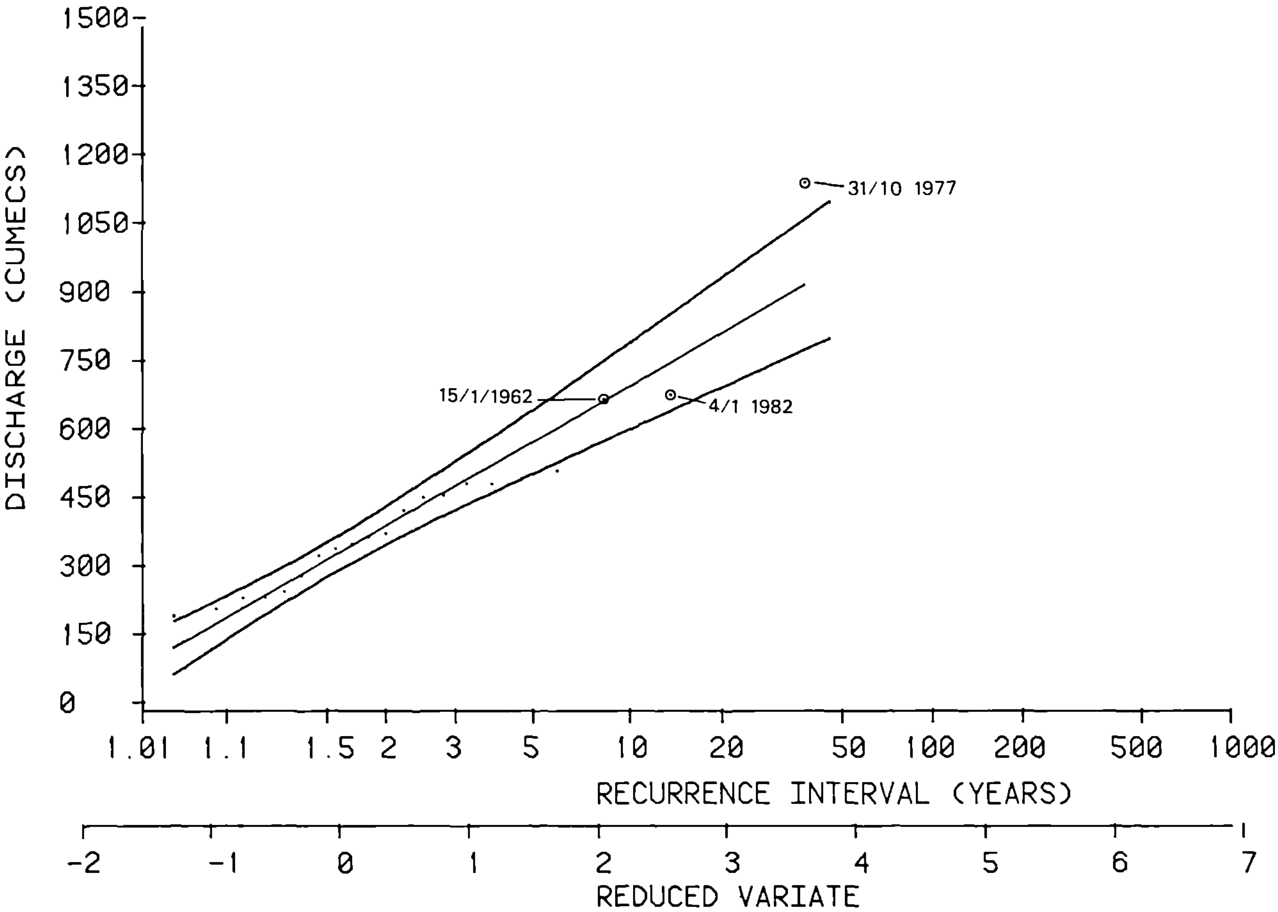
TILL CATCHMENT AT ETAL 1956-1969



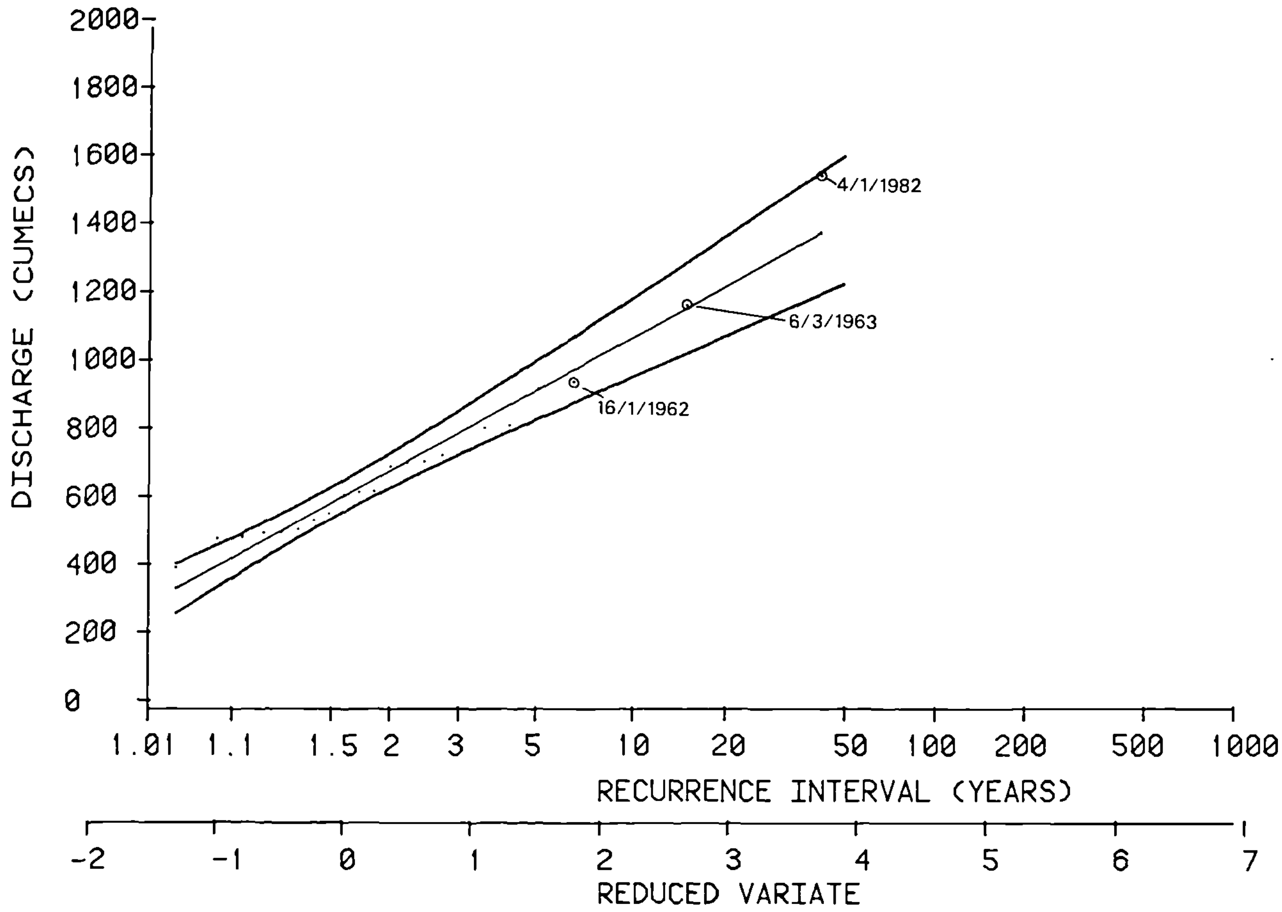
TWEED CATCHMENT AT PEEBLES 1949-1982



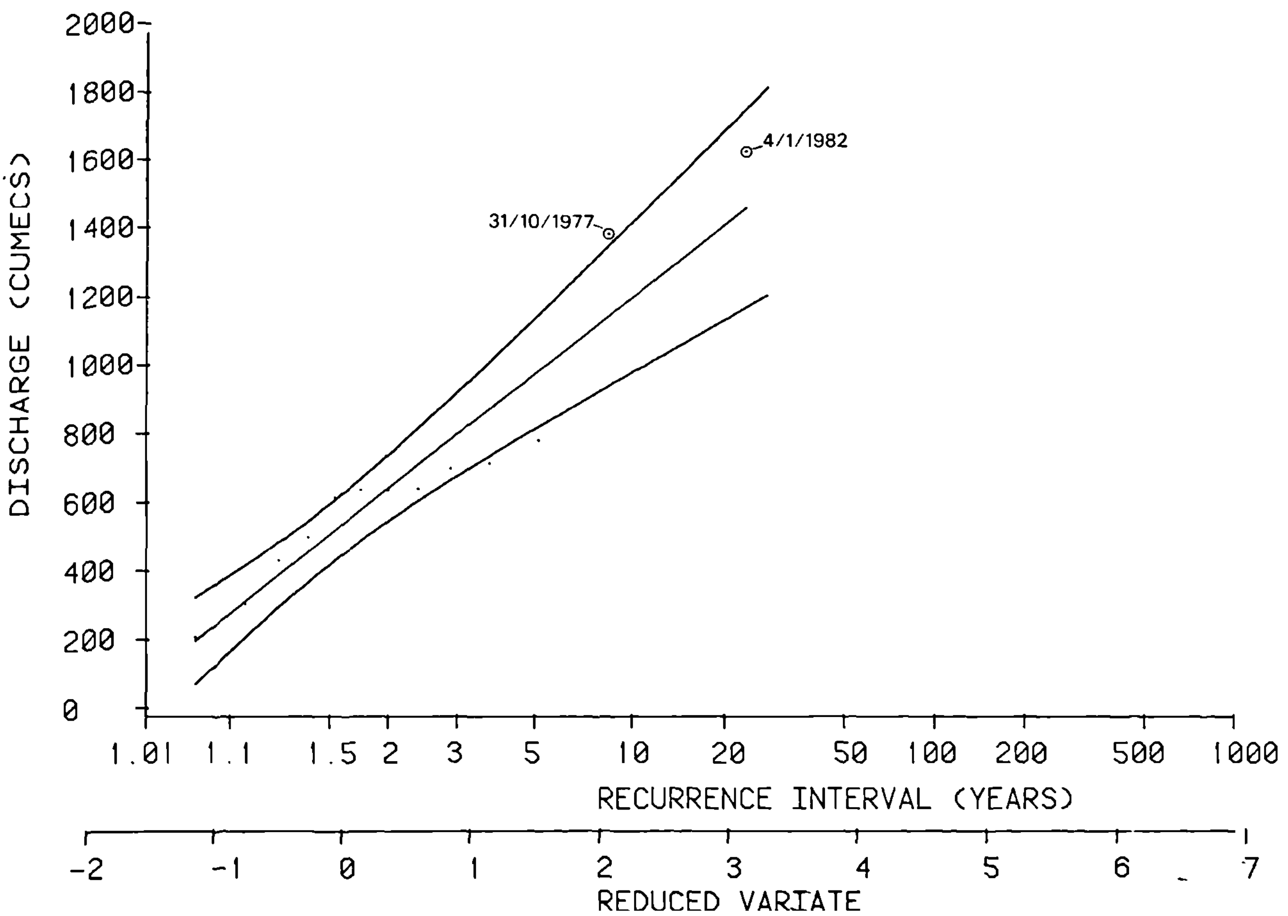
TWEED CATCHMENT AT BOLESIDE 1962-1982



TWEED CATCHMENT AT NORHAM 1960-1982



TWEED CATCHMENT AT SPROUSTON 1970-1982



APPENDIX 3.1

Cross-section bed particle size percentiles for the Dee study reaches

Study reach	D_{16} (m)	D_{50} (m)	D_{84} (m)	D_{90} (m)
1: Quoich confluence				
Section 1	0.041	0.082	0.128	0.163
Section 2	0.048	0.076	0.284	0.461
Section 3	0.031	0.066	0.187	0.256
2: Ey confluence				
Section 4	0.038	0.065	0.142	0.175
Section 5	0.032	0.079	0.142	0.194
Section 14	0.060	0.090	0.201	0.274
Section 13	0.056	0.100	0.169	0.223
3: Gleann an t-Slugain				
Section 1	0.035	0.071	0.169	0.231
Section 2	0.050	0.119	0.247	0.315
4: Lui Water				
Section 2	0.026	0.050	0.072	0.080
Section 3	0.033	0.052	0.108	0.388
Section 4	0.033	0.071	0.187	0.215
Section 5	0.026	0.054	0.082	0.092
5: Clunie Water				
Section 5	0.016	0.052	0.137	0.175
Section 6	0.038	0.062	0.106	0.124
Section 7	0.041	0.062	0.091	0.100
Section 8	0.048	0.082	0.152	0.181

Study reach	D_{16} (m)	D_{50} (m)	D_{84} (m)	D_{90} (m)
6: Luibeg Burn				
Section 1	0.047	0.121	0.284	0.338
Section 2	0.023	0.097	0.181	0.208
Section 3	0.048	0.072	0.111	0.128
7: Derry Water				
Section 1	0.022	0.033	0.050	0.058
Section 2	0.010	0.016	0.024	0.026
Section 3	0.015	0.024	0.039	0.044
Other reaches				
(a) Ey Burn				
Section 1	0.023	0.069	0.175	0.231
Section 2	0.024	0.052	0.130	0.147
Section 3	0.041	0.087	0.239	0.320
Section 6	0.076	0.169	0.832	0.891
Section 7	0.052	0.119	0.256	0.304
Section 8	0.027	0.066	0.187	0.223
Section 9	0.020	0.044	0.069	0.082
Section 10	0.023	0.039	0.059	0.066
Section 11	0.001	0.015	0.060	0.073
Section 12	0.056	0.132	0.315	0.362

Study reach	D_{16} (m)	D_{50} (m)	D_{84} (m)	D_{90} (m)
(b) Quoich Water				
Section 4	0.057	0.086	0.187	0.256
Section 5	0.058	0.089	0.208	0.256
Section 6	0.056	0.090	0.223	0.294
Section 7	0.048	0.084	0.163	0.184
Section 8	0.034	0.074	0.152	0.201
(c) Clunie Water				
Section 1	0.032	0.084	0.338	0.723
Section 2	0.038	0.076	0.163	0.239
Section 3	0.052	0.087	0.175	0.215
Section 4	0.045	0.087	0.175	0.274
Section 9	0.027	0.062	0.128	0.147
(d) River Gelder				
Section 1	0.000	0.044	0.091	0.106
Section 2	0.057	0.115	0.235	0.294
Section 3	0.073	0.137	0.327	0.568
(e) Lui Water				
Section 1	0.052	0.108	0.320	0.445

APPENDIX 3.2

Cross-section bed particle size percentiles for the Spey study reaches

Study reach	D_{16} (m)	D_{50} (m)	D_{84} (m)	D_{90} (m)
1: Feshie confluence				
Section 8	0.037	0.066	0.119	0.137
Section 9	0.044	0.124	0.265	0.299
Section 10	0.052	0.108	0.194	0.247
2: Nethy confluence				
Section 1	0.034	0.058	0.097	0.108
Section 2	0.042	0.064	0.097	0.117
Section 3	0.039	0.060	0.090	0.097
Section 4	0.037	0.059	0.086	0.094
3: Druie near Inverdruie				
Section 1	0.075	0.194	0.395	0.430
Section 2	0.056	0.090	0.117	0.126
Section 3	0.041	0.062	0.095	0.106
4: Feshie near Lagganlia				
Section 7	0.065	0.104	0.223	0.362
Section 6	0.052	0.106	0.274	0.362
Section 5	0.054	0.087	0.197	0.256

Study reach	D_{16} (m)	D_{50} (m)	D_{84} (m)	D_{90} (m)
5: River Tromie				
Section 3	0.069	0.104	0.187	0.223
Section 4	0.060	0.094	0.155	0.172
Section 5	0.060	0.102	0.187	0.256
Section 6	0.066	0.108	0.155	0.179
6: Avon at Tomintoul				
Section 1	0.043	0.076	0.124	0.160
Section 2	0.037	0.079	0.137	0.231
Section 3	0.048	0.095	0.204	0.243
Section 4	0.051	0.095	0.239	0.320
7: Avon near Foals Craig				
Section 1	0.070	0.111	0.197	0.223
Section 2	0.070	0.111	0.265	0.326
Section 3	0.075	0.124	0.215	0.247
Section 4	0.070	0.119	0.194	0.223
Section 5	0.058	0.084	0.169	0.187
8: Dorback at Aittenlia				
Section 1	0.028	0.039	0.075	0.087
Section 2	0.029	0.052	0.094	0.124
Section 3	0.000	0.046	0.071	0.080
Section 4	0.033	0.053	0.075	0.079

Study reach	D_{16} (m)	D_{50} (m)	D_{84} (m)	D_{90} (m)
Other reaches				
(a) River Feshie				
Section 1	0.038	0.060	0.256	0.315
Section 2	0.022	0.044	0.181	0.231
Section 3	0.031	0.084	0.181	0.265
Section 4	0.044	0.097	0.215	0.247
Section 12	0.037	0.062	0.137	0.169
Section 13	0.043	0.084	0.181	0.208
Section 14	0.039	0.063	0.111	0.130
Section 15	0.066	0.108	0.169	0.139
Section 16	0.048	0.082	0.126	0.142
(b) River Tromie				
Section 1	0.030	0.056	0.097	0.128
Section 2	0.064	0.133	0.388	0.512
(c) Conglass Water				
Section 1	0.037	0.100	0.201	0.256
Section 2	0.051	0.090	0.194	0.256
Section 3	0.030	0.062	0.090	0.095
Section 4	0.033	0.064	0.119	0.140
Section 5	0.045	0.067	0.090	0.097

APPENDIX 3.3

Cross-section bed particle size percentiles for the Tweed study reaches

Study reach	D_{16} (m)	D_{50} (m)	D_{84} (m)	D_{90} (m)
1: Bowmont Water				
Section 1	0.041	0.082	0.128	0.163
Section 1	0.056	0.100	0.181	0.201
Section 2	0.034	0.076	0.128	0.152
Section 3	0.033	0.058	0.128	0.152
Section 4	0.050	0.094	0.152	0.175
2: Boonreigh Water				
Section 1	0.039	0.054	0.084	0.097
Section 2	0.045	0.069	0.150	0.169
Section 3	0.042	0.064	0.128	0.145
3: Cleekhimin Burn				
Section 1	0.025	0.047	0.100	0.115
Section 2	0.036	0.055	0.108	0.130
Section 3	0.033	0.049	0.100	0.135
4: Monynut Water				
Section 1	0.017	0.039	0.074	0.091
Section 2	0.025	0.038	0.066	0.082
5: Dye Water confluence				
Section 1	0.023	0.054	0.100	0.104
Section 2	0.033	0.060	0.084	0.094
Section 3	0.041	0.066	0.097	0.108

Study reach	D_{16} (m)	D_{50} (m)	D_{84} (m)	D_{90} (m)
Other reaches				
(a) Jed Water				
Section 1	0.024	0.056	0.104	0.119
Section 2	0.023	0.060	0.128	0.431
Section 3	0.017	0.049	0.087	0.115
(b) Borthwick Water				
Section 1	0.019	0.062	0.142	0.175
Section 2	0.020	0.052	0.128	0.147

Appendix 4.1

Dee study reaches: Bankfull discharge values calculated by alternative equations

Study reach	Charlton (m^3 s^{-1})	Bathurst (m^3 s^{-1})	Simons & Senturk (m^3 s^{-1})	Darcy-Weisbach (m^3 s^{-1})
1: Quoich confluence				
Section 1	148.1	203.1	244.2	115.2
Section 2	11.2	23.3	12.8	17.6
Section 3	17.7	27.4	19.8	18.9
2: Ey Confluence				
Section 4	75.5	95.2	117.1	56.2
Section 5	76.2	97.3	124.9	56.7
Section 14	30.3	45.5	37.3	29.8
Section 13	24.3	35.2	30.2	23.9
3: Gleann an t-Slugain				
Section 1	29.8	41.5	36.9	27.6
Section 2	27.5	39.4	28.3	27.9
4: Lui Water				
Section 2	52.1	64.8	101.2	36.3
Section 3	22.3	50.1	61.8	29.6
Section 4	37.5	51.1	43.7	32.3
Section 5	16.8	22.2	20.9	13.4
5: Clunie Water				
Section 5	17.5	27.8	15.1	18.5
Section 6	14.9	22.7	12.4	14.0
Section 7	51.4	67.2	73.5	39.9

Study reach	Charlton ($m^3\ s^{-1}$)	Bathurst ($m^3\ s^{-1}$)	Simons & Senturk ($m^3\ s^{-1}$)	Darcy-Weisbach ($m^3\ s^{-1}$)
6: Luibeg Burn				
Section 1	168.7	247.9	176.4	157.1
Section 2	80.7	117.7	87.0	74.9
Section 3	18.3	25.5	20.7	15.8
7: Derry Water				
Section 1	12.4	15.5	22.0	8.8
Section 2	15.4	17.9	49.1	9.2
Section 3	55.6	64.4	191.2	32.9
Other reaches				
(a) Ey Burn				
Section 1	108.2	143.6	154.8	85.5
Section 2	175.2	216.5	296.6	121.3
Section 3	54.7	79.8	64.3	52.5
Section 6	57.2	90.3	38.4	73.7
Section 7	17.4	26.1	16.3	18.8
Section 8	7.4	11.6	5.5	8.5
Section 9	11.5	14.4	21.2	8.3
Section 10	15.3	18.6	31.9	10.3
Section 11	23.3	28.0	57.5	15.4
Section 12	36.3	54.1	33.1	39.4

Study reach	Charlton ($m^3\ s^{-1}$)	Bathurst ($m^3\ s^{-1}$)	Simons & Senturk ($m^3\ s^{-1}$)	Darcy-Weisbach ($m^3\ s^{-1}$)
(b) Quoich Water				
Section 4	12.3	21.2	11.9	14.8
Section 5	22.8	35.3	23.8	23.2
Section 6	7.9	16.9	4.6	12.6
Section 7	35.7	55.1	30.8	36.2
Section 8	18.6	31.4	16.6	20.8
(c) Clunie Water				
Section 1	21.5	46.2	30.7	31.6
Section 2	25.2	44.7	26.2	29.9
Section 3	40.8	57.5	50.3	37.1
Section 4	8.7	18.3	6.7	13.2
Section 9	16.8	22.7	19.4	14.6
(d) River Gelder				
Section 1	15.8	19.3	28.3	11.1
Section 2	25.1	38.5	25.5	26.9
Section 3	11.3	24.4	14.0	17.9
(e) Lui Water				
Section 1	24.6	41.4	25.4	29.7

APPENDIX 4.2

Spey study reaches: Bankfull discharge values calculated by alternative equations

Study reach	Charlton ($m^3 s^{-1}$)	Bathurst ($m^3 s^{-1}$)	Simons & Senturk ($m^3 s^{-1}$)	Darcy-Weisbach ($m^3 s^{-1}$)
1: Feshie confluence				
Section 8	135.3	165.2	235.5	93.6
Section 9	37.3	55.0	36.6	36.2
Section 10	47.3	69.5	57.5	44.4
Section 11	86.3	104.6	153.9	59.3
2: Nethy confluence				
Section 1	13.6	17.0	22.3	10.0
Section 2	13.9	18.1	22.8	10.7
Section 3	37.5	45.2	65.2	26.2
3: Druie near Inverdruie				
Section 1	16.9	27.7	13.3	21.8
Section 2	30.2	39.2	37.9	24.4
Section 3	17.6	23.0	22.6	14.2
4: Feshie at Lagganlia				
Section 5	73.8	103.1	97.8	63.9
Section 6	69.0	112.9	75.3	72.4
Section 7	99.0	163.6	135.0	103.6

Study reach	Charlton ($m^3\ s^{-1}$)	Bathurst ($m^3\ s^{-1}$)	Simons & Senturk ($m^3\ s^{-1}$)	Darcy-Weisbach ($m^3\ s^{-1}$)
5: River Tromie				
Section 3	25.0	35.5	27.7	23.8
Section 4	22.0	29.8	24.5	19.5
Section 5	25.7	39.0	32.4	25.1
Section 6	44.6	58.3	60.5	36.3
6: Avon near Tomintoul				
Section 1	136.2	183.7	223.5	108.5
Section 2	146.9	209.6	270.8	121.9
Section 3	80.9	114.6	92.0	75.3
Section 4	100.8	145.1	123.3	93.1
7: Avon at Foals Craig				
Section 1	103.4	131.0	136.9	78.0
Section 2	68.5	97.9	76.0	62.8
Section 3	78.8	107.7	91.5	68.6
Section 4	78.6	105.6	95.3	66.9
Section 5	24.5	32.8	27.7	21.6
8: Dorback Burn				
Section 1	10.5	14.9	7.5	9.2
Section 2	12.3	19.2	10.4	12.0
Section 3	23.1	31.2	22.1	19.0
Section 4	19.8	24.1	34.6	13.9

Study reach	Charlton ($m^3\ s^{-1}$)	Bathurst ($m^3\ s^{-1}$)	Simons & Senturk ($m^3\ s^{-1}$)	Darcy-Weisbach ($m^3\ s^{-1}$)
Other reaches				
(a) River Feshie				
Section 1	24.7	39.8	24.2	27.2
Section 2	43.2	61.1	54.9	39.1
Section 3	178.9	237.9	274.0	138.4
Section 4	116.1	149.2	146.3	88.1
Section 12	209.0	295.6	331.8	186.9
Section 13	48.3	69.1	52.4	45.1
Section 14	79.7	116.9	84.3	71.9
Section 15	22.4	40.9	20.9	27.2
Section 16	29.0	44.0	25.9	27.3
(b) River Tromie				
Section 1	22.0	30.7	31.2	19.0
Section 2	19.2	34.0	17.8	25.7
(c) Conglass Water				
Section 1	16.3	21.8	18.9	14.3
Section 2	4.0	6.3	4.2	4.3
Section 3	11.5	14.4	15.5	8.6
Section 4	14.4	19.4	18.9	12.0
Section 5	18.9	23.7	29.0	13.9

APPENDIX 4.3

Bankfull discharge values calculated by alternative equations

Study reach	Charlton ($m^3\ s^{-1}$)	Bathurst ($m^3\ s^{-1}$)	Simons & Senturk ($m^3\ s^{-1}$)	Darcy-Weisbach ($m^3\ s^{-1}$)
1: Bowmont Water				
Section 3	7.1	9.0	8.2	5.8
Section 4	5.1	7.2	4.4	5.0
Section 1	3.3	4.8	2.4	3.5
Section 2	7.2	10.3	6.2	6.9
2: Boonreigh Water				
Section 1	22.6	28.8	36.3	17.0
Section 2	9.2	12.5	9.7	8.3
Section 3	12.2	16.3	13.4	10.7
3: Cleekhimin Burn				
Section 1	48.7	40.5	30.3	24.7
Section 2	6.4	10.8	0.9	7.1
4: Monynut Water				
Section 1	5.7	7.6	6.8	4.6
Section 2	11.9	13.6	22.3	8.0
5: Dye Water confluence				
Section 1	20.8	28.7	20.4	17.5
Section 2	20.5	26.6	29.6	15.8
Section 3	14.5	19.3	18.7	11.8

Study reach	Charlton ($m^3\ s^{-1}$)	Bathurst ($m^3\ s^{-1}$)	Simons & Senturk ($m^3\ s^{-1}$)	Darcy-Weisbach ($m^3\ s^{-1}$)
Other reaches				
(a) Jed Water				
Section 1	163.7	194.7	352.6	102.2
Section 2	48.4	96.4	129.1	55.5
Section 3	97.3	115.6	232.7	61.4
(b) Borthwick Water				
Section 1	41.4	63.7	76.0	36.8
Section 2	41.1	46.0	47.9	28.2

Detailed reference to estate muniments

(Source: Register House, Edinburgh)

Estate papers referenced	
GD/248/56/4	Gordon Castle muniments
GD/248/1564	Gordon Castle muniments
GD/248/826	Gordon Castle muniments
GD/248/841	Gordon Castle muniments

Detailed estate plan references

(Source: West Register House, Edinburgh)

Register House Plan No.	Description of plan
RHP 3491	c1753 Plan of Castletown of Braemar. No scale. original penes- Farquharson of Invercauld muniments.
RHP 2200	1862 Plan showing the proposed channel of the river Feshie at its confluence with the river Spey. Surveyor P. MacBey, MacIntosh of MacIntosh Muniments [1:1,600].
RHP 1312/4	1858 Plan of the confluence of the rivers Trommie and Spey - showing the lines of a proposed channel for the Trommie and for deepening the channel of the Spey [1:1,560]. H. Morrison, Inverness.
RHP 1312/1	Specification of proposed channel
RHP 1312/2	Estimation of costs
RHP 8966	c 1790 Mains of Dalvey
RHP 811	1826 Plan of the lands N of the Dee at Inverey. [c 1:13,000] J. K. and W. P. Lindsay's papers.

Register	Description of plan
RHP 1837	1838 Kinrara. Surveyor: Robert Ray [1:3,200].
RHP 20739	1909 Plan of Wiselawmill and Farmfoot showing the course of flood water of the Cleekhimin Burn. Drawn by Lauderdale Estate Office.
RHP 1902	1740 A map of the Barony of Stobo in the Sherreffdom of Peebles now belonging to Charles Murray Esq. with with the Parks and Improvements made upon it by Sir Alexander Murray of Stanhope. Surveyor: Andrew Bearhop [1:15,800].
RHP 3703	(1821) Plan of the estate of Whitehall as surveyed by J. Blackadder. Tods, Murray and Jamieson's papers [1:7,900].
RHP 224/2	1842 The position, extent and boundaries of the lands called the commonty of Greenlaw and Dogden Moss. Surveyor: James Cunningham [1:23,800].
RHP 1439	Plan of the river Tweed at Peebles, coloured to show proposed embankment. Brodie, Cuthbertson and Watson's papers [1:1,920].

Register House Plan No.	Description of plan
RHP 31322	Mid 18th C. Mill of Allanaquoich and Mill of Delmore.
RHP 3645	1808 Plan of Mains and Forest of Invercauld and farms of Clunie and Keiloch. Surveyor: George Brown [1:8,900].
RHP 8906	18th C. Plan of grounds called the eastern meadows of Coulnakyle. Surveyor: William Forbes.
RHP 13995	1858 Plan of the Forest of Abernethy.
RHP 3964	1772 Plans of lands and lordship of Abernethy. Surveyor: G. Taylor.
RHP 8893	1771 Plan of Coulnakyle showing proposed alteration of the course of the River Nethy. Surveyor: P. May.
RHP 13936	1811 Plan of Balliefirth, Culreach, Beg meadows of Coulnakyle. Surveyor: George Brown.

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