To my mother and father

UNIVERSITY OF SOUTHAMPTON

DRAINAGE NETWORK CHANGES IN BRITAIN SINCE 1840: THE STUDY OF 18 SMALL BASINS BY THE ATTESTATION OF ORDNANCE SURVEY LARGE-SCALE MAPS

by

Jeremy Charles Ovenden

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ABSTRACT

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DRAINAGE NETWORK CHANGES IN BRITAIN SINCE 1840: THE STUDY OF 18 SMALL BASINS BY THE ATTESTATION OF ORDNANCE SURVEY LARGE-SCALE MAPS

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Throughout Britain, changes in drainage network extent over the last 150 years are identified for 18 British catchments representing a wide variety of basin types and environments. 89% of the catchments examined demonstrate extension of the drainage network which ranges from a 2.68% increase in the Plym basin to a 438% increase in the catchment of the Hodge Beck.

Several potential data sources are examined, concluding that five editions of Ordnance Survey 1:10560 and 1:10000 Series maps provide an important and unrivalled source of historical data for the study of drainage network change. The data these maps afford are substantiated and explored by field survey for eleven basins, enabling significant amounts of network change to be attributed to flush metamorphosis (9 basins), pipe burst (9 basins) forest or agricultural drains (10 basins) and urbanisation, construction work and storm water disposal (6 basins).

The monitoring, by repeated cross-sectional measurements, of sites of network extension by the natural metamorphosis of flushes at Plynlimon Central Wales, and man-induced link creation in the New Forest, Hampshire, indicates trigger mechanisms and processes responsible for drainage network extension. These identified processes and controls are combined with important catchment parameters controlling change (identified by regression analysis and field survey) to form a provisional model for drainage network change.

CHAPTER 1 INTRODUCTION

The drainage network is one of the most sensitive characteristics of the drainage basin, because it adjusts rapidly to changes of input to the system in the form of precipitation, and to changes of controls on the system in the form of other basin characteristics. Changes can therefore reflect the extent of man's influence within a drainage basin. Lewin (1979) observed that human activity in the vicinity of river channels has often proceeded in complete ignorance of, and totally oblivious to the changes of river network, planform and channel morphology that may result. The complete understanding of rivers, approached through each of these categories of change is desirable if the future activities of man on river floodplains is to continue in safety.

If the need for a study of drainage network change is to be fully appreciated, recent trends in fluvial geomorphology require brief examination as does the position of fluvial studies in the context of geomorphology.

1.1. BROAD DEVELOPMENTS IN 20TH CENTURY GEOMORPHOLOGY

Broad reviews of trends in geomorphology in the 20th Century are provided by several authors including Brown and Waters (1974), Thornes and Brunsden (1977) and Schumm (1979). All these authors identify major trends in the evolution of geomorphology that provide a background for present studies in the subject. The first of these fundamental developments is that of denudation chronology and evolutionary or time-dependent studies, also referred to by Brown and Waters (1974) as the 'Wooldridge and Linton approach'. This type of approach is reviewed in many of its aspects by Thornes and Brunsden (1977) while change over time is basic to the approach of Schumm (1979).

The second fundamental development is one of accurate descriptions of mechanisms and rates of operation of geomorphic processes over short time periods. Schumm (1979) specifically notes that

'details of landscape evolution require elaboration

> *(if only to be of value to management and control attempts). Therefore an understanding of the functioning of geomorphic systems over short spans of time is mandatory.'*

In addition to these trends Thornes and Brunsden (1977) identify a changed direction for studies - the adoption of a systems-based attitude towards geomorphological investigations - while Thornes (1979) suggests that research needs progressively to become more applied. To such an end Thornes recommends the development of new methods and techniques directed towards specific applications, and the recognition of potential research areas. The beginnings of a basis for this study of drainage network changes can be obtained by combining these last suggestions with Gregory and Walling's (1974) observation that

> *'perhaps the most significant force within geography has been exerted by the realisation that the study of geomorphology can only be fully implemented by embracing an appreciation of contemporary process. Evaluation of the significance of present processes for recent landform changes can be the basis for interpreting the extent to which process-response systems must have been different in the past and also for establishing relationships which are fundamental to landform interpretation.'*

1.2 RECENT TRENDS IN FLUVIAL GEOMORPHOLOGY

Fluvial geomorphology originated in the U.S.A., stimulated initially by significant papers such as those by Horton (1945) and Schumm (1956) although the approach to processes operating in small catchments and recent trends of utilising the techniques of the hydrologists has been suggested (Brown and Waters, 1974) to have resulted from the publication of *Fluvial Processes in Geomorphology* (Leopold, Wolman and Miller 1964). Recent progress has been summarised by Gregory (1977, 1978a) as occurring in three directions - elaboration of existing themes, development of existing ideas and the emergence of clearer objectives for fluvial geomorphology. Gregory also notes a tendency to become more applied, which requires an emphasis on short-term changes so that a knowledge of recent changes may be the basis for predictions. This recent progress is reviewed in *Research on Geomorphology of Water-Produced Landforms* (N.E.R.C. 1976) which identifies future research needs for fluvial fields. An important section of these recommendations states, as a general topic, that

> *'Research should be directed towards an understanding of the ways in which channels are extended or become infilled.'*

and five approaches are suggested for examination; these are the initiation of first-order channels during storms and their subsequent history, channel modifications near stream heads, equilibrium of channel heads, expansion and contraction of wetted stream channels and effects of human activity on drainage networks.

Academic reasons for the need for a study of drainage network changes are thus established by the designation of this field as a priority research area by N.E.R.C. in their 1976 review. The topic of recent drainage network change arises as a logical sequel to work that has recently been undertaken on changes of river channel geometry and on channel patterns which, as has already been mentioned, when coupled with studies of drainage networks, encompass the various methods by which man's influence on drainage basin morphology may be approached. Thus the study of drainage network change can be visualised as a study potentially leading to applied research through its inclusion of the effects of human interference upon the drainage network. N.E.R.C. (1976) identified the initiation of stream channels together with the stability of stream heads as being of considerable importance to the geomorphologist as well as to the hydrologist wishing to predict water flow or to the engineer engaged in controlling stream channel formation. Additionally the disruptive effect of gullying (frequently suggested as the initial step in the formation of permanent network extension) on agriculture as well as upon communications makes it desirable that the nature, causes and effects of gullying in relation to the drainage system should be fully understood.

1.3 AIMS OF RESEARCH

The aims of this study are four-fold.

a. To establish whether drainage networks in Britain have changed during the last two centuries. This is approached by endeavouring to identify in several contrasted relief and rainfall areas in Britain the nature of drainage network changes in response to natural as well as man-induced changes of land drainage and runoff.

b. To conclude how extensively changes in drainage networks have occurred in Britain, to summarise the diversity of causes of change and to predict, in general terms, where change is likely to occur in the future.

c. To provide some insight into the processes of network change operative over short time periods through detailed monitoring of small changes in channel and bank morphology.

d. To assess the extent of man's influence on changes of the natural drainage system.

After the review of the literature (Chapter 2), Chapter 3 examines the feasibility of Ordnance Survey map comparisons for deriving data pertaining to changes in drainage networks. The development of this cartographical technique is continued in Chapter 4 introducing field survey at change locations in a particular drainage basin. Field survey is then (Chapter 5) applied to ten other areas in Britain.

Other possible data sources for drainage network changes are considered in Chapters 6 and 7 while the analysis and conclusions of the study are presented in Chapter 8.

CHAPTER 2 THE PROGRESS OF STUDIES OF DRAINAGE NETWORK CHANGE DURING THE TWENTIETH CENTURY

Until recently (i.e. Gregory 1979), very little attention has been paid in geographical literature to changes in drainage network patterns over any timescale, and much of the literature that is available is concerned only with long time scales and non-British environments. Most studies relevant to the British context are concerned with short term variations in the drainage network caused by specific climatic events. Such studies as there are of long term changes concern the effect of changed hydrological conditions, exemplified by the studies of dry valleys (Gregory 1966 a,b). Between the study of specific short-term changes and general reviews over long periods, lie a wide middle sector of drainage network changes which are in Britain as yet largely undocumented. This study, by covering changes in British drainage networks over the last 150 years, will, it is hoped, begin to fill this serious gap.

In order to obtain an overall impression of the extent and distribution of network change, all direct and inferred references, from such sources as peat erosion studies, specific references to gullying, and descriptions of cloudbursts and other extreme events, were located on an outline map of Britain (Figure 2.1). On this map the distribution of sites is predominantly in upland Britain, with the Pennines and the Peak District attracting considerable attention, although perhaps more surprisingly several sites of change occur on the heathlands of Southern England.

In this review of the relevant literature, various ways of grouping the studies suggest themselves. Division according to the mechanisms and forms of change (i.e. cloudbursts, gullying, peat erosion) or a temporal division, allowing network change to be considered anywhere on a timescale of thousands of years through to a matter of days or hours, are possible bases for grouping of the

FIGURE 2.1 DISTRIBUTION OF NETWORK CHANGE BY REFERENCE TO SITES OF CLOUDBURSTS GULLYING AND PEAT EROSION.

literature. The classification based on mechanisms or the forms that change may adopt creates problems in that the boundaries of each category are ill-defined and some forms lie across category boundaries. An illustration of this problem is the difficulty of separating gullying from peat erosion in some areas of the Pennines. Another possibility is the division of network change into the extension and contraction of the drainage network. Problems exist in this categorisation because certain features such as gullies represent extension of the drainage network at their inception, but a change in the prevailing hydrological conditions may result in their becoming relict in nature so that the gullies then represent contraction of the drainage network.

The beauty of the time-scale approach, as a basis for grouping the literature, is that categories arising from other classifications are easily incorporated. In addition, the relevant, and occasionally extremely important, American and other non-British examples can more easily be integrated and accommodated within the timescale classification.

Although there is little literature that is specifically concerned either with long term changes in drainage network or with network dynamics, there is much literature that touches on these subjects. This marginal literature must be considered as a background to the present investigation. The clearest way of showing the topics covered and the methods used in these diverse studies is to present them in tabular form. This is attempted in Figure 2.2, locating a particular type of study according to the date when it was first developed. During the course of sketching the development in this way, two trends, of convergence and divergence, could be discerned and these form the basis of Sections 2.2 and 2.3.

This study concentrates on the period of the last 150 years, and uses shorter-term development over a maximum period of 20 months to give possible insight into processes of network change.

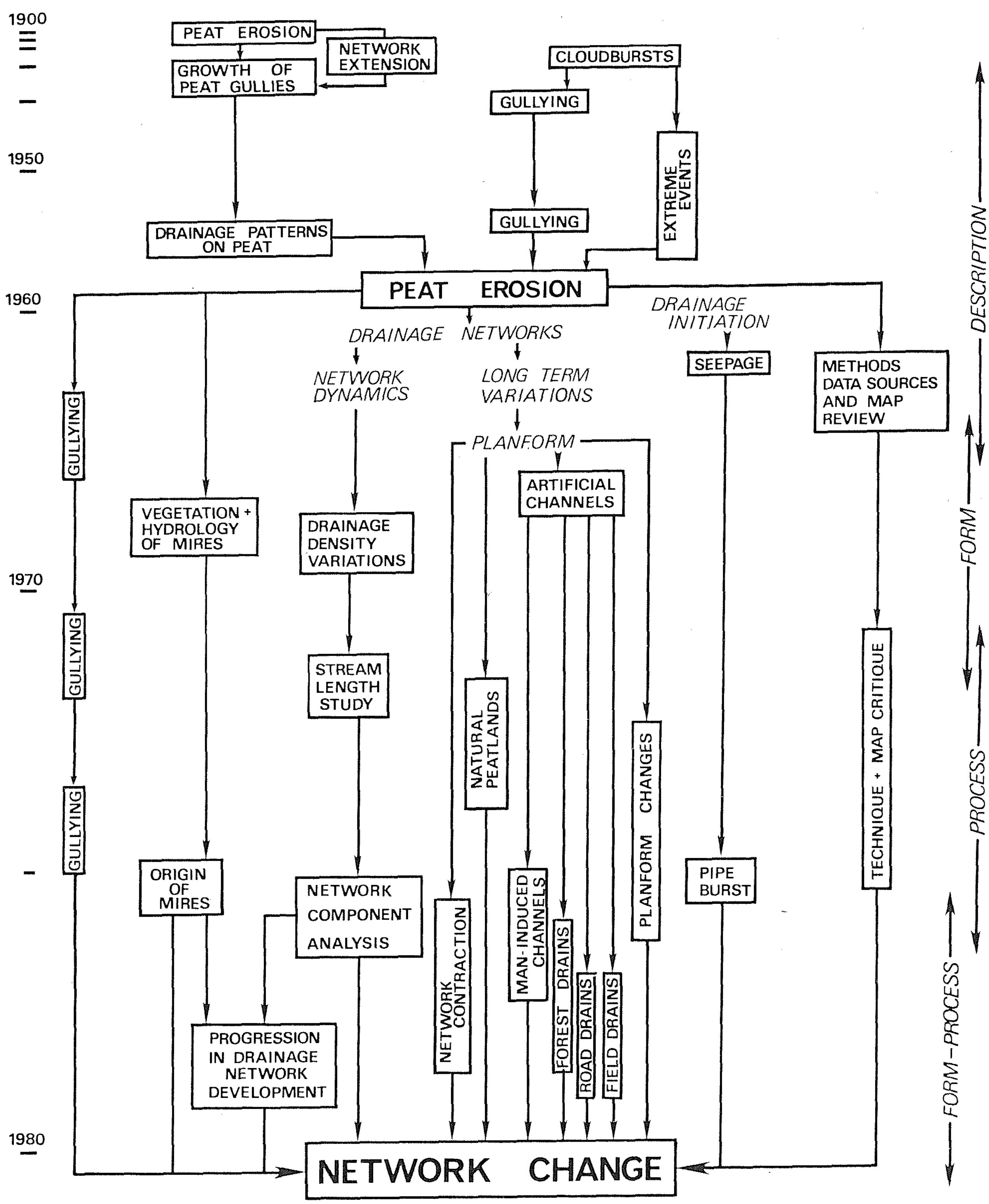


FIGURE 2.2 THE CONTEXT AND EVOLUTION OF THE STUDY OF DRAINAGE NETWORK CHANGE

2.1 CONVERGENCE AND DIVERGENCE

Since 1900, empirical studies pertinent to drainage network change can be viewed in two groups. A convergent group is represented mainly by the early studies of peatlands which, in the late 1950s and early 1960s, culminated in several studies of erosion verging on the study of drainage network changes. Amazingly, these studies on peat erosion generated further studies of gullying, drainage initiation, studies of mires or bogs and short term variations in drainage network extent without considering as a subject permanent changes in the drainage network. Subsequently, a trend of divergence from the subject of drainage network change becomes apparent with the appearance of a second group of studies on various aspects of drainage networks, although the potential of such studies in relation to drainage network change does not appear to have been fully realised or explored. With the emergence of studies founded on the form-process paradigm post 1965, it was perhaps inevitable that studies of human influences on the natural drainage system would point gradually towards a critical examination of changes in drainage network extent. Figure 2.2 demonstrates how well a study of drainage network changes follows up many of the divergent paths deriving from the peat erosion studies of the early 1960s.

Over the span of the Twentieth Century the literature referring to drainage network change may be seen to have passed through several distinct phases which to some extent has governed the direction that research has taken. The first half of the century may be classified as the static phase when the predominant approach adopted by authors was the general description of the effects of cloudbursts and other extreme climatic events.

From the mid-1950s the approach is more specific, and we find detailed observations of the nature of particular fluvial landforms exemplified in the studies of gullies and sites of peat erosion (e.g. Tuckfield 1964, Bower 1961). These studies of form become prevalent, only to be superseded in the late 1960s by a concentration on process with studies of drainage density variations and the hydrology of mires. It is not until the 1970s that these form and process approaches combine, allowing studies such as those of pipe bursts, natural progression of drainage network components and the effects of the various artificial channels on the hydrograph of a particular stream.

2.2 CONVERGENCE

Some of the earliest allusions to drainage network changes in Britain are found in the early studies of peat erosion principally by Crampton (1911), Elgee (1912) and Moss (1913). Elgee (1912) recognised that erosion rates of peat varied spatially, the moorlands of N.E. Yorkshire showing appreciably less peat erosion than those in the Pennines. Both Crampton (1911) and Moss (1913) discussed peat erosion in some detail and it is in this context that Moss referenced the earliest discovered example of drainage network change stating that the retrogression in the cotton-grass moors is apparently initiated by the cutting back of streams at their sources. The evidence presented for this was that certain streams on the Derbyshire Peak had extended their courses over the period between different editions of Ordnance Survey 1:63360 maps. This important reference will be discussed in detail in Section 3.1.1.

Another reference to drainage network extension by Hollingworth (1934) referred to an area north west of High Pike in the Lake District where headward extension of peat gullies was traced by successive representation of an old mining track. Additionally, Hollingworth (1934) in his conclusions mentioned the effect that peat erosion has on runoff, on river regimes, on erosion within stream courses, and on the hydrograph for points downstream; this represented an advanced paper for its time.

These early studies of peat erosion provided the backbone for one of two major 'branches' of the literature dominating the period of convergence (Figure 2.2) and fed directly into the more numerous references of the early 1960s on various aspects of peat erosion which marked the end of the period of convergence.

The other major branch of the early literature, relevant to drainage network change, is that describing cloudbursts and other extreme events, and includes the important aspect of gullying. Although many of the numerous examples of this type of study include implications of extensions to the drainage network, only comparatively few contain specific references. The articles by Huddleston (1930), Arkell (1955) and Green (1955) in particular invite comment. Huddlestone (1930) illustrated the transient nature of gullies in the hydrological network with his observation that storm water runoff disappeared through a series of swallow holes in the bed of a gully and failed to disturb a dry stone wall built across the actual bed of the feature. Arkell (1955) described the conditions that scoured out a gulch near the hamlet of Coryates which after the storm of 18th July 1955 looked like a 'desert wadi'. Arkell in summing up his observations stated the following:

> *'It is, in fact these comparatively rare events that really mould the landscape ..... Lyell's principle of uniformitarianism ('the processes of the present are the key to the past') becomes credible only when it is realised that the exceptional cloudburst is really part of the normal weather pattern and from the point of view of denudation, the important part.'*

The pertinence of this statement in the context of network extension will become clearer during the course of this study.

The North Exmoor floods of August 1952 have been well documented, and Green (1955) provided an example of the type of article available. Amidst mention of the destructive elements of the 1952 flood there exist several references to runoff concentrating itself due to some restriction or construction and then entrenching itself. According to Green this is especially common in the absence of vegetation due to the occurrence of moorland tracks and similar unvegetated areas, a theme which is to recur throughout later references to gullying (i.e. Tuckfield 1964).

Specific references to gullying, sometimes the result of individual storms, are numerous in the literature and provide an important extra dimension to knowledge of the effects of cloudbursts. Some of the most important papers are by Grave Morris (1942), Learmonth (1950), Thomas (1956) and Baird and Lewis (1957). Grave Morris (1942) was concerned with observations on a specific gully formed during the course of a storm occurring on the 22nd June 1941. According to the author the factors contributing to formation were a combination of exceptionally heavy rainfall, the drumlin into which the gully was cut and the existence of ridges and furrows running down the slope, the latter condition illustrating once again the importance of drainage concentration in the initiation of channel extensions or gullies. The Learmonth (1950) study concerned gullies in many parts of the Lammermuirs which

> *'added to their cone of debris, so impeding roads and changing the course of streams, and a few fresh gullies were formed by scouring in ditches'*

This reference illustrates the effects of human interference in the drainage network for a specific area. Baird and Lewis (1957) considered the direct results of exceptional rainfall to be a major factor in the formation of gullies in the Cairngorms, while, in the study of five different categories of gullying in the Brecon Beacons, Thomas (1956) singled out the erosion of drainage ditches associated with afforestation of the area as a major type of gullying, claiming that the recognition of this resulted in greater care in the planning of initial drainage operations, particularly with regard to pattern and gradient.

The two-fold division into peat erosion and cloudbursts and their effects (with specific reference to gullying) effectively summarises the state of the literature relevant to drainage network changes at the beginning of the 1960s. Immediately afterwards, further studies on various aspects of peat erosion showed a renewed interest. However the seemingly logical progression from these studies to examination of network change did not occur and these studies may be regarded as marking the end of the convergence period and the beginning of the divergence period which was to last for two decades.

2.3 DIVERGENCE

Studies of peat erosion in the early 1960s may be seen to arise directly from the work on peat gullying and erosion already cited, and dating from the early decades of the century. They began with a paper (Johnson 1958) examining drainage patterns on peat moorlands. Evidence of the inspiration for this paper is seen in the discussion of Moss's (1913) work on the Derbyshire Peak while Johnson's own additional evidence is used to qualify his statement that

> *'a marked lengthening of the stream courses within the peat moss has taken place.'*

From a consideration of both Moss's conclusions and 1:10000 scale aerial photographs, taken in 1953, Johnson demonstrated that

> *'many streams had reached the full length of their courses by the date of survey of the map (1911) e.g. Jaggers Clough, Blackden Rind, and Grindsbrook Clough have not enlarged their headwater drainage area to any great extent. However, other streams show evidence of cutting back e.g. the Kinder Downfall stream and Fair Brook have cut back beyond the point noted as the rise by the Surveyors, by as much as two hundred yards. On the gently-inclined dome-shaped elevation of Featherbed Moss, long feeder streams are cutting back actively, and have reached points nearly a quarter of a mile beyond the stream sources noted by the survey.'*

Also worthy of note from the same paper is an early reference to a process of network extension in the tendency of the peat moss to develop a drainage system of its own by means of water seepage. This frequently causes collapse of the peat surface, leading eventually to an open channel, and later a gully.

This paper is the source of numerous comments on general peat geomorphology and hydrology, in which the erosion of peat and the extension of peat gullies form substantial sections in the paper. However papers by two other authors are prominent in the literature, namely those of Bower (1960, 1961, 1962) and of Tallis (1964, 1965, 1973) and doubtless these are responsible for the inception of several approaches which may be seen to arise directly from peat erosion studies including network component analysis, drainage initiation, and peat hydrology.

Bower's work centred mainly on types of peat erosion and their distribution (1961), and on the causes of erosion (1962). In the later paper Bower defined three causes of peat erosion: erosion as part of the peat accumulation cycle (blanket peat, it is suggested, is an inherently unstable system), erosion caused by climatic change, and erosion or accelerated erosion induced by biotic activities including burning, grazing and artificial drainage. Tallis in a series of papers on the Southern Pennine peats followed the initial work by Bower, and the most crucial papers relevant to a study of drainage network change are those of his concerned with the patterns of erosion (Tallis, 1964), with the evidence for recent erosion (Tallis, 1965), and with direct observations of peat erosion and peat hydrology on Featherbed Moss, Derbyshire (Tallis, 1973). It is in the 1965 and 1973 publications that direct mention is made of, and supporting evidence is given for, extension of the drainage network where peat stratigraphic and pollen analytical studies of the upper layer of peat are used to produce reconstructions of the past local environment of streams at specific locations. Evidence from such methods, including soot contamination of layers of peat, suggests that the deepening of the lower reaches of the stream-course on Featherbed Moss and the formation of all the upper reaches occurred at some date after 1770. Tallis clearly identified two distinct phases of stream erosion in the Southern Pennine blanket bogs:-

> '1. *A very slow headward extension of streams into the peat blanket along pre-established lines of weakness (the pre-glacial stream channels) beginning c.3000 B.C. and continuing into historic times; but even by A.D.1300 this extension may not have reached the limits of the pre-glacial stream channels in many areas.*

> 2. *A very rapid extension of gullying after c. A.D.1770. On Featherbed Moss at least 200m. of stream-course would appear to have developed in the last 190 years.'*

Tallis's more detailed paper (1973) examined the viability of this dating in the light of 12 months' direct observations on the method and rate of peat erosion in a second, similar, drainage gully. Tallis concluded that his earlier suggestions concerning erosion rates are feasible and suggested that snow melt and heavy rain (when stream flow exceeds 40-50 litres per minute) caused substantial peat erosion, while frost is crucial in loosening peat. These dates indicate that the erosion of the streams may have been fairly recent and this may be related to anthropogenic disturbance of the moss surface, moor-burning being suggested as the cause of peat erosion on Featherbed Moss.

These studies in peatlands, although seemingly on convergent paths to a study of permanent change to drainage networks, never actually reached the topic. Instead, over the last fifteen years, several divergent paths were taken by geomorphologists which are only marginally relevant to network changes. It is these alternative paths that will now be discussed beginning with studies of drainage initiation.

Studies of drainage initiation were presented in a series of excellent papers by Bunting (1960, 1961, 1964). Unfortunately, and somewhat inexplicably, it is a topic that has received little attention since. Bunting suggested that moisture moves in narrow concentrated lines of relatively deep soil characterised by *juncus*, which he termed seepage lines, and that these form a dendritic pattern linked directly to visible drainage lines. This is also one of the earlier hydrological references to a feature common in upland catchments which has since become known by the term flush (Newson and Harrison 1978). Bunting (1961) considered the role of seepage moisture in soil formation, slope development and stream initiation stating that:-

> *'corrosion of bedrock in seepage hollows is considered to be a major factor in the headward extension of first-order streams.'*

He suggested that this process takes place selectively, and that removal of the finer particles is accomplished by subsurface as well as surface flow. In his publication of 1964 Bunting elaborated previous papers differentiating between 'seepage lines' and 'percolines' in that the former contain surface water in wet periods. This appears to be the most recent statement in this particular line of research save for brief peripheral comments on the effects of seepage steps in the New Forest (Tuckfield, 1973).

Studies of the initiation of drainage by piping and pipe-bursts have been undertaken by Jones (1971) and Newson (1975) respectively and these are considered in detail as they become relevant to ongoing work at fieldsites described in Chapter 7.

A line of enquiry, initially developed in the 'convergence' period of the literature review, was that of gullying, and isolated references continue throughout the divergence period of the literature, although they become more process orientated.

Tuckfield (1964) described six gullies in the northern part of the New Forest, and concluded that they originated during very heavy rain in the superficial deposits on convex slopes of heathland areas where the vegetation cover had been destroyed by man. Information from this paper has been re-presented in Table 2.1 from which it is clearly evident that in all cases some man-created event has been responsible for the initiation of the gullies by drainage concentration. Recent visits by the author to all of the sites described by Tuckfield in this paper have revealed substantial healing of the gullies, in some cases to such an extent that former gullies are unrecognisable in the field today. The paper did however serve to stress the influence of man in initiating the gullying process, and also emphasised the transient nature of the majority of these features. It was this latter point particularly that caused reconsideration of the role of the gully in the functioning hydrological

Location	Feature Causing Drainage Concentration	Date of Feature	Start of Gullying
A. South Slope of Acres Down	Track	-	By 1968
B. West Slope of Acres Down	Firebreak	1951	1951
C. West Slope of Acres Down	Vegetation-Free Strip	-	By 1968
D. South-West Slope of Stoney Cross Plain	Gas Pipe Construction	1959	1959
E. Marrowbones Hill	Track	-	By 1963
F. Foulford Bottom	Track	-	By 1963

TABLE 2.1 FACTORS INITIATING GULLY DEVELOPMENT NEW FOREST, HAMPSHIRE (AFTER TUCKFIELD 1964, 1974)

network, and resulted in its omission from detailed investigation (see Section 6.3). Several other papers concerning studies of specific gullies have been presented since Tuckfield's work, including Fairbairn (1967) and Harvey (1974), while Brown (1970) showed the frequency and distribution of such features over Southern England. A study of gullying, this time with respect to network change was made by Gregory and Park (1976) where the development over the last 20-25 years of a short gully in Central Devon was related to a changed runoff pattern consequent upon road metalling some 28 years ago. The conclusion drawn by the authors emphasised the effect of man on the development of the feature and stressed that the magnitude of his influence on the drainage network may hitherto have not been fully appreciated. On similar lines to Gregory and Park (1976), but on a considerably larger scale, is the book by Cooke and Reeves (1976) which examined arroyo formation in the American Mid West, concluding that there is strong evidence of the drainage concentration hypothesis for arroyo development. Cooke and Reeves also stated that:

> *'the discharge of water in a drainage system - an isolated event in a system characterised by ephemeral flow - is governed by several independent and semi-dependent variables. The more important of these are climate, vegetation, dimensions of the basin and ground materials.'*

With the last two variables remaining constant, the authors attempted to explain the identified increase in valley floor discharge in terms of climatic or vegetational change, and so make one of the first real attempts to identify major causes of channel entrenchment.

2.3.1. Network Plan Form

Perhaps the major divergent branch of the literature from the studies of peat erosion in the early 1960s is that grouping studies of drainage networks (Figure 2.2). A distinction can be made between studies which concern potential long-term variations in the drainage network (considered in this Section) and short-term variations considered in the context of network dynamics in Section 2.3.2.

One of the first important papers to consider the extent of artificial drainage channels in England and Wales was that by Johnson (1966). Johnson observed that agricultural drainage works started on the mountain slopes, where thousands of miles of 'grips' were cut to improve the sheep grazing, but drainage was also widespread in lowlands where

> *'nearly every hedgeline represents also the line of a ditch. Fields differ in size according to district topography, etc. but at a conservative estimate there is an average of at least 5 miles of ditch per square mile, and in England and Wales there is something of the order of 185,000 miles of ditch.'*

Contemporary with Johnson (1966) is the paper by Howe Slaymaker and Harding (1967) which assessed the importance of drainage works on aspects of flood hydrology from observations in the upper catchments of the severn and Wye. The authors stated that

> *'By 1966 the effective drainage density had been increased considerably by the introduction of open plough ditches associated with afforestation and land drainage.'*

and this resulted both in increased amounts and in increased speed of runoff from major storm events. It was further suggested that the effects of open plough ditches in afforestation would be intensified by land drainage works for agricultural purposes. In spite of these observations by Johnson (1966) and Howe Slaymaker and Harding (1967) there have been few subsequent studies of artificial network components or of extent of the drainage network. An exception to this is the extensive work undertaken by the Field Drainage Experimental Unit, Ministry of Agriculture Fisheries and Food as referenced in several papers by Green (i.e.1976). Field drains, and to some extent road drains, have also been considered by Marshall, Wade and Clare (1978) who estimated the length of drainage channels in England and Wales as 128,000km. which is compared with the main river length of 30,511km. over the same area. Forest drains have been briefly considered by Jones (1975), Tuckfield (1976), Williams (1977) and Newson and Harrison (1978). Of the remaining studies of network extent, man-induced channels created by indirect events rather than direct ditching have been referenced by Tuckfield (1964) and more recently by Gregory and Park (1976), while studies of natural peatlands have proceeded throughout the divergence period (i.e. Mosley 1972, Moore & Bellamy 1974, Tallis 1973).

Contraction of the drainage network is a subject that has received little attention. Pelham (1964), in one of the few papers available, presented general evidence to show that the water table in the chalk around Southampton had fallen by as much as 60 feet. Methods used to identify this fall included the recording of well depths, evidence from Saxon charters which showed that streams rose substantially higher up their valleys than they normally do today, and evidence provided by examination of mill leats and races. The latter evidence is the presence of swallow-holes in a specific mill-stream bed at Soberton on the Meon which indicates that the mill-race is now perched; the absence of clay lining on the mill-race indicates that this was not the case when it was first constructed. Another specific example of contraction of the drainage network, from the same source, is seen in the severance by a railway cutting of the upper reach of Cheriton Brook (a head tributary of the Itchen), a clear example of human influence on the drainage network. A more recent reference to man-induced contraction of the drainage network is provided by G.P. Williams (1977) in an account of Washington D.C.s vanishing springs and waterways. From comparisons of present and past editions of maps, Williams claimed that over the years man has caused streams to become underground sewers or has obliterated them completely. Sediment is identified as a major cause of network contraction; it is suggested that this sediment has become available in the last 200 years and that this shrinkage pattern will continue unless efforts are made to retain freshly-exposed dirt at construction areas, ploughed fields, and such sites.

The final aspect of the literature concerning long-term variations of network extent is the specific study of planform changes, a concept identified in the U.S.A. in the early 1970s using different editions of large scale maps of the drainage network (i.e. Burkham 1972, Leopold 1973, Brice 1974). In Britain the identification of changes in river planform has been largely the work of Lewin (1972) and Hooke (1977) and several recent papers have appeared in collaboration with other authors (Lewin and Hughes 1976 , Hooke and Perry 1976, Lewin, Hughes and Blacknell 1977). One of the most substantial accounts (Hooke 1977) examined, by field measurement and from data derived from historical maps over the past 130 years, the distribution of channel pattern changes for Devon streams over both space and time. This work demonstrated that considerable changes in river planform occur, with the channels shifting at a rate of as much as 4 metres per annum.

2.3.2. Network Dynamics

The paper by Gregory and Walling (1968) heralds the beginning of studies concerning short-term variations in the drainage network extent which since then has become a particularly popular line of enquiry. In this paper the whole concept of a static value for drainage density is questioned after evidence from several small catchments in S.E. Devon showed stream length to vary substantially with different rates of discharge. A similar type of study for the Institute of Hydrology's Ray Catchment at Grendon Underwood was undertaken by Blyth and Rodda (1973) where stream lengths were measured once a week over a period of a year. The main controls on total length of flowing channel were found to be the effective rainfall during the previous week and the extent of the flowing network during the previous week. Common to both papers, after the dynamic character of the drainage network had been viewed in the field, was a degree of scepticism concerning the accuracy of the cartographical representation of stream channels. Gurnell (1979) related variations in a drainage network, mapped for a small New Forest catchment during a storm, to certain parameters of the catchment including precipitation, soil moisture content, discharge, vegetation and rock type. Consideration of certain components of the drainage network together with the factors affecting their behaviour is an integral part of these studies, but has also formed the basis for specific studies (e.g. Morgan 1971, Day 1978). In a study of first order streams in Malaya, Morgan concluded that precipitation within the previous 2 hours was a major determinant of fluctuations in the position of the stream source, while Day (1978), from field observations near Armidale, New South Wales, suggested that very small increments in rainfall promoted small increases in stream length, and thus stream length change was a sensitive indicator of catchment response to rainfall and as such can be highly correlated with discharge. The extent of stream network changes during and after the 1976 drought was examined by Anderson and Burt (1978) in the Southern Cotswolds who discovered the strong control of rock type in determining the network diminution and the speed and extent of subsequent recovery. The authors found that the water table elevation determined the considerable stream head contractions on limestone dipslopes, while networks occurring on clay displayed smaller reductions in stream length, with some streams continuing to flow throughout the drought.

Perhaps the link between studies of short-term variations in drainage network extent and detailed studies of components comprising the drainage network is provided by Hanwell and Newson (1970). For a small catchment in the Mendips a drainage network was surveyed in a normal flood condition such as occurred on the 22nd February 1970. All definite lines of flow were mapped and apart from

> *'natural features like rills and trickles over flushes, others induced by land drains, gripes, ditches, furrows, field headland banks, well-trodden paths and sunken lanes were included'*

This paper appreciated, probably for the first time, the role played by various man-induced features of the drainage network and thus may be seen to lead to studies of drainage network components. Some of these components have already been discussed (e.g. drainage initiation, seepage lines, percolines) and others such as perennial pipes (Chapter 7) are discussed in context in specific chapters.

2.3.3. Network Topology

An important recent development in hydrological studies is concerned with topological properties of drainage networks from which arise the present studies of natural progression as a form of drainage network development. The studies of specific types of drainage link, principally by Abrahams (1972, 1976, 1977) and Abrahams and Campbell (1976), follow the earlier work by Shreve (1967) and Mock (1971) who had introduced studies of drainage network topology, and Smart (1969) who initiated analysis of the distribution of various components of the drainage network. It is this latter type of analysis initiated by Smart, that Abrahams has largely followed.

Abrahams (1976) investigated, using the space-time substitution, the differing length distributions of various drainage links, and the effect of declining relief on mean lengths of both interior and exterior links. Later papers elaborated on this general theme. Abrahams (1977) concluded that the planimetric properties of mature drainage basins vary both with space and time in response to changes in relative relief. Abrahams and Campbell (1976) examined difference in length distributions of source and tributary source links for two channel networks developed in dissimilar materials under disparate climatic conditions. The observed differences were attributed to a tendency for the lengths of tributary source links to increase downstream with increases in the lengths of the main valley sides on which they had developed.

It was perhaps inevitable that network component analysis should lead to the concept of some form of hierarchy of network component types, and therefore to natural progression as a form of drainage network development. These studies of natural progression of the drainage network are the work of Eyles (1977a,b) for field areas in New South Wales. From documentary sources together with aerial photographs and fieldwork, covering the period 1820 to the present day, Eyles claimed that drainage lines, which in 1820 contained chains of ponds, had followed a sequence of changes, as the result of cultural influences. The suggested temporal sequence is chain of 'scour' ponds, discontinuous gully, continuously-incised channel, channel containing 'fixed bar' ponds, and permanently-flowing streams.

Studies marginally related to the concept of natural progressions in drainage networks have been approached by a different, less-prominent, branch of the literature, that groups the study of the hydrology, origins, and the control and influences on mires or bogs (the component at the head of any progressive development of the drainage network). The few references available begin with Ingram (1967) who considered the probable interaction between hydrology and plant growth in mires - the most headward components of the drainage network. He suggested that, frequently, the presence of a 'water track' or 'flush' is detected only by a belt of distinct vegetation. Recently, Moore (1975) has examined the origin of blanket mires producing evidence for linking their formation with the activities of pre-historic man rather than just to climatic changes. This paper complements the findings of Eyles (1977a,b) that human interference has been responsible for initiating modification of drainage network components. The examination of both the hydrological processes that man's activities affect and the resultant modifications to fluvial forms within mires, progresses logically to the examination of natural development within drainage networks.

A review of maps as sources of data, together with critiques of their use for historical studies form a major branch in the divergence period literature but this is considered in Chapter 3 because of its relevance to a feasibility study of the use of maps in detecting changes in the drainage network.

The situation arrived at by the late 1970s, as summarised in Figure 2.2, is one of increasing fragmentation of the various parts required in a study of drainage network changes. The constituent parts of this fragmentation are gullying, the development and characteristics of mires or bogs, natural development of drainage networks, network component analysis, short term changes in drainage network extent, studies of various artificial network components, drainage initiation (particularly by seepage and piping) and cartographic reviews and critiques. It is suggested that all these various branches of the literature, are relevant to studies of changes in drainage networks (Figure 2.2).

2.4 THE IDENTIFICATION OF CHANGES IN DRAINAGE NETWORKS

By way of summary of the literature reviewed, the direct references to network extension in the British literature are collected together in Table 2.2. Noticeable is the paucity of direct or specific references to long-term drainage network change, and of the five papers presented, three - those of Moss (1913), Johnson (1958) and Tallis (1965) - refer to the same general area, namely the Derbyshire Peak. In these five studies no less than three different media are used to detect changes, these being various scales and editions of maps, aerial photographs and field evidence. In view of this use of different sources and the lack of previous studies of changes in drainage network extent, original approaches to the identification of change were required and these are considered in Section 2.4.1.

2.4.1 Possible Methods for Studying Network Change

After a consideration of the available relevant literature it was felt necessary to compile a list of potentially suitable techniques for the identification of changes in drainage networks. These can be conveniently divided into specific (or precise) and general techniques with the specific techniques sub-divided into historical and empirical methods. These are presented in Table 2.3.

Within the historical subdivision of the specific techniques, the maps of the Ordnance Survey were, over the last 150 years, considered a major source of data with most editions of the large-scale maps representing revised hydrological data. The tithe maps were considered as a possible useful temporal extension to Ordnance Survey maps.

Author	Date	Area	Media Used	Date	Scale	Channel Regime	Extension Quoted
Moss	1913	Derbyshire Peak	Maps 1st and 2nd edition	1840-1887	1:63630	Perennial	General 3/4 mile extension
Hollingworth	1934	N.W. of High Pike, Lake District	Maps 2nd or 3rd edition + Field evidence	c. 1900-1934	1:10560	Ephemeral	100-200 yards on specific gullies
Johnson	1958	Kinder Downfall Fair Brook Featherbed Moss	Maps 3rd edition + aerial photographs	1911-1953	1:10560	Perennial	200 yards 200 yards 440 yards
Tallis	1965	Featherbed Moss	Field evidence	c. 1965	-	Perennial	200m. since 1770
Newson	1975	Cerrig-yr-Wyn, Plynlimon	Field evidence	5th-6th Aug.1973	-	Perennial	30m.(approx.)

TABLE 2.2 STUDIES OF DRAINAGE NETWORK EXTENSION IN BRITAIN

PRECISE		
(i)	Historical	Comparison of different editions of Ordnance Survey maps, used by Moss (1913) and an important possibility.
		Consideration of tithe maps for early drainage networks.
		Consideration of estate maps, deeds and other record documents for early drainage networks.
		Surveyors' notebooks, original drafts of maps and surveyors' operational manuals linked to Ordnance Survey maps.
(ii)	Empirical	Resurveying of cross-profiles on select gullies to monitor change.
		Aerial photograph interpretation.
		Headward erosion of drains as measured against some form of control.
		Continual detailed survey of both potention natural and man-induced change sites.
		Vegetation succession as supporting evidence to other empirical techniques.
GENERAL		
		Perception of Landowners (e.g. Farmers, Commoners).
		Travellers' Notes.
		Newspaper Articles.
		Allusions to network change in the geographical literature and that of associated disciplines.

TABLE 2.3 TECHNIQUES AVAILABLE FOR THE STUDY OF NETWORK CHANGE

Estate maps and deeds were also considered as potential information sources for drainage networks because streams often represent land ownership boundaries while the location of sources and springs were accurately positioned because they provided essential water supplies for isolated farms. Finally in the historical category, the use was envisaged of surveyors' manuals, notebooks and original drafts of map sheets, relating to the original survey of the area in a similar way to Eyles (1977a,b) in Australia and Cooke and Reeves (1976) in America.

Empirical techniques for the identification of network change included the re-surveying of cross-profiles on select gullies where cross-profile information had been published in order to determine the behaviour of the feature over a time span. Sites considered included the New Forest gullies (Tuckfield 1964) and the gullied tributary of the River Burn, Devon (Gregory and Park 1976). Aerial photograph interpretation was also considered a possible technique for some sites, either with examination of photographs of successive dates or simply as a means of updating maps where recent surveys were unavailable.

The need for some technique suitable for the absolute dating of drainage network change led to the measurement of head extension of drains over dateable inclosure boundaries within the New Forest, Hampshire; while it was hoped that the repeated survey of certain sites over a two year period would provide evidence of any active drainage network extension. The final category within the empirical division of techniques was that of the study of vegetation succession where the behaviour of certain species may reflect the moisture availability of certain sites and lend supporting evidence at sites where drainage network extension was being monitored repeatedly.

The general techniques that seemed appropriate for use in a study of drainage network change were landowner perception, to see whether actual evidence of change could be obtained to support inferred change, and travellers' notes which may provide dateable descriptions of limits of streams. Newspaper articles and general publications in geographical and other relevant literature were also considered as possible sources of data. A critical appraisal of these various general techniques will be found in Section 6.1 along with certain empirical techniques in Sections 6.2 and 6.3; the more successful empirical techniques form the basis of Chapters 3, 4, 5 and 7 and Section 6.4.

CHAPTER 3 AN EVALUATION OF CARTOGRAPHIC AND DOCUMENTARY SOURCES IN BRITAIN FOR MAP NETWORK COMPARISON

3.1 THE USE FOR MAPS IN DRAINAGE NETWORK ANALYSIS

It has long been recognised that the geomorphologist must depend, for a substantial part of his factual information, upon the maps published by the official survey agencies, since these provide a potential source of data that could otherwise be obtained only by expensive and time consuming field studies.

It is however, essential that data provided by maps are accurately interpreted before proceeding with any form of morphometric analysis. While the use of maps is still of assistance for current hydrological investigation, it is absolutely imperative in studies of fluvial landform changes because fieldwork cannot be used to provide survey data of past hydrological conditions. In any study of changes in the drainage network in Britain during the nineteenth and early twentieth centuries it is necessary to resort almost exclusively to older editions of the Ordnance Survey maps. Searching still further into the past, the tithe maps and indeed maps produced by other agencies may well offer representations of the drainage network for the early part of the nineteenth century, but their accuracy and reliability must be carefully considered. Peel (1949) comments that:

> *'Maps are not however designed expressly for his (i.e. the geomorphologist's) benefit and even the best cannot provide more than a partial definition of the ground, or one more accurate than its scale will permit.'*

In addition, maps are quite meaningless without a knowledge of the principles underlying the information depicted on them and these principles may vary for maps of different scales, dates and editions. Geographical literature in general, but particularly the hydro-geomorphological literature, shows a loose attitude towards the interpretation of data extracted from maps. Often this interpretation seems to have suited the author's personal idea of what a map convention might represent with an apparent disregard for any principles governing the depiction of features on a map. This is well illustrated by the indiscriminate use by several authors of 'mesh-length' and 'contour crenulation' methods for the delimitation of the drainage network regardless of what the 'blue line' network represented in the first place.

Accurate and reliable maps are clearly of paramount importance for an analysis of the relative positions of streams and their sources, and of the distribution of marshland, ditches and the various other elements which comprise the drainage network. Therefore, the initial instructions to the surveyors must be examined to establish the conventions whereby features existing on the ground were represented on the map. The consistency of these conventions from map edition to edition must then be carefully checked to ensure that similar controls apply to each map network to be compared.

3.1.1. The Use of Early Ordnance Survey Maps in Drainage Network Comparisions

The value of the early editions of the Ordnance Survey's large-scale maps and plans as a source of general historic data is well established, and an awareness of this led the Davidson Committee in their report of 1938 to recommend the continuation of the 1:10560 and 1:2500 scales to maintain the map sequence. Subject then to qualification because of possible inconsistencies between editions, the various scales of Ordnance Survey maps provide a potential data source from which drainage networks may be abstracted and compared to establish any changes. The concept of tracing changes of a landform or a feature by the use of maps has been well demonstrated in several British Coastal Studies. De Boer and Carr (1969) used maps and charts pre-dating the Ordnance Survey to examine changes at Spurn Point and Orfordness. Although certain general observations are made from these early maps, De Boer points out that the first map to be fully satisfactory for this type of analysis was the First Edition Ordnance Survey 1:10560 map. Systematic examination of various editions of several scales of map was used by Carr (1962) when investigating historical cartographic accuracy of three coastal areas in Britian, and again Carr (1972) and Carr and Gleason (1972) used early maps, together with maps of the Ordnance Survey, to trace the development of Chesil Beach. The potential demonstrated in these map comparisons for coastal change may well have an easier application to drainage networks because of the absence of complicating factors, such as consistency of tidal levels between map edition and rapid change due to coastal erosion and accretion.

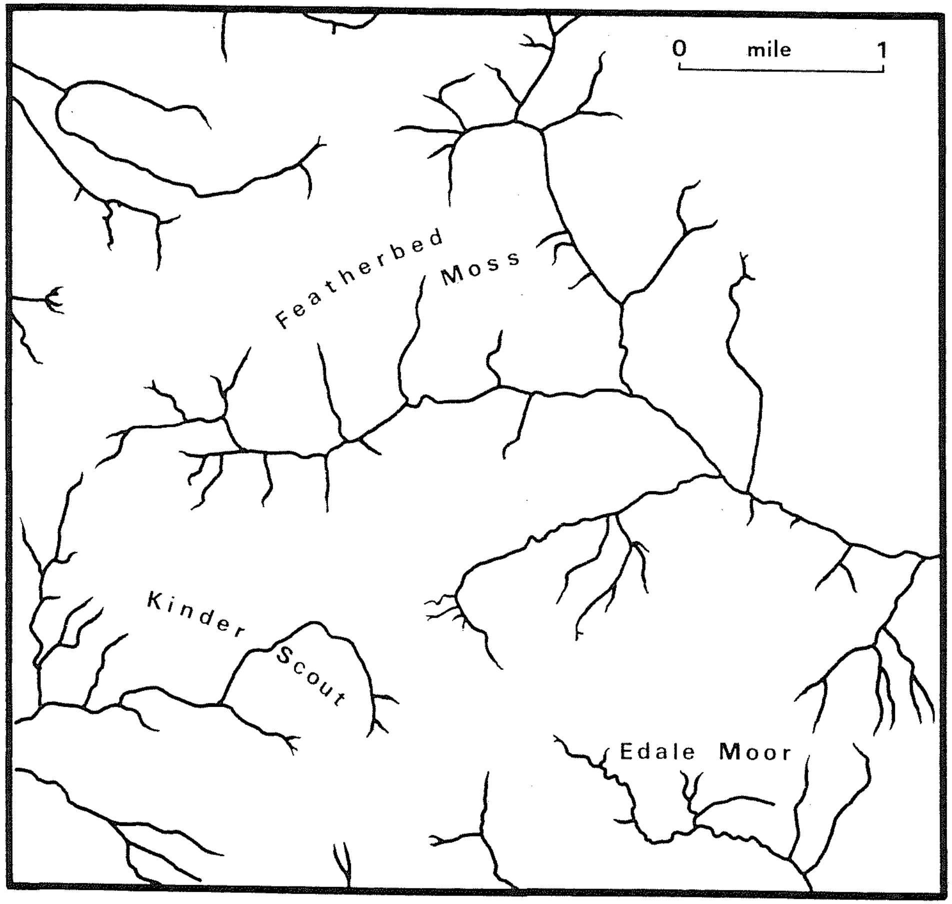
Coppock (1973) also made use of successive editions of Ordnance Survey maps to demonstrate afforestation and vegetation changes for particular areas. More specifically, in the hydrological field, Hollingworth (1934) illustrated headward extension of peat gullies north-west of High Pike in the northern part of the Lake District by reference to the changing position of an old mining track on successive editions of 1:10560 map, supported by field evidence. Moss's work (1913) for the Derbyshire Peak compared the First and Second Editions of the 1:63360 maps concluding that streams were extending into the peat mass. It is valuable to examine Moss's work in more detail because The Peak is an area which has since been extensively studied by various authors (Bower 1960, 1961, Mosley 1972). Although it is impossible to define Moss's fieldwork area exactly a general map of The Peak drainage network (Figure 3.1) for the First and Second Editions 1:63360 maps clearly demonstrates the validity of his claim that:

> *'Streams on the peak are shown on the revised Ordnance Survey maps (1870-1880) to be nearly 3/4 mile (1.2km.) longer than they were when The Peak was originally surveyed in 1830'*

Whether this extension can be attributed in part or in its entirety to a growth in the drainage network, or whether

FIGURE 3.1

THE PEAK : NETWORK CHANGE



1 : 63,360 (surveyed 1840)

1 : 63,360 (surveyed 1887)

it is the result of changing conventions employed by the Ordnance Survey, is a subject demanding further investigation. Moss did present further evidence for some form of network change stating that the streams

> *'are now (i.e. 1913) 1/4 mile (0.4km.) longer than they are shown to be on the revised maps of 1879'*

Unfortunately the term 'now' is ambiguous and could refer either to field evidence or to further map evidence using the Third Edition 1:63360 map of 1907. Whatever the source, it would still seem to indicate the occurrence of some form of progressive growth in the network which may well be unaccounted for by just changes in map conventions. The amount of change between the First and Second Editions of 1:63360 maps for the Derbyshire Peak is summarised in Table 3.1

Edition	Date	Total Stream Length	Drainage Density
First	1830	58.125 km.	0.82 $km.km^{-2}$
Second	1887	78.44 km.	0.91 $km.km^{-2}$

TABLE 3.1 DIFFERENCES IN THE DRAINAGE NETWORK DEPICTED ON EDITIONS OF 1:63360 ORDNANCE SURVEY MAPS FOR THE DERBYSHIRE PEAK

This change would appear to divide into two major categories (Figure 3.1): extensions to existing drainage links, well illustrated on Featherbed Moss, and the creation of new drainage links particularly in the Kinder Scout - Edale Moor area. The considerable apparent change that has occurred between the editions would, in the opinion of the author, be very difficult to attribute totally to changes and errors in Ordnance Survey methods. These may include misinterpretation, on the part of the surveyor of the boundary between the flush and ill-defined channel categories, changing conventions employed by the Ordnance Survey, or cartographic inaccuracies introduced during the production of the map.

Since this early work by Moss, more evidence has been presented for actual network change as a result of more detailed work on the Derbyshire Peak notably by Johnson and Tallis. Johnson (1958) from a comparison of the 1:10560 'County Series' map of 1911 and air photographs taken in 1953 recognised 200 yards of extension on both Kinder Downfall Stream and Fair Brook with 1/4 mile of extension on Featherbed Moss. Tallis (1965, 1973) adds further weight to Moss's extension hypothesis concluding that 200 metres of stream course have developed in the last 190 years on Featherbed Moss.

Moss's pioneer work on drainage network changes does have severe limitations in that the 1:63360 scale used for the study is too small in detail for this type of analysis and there is no apparent awareness of problems of comparability of the two map editions concerned. Nor is there any statement of Moss's or the Ordnance Survey's operational definition of a stream channel in the field, if in fact he did use field evidence for the latter part of his study.

The remainder of this chapter considers firstly a review of the literature relevant to the use of maps for network delimitation (3.2), then selects the most suitable scale and editions of map for the purpose (3.3) before examining the feasibility of map drainage network comparison (3.4). Finally a case study of the New Forest demonstrates the potential of the technique (3.5).

3.2 MAP ACCURACY AND DRAINAGE NETWORKS

3.2.1. Map Accuracy

General claims of inaccuracies in the contents of maps provided by official mapping agencies are as old as the maps themselves, although scrutiny of the various scales and editions of maps with a view to selecting the most appropriate for a particular type of study is a facet that has been seriously neglected. Only since the 1970s has scale been given the attention it deserves in morphometric studies, while changes of convention between editionsremains completely forgotten.

Nevertheless in Britain the question of accuracy has fared better than in most countries, with frequent revision of Ordnance Survey's aims and methods, and much constructive criticism reflected particularly in the Donnington Report (1893) and the Davidson Committee Report (1938). The search for sources of historic data in many branches of geography has led to a recognition of the importance of early editions of maps. This is particularly true of Britain whose map coverage, since the birth of the Ordnance Survey, is widely acknowledged to be the finest in the world. However, only since the recent rise of morphometric studies has the map been used for scientific analysis - a role that requires careful consideration of survey and cartographic accuracy, with reliability of the information extracted from maps assuming a quantifiable rather than an abstract nature. This upsurge of interest in map accuracy resulting from the need for a more scientific approach to hydrological and fluvio-geomorphological studies, is reflected in the literature of the past few decades (Morisawa 1957, Schneider 1961, Chorley & Dale 1972, Werritty 1972, Drummond 1974, Gardiner 1975).

Peel (1949) looked generally at the use of Ordnance Survey maps in geomorphological fieldwork. He concluded that a lack of recent revision in the 1:2500 and 1:10560 series maps is not a problem since physical features change slowly by comparison with other features such as housing and communications. Deficiencies in maps, according to Peel, relate to omissions of information rather than to inaccuracies in the information depicted and he identified rivers as being particularly prone to these omissions (presumably referring to the omission of network links). These statements must be treated in the context of Peel's original comments that 1:63360 maps and the smaller scales have little or no application in geomorphology and that even in Great Britain maps are only good for generalised analysis - the data they afford must be supplemented by direct observation. Although these observations were developed during work on erosion surfaces many points can be of equal relevance to drainage networks.

Inaccuracies in contours depicted on the Ordnance Survey maps and problems of relief interpolation have provided subjects for much debate notably by Crone (1953) and Clayton (1953). Clayton, particularly, notes the differences between surveyed form lines and interpolated contours the latter often created from hill sketchings. The serious implication of this on the contour crenulation and slope crenulation methods for delimiting network extent will become clearer in Section 3.2.2 of this chapter.

Carr (1962) in a study of changes at coastal locations in Britain observed that there has, on occasions, been an all too ready willingness to accept documentary material without adequate scrutiny - perhaps the first indication of the need to qualify in some way the information depicted on maps. Carr draws attention to the survey date printed on most map sheets and, by using evidence of coastal change from other sources, explains that there is no guarantee that the information depicted is of the alleged date of survey and that in some cases it may be twenty years before the publication date of the map. An important reference is also made to problems of planimetric accuracy associated with paper distortion of older maps, a problem often accentuated by photocopying.

3.2.2. Drainage Networks and Map Representations

Harley (1962, 1975) has made an attempt to place the present maps of the Ordnance Survey in historical perspective and while the later publication in particular provides many clues to the internal procedures employed by the Ordnance Survey, there is still a need for a detailed study of maps specifically from geomorphological viewpoints. The hydrologist, in all morphometric work utilising maps, needs to know the precise answer to a number of questions. These include: the point to which a stream in the field is represented as a stream on a map, the account taken of the dynamic nature of the network and thus what does the blue on a map actually represent, and the accuracy with which a stream is depicted on both present and past map editions. These questions, important and relevant to all morphometric studies, have been almost totally ignored in the literature of the past few decades. Most morphometric studies have accepted the map definition of the network as sufficient for their purpose or else have extended it by various methods to include all linear depressions indicated on the map regardless of what the blue line represented in the first place.

Some authors have attempted to give a field definition of what they consider a stream to be. Melton (1957) provided an operational definition of a stream channel in the field as:

> *'a permanent clearly-defined trench or trough clearly showing evidence of scour by channel flow and bounded by valley sides sloping towards the axis'.*

Maxwell (1960) was more specific in his definition of a stream in the field and suggested criteria for the identification of stream channels in the San Dimas area of California. These included the presence of stream banks, the presence of suspended and oriented debris, the presence of wash marks and continuity with a larger channel. Each channel mapped by Maxwell satisfied at least two of these requirements. Scheidegger (1966) made passing reference to the problems of stream definition noting that as a channel system is followed up stream the stream flow becomes intermittent and the channels fork into a network of smaller channels which perhaps lose themselves in a multitude of gullies and rills. Little further literature exists on the subject of field definition of a stream channel until the excellent review paper by Chorley and Dale (1972). They suggested that five main considerations affect the definition of the existence and extent of a stream channel network; these are channel size, connectivity with the main network, pattern, permanence and the role played by the feature in basin runoff. From this it may be surmised that background information on basin hydrology is often employed directly or indirectly to assess the limits of the network accurately.

Once the network has been defined in the field, difficulties arise in the accurate representation of the field network by the cartographer and in the consistency shown in the selection of rivers and links for drawing. In addition, there is the problem of the nature of channels portrayed by the 'blue-line' on the map. In the past authors (e.g. Kennedy 1978) have stated or implied, that the 'blue-line' represents only the perennial network. However, Ordnance Survey legislation, which depicts all rivers at 'normal winter level', would seem to contradict this, the inference being that many of the intermittent or seasonal channels may be included because they show evidence of flow during the wetter winter season. Horton (1945) seems to have agreed with the Ordnance Survey's approach since all permanent network stream channels both perennial and intermittent were included in his analysis and, like Langbein (1947), his drainage density values were based on the 'blue-line' network depicted on topographic maps of 1:62500 scale. Strahler (1964), following this lead with his standard channel definition, stated:

> *'as including all intermittent and perennial flow lines located in clearly-defined valleys'.*

Many authors have found the 'blue-line' as depicted on maps of the various official mapping agencies quite unacceptable for morphometric analysis and so have suggested alternative methods for delineating the drainage network from maps. A basic agreement seems to be that the drainage network is under-represented on maps and thus needs to be extended in some methodical way. This was first stated by Horton (1945) when he recommended the use of mesh lengths obtained by extending the line of each stream course to the watershed. The use of contours to assist the interpretation of the drainage network has been well documented. Miller (1953) observed that in identifying the stream channel network it is necessary to pay close attention to contour configuration and not to depend on the streams shown on the maps. Further methods for extending stream courses shown on maps have been developed since Horton's 'mesh lengths', the most popular being by the contour crenulation method (Carlston 1963, Melton 1957, Morisawa 1957). This method of defining the drainage network has been much debated. Morisawa (1957) compared the method with results obtained from field survey, concluding that they gave similar results with longer channel lengths occurring than were depicted on the U.S. Geological Survey (USGS) 1:24000 topographic maps. Schneider (1961) in a rework of Morisawa's data suggested that on the basis of poor correlations alone the 'contour crenulation' and 'blue-line' methods do not give reliable estimates of the true value of the drainage density when compared with actual field measurements. Channels inferred from the 1:24000 USGS maps were tested in the field by Coates (1958) resulting in the observation that fingertip tributaries could seldom be determined from a map.

Shortcomings of the contour crenulation method are summarised by Chorley and Dale (1972) as being that the significance of crenulation and inflections in the contours is dependent upon the accuracy of the map concerned. In consequence the accuracy of not only the 'blue-line' needs to be questioned but also that of the contours, particularly in view of Clayton's (1953) comments on problems of interpolated contours. Chorley and Dale also note the very real problem of operator variance in the identification of the more headward parts of drainage networks when using topographic maps.

Recent refinements to the contour crenulation method of defining a network have been suggested by Kennedy (1978) and Smart (1978). Kennedy suggests that:

> *'the junction of an unbranched perennial (or 'blue-line') channel be taken as the starting point for definitions and that the entire contour crenulation network tributary to that point be considered the first-order stream'.*

Smart points out the failings of the contour crenulation method suggesting a more objective method in which stream sources are identified by a quantitative slope criterion. The source of a channel is identified by him as the point where it is crossed by the highest contour spaced more than some predefined critical distance from the next lowest contour. This method reduces streams to about twenty per cent of the value obtained by the contour method. However both methods still place a heavy reliance on the accuracy of the contours on maps and fail to acknowledge that a difference exists, in some areas a very marked difference, between valley networks and the present stream network. It is for this reason, coupled with operational problems of defining the network from contour crenulations as well as Ordnance Survey legislation (an item which will become clearer later in this chapter), that the 'blue-line' method as in fact used by Gregory (1966a) in preference to the contour crenulation method, has been selected for the study of drainage networks throughout this thesis.

Many of the studies alluded to above are for maps of a variety of scales produced by different mapping agencies for widely differing physical environments. Therefore, with such widely differing standards, it is impossible to draw any meaningful conclusions as to the most accurate and most appropriate method of identifying the network from maps. Indeed it is likely that there is no single world-wide solution of general applicability as suggested by Gregory and Gardiner (1975). Some consistency of scale, a knowledge of the physical environment and an examination of the internal workings of the major mapping agencies are needed to make sure that the same components of the drainage network are being represented in each case by the 'blue-line'.

Horton (1945) made an important observation on the subject of map scale:

> *'for accuracy, drainage density must, if measured directly from maps, be determined from maps on a sufficiently large scale to show all permanent natural stream channels'.*

It is a well-known fact that the depicted drainage network for a particular area varies according to the scale of map employed for analysis, and many case studies exist both in Britain and abroad to illustrate the point. Schick (1964) in a comparison of modern topographic maps of Israel of the 1:20000 and 1:2500 Series found that the 1:20000 Series underestimated total stream length by 11.1% and drainage density by 9.7% as compared with the 1:2500 maps. Werritty (1972) came to similar conclusions for Britain where both 'regression analysis' and 'ANOVA' proved the 1:2500 maps to represent the true field network closely while the degree of correspondence between the 1:25000 and the true field network was extremely poor.

For Britain the 1:25000 Second Series and the 1:10560 Regular Edition are recommended by Gardiner (1975) as the best maps for drainage network analysis although the 1:2500 also offer excellent data sources with a reservation that operational problems are introduced when considering large areas because of their large scale. Gardiner (1975) also illustrates the importance of map scale by comparing the drainage network represented on the NW section of Sheet SS31 1:10560 Regular Edition, with the Provisional and Second Series 1:25000, and the Seventh Series 1:63360 representations of the same network. Unfortunately no appreciation is made of the different survey dates covered by these various editions, nor of a possible change of the drainage network that could have occurred as a result of the considerable human interference in the area. The 1:25000 Provisional Edition represents the earliest portrayal of the network circa 1905, while the 1:25000 Second Series and the 1:10560 Regular Edition represent a recent depiction of the network circa 1960. Table 3.2 reproduced in Section 3.3.2 of this chapter, shows the ratio of streams depicted on the Second Series 1:25000 maps to those depicted on the 1:25000 Provisional Edition (also from Gardiner 1975) and may not totally reflect cartographic and surveying changes as suggested by the author, but a real change in the extent of the network over the time period of the two surveys. To avoid such confusion Parry (1979) suggests that:

> *'the perfect map records a landscape ..... as it existed at a single and definite moment in time. The date of that moment should be recorded in the map margin'.*

Although widespread differences have been demonstrated in the network depicted on different editions of 1:25000 scale map (Gardiner 1975, Gregory 1978b Parry 1979) no recommendations have been made of the most suitable editions for the abstraction of the drainage network. Likewise no advice exists on the editions of large-scale maps best suited to an analysis of drainage networks. An examination of the most suitable scale and edition will be made in Sections 3.3.2. and 3.3.3. of this chapter.

In this brief discussion of scale, some reference has been made to the relationship of the map network to the true field situation. The accuracy with which a map reflects the actual field situation is possibly the most important factor, for or against, the suitability of maps for drainage network analysis. Many criticisms have been levelled at the accuracy with which streams are represented on maps. Clearly, the correct, or at least the consistent, identification of sources and channels on maps, air photographs, and in the field, is of fundamental importance in the study of channel networks (Shreve 1966). The degree of accuracy in the depiction of the network has been greatly improved recently with technological advances, including the use of colour photographs (Schneider 1968), radar imagery (McCoy 1969) and infra-red photography (Cantrell 1964) all of which make water-bearing channels more easily identifiable from the air. However, great care must be exercised in the use of conventional aerial methods since photo quality and vegetation can lead to erroneous representation of the network (Jennings 1967).

In the past the 'blue-line' network has been subjected to some scathing criticism. Langbein (1947) working in the U.S.A. suggested that streams vary with season and wetness of year in which the survey was made as well as with the judgement of the topographer and cartographer. Scheidegger (1966) in a similar view demonstrated that 'blue-lines' shown on printed maps are extremely arbitrary and appear to depend on the channel flow observed during the period of survey, or indicated at a given moment of time by air photographs, while Gregory (1966b) presented a similar view:

> *'the available pattern of watercourses shown on existing maps is subject to certain limitations, principally the time of year when the map was surveyed'.*

Maxwell (1960) found discrepancies between the map and field situations which included the mapped lengths of certain first-order streams, the omission of some small first-order channels, the precise positions of some channel junctions and differences in the degree of sinuosity recognised.

In Ghana, a claim that inconsistencies exist in the rivers chosen for inclusion on the 1:250000 series maps has been made by Yoxall (1969), while in another study in America relating field and map networks using larger scale maps, Morisawa (1957) found that the USGS 1:24000 topographic maps tended to under-represent the true field network. This is a view generally supported not only in America but throughout the rest of the world with maps of a similar scale. Drummond (1974) undertook a review of several map-producing agencies in the U.S.A. on the whole question of *'When is a stream a stream'*. He concluded that most government agencies have developed their own rules concerning the inclusion of streams on their published maps and that the user should be conversant with the actual rules governing the representation of streams on maps.

The situation arrived at after an examination of this particular field of literature is well summarised by Chorley and Dale (1972), although their recommendations still seem to be largely ignored in the literature of today.

> *'It is clear that even for comparative studies, statements involving the length of drainage channels measured from maps or derivatives of stream length (i.e. drainage density) must be accompanied by background information. Before comparison between such measures is made it is necessary to know, for example:*
>
> *The method by which the topographic survey was conducted.*
> *The rules governing both the insertion of stream lines and contour crenulations.*
> *The character of the vegetational cover.*
> *The precise operational definition of a stream channel adopted by the investigator.'*

Stated more simply, and as a fitting conclusion to this section, a map can only be as accurate as the rules and regulations governing its surveying and draughtsmanship allow and information contained within the map must be related to a specific date.

3.3 ORDNANCE SURVEY HISTORY AND CHOICE OF SCALE AND EDITIONS MOST SUITABLE FOR NETWORK CHANGE ANALYSIS

3.3.1. Ordnance Survey History

Prior to an appraisal of the various scales of maps it would seem logical to examine briefly just what is available. In order to do this and place each scale in its historical perspective it is necessary to look at the more important events in the history of our major British mapping agency.

The Ordnance Survey is generally considered to have been formally founded in 1791 with roots extending back to the civilian and military cartography of the eighteenth century (Skelton 1962). The Survey's first publication was the 1:63360 series which was begun in 1801 in Kent and by 1873 covered the whole of England and Wales. Although providing the first uniform coverage of England and Wales, it was soon recognised that the 1:63360 scale was too small for many purposes and before its completion larger scales had been already introduced. In 1824 the Irish survey used a 1:10560 scale for a complete survey of Ireland for taxation purposes and in 1840 this scale was authorised for the survey of those areas of Northern

England and Scotland which were as yet uncovered by the 1:63360 series. However it was soon apparent that the 1:10560 scale was still too small for all the purposes that a national survey should fulfil. Over the next decade the choice of the most suitable basic scale for the maps of Great Britain caused a controversy to rage known as the *'Battle of the Scales'*. The final decision of the committee set up to investigate this matter was not made until 1858 when the 1:2500 scale was adopted for cultivated areas, the 1:10560 scale for uncultivated areas and a 1:500 series for towns of over 4000 populus. Smaller scale maps were to be derived from these basic three. Much of the work of the Ordnance Survey for the remainder of the nineteenth century was the implementation of the 1858 decisions - the initial 1:2500 survey for example was not completed until 1896. In the last decade of the nineteenth century and the early years of the twentieth the history of the Ordnance Survey seems to have been dictated by finance. The abandonment in 1893 of the 1:500 series and the reduction of manpower in the 1920s was followed after the Great War by placing the revision of the 1:2500 and 1:10560 series on a forty instead of twenty year cycle for all areas with a population of under 100 per square mile. This was a tragic blow for the physical geographer since many of the geomorphogically interesting areas occur in low population areas, and thus have far fewer revisions than the well-populated areas.

By 1935 it had become evident that the restrictions imposed on the Survey in the early years of the twentieth century had left it totally inadequate for most planning purposes and so a departmental committee was established to review the whole state of the Survey. The Davidson Committee's final report was not published until 1938 but has had a considerable influence on the recent progress of the Ordnance Survey up to the 1960s. For the purpose of this study the most important decisions made by the committee were that the 1:2500 series should be retained and recast on a national, as opposed to county, grid and that the 1:63360 series should be retained in its original form. In addition it was recommended that a new medium scale derived map, a 1:25000 series, be introduced experimentally and extended to cover the whole country if successful. Other recommendations included that additional contours should be introduced as soon as possible and that a system of continuous revision should be adopted for the large scale plans. Since the Davidson Report technological changes and the adoption of suitable scales for use with metric units of measure have led to the modification and abandonment of some of the suggestions of the committee.

To summarise it is suggested that four series of Ordnance Survey maps should be considered in any feasibility study for map derived drainage network comparision; the 1:63360 series, the 1:25000 series, the 1:10560 (including the metric 1:10000 series) and the 1:2500 series.

3.3.2. Map Scale Suitable for Analysis of Network Change

With only sparse literature available on the most suitable scale for morphometric analysis it was necessary to undertake a further detailed examination of the information shown on the various map scales, with careful consideration of the accuracy of the older map editions as well as the current ones.

The 1:63360 maps, although used in the past by Moss (1913) and although providing the longest time span for data, were rejected for two reasons. Firstly, because of their small scale and the consequent degree of generalisation in their portrayal of drainage networks, and secondly because the accuracy of the earlier maps is somewhat dubious for they represented the first systematic survey of the whole country at a time when surveying techniques were relatively primitive. It is probable that the draughtsmen had a fair amount of licence in the inclusion and omission of network links in the interests of clarity, as well as in the modification of the original drafts. For example the J.B. Harley footnote on the David and Charles reprint of the First Edition 1:63360 Salisbury sheet states that:

> *'proof impressions of the map, both in outline and later in finished state, printed from a press in the tower, were then circulated for correction to be made by well-informed gentry within the country.'*

The implications of this extract on drainage network comparisons using the First Edition 1:63360 would have been serious.

The 1:25000 series is a comparatively recent introduction resulting from recommendations presented by the Davidson Committee (1938). The Provisional Edition were derivative maps partly constructed from the most up to date 1:10560 County Series which was generally the Third edition (1891 -1914). More recent material used in the Provisional Edition included the GSGS 3906 maps (1:25000, Cassini projected War Office maps produced rapidly to meet the needs of defence and rearmament) and field revision executed at a 1:10560 scale to provide material for updating the 1:63360 and other smaller scale map series. The Second Series (dating in its present format from 1961) is produced by direct reduction from the fair drawings of the 1:10560 Regular sheets. A maximum of these two editions exist (ignoring the eleven Devonshire sheets of the abortive Regular Edition) with the second series at present incomplete for parts of Britain, giving a very limited timespan for data. In addition, considerable variations have been shown to exist between the networks depicted on the 1:25000 Provisional and Second Series editions (Gardiner 1975, Gregory 1978b). Generally the Provisional Edition shows substantially fewer drainage links than the newer Second Series as illustrated in Table 3.2 reproduced below. This raised serious problems of network consistency when the drainage network for a particular area is derived from the different editions of 1:25000 map and makes the series unsuitable for network analysis. The drainage network on the 1:25000 series does however have the distinction of being depicted in blue which greatly facilitates its identification.

The rejection of both the 1:63360 and 1:25000 maps for the purpose of temporal analysis of network changes left a choice between the 1:10560 (including the incomplete

1:10000 Metric Edition) and the 1:2500 series. The 1:10560 or six-inch scale was finally adopted as the most suitable for the project for several reasons. The 1:10560 maps, dating from 1840, provide the longest historical record of any Ordnance Survey maps (excepting the 1:63360 already discarded) although the actual time span varies considerably from area to area depending on the date of the first survey and the date of the most recent revision. The counties of Lancashire and Yorkshire have a bonus in this respect since they were surveyed at the 1:10560 scale in the 1840s, and then resurveyed in the 1880s, in line with the rest of the county.

Area	Map Sheet	Quadrant	Ratio
S. Scotland	NT 20	SE	1.27
	NT 30	SE	1.10
N.E. England	NZ 34	SW	1.10
	NZ 24	SW	1.13
S.W. England	SS 40	SW	1.31
	SS 50	SE	1.80

TABLE 3.2 RATIOS OF STREAM LENGTHS SHOWN ON 1:25000 SECOND SERIES MAPS TO STREAM LENGTHS SHOWN ON 1:25000 PROVISIONAL EDITION MAPS FOR 25 1 KM. GRID SQUARES IN EACH AREA (GARDINER 1975)

The 1:10560 maps are also the largest scale maps to cover the whole of Great Britain down to low water mark since legislation in 1853 dictated that only cultivated and urban areas would be represented at the larger scale of 1:2500. From the point of view of consistency of scale the selection of the 1:10560 rather than the 1:2500 removed the need to change scales when mountain and moorland areas were being considered. The 1:10560 maps are the largest scale maps to show contours. Contour crenulations are particularly useful, in the absence of colour in distinguishing the watercourses from field boundaries and other features, and contours are not shown in the 1:2500 series. In terms of accuracy and detail the 1:10560 maps are post 1881 identical to the 1:2500 series because they were produced by direct photo-reduction from the larger scale (Harley 1975) and the 1:10560 series offer advantages over the 1:2500 series in terms of the number and size of maps handled. Between 1856 and 1881 the 1:10560 maps were derived from the 1:2500 series both maps carrying the same date of survey.

3.3.3. Appraisal and Selection of 1:10560 Map Editions

Once the 1:10560 series had been selected as the basic scale for analysis of network change, a review and appraisal of the various editions available was required to determine those most suitable.

In Britian there exist a maximum of five or six editions of 1:10560 or 1:10000 scale maps from which network information may be abstracted although for some areas there may be considerably fewer than this number. At this point it may be useful to clarify the Ordnance Survey terminology with respect to surveys and revisions. A resurvey involves a fresh approach to the area concerned in which all material from previous surveys is ignored. A resurvey is differentiated from a major revision where all the information on the map is subjected to a complete and systematic revision. In this category of revision, water features are treated with the same importance as any other topographical feature. When, however, a map is revised for major changes only, it only records information that is likely to directly affect the public such as changes in housing and communications. The drainage network is not altered in this type of revision and so for the purpose of comparision of drainage networks, only the major revisions which largely correspond with the editions of map are useful. This gives for all areas of Britian two, and for certain areas three, complete revisions of the drainage network for the nineteenth and the early decades of the twentieth centuries; a First Edition (1854-1888) a Second Edition (1891-1914) and the incomplete Third Edition (1904-1924). In addition there exists for the counties of Lancashire and Yorkshire an early surveying of the 1840s although the counties concerned were later resurveyed in the 1880s. These editions are usually referred to collectively as the 'County Series'. After the 1939-45 War a Provisional Series and later the National Grid Provisional Edition were issued but since, by and large, these editions are 'County Series' information recast on the National Grid, they can be dismissed from the point of view of drainage network analysis since they do not represent a revision of the drainage network. This leaves the more modern 1:10560 Regular Series and 1:10000 Metric Edition both of which considerably lengthen the period over which networks can be examined, although the Metric Edition requires the time-consuming task of reduction for the purpose of comparison. A summary of the suitability of editions of 1:10560 scale maps for use in a study of network changes can be found in Table 3.3.

3.4 FEASIBILITY OF MAP NETWORK COMPARISON

3.4.1. Data Quality Problems with the Use of Maps

Brief mention has already been made of the problems of abstracting information from maps which have been criticised by authors for being at the best generalisations of the drainage network and at the worst imaginative cartographic exercises unrelated to the true situation.

Gregory and Walling (1968) and Blyth and Rodda (1973) have demonstrated the essentially dynamic nature of the drainage network while Gurnell (1979) has criticised data based on maps in hydrological research claiming that the fundamental problem is that a very dynamic index is being viewed in a static manner. Ovenden and Gregory (1980) have commented on the fact that

Edition of 1:10560 Map	Date of Surveying	Compilation Source	Usefulness for Network Change Analysis
'County Series' Original Lancs. and Yorks. Survey	1840-1854	New Survey	Earliest large scale surveying of parts of England: USEFUL
'County Series' First Edition	1854-1888	New Survey (Resurvey for Lancs and Yorks.)	First complete large scale surveying of England and Wales and Scotland: USEFUL
'County Series' Second Edition	1891-1914	Resurvey	First and only complete revision of England and Wales: USEFUL
'County Series' Third Edition	1904-1924	Resurvey	Incomplete: USEFUL FOR AREAS REVISED
Post-War Provisional	1891-1924*	'County Series' information with some updating from 1:10560 survey for Civil Defence purpose	No additional information over Third (or where no Third, Second) Edition of the 'County Series'
National Grid Provisional	1891-1924*	'County Series' information re-cast on National Grid with some 1948-57 revision at 1:10560 scale associated with Seventy Series 1:63360	No additional information over Third (or where no Third, Second) Edition of the 'County Series'
National Grid Regular	1946	Resurvey	First new survey for certain areas since nineteenth century: USEFUL
Metric	1969	Resurvey	Needs reducing to 1:10560 for comparability. USEFUL

* Some revision for major changes only

TABLE 3.3. SUITABILITY OF EDITIONS OF 1:10560 SCALE MAPS FOR NETWORK CHANGE ANALYSIS

a particular topographic map will provide only a single value for the range of densities which mark the extremes of short-term drainage network expansion and contraction. In order to determine exactly what single value of the drainage network is represented by the blue lines on British maps and also to examine the comparability of the conventions used in the different map editions, it was decided to attempt a review of the working methods of the Ordnance Surveyors.

3.4.2. Appraisal of Possible Sources of Information Concerning Ordnance Survey Working Methods

Information contained in notebooks used by mapping agencies' surveyors has been used in the past,(Eyles 1977a,b) to trace the development of a drainage system from a chain of ponds to a gully in Australia. The existence of such notebooks has also been suggested for America and New Zealand, and so the Ordnance Survey at Southampton were contacted to see if such documents existed for their British Survey. Unfortunately, it transpired that the surveyors employed by the Survey were expected to place all their workings and notes on the official survey sheets provided and so no notebooks existed. However, the existence of a series of Ordnance Survey internal publications containing field instructions to surveyors was acknowledged. These documents are known collectively as the 'red books' although the individual titles of each edition do vary. Since they were circulated as departmental documents and were not published officially, they have not been automatically deposited in a copyright library and hence are untraceable by conventional methods. They are known to have existed for the last century but to date only those for the twentieth century have been located. However, the early manuals of the twentieth century almost certainly continue many nineteenth-century aspects of specification and thus a fair idea of nineteenth-century practice can be obtained despite the non-availability of manuals.

3.4.3. Surveyors' Instruction Manuals

The most recent manual *'Instructions to Field Examiners and Revisers 1952'* indicates that the drainage network depicted on modern large scale maps is selective because while permanent clearly-defined drains are shown section 114b states:

> *'catch drains alongside hedges, railways and roads, and single drains in water meadows will not be shown'*

The Survey attempts to represent the network at a consistent hydrological state by instructing the surveyors to represent the network at *'normal winter level'* although no operational definition of this term is given in the manual. When approached on this matter Mr. Gawthorne of the Ordnance Survey Publicity Department at Southampton, himself an ex-surveyor, seemed to think there was no problem in representing a dynamic drainage network. He emphasised the use by surveyors of morphological and other physical evidence such as trash lines and disturbed vegetation to detect the presence of a channel rather than just depicting the avenues of flowing water as observed in the field on a particular day. It is presumably for this reason that Harley (1975) states that streams will not have been surveyed up a hillside beyond a point where they have well-defined channels. The surveyors were also quick to emphasise the degree of contact with local people over any information that was in doubt. For example a problem such as the normal position of a stream source, if unclear from physical evidence, may well be solved with help from evidence presented by local, longstanding landowners. A consisent method of identification of the drainage network by the Ordnance Survey is essential because on many maps the surveying dates for adjacent grid squares may vary by several months. Indeed the revision charts in the margin sometimes indicate a different year for the resurvey. This fact clearly invalidates the argument that the network depicted on a map is only a representation of the network at one specific point in time.

In the 1952 Manual great care is taken to preclude any ambiguities which could arise at the extremities of the network by explicitly stating in section 120c that:

'The source of a stream will be defined by one of the following terms:

1. 'Collects' (Col) - 'Where the source is a bog or marsh'

2. 'Spring' (Spr) - 'Where the source is a natural spring'

3. 'Issues' (Iss) - 'Where the source is an emission from an agricultural drain or where the stream re-emerges from the underground.

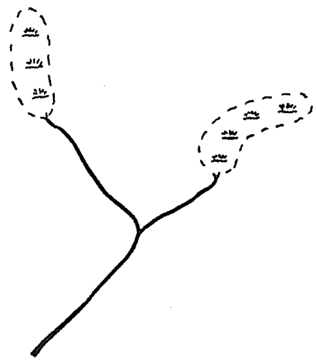
Where a stream disappears underground the point will be annotated 'sinks' (sks). Where a stream spreads on a sand or shingle beach, or in a marsh, it will be so shown and described by the word 'spreads' (sp).'

Although the Survey has no official signs for flush or gully these seem to be indicated by linearly arranged marsh signs which designate flush while less commonly hachures extending from the terminus of exterior links designate gullies. (Figure 3.2)

It may seem from these statements that the operational definition of the network as depicted on recent Ordnance Survey maps by the blue lines would appear to be in no doubt whatsoever. However while these sections from the Surveyors' Instruction Manual admirably cover many problems of map convention and hint at some Ordnance Survey working methods, there is absolutely no way that these rules can allow for misinterpretation on the part of the surveyor or indeed prevent any cartographic error that might present itself at a later stage of map production. While these definitions provide a basis for an understanding of the drainage network depicted on the most recent large scale maps, before any analysis of network change can be executed by comparison of maps of different dates, it is also necessary to examine the Surveyors' Instructions referring to previous editions.

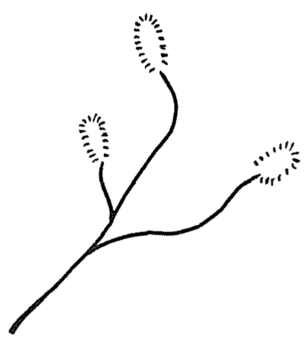
The earlier manuals of the survey, including the earliest yet located which is a 1905 revision of a nineteenth-century manual, were found in the Ordnance Survey's archives. This 1905 Manual contains definitions

(A)



Linearly arranged marsh symbols designating flush

(B)



Hachures branching from exterior links representing gullies

FIGURE 3.2 CONVENTIONS USED BY THE ORDNANCE SURVEY TO INDICATE (A) FLUSH AND (B) GULLY which are remarkably similar to the 1952 edition and are if anything more explicit including cautionary notes as well as specific guidelines. The *'Instructions to Examiners and Revisers (revised to 1905)'* is identical to the current manual in the operational definitions of the components of the drainage network represented except that roads are not mentioned in the section stating that catch drains alongside railways will be omitted, presumably because they were largely irrelevant at the time. Although the use of the term 'normal winter level' does not occur in the 1905 Manual, section 140 states that

> *'Ordinary channels .... if possible should be surveyed when at normal level'.*

An important cautionary note with the same theme is also found in the 1905 Manual indicating that an awareness exists of the dynamic nature of the drainage network and an attempt is being made to be as consistent as possible in its representation.

> *'Examiners often alter the surveyed lines of water features merely because they see them at a more dry or wet season of the year'.*

Thus, to summarise this section, the Ordnance Survey large-scale maps of the late nineteenth and early twentieth centuries are selective in their representation of the drainage network but are consistent from edition to edition in the components omitted. The conventions and the hydrological state of the network (represented at some sort of winter level) also remain remarkably constant throughout the period of study. Consequently from an examination of the various instruction manuals it would seem fair to conclude that it is feasible to compare the networks depicted on the various map editions.

3.4.4. Problems of Map Comparison of Drainage Networks.

Potentially the most serious problem in the comparison of drainage networks abstracted from different editions of Ordnance Survey maps is that a projection change occurs which is relevant to channel length and therefore drainage density as well as to the extent of the drainage network.

Prior to the introduction of the National Grid the projection used for the early 'County Series' editions of the Ordnance Survey 1:10560 and 1:2500 maps was the Cassini, and no fewer than thirty-nine county meridians existed at the time of the Davidson Committee's report of 1938. The use of so many county meridians resulted in frequent discontinuities along county boundaries, and one of the suggestions made by the Davidson Committee was that a new National Grid be adopted with just a single meridian. The Cassini Projection with a single central meridian was unsuitable due to distortion which at the eastern and western limits of the county would have extended the representation of the topography by nearly 0.1% in a north-south direction (Harley 1975) and so the more appropriate Transverse Mercator Projection was adopted.

However this inconsistency has been largely ignored because it was felt that, for an analysis of the small basins envisaged, the errors in link lengths due to the different projections would be negligible, and an accurate enough measure of link length would be obtained by adjusting the position of the early maps for each measurement so that the fork of the first order tributary coincided with the corresponding fork on the grid-series map. Care had to be exercised where an obvious change in channel course had occurred and consequently channel forks could not be matched, and in such cases the best possible correspondence of the networks had to be used. Projection is irrelevant to the other forms of network change since it cannot create or destroy drainage links.

The clarity of the various 'County Series' map editions varies considerably with reference not only to general map clarity but also to specific network depiction. The First Edition 1:10560 is extremely clear in its representation of streams where they are shown normally as double lines, while the Second and Third Editions are more difficult, due mainly to the rivers being represented by single lines which in monochrome can be very confusing. Tracing of the network in open moorland presents few problems but the situation in enclosed areas, and especially in urban areas, becomes very complex. Since at least the turn of the century Section 136 of the Ordnance Survey's *'Instructions to Examiners and Revisers 1905'* states that

> *'The direction of flow is indicated by an arrow on each trace'*

but unfortunately in practice there seems to be no rule about labelling each exterior link methodically to avoid confusion with field boundaries and other features. The problem is particularly acute on certain rock types such as limestone, where dry walls tend to follow the valley bottoms and representation can be very misleading even when using contours to help define the network. The reduced clarity of the Second and Third Editions over the First is also due to the fact that after 1881 the 1:10560 maps were produced by direct photographic reduction from the 1:2500 scale. The resulting detail is fine but often too complex so that it is sometimes necessary to consult the relevant 1:2500 map, to clarify certain points.

In general however these problems are trivial and can be overcome with care, time and a wise choice of areas.

3.5 PILOT STUDY: THE NEW FOREST, HAMPSHIRE.

3.5.1. The Physical Setting

Once the feasibility of comparing drainage networks from large scale Ordnance Survey maps had been investigated, it remained to select a local area, for which 1:10560 maps were easily available, on which to test the technique. The area chosen was that within the perambulation of the New Forest in Hampshire, an area of some 377 km^2, since it was felt that this would give an indication over a sufficiently large sample area whether network change could be abstracted from different map editions of the Ordnance Survey. The area within the perambulation of the New Forest includes headwaters of four major rivers, of which the most important in terms of area drained, is the Lymington, draining the South and Central Forest. The Beaulieu and Cadnam rivers drain the extreme eastern and north-eastern parts of the New Forest respectively while the western part of the Forest is drained by the headwaters of the Avon.

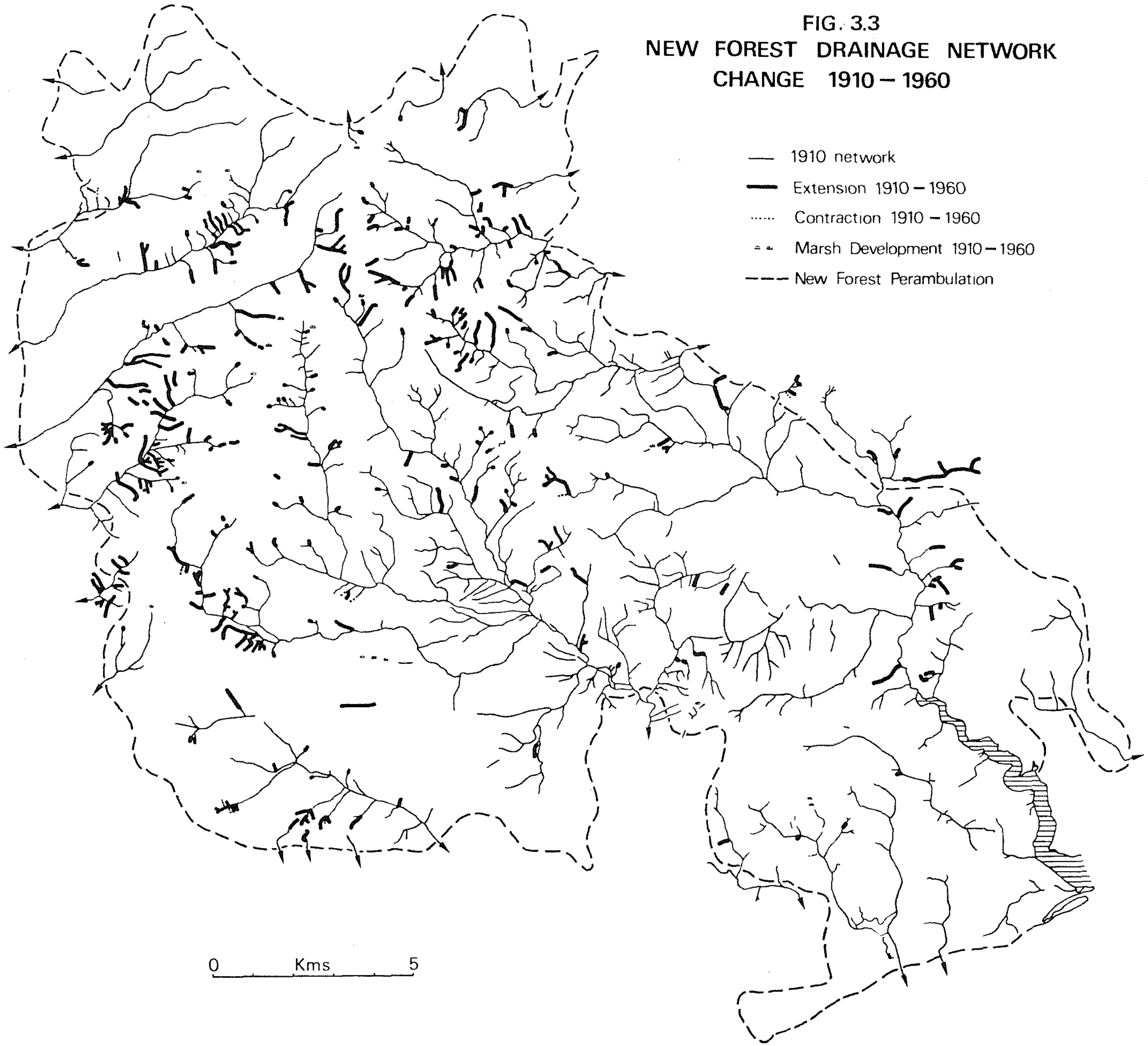
3.5.2. The Methodology of Map Network Comparisons

It was decided to utilise the Third Edition of the 'County Series' with surveying dating from between 1906-1910, and wherever possible the Regular Grid Series Edition of the late 1950s and early 1960s. Both these editions have relatively short timespans for surveying resulting in the most uniform representation of the drainage network. In addition, the Third Edition 'County Series' was the earliest series for which the Ordnance Survey's instructions to their surveyors have been located, the relevant publication being *'Instructions to Examiners and Revisers (revised to 1905)'*.

The drainage network was traced from each map to give a complete network for both the County Edition and the Regular Grid Series. In addition to the 'blue-line' network it was decided to include all bog and areas of flush so that a complete hydrological map was obtained. It was felt also that the inclusion of all bog and flush, where connected to the existing 'blue-line' network, would help to illustrate where mapping errors could have occurred through differing concepts of what represents a flush and where the change to poorly-defined channel occurs in the field.

The two sets of tracings were superimposed, the 'County Series' above, so that extensions would be clearly shown, and all points of change clearly marked on the 'County Series' tracings. A reduction of this map can be found as Figure 3.3. All locations of change in the networks, both extension and the few points of contraction, were then rechecked with the original maps to minimise operator errors. Points of change were

FIG. 3.3
NEW FOREST DRAINAGE NETWORK
CHANGE 1910 – 1960



measured with an opisometer and were then classified according to the various categories of change found in the Forest. The measurements obtained were totalled for each category and then the categories collected to give values for the amount of extension and contraction within the New Forest perambulation.

3.5.3. Drainage Network Change Within the New Forest

Figure 3.3. demonstrates emphatically that it is possible to detect network change by comparison of different editions of Ordnance Survey 1:10560 maps. A conservative estimate of network extension provided by a summation of the opisometer readings indicates that some 80 km of network extension has occurred in the fifty years separating the surveying dates of the two map editions, while network contraction is negligible, occurring at only a handful of points.

An examination of Figure 3.3. indicates that network change consists of more than one type. Extensions of existing link lengths seem to be an important method of network extension in the Forest as does the creation of new exterior links by some unknown cause or causes, sometimes connected, sometimes unconnected, to the existing network. Less common are new interior links sometimes developed along areas shown as marsh, bog or flush on the 'County Series' maps. Examples of network contraction include the reduction in length of an existing exterior link and the complete abandonment of such a link.

The clustering of locations of network extension is well illustrated in the change density map (Figure 3.4.). While there is evidence of a concentration of network extension in the North-West region, which incidentally is the highest part of the Forest, a superimposition of the New Forest Inclosures on the drainage map of the Forest as a whole (Figure 3.5.) shows no conclusive evidence for change being associated with either heathland or inclosures. However, in the

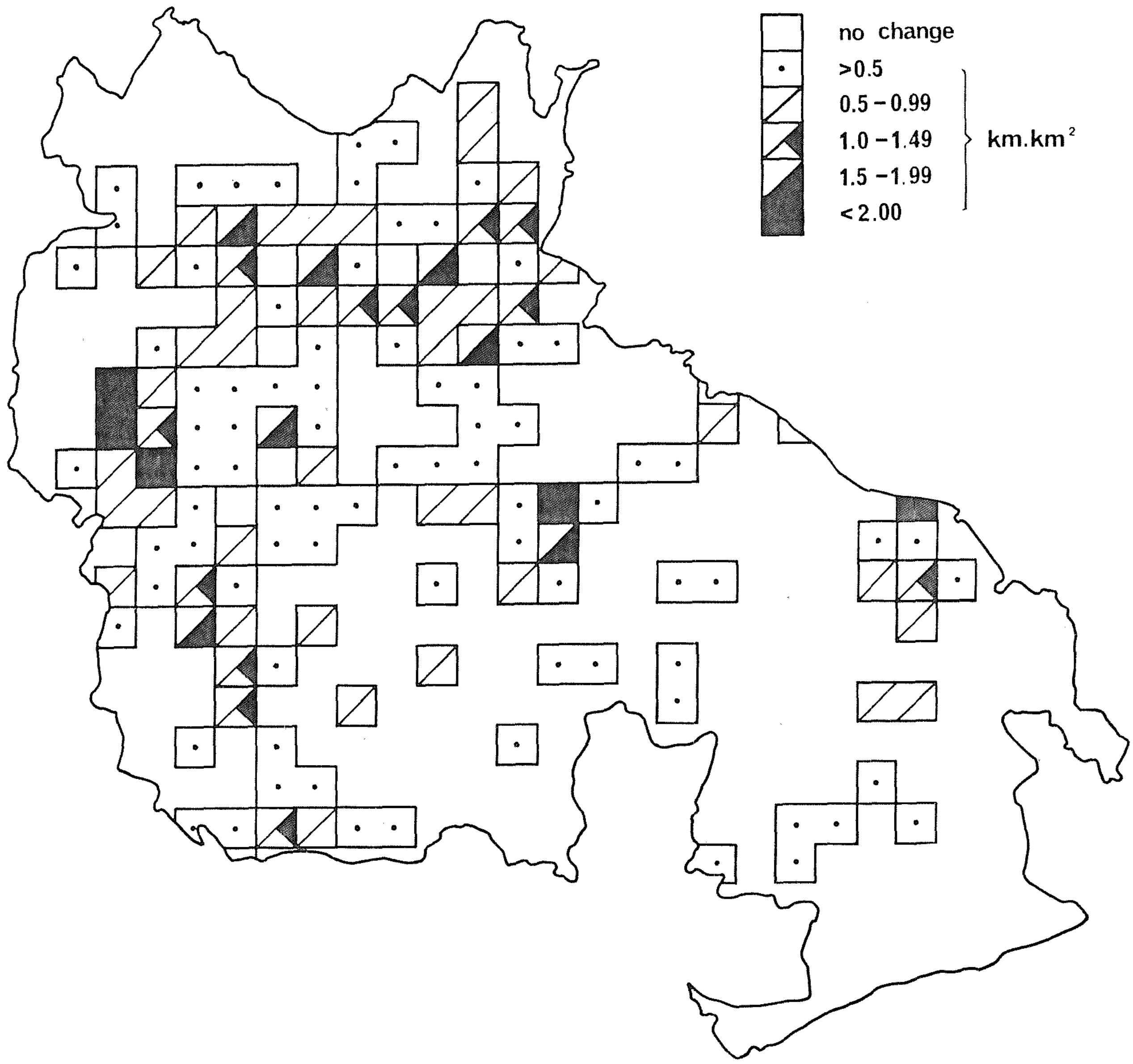
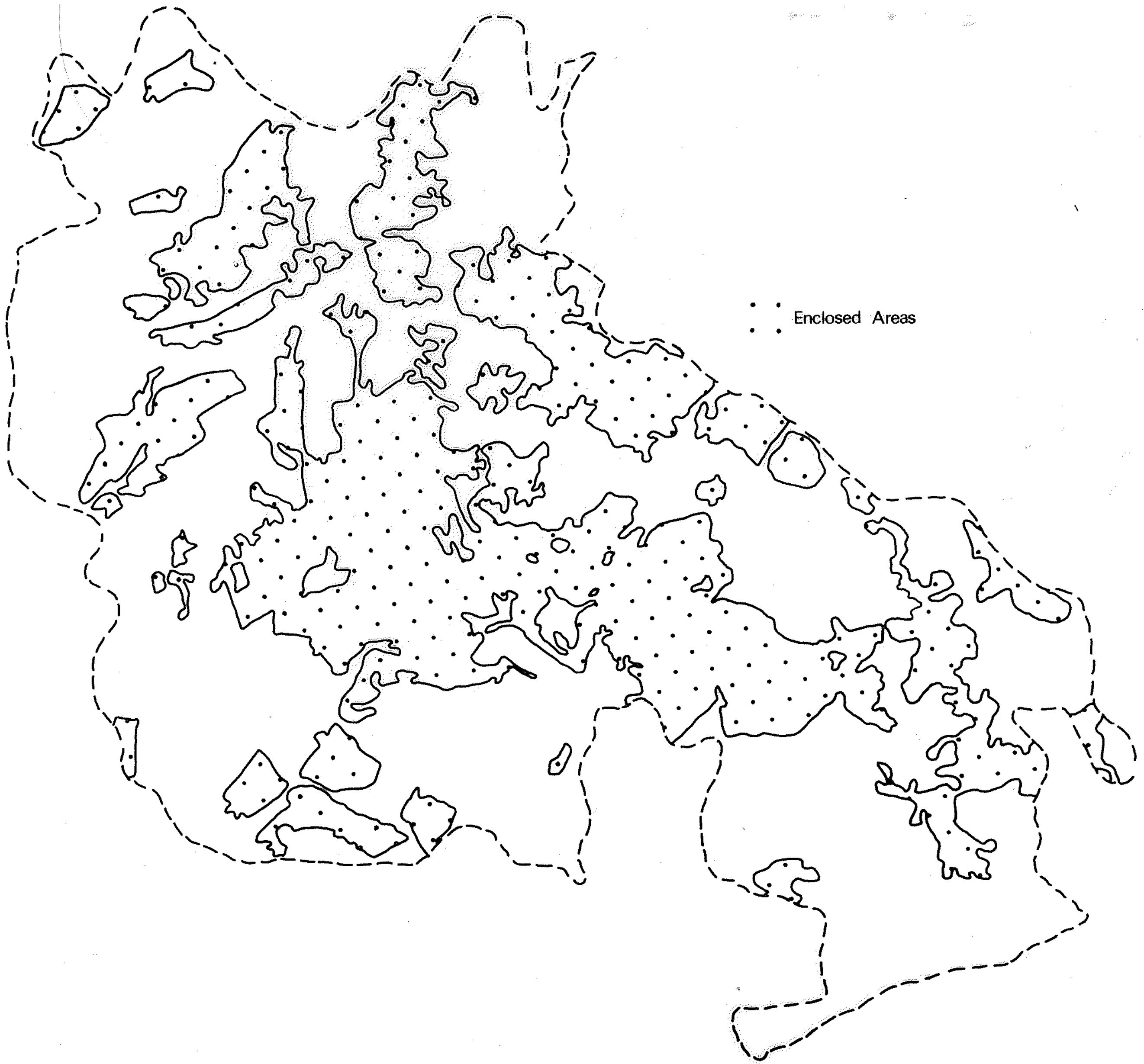


FIGURE 3.4 NEW FOREST DRAINAGE DENSITY CHANGE 1910-1960


Enclosed Areas

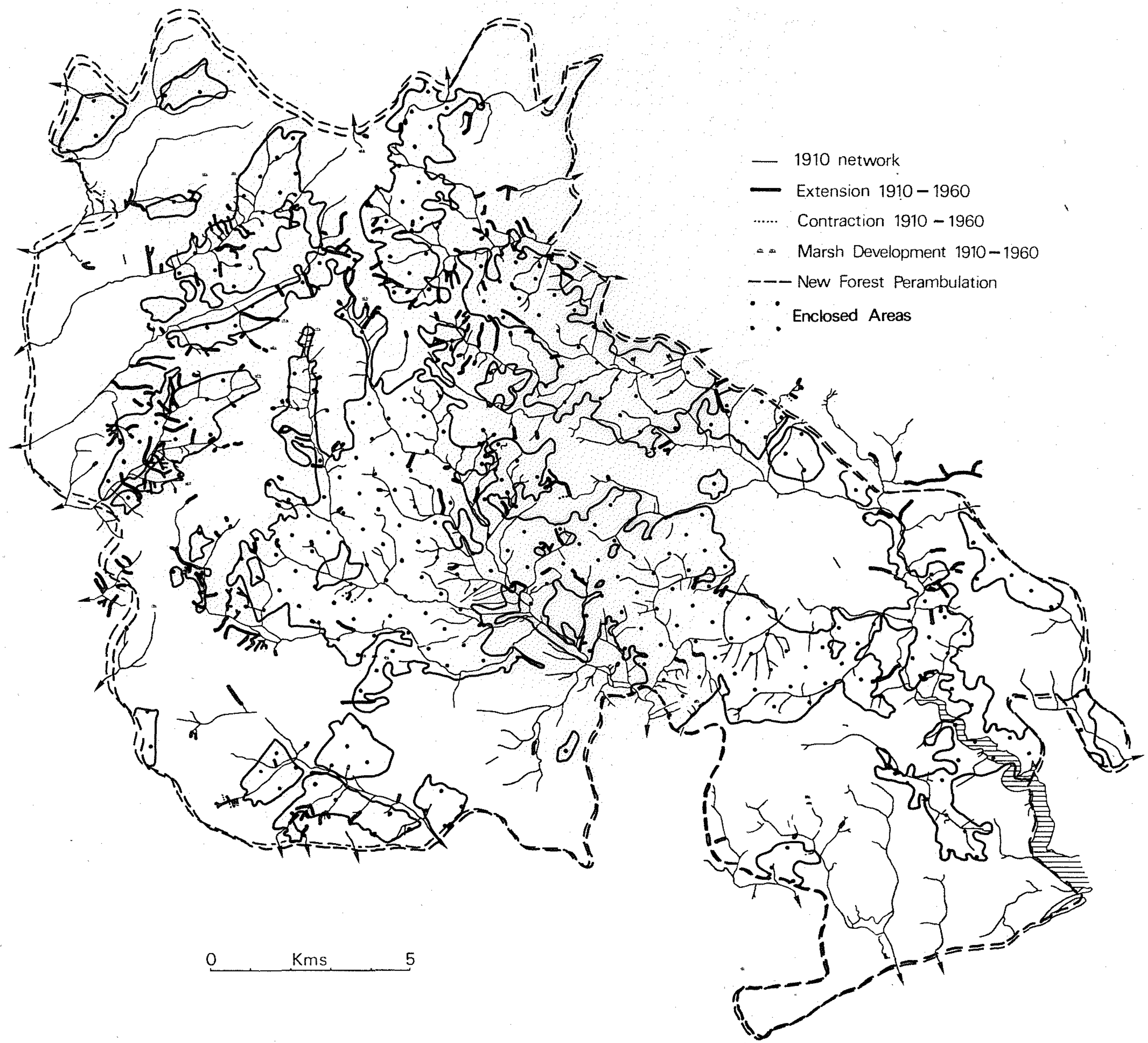


FIGURE 3.5 NEW FOREST DRAINAGE NETWORK CHANGE 1910-1960 WITH INCLOSURE DISTRIBUTION

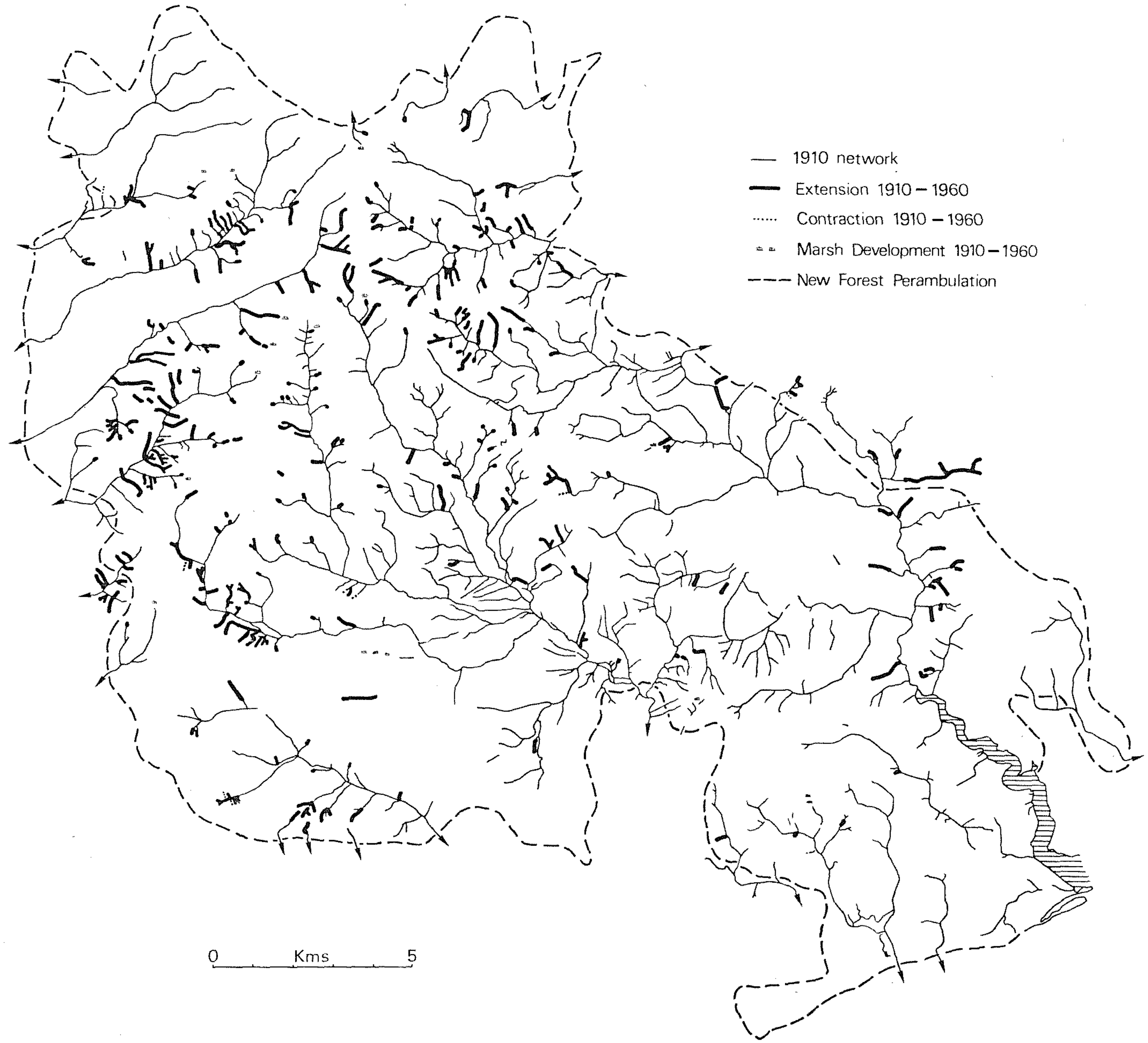


FIGURE 3.5 NEW FOREST DRAINAGE NETWORK CHANGE 1910-1960 WITH INCLOSURE DISTRIBUTION

North-West sector of the New Forest, extension seems almost exclusively confined to the inclosed areas and the area immediately around their boundaries. Without fieldwork at each location of change to determine the reasons for extension over the whole area of the New Forest, it is impossible to draw further meaningful conclusions. However, the study does indicate the possibilities of map network comparison, and demonstrates the scale at which network change has occurred over a fifty-year period for a lowland heath area in Britain.

It is impossible to say precisely how much of the 80 km of extension can be attributed to a real extension of the network or how much is due to mapping errors or surveyors' misinterpretations. Evidence from the relevant instructions to the Ordnance Survey surveyors indicates that conventions have remained constant throughout the period covering the two maps and so this factor is unlikely to be responsible for any change. Even allowing a generous 15-20% of this apparent extension for cartographic errors and surveyors' misinterpretation, it still leaves a considerable length of extension that can be confidently attributed to real network extension. In consequence one must conclude that the evidence provided by this examination of a lowland heath is sufficiently encouraging to proceed with further detailed investigations within the area, and to apply the techniques developed to a range of other Britich environments.

CHAPTER 4 DEVELOPMENT OF CARTOGRAPHIC ANALYSIS OF DRAINAGE NETWORK CHANGES BY FIELD EXAMINATION

The many problems that arise from placing a heavy reliance on the Ordnance Survey's 1:10560 map as a single source for data on network change, have been reviewed in the previous chapter. Possibly the most serious criticism to date is that the evidence has been extracted from the data of one source, namely the Ordnance Survey, with no additional information to support or strengthen the argument.

Alternative sources to the Ordnance Survey, for such data, could be either cartographical or empirical. An appraisal of alternative cartographical sources, such as the use of tithe, estate and various privately-produced maps, to supplement maps of the Ordnance Survey will be considered in a later chapter. The remainder of this chapter will be concerned with empirical methods for the identification of network change.

4.1. THE NEED FOR DETAILED FIELD EXAMINATION OF POTENTIAL NETWORK CHANGE LOCATIONS

It was suggested in the previous chapter that the impressive figures for network change over the whole of the New Forest area, were too high to be dismissed merely as arising from inaccuracies in surveying and production of the map. This implies an actual change in network extent, and in an attempt to find alternative evidence to map data for such change it was decided to examine in the field each location of apparent network change. The aims of this field examination were two-fold. Firstly to see whether there was any evidence that this assumed change of network extent had actually taken place and secondly to attempt to identify the cause or causes for any change from evidence presented at each location.

Any real change in network extent would be confirmed by field examination. Additionally the type of change could be identified as well as the nature, amount and the possible causes for the change. Results obtained by such a method are not subject to the accuracy of the map as a totally cartographic comparison would be. Such field examination would restrict the use of large-scale Ordnance Survey maps to simply providing sites where changes in the drainage network may have recently occurred.

Clearly such a detailed field investigation would be impractical for the whole New Forest area (Figure 3.3.) and therefore it was necessary to select a suitable small area within the New Forest perambulation to execute such a study. If field examination produced evidence and explanations for recent changes in drainage network extent then the argument constructed in the previous chapter, on map evidence alone, would be complemented providing conclusive evidence for network change. Unfortunately, however, such field examination is unable to produce accurate measurements of length change over an exact time period and consequently there is also a need for methods that will provide more chronological stages for interpretation of changes in drainage networks. Such a method using New Forest inclosure boundaries as a datum point over which extension can be measured exactly will be illustrated in section 6.4.

4.2. OPERATIONAL DEFINITIONS OF DRAINAGE NETWORK COMPONENTS

Whilst investigating particular locations of apparent change in the field it was decided to check the complete hydrological network using definitions as close as possible to the criteria used by the Ordnance Survey in their surveyors' instruction manuals. The use of Ordnance Survey criteria for the delimitation of the network means that as uniform a survey as possible is obtained which is completely up to date for each basin considered. This is essential since areas which are covered only by the Regular Edition maps may be as much as twenty years out of date, while even for areas revised (or resurveyed) recently a useful check for the 'metric map' network is obtained.

4.2.1. Components of the Drainage Network

A necessary early step in defining stream channels in the field is an examination of the various elements comprising a drainage network. These various elements are illustrated in Figure 4.1. A drainage network largely comprises an arrangement of sources and drainage links although it may include some form of unconcentrated or interrupted flow represented for example by marsh or flush. Sources are largely self-explanatory, a common form being the spring (Oxford Dictionary *'Place where water wells up from the earth'*). A spring may be either natural or man-created and may not necessarily be well-defined. In such a case it may take the form of a seepage line or seepage zone, giving rise to a bog (Ordnance Survey definition *'wet, spongy ground' - often incorrectly termed marsh)* or a flush. The latter term has its origins in the ecology literature and was first used by Fraser (1933) to indicate a soil type upon which flush vegetation grew. Such a soil is

> *'irrigated by free-moving water which passes over or through it from springs or other local sources of water'*

Pearsall (1950) on the same subject comments that

> *'there is a flushed area around every spring-head and around every rivulet. However the water need not emerge as a separate spring but may perfuse the surface soil - a type of flush that can be recognised by a zone of greener vegetation'.*

More recently the term flush has been introduced into hydrological literature as an important feature of the drainage basin in a number of parts of Britian, particularly with the concept of the adjustment of network extent by ephemeral features in response to storm events. Perhaps surprisingly then, the term flush has only been specifically defined by Newson and Harrison (1978) for the upland catchments of the Severn and Wye rivers as

> *'juncus-covered peaty channels'*

The importance of flushes both as locations for throughflow or pipe flow and as potential locations of network change have been illustrated by Ovenden and Gregory (1980) for the basin of the Dove in the Peak District. Thus the original ecological connotation of the term flush as a richer

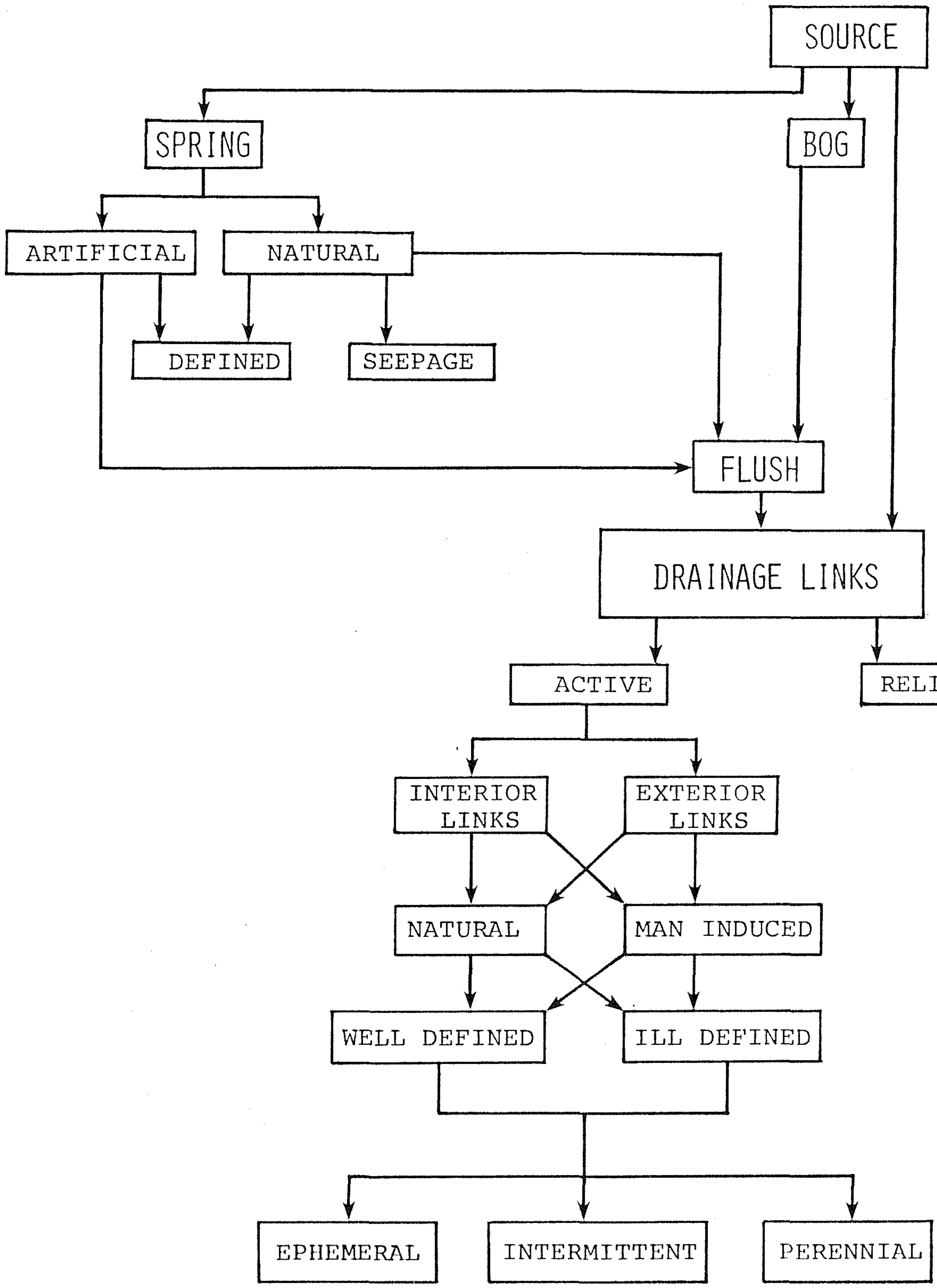


FIGURE 4.1 ELEMENTS OF THE DRAINAGE NETWORK

vegetational zone has changed somewhat, the hydrological term now denoting an important part of the drainage network representing either surface or subsurface flow or a combination of both, the presence of which is detected by a distinct band of vegetation.

The most important element of the drainage network comprises the actual drainage channels which can be sub-divided into a series of drainage links. Shreve (1966) proposed the idealised concept for drainage links where only one path exists between any two points on the network and each link at its upstream end terminates either in a source or connects to two other links. Consequently exterior links (terminating at their upstream end in sources) and interior links (terminating at their upstream ends in a fork) are distinguished.

A distinction, at this point, can be made between active links, those which function as part of the present network, and relict links which existed in the past, their presence being implied by such features as dry valleys, healed gullies, or other depressions represented on the 1:10560 maps by contour crenulations. However, only the active links are considered here since the relict links are only implied and are irrelevant to the present functioning network.

Two further sub-divisions of drainage links commonly found in the hydrological literature are the distinctions between well and ill-defined channels and between ephemeral (event tied), intermittent (seasonal) and perennial (permanent) channels.

This brief insight into the drainage network components helps to highlight the more important elements and therefore those that need most attention in field-delimitation of the network.

4.2.2. Existing Field-Definitions for Components of the Drainage Network

Although many instances of field-checking of a particular map-derived drainage network, for a whole variety of hydrological purposes, have been cited there are surprisingly few examples of definitions of a stream channel. Most of the examples that exist are taken from England, the U.S.A. or Australia and refer only to a particular area (Table 4.1). There seems to have been little attempt by most of the authors to extend the applicability of their definition or to present a national or international classification into which their particular regional classifications fits, while the vagueness of some authors' definitions of a channel is apparent (Table 4.1). The term flush is of very recent introduction to hydrological terminology and consequently has only been generally defined (Newson and Harrison 1978). Therefore precise definitions of flushes and channels, the major components of the drainage network, needed to be established for Britain. This was done using the author's personal experience throughout Britain and incorporating some of the more useful aspects from the general literature.

4.2.3. Definitions for Network Components

The definitions arrived at covered only flushes and channels since it was felt that existing definitions, already cited for the other components of the network, (Section 4.2.1.) were adequate. Details of the surveyors' methods were discussed with the Ordnance Survey to try to determine those main features which distinguished a *'blue-line'* channel from a flush on the 1:10560 series maps. These results were then integrated into a rough draft of channel definitions to give Table 4.2 which is an attempt to produce a set of definitions for channels and flushes in Britain, as consistent with Ordnance Survey methods of working as possible. These definitions were later used in the field to check the existing 1:10560 map-network, deleting and adding drainage links where necessary to bring them up to date.

AUTHOR	DATE	AREA CLASSIFICATION DEVELOPED FOR	CLASSIFICATION DETAILS
Melton	1957	Western States, U.S.A.	'A permanent clearly defined trench or trough clearly showing evidence of scour by channel flow and bounded by valley sides sloping towards the axis.'
Maxwell	1960	San Dimas, California, U.S.A.	'A channel must show the following attributes:- The presence of stream banks The presence of suspended and oriented debris The presence of wash marks Continuity with a larger channel'
Strahler	1964	-	Channel definition 'as including all intermittent and perennial flow lines located in clearly defined valleys.'
Gregory & Walling	1968	S.E. Devon, England	'Total length of concentrated detectable channel flow.'
Chorley & Dale	1972	-	'Channel size, connectivity with the main network, pattern permanence, and role played by feature in basin runoff.' All considered for the existence and extent of a channel network.
Werrity	1972	Devon and Somerset S.W. England	'A channel is a watercourse clearly incised with steep-sided banks in which water could be seen to flow or in which there was definite evidence of recent runoff. e.g. Imbricated pebbles, ripples, debris suspended over branches or roots of trees.'
Blyth & Rodda	1973	Grendon Underwood, North Bucks, England	Network extent: 'Highest points on each tributary where no flow could be detected were taken as the limits of the functioning channel system.'
Day	1978	Armidale, N.S.W., Australia	'Flowing stream length (defined Gregory & Walling 1968)'
Richards	1978	Exmoor, S.W. England	Channels identified by 'flattened grass, imbricated pebbles and channel incisions.'

TABLE 4.1 EXAMPLES OF OPERATIONAL DEFINITIONS OF STREAM CHANNELS

TABLE 4.2

DEFINITIONS OF NETWORK COMPONENTS

Some or all of the following properties were required to identify:-

Stream Channels	Flush
Linear depression with signs of channel incision.	Linear bog/marsh.
Evidence of recent flow indicated by debris including trash lines, imbricated pebbles, and modified vegetation.	Evidence of recent water flow without indication of banks or removal of vegetation.
Connectivity or logical integration with the drainage network.	Evidence of connectivity with main network and tributary to ephemeral intermittent or perennial channel.
Unvegetated banks to incised portion.	Presence of a distinct vegetation zone which is *sphagnum* in lowland catchment or *juncus* in upland basins.

4.3 FIELD SURVEY

With the theoretical need established for detailed fieldwork to supplement changes inferred from map-derived networks, it remained necessary to select an accessible area of manageable proportions to see if evidence existed for channel change on large-scale maps and whether reasons for this change could be determined in the field.

4.3.1. The Physical Setting

The basin of Highland Water, a tributary of the Lymington, which drains the central part of the New Forest was chosen for the pilot study. Possessing a basin area of some 11.30 km^2, the catchment rises at its highest point in the extreme north to 111m falling to some 37m O.D. at the mouth of the catchment. The easy access to all parts of the basin, the contrasts available between enclosed and open land, and the knowledge of the basin gained through previous fieldwork, all contributed to its selection for the pilot study. Additionally, Highland Water is already the focus of much work by members of the Southampton University Geography Department, and measurements were already under way on one particular drainage link in connection with network extension resulting from storm runoff input from newly-constructed road drains on the recent A31 improvement scheme near Stoney Cross (Section 7.1).

Before commencing detailed fieldwork within Highland Water it seemed logical to first consult all useful editions of the 1:10560 maps to obtain a complete cartographic record of the stream network throughout the years covered by the Ordnance Survey.

4.3.2. Detailed Map Analysis

The basin of Highland Water had already been examined as part of the New Forest study (Section 3.5) for the 1910 and 1961/5 surveyings but it was considered desirable to examine the results of earlier surveying in an attempt to discover whether progressive extension was occurring from edition to edition or whether the change was random. In addition, the time distribution of the change required examination to see whether change was distributed regularly throughout, or concentrated at one end of the survey period. The answer to this problem may well give useful clues to the processes causing the change.

A search revealed that Highland Water is covered by four suitable editions of 1:10560 scale maps. These comprise the First Edition 'County Series' (surveyed between 1869 and 1871), the Second Edition 'County Series' (revised 1895-1896), the Third Edition 'County Series' (revised 1907) and the Regular Grid Edition (surveyed 1961/5). The network was traced from each of the four maps, and the length at each survey measured with an opisometer. Drainage densities were then calculated to allow meaningful comparison between the four surveys (Table 4.3.).

This table illustrates the consistency or stability of the network over the forty-year span 1869 - 1907 and the subsequent expansion to the 1961/5 figure. The details of these changes to the Highland Water network during the period 1869 to 1961/5 are clearly illustrated in Figure 4.2. This demonstrates that although the total stream lengths for the early surveyings are virtually identical, they disguise the fact that change has occurred at several location. Between the 1869 and 1895 surveyings, change has occurred at four locations, small amounts of extension at three of them and a more extensive apparent contraction of the network at the remaining location (Figure 4.2). The networks depicted on the 1895 and 1907 surveys are identical perhaps unsurprisingly so since a mere twelve years separates the two surveys. The consistency of these two editions does mean that the 1907 survey confirms the correctness of the changes occurring 1869 - 1895.

No fewer than nine important locations of change have occurred between the 1907 and 1961/5 surveys, all representing extensions to the stream network. Slight discrepancies between networks of the order of one millimetre as measured on 1:10560 maps have been discarded, since it was felt that such small amounts of change could not be inferred from the 1:10560 maps with any degree of

MAP EDITION	SURVEY DATE	ΣL (km.)	Dd (km. km^{-2})
First Edition 1:10560	1869	18.08	1.60
Second Edition 1:10560	1895	18.00	1.59
Third Edition 1:10560	1907	18.00	1.59
Regular Edition 1:10560	1961/ 1965	19.77	1.75

TABLE 4.3 HIGHLAND WATER: STREAM LENGTH AND DRAINAGE DENSITY VALUES 1869 - 1961/1965

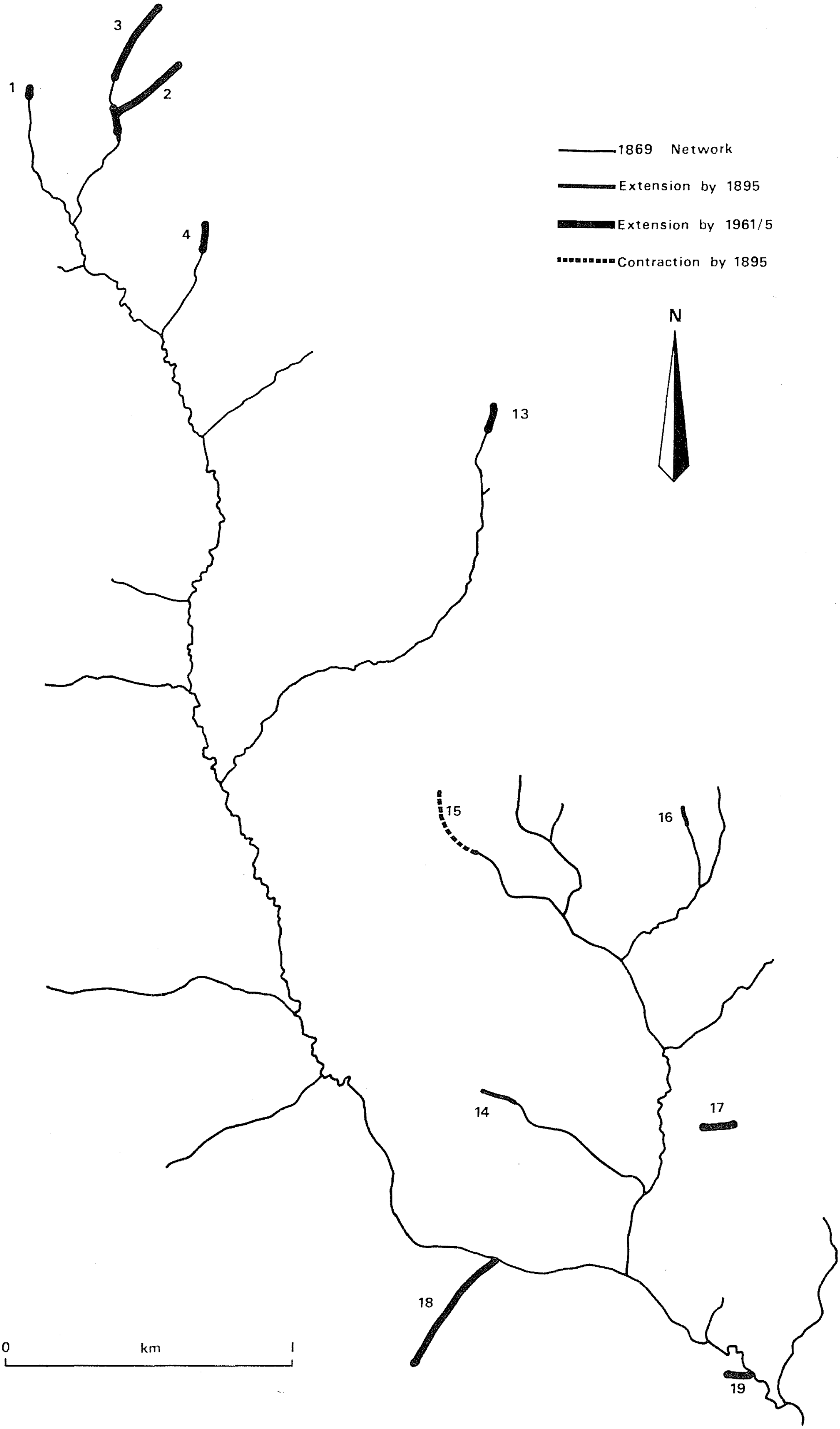


FIGURE 4.2

HIGHLAND WATER NETWORK CHANGES 1869–1961/5

certainty. Of the nine locations of change, four represent new exterior links, one a new interior link and the remaining four examples represent extensions to existing links. The amount of change, in terms of actual length, represented by these various categories of change is illustrated in Table 4.4. While extensions to link lengths and the creation of new exterior links are numerically the most important elements of network change in the Highland Water catchment over the period 1907 - 1961/5, the creation of new exterior links are by far the more important in terms of amount of extension, accounting for some 64.3% of the total extension. Extensions of link length and the creation of new interior links account for 30.5% and 5.2% respectively.

However, before such analysis becomes meaningful, the authenticity of these assumptions of drainage network change must be checked and confirmed in the field.

Before moving on to detailed field survey, a brief examination of rainfall records for rain gauges near to Highland Water was made to determine whether any correlation existed between years of higher rainfall and greater mapped network extent. Two possible methods exist for such analysis, which entails examining rainfall of the actual survey years or a general review of rainfall amounts over the period concerned to look at general trends in rainfall amount. In the first method rainfall for the four survey years (1869, 1895, 1907 and 1961) was checked at meteorological stations listed in 'British Rainfall'. Unfortunately, there have been considerable changes in the situation of the gauges themselves and no gauge relevant to Highland Water remains unchanged through the total period 1869 - 1961. Indeed, no stations at all exist within the New Forest area for 1869 (corresponding with the First Edition Survey), and more surprisingly very few for the 1961 Survey. Stations at Lyndhurst and Fordingbridge (Table 4.5) demonstrate 1907 as a wetter year than 1895, particularly for the Lyndhurst station, although the networks as represented by the Ordnance Survey are identical. Unfortunately, both these stations had been abandoned by the time of the 1961 Survey (most of Highland Water was surveyed in this year with only one

CATEGORY	OCCURRENCES IN BASIN	EXTENSION ACCOUNTED FOR (m)	PERCENTAGE OF TOTAL EXTENSION
New Interior Link	1	73.9	5.2%
Extension of Link Length	4	438.0	30.5%
New Exterior Link	4	924.0	64.3%

TABLE 4.4 HIGHLAND WATER: THE IMPORTANCE OF THE VARIOUS CATEGORIES OF NETWORK EXTENSION (1907 - 1961/1965)

	RAINFALL TOTALS (INCHES)			
STATION	1869	1895	1907	1961
LYNDHURST (Cuffnells)	No Stations	29.20	36.55	-
	in			
FORDINGBRIDGE (Oaklands)	New Forest	29.25	30.51	-

TABLE 4.5 RAINFALL RECORDS CORRESPONDING TO O.S. SURVEY YEARS FOR LYNDHURST AND FORDINGBRIDGE STATIONS, NEW FOREST, HAMPSHIRE.

or two links revised in 1965), and therefore further comparisons were impossible. Currently the nearest gauge to the old Fordingbridge station is that at Redlynch, but it was introduced only recently and no records exist for previous years. Although only a very crude indication of index of wetness is obtained by such data it may, if gauges can be located whose positions remain unaltered over long periods, dispel any positive association between network length and rainfall total. It therefore provides negative evidence for the recording by surveyors of the avenues of flowing water as seen in the field during a particular period. Major criticisms of this method include the point that while account is taken of annual precipitation, there is no appreciation of monthly rainfall variations. The technique would be far sounder if such analysis was based on monthly totals corresponding to the months in which the surveying actually occurred. Unfortunately, such data were not readily available at the Ordnance Survey and therefore the less satisfactory annual totals were used. In addition, analysis of rainfall for the surveying years only, rather assumes that all change occurred within these years. A major channel extension occurring in the year following a survey, as a result of exceptionally heavy rainfall, may be merely a response to a freak climatic event, but because channels are created faster than they disappear, this relict channel may well be represented on the next survey.

Another possible approach to this problem of compatability of rainfall over the period of the surveys is to look at general trends in the rainfall amounts (Lamb 1977, Rodda and Sheckley 1978) to see if the values are consistent over a particular period. Lamb (1977, Figure 18.25) has shown such an approach where precipitation, registered by successive decade averages, is presented for England and Wales over the period 1730 to 1960. The very generalised precipitation record highlights the consistency of rainfall over the period covered by the Ordnance Survey although a slight increase can be detected in the 1880s with a slight decrease in the 1890s and 1900s. However, the collection of such data takes a long time, and the results obtained are too generalised to be of much importance to specific drainage networks.

4.3.3. Detailed Field Survey

During the early part of 1979 the network of Highland Water was walked and surveyed using the criteria presented in Table 4.2. (Section 4.2.3.). Additional distinctions were made between perennial or intermittent channels, and ephemeral channels (including the various gullies within the catchment). In addition, road catch-drains, although not shown by the Ordnance Survey on their 1:10560 maps, were included because they are becoming an important element of the drainage network with the efficient road drainage associated with recent road improvements. These catch-drains at the very least represent important ephemeral channels and some major ones probably qualify as intermittent channels. No distinction was made between perennial and intermittent channels because the Ordnance Survey, by representing the drainage network at *'normal winter level'* presumably include both categories under the *'blue-line'* network.

The continuing growth of the network during the twentieth century is well illustrated in Table 4.6, where drainage density has increased from 1.60 km.km^{-2} in 1869 to 2.10 km.km^{-2} in 1979. Although the comparison of the 1869 map network with the 1979 surveyed network (which includes road drains and ephemeral channels) is not absolutely fair, it is certainly feasible since the field evidence suggests that the ephemeral channels are a direct response to recent interference within the catchment by man. Such human interference would not be applicable to the 1869 Survey, neither would road catch-drains have had the same importance then.

The locations of the various types of change within Highland Water can be found in Figure 4.3. The numbers alongside each location of change in both Figures 4.2

MAP EDITION OR SURVEY CATEGORY	SURVEY DATE	≤ L (km)	Dd (km.km^{-2})
First Edition 1:10560 O.S.	1869	18.08	1.60
Second Edition 1:10560 O.S.	1895	18.00	1.59
Third Edition 1:10560 O.S.	1907	18.00	1.59
Regular Edition 1:10560 O.S.	1961/5	19.77	1.75
Regular Edition Map Network + 1979 Field Survey (using O.S. criterion)	1979	21.07	1.86
1979 Survey + Flushes	1979	21.81	1.93
1979 Survey + Flushes + Ephemeral Channels	1979	22.20	1.96
Total 1979 Network + Road Catch-drains	1979	23.73	2.10

TABLE 4.6 HIGHLAND WATER: NETWORK EXTENSIONS 1869 - 1979

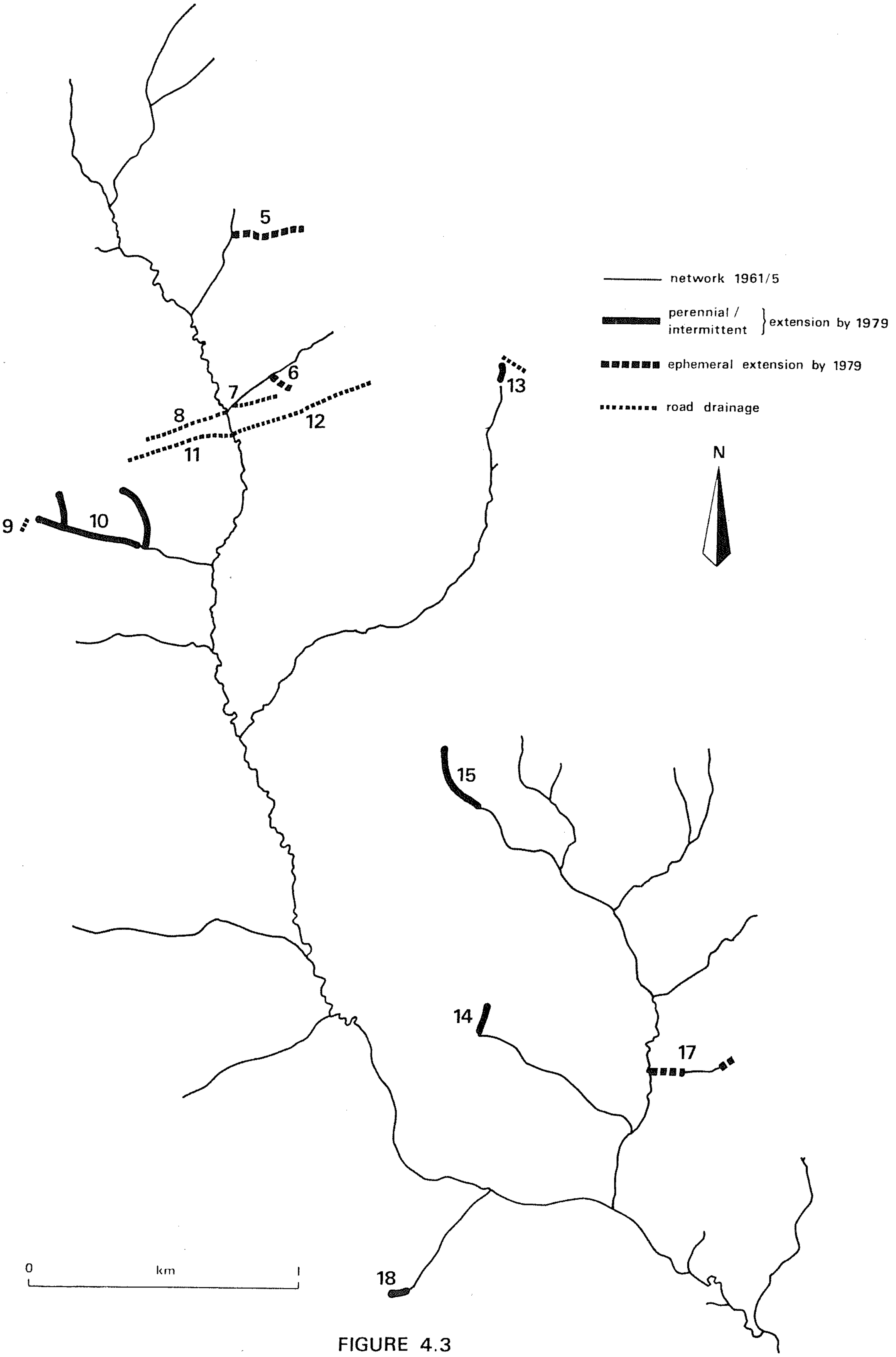


FIGURE 4.3

HIGHLAND WATER NETWORK CHANGES 1961/5–1979

and 4.3 correspond to numbers in the text.

Recent change may be broken down as follows. Firstly six locations of perennial or intermittent channel development since the 1961/5 Survey, with a further three locations of recent ephemeral channel development and one area of considerable flush development. In addition to these conventional aspects of the drainage network are the road catch-drains associated with recent improvements to the A31 Bratley-Ringwood trunk road.

4.3.4. Explanations for Network Changes

Field examination at each location of change revealed considerable evidence of the causes of network extension. Consequently the nineteen points of change in the Highland Water catchment were grouped into five categories according to the predominant reason for change. These comprise natural network extension, drainage extension associated with Stoney Cross wartime airfield, drainage extension associated with the A31 road improvement scheme, network change due directly or indirectly to the activities of the Forestry Commission, and a final category of possible surveying error or misinterpretation.

Examples of what appears to be natural network change are found at Sites 1, 4 and 17 and occur at locations where there is little evidence of direct human influence. For the most part they are small amounts of extension, Sites 1 and 4 being apparent metamorphoses of what appears to be former flushes into well-defined channels. In both cases the impetus for this metamorphosis appears to be an increased input of water arising from drainage of near-by forest tracks. Site 17 certainly represents the creation of a new exterior link, possibly along the path of a former flush, which recent field survey now shows extends further than was represented on the 1961/5 Survey. At the head of this recent extension exists the impressive gully described by Tuckfield (1964) which developed along a firebreak first cleared in 1951. It is the drainage concentration caused by this feature that appears to have been responsible for the metamorphosis of this flush to a well-defined channel, seen not only immediately below the gully but also in the new interior links (Plate 4.1).

Road drainage is a major source of network extension in Highland Water; Sites 6 to 12 inclusive are the direct result of recent road improvements (and associated drainage work) to the A31 Brately-Minstead trunk road. The origins of the recent ephemeral exterior link (Site 6) can be traced to a small gully which had developed on the bare roadside verge during the last few months of 1978. This gully, the direct result of storm runoff from the impervious road surface, now feeds this short ephemeral link which connects with the existing perennial network (Plate 4.2). Sites 7, 8, 9, 11 and 12 represent catch-drains the longest of which (11 and 12) certainly qualify as intermittent and possibly even perennial (Plate 4.3). Catch-dams are located in the drain at Site 7 in an attempt to arrest erosion down the steep slope (Plate 4.4). The complex of network extension at Site 10 is the direct result of storm-water disposal with outlet pipes situated at the head of each link. This complex is the subject of a detailed investigation described in Section 7.1. The extension since the 1961/5 Survey at Site 18 together with the considerable length of flush is the result of minor road drainage.

Network extension at Sites 2 and 3 can be confidently attributed to drainage associated with Stoney Cross wartime airfield. At its upstream end, the perennial link length extension at Site 3 ends at the outlet of a twenty-four inch diameter main drainage pipe from the airfield, (Plate 4.5) while the new intermittent exterior link at Site 2 ends in a 'soakaway' at the edge of the airfield. The new interior link at Site 2 is probably the result of an increased input of water from the airfield resulting in the metamorphosis of a former flush to a definite channel. The ephemeral exterior link (Site 5) is the result of drainage disposal

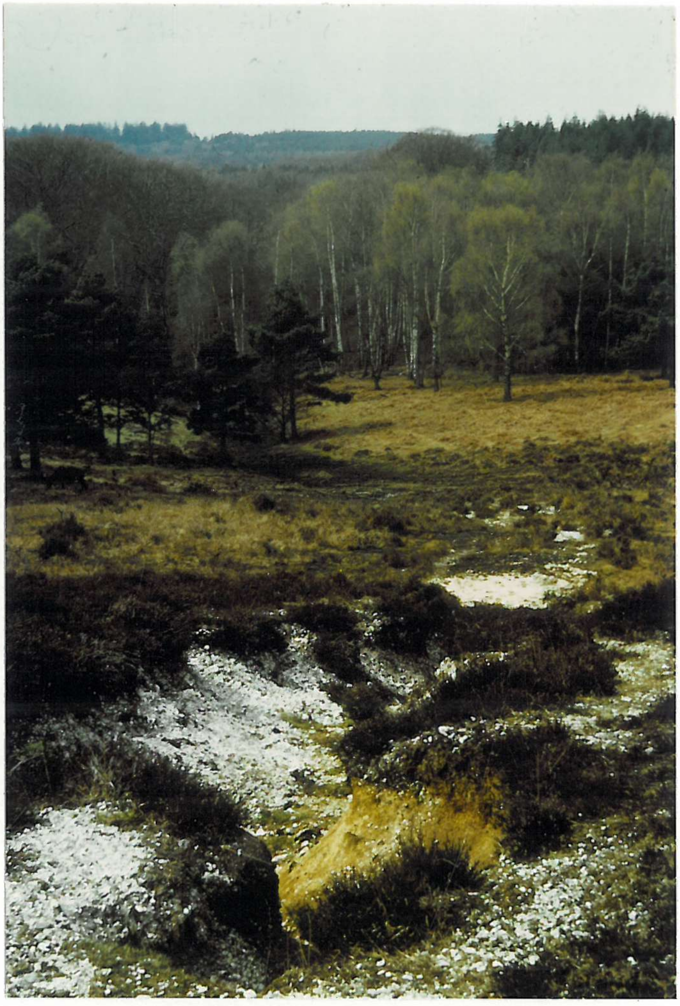


PLATE 4.1 HIGHLAND WATER: THE METAMORPHOSIS OF A FLUSH TO A WELL-DEFINED CHANNEL MAY BE THE RESULT OF DRAINAGE CONCENTRATION CAUSED BY A GULLY (SITE 17).

PLATE 4.2 HIGHLAND WATER: A NEW EPHEMERAL LINK DEVELOPED IN ASSOCIATION WITH A SMALL GULLY INITIATED ON A BARE ROADSIDE VERGE (SITE 6).

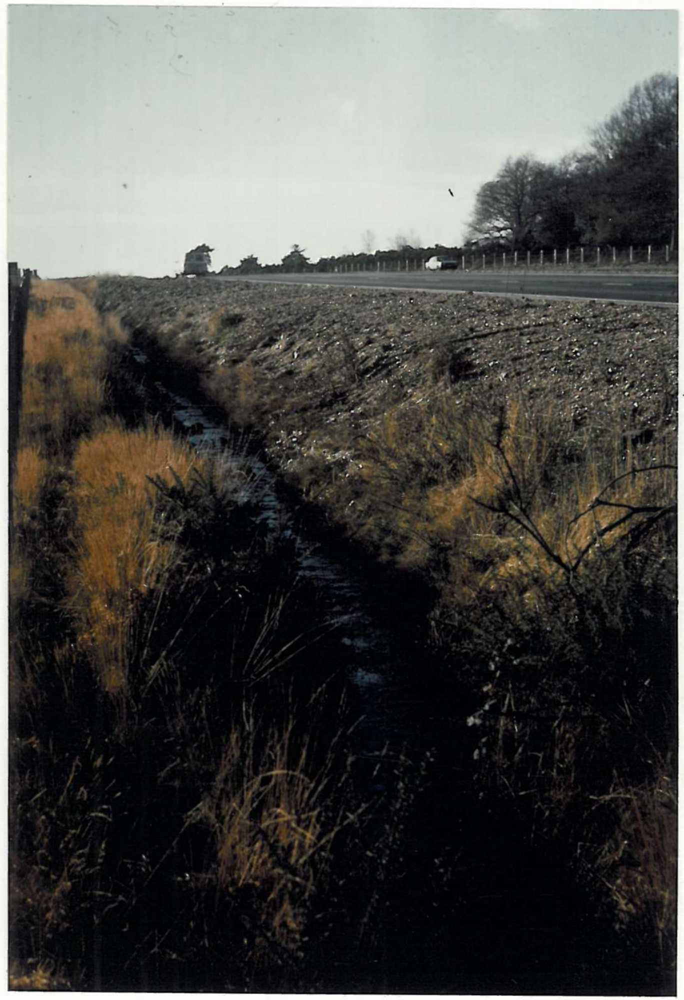


PLATE 4.3 HIGHLAND WATER: MAJOR ROAD CATCH DRAIN OF PERENNIAL/ INTERMITTENT REGIME (SITE 11).

PLATE 4.4 HIGHLAND WATER: CATCH DAMS LOCATED WITHIN CATCH DRAINS IN AN ATTEMPT TO ARREST EROSION (SITE 7).

PLATE 4.5 HIGHLAND WATER: PERENNIAL LINK CREATION, THE RESULT OF SUB-SURFACE DRAINAGE FROM STONEY CROSS AIRFIELD (SITE 3).

from a concrete chute at the southern extremity of the airfield. A more-detailed review of Stoney Cross airfield in the context of the whole Central Forest stream network will be found in Section 7.3.

Another important cause of network extension in the Highland Water catchment is provided by the work of the Forestry Commission. This is mainly a direct influence in the form of the construction of drainage ditches associated with the afforestation of large areas of the catchment. Examples of such an influence, where the existing stream network has been complemented or extended by ditching, are found at Sites 14, 16 and 18. Frequently a complex arrangement of ephemeral drains is associated with these main drainage ditches. Extension at Site 13 is the result of a Forestry Commission track; extension here, by the 1961/5 Survey, is probably another example of the metamorphosis of a flush to a channel caused by increased inputs of water from the track, while the recent extension is ditching along the forest track with a feed drain to the former stream head for efficient drainage.

This leaves one change location (Site 15) unaccounted for. The 1869 Survey here shows a length of stream which is omitted by the 1895, 1907 and 1961/5 Surveys. However, 1979 field survey reveals that the length concerned does in fact exist as an old, but well-defined and certainly intermittent drainage ditch extending to a gravelled Forestry Commission road. The ditch has had no maintenance for a very long time, and in many parts is almost completely covered by debris. This almost certainly looks like a case of surveyor misinterpretation in the 1895 Survey which has been perpetuated in recent surveys.

4.3.5. Summary

One must therefore conclude that there is ample and incontrovertible evidence in the basin of Highland Water for the occurrence of network change over the last 120 years, most of which can be adequately explained by factors identified during field survey. Moreover the differences in network extent as depicted on the different editions of Ordnance Survey maps, in all but one instance, do represent a real change in the drainage network. Field survey has demonstrated the importance of several factors in extending the stream network over the last century and these, by way of summary, are listed chronologically in Table 4.7 as a series of events. These results then, based on the use of different editions of Ordnance Survey maps to detect potential points of network change, are sufficiently encouraging to proceed with similar investigations for a range of climatic and relief environments through Britain.

4.4. NATIONWIDE SELECTION OF DRAINAGE NETWORKS FOR MAP ANALYSIS

With the success of the detailed study of the Highland Water catchment, a comprehensive study representative of the whole of Britain was required to gain some impression of the distribution of network change and its importance throughout the country.

4.4.1. Criteria for the Selection of Areas

At the outset the single criterion governing the selection of twenty or so suitable drainage basins was that as wide a range as possible of relief and climatic types throughout Britain should be covered. Several other criteria were quickly added in the interests of economy of time, soundness of method and the success of the project. The complete list of criteria for selection of basins for study reads as follows:-

1. Basins should cover a range of climatic and relief types.
2. Natural and man-modified basins should be included.
3. Basins must be of a manageable size.
4. Basins should have a clear First Edition 1:10560 map.
5. Basins should have either a 1:10560 Regular or 1:10000 Metric Edition map.

EVENT	DATE	IMPLICATION
Inclosure Construction	1869	Drain construction associated with inclosure and feeding into Highland Water.
Road Metalling (A 31)	c.1900	More efficient runoff and possibly some organised drainage.
Stoney Cross Airfield Construction	1943	Sub-surface airfield drainage pipes fed into the head of Highland Water
Forestry Commission Activity	post 1960	Drain construction associated with recent plantings particularly in lower end of basin.
Countryside Act - Amenity and Recreation	1968	Forestry Commission responsible for public access. Road and car-park construction, generating increased runoff and necessitating more drains.
Road improvements to A 31	1976/ 1977	Dual carriageway crossing Highland Water with organised drainage disposal into the existing stream network.

TABLE 4.7 HIGHLAND WATER: SUMMARY OF EVENTS

6. Within the restriction imposed by 4 and 5 basins must have a homogeneity of surveying date.
7. Basins should have good access

The need for a range of climatic and relief types inclusive of both natural and man-influenced basins, is self-evident in that the aim of the study is to determine the distribution and extent of network change throughout Britain and therefore a selection including as many different types of basin as possible would provide the best cross-section. The main restriction on the size of basin employed was the operational factor of the numbers of maps required, because the collection of large numbers of the 1:10560 series proved excessively time-consuming. Consequently a general upper limit of some six maps was set with an optimum number of four. With the use of monochrome by the Ordnance Survey a clear First Edition map is essential because the use of single lines to depict networks, as used on the later quarter sheets, causes confusion with field boundaries and other details. The problem is particularly acute in urban and enclosed areas although, where possible, examples of such networks were included. In general therefore the whole sheet 'County Series', with their depiction of the network in double lines, provides a clearer picture of the drainage network than the quarter sheet 'County Series' with their single-line representation of the drainage network which superseded them. A Regular 1:10560 or Metric 1:10000 Edition is essential, as summarised in Table 3.3 in the last Chapter, because these are the only editions to provide new survey information since the 'County Series' maps. This criterion more than any of the others most severely restricts the areas that can be utilised because large areas of Upland England and Wales have only provisional coverage at the 1:10560 scale (Figure 4.4). The homogeneity of the surveying date, within the restrictions imposed by the various map editions, is also important. It is preferable for the span of survey dates for a network to be as short as possible with four to five years acceptable in this respect. In general, this is

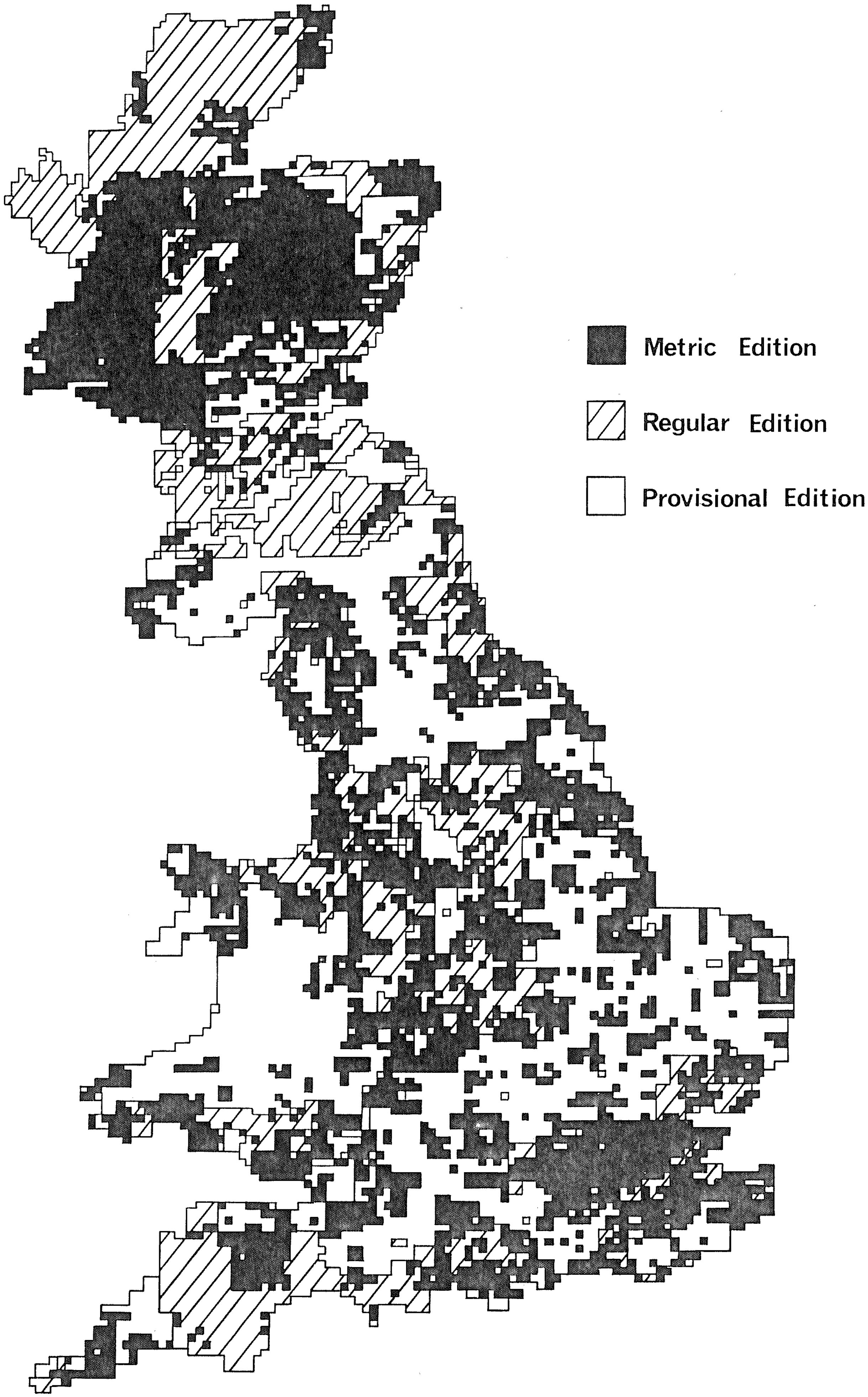


FIGURE 4.4 ORDNANCE SURVEY 1:10560 and 1:10000 COVERAGE FOR BRITAIN

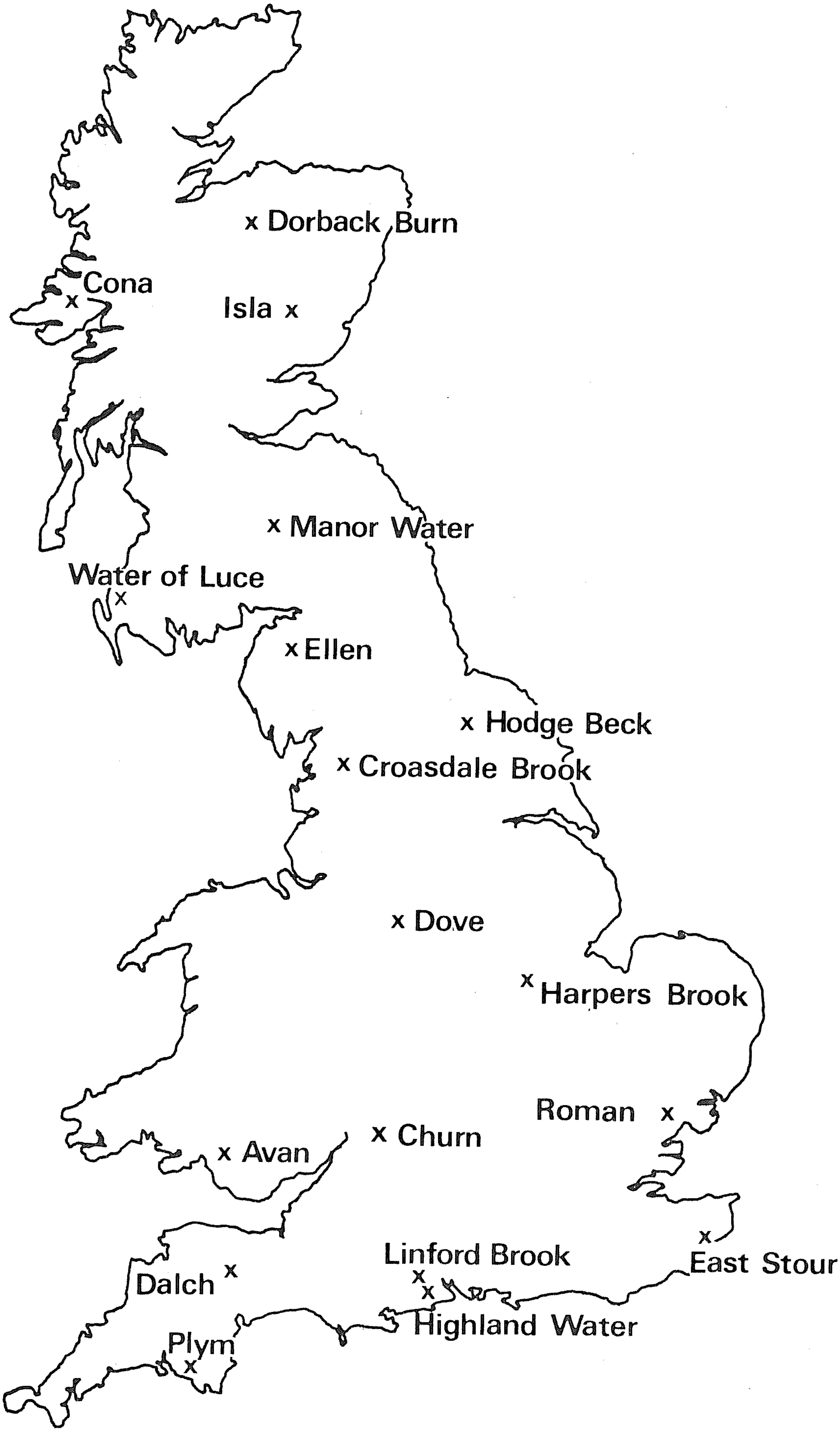


FIGURE 4.5 CATCHMENTS SELECTED FOR DRAINAGE NETWORK CHANGE ANALYSIS

NETWORK (Gauge or Lowest Point)	General Location	Basin Area (km)	Catchment Relief (m) Highest Point	Lowest Point	SAAR (mm)	M52D (mm)	Basin Characteristics
AVAN (Cymmer)	Rhondda	16.48	560	183	2377	125.0	Afforested + Pasture + Urban Ribbon Development
CHURN (Colesborne)	Cotswolds	22.86	289	156	817	53.0	-
CONA (Corrlarch)	Ardgour	22.67	849	98	1998	140.0	Glen: Rough Pasture
CROASDALE (Croasdale Flume)	Forest of Bowland	8.75	540	200	1839	95.0	Moorland + some enclosed Pasture
DALCH (Wonham)	Central Devon	17.39	231	132	1038	60.0	-
DORBACK BURN (Lochindorb)	Strathspey	18.19	504	298	1237	63.0	Moor: Rough Pasture
DOVE (Hollingsclough)	Peak District	8.05	552	285	1232	67.5	Pasture - enclosed + improved
EAST STOUR (Bested Hill)	Vale of Kent	43.57	175	48	760	55.0	Agricultural
ELLEN (Stockdale)	Northern Lake District	4.46	628	195	1224	59.0	Moor - partly enclosed
HARPERS BROOK (Oakley Grange)	Rockingham Forest	17.72	137	82	607	46.5	-
HIGHLAND WATER (Millyford Bridge)	New Forest	11.30	111	37	830	60.0	Lowland Heath - part Afforested
HODGE BECK (Bransdale Moor)	North York Moors	4.43	448	312	1057	62.9	Moor - Afforested
ISLA (Linns)	Grampians	53.46	1068	366	1427	90.4	Moor - Rough Pasture
LINFORD WATER (Linford)	New Forest	10.84	104	37	830	60.0	Afforested
MANOR WATER (Langhaugh)	Southern Uplands	23.22	815	260	1252	61.0	Moor - Rough Pasture
PLYM (Trowlesworthy)	South-West Dartmoor	18.65	491	234	1560	90.0	-
ROMAN (Heckfordbridge)	Colchester, Essex	25.89	62	15	575	46.0	Agricultural + some Urban
WATER OF LUCE (Craigoch)	Wigtownshire	13.00	439	181	1631	63.0	-

TABLE 4.8 DETAILS OF THE CHOSEN DRAINAGE BASINS

PREDOMINANT CATCHMENT LANDUSE	AVERAGE ANNUAL PRECIPITATION 1916-50	
	HIGH (Above 1050mm)	LOW (Below 1050mm)
Forest	Ditches (Perennial/ Intermittent)	Ditches (Ephemeral)
Moorland	Natural change possibly reflecting secular climatic changes	Some natural change
Pasture	Little change	Little change
Agricultural	Field Drains (Intermittent)	Field Boundary Drains (Ephemeral)
Urban	Perennial or Intermittent Drains associated with a variety of construction work	Ephemeral drains associated with a variety of construction work

TABLE 4.9 PREDICTED CATEGORIES OF NETWORK CHANGE FOR SELECTED DRAINAGE BASIN TYPES

not a problem with the First Edition 1:10560 or the Metric Edition maps which both possess a very short survey span (except in the case of the First Edition where basins fall across county boundaries) but it is more so with the Regular series maps. This criterion also helped to keep the average size of drainage basins down because, over a certain size, surveying dates began to vary sometimes quite substantially and were unacceptable. Access to basins was the least important criterion, designed only to save time at the field examination stage.

It is not intended that this study should in any way compete with the extensive work carried out by the Field Drainage Experimental Unit (MAFF) and consequently land drainage receives only passing attention in this study.

4.4.2. The Selected Basins

With these restrictions the seemingly impossible task of selecting twenty or so suitable basins from the whole of Britain becomes quite manageable because for many areas only a handful of basins satisfied all the required criteria. The distribution of the catchments selected is shown in Figure 4.5 together with a review of basin properties (Table 4.8).

Reference to Table 4.8 reveals that the presented drainage basins can be categorised according to rainfall (either average annual precipitation 1916 - 50 or intensity of rainfall), relief extremes or the predominant land use within the catchment. However the catchments with the highest basin relief generally possess the highest average annual precipitation and also experience the highest rainfall intensities enabling them to be classified into similar groups by any of these variables. Sub-division of these fundamental groups may then be made according to land use (i.e. afforested, urban or agricultural basins). Using an arbitrary figure for average annual precipitation of 1050 mm. a broad classification is proposed which can be used as a basis for predicting expected types of change to be found within certain types of drainage basin (Table 4.9).

CHAPTER 5 CARTOGRAPHICAL ANALYSIS AND FIELD SURVEY OF SELECTED DRAINAGE NETWORKS

5.1 DETAILS OF COVERAGE

The selection of only eighteen drainage basins was considered to be justified because they still permitted comprehensive coverage of the major types of drainage basin found in the British environment in terms of geology, average annual precipitation, rainfall intensity (and thus drainage density), relief differences and land use. Some reservations are held in that much of the Pennines and Central Wales was unrepresented but this was due to the paucity of Regular or Metric Edition 1:10560 and 1:10000 maps. In addition problems of delimiting the network in urban areas dictated that the Avan catchment in South Wales, and to a lesser extent the Roman catchment in Essex, would be the only representatives from partly-urbanised catchments.

Southern lowland heaths are represented by the New Forest catchments of Highland Water and Linford Water, the latter being totally afforested, while Harpers Brook and the East Stour are examples of lowland agricultural basins. Five basins were eventually chosen from Scotland - those of Cona, Dorback, Isla and Manor Water, representing upland catchments of varying rainfall, with the coastal basin of the Water of Luce also included.

The Croasdale (predominantly moorland), Ellen (moorland), and Dove (pasture) basins represent small upland catchments from Lancashire, the Lake District and the Peak District respectively, while the small totally-afforested catchment of Hodge Beck in the North York Moors was included to show the influence of the Forestry Commission on the drainage network. Two basins, those of the Dalch in Central Devon and the Plym (south-west Dartmoor) represent the South West

BASIN	AREA	FIRST EDITION SURVEYED	FIRST EDITION ΣL(km.)	FIRST EDITION Dd.(km.km^{-2})	METRIC EDITION SURVEYED	METRIC EDITION ΣL(km.)	METRIC EDITION Dd.(km.km^{-2})
Churn	22.86	1881/2	14.435	0.63	1972/4	15.075	0.66
Dalch	17.39	1887	25.18	1.45	1970	34.265	1.97
Harpers Brook	17.72	1885	14.94	0.84	1969/72	14.64	0.83
Hodge Beck	4.46	1853/4	4.05	0.91	1975	21.80	4.92
Linford Water	10.84	1869/71	13.30	1.23	1960*	20.75	1.91
Plym	18.65	1882/5	20.51	1.10	1950*	21.06	1.13
Water of Luce	13.00	1846/56	31.80	2.45	1976	33.475	2.575

* Regular Edition used

TABLE 5.1 DETAILS OF NETWORK CHANGE FOR BASINS UNCHECKED IN THE FIELD

Peninsular with the Churn catchment the sole representative from the Cotswolds.

A certain element of duplication existed even within these eighteen examples, and eventually some ten of the most interesting and varied basins, in terms of network change types and amounts, were field-checked, these being described in Section5.3. The less-interesting basins are considered briefly in Section 5.2, the details of drainage network change being presented in Table 5.1.

5.2 CARTOGRAPHIC ANALYSIS

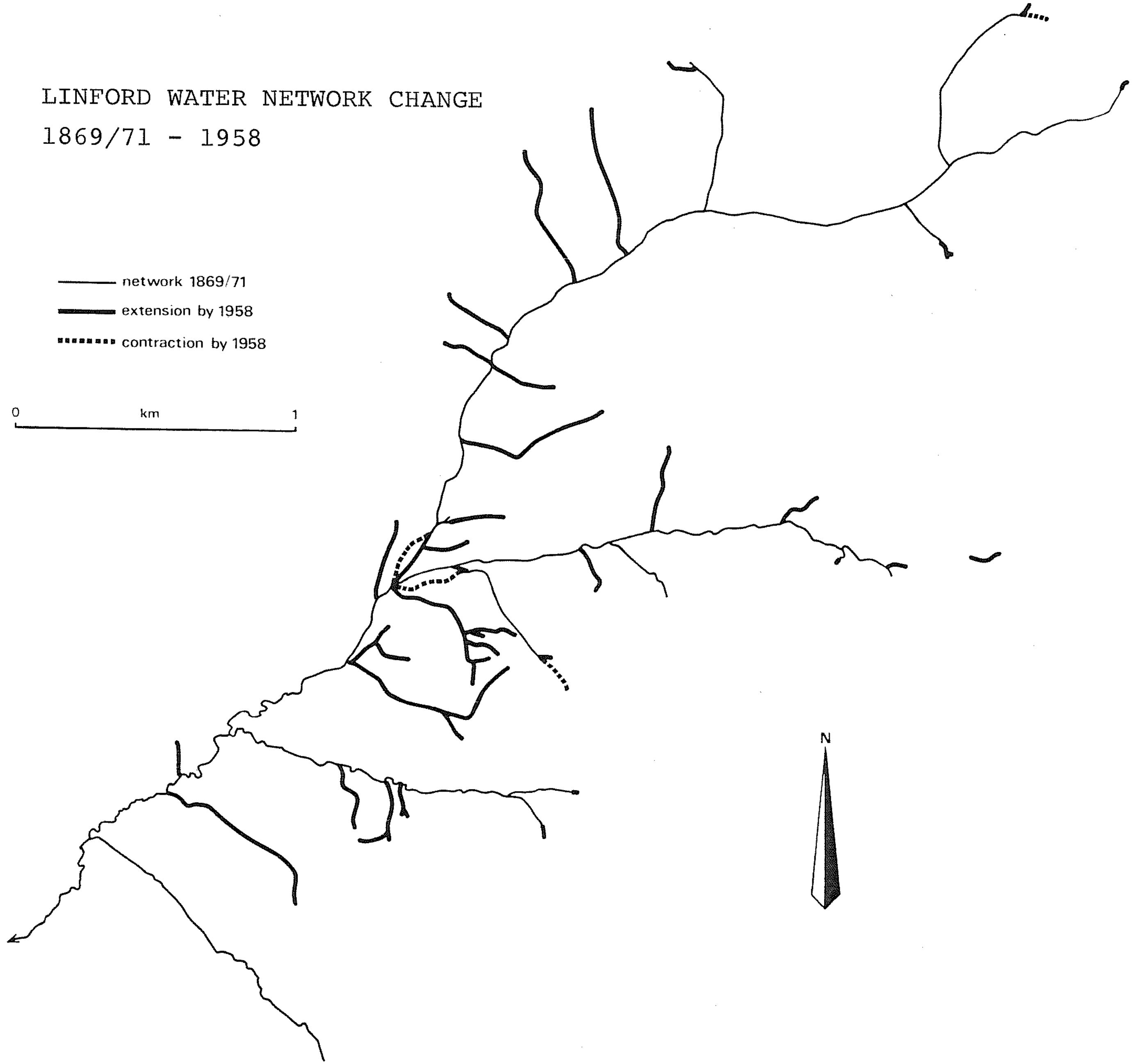
5.2.1. Linford Water

The small, afforested catchment of Linford Water (10.84 km^2) was included to complement the findings of Highland Water since Figure 3.3 had shown Linford Water to represent one of the most concentrated areas of network change within the New Forest perambulation. Figure 5.1 demonstrates that much of the network extension in the Linford Water basin is the result of new exterior links. A high proportion of these are clearly marked 'drain' on the Regular Edition 1:10560 (dated 1960) and occur within the confines of the inclosure. In the light of field work in the Highland Water catchment, these can confidently be attributed to Forestry Commission ditching associated with the afforestation of the area. Extension in the extreme headwaters of the catchment is considered in relation to extension over Milkham Inclosure Boundary (Section 6.4.2.).

5.2.2. Hodge Beck

A similar explanation for network extension is seen in the small catchment of Hodge Beck (Figure 5.2) which demonstrates an increase in network length from 4.05km in 1853/4 to 21.80km in 1975, an increase in drainage density of 4.01$km.km^{-2}$. This is, in fact,

FIGURE 5.1 LINFORD WATER NETWORK CHANGE 1869/71 - 1958



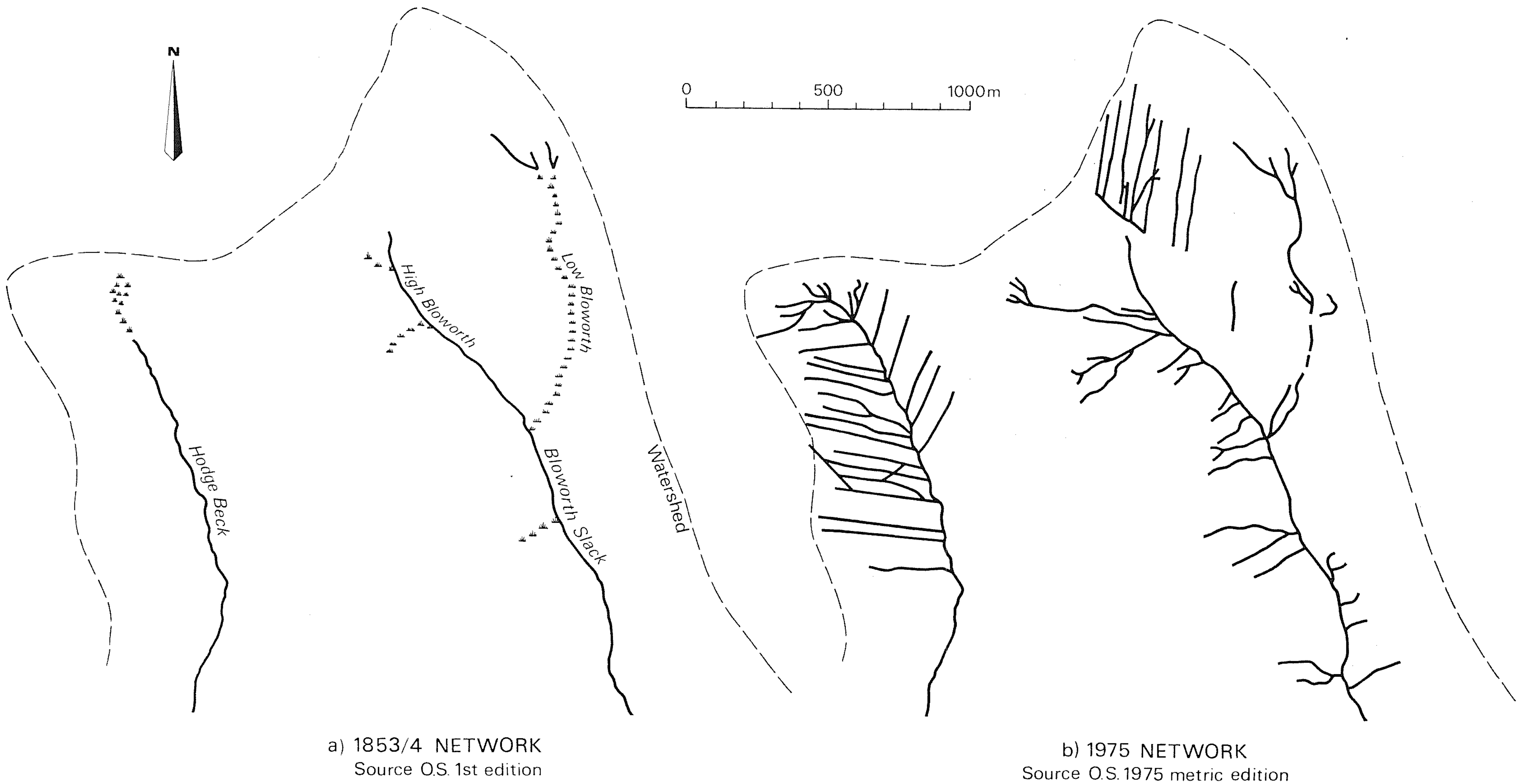


FIGURE 5.2 HODGE BECK NETWORK CHANGE 1853/4 - 1975

the largest increase in drainage density found in any of the eighteen basins examined. The regularity, straightness, and pattern of the new channels indicates once again that drainage improvements associated with the recent afforestation of the headwaters of the basin by the Forestry Commission were responsible for the extension.

5.2.3. Plym

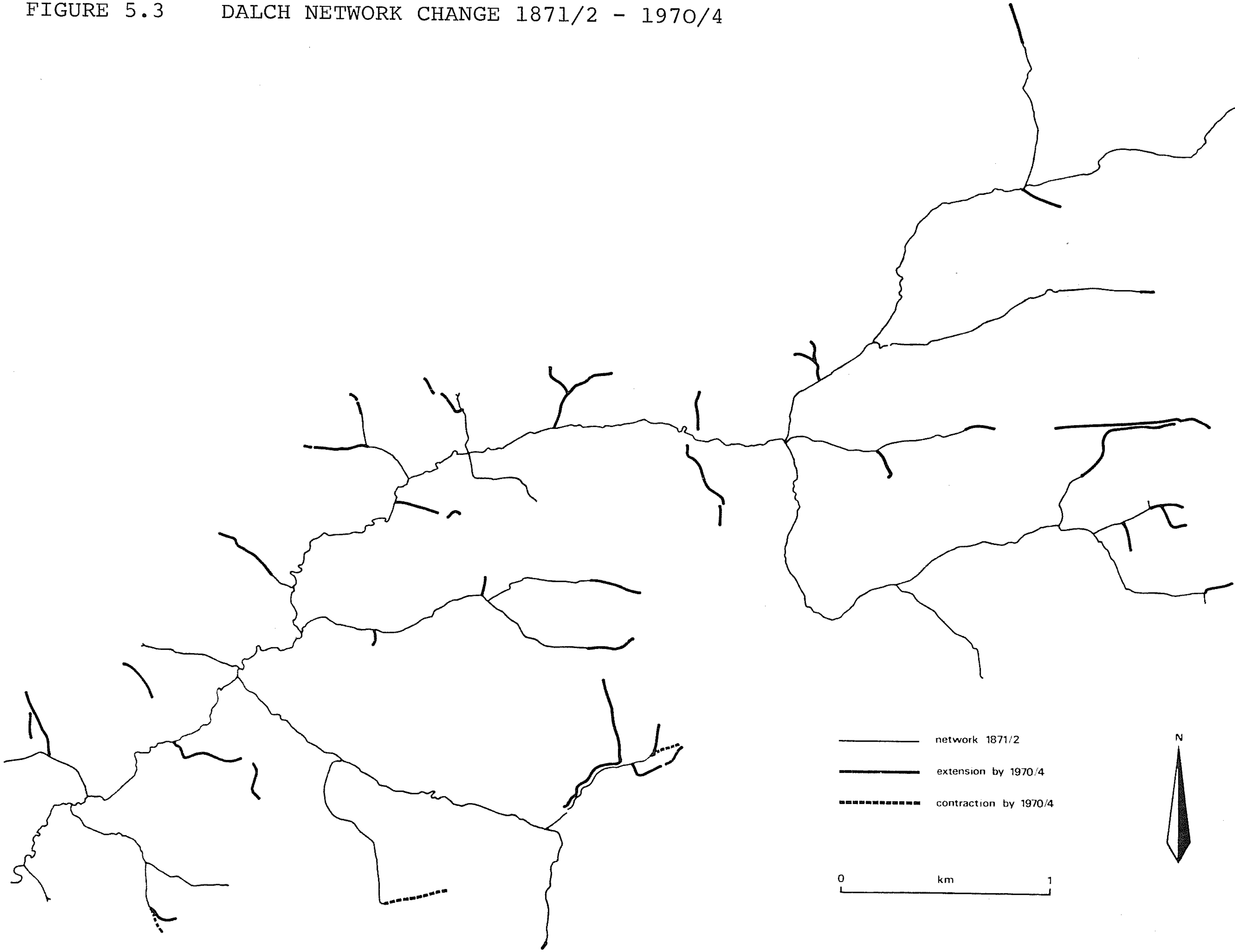
The catchment of the Plym (18.65km^2), situated on the south-west slopes of Dartmoor, is one of two basins representative of South-West England and as with many of the Dartmoor streams there has been considerable human-interference manifested in the occurrence of mining leats. Little change has occurred in the drainage network over the period 1882/5 to 1950 except for the creation of short lengths of interior links where formerly the stream courses were discontinuous. Single examples are found of the extension of an existing link length and the creation of a new exterior link. These all result in an increase in total stream length of 0.55km which has an insignificant effect on the drainage density between the two dates.

5.2.4. Dalch

The Dalch catchment, located in Central Devon, contrasts with the Plym because considerable extension of the drainage network has occurred, the details being presented in Figure 5.3. Total stream length over the period 1887 to 1970 has increased from 25.18km to 34.265km, causing a considerable increase in drainage density from 1.45 to 1.97km.km^{-2}.

Network extension is predominant within the catchment and is totally accounted for by the extension of existing link lengths and the creation of new exterior links some of which remain unconnected to the main network. Several of these extensions probably represent

FIGURE 5.3 DALCH NETWORK CHANGE 1871/2 - 1970/4



agricultural drains although further analysis is impossible without extensive field checking. A solitary example of contraction occurs, this being the shortening of one drainage link, its former artificially-straight course, around the periphery of a field boundary, suggesting the decay of a drainage ditch.

5.2.5. Water of Luce

The only Scottish basin not to be examined in the field was that of the Water of Luce, a high rainfall coastal basin in Wigtownshire. The main reason for its omission was the presence of large tracks designated 'swamp' on the First Edition 1:10560 map. Extensive changes in river course have occurred within the basin as well as many examples of extension and contraction of the network although, overall, the basin shows a slight increase in stream length reflected in the drainage density increase from $2.45km.km^{-2}$ in 1846/56 to $2.575km.km^{-2}$ in 1976.

The complex pattern of change within the catchment is largely accounted for by the contraction, or in several cases the complete abandonment, of exterior links and the extension or creation of exterior links, although no clear reasons for these changes can be inferred from map evidence alone.

5.2.6. Harpers Brook

Harpers Brook was selected as a lowland, low precipitation drainage basin representative of the English Midlands. This catchment is one of two that show a decrease in total stream length over the period considered. By 1967/72 the total stream length of 14.94km. in 1885 had contracted to 14.64km. These figures however disguise the incidence of some extension within the catchment. This extension is confined to the extreme head of the catchment and is accounted for by new exterior links and extensions to existing link lengths around the periphery of the site of Desborough Airfield. It may be inferred from map evidence alone that these new drains were constructed to conduct runoff from the airfield complex, a similar situation to that occurring in the headwaters of Highland Water due to the presence of Stoney Cross Airfield (Section 4.3.3.). The contraction within Harpers Brook is largely accounted for by the abandonment of a single link length which may be connected with the establishment of a quarry during the time period between the two surveys.

5.2.7. Churn

The final basin omitted from field checking was that of the River Churn, situated in the Cotswolds and possessing the lowest drainage density of any of the basins considered (Table 5.1). Like the Plym, little change has occurred within the catchment reflected by the slight increase in drainage density from $0.63km.km^{-2}$ in 1881/2 to $0.66km.km^{-2}$ by the time of the 1972/4 survey. This extension is mainly attributed to short lengths of new exterior links although there is also a significant extension to an unconnected exterior link.

5.2.8. Summary of Map Analysised Basins

The conclusions drawn from examinations based exclusively on map analysis are extremely tentative and, excepting where Forestry Commission activity is obvious, are based on pure speculation. The following section therefore examines the next stage of the analysis where the locations of network change within catchments are examined individually to determine more accurately the nature and causes of change.

5.3. FIELD SURVEY OF SELECTED DRAINAGE NETWORKS

In addition to the seven basins analysed exclusively on the basis of cartographic evidence, a further ten basins,

		FIRST EDITION			METRIC EDITION		
BASIN	AREA	SURVEYED	ΣL (KM.)	Dd (KM.KM^{-2})	SURVEYED	ΣL (KM.)	Dd (KM.KM^{-2})
Avan	16.48	1875/7	41.11	2.49	1961*	43.65	2.65
Cona	22.67	1872	77.45	3.42	1972	91.00	4.01
Croasdale Brook	8.75	1847	13.41	1.53	1977	23.28	2.66
Dorback Burn	18.19	1868/71	23.28	1.28	1969	22.58	1.24
Dove	8.05	1870/9	15.53	1.91	1971/2	17.87	2.22
East Stour	43.57	1871/2	73.25	1.68	1970/4	79.72	1.83
Ellen	4.46	1862	11.42	2.56	1976	12.17	2.73
Highland Water	11.30	1869	18.08	1.60	1960*	19.77	1.74
Isla	53.46	1862	69.43	1.30	1969/70	98.65	1.84
Manor Water	23.22	1856	50.78	2.18	1962/4*	54.23	2.33
Roman	25.89	1875/6	21.27	0.82	1954/62*	28.68	1.11

* Regular Edition

TABLE 5.2 DETAILS OF NETWORK CHANGE FOR FIELD SURVEYED BASINS representing a cross-section of basin types, were examined both cartographically and in the field. Of these ten basins four were selected from Highland Scotland, one from South Wales, and the remaining five examples chosen from areas in England, two representing lowland, and three upland, situations. Each of these basins is now considered in detail.

5.3.1. Dorback Burn

The most northerly basin to be field-examined was that of Dorback Burn, located in the Eastern Grampians, and a tributary of the River Findhorn. Dorback is essentially an upland basin of some 18.19km^2 comprising rugged moorland except for a small area which is enclosed. It rises at its highest point to 504m. dropping to some 298m. O.D. at the entrance to Lochindorb.

Comparison of the Ordnance Survey First (1868/71) and Metric (1969) Editions of the 1:10560 and 1:10000 scales respectively revealed that Dorback was one of only two basins, out of the eighteen sampled, to show a net decrease in total stream length over the one hundred year period (Table 5.2). This decrease in stream length is reflected in a small reduction in drainage density from 1.28 to 1.24km.km^{-2}. However, considerably more change has occurred within the catchment than these average figures suggest, comprising nine locations of extension and a further eight major locations of contraction as well as two small insignificant contraction points; the details of these changes are given in Figure 5.4.

After field survey, extension within the Dorback catchment can be categorised as of two major types. The first and most important group is that of the metamorphosis of a former flush to a well-defined channel, although the stream may be at any stage in this transition. Examples are found of this type of network extension at Sites 1, 2 and 3 although no apparent reason for the change can be inferred, while at Site 9 the transformation of a considerable length

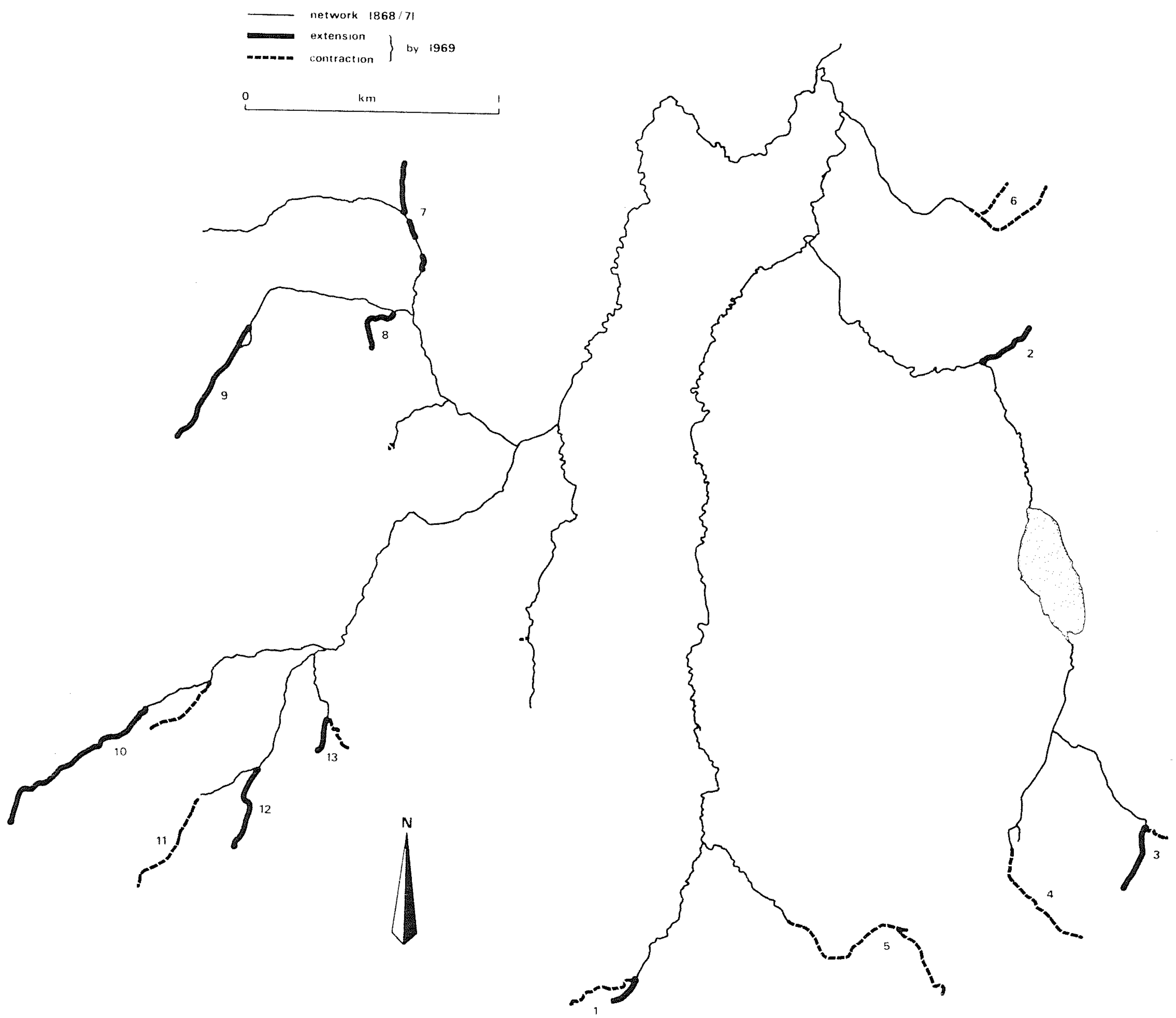


FIGURE 5.4 DORBACK BURN NETWORK CHANGE 1868/71 - 1969

of flush has been accomplished by ditching (Plate 5.1), possibly in connection with drainage to improve the suitability of the moor for grouse.

The second group of extensions consists of what appears to be the initiation of a straight narrow channel cut through the turf cover. The channel possesses many characteristics of exposed pipe sections as observed specifically at Plynlimon (Section 7.2) but encountered also at other upland sites throughout Britain. The extension at Site 10 represents a major link-length extension of the order of 0.7km. but sections of this link still flow underground possibly indicating its origins as part of a pipe network. Sections of the extension at Site 12 are very similar but are interspersed with sections of ill-defined flush-like channel, possibly indicating a transitional stage in the development of pipe-like channels through flushes.

The considerable length of contraction within the Dorback basin has been classified into three groups. The first group, represented by Sites 3 (Plate 5.2), 4 and 6, comprise channels that seem to have reverted to flushes although no clear evidence exists as to why they should have done so. Many apparent stages in this reversion process can be observed. Site 4 demonstrates definite surface movement of water through a healthy flush although no recognisable channel exists, while the reverted flushes at Site 6 represent a much later stage with no surface water, and the juncus growth is by no means continuous along the decayed flush.

The second group of contraction sites are those where there is now a largely enclosed pipe-channel but where this has not been represented by the Ordnance Survey on the recent map edition. This could be due to survey inaccuracies or to the natural process commented upon by Newson and Harrison (1978) where open channels have a tendency to become enclosed by the growth and movements of peat over the top and are prevented from being completely enclosed only by active erosion of the peat. The latter seems to be the more feasible because the detection of extension at sites located from map evidence would support the accuracy of the two surveys involved. This type of apparent contraction is found

PLATE 5.1 DORBACK BURN: FLUSH METAMORPHOSIS TO CHANNEL DUE TO DITCHING (SITE 9).

PLATE 5.2 DORBACK BURN: CONTRACTION OF THE NETWORK DUE TO DRAINAGE LINK REVERTING TO FLUSH (SITE 3).

at Sites 1, 5 and 10. The importance of this type of channel in the functioning hydrological network is emphasised by the creation of a new length of flush of some 30-40m. length, at the head of an apparently contracted link at Site 1.

The third group consists of those locations of contraction that fail to fit into either of the two main groups. Field survey shows that the channel at Site 11 still persists as a well-defined channel and it is difficult to explain why it has been omitted from the recent survey (1969) particularly when its presence is implied by a small loch which presumably supplies its water. This then appears to be a case of survey error. No evidence for the existence of a channel at contraction Site 13 exists but it is possible that this represents the final decay stage of a former drainage link.

To summarise, network change within the Dorbach catchment seems to be largely controlled by the metamorphosis or decay of flushes and by the initiation (and later modification) of pipe-like channels. Within the latter category much of the inferred contraction, with respect to enclosed channels, is shown by field survey not to be contraction at all but merely a change in the physical nature of the channels concerned.

5.3.2. Cona

The River Cona (22.67km^2) was one of the largest basins considered in this project with over one hundred locations of extension and some fifty locations of contraction, excluding course changes both at the extremities of the network and along the stream course. Extension is of far greater significance than contraction within the catchment as reflected by the total stream length figures of 77.45km. in 1872 as compared with 91.0km. in 1972. Figure 5.5 clearly indicates the generally short lengths of contraction as compared with the substantial lengths of extended links. Fieldwork was confined to two sample areas due to the

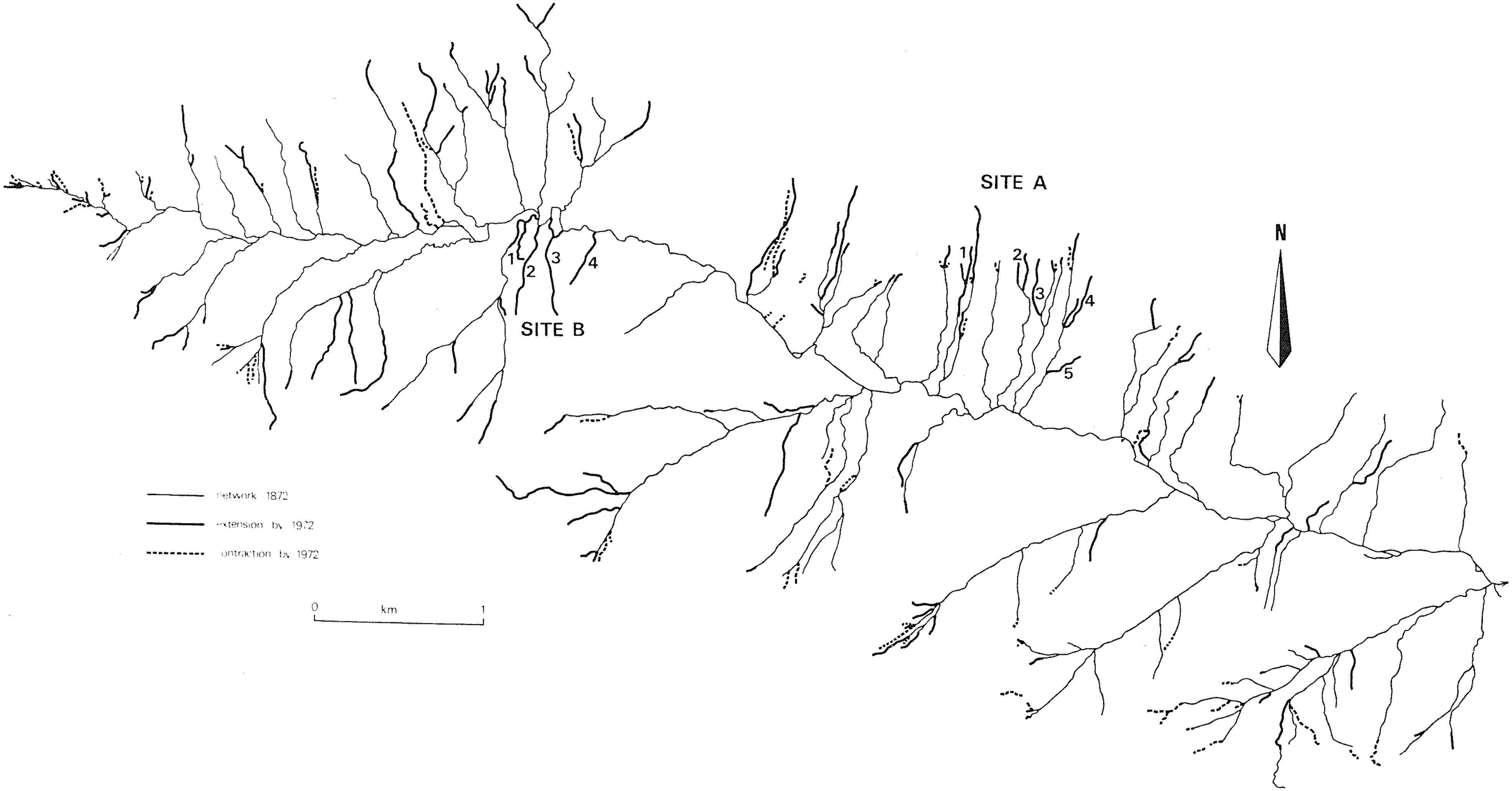


FIGURE 5.5 CONA NETWORK CHANGE 1872 - 1972

remoteness and inaccessibility of the area. Their positions are shown in Figure 5.5, and both are sites of predominant network extension and as such typify the Cona system. Site A is situated on the steep side slopes of the main valley and is typical of extension on the steeper slopes of the catchment, while Site B is located on gentler slopes towards the head of the catchment.

For the examination of Site A it was a real problem to establish exact location in the field because few landmarks existed to assist orientation. Consequently, several stream channels were often grouped under the same number, the comments applying generally to a whole group of channels. Small course changes at the heads of tributaries and short insignificant exterior links were ignored because of the difficulty in determining precise location. All the extended channels around Site 1 at Field Area A are meandering, well-defined streams less than 0.3m. in width. In some cases these appear to occupy a linear depression which may well be a former flush (Plate 5.3). These channels have every appearance of opened pipes, and further evidence for this origin is seen perhaps in the numerous streams, unmarked on the recent Ordnance Survey map, and which are now often located only by the sound of water flowing down the steep upland slopes. Their presence is often detected only because of their reversion to short sections of saturated overland flow, characterised by flush vegetation, before disappearing into pipes once again. It is suggested that the opening of these pipes during exceptionally heavy rainfall may well be the cause of network extension at Site 1 and indeed this may be a major cause of network extension in upland Britain generally.

Sites 3, 4 and 5 represent examples of flushes which have been metamorphosed to channels. At Site 3 this transition is still much in evidence with plenty of *juncus* vegetation still in the channel, collapsed sections of pipe, and sections of definite flush, while at Site 4 this transition has been largely completed (Plate 5.4). Associated with such sites of recent extension are signs of bank instability indicating that the new channels have

PLATE 5.3 CONA: CHANNEL FORMED BY PIPE BURST AND OCCUPING A LINEAR DEPRESSION POSSIBLY INDICATIVE OF A FORMER FLUSH (SITE A LOCATION 1)

PLATE 5.4 CONA: FLUSH METAMORPHOSIS TO CHANNEL COMPLETED (SITE A LOCATION 4).

PLATE 5.5 CONA: BANK INSTABILITY ON RECENTLY CREATED LINK (SITE A LOCATION 4)

PLATE 5.6 CONA: NEW LINK TERMINATING IN A SERIES OF FLUSHES EMPHASISING THE ROLE IN THE PRESENT FUNCTIONING NETWORK (SITE A LOCATION 5)

not matured since the event which created them (Plate 5.5). Site 5 represents another example of the metamorphosis of a flush to a channel, and, like those at Site 4, occurs on generally gentler slopes than the other sites. The new link ends in a series of flushes (Plate 5.6), not represented on the recent survey, which presents supporting evidence for network extension between the two surveys. The channel at Site 2 appears incised, well-defined and long-established with no evidence of its implied recent creation.

A further four sites of network extension were investigated as Field Area B. Two of these Sites, 1 and 3, are associated with peat erosion. Site 1, on low slopes, is characterised by a poorly-defined channel which may well be of an intermittent nature, while a better-defined channel is found as the slope increases. Site 3 is a typical peat gully which, as its width decreases, degenerates into closed pipe-sections. Sites 2 and 4 are further examples of the transformation of a former flush to a well-defined channel, Site 2 showing evidence of collapsed pipe sections, indicating the cause of the change.

Therefore, the two main channel forms that recently-extended drainage links assume in the Cona Valley, on the evidence of examination of the two field areas, are the narrow pipe-like channels and the flush to channel metamorphosis, the latter occurring over both bedrock and peat.

5.3.3. Isla

The Isla Basin, located in the Eastern Grampians, is the largest basin considered in the project comprising 53.46km^2 of rough upland moor. Over this sizeable area a considerable drainage density increase has occurred over the period 1862 to 1969/70 from 1.30km.km^{-2} to 1.84km.km^{-2}. In addition to its being the largest basin considered for the project it also includes the highest relief (1068m). The average annual precipitation for the catchment is 1427mm. with the maximum two-day rainfall (with a return period of five years) 90mm.

Like the Cona, field-checking had to be confined to sample areas representing some 38 locations of change, occurring between the years 1862 and 1969/70. These examined sites of network change represented 45% of the total number of change sites within the catchment. Two of the three areas chosen for field checking were located in the headwaters of the Isla network, the main area being in Caenlochan Glen, while a smaller tributary towards the mouth of the catchment, containing several contraction points, was examined on a third site to provide a contrast. The Isla basin, as Figure 5.6 and Table 5.2 suggest, is again largely an area of extending networks. Field work in the Isla basin was hampered to some extent by snow banks covering some of the change locations, a rather unexpected problem in mid-June. It was realised that the extra water from melting snow could possibly over-emphasize flushes and channels so an attempt was made to interpret all the hydrogical components in the light of this greater moisture availability.

Field examination of the twenty locations of apparent change in Caenlochan Glen revealed that all the three examples of contraction, Sites 5, 10 and 16, represented the degradation of a former channel to a flush. At Site 5 (Plate 5.7) little evidence of a flush remained save a few isolated clumps of *juncus*, while at Site 10 sections of flush were interspersed with sections of enclosed pipe and dry open channel. The contracted section at Site 16 represented a healthy flush.

Of the seventeen sites of extension, two, Sites 4 and 18, represented well-defined channels with no evidence of their recent origin, and a further four, (Sites 2, 6, 7, and 20) demonstrated the initiation of a narrow exposed pipe-like channel. Site 2 (Plate 5.8) is shown as an example of this category. Another six extension sites represented the transformation of a flush to a well-defined channel, the flushes at Sites 3 and 11 occurring on peat, the one at Site 12 on gravel, and those at Sites 9, 14 and 1 representing

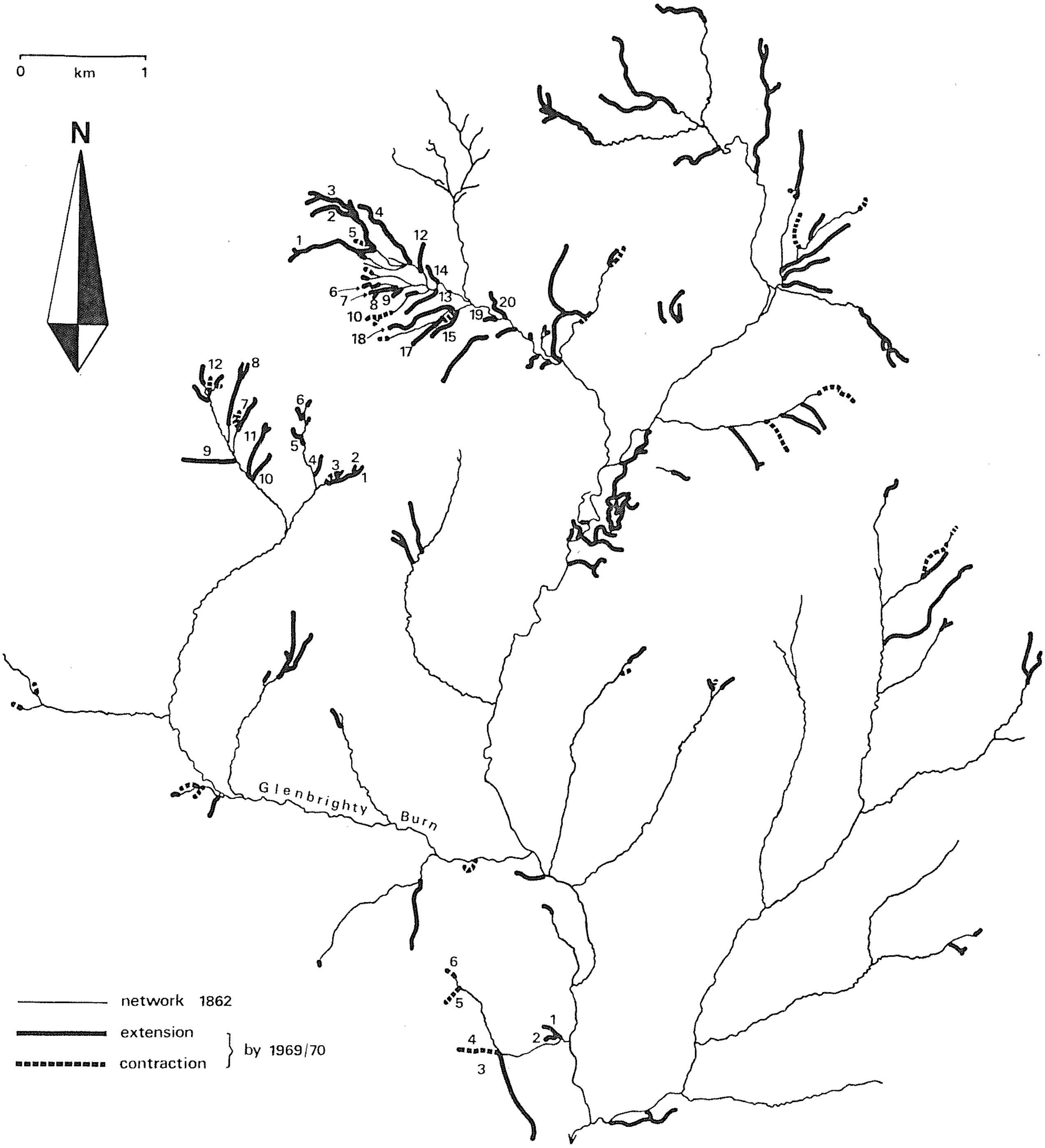


FIGURE 5.6 ISLA NETWORK CHANGE 1862 - 1969/70.

PLATE 5.7 ISLA: TOTAL LINK CONTRACTION WITH *JUNCUS* MARKING THE FORMER POSITION (CAENLOCHAN GLEN SITE 5).

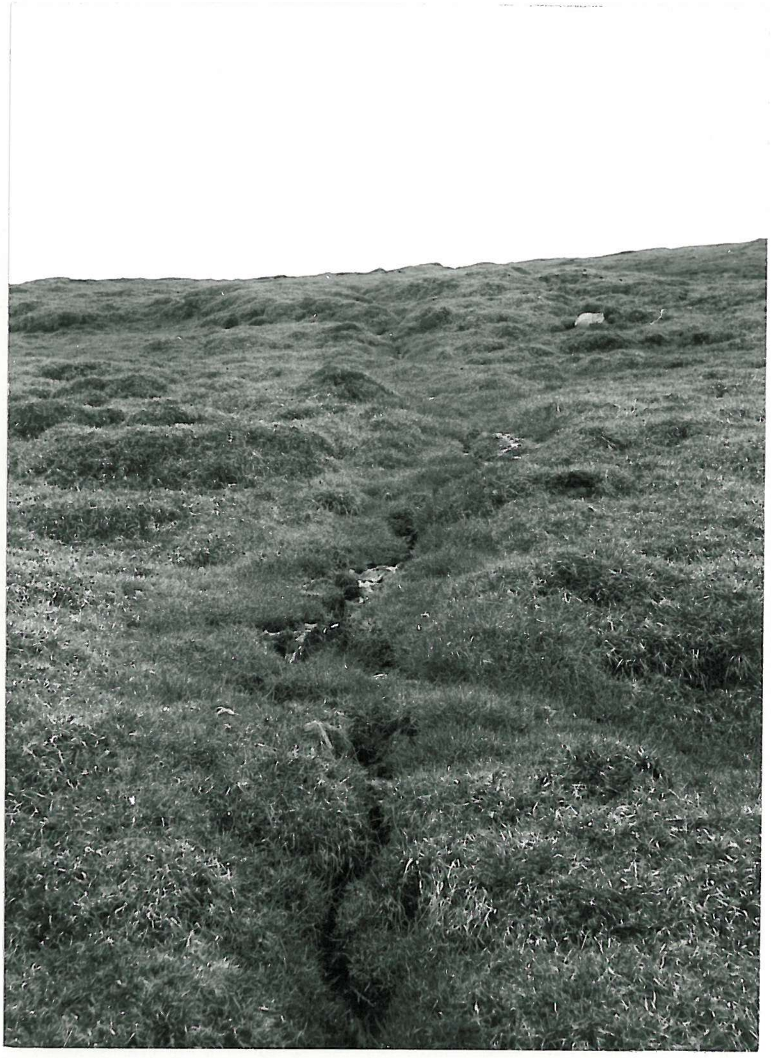


PLATE 5.8 ISLA: CHANNEL INITIATED BY SHALLOW PIPE BURST. (CAENLOCHAN GLEN SITE 2).

more conventional flushes, the latter being spring-fed, rising immediately below a rough moorland track. The remaining five locations of extension, Sites 8, 13, 15, 17 and 19, are intermediate between a flush in the early stages of metamorphosis and the initiation of a pipe-like channel. All these sites demonstrate the two types in close proximity suggesting a connection between the two. This connection is perhaps implicit in the definition of the term flush, which, as a zone for concentrated throughflow, is a likely location for piping to develop. In high-intensity storms, evidence reported in the literature suggests that pipes may be incapable of holding the large volume of water produced and may literally burst. The result is that sections of flush are transformed to a well-defined channel but may be isolated by sections of the former flush not affected by the burst. This results in the juxtaposition of the two types of channel as often witnessed in the field. This important process of pipe burst will be referred to in greater detail in Section 7.2 in connection with experimental sites at Plynlimon, Central Wales.

The second headwater site, on Glenbrighty Burn, contains a further twelve examples of network change although snow prevented a comprehensive field check, completely obliterating Sites 10 and 12. The only contracted link which could be examined in detail in the field provides yet another example of the degradation of a former channel to a flush although even the existence of a flush is only just recognisable in the field today. Extension is largely accounted for by the metamorphosis of flushes to channels occurring at Sites 1 to 9 inclusive, runoff in the case of Sites 1 and 2 is provided by a track, while Site 4 is fed by a natural spring, and Sites 3, 5, 6 and 7 are fed by melting snowbanks. Site 9 begins as a bedrock flush but progresses downstream to a well-defined channel, the result of a network of artificial drains. This leaves Site 11 which, on Glenbrighty Burn is the only example of the iniation of a narrow pipe-like channel flowing down a steep slope although it degenerates, at its upper end, to several flushes.

Infrared colour film clearly highlights the nature of these head flushes which are in the initial stages of metamorphosis to stream channels (Plate 5.9).

The final field site in the Isla Valley is the small tributary of Eskielogie Burn where a further seven locations of network change were examined. Contracted links exist at Sites 4, 5 and 6, the first two being ditches. The contracted links at Sites 4 and 5 still exist today; at Site 4 it seems there has been recent maintenance of an old ditch, while the link at Site 5 is lost in a maze of recent drains, constructed around 1975 to improve grazing. The apparent contraction at Site 6 represents a flush-channel marginal zone and as such indicates the degradation of a former length of channel to flush. The new ditch at Site 3 (Plate 5.10) is included in extension of the network as typical of the many ditches feeding the partly-ditched flush at Site 7. Progression to a well-defined channel occurs downstream, probably due to the increased water from ditching, but thick *juncus* growth persists through this change. Of the remaining two sites of extension Site 1 represents a simple progression from flush to channel while Site 2 is a short ephemeral length of channel appearing to act as an anastomosing channel during high flows in the main stream.

5.3.4. Manor Water

Manor Water, the final Scottish basin to be field-checked, is situated in the Southern Uplands. The small drainage density change from 1856 to 1962/4 of 2.18 to 2.33km.km^{-2} hides the considerable number of locations of network change representing both extension and contraction (Figure 5.7). Although originally it was hoped to field examine all changes in the network, this proved impossible due to construction work on the Manor-Ettrick tunnel and to the recent ditching and planting activities of the Forestry Commission. These activities made survey of the extreme lower basin either

PLATE 5.9 ISLA: INFRARED COLOUR FILM ILLUSTRATES THE NATURE OF HEAD FLUSHES IN THE INITIAL STAGES OF METAMORPHOSIS (GLENBRIGHTY BURN SITE 11).

PLATE 5.10 ISLA: RECENT DITCHING REPRESENTING NETWORK EXTENSION SINCE 1969/70 SURVEY (ESKIELOGIE BURN SITE 3).

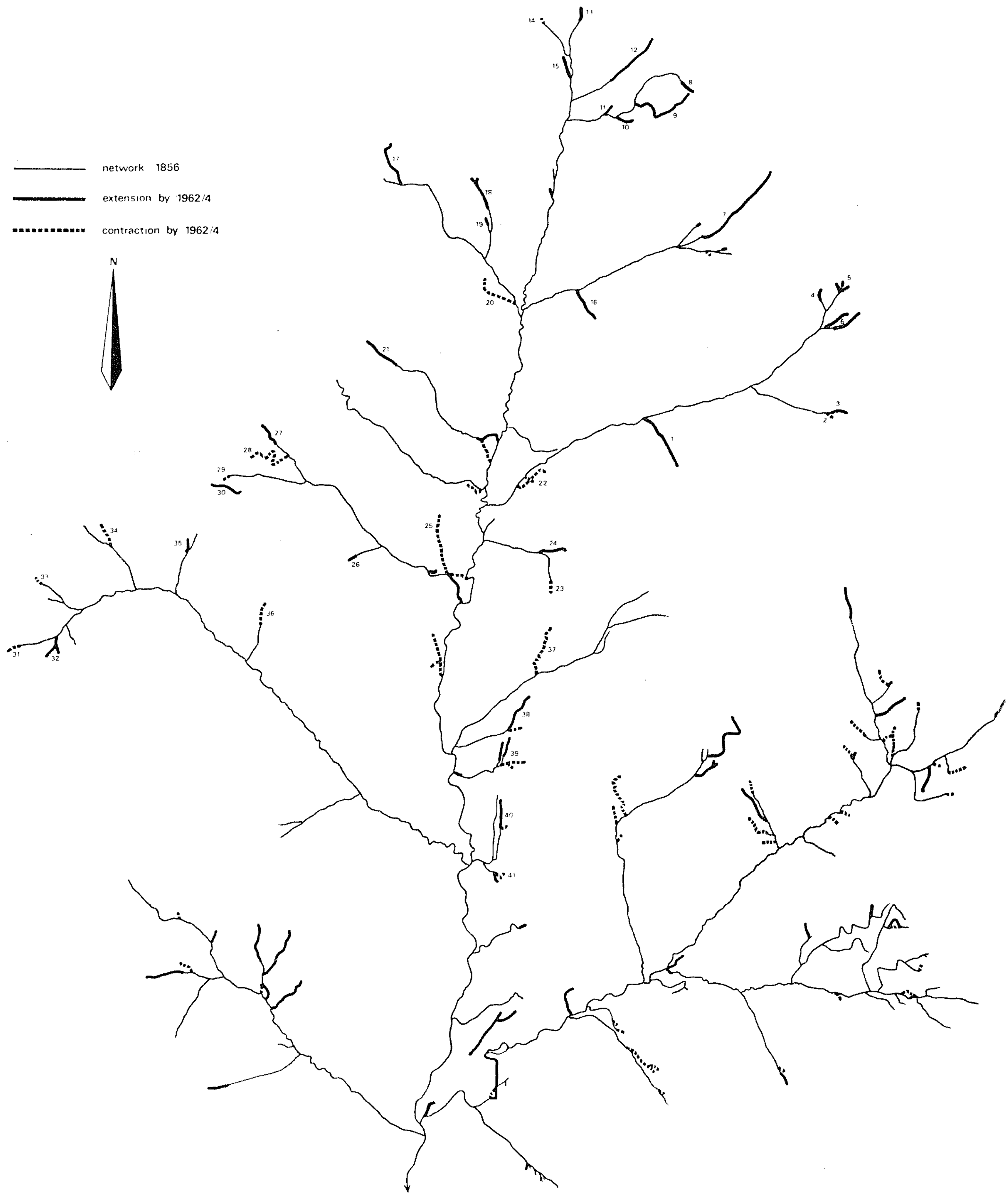


FIGURE 5.7 MANOR WATER NETWORK CHANGE 1856 - 1962/4

impossible or extremely difficult and as a result work was confined to the network upstream of the Linghope Burn tributary junction. The Manor Water catchment is predominantly upland pasture and is characterised by a marked range of relief from 815m. to 260m. Average annual precipitation is 1252mm. although it is not an area of high intensity rainfall, the 2 day maximum figure being 61mm.

An interesting point in the Ordnance Survey's representation of the Manor Water network is the use of hachures on the Linghope Burn tributary at the extremities of some of the drainage links. Mostly, these are associated with contraction of the drainage network over the period 1856 to 1962/4. It was hypothesized that these hachures are an unofficial Ordnance Survey symbol for a gully, a fact it was hoped to confirm during field survey.

Forty-one locations of network change were examined in the course of field checking the upper section of the catchment, resolving into twenty-four sites of extension, thirteen of contraction and four locations of mixed change. Generally, extension is of far greater importance in the headwater areas with contraction gaining an ever-increasing proportion of change downstream. There is considerable evidence for small-scale gullying in the Manor Water catchment probably helped by the unconsolidated shale bedrock. Numerous scars exist on the steep slopes where pipes have burst, their debris tails stretching downslope. However one tributary alone, that of Linghope Burn, possesses gullying of a spectacular scale by British standards and will be referred to in the report on field checking the area.

Field examination allows most network extension in Manor Water to be divided into the familiar groups of flush metamorphosis to channel, the initiation of a pipe-like channel, and a combination of both pipe collapse and flush metamorphosis. Only a single example of the creation of a pipe-like channel exists (Site 8) in connection with peat erosion, while six examples of a combination of flush metamorphosis and pipe collapse are located at Sites 10, 16, 1, 18, 19 and 24, those at Sites 10 and 16 being spring-fed. This leaves the metamorphosis of flushes to channels as the dominant and most important group in terms of network extension, with some fourteen examples. Nevertheless, considerable variations exist within this broad grouping. Sites 3, 6, 9, 12, 13, 21, 26 and 32 present classic examples of this metamorphosis with Sites 6, 13 and 26 showing recent flush developments since the 1962/4 Survey, and with Site 32 demonstrating a probable shift in the position of springs. Site 15, which is at a much earlier stage in the transition process, can also be added to this list. Site 3 was chosen as representative of this group (Plate 5.11) demonstrating the active metamorphosis as seen in the clear sheer face boundary between flush and stream, the latter emerging from pipes beneath the flush. The transformation of flushes at such locations appears to be accomplished by a natural process, and contrasts with the remaining examples of network change. The particularly good example of the metamorphosis of a flush at Site 17 (Plate 5.12) has been accomplished by increased inputs of water from ditches alongside a rough track running around the watershed (Plate 5.13) while the metamorphosed Sites 4 and 5 have gullied, also probably due to the nearby presence of a track. The use of infrared colour film at Site 17, once again, helps to define the boundary of the ill-defined channel resulting from flush metamorphosis (Plate 5.14). Site 11 is of interest because the metamorphosed flush has occurred at the bottom of what appears to be a stabilised and relict gully. Of a similar nature is the metamorphosis at Site 7 where although the upper section is still definitely flush as opposed to the channel as depicted by the Ordnance Survey, the lower section of the transformed flush is incised. The smaller changes at Site 7 are conventional metamorphosis locations. Thus, Sites 7 and 11 represent another category of flush, that of the incised variety which may well be some form of degradation of a former gully. These sites may also demonstrate the transient nature of flushes relating to

PLATE 5.11 MANOR WATER: ACTIVE FLUSH METAMORPHOSIS (SITE 3).
N.B. The strong piping influence.

PLATE 5.12 MANOR WATER: FLUSH METAMORPHOSIS TRIGGERED BY CATCH DRAINS ALONG A MOORLAND TRACK (SITE 17)

PLATE 5.13 MANOR WATER: CATCH DRAINS ALONGSIDE A TRACK HAVE RESULTED IN FLUSH METAMORPHOSIS (SITE 17).

PLATE 5.14 MANOR WATER: INFRARED COLOUR FILM CLEARLY DELINEATES THE ILL-DEFINED CHANNEL (SITE 17).

short-term or short-lived positions of the spring line. The term 'spring line' itself requires interpretation because this is also a transient feature reflecting the water level within the ground, and therefore its position varies as does stream length, and possibly flush length, according to moisture availability. The spring line will therefore have a range of positions reflecting ephemeral, intermittent and perennial extensions to the drainage network.

A fourth category of extension, peculiar to date to the Manor Water catchment, is that of gullying (represented at Sites 27, 30 and 35) although the process is of greater importance in contraction of the network. At Site 27 the whole of the extended link is virtually a healed gully but with signs of current head extension, while at Site 35 the surveyors have represented a recent gully as part of the perennial network when in fact there is no evidence today that it is part of this network. However, field examination reveals that part of a nearby unaltered link as confirmed on the 1856 and 1962/4 Surveys, has in fact contracted slightly, the implication being that in 1962/4 this gully may have represented a perennial extension which has since contracted. The gully at Site 30 possesses a curious right-angle bend and certainly represents perennial extension. The sharp angle in the direction followed by the gully is difficult to account for in terms of simple stream erosion but may be easily explained as the intersection of two major pipes which originally controlled the direction of water flow and have since collapsed (Plate 5.15).

The dominant categories of contraction within the catchment are those of channel degradation to flush and relict gullying although single examples are found of both an apparently contracted channel still existing (Site 25), and a location with no evidence of a former stream course (Site 22). All four sites of relict gullies (31, 33, 34 and 36) occur within close proximity to each other on the tributary Linghope Burn. They are all shown on the 1856 Survey to be part of the perennial network but today represent relict or at the

PLATE 5.15 MANOR WATER: THE INTERSECTION OF MAJOR PIPES MAY EXPLAIN THE SHARP BEND IN THE GULLY (SITE 30).

very best ephemeral features. The gully at Site 36 has extended along the course of what appears to be a former flush. The gullies are cut into a red sandy shale and are of sizeable proportions for British examples but, curiously, occur on no other drainage links in Manor Water. Six examples are found of the final category of network contraction, that of channel degradation to flush. At Sites 2, 7, 14, 23 and 29 flushes are still clearly visible but at Site 20 the presence of a former channel is only just recognisable in the field. Little field evidence exists as to why these reversions to flushes should have occurred except at Site 2 where a shift in spring position seems likely.

The checking of change locations between Sites 37 and 41 proved to be impossible due to recent downslope ditching by the Forestry Commission. This has obscured many of the extended links and has effectively obliterated the contracted links which are in any case generally more difficult to locate in the field.

Consequently, network change in the Manor Water catchment is largely accounted for by the creation or abandonment of gullies together with fluctuations in flush lengths and the initiation of pipe-like channels.

5.3.5. Ellen

The Lake District is represented by the small catchment of the River Ellen (4.46km^2) situated in the Uldale Fells. The sharp relief difference from 628m. at the head of the catchment to 195m. at the mouth results in extremely steep slopes which together with the average annual rainfall of 1224 mm. makes the basin potentially interesting for analysis. The catchment is largely unenclosed rough moorland although some enclosed and improved pastures are found in the lower areas of the basin around Stockdale Farm. Like Manor Water, the small drainage density change between the years 1862 and 1976 disguises the fact that some twenty five locations of network change exist within the basin. Thirteen of these sites are accounted for by extension of the drainage network, the other twelve being contraction points and generally of less importance in terms of length of change. The distribution of these sites is illustrated in Figure 5.8.

While the categories of change within the Ellen catchment are on the whole similar to those already seen on the Scottish Upland catchments, there are the addition of agricultural drains as an important element of network extension. These are found at Sites 3, 6 and 7, the former due to the construction of a ditch to carry water away efficiently from a farm track. Site 6 consists of drainage ditches almost completely obscured by *juncus*. Site 7 is a simple enclosure ditch with a length of flush above it some of which has been transformed to an ill-defined stream channel by cattle trampling.

A single example of the creation of a new pipe-like boulder channel occurs at Site 20, originating on a footpath, but no evidence of a former flush exists on this site although an abandoned flush occurs in a quite separate depression some five metres to the side of this new channel. The extension at Site 5 consists, at its upper extremities, of a linear depression with the remains of *sphagnum* indicating the presence of an ephemeral, but certainly neither intermittent or perennial, channel while further downstream there is clear evidence of the metamorphosis of a flush to a channel. All the remaining sites of network extension (Sites 2, 6, 8, 10, 11, 12, 15, 18 and 19) represent simple conventional examples of flush metamorphosis, Site 19 ending in an area of diffused flow and Site 15 representing a gullied flush. The metamorphosed link at Site 2 originates at the base of a stone wall and on the evidence of a flush (unmarked by the Ordnance Survey) is probably fed by seepage from a nearby stream.

Contraction within the Ellen catchment is largely accounted for by the degradation of channels to flushes such as at Sites 9, 13, 14, 16, 17, 21 and 23, the latter including a section of ephemeral ditch (Plate 5.16). This ditch could possibly have been marked on the 1862 Survey in error or, alternatively, such artificially created ditches may behave according to 'Catastrophy

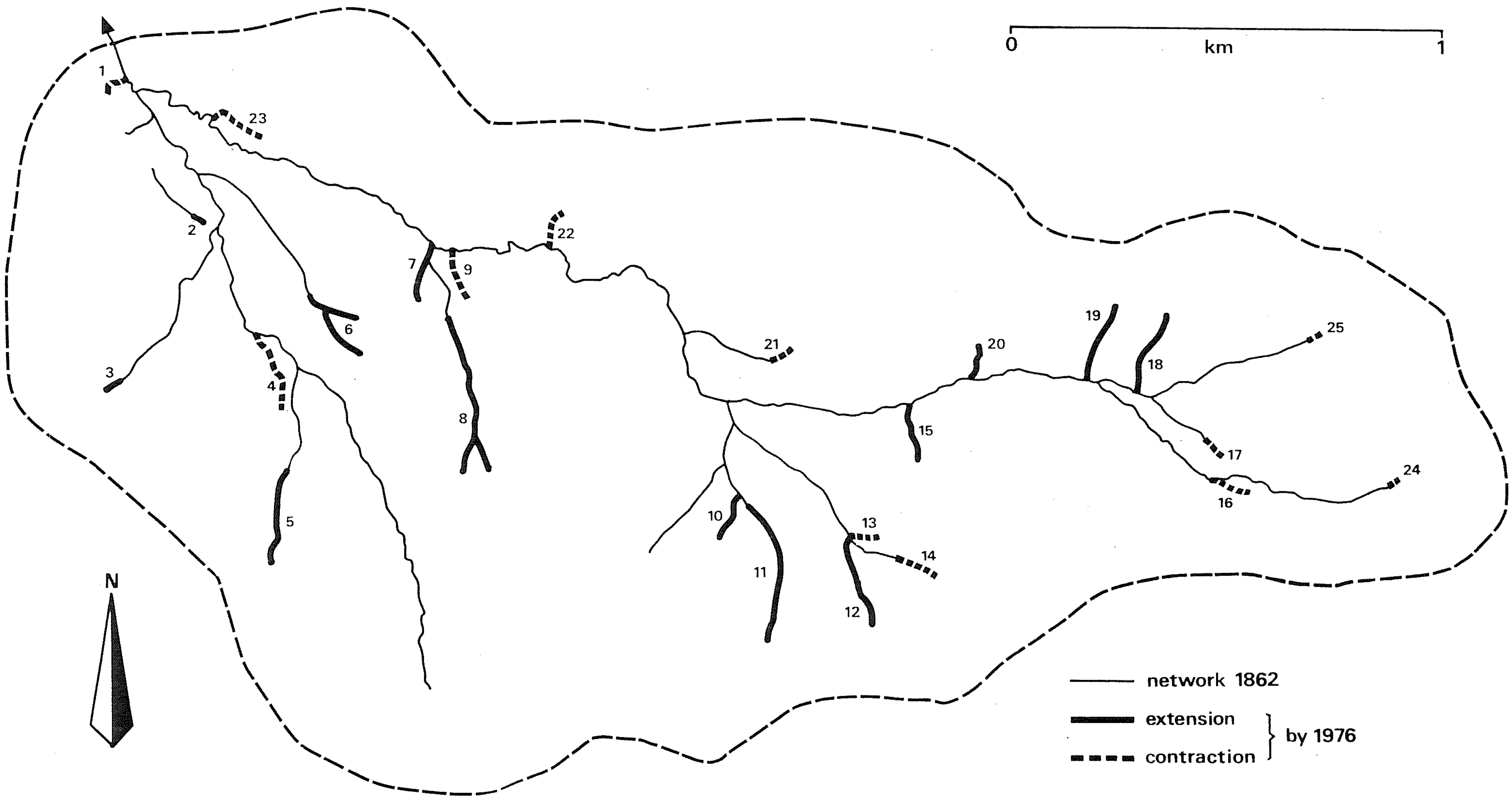


FIGURE 5.8 ELLEN NETWORK CHANGE 1862 - 1976

PLATE 5.16 ELLEN: A LENGTH OF EPHEMERAL DITCH REPRESENTING CONTRACTION OF THE DRAINAGE NETWORK 1862-1976 (SITE 23).

PLATE 5.17 ELLEN: APPARENT CONTRACTION OF THE NETWORK DUE EITHER TO SURVEY ERROR OR TO THE DEGRADATION OF A FORMER CHANNEL TO FLUSH. VIEW UPSTREAM (SITE 22).

PLATE 5.18 ELLEN: THE MARGINAL ILL-DEFINED CHANNEL/ FLUSH REPRESENTS CONTRACTION OF THE NETWORK 1862-1976. VIEW DOWNSTREAM (SITE 22).

Theory' in that they are suddenly created by man and if natural forces are subsequently unable to maintain the feature it gradually fades, with time, into a component of less and less hydrological importance until ultimately it becomes relict or disappears completely, Short lengths of gullied flushes, which according to the 1976 Survey no longer possess intermittent or perennial channels, are found in the steep headslopes of the catchment at Sites 24 and 25. No evidence of a former channel could be detected in the field at Site 4, while Sites 1 and 22 represent channels which exist and seem to have been omitted from the 1976 Survey in error. Site 1 represents a drainage link originating at the ruins of the old water supply to the farm, and Site 22 represents the early stages of a metamorphosis of a flush (Plates 5.17 and 5.18). The thick *juncus* growth and the presence of flowing surface water makes its omission from the recent survey surprising.

5.3.6. Croasdale Brook

The only basin representing the Pennine area is that of Croasdale Brook to Croasdale Flume gauge (10.14km^2), a tributary of the Lancashire Hodder. Croasdale is covered by an early survey of 1847 providing a potential span of some 130 years over which to examine network change. The catchment consists mostly of unenclosed rough moorland although, like the Ellen, it does have a small amount of enclosed, improved pasture towards the lower end of the basin with some peat on the interfluves. Basin relief varies from 540m. to 200m. with an average annual precipitation of 1840mm.

The earliest 1:10560 maps of the area were published in 1847, and this network is compared in Figure 5.9 with the most recent complete survey of the catchment provided by the 1907 'County Series' Edition. A more recent 1:10000 Metric Edition, surveyed in 1977, is available for the upper part of the catchment only. The differences between the networks mapped in 1847, 1907 and 1977 are illustrated in Figure 5.9. According to cartographical

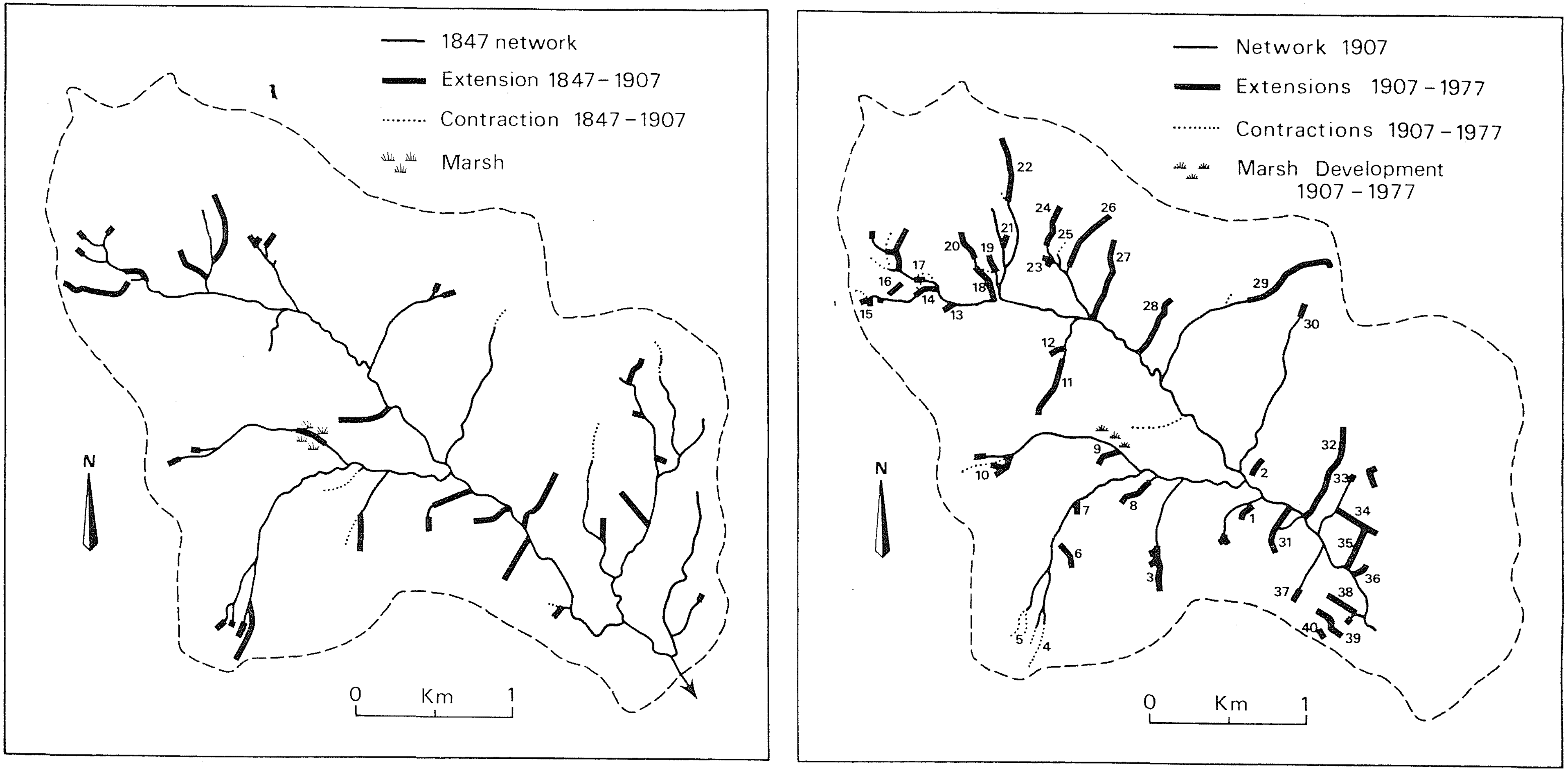


FIGURE 5.9 CROASDALE BROOK NETWORK CHANGE 1847 - 1977

evidence, total network extension for the sixty-year period 1847-1907 amounts to some 5km. while contraction amounts to only 0.85km. The density of the drainage network shown in 1870 is 1.91km.km^{-2} whereas that recorded for the 1907 Survey is 2.28km.km^{-2}, but the net increase of 0.37km.km^{-2} disguises the existence of possible network contraction at five locations within the basin. Changes in the catchment over this period involve changes in the lengths of several exterior links as well as in the creation of new exterior links. However, the most important method of network extension in the Croasdale Brook catchment, in terms of stream length, is the creation of new exterior links.

The 1977 Survey, completed for the upper 8.75km^{2} of the basin, indicates that considerable extension has occurred since the 1907 Survey (Figure 5.9). Many of the recent extensions of link length occur as further extensions on links already shown to have extended between the 1847 and 1907 Surveys indicating progressive extension of the network. In addition, several new exterior links have been created, particularly towards the lower end of the catchment associated with enclosed areas.

The changes in the network between 1907 and 1977 were selected for examination in the field because the surveyors' instructions relating to the early 1847 Survey had not been located and therefore the 1847 drainage network represented could not be qualified precisely.

Croasdale is predominantly a basin in which extension of the stream network occurs with 34 out of the 40 change locations being sites of extension, and only 3 sites representing contraction; 3 further sites include examples of both extension and contraction. As a result of these changes total stream length has increased from 13.41km. in 1847 to the present impressive figure protrayed in the 1977 Survey of 23.28km. This reflects a substantial increase in drainage density from 1.53 km.km^{-2} to the present 2.66km.km^{-2}, one of the biggest increases in drainage density found in any of the basins.

Three categories of network contraction are found in the Croasdale catchment two of which are associated with the erosion of peat. Peat gullies with no evidence of perennial or intermittent streams are found at Sites 4 and 5, while abandoned peat pipes marked on the 1907 Survey, but omitted from that of 1977, exist at Sites 10 and 15. The remaining category of contraction is that of channel degradation or reversion to flush with Site 26 representing a present flush and Site 18 a decayed flush with only a linear healed depression and occasional *juncus* clumps indicating the existence of a former stream channel.

Network extension within the Croasdale catchment has been divided into the familiar groupings of flush metamorphosis to channel and pipe-like channel initiation with the additional categories of peat piping and artificial ditching, the latter occurring only in the enclosed lower part of the catchment. In addition to these four groupings a single example (Site 7) exists of an ephemeral or marginal intermittent channel being represented as an extended link. Sites 32 and 34 - 41 inclusive comprise ditches, of which Sites 39, 40 and 41 probably represent only ephemeral or at the best, intermittent features. Site 37 is probably an example of the ditching of an already existing channel but this is difficult to confirm because of modifications caused by the trampling of cattle.

Network extension resulting from piping within the peat is confined to the higher extremities of the network, examples being found at Sites 3, 10, 13, 15, 16, 17 and 30. This type of network change is usually confined to deep peat. It is sometimes associated with sites of network contraction and may well be due to shifts in the importance of certain pipes as peat erosion on the nearby interfluves continues, subsequent collapse revealing their existence. Site 17 represents a new interior link its omission from the 1847 Survey implying the presence of some sub-surface water movement probably in the form of a pipe.

Some five examples of the initiation of pipe-like boulder channels possessing boulder beds are found on the steeper slopes of the catchment at Sites 21, 22, 23, 27 and 28. Site 22 possesses a considerable length of flush above the recent channel extension. Sites 27 and 28 are of considerable interest due to the apparent alternation of pipe and flush-like sections according to the severity of the slope. The pipe-like channel at Site 27 grades into a flush towards the gentler lower parts of the slope, while at Site 28 pipe-like channels appear on the steep upper and lower slopes with an intermediate section of flush where the slope momentarily eases. In these instances the angle of slope seems to determine the form that the channel extension adopts.

By far the greatest number of sites of channel extension, fifteen in all, are accounted for by the metamorphosis of flushes to channels. Natural examples are found at Sites 1, 2, 9, 12, 19, 20, 24, 25, 31 and 33, the straight course at Site 19 probably indicating its origins as a pipe. The examples of metamorphosis at Sites 11 and 14 are the result of runoff from nearby gravel tracks, while Site 29 represents more of a boulder flush similar to those found in the Isla catchment. At Sites 6 and 8 piping has exerted a strong influence, the channel at Site 8 showing signs of pipe roof collapse in a former flush, while the flush metamorphosed channel at Site 6 disappears for short sections into pipes.

In conclusion, the Croasdale catchment exhibits many of the features and categories of network change already seen to have occurred in other areas of Upland Britain. Enclosure in the lower part of the catchment and the presence of peat areas towards the interfluves have resulted in different categories of change, namely the extension of the drainage network by ditching, and drainage change associated with the erosion of peat.

5.3.7. Dove

The 8.05km^2 comprising the Dove catchment is situated in the Peak District immediately south of Buxton and consists mainly of enclosed and improved upland pasture. The extreme upper northern part of the catchment is composed of limestone, progressing to grits for the remainder of the catchment. The basin of the Dove receives an average annual precipitation of 1230mm while relief varies from 552m. on Axe Edge (the highest part of the catchment) to 285m. at the Hollingsclough Gauge. The A53 Buxton-Leek trunk road passes around the catchment divide at the head of the network.

The Dove catchment is an area where detailed cartographic analysis was used, reflected by the consideration of four different editions of 1:10560 and 1:10000 maps. Details of the map editions, together with the variations in total stream lengths that they depict are shown in Table 5.3 while the details of extension and contraction are found in Figure 5.10.

Map Edition	Survey Date	ΣL (km)	Dd ($km.km^{-2}$)
First Edition 1:10560	1870/9	15.528	1.93
Second Edition 1:10560	1897	15.085	1.87
Third Edition 1:10560	1919	16.664	2.07
Metric Edition 1:10000	1971/2	17.867	2.22

TABLE 5.3 DOVE STREAM LENGTHS AND DRAINAGE DENSITY VALUES 1870-1970

Examination of Figure 5.10 reveals the relative stability of the Dove network over the period 1870/9 - 1897 with only four locations of change. Of these changes two represent contracted exterior links, one a short interior link extension, and the fourth a significant extension of link length. An interesting observation is that both the links at Sites A and C, shown as having contracted over the period in question, are once again represented on the 1919 Survey as channels, at Site C accompanied by considerable further extension. By the 1919 Survey there are, in addition to those just mentioned, a further five locations of extension comprising new exterior links, three extensions of link length and one new interior link. A single contraction point exists in the form of a contracted link. However by the time of the recent Metric Survey of 1971 two of

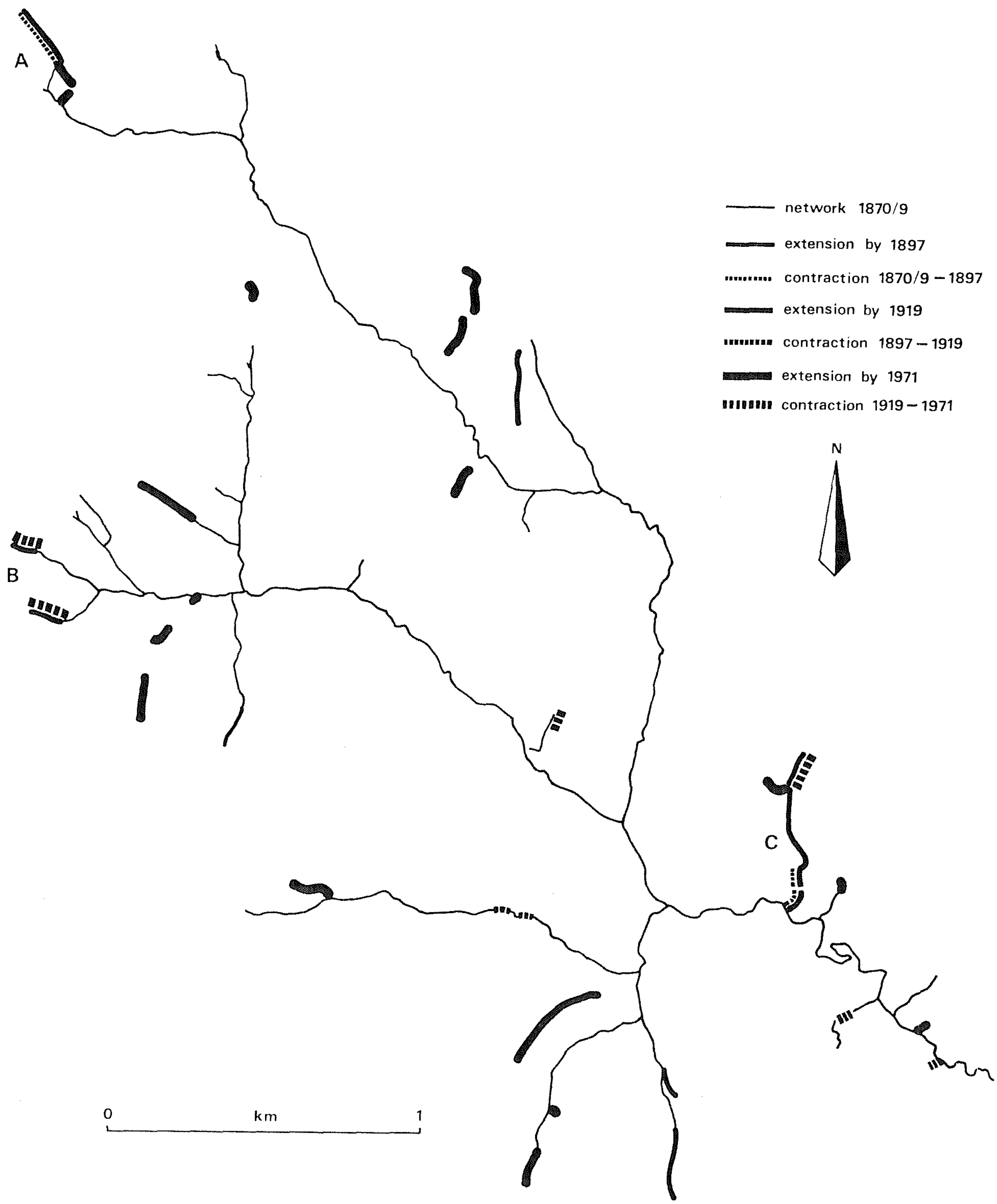


FIGURE 5.10 DOVE NETWORK CHANGE 1870/9 - 1971

these extensions of link length in the west of the catchment (Site B) had reverted to their 1897 positions while a link at Site C had contracted. Nevertheless, considerable further extension had occurred at a total of fourteen sites with only three additional small and unimportant locations of contraction. The apparent instability of the network at Sites A, B and C may well be reflecting the transitory nature of man-created drainage links.

The Metric Edition 1:10000 maps were used as a basis for field checking, and Ordnance Survey criteria were employed for the recognition of channels and flushes in the field (Table 4.2). In addition, a distinction was made in the field between flushes with or without actual or recent evidence of surface flow, while road drainage was included where, on steep slopes within the catchment, it became a direct and important element of the drainage network. Eleven locations of network change were examined in the field and most of these demonstrated considerably more extension than that inferred from examination of Ordnance Survey maps. These extensions were added to the drainage map already obtained from cartographical evidence, the resultant network being shown in Figure 5.11. This figure clearly indicates the considerable extension that has occurred in the last seven years within the Dove catchment.

Field investigation reveals that three categories of extension exist, namely ditching associated with road drainage, the transformation of flushes to well-defined channels, and a single example of the initiation of a pipe-like channel within a flush (Site 6) which is probably due, at least partly, to cattle trampling.

Extension at Sites 1 - 5 inclusive in the west of the catchment can, after field inspection, be confidently attributed to the presence of the A53 trunk road. All these sites show sections where the transformation of flushes to well-defined stream channels has occurred, while in the case of Sites 1, 3, 4, and 5 additional ditching has extended the network still further. At

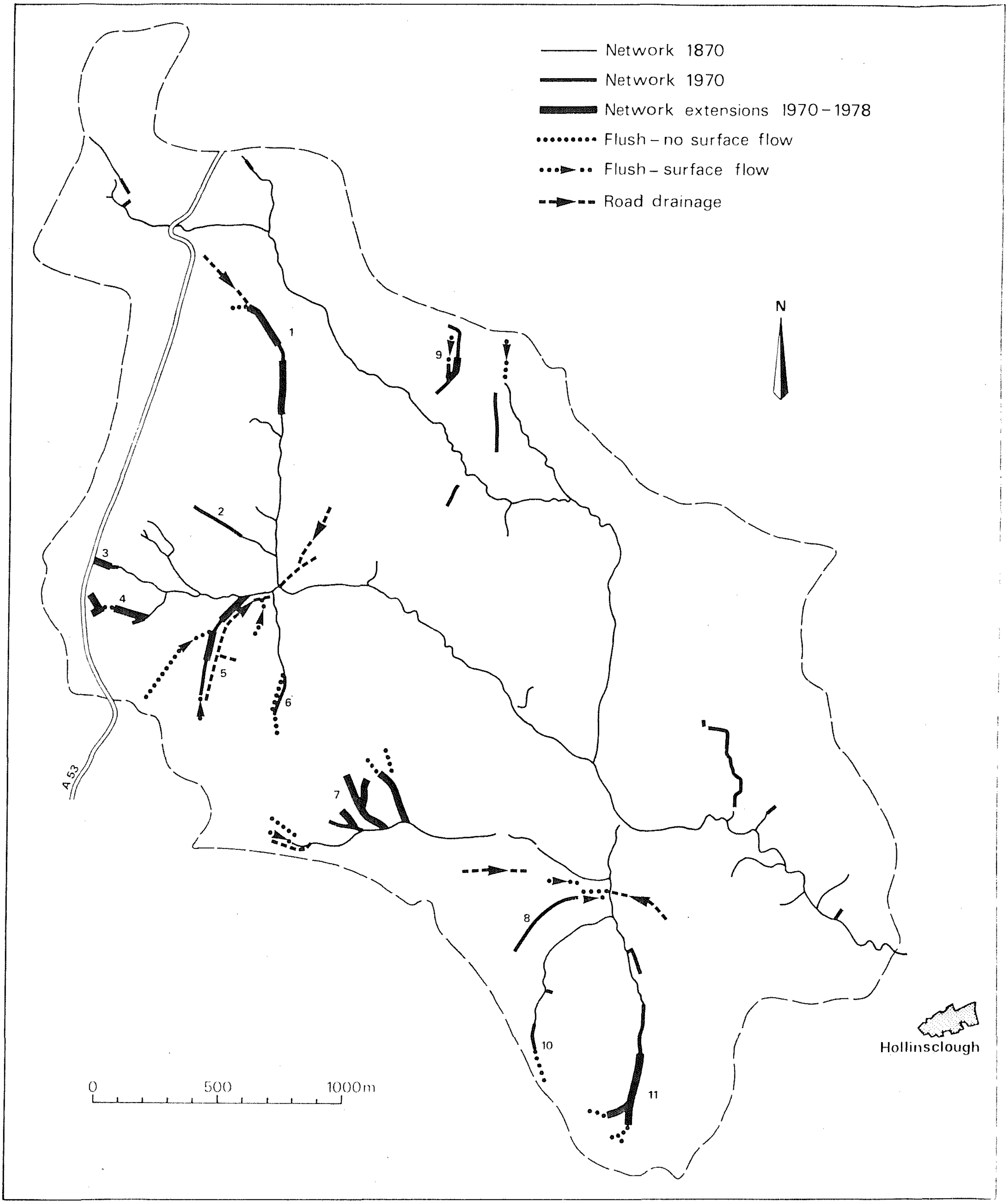


FIGURE 5.11 DOVE NETWORK CHANGE 1970 - 1978

Sites 3 and 4 the ditching extends to the foot of road drainage outlet pipes providing conclusive evidence as to the origin of the additional water necessary for the transformation of flush to channel. All the remaining extension-sites are accounted for by the transformation of flushes to channels the trigger mechanism for Sites 8, 10 and 11 appearing to be storm water drainage from a farm located at the top of the valley. The transformation at Site 10 has been accomplished by drainage concentration due to the instalment of a pipe beneath a track crossing a flush.

Thus network extension in the Dove catchment can be largely accounted for by the directing of stormwater drainage from both roads and farms to the natural stream network resulting, sometimes with help of ditching, in the conversion of flushes to channels. Elsewhere in Britain, Gregory and Park (1976) have shown that the directing of stormwater runoff from roads can lead to the erosion of a pre-existing stream channel, and it appears that in the Dove basin the modified runoff pattern has been responsible for the development of well-defined channels where only flushes existed before.

5.3.8. Roman

Of the eleven drainage basins selected for field examination two catchments were from lowland Britain. The first of these to be considered was that of the Roman down to Heckfordbridge an area of 25.89km^2. Situated near Colchester, Essex, the Roman catchment is predominantly agricultural and with 575 mm. of rain has the lowest annual rainfall total of any of the basins. Relief ranges from 62m. at the head of the catchment to 15m. at Heckfordbridge. Included within the catchment are the urban areas of Marks Tey and Copford while the basin is crossed by the London-Colchester railway and the A12 dual carriageway road.

The Roman demonstrates a marked increase in total stream length over the period 1875/6 - 1954/62 from 21.27km. to 28.68km. resulting in a drainage density increase from 0.82km.km^{-2} to 1.11km.km^{-2}. In addition the new metric maps, as yet unavailable for the complete catchment, demonstrate considerable further extension some of which has been detected and mapped during the course of fieldwork. The change from 1875/6 to 1954/62 may be broken down into 25 major locations of change, five representing contraction, and the remainder extension, of the drainage network (Figure 5.12).

As may be expected in a lowland agricultural area, much of the network change can be explained by field drainage ditches. No evidence of the implied extension of drainage links could be found at Sites 17 and 23. That at Site 17 is not shown on the new metric map and thus may represent a short-lived man-created link, while no sign of the field boundary or the associated ditch could be found at Site 23. Of the other Extension Sites 4, 8, 9, 11 and 20 classify as minor field ditches with evidence of marginal intermittent/ ephemeral flow, while all other sites are major field boundary ditches. Only at Site 7 can the extension be confidently classed as perennial with Sites 1, 2, 5 and 6 classifying as perennial/intermittent borderline. (Plate 5.19 shows a typical perennial/intermittent borderline field boundary ditch at Site 2). The ditches at Sites 12, 13, 14 and 19 classify as of an intermittent regime with the extension at Site 19 an important recent addition to the drainage network represented on the 1971 Metric Survey, but not on the Regular 1954/62 Survey. The field boundary ditches at Sites 16, 18, 20, 24 and 25 are ill-maintained, and largely overgrown; they can qualify only as ephemeral or marginal intermittent channels.

Of the five points of contraction in the catchment no evidence of the former channel could be found at Sites 3, 10 or 22. At Sites 3 and 22 unbroken ploughed fields without a contemporary channel existed over the implied sites of former channels, while at Site 10 a brickworks had effectively obliterated any sign of the former network. At Sites 15 and 22 evidence of apparently contracted links exists, both representing road catchment-drains although at Site 22 the ditch is very much a

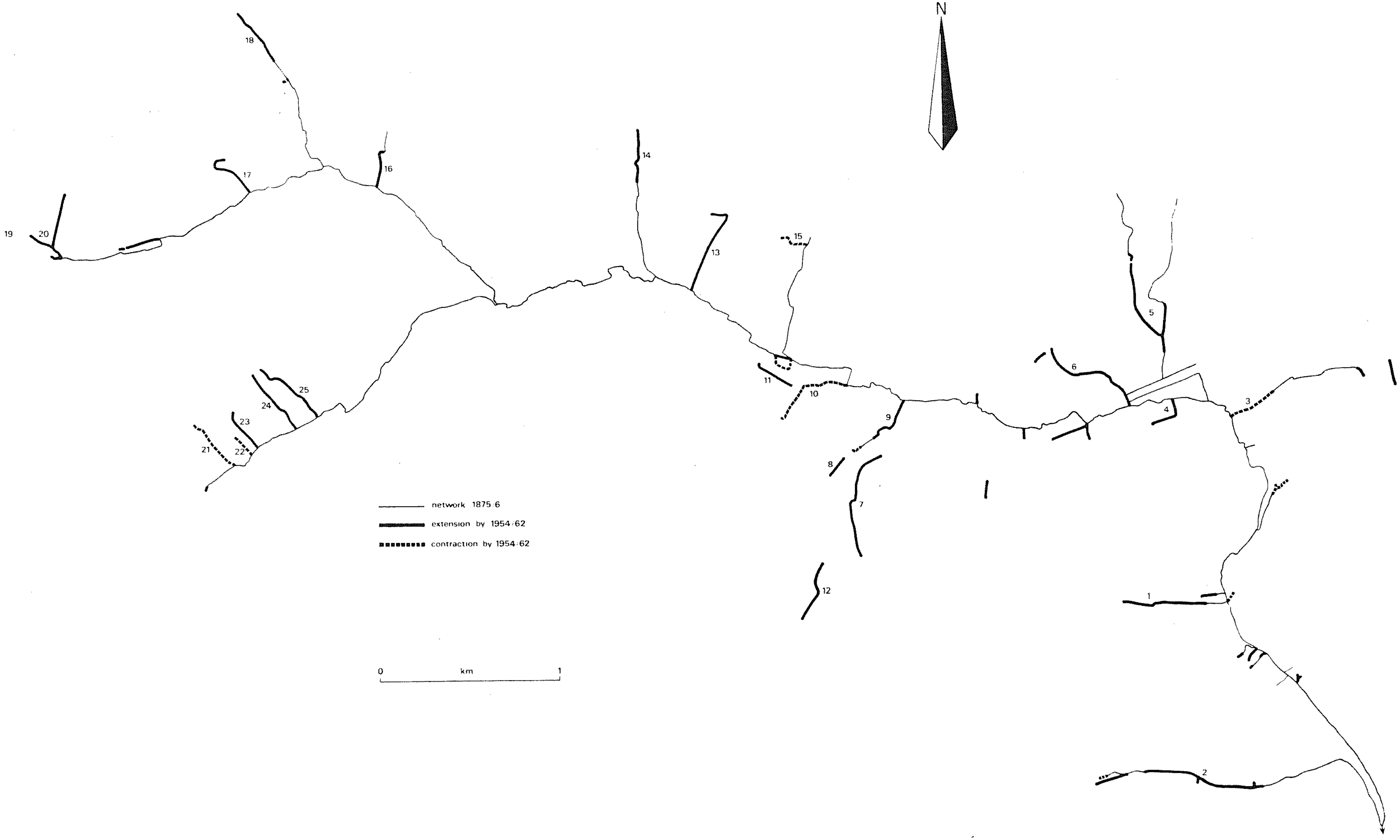


FIGURE 5.12 ROMAN NETWORK CHANGE 1875/6 - 1954/62

PLATE 5.19 ROMAN: A TYPICAL FIELD BOUNDARY DITCH OF PERENNIAL/INTERMITTENT REGIME (SITE 2).

relict or at the very best an ephemeral feature.

Consequently, network change within the lowland Roman catchment is almost totally explained by the changing field patterns and their associated drainage works.

5.3.9. East Stour

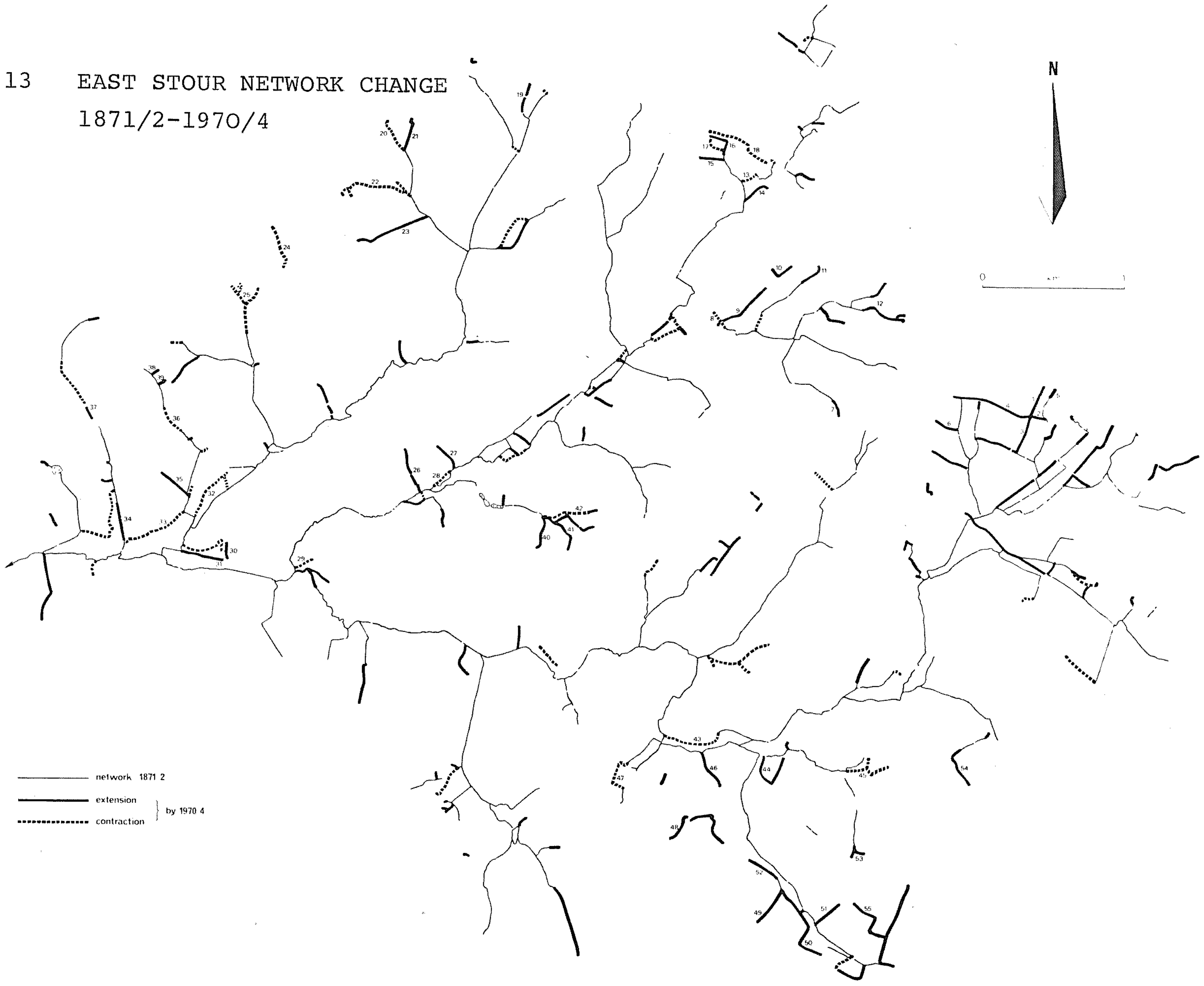
The remaining example of a field-examined lowland basin is that of the East Stour River to Evegate Mill an area of 43.57 km^2. Situated in the Vale of Kent the East Stour basin is predominantly an area of cereal production. Several urban areas are contained within the catchment, those of Sellinge, Lympne and Brabourne Lees being the largest, as well as Ashford Airport and Folkestone Race Course.

Although the catchment shows a mixture of both extension and contraction sites over the one-hundred year period 1871/2 - 1970/4, it is extension of the network that predominates (Figure 5.13). Total stream length over the period concerned rose from 73.25km. to 79.72km. increasing the drainage density from 1.68 to 1.83$km.km^{-2}$.

With an area as large as the East Stour, and with the sites of network change so dispersed throughout the catchment, field checking had to be confined generally to the larger clusters of change. Even so fifty-five sites of network change were investigated in the field, comprising thirty-four locations of extension and eighteen of contraction, with the remainder containing examples of both (Figure 5.13).

Like the Roman, a high proportion of the network change can be accounted for by field boundary and field drains, but in as large a catchment at the East Stour single examples of other categories would be expected. Such categories include the construction of drains associated with Folkestone Race Course (Site 44), the creation of a new spring within a quarry (Site 48) and extension due to storm runoff from a farm (Site 46). However, there is no evidence of a stream link at Site 2

FIGURE 5.13 EAST STOUR NETWORK CHANGE
1871/2-1970/4



where, according to cartographical evidence, the network has extended, or of recent extension at Site 14 where a well-established channel exists with no evidence of its apparent recent inception. A more important category of change within the East Stour catchment is that of extension due to road drainage which has occurred at Sites 7, 19, 53 and 54 and also possibly at Sites 9 and 10. Two connected examples of flush metamorphosis to channel occur in the catchment at Sites 26 and 27 where the physical conditions in the form of well-defined valleys make an ideal situation for such a process to operate.

All the remaining extensions to the network are the result of drainage ditches which generally are faithfully portrayed and correctly labelled on the Metric Edition maps. The term 'drain' on this edition denotes a recently-dug ditch, either straight or of some other form of regular pattern which shows no signs of meandering. Two examples of major field-boundary ditches occur at Sites 1 and 3 (Plate 5.20) where the regime is probably intermittent, while Sites 12, 15 and 16 demonstrate ephemeral mid-field drains. At all other sites of extension the regime is marginal intermittent/ephemeral - a distinction difficult to elaborate further with mid-summer field checking. Site 23 (Plate 5.21) is presented as an example of this category.

A good deal of variation in the categories of network contraction is found within the catchment. The contracted link at Site 28 is due to a decayed Mill Leat while the construction of a sewage works at Site 29, Folkestone Race Course at Sites 43 and 45, and a housing estate at Sites 24 and 25 has obliterated former drainage links. In addition, construction work on the new South-East Motorway has removed any evidence of contraction at Sites 36 and 37. No trace of the former network could be found at Sites 17, 18, 20, 22, 31, 32 or 33 where all the locations are now unbroken cereal fields demonstrating the transient nature of many of these artificially-created drainage channels. Evidence of former drainage links was found at Sites 42 and 47, the latter representing a relict field boundary ditch.

PLATE 5.20 EAST STOUR: A MAJOR FIELD BOUNDARY DITCH OF INTERMITTENT REGIME (SITE 3).

PLATE 5.21 EAST STOUR: A DUAL PURPOSE FIELD BOUNDARY AND CATCH DRAIN OF INTERMITTENT/EPHEMERAL REGIME (SITE 23).

The links at Sites 8 and 13, represented as having contracted over the period 1871/2 - 1970/4, still in fact exist in the field, but both represent road catch-drains and presumably were therefore omitted from the recent map under clause 114b of the Ordnance Surveyors' Manual.

Thus, while several solitary examples of freak reasons as well as more familiar causes for network change are found within the East Stour catchment, it is the changing patterns of field boundary and field drains that hold the key to a substantial part of network change within the catchment.

5.3.10. Avan

The only basin to represent Wales, due to the limited coverage of the Metric Survey in this part of the country, is that of the Avan, a valley situated to the west of the Rhondda and disfigured by the extraction of coal. Many of the steep slopes within the catchment are under the auspices of the Forestry Commission with a little pasture occurring on the more gentle slopes towards the lower end of the catchment. The relief contrast, from 560m. to 183m., coupled with the highest rainfall of any of the catchments examined (2377mm) ensures a variety of sites of network change within the Avan basin. However, the frequency of sites of network change within the catchment is somewhat disguised by the small change in network length over the period 1875/7 - 1961 of 2.54km. Figure 5.14 gives details of the change sites and also demonstrates the even division of change into extension and contraction sites. The instances of contraction in the Avan catchment were the greatest encountered in any of the cartographic examinations, a factor contributing to the choice of the area for field examination. Fifty-three sites of network change were examined in the field and these demonstrated a variety of reasons and causes for modification of the drainage network.

The activities of the Forest Commission are a major cause of network extension within the catchment with

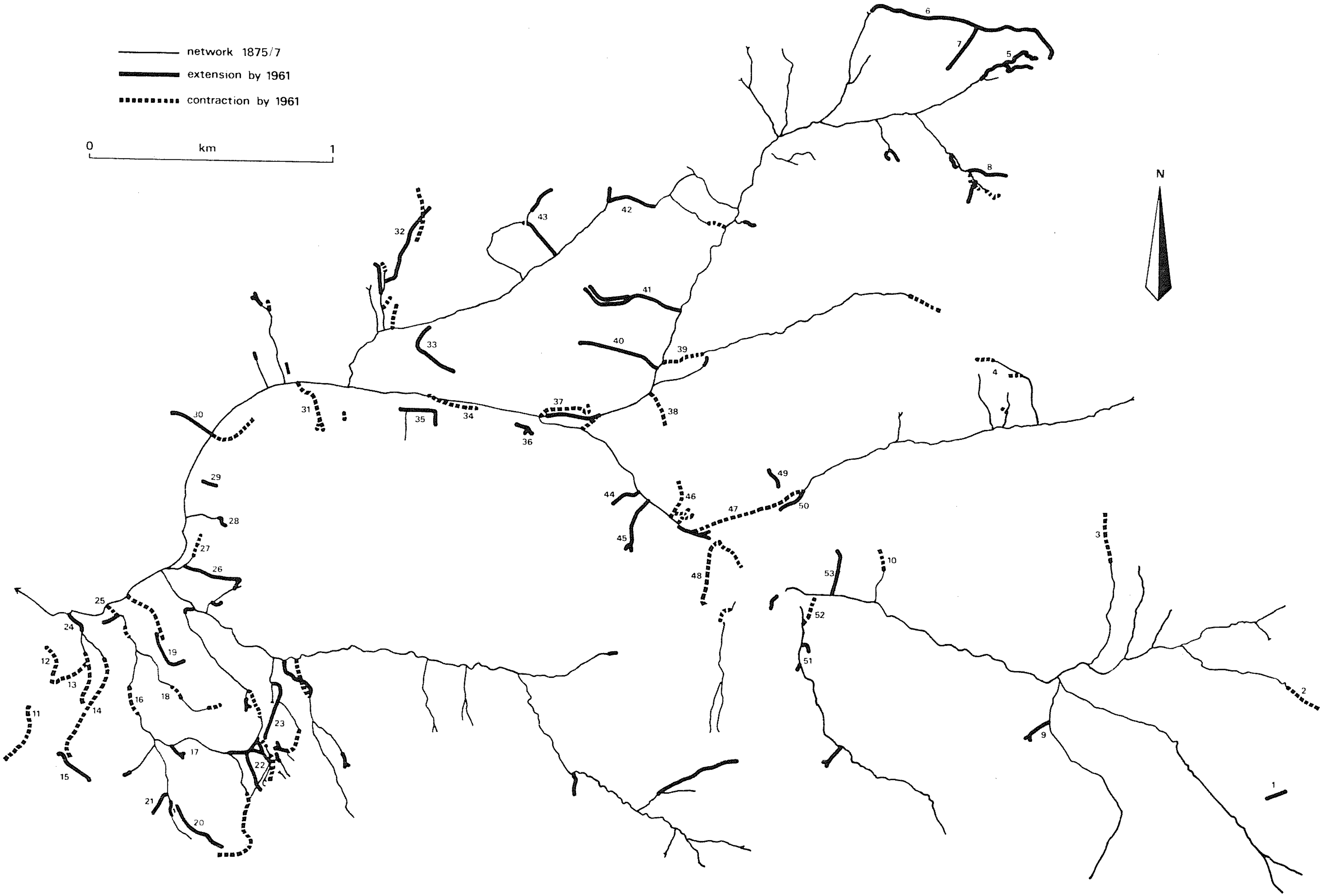


FIGURE 5.14 AVAN NETWORK CHANGE 1875/7 - 1961

ditching occurring at Sites 1, 2, 7, 8, 30, 32, 33, 40, 41, 42, 43 and 49, while catch-drains along Forestry Commission tracks also produce extension (Site 6). In addition, the apparent contraction of a link at Site 4 still in fact exists as another catch-drain to a track. Within these headwater areas of the Avan considerably more drainage exists than that shown on the metric 1:10000 Ordnance Survey maps due to the 'herringbone' pattern of ephemeral/intermittent forest drains.

The metamorphosis of flushes to channels is another major category of network change within the catchment with examples at Sites 9, 17, 20, 23, 26, 29, 44, 45, 51 and 53. The considerable flow that is to be found in some of these new channels is well illustrated at Site 45 by the large diameter of the pipe conveying flow under the A4107 road and also the presence of a sizeable footbridge (Plate 5.22).

Several minor categories of change exist including peat flush development (Site 5), field boundary drain construction (Site 22) and the creation of a new interior link (Site 24). This new interior link may possibly be due to a lateral shift in the course of the main stream channel. Several examples of drains are also found and their function varies from the drainage of waste land (Site 15) to the conveyance of storm runoff from roads (Site 19). The extension of an old ditch at Site 28 has also occurred due to runoff from a nearby track. Two examples with little or no evidence of a supposed extension to the drainage network, were Sites 21 where a decayed link appeared to have once carried water from a cattle grid pit, and the shorter of two new exterior links at Site 51 where no evidence of extension could be detected.

The categories of contraction within the Avan catchment are just as fragmentary as those of extension but some categories dominate, the most important of which is that of the artificial piping of the former network underground - a category not representing contraction to the real network at all. This occurrence has two major causes, the first being housing as illustrated at Sites 11, 12, 13, 14, 31, 47 and 48, and the second

PLATE 5.22 AVAN: THE IMPORTANCE OF A RECENT METAMORPHOSED CHANNEL (PICTURE CENTRE) IS ILLUSTRATED BY THE CAPACITY OF THE PIPE BENEATH THE ROAD AND THE PRESENCE OF A FOOTBRIDGE. (SITE 45).

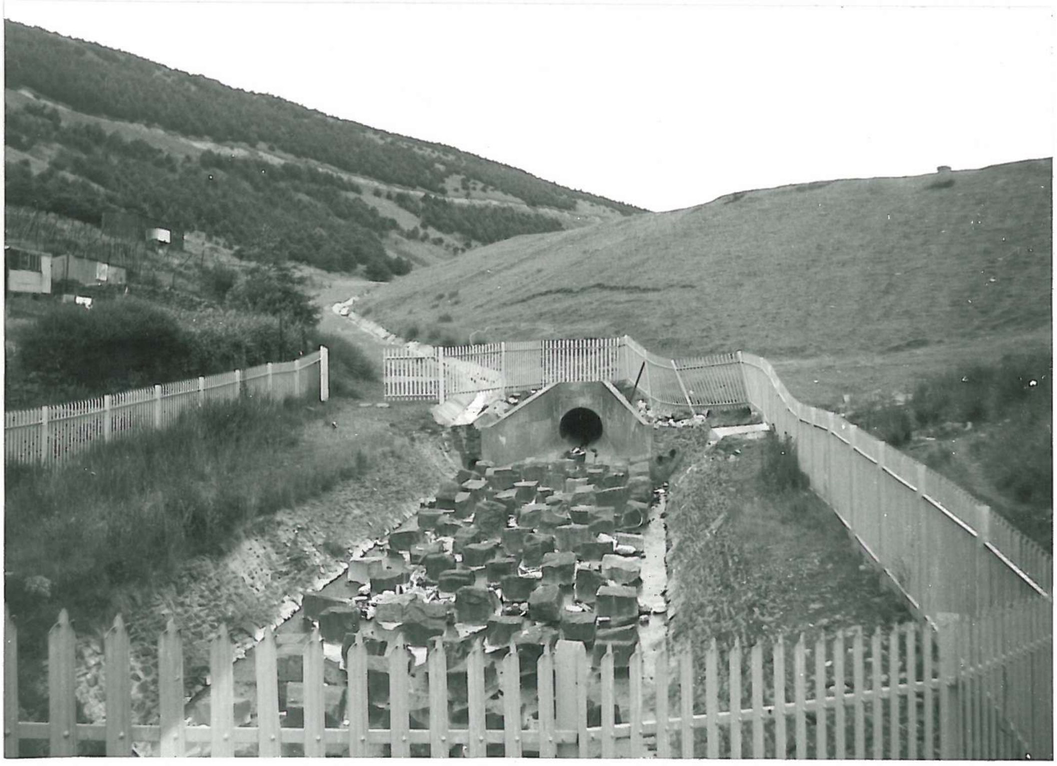


PLATE 5.23 AVAN: THE APPARENT CONTRACTION OF THE LINK (SITE 47) IS DUE TO ARTIFICIAL PIPING DUE TO SPOIL TIP RECLAMATION (UPSTREAM) AND RESIDENTIAL DEVELOPMENT (DOWNSTREAM).

coal-tip reclamation found at Sites 34, 35, 36, 37, 47 and 52. Plate 5.23 shows part of the apparent contraction to a drainage link at Site 47 demonstrating the artificial piping necessitated by spoil tip reclamation (upstream) and housing (downstream of photograph). Associated with the latter category is the extension at Site 50 which represents an artificially-created overflow channel to the piped channel at Site 47. The frequent enclosure of a former channel through a reclaimed tip is necessitated by the incohesion of the coal mining waste and thus its susceptibility to rapid erosion. Site 37 demonstrates another aspect of the problem where the material demanded the construction of a steel waterfall and open concrete channel to guide the stream safely through the area (Plate 5.24). The construction of a factory at Site 16 and a football ground at Site 39 (Plate 5.25) have resulted in isolated examples of the artificial piping of the network.

Single examples of the reversion of an old ditch (Site 10) and channel (Site 38) to flush are found, while the contracted links at Sites 18 and 27 now represent relict field boundary ditches. The instance of apparent contraction of the link at Site 25 may be due to Ordnance Survey error because the link concerned still clearly exists today but is under dense tree cover. The contraction at Site 3 also appears to have been misrepresented because the location appears much like a site of the recent initiation of a pipe-like channel, although the anomaly could be explained in terms of modifications that may have occurred in the eighteen-year period since the area was surveyed. No trace of the former network could be detected at Sites 30 and 46, while at Sites 8 and 32 what were possibly old drainage ditches have been obliterated by the modern patterns of Forestry Commission drains. The listing of contraction in the Avan catchment is completed with the confused sites at 22 and 23 where the thick *juncus* and obvious man-interference make any attempt to identify reasons for change impossible.

Field examination of the Avan catchment has revealed that much of the extensive contraction shown by the

PLATE 5.24 AVAN: CONCRETE CHANNELS AND STEEL WATERFALLS GUIDE THE RE-ALIGNED CHANNEL (SITE 37) THROUGH A RECLAIMED TIP AREA.

PLATE 5.25 AVAN: NETWORK CONTRACTION DUE TO THE ARTIFICIAL PIPING OF THE NETWORK BELOW A FOOTBALL GROUND (SITE 39).

Ordnance Survey is in fact merely an artificial enclosing of an existing stream channel due to construction or tip-restoration work. Apparent contraction such as that found in the Avan catchment is probably very common in urban areas where channels need to be enclosed for construction purposes. Indeed it has been commented on by Williams (1977) in connection with Washington D.C.'s vanishing springs and waterways, where over the years man has converted streams to underground sewers, or in some cases completely obliterated them by infill. Consequently the actual net extension in the Avan basin is considerably greater than that indicated by the figures given in Table 5.2. The major reasons for extension are the activities of the Forestry Commission and the metamorphosis of flushes to channels.

5.4. CONCLUSIONS AND SUMMARY OF FIELD SURVEYS

5.4.1. General Results

Comprehensive study of the eighteen British drainage basins complements the findings of the pilot study of Highland Water in that it confirms that changes in the drainage network can be expected to occur with time and that these changes may be located by reference to different editions of Ordnance Survey 1:10560 and 1:10000 maps. Such changes occur in a spectrum of basin types and environments although causes and reasons for change vary widely between catchments and sometimes between areas within the same catchment. Drainage network changes appear to be most concentrated in the more urban catchments although further investigation of this feature was hampered by the problems of accurately delimiting and separating the network from the multitude of other confusing cartographical urban detail. Of the field-examined catchments concentration of drainage network change would seem to reach a peak in the urban ribbon development of the Avan catchment where urban influences, spoil heap reclamation, and the activities of the Forestry Commission are fused.

Changes in the drainage network are by no means confined to changes resulting directly or indirectly from the present activities of man within the drainage basin. Indirect influences are extremely difficult to determine because their origins may lie in the distant past. For example the clearing of forests by burning and cutting during earlier phases of land use change may have had a strong influence on vegetational and ecological trends in general, and the drainage network may still be responding to these effects. Catchments such as those of the Cona, Isla, Dorback and Manor Water represent drainage basins more or less removed in differing degrees from the more obvious direct influences of man.

Evidence drawn from the eighteen drainage basins studied suggests that extension generally accounts for a far greater proportion of network change within a catchment than does contraction and is consequently of greater importance (Tables 5.1 and 5.2). Dorback Burn and Harpers Brook catchments are two exceptions, and show a slight decrease in stream length. In the Dorbach basin so much implied contraction was not confirmed in the field, that the net result was a slight extension of the drainage network over the period of the surveys. The even smaller contraction of the drainage network in the Harpers Brook catchment was not examined in the field but was deduced from map evidence to be due to the presence of considerable human activity in the form of airfield construction and quarrying. This may reflect a general trend in that the contraction of the drainage network appears most prominent in basins directly affected by man as exemplified by the Avan, the lower part of Manor Water and the East Stour catchments.

However, possibly the most refreshing general conclusion from the examination of the eleven basins that were field-checked was confirmation of the accuracy of the two surveys involved; with very few exceptions field evidence confirmed a real change in network at each potential location of network change. It would be difficult to find greater proof of the accuracy of the drainage network as depicted on the large-scale maps of the

Ordnance Survey.

5.4.2. Summary of Drainage Network Change

The effect of the concept of network change on the various principal components of the hydrological network, in terms of the possible ways that components may change with time, is summarised in Table 5.4.

While the categories of flush, channel and drain have been thoroughly investigated during the course of fieldwork, that of bog or marsh has assumed a very much lower significance. This is partly because it is far more difficult to appreciate the role of a bog in the context of the hydrological network without extensive fieldwork, and this was impractical in this study. However, it is clear from general fieldwork that the influence of bog and marsh areas on the drainage network does vary substantially from area to area.

The recognition of 'water tracks', defined (Sjors 1948) as courses within a bog which have more active movement of water downslope, within the New Forest bogs during times of saturation of the peat, as potential water supplies for flushes must have relevance for other areas. Bogs may well play an important, but as yet unassessed, role in the metamorphosis of flushes to channels for their presence as large sponges regulating water (Moore and Bellamy 1974) helps to explain why newly-created channels often assume an intermittent rather than an ephemeral form. Consequently, the extension or contraction of a marsh or bog has an important influence on the regime that newly created drainage links adopt in the context of the network as a whole, whether viewed on a short or longer timescale. Extension of a bog is thus interpreted as the response of the bog to wet conditions where saturation of the peat will lead to 'water tracks' across the bog surface which ultimately feed flushes. Contraction of the bog is viewed in the opposite manner when the exsiccation of the bog leads to the abandonment of 'water tracks' and the cessation of the supply of water to flushes and thus to the drainage network.

COMPONENT	CHANGE: EXTENSION	CHANGE: CONTRACTION
BOG or MARSH	Certain 'water tracks' become dominant during saturation and act as feeds for flushes.	Abandonment of 'water tracks followed by isolation of the bog from the network and the cessation of the water source.
FLUSH	Metamorphosis to stream channel.	Degradation to linear depression, either ephemeral or relict.
CHANNEL	Transformation from ill-defined to well-defined state as the channel becomes more established.	Initially to flush but may disappear altogether.
DRAIN	- By metamorphosis of length of artificially-created flush above it. - By head erosion of 'head step'.	Degradation to flush initially but may become an ephemeral linear depression then a relict feature.

TABLE 5.4 POSSIBLE CHANGES OF DRAINAGE NETWORK COMPONENTS

Within this broad classification of the drainage network components the various elements of these components will be examined. The details of the types of change predominating in a basin, the common forms that change adopts, and the reasons for change are presented in Table 5.5 for each of the eighteen basins initially examined cartographically.

As would probably be expected, the elements of the drainage network that predominate for most of the catchments, are those of link lengths and the creation/abandonment or extension/contraction of exterior links. The proportion of network change accounted for by each of these two elements does vary substantially between catchments. Sometimes associated with the additional water provided by new exterior links or extended links are the creation of new interior links downstream. These interior links are an element of extension in the Hodge Beck catchment (Figure 5.2) and constitute the most important element of the Plym catchment. Interior links also feature prominently in apparent network contraction seen particularly in the Avan catchment where the stream course has been artificially enclosed due to urbanisation.

Reasons for network change in the various catchments analysed are diverse, varying from drain-construction to gullying, and from flush metamorphosis to urbanisation. Similar types of change within the network components may originate from substantially different causes. For example, the extension of a link length may be the direct result of ditching, the artificial inception of a spring, or the metamorphosis of a length of flush to channel. By contrast, certain influences are present in both highland and lowland basins, the most noticeable being the Forestry Commission whose influence is found not only over much of Highland Britain but also over extensive areas of Lowland Britain, the New Forest being a prime example.

A logical progression from Table 5.5 is the classification of drainage basin change according to the dominant element of either extension or contraction and to the proportion of each element contained within a particular

KEY TO TABLE 5.5

1. Forest Drains
2. Agricultural Drains
3. Flush Metamorphosis
4. Pipe Burst
5. Gullying
6. Construction Work
7. Urbanisation
8. Storm Water Disposal
9. Miscellaneous

	DOMINANT ELEMENT OF CHANGE		PREDOMINANT CHANGE TYPE(S) EXTENSION			CONTRACTION			CAUSES/EXPLANATION OF CHANGE								
	Extension	Contraction	New Ext. Link	New Int. Link	Link Length	Ext. Link	Int. Link	Link Length	1	2	3	4	≠5	6	7	8	9
Avan	Extension		+	–	+	+	+	+	+	–	+	–	–	+	+	–	+
*Churn	Extension		+	–	–	–	–	–	.	.	.	.	.	.	.	.	.
Cona	Extension		+	–	+	–	–	–	–	–	+	+	–	–	–	–	–
Croasdale Brook	Extension		+	–	+	–	–	–	–	+	+	+	–	–	–	–	–
*Dalch	Extension		+	–	+	–	–	–	.	+	.	.	.	.	.	.	.
Dorback Burn		Contraction	–	–	–	+	–	+	–	–	+	+	–	–	–	–	–
Dove	Extension		+	–	+	–	–	–	–	+	+	–	–	–	–	+	–
East Stour	Extension		+	+	+	+	+	+	–	+	–	–	–	+	+	–	–
Ellen	Extension		+	–	+	+	–	+	–	+	+	–	–	–	–	–	–
*Harpers Brook		Contraction	+	–	+	+	–	–	–	–	–	–	–	+	–	+	+
Highland Water	Extension		+	–	+	–	–	–	+	–	–	–	+	+	–	+	+
*Hodge Beck	Extension		+	+	+	–	–	–	+	–	+	–	–	–	–	–	–
Isla	Extension		+	–	+	–	–	–	–	–	+	+	–	–	–	–	–
*Linford Water	Extension		+	–	+	–	–	–	+	.	.	.	.	.	.	.	.
Manor Water	Extension		+	–	+	+	–	+	–	–	+	–	+	–	–	–	–
*Plym	Extension		–	+	–	–	–	–	.	.	.	.	.	.	.	.	.
Roman	Extension		+	+	+	–	–	–	–	+	–	–	–	–	+	–	–
*Water of Luce	Extension		+	–	+	+	–	+	.	.	.	.	.	.	.	.	.

*Causes of extension have been inferred from map evidence

≠See key opposite

<u>Note</u> + = Present
– = Absent
. = Unknown

TABLE 5.5. <u>SUMMARY OF NETWORK CHANGE</u>

basin. Such an attempt at classification is presented in Table 5.6, where five categories of basin type are shown. These vary from the extension type in which extension accounts for at least 95% of the total change, through categories where extension is progressively less important, to basins where contraction is dominant, although in this latter category extension of the network is still a very important element. The final category of drainage basin change type is that of 'little change' where the network has remained more or less consistent over the time period examined.

After examination of the distribution of basins in Table 5.6, the reasons for the differing importance of drainage network extension is difficult to explain. There is no noticeable correlation in terms of basin size, rainfall amount, rainfall intensity, slope or even general human interference within the basin. However, this topic will be examined in more detail during the course of Chapter 8.

5.4.3. Expected Causes of Change according to Basin Type

It would seem appropriate to end this chapter with a prediction of the expected causes of drainage network change given the basin situation and the amount of human interference within the catchment. An attempt at this type of analysis is given in Table 5.7. The rather crude divisions in this table between natural and man-induced, and between upland and lowland, require qualification. The term natural is applied to basins where there is no evidence of man-created impermeable surfaces which may serve as supply areas for runoff whether these be roads, regularly-used tracks, airfields or residential areas. The term man-induced may here be taken as including all other areas. The division between upland and lowland basins is clearly seen by referring to the highest points in the catchments as presented in Table 4.8 section 4.4.2. In this table the general relief of the basins of the East Stour, Harpers Brook, Linford Water, Highland Water and the Roman is clearly

BASIN TYPE	DETAILS OF CLASSIFICATION	EXAMPLES
1. Extension	Extension accounts for at least 95% of change.	Linford Water; Dalch; Hodge Beck: Dove: Highland Water.
2. Extension Predominant	Extension accounts for at least 70% of change but not more than 95%.	Cona; Isla; Croasdale; Roman.
3. Extension/ Contraction	Net extension but contraction important element accounting for at least 40% of change.	Water of Luce; Manor Water; Avan; East Stour; Ellen.
4. Contraction/ Extension	Net contraction but extension an important element accounting for at least 40% of change.	Harpers Brook; Dorback Burn*.
5. Little Change	Indicates stability of the network.	Plym; Churn.

* Dorback Burn after field examination could be placed in category 3 since much of the contraction is only apparent.

TABLE 5.6 DRAINAGE BASIN CLASSIFICATION ACCORDING TO DOMINANT ELEMENT OF CHANGE AND ITS PROPORTION.

	BASIN TYPE	EXPECTED CAUSES OF EXTENSION	EXPECTED CAUSES OF CONTRACTION
UPLAND	Natural	- Flush metamorphosis - Pipe bursts	- Channel degradation to flush.
UPLAND	Man-Influenced	- Forestry Commission drains - Drainage ditches: (i) Grouse Moors (ii) Improved Pasture	- Spring position changes due to urbanisation. - Artificial course changes (e.g. new ditches tapping water source previously feeding older ditches).
LOWLAND	Natural (e.g. Heathlands)	- Some flush metamorphosis	- Some channel degradation.
LOWLAND	Man-Influenced	- Agricultural field drains - Road, farm, airfield, drains - Forestry Commission drains	- Disappearance of field-boundary ditches with coalescence of fields. - Urbanisation + mining waste landscaping.

TABLE 5.7 SUGGESTED CAUSES OF NETWORK CHANGE

different from that of the remaining catchments. From these figures a tentative upper limit of 200m may be fixed for the highest relief of a lowland catchment.

Flush metamorphosis and channel degradation are common to both highland and lowland natural catchments although they are more widespread in highland basins. However pipe bursts are, on the evidence of the limited fieldwork executed, confined to upland catchments. Extension of the drainage network by drains is a common feature of both highland lowland catchments and is indicative of man's presence within a basin. The Forestry Commission is mainly responsible for drains in upland catchments while in lowland catchments the origins of drains are more diverse.

The nature of network contraction depends largely on the land use in the catchment. Consequently, contraction in lowland agricultural basins is largely accounted for by the disappearance of field boundary drains when fields are amalgamated, while in urban areas apparent contraction of the network occurs due to urbanisation or spoil tip reclamation enclosing streams.

CHAPTER 6 EVALUATION OF ALTERNATIVE SOURCES OF DATA

6.1 CONSIDERATION OF SOURCES OF GENERAL DATA FOR DRAINAGE NETWORK CHANGE

Chapter Two concluded with the presentation of several hypothetical techniques for the study and identification of network changes in Britain. The methods contained within the category of 'precise techniques' (Section 2.3.2.) will be considered in more detail later in this section; the alternative cartographic sources are considered in Section 6.2 and the alternative empirical sources in Section 6.3. All those techniques categorised in the section on 'general techniques' were eventually discarded, the reasons for this being presented below.

6.1.1. General Techniques for the Identification of Drainage Network Changes

The perception of farmers, commoners and other long-standing landowners as to general extension and contraction of streams on their property, although theoretically useful, is in practice difficult to use and can at the best provide only supporting evidence to supplement more precise information. It requires an acute awareness on the part of a landowner to recognise the hydrological changes that may have occurred on his property; also, a number of years' residence on the same property are needed for the landowner to be in a position to comment. The likelihood of these requirements coinciding with those satisfying the cartographic viewpoint (presented in Section 4.4.1.) is not very high.

Although the use of travellers' notes has been demonstrated for drainage network changes in America (Cooke and Reeves 1976) and Australia (Eyles 1977a,b) they proved to be of no use in a British context where exploration of the country at a much earlier date went largely unrecorded. Additionally, rivers in a area like New South Wales

(Eyles 1977 a,b) are exceptional features and of clear cut stream types whereas in a temperate area such as Britain stream types are more indistinct and there are plenty of other features upon which to comment. These facts, together with the difficulties of stardardising various authors' perception, led to the dismissal of travellers' notes as a consideration in network change analysis.

Newspaper articles and passing or implied references in geographical publications, and those of other associated disciplines, are also of use only as supporting evidence and rarely refer to areas which have suitable map coverage. In addition newspaper articles are inherently subjective and are often designed to be deliberately alarmist to best present a certain concept to the widest possible spectrum of the British public. This results in coverage of only extreme examples such as the Lynmouth Floods of 1952 with more moderate incidents left unrecorded.

With these decisions on the use of the general techniques for the determination of network change, it remained to consider the alternative 'precise techniques'.

6.2. ALTERNATIVE CARTOGRAPHICAL SOURCES

In addition to the maps produced in Britain by the official agency, namely the Ordnance Survey, there exist a number of private sources for maps which must for completeness be examined and their potential discussed.

6.2.1. Tithe Maps

By far the most important group of maps to be considered are those produced by the Tithe Commissioners. The period warranting consideration is that covered by the tithe maps immediately prior to the introduction of the first large-scale maps of the Ordnance Survey. The counties of Lancashire and Yorkshire, covered by the trial large-scale survey of about 1840, are exempt from consideration because the maps here would present no hydrological information additional to that in the early Ordnance Survey maps. For a large part of rural England and Wales the tithe surveys extend the historical record of the drainage network by between 20 and 40 years. The tithe surveys do not extend to Scotland and therefore a uniform cartographical record for all areas cannot be considered.

Against the relatively short extension to the historical record of England and Wales provided by the tithe maps must be weighed the difficulties of converting to a scale of 1:10560 or 1:10000 for comparison purposes, since most of the tithe surveys were executed at a scale of either three or six chains to one inch. However this is not an insurmountable problem for the tithe surveys have been used previously in Hydrological studies by Hooke (1977) and many authors have paid testimony to their accuracy including Prince (1959) and Hooke and Perry (1976).

In order to assess the value of the tithe surveys in drainage network change, two areas, covering parts of Highland Water and Linford Brook in the New Forest, Hampshire, were selected for a comparison study between the drainage networks represented on the tithe maps and the First Edition 1:10560 map. Unfortunately the proposed networks, lying on the Ellingham and Minstead Tithes, were not covered, both occurring in surroundings which were classified as 'waste'. This illustrates the selectiveness of the areas considered by the tithe surveyors, and the consequential difficulty of obtaining a complete drainage network in any marginal agricultural zone. Eventually Fleet Water, a head tributary of Bartley Water in the Parish of Minstead, was selected for the tithe-Ordnance Survey comparision and the results are presented in Figure 6.1.

Over this small area the tithe survey shows substantially fewer drainage links than the First Edition 1:10560 map but includes a single example of an additional link. It is not only the small exterior links that are omitted on the tithe survey but also substantial links such as those at Sites I and J as well as an important length of interior link (Site E). Closer examination of these omissions reveals that stream courses are

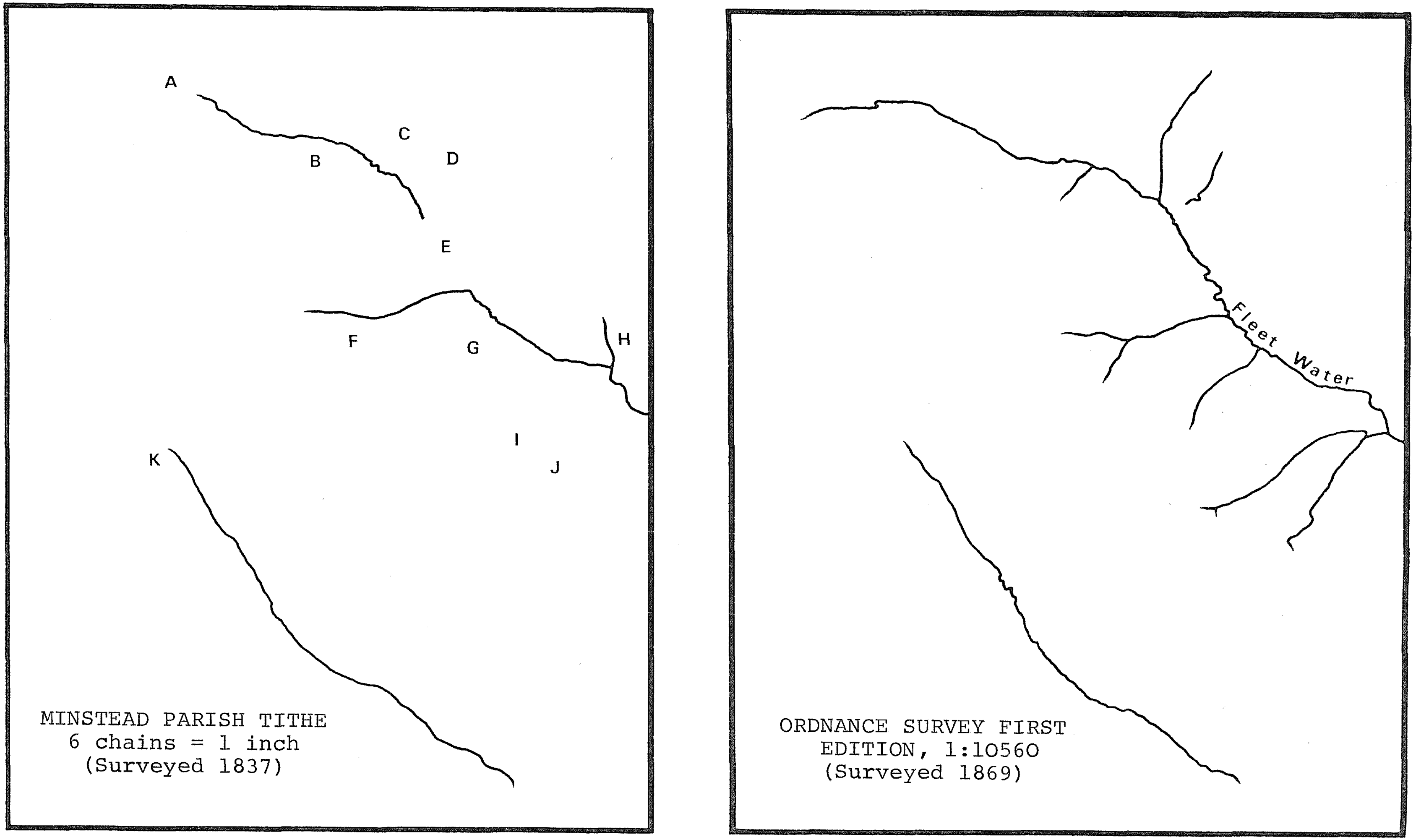


FIGURE 6.1 COMPARISON OF TITHE AND ORDNANCE SURVEY DRAINAGE REPRESENTATION.

incomplete from field to field and, where waste land occurs between cultivated areas, streams are omitted altogether.

At this level of analysis the drainage network represented on the tithe maps would seem to be considerably inferior to that presented on the large scale Ordnance Survey maps. A cautionary note in this comparison is that the tithe survey was conducted in 1837 some 32 years before the Ordnance Survey coverage and so this change could be due in part or in its entirety to drainage network development. However, the systematic cartographical analysis in the basins of Highland Water (Table 4.3, Section 4.3.2.) and the Dove (Table 5.3, Section 5.3.7.) supported by field survey, shows that most of the extension to the drainage network has occurred in the last fifty or so years and that both networks show a remarkable consistency throughout the nineteenth century from survey to survey. If the consistency of these particular drainage networks over the Nineteenth Century applies to the whole country, then the amount of change implied on Fleet Water would seem unlikely. Consequently the accuracy of the tithe surveyors' depiction of streams must be open to doubt. Thus although the tithe surveys provide a slightly longer time period over which to examine network change, the extra years cover a period when the network may have been at its most stable. In addition no surveying manuals exist to enable the represented network to be qualified. These factors together with the example study were the main factors affecting the decision to abandon work on the tithe surveys.

6.2.2. Estate Maps, Deeds and other Record Documents

Official documents such as deeds and estate maps often contain accurate representations of specific drainage links in connection with territorial boundaries and the provision of water supply, and may well be useful to supplement or complement Ordnance Survey material for specific link studies. However, their usefulness in a more general context is hindered because they cover only random small areas and therefore cannot be used for a comprehensive study of a complete drainage basin.

6.2.3. Surveyors' Notebooks and Original Drafts of First Edition Maps

The case for reference to notebooks containing the surveyors' actual working when considering the survey of specific sheets was briefly alluded to in the course of Section 3.4.2. While these have proved invaluable in the Australian (Eyles 1977a, b) and American context, the existence of equivalent British manuals has been denied by the Ordnance Survey and no further inquiry was possible. With the original drafts of First Edition maps, as with the estate and other privately produced maps, it was considered that the extra information they may produce would not justify the time taken to locate and sift through them.

These decisions eradicated all the historical sub-division of the 'precise techniques' for the identification of drainage network change except the examination of large-scale Ordnance Survey maps.

6.3. ALTERNATIVE EMPIRICAL SOURCES

Four empirical methods for the identification and measurement of network change are to be considered in this section. They comprise the resurvey of cross-profiles on gullies originally measured by other authors, the interpretation of aerial photographs, the frequent survey of active network extension sites both natural and man-induced, and the head erosion of artificial drains. Of these methods, only the head-erosion of drains, and the frequent survey of natural and artificial extension sites were eventually employed in the study.

6.3.1. Aerial Photographs

Several factors contributed to the decision not to employ aerial photographs for the detection of changes in drainage networks. Much of the black and white photographic coverage held at the Department of the Environment was undertaken by the Royal Air Force immediately after the last war, the results being extremely variable in quality. Often the photographs are too poor for details of the drainage network to be abstracted while occasionally certain sections of the photographs are obliterated by cloud cover. In addition, the scale of about 1:10000 usually chosen for these photographs is too small to give the minute detail required if small changes in the drainage network are to be detected. The nature of the study dictates that it is the peripheral links, by nature the smallest, that are the most interesting and it is these that are not easily detectable on the 1:10000 scale photographs due often to their form being obscured by vegetation cover. Lo (1976) has demonstrated that black and white infrared film can help to detect channels in afforested areas, his study in New Brunswick, Eastern Canada showing a 37% improvement over panchromatic film. However the most serious problem with the use of aerial photographs in work of this kind is that the drainage network portrayed cannot be qualified as it could on the large-scale maps of the Ordnance Survey. Consequently short-term expansions and contractions of the drainage network are picked up on the photographs and they thus require extensive field-checking to determine the regime of the various channel links.

Evans (1974) has shown that severe restrictions exist with the use of colour aerial photography due to its being badly affected by haze and exposure problems with sun angles of less than 30°. Consequently, good colour photographs are rare but in any case coverage is not yet widespread enough to be employed on any nationwide survey. Other types of colour aerial photographs such as infrared (Cantrell 1964) and false colour film (Lo, 1976) have been shown to detect channels containing water with great facility although their full potential has not yet been realised.

The edge-enhancement of radar images (McCoy 1971) is another technique for drainage network identification. This produces a measurable line pattern which appears to be strongly related to total length of streams in a basin. However, all these techniques are extremely costly and such data are not readily available. They are also generally available only on very small scales and have limitations inherent in their methodology. The infrared photographs detect water not specifically channels, and the radar images offer only generalised lengths of channels, not precise lengths. This makes both techniques unsuitable for network change analysis. For these various reasons and in view of the success of the map analysis it was decided not to utilise aerial photographs and radar images in network analysis.

6.3.2. Gully Cross-Section Analysis

At the outset of drainage network analysis it was thought that the gully played a far more important role than subequent findings have proved that it does. Examples where large-scale gullies (as opposed to those merely forming part of a peat erosion cycle) have been created and perpetuated as part of a perennial network, such as in the case of a tributary of the River Burn (Gregory & Park 1976), are comparatively rare, assuming that the available literature accurately reflects the true situation. Examination of the New Forest Gullies (Tuckfield, 1964) shows what appears to be a more common situation where gullies created in the past by specific or combinations of events are either perpetuated in the present landscape as relict features, or gradually disappear with time. This has happened to such an extent in the New Forest that several of the gullies described in 1964 are only just recognisable in the field today while the infilled and vegetated nature of others fails to allow them to be qualified even as relict channels. Most of the remaining sites categorise only as marginal ephemeral channels with only 'Gully B' as a definite ephemeral channel which may have contributed to the metamorphosis of a certain drainage link on Highland Water (Plate 4.1, Section 4.3.3.). Although this healing process may not necessarily be so marked in other areas, many gullies such as those described on Linghope Burn, Manor Water (Section 5.3.4.) do show certain relict qualities normally typified by stable vegetation cover.

6.3.3. Other Empirical Techniques

The two remaining empirical methods for the identification of network extension, namely the head-erosion of drains and the frequent survey of potential natural and artificial extension sites, form the basis of sections 6.4 and 7.1/7.2 respectively.

6.4 THE NEW FOREST INCLOSURES

The need for exact measurement of network change over a well-defined time period has been mentioned in Chapter 4. A suitable technique to provide quantifiable data would require the presence of some physical feature that restricted the stream network at a certain definable date. The location of this restriction must still be recognisable in the present-day landscape so that it can thus be used to measure how the extent of the stream network has changed over the intervening time period.

A technique fulfilling these requirements, which is not dependent upon map accuracy or surveyors' interpretation, is based on the measurement of stream-head extension over datable inclosure boundaries.
The coincidence of inclosure boundaries and the headwaters of a river system may be confined only to the New Forest area and therefore the technique is not necessarily capable of wider application. However, it does provide useful supporting evidence to map-based interpretations of network change within the New Forest area and also, since the time period is defined, it gives some idea of the rate at which the process of network extension by headward erosion can proceed.

It was the general practice, when constructing the New Forest Inclosures, to extend the existing network of streams to the inclosure boundary for drainage purposes, although in some cases the position of the boundary was determined to pass through the existing stream network. In addition new drains were introduced, at the time of inclosure, which also terminated at the inclosure boundary. It is possible to date these inclosure boundaries by reference to records held by the Forestry Commission, because the dates of the official Inclosure Acts for the New Forest are usually well before the actual construction of the inclosures. Because these boundaries were an important influence upon the limits of the stream network at the time of inclosure, as indeed testified by the First Edition 1:10560 map, this therefore provides a datum against which any subsequent extension of the stream network can be surveyed using the field survey definitions of flush and channels listed in Table 4.2. The use of these definitions is an attempt to maintain consistency between Ordnance Survey data and those of field survey enabling an exact amount of extension to be obtained over a defined time period.

Three New Forest Inclosures are suitable for this type of analysis. They are Slufters Inclosure, drained by the headwaters of Bratley Water, itself a tributary of the Lymington; Milkham Inclosure, drained by the headwaters of Linford Water; and Islands Thorns Inclosure, drained by Latchmore Brook. Both Linford Water and Latchmore Brook are tributaries of the Avon.

6.4.1. Slufters Inclosure

The original Inclosure Act for Slufters dates from as early as 1808 although the first land was not enclosed until some fifty years later when the western perimeter was enclosed and planted mainly with Scots Pine *(Pinus Sylvestris)* although some oak *(Quercus Robur)* also dates from this period. The eastern perimeter of the inclosure was planted some seven years later in 1869 and the inclosure boundary rampart is also contemporary with these perimeter plantings. The original rampart and boundary fence of Slufters Inclosure coincides with the modern boundaries and is thus well maintained permitting easy recognition of the limits of the original inclosure.

Field survey in 1978 indicated that drains, inserted within the inclosure at the time of construction and therefore terminating at the inclosure boundary, had extended their heads, in some cases quite substantially, into the uninclosed land the other side of the inclosure fence. Such field survey discriminated between flushes and well-defined channel extension, recognising some fifteen sites of channel developement, six possessing associated flush development. In addition two sites of flush development alone occurred, one associated with a nearby seepage step and the other with runoff from the disused Stoney Cross airfield complex. The location of these sites is given in Figure 6.2. The most recent 1:10560 Regular Edition map (surveyed 1961) provides supporting evidence for extension over the inclosure boundary at nine of these 15 sites (Figure 6.3). The other six sites therefore must represent recent metamorphosis of flushes (features which may not necessarily have been represented by the Ordnance Surveyors in the 1961 Survey) to well-defined stream channels. Details of the extension at each site may be found in Table 6.1, the letters corresponding with those in Figure 6.2.

The nature of this extension contrasts with the existing network, often forming a sharp angle with the original ditch and sometimes following the inclosure boundary for a short distance before becoming tangential. In the field the straight regular pattern of the inclosure ditches is easily distinguished from the meandering and irregular width and depth of any subsequent extensions. The differing amounts of extension at the various sites around the periphery of the inclosure have no easy explanation. The impressive lengths of extension at Sites G, H and I appear to be due, at least in part, to the presence of the A31 road which generates additional runoff. At all other locations the drains, located in depressions, appear to act as convergence points for overland flow.

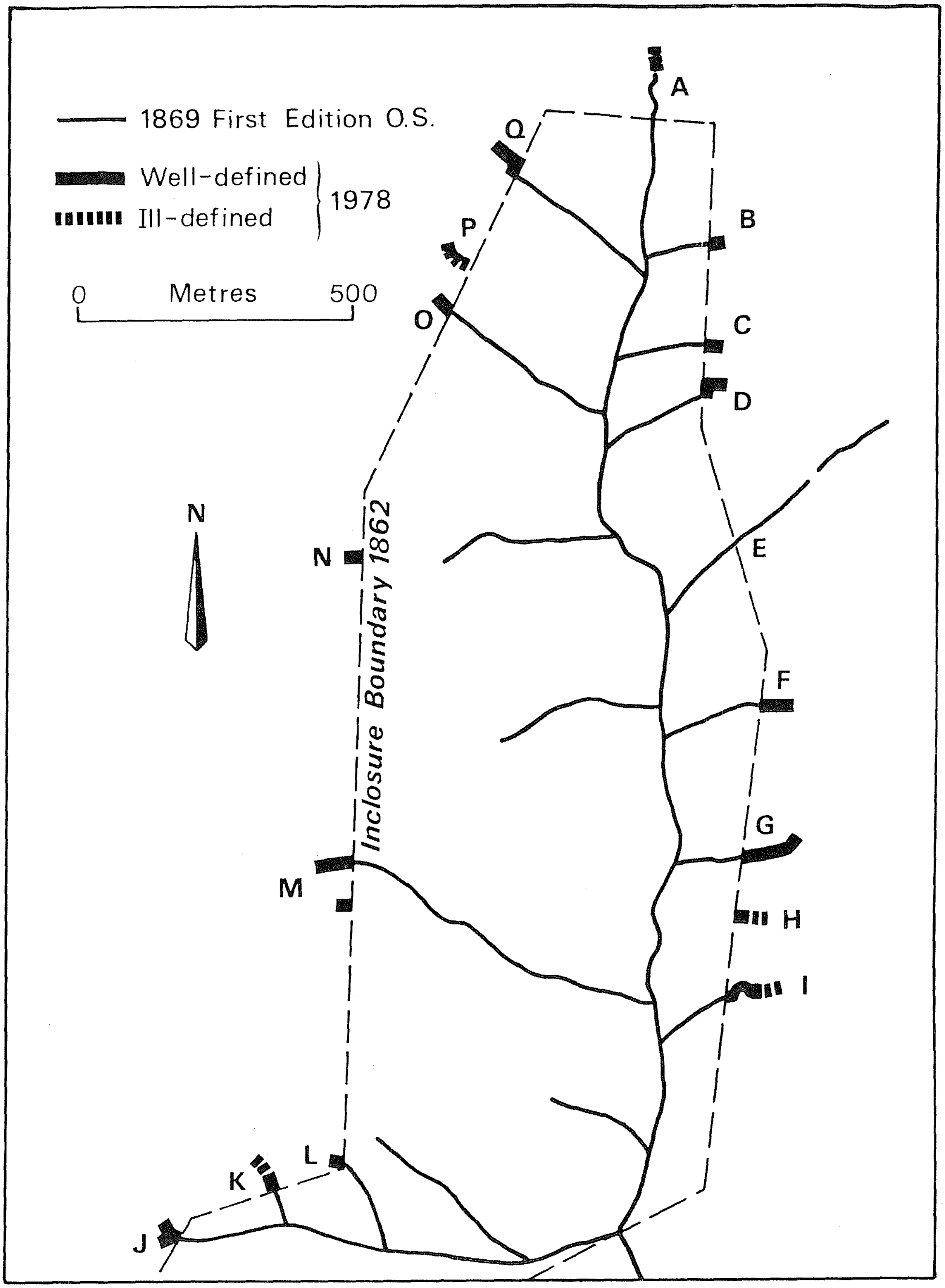


FIGURE 6.2 SLUFTERS INCLOSURE

(A) (B)

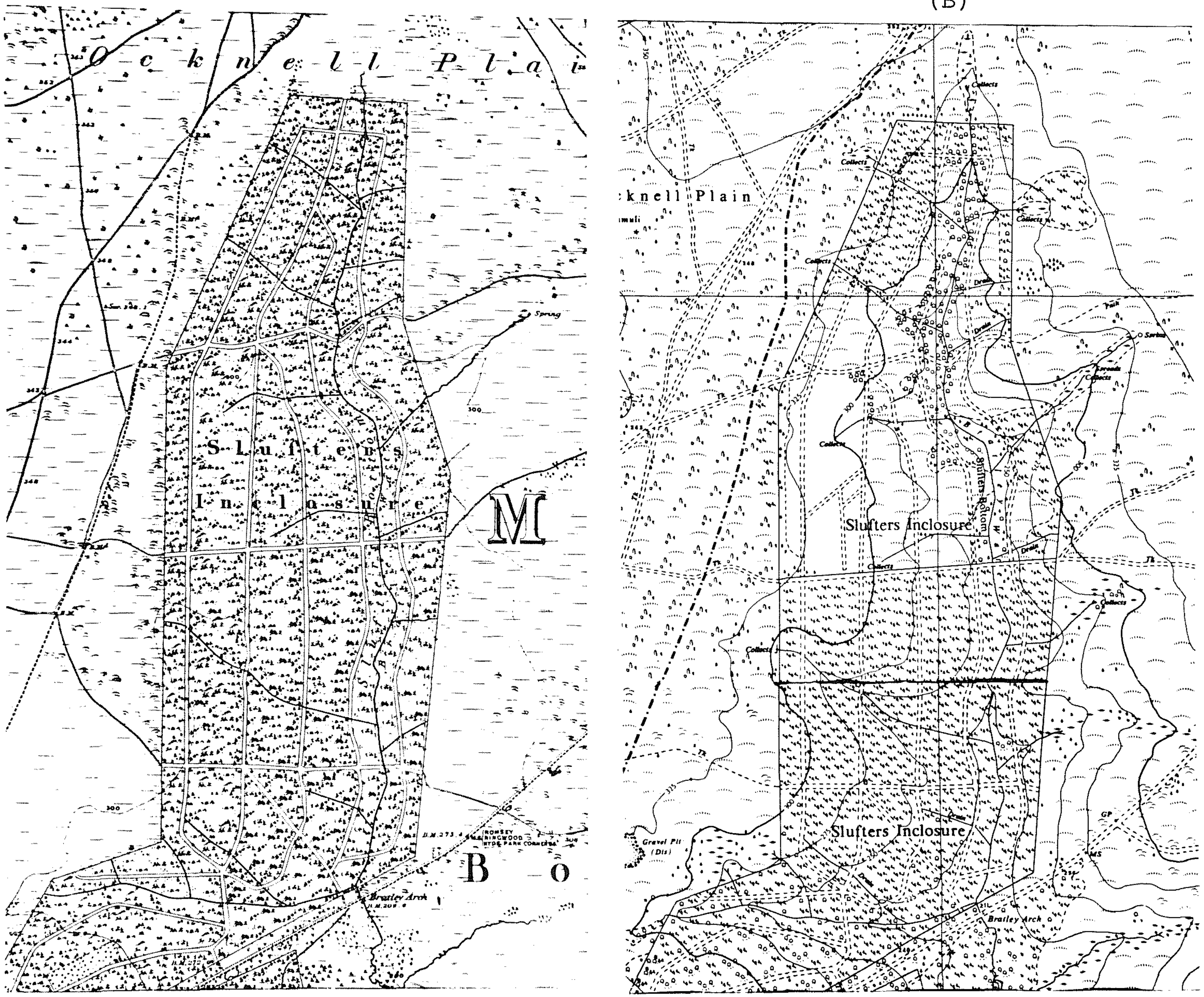


FIGURE 6.3 SLUFTERS INCLOSURE EDITION COMPARISON: (A) FIRST EDITION (1869) (B) REGULAR EDITION (1961)

SITE	EXTENSION DESCRIPTION	CHANNEL TYPE
A	Morphological evidence suggest no significant change in source location; some flush development.	Perennial
*B	11m of well-defined channel + flush/marsh.	Perennial
C	16m of ill-defined channel.	Perennial
D	20m of channel. Morphological evidence for recent water action though channel dry.	Intermittent
E	Stream regime intermittent above break representing network contraction	-
F	30m of well-defined channel: no flush	Intermittent
*G	15m of well-defined channel + 18m of ill-defined channel + flush: considerable extension.	Perennial
H	New channel is tangential to enclosure boundary ditch; some flush development	Intermittent
*I	55m of well-defined channel + considerable flush development	Perennial
*J	Extension initially along boundary fence then tangential. 5m of well-defined channel + 5m of flush.	Perennial
*K	14m of well-defined channel + 10m of flush	Perennial
*L	8m of well-defined channel from boundary fence.	Intermittent
M i	5m of ill-defined channel	Perennial
* ii	40m of extension initially along enclosure boundary. Some evidence of ditching.	Intermittent
N	8m of gully. Possible headward erosion of a drain not initially dug to enclosure boundary	Ephemeral
*O	15m of well-defined channel	Perennial
P	Ill-defined channel; source possibly a spring (due to raised water-table caused by road drainage).	Perennial
*Q	15m of well-defined channel + 10m of flush; extension initially following enclosure boundary (marked erosion).	Perennial

* Supporting map evidence (1960 revision)

TABLE 6.1 NETWORK EXTENSION OVER INCLOSURE BOUNDARIES

SLUFTERS INCLOSURE - BRATLEY WATER

This results in the creation of ill-defined channels representing the headward erosion of existing drains, the length of channel created reflecting the amount of available water.

Although Slufters Inclosure provides the best example of this type of analysis, both Milkham and Islands Thorns Inclosures show isolated examples of similar occurrences.

6.4.2. Milkham Inclosure

Work began on the inclosure at Milkham in 1861, the perimeter areas being largely planted with Scots Pine (*Pinus Sylvestris*). Like Slufters Inclosure, Milkham possesses a well-defined inclosure boundary comprising a fence situated on a hedge bank with a surrounding ditch. Three locations occur where the existing stream network was extended to the inclosure boundary at the time of inclosure construction (Figure 6.4). At the first location there has been no change in the perennial network although a short section of ephemeral channel exists with dead *sphagum* occurring over a further 20m indicating the presence of an intermittent flush. The second site demonstrates major network extension over the inclosure boundary in the form of 30m of well-defined channel and flush reaching to, and fed by, catch-drains from a minor road running around the head of the inclosure (Plate 6.1). So marked has been the extension at this site that an attempt has been made to arrest headward erosion of the well-defined perennial channel by the placement of logs perpendicularly across the stream. This has resulted in a significant headstep (Plate 6.2). The extension at Site 3 consists of a short section of new channel branching from the original drain. At the inclosure boundary an abrupt change of direction occurs with the channel following the boundary for 15m. Two short tributaries of some 10m length join this inclosure boundary ditch at right-angles. In addition the original drain to the inclosure boundary, duplicated by the new link, has assumed an intermittent/ephemeral nature. The close proximity of a forest track may well have caused

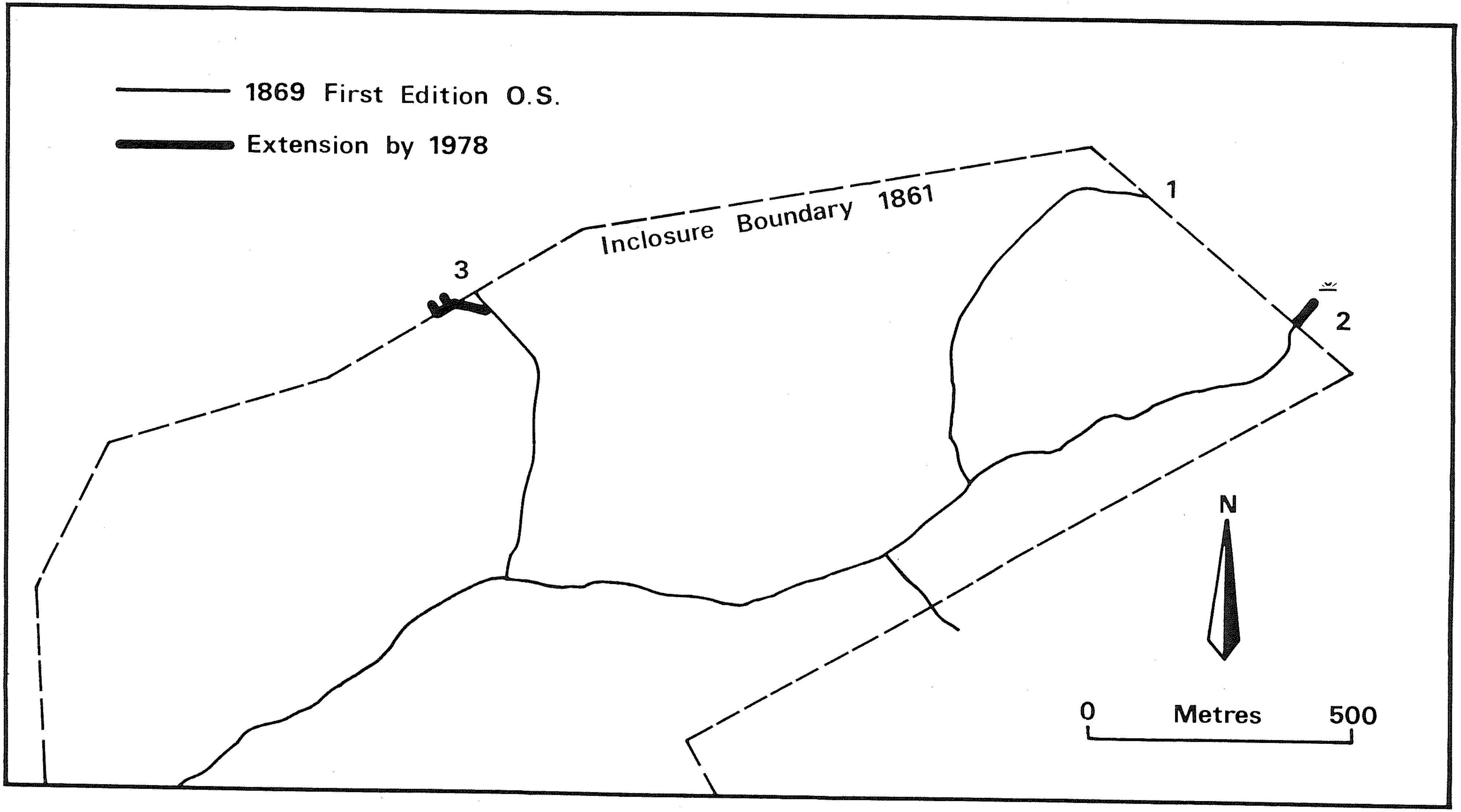


FIGURE 6.4 MILKHAM INCLOSURE

PLATE 6.1 MILKHAM INCLOSURE: EXTENSION OVER INCLOSURE BOUNDARY COMPRISING WELL-DEFINED CHANNEL AND FLUSH DEVELOPMENT (SITE 2).

PLATE 6.2 MILKHAM INCLOSURE: THE ACTIVE HEADWARD EROSION IS ILLUSTRATED IN THE PLACEMENT LOGS ACROSS THE STREAM IN AN ATTEMPT TO ARREST EROSION (SITE 2).

the initiation of this new channel.

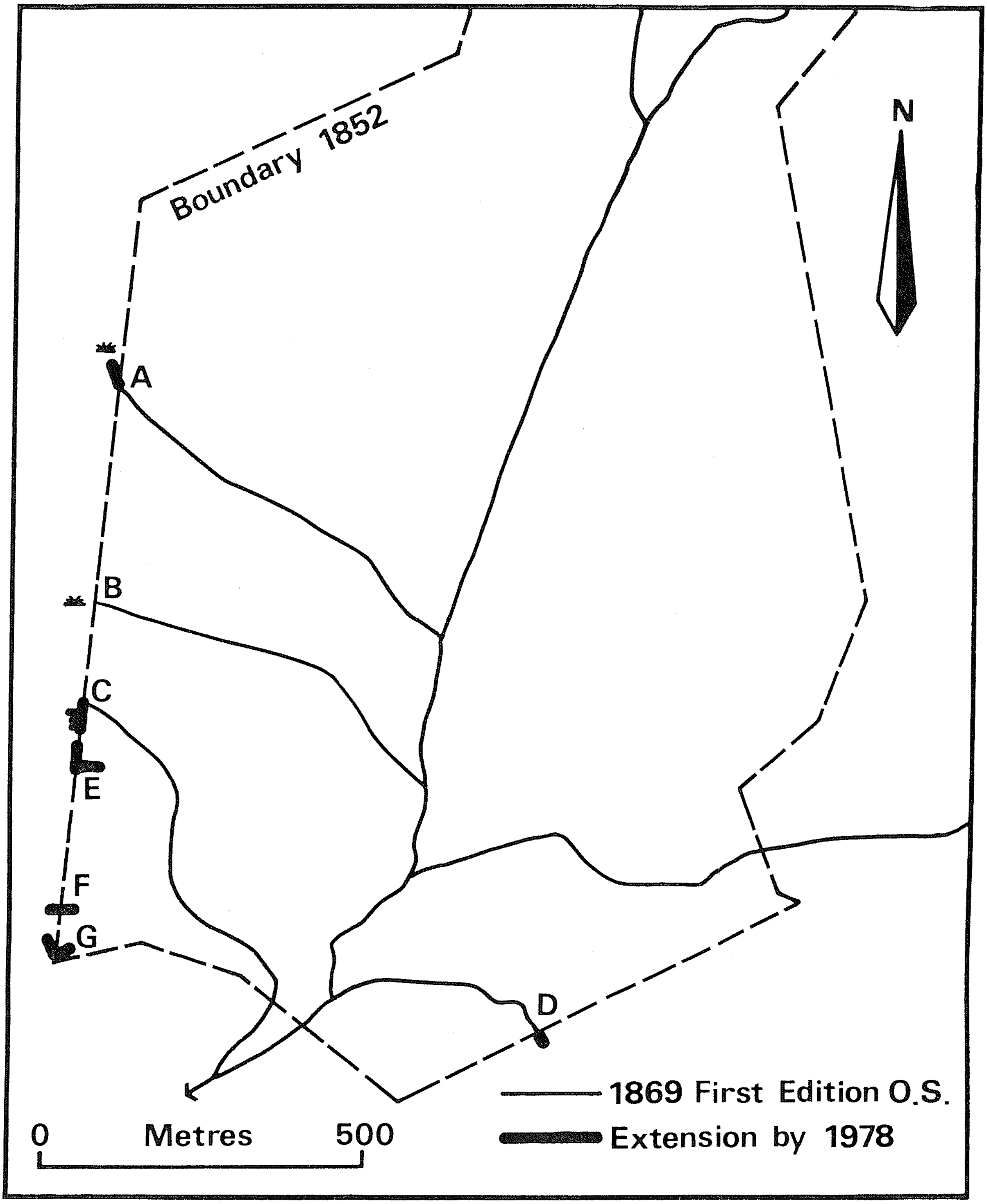
6.4.3. Islands Thorns Inclosure

Islands Thorns, constructed in 1852 and largely planted with oak *(Quercus Robur)* and Scots Pine *(Quercus Robur)* possesses an ill-defined inclosure boundary. Evidence of the former boundary is provided by a decayed ditch and rampart with the occasional fence-post, located some way from the apparent boundary edge of the present day inclosure. Four potential sites exist where streams terminated at the original inclosure boundary at the time of inclosure (Figure 6.5), Site D demonstrating the most impressive extension with some 10m of well-defined channel. Site A comprises 5m of new channel across the inclosure boundary and a 50m length of flush which possesses a considerable surface flow. Site B demonstrates no change over the 120-year period, while Site C demonstrates perennial extension along the inclosure boundary with considerable erosion of the boundary ditch. Several marginal channel/flush features, which rise at the foot of a seepage step, feed this stream.

In addition to these sites there exists three examples of additional perennial channel and flush development around the periphery of the inclosure (Sites E, F and G). These sites may well be associated with more recent ditching connecting with the main drainage network, but confirmation of this was impossible due to dense vegetation in a rather ill-maintained area of the forest.

6.5. SUMMARY

The contents of this chapter have been essentially an appraisal of various alternative techniques and data sources for the analysis of drainage networks. These divide conveniently into historical and empirical categories. The early part of the chapter supports by default the large scale maps of the Ordnance Survey as an important and unrivalled source of data for historical analysis of changes in drainage network extent. The



6.5 ISLANDS THORNS INCLOSURE

MEDIA OR METHOD	COVERAGE	SCALE	ACCURACY OF NETWORK DEPICTED	RATING FOR NETWORK CHANGE IDENTIFICATION
Landowner Perception.	Specific Sites.	-	Subjective.	Useful only as supporting evidence to information procured more scientifically.
Travellers Notes.	Low.	-	Impossible to standardise.	No use in Britian.
Newspapers.	Major events only.	-	Subjective.	Useful only as supporting information.
Ordnance Survey Large-Scale Maps.	Complete.	1:10560/ 1:2500.	High.	Excellent data source for drainage change.
Tithe Maps.	Cultivated areas of England and Wales.	3 or 6 chains to the inch.	Varies within tithe sheets.	Low.
Estate Maps, Deeds + Record Documents.	Specific sites.	Various.	Varies.	Useful as supplement to O.S. data for specific drainage link studies.
Surveyors Notebooks.	None.	-	-	
Aerial Photographs (B + W).	Complete.	Various.	Impossible to standardise.	Low.
Infrared + Radar Imagery.	Incomplete.	Small.	Impossible to standardise.	Low.
Gully Cross Profile Analysis.	Specific sites.	Field Investigation	High.	Feasible technique but of limited use.
Head Erosion of Drains.	Specific sites.	Field Investigation	High.	Useful though of limited applicability.
Site Surveys.	Specific sites.	Field Investigation	High.	High usefulness if sites are representative of types of change.

TABLE 6.2 USEFULNESS OF SOURCES AND TECHNIQUES IN THE IDENTIFICATION OF NETWORK CHANGE IN BRITAIN

tithe maps, the estate maps and other record documents are of little use due to the restricted areas considered.

The head erosion of drains, and repeated survey of natural and man-induced areas of change are useful empirical techniques that provide alternative evidence to maps of the Ordnance Survey in detecting overall extension to drainage networks over various time scales. Slufters, Milkham and Islands Thorns Inclosures have been shown to contain several examples of the head erosion of drains over inclosure boundaries. Repeated surveys have been indertaken at sites in the New Forest and at Plynlimon, Central Wales and the evidence from these experimental sites forms much of Chapter 7.

Aerial photographic interpretation and gully cross-profile re-measurement, after examination, were not considered useful techniques for drainage network change analysis. These conclusions are summarised in tabular form (Table 6.2).

CHAPTER 7 SITE EVIDENCE FOR DRAINAGE NETWORK CHANGE

An evaluation of empirical sources for data pertaining to network change was made in Chapter 6 concluding that detailed analysis, in the form of the re-survey of channel cross-sections at select sites, would be feasible and could provide valuable additional evidence for the occurrence of network change in Britain. Two such sites were considered for the purposes of this study; the first, the initiation of a man-induced drainage link connecting with Highland Water in the New Forest, Hampshire; the second, the natural extension of existing drainage links by flush metamorphosis occurring in the Institute of Hydrology's experimental catchment in the headwaters of the River Wye, Plynlimon, Central Wales.

The evidence of field survey, presented in Chapter 5, showed that these sites were representative of the major categories of network change in Britain. Chapter 5 also defined methods by which network change could occur and the forms that it may adopt. It was hoped that a detailed survey of particular sites would complement these findings by giving some idea of the rate at which new channels can be created and absorbed into the intermittent or perennial network.

Highland Water is the subject of Section 7.1, while the sites in the Upper Wye Basin are considered in Section 7.2. In Section 7.3 a case study is presented of the impact on the drainage network of a concentrated area of human activity, namely the wartime airfield at Stoney Cross in the New Forest, Hampshire.

7.1 HIGHLAND WATER SITE

During the course of field survey within the basin of Highland Water a major category of network change within the catchment was found to be the result of drainage from the A31 Minstead-Bratley trunk road. Much of the extension occurring since the last survey of the basin by the Ordnance Survey in 1961/5 was observed to be due to recent upgrading of the section in question to dual-carriageway status (Section 4.3.3). Many ephemeral drainage links, gullies and intermittent road drains were shown to be due to this road improvement scheme, (Section 4.3.3) but there is one major site of perennial channel initiation (Site 10; Figure 4.3). It is with this single site that this section is concerned because it demonstrates the inception of new drainage links due to the indiscriminate disposal of runoff from highway engineering.

7.1.1. Site Description

Cartographic evidence, over the period 1869 to 1961/5, demonstrates the consistency of length of this particular drainage link which is situated immediately south of the A31 road and represents the first tributary below the road crossing of Highland Water. Consequently, the considerable extension to the drainage network since the last survey implies the presence of a 'trigger' mechanism which has already been confirmed by field survey to be the recent road improvement activities.

This site has been monitored since October 1977 when it was first realised that the engineering contractors intended to dispose of surface runoff into the heads of a series of linear depressions which lead eventually into a channel before joining the Highland Water. During the remainder of 1977 and the first half of 1978 the original road was reprofiled, resurfaced and installed with a new drainage system to form the westbound carriageway, while a new eastbound carriageway was constructed. A system of drains from both carriageways conducts water falling on the impervious surface into the heads of these linear depressions. The water is distributed into the headwater forks of the main flush (as the linear depressions have now become) by five outlet pipes, four on the western fork and one on the eastern. No evidence of a pipe exists on the remaining exterior link, the flow here probably being the result of seepage. The detailed position of these outlet pipes together with the extension of the drainage link are given in Figure 7.1.

The road improvement scheme and associated drainage

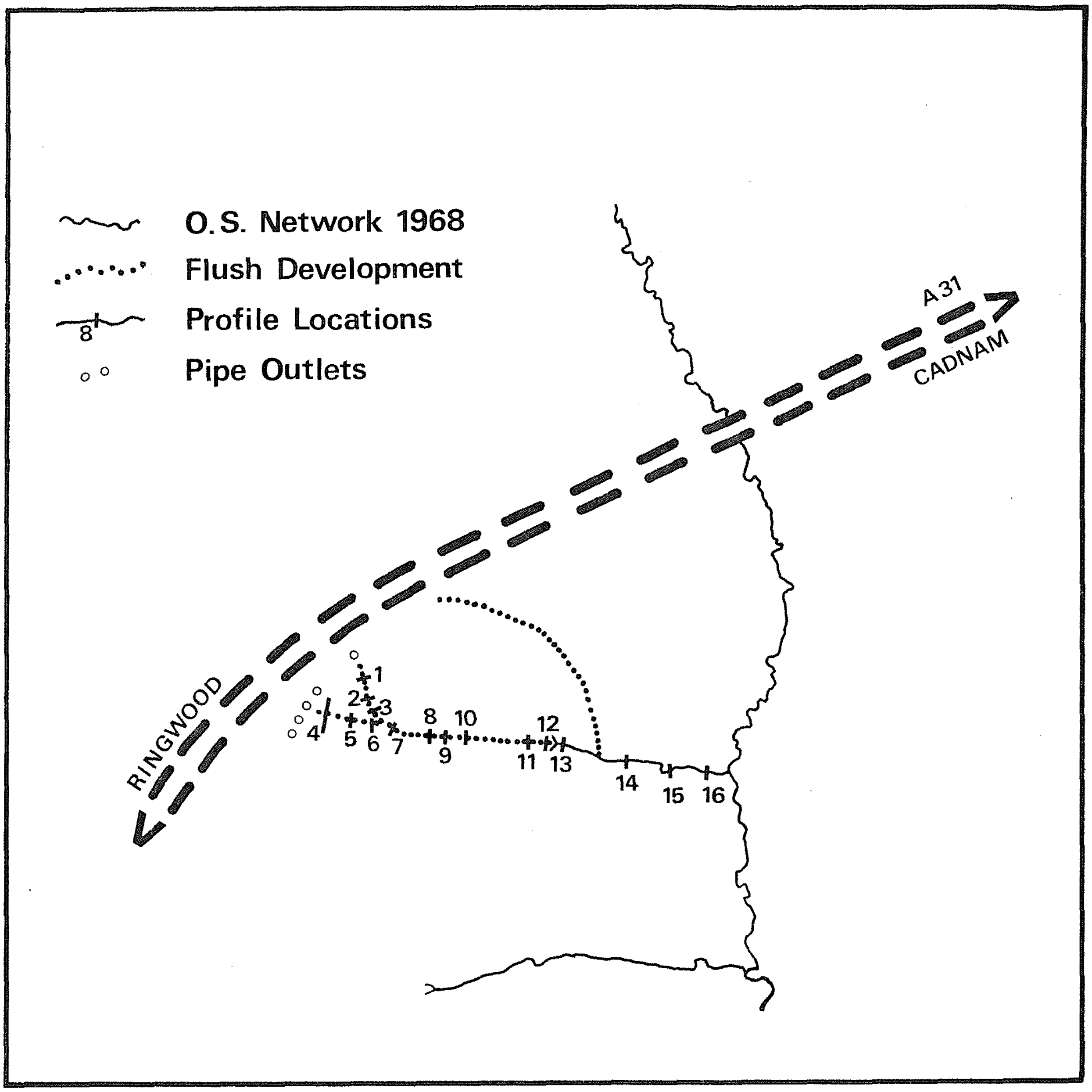


FIGURE 7.1 HIGHLAND WATER FIELD SITE

work does not alter the drainage area of this particular network link (0.358km^2) but it does create 0.008km^2 of impervious area which leads to the rapid and efficient disposal of water into the channel network. The construction of the two carriageways alone results in 2.23% of the catchment area becoming impervious.

The positions of sixteen cross-profiles were fixed in December 1977 by the use of wooden pegs and the first survey of these cross sections was completed by early February 1978. Heights were obtained from a quickset level but horizontal distances were taken from a tape stretched across the profile because this was considered to be more accurate than tachometry for such detailed work. Three profiles were situated on each of the forks of the main flush with a further six on the section from the fork to the most headward point of the original Ordnance Survey location of the stream source. The remaining four profiles were located on the existing stream to determine whether any discernible change in channel cross-section occurred as a result of the new lengths of channel and associated increase in discharge. Originally it was intended to re-survey these sixteen profiles every three months but is was soon realised that insufficient change, excepting vegetational variations, occurred between surveys to justify this interval. Even a survey of selected profiles some twelve months after the original survey still revealed very little change apparent from a comparison of the cross-profiles alone, and it was decided to re-survey after 21 months, the longest time interval available for thesis purposes. This also meant that the seasonal state of the vegetative cover would be similar for both surveys, thus there would be the least possible error due to growth and vegetation dieback. The survey data were punched and analysed by a 'Calcomp' routine which produced the profile comparisons found in this chapter.

The detail of the two surveys varies to some extent, the early survey in general being more detailed, mainly because with the diffused flow at the time of the first survey any one of several 'water tracks' could become the dominant one and therefore every possible channel path needed careful survey. By the time of the later survey the dominant channel had established itself and therefore only the area immediately around the channel required detail survey; only the major breaks of slope were documented for the rest of the profile.

7.1.2. Results from Re-Surveys

The channels demonstrate very little morphological change immediately evident from the profile comparisons because gullying of the flush had not occurred during the 21 months of monitoring although this looks a distinct possibility in the immediate future, given a storm of sufficient intensity.

The changes on both the eastern and western head flushes (Profiles 1 to 6 inclusive) are largely accounted for by the destruction of *molinia* tussocks which previously prompted the diffusion of flow over the base of the flushes. This has resulted in a concentration of flow along the thalweg of the flush. Profiles 2, 3 and 5 (Figure 7.2) are representative of this type of change. Below the confluence of the flushes, Profiles 7, 8 and 9 also demonstrate the degradation of *molinia* tussocks but this is confined to areas towards the edges of the profile, because a striking stability of the wetted perimeter is apparent over the survey period. Examples of this type of change are provided by Profiles 7 and 8 (Figure 7.2). At Profile 10 the removal of *molinia* tussocks occurs actually within the channel causing a decrease in channel roughness. This removal of tussocks has also resulted in an overall shallowing of the channel (Figure 7.3). However, Plates 7.1 and 7.2 clearly demonstrate the vegetational changes that have accompanied the gradual establishment of a well-defined channel where formerly only flush existed.

The profiles across the most incised section of the flush (Profiles 11, 12 and 13) were still characterised by diffused flow at the time of the second survey. Sites 11 and 12 are located approximately at the origins of the source prior to road improvements (mapped by the Ordnance Survey in 1961/5) where the vegetation, characteristic of

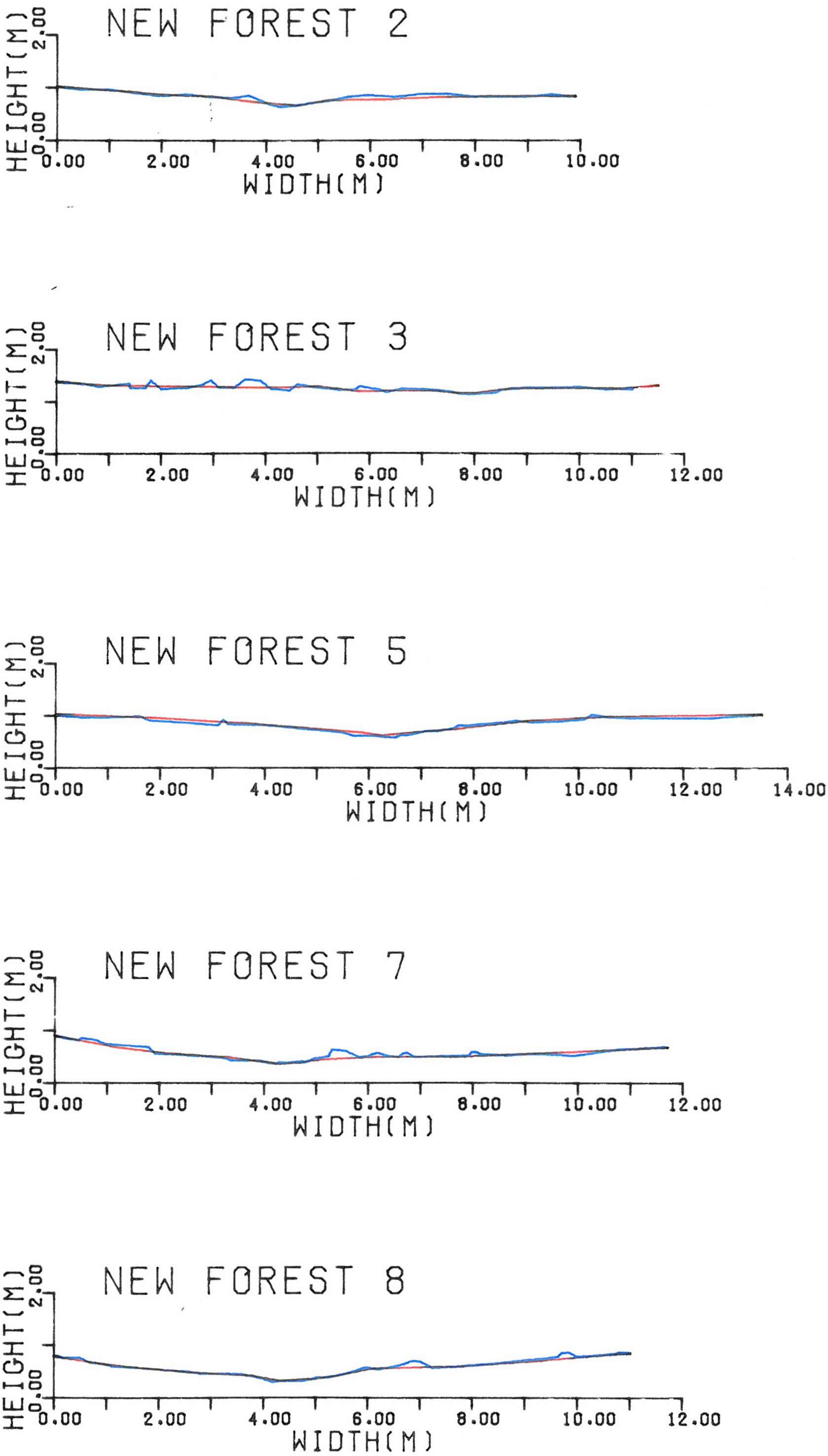


FIGURE 7.2 HIGHLAND WATER PROFILE COMPARISONS

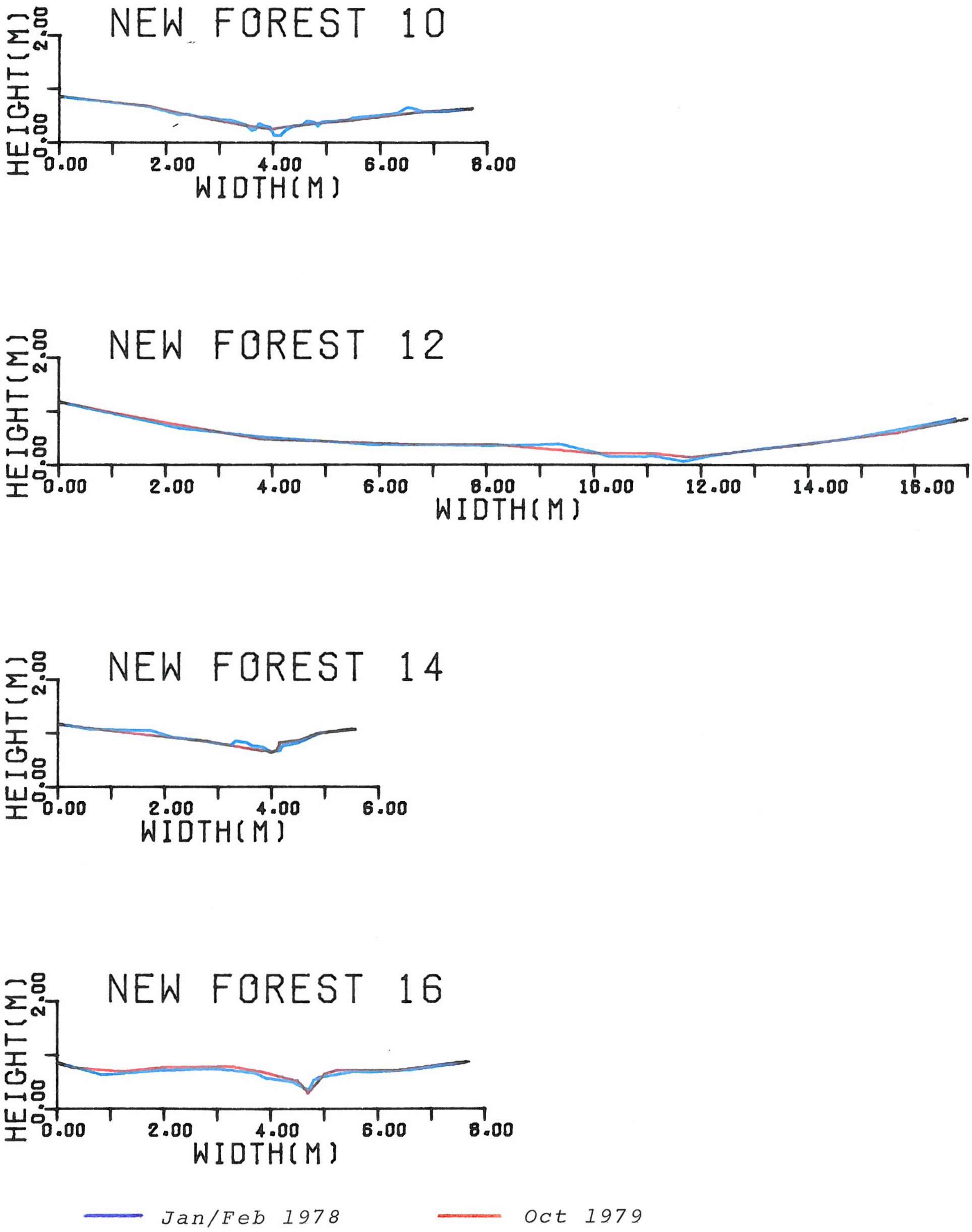


FIGURE 7.3 HIGHLAND WATER PROFILE COMPARISONS

PLATE 7.1 HIGHLAND WATER: PROFILE 10 (JANUARY 1978)
N.B. Presence of *juncus* characteristic of flushes.

PLATE 7.2 HIGHLAND WATER: PROFILE 10 (JANUARY 1979)
N.B. Clearer emergence of well-defined channel, eradication of some within-channel vegetation and virtual disappearance of *juncus*.

such a source area, may have prevented any rapid morphological change such as has occurred higher up the flush. Even at these profile locations there is some evidence of the beginnings of the destruction of *molinia* tussocks resulting in a general smoothing of the profiles. Profile 12 occurs immediately above a significant headstep indicating active erosion, but this had not migrated upstream during the period of survey. Profile 12 is illustrative of this section of the flush (Figure 7.3).

The three profiles located on the existing well-established channel (Profiles 14, 15 and 16) show little change. Site 14 demonstrates the removal of *molinia* tussocks while Profile 15 shows a general shallowing of the channel presumably reflecting vegetational growth within the channel itself. The final profile (Site 16) is the only location to show any real incision of the stream over the survey period and this is complemented by a raising of bank levels on either side of the channel (Figure 7.3). This may represent a rapid growth of vegetation on the banks adjacent to the channel where the greatest concentration of nutrients occurs.

7.1.3. Summary and Provisional Model for Drainage Component Progression in Lowland Basins

The field site on Highland Water demonstrates the rapid metamorphosis over a period of 21 months of a former linear depression (with some areas of marsh towards its lower extremities) to a channel, due largely to increased inputs of water as a result of road drainage disposal. The dry depressions observed in the summer of 1977 have been transformed to sections of well and ill-defined channel. This concentration of flow has been reflected in vegetation changes in the form of the removal of *molinia* tussocks from within the channel zone and in the upslope migration of heather species away from the wetter areas.

A sequence for stream development as observed in the study of this particular drainage link is presented in Figure 7.4 together with idealised profiles

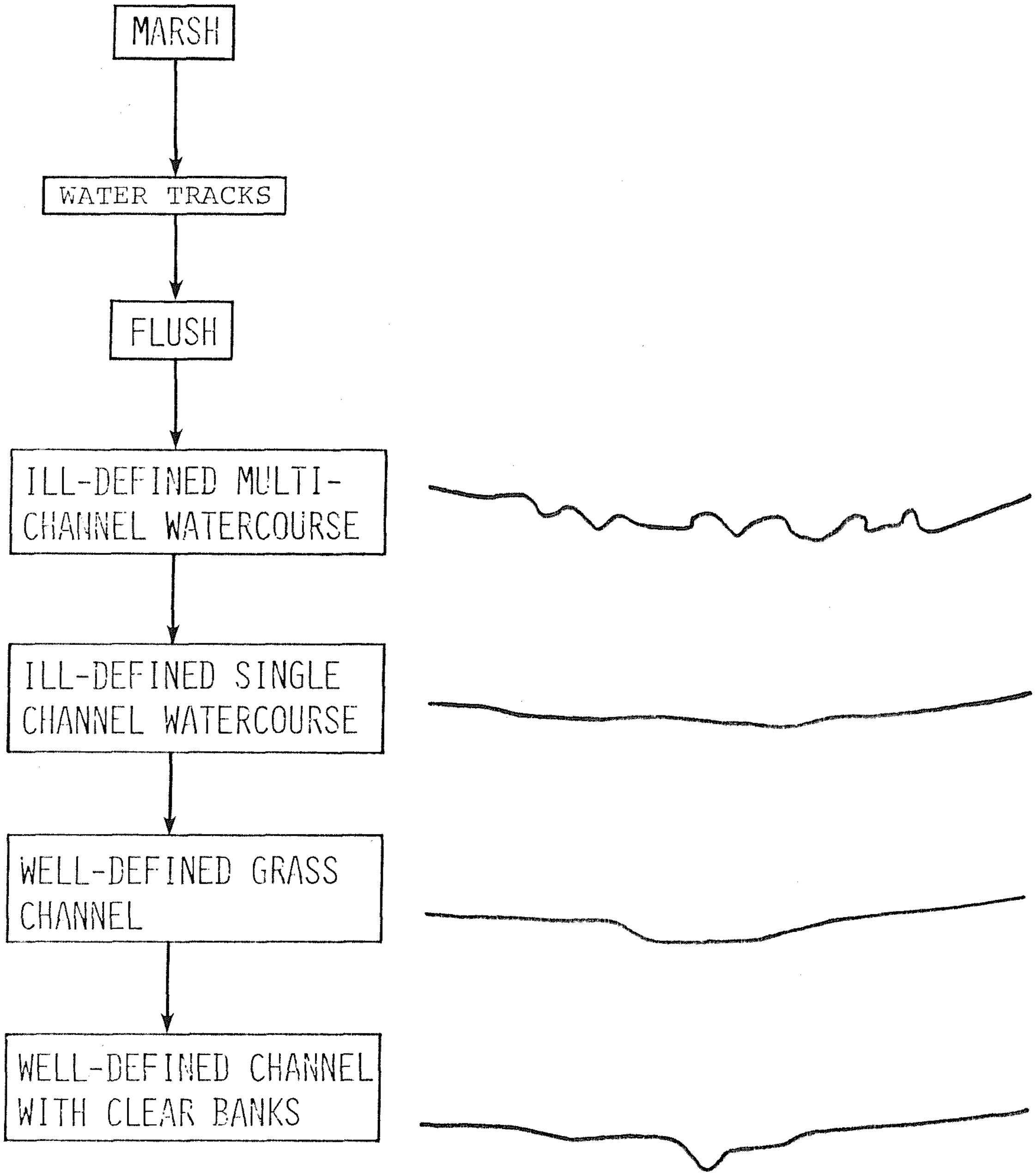


FIGURE 7.4 SUGGESTED SEQUENCE FOR STREAM DEVELOPMENT IN LOWLAND CATCHMENTS

representing each stage of the development. Its applicability to areas outside the New Forest has yet to be confirmed, but all the suggested categories of streams will be recognised by those familiar with the Forest's rivers.

The Highland Water study has shown how the creation of small impervious areas can contribute enough water to create drainage links initially and then modify them, with a resulting increase in efficiency, thus highlighting the rapidity with which change to the drainage network can occur, as a result of the direct influence of man. Gregory and Park (1976) demonstrated the effect on a component of the drainage network caused by the metalling of a short stretch of road with the gullying of a particular link in the catchment of a tributary of the River Burn (0.55km^2). In another study, Gregory (1974), the creation of an impervious surface over 12.4% of a small catchment (0.26km^2) on the N.E. Margine of Exeter resulted in the doubling of peak discharge, a reduction of lag time to half its former value and increased percentage runoff by at least 0.9%. The downstream implications of such modified hydrographs, caused by the more efficient transport of water away from the basin, requires that the effects of the disposal of storm water runoff from such sites should be carefully scrutinised in future research.

7.2 EXPERIMENTAL SITES OF NETWORK EXTENSION IN THE WYE CATCHMENT, PLYNLIMON.

7.2.1. General Hydro-Geomorphology of Plynlimon

The Wye catchment upstream of Cefn Brwyn, and under the auspicies of the Institute of Hydrology, is one of the few sites in Britain where extension of the drainage network has been documented (Newson 1975). This was in connection with the metamorphosis of a length of flush (with associated perennial pipes) to a perennial channel during the course of a single storm occurring during the night of 5th/6th August 1973 when in excess of 70mm. of rain fell during a six hour spell between 2300 on the 5th and 0500 on the 6th (G.M.T.).

Gilman (1972) has demonstrated that an important component of the drainage network in the Wye catchment is the perennial pipes which he discovered flowing beneath the peat-filled flushes. The importance of pipes as a component of the drainage network had been recognised by Jones (1971) who stated in an important paper on piping that

> *'piping has been associated primarily with drylands yet evidence of piping is available from a large range of climatic regions. In particular, soil piping is found to be widespread in the United Kingdom'*

From a study of a number of areas in England and Wales Jones also observed that

> *'many pipes in areas studied appear to be dormant or relatively inactive and may well be in approximate equilibrium with the soil pore and channel subsystem. However when equilibrium is destroyed (e.g. by stream incision) pipes can form loci for channel extension.'*

This extract identifies one of the few suggested causes for network extension in Britain and in fact Plynlimon is cited as one of the study areas. Relevant background to the understanding of the Plynlimon flush sites includes the observations that piping associated with water sources such as percolines will have a better chance of development, and that piping should increase both the likelihood of drainage network extension and the rate at which it occurs.

A combination of perennial pipes with the tendency of peat to glide downslope, first commented upon by Troll (1944), may be a major factor governing the extension of drainage networks in Upland Britain for reasons that will become clearer below. Writing about the Wye catchment, Newson (1975), observed that the long profiles of flushes and the numerous tears and potholes through the peat to pipes below, suggest that the peat infill of these flushes is moving down bedrock gullies particularly during flood events. Ample evidence of this is seen in the field on Plynlimon in the multitude of cracks and tears in the peat at the periphery of the flushes.

Evidence of similar movement of peat downslope in flushes has been observed on Muckle Moss in Northern England (Moore & Bellamy 1974) where a forest fence that crossed a flush bowed and eventually fractured. The measured rate of movement downslope in the centre of the flush was of the order of 5cm. per annum. The result of such downslope movement is that frequently the courses of the perennial pipes within the peat mass are blocked, or at least restricted, causing a proportion of the discharge during severe storms to surface from the pipes for short distances. Such build-up of water pressure during extreme rainfall, particularly when the peat has been weakened by shrinkage and cracking after a dry spell, may cause a complete rupturing of the peat resulting in the peat infill sliding in huge sections down to the valley bottom. It is such an occurrence that is described by Newson (1975) when during a storm in August 1973 the creation of some 30m. of new channel occurred on the Cerrig-yr-Wyn Flush replacing what was formerly a perennial pipe. In this particular burst the important variable may have been an old mining leat which provided additional water to the flush, creating a line of weakness along which failure subsequently occurred.

7.2.2. Choice of Site and Site Details

A growing acquaintance with the Institute of Hydrology's Plynlimon Catchment during 1976 and 1977 revealed the occurrence of many similar sites to the Cerrig-yr-Wyn Flush within the headwater areas of the River Wye which may behave in a similar fashion to the documented flush. This was confirmed by Newson (1980) in his general comments on the effect of the 1975/76 drought over large areas of the Wye Catchment where peaty flushes cracked and their bog vegetation was killed, resulting in increased potential for catastrophic channel extension as a result of heavy rainfall. Consequently the opportunity was taken to monitor sample sites although, because of the thesis timetable, only a fifteen-month period was available for observations. The location of these sites in the context of the Institute's experimental catchment is given in Figure 7.5.

Site A, the most interesting and important of the three sites, is situated on the southernmost headwater

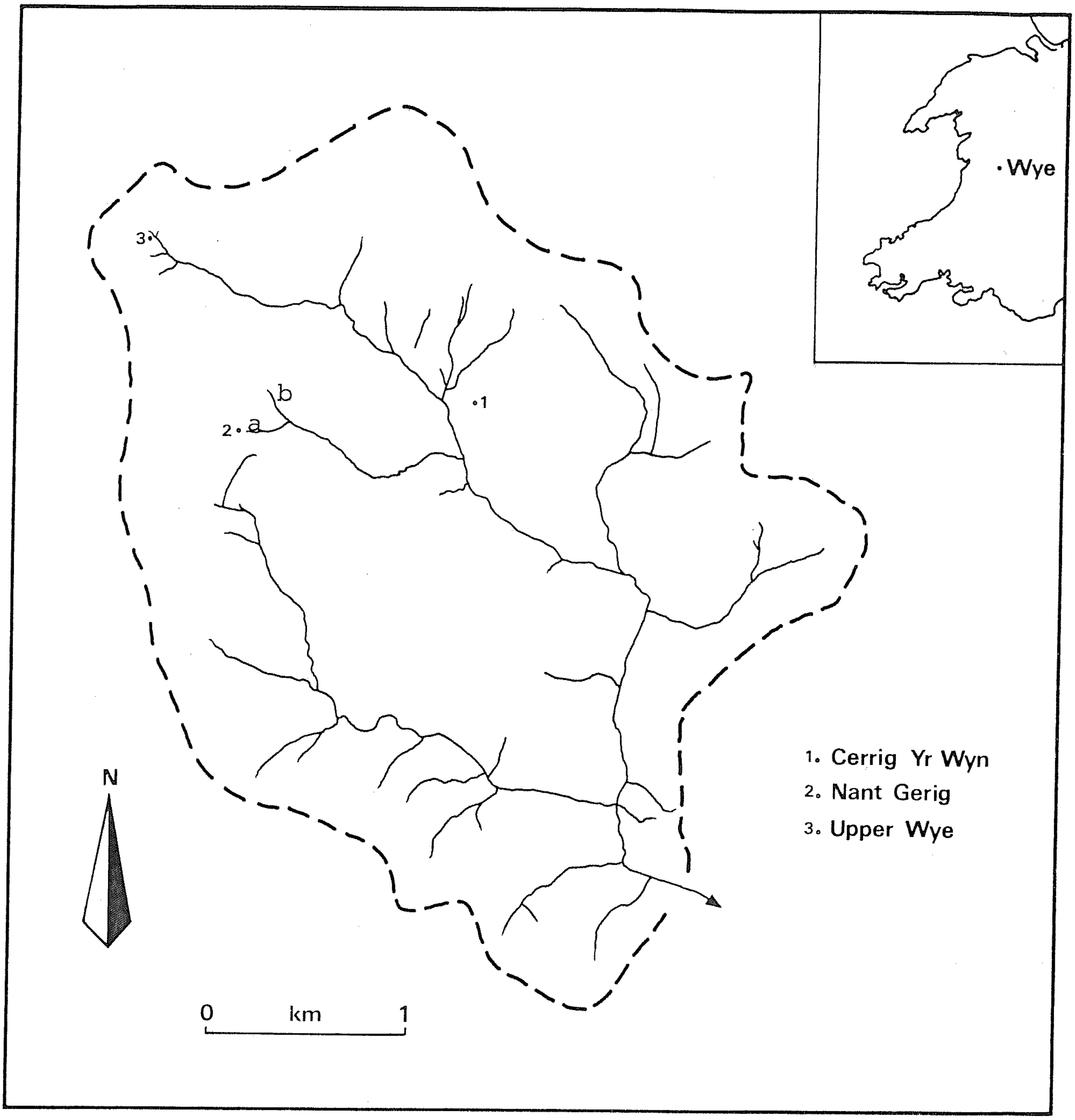


FIGURE 7.5 THE LOCATIONS OF THE PLYNLIMON FIELDSITES AND THE CERRIG-YR-WYN FLUSH WITHIN THE WYE CATCHMENT.

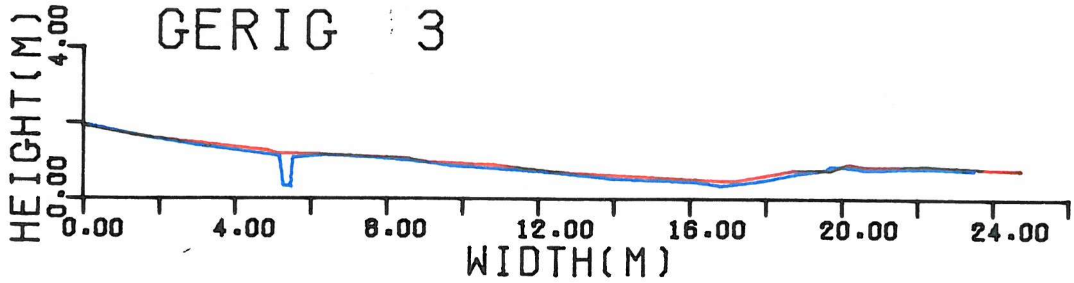
tributary of the Nant Gerig Stream. Ten cross-profiles were located across this flush because it appeared to be in an advanced state of development as far as metamorphosis to a stream channel was concerned, and therefore there seemed to be a reasonable chance that some change may occur within the eighteen months available for monitoring. Seven profiles were located at 5m. intervals from the beginnings of the stream at the base of the feature upwards to the scars and tears marking the top of the flush, with a further three profiles positioned at 10m. intervals above the flush. The flush itself is well delimited in morphological terms with clear lateral boundaries marked by cracking and collapsing of the peat surface, but there is also a clear vegetational zone marking the flush which is dominated by *juncus* (Plate 7.3). All over the flush, sections of pipe-roof collapse and tears reveal the presence of substantial perennial pipes below the surface, all the evidence pointing towards some form of downslope movement of the peat mass. With this downslope movement in mind rows of pegs were set up across the flush at several profile sites to try to determine rates of movement of the peat, but no discernible surface movement occurred between April 1978 and October 1979.

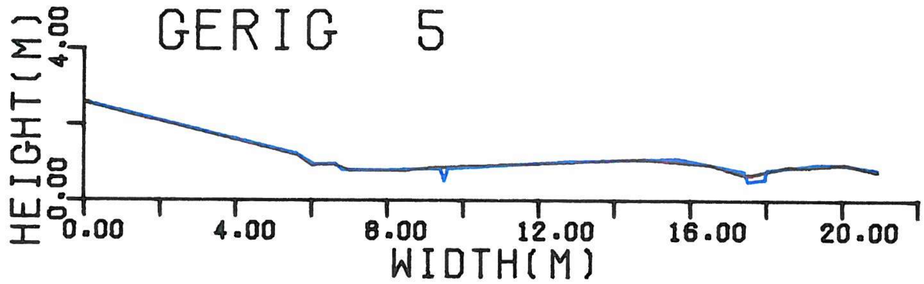
Although catastrophic failure, similar to that of the Cerrig-yr-Wyn Flush, has not yet occurred at Site A during the period of monitoring, there are small but significant changes evident from comparisons of the two surveys. Sites 2, 4, 8 and 10 show little change occurring over the period of survey, a general observation applicable to most of the profile sites with the possible exception of Site 1. However Sites 3, 5 and 7 (Figure 7.6) do show the healing or, more specifically, the closing of cavities formed in the peat mass by the collapse of sections of the underground pipe network. Profile 6 (Figure 7.7) demonstrates the inception of a new section of pipe collapse while Profile 9 (Figure 7.7) shows the infill that has occurred to a particularly deep cavity formed by pipe collapse over the 15 months of monitoring.

All these profiles demonstrate slight inflections in the general levels of the peat mass indicative of either internal movements within the peat or a possible gradual

PLATE 7.3 NANT GERIG FLUSH

Note the *juncus* domination and the defined boundary between flush and channel.





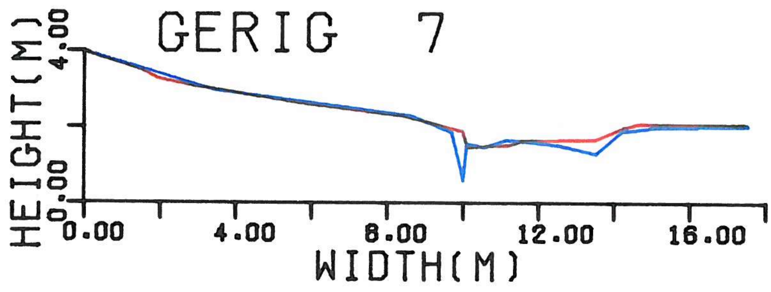


FIGURE 7.6 NANT GERIG PROFILE COMPARISONS

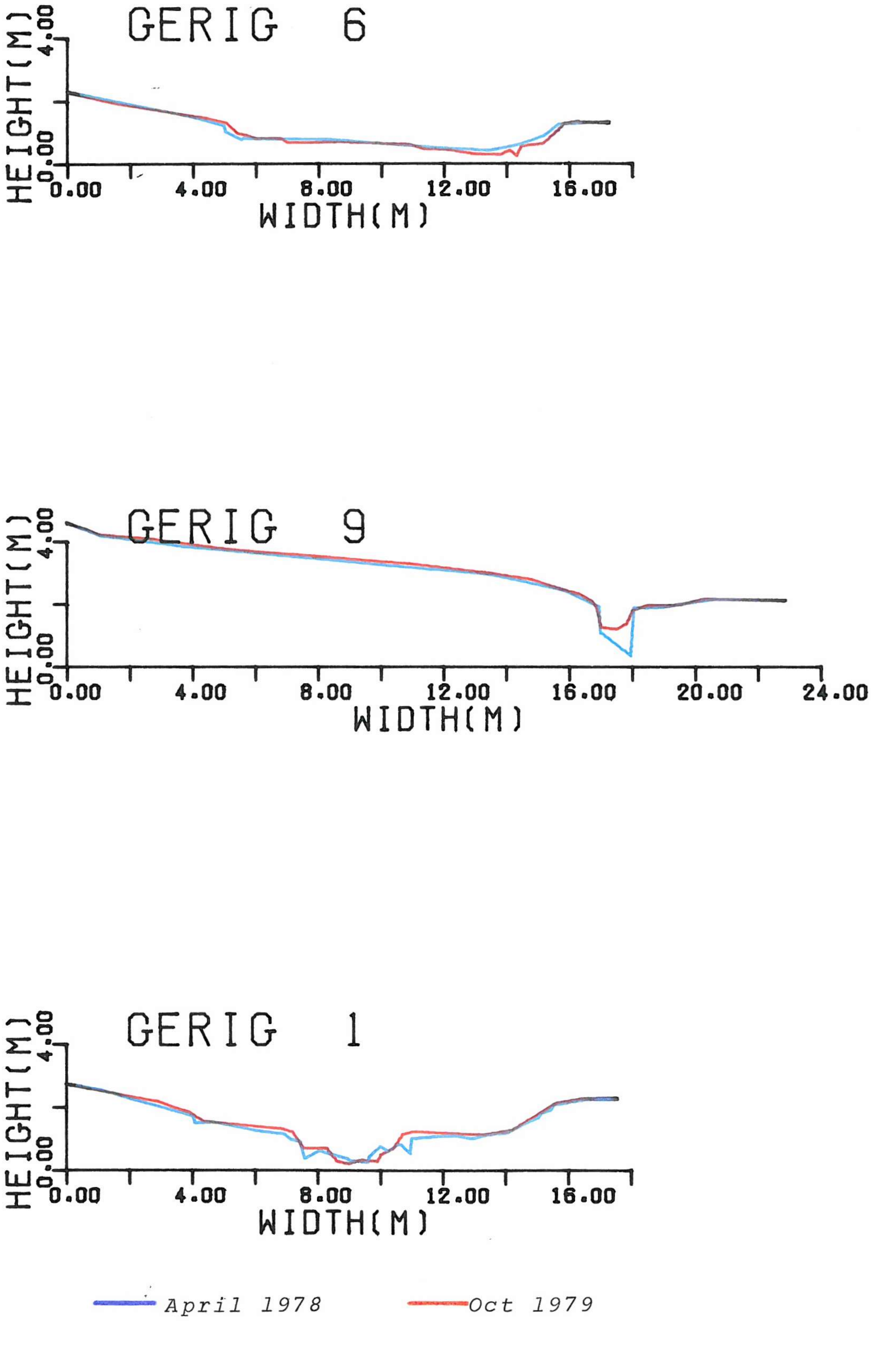


FIGURE 7.7 NANT GERIG PROFILE COMPARISONS

movement of the whole mass downslope. This possible downslope movement would seem to be confirmed by the significant changes that have occurred at Profile 1 situated at the base of the flush, and at the source of the drainage link and therefore in a position to suffer most from downslope movement. Although the basic structure of the profile remains unaltered there have been significant morphological changes particularly towards the centre of the feature, including the closure of cavities formed by pipe collapse (Figure 7.7).

Site B is also situated on the Nant Gerig but on a different headwater tributary. The collapse of pipe roofs and the tearing and fracturing of the peat around the periphery of the feature were not as advanced on this flush as on that at Site A, although once again substantial flow was occurring from the perennial pipe outflow at the base of the feature. Six profiles were located across the flush and were surveyed in May 1978. Field inspection in October 1979 revealed that the flush had changed but not by the expected method. Morphologically, the feature was unchanged from the May 1978 survey but there had been a significant increase in the amount and density of the vegetative cover. This resulted in the flush assuming a more stable appearance an anomaly that can be explained by brief examination of the implications within the term 'flush'.

By definition, a flush is a location of a concentrated linear zone of nutrients, and if therefore no catastrophic failure of the feature occurs, the nutrient zone results in a lush vegetational growth which restricts any surface flow and generally helps to stabilise the feature. Under the binding qualities of the vegetation cover the force required to cause the failure of the flush becomes greater and therefore the likelihood of failure becomes correspondingly less. It is the latter sequence that the flush at Site B has adopted with the result that the feature has stabilised.

Site C, situated at the source of the Wye on the extreme headwaters of the Afon Cwy, was a slightly different feature from the two flushes already mentioned because it takes more the form of an ephemeral gully providing an extension to the perennial network and occurs on a much steeper slope. There is a pipe network which issues from the base of the feature but discharge is less substantial than on the two examples already examined. A total of eight profiles were located at 5m. intervals across the gully, four actually on the feature itself, one across the issuing stream, and a further two above the gully to monitor any head erosion. The bottom three profiles were located on a stable grassed part of the gully which showed no evidence of change over the period May 1978 to October 1979, and so these together with the two above the head of the feature (also grassed with no evidence of change) were not re-surveyed. This left three profiles situated on the upper part of the feature which due to the presence of loose shale bedrock were re-surveyed because it was impossible to discern any change by observation alone.

Of these three profiles, 3 and 4 showed some signs of change where, in both cases, a shallowing of the depth of gully had occurred (Figure 7.8). This infill appears to be due to the downslope creep or rolling of shale fragments down the steep slope, phenomena probably prevalent during freeze-thaw processes of the winter months. In addition, a small amount of downslope movement has occurred of material which comprises the banks of the gully. Again, this process is attributable to downslope movement of material probably assisted by the trampling of edges by sheep.

7.2.3. Summary and Implications of Detailed Site Analysis

A general survey of the Plynlimon area, with detailed site investigations, shows that potential sites where natural extension to the drainage network may occur are widespread. The mechanism of extension, namely the conversion of perennial pipes to channels by bursting of the peat, has been shown in the past to produce a 30m. extension to a drainage link during the course of a single storm (Newson 1975) but similar extension did not occur at the selected sites during the period of monitoring.

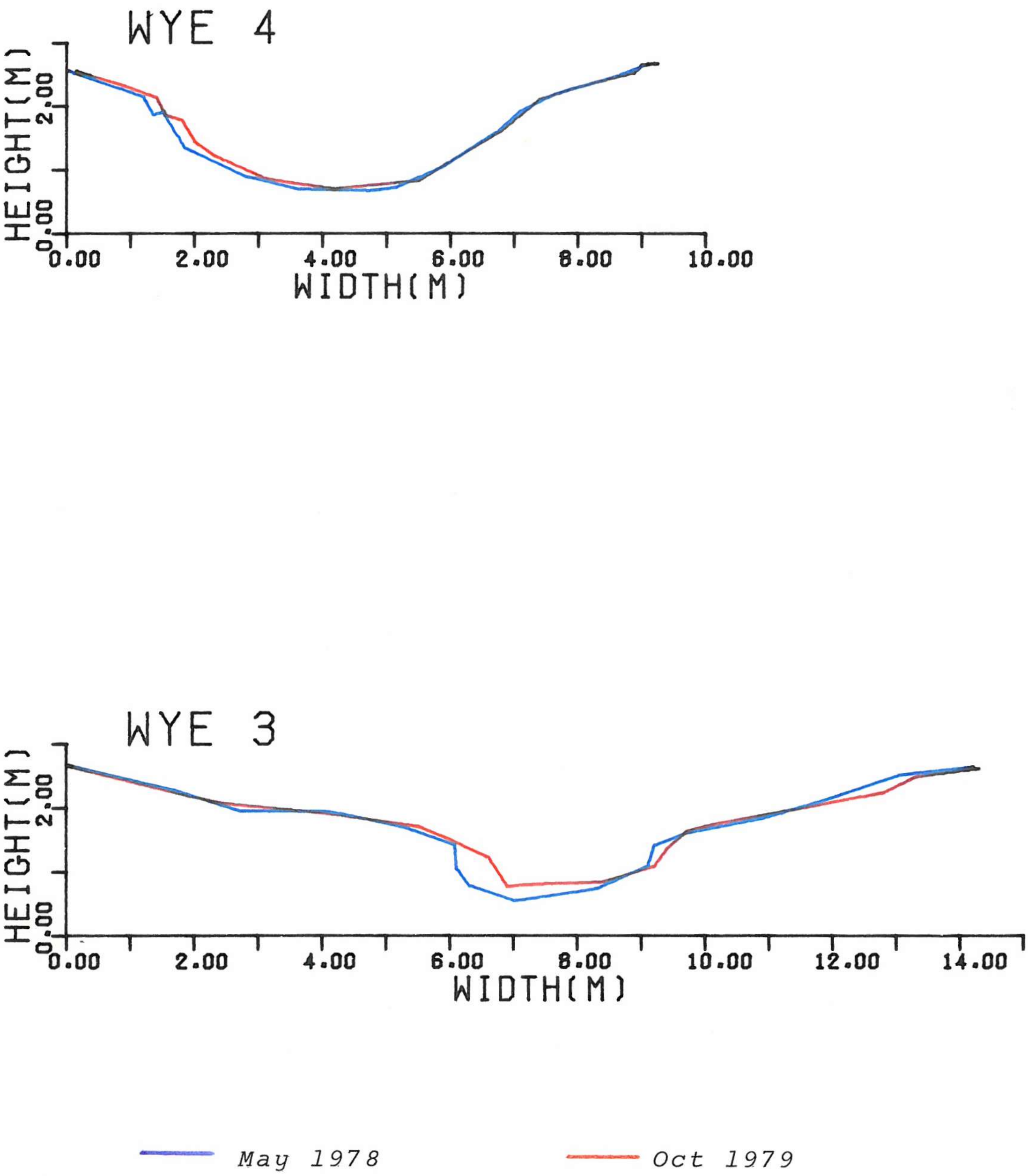


FIGURE 7.8 AFON CWY PROFILE COMPARISONS

Such extension, although representing a physical extension to the drainage network from the surveyor's point of view, is not an actual extension of the network at all to the hydrologist, but merely a change in state of the drainage links from pipe to channel. Although this length of channel will now be mapped it will represent little, if any increase in the discharge occurring lower down the drainage link. Consequently, there is a need for more field attention to be paid to perennial pipes (particularly in upland catchments where they have been the best documented) because calculations based exclusively on the Ordnance Survey's 'blue-line' network may severely underestimate the discharge occurring at a particular point downstream.

7.3. STONEY CROSS AIRFIELD STUDY

7.3.1. The Physical Setting

The site of the airfield at Stoney Cross provides an ideal location to examine the degree, speed and permanency with which man can influence the natural drainage system because the date of airfield construction can be fixed. Stoney Cross Airfield occupies approximately 1.5km^2 of plateau from which the headwaters of six distinct streams radiate being those of Latchmore Brook, Dockens Water, Highland Water, Bratley Water, Coalmeer Gutter and King's Garn Gutter.

The life span of the airfield was short since it was constructed in 1942 during the last war and abandoned soon after in 1946. However, the influence of the site on the radiating drainage network has been less transient, the critical factor being the underground and surface drainage connected with the concreted runways of the airfield. The underground drainage consists of a grid of 24 inch diameter pipes which channel runoff from the airfield surface into the headwaters of existing drainage networks. The influence of such outlet pipes on the extent of the drainage network was first observed in connection with the field survey of the extreme headwaters of Highland Water (Section 4.3.3.). It is the effect on the surrounding drainage networks of these outlet pipes together with runoff from the periphery of the airfield, that is examined in the following sections.

7.3.2. The Method

The area in question is covered by three Official Surveys by the Ordnance Survey, those of 1869/71, 1907 and 1961/5 between which periods changes in drainage network extent were examined. These surveys show the network to be consistent over the period 1869/71 - 1907 with only one location of change (Figure 7.9) which is more likely to be connected with the A31 road than with the airfield. However by the time of the most recent survey of 1961/5 a considerable increase in the length of the drainage network of all streams bordering the airfield had occurred, an increase of stream length which, in view of the previous consistency, can only be termed exponential. Over the period 1907 - 1961/5 the only physical change to the area immediately adjacent to these locations of change appears to be the introduction of the airfield in 1942. In view of the findings in the headwaters of the Highland Water system (Section 4.3.3.) all locations of change in the drainage networks concerned were field checked.

7.3.3. Field Examination of Airfield Sites

The results of field examination confirmed the cause of drainage network extension in this area to be as suspected. Of the fourteen sites examined four represented the head extension of the pre-airfield drainage network to pipe outlets from the airfield drainage (Sites B, F, I and M). A further two Sites (G and H) possess concrete chutes which direct water from the runway surface, concentrating runoff and causing channels to be formed. At all other sites extension had been accomplished without any artificial drainage induction except the effect of the impervious runway material generating runoff. At Sites A and J this had resulted in extensive lengths of flush which

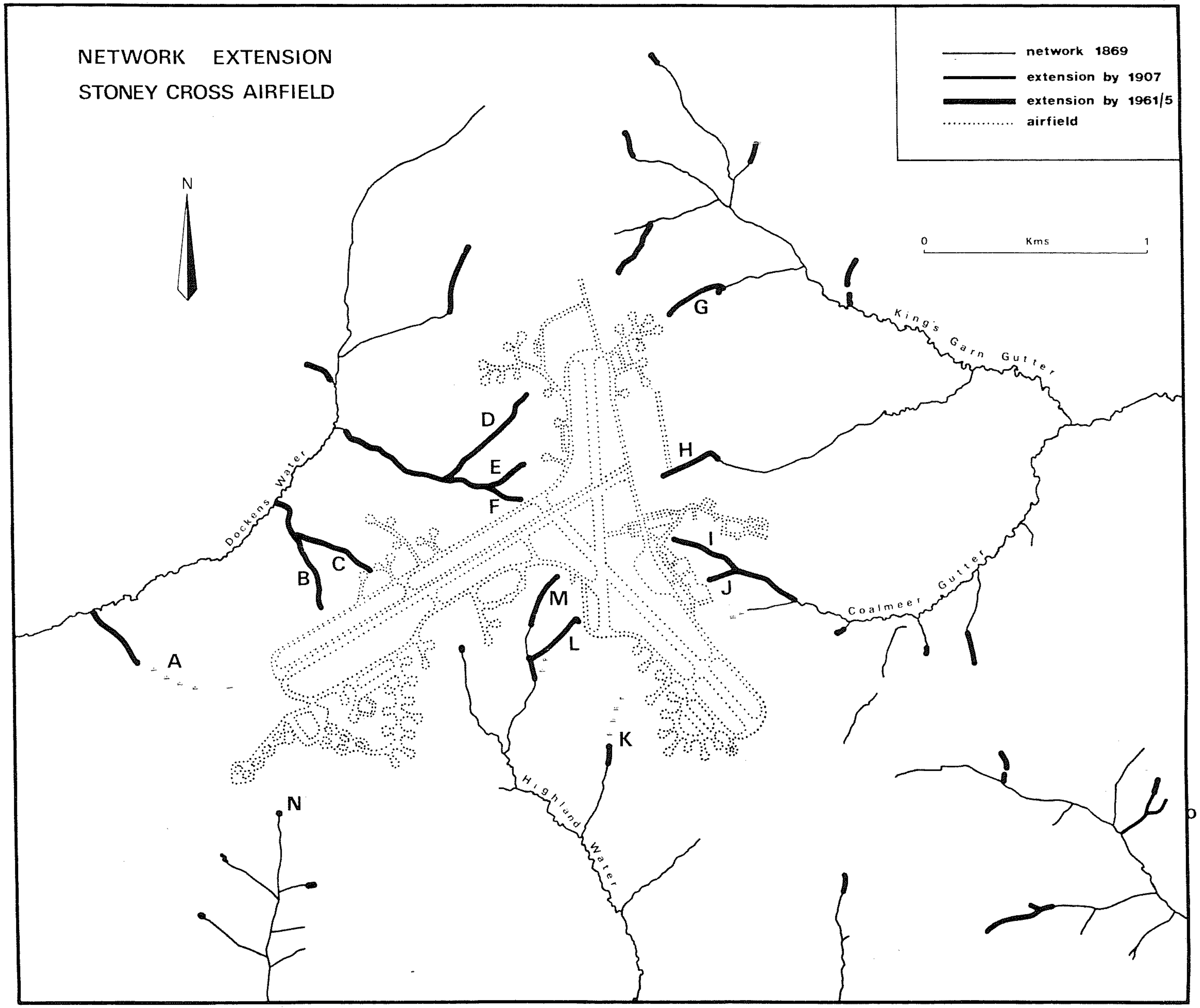


FIGURE 7.9 NETWORK EXTENSION AROUND PERIPHERY OF STONEY CROSS AIRFIELD

SITE	NETWORK	DETAILS OF EXTENSION	REGIME OF NEW LINK
A	Dockens Water	Extensive length of well-defined flush from airfield periphery. Stream & channel begin when flush is joined by an inclosure ditch.	Intermittent (Perennial downstream)
B	Dockens Water	Stream initiated at mouth of 24" diameter pipe.	Perennial
C	Dockens Water	Channel begins at slight break of slope 10m. from airfield periphery.	Ephemeral
D	Dockens Water	Channel originates almost on edge of airfield with short length of flush.	Perennial
E	Dockens Water	See 'D'	Perennial
F	Dockens Water	Stream originates at mouth of pipe from main runway.	Perennial
G	King's Garn Gutter	Channel initiated 40m. downslope from concrete chute and 'splash pad'.	Perennial/Intermittent
H	King's Garn Gutter	Channel initiated 40m. from edge of runway and pipe inserted through King's Garn Gutter Inclosure boundary.	Intermittent
I	Coalmeer Gutter	Channel begins at mouth of pipe.	Perennial
J	Coalmeer Gutter	Channel initiated at break of slope (severe headstep) with length of flush to edge of runway.	Perennial/Intermittent
K	Highland Water	Channel originates from base of concrete chute.	Ephemeral
L	Highland Water	Ill-defined channel from edge of airfield.	Intermittent
M	Highland Water	Stream originates in pond caused by 24" diameter pipe.	Perennial
N	Bratley Water	Extensive length of flush extending from existing channel towards airfield.	Intermittent

TABLE 7.1 DETAILS OF NETWORK EXTENSION AROUND PERIPHERY OF STONEY CROSS AIRFIELD

eventually graduated to channels, while at Sites C, E, D, H, L and N the channels started more or less on the airfield boundary. The channels at Sites E and D carried additional evidence of recent ditching presumably by the Forestry Commission as part of the drainage of North Bentley Inclosure. The sinuous course of these drains is atypical of Forestry Commission practice indicating the presence of a drainage network component prior to the ditching. Full details of each site including the regime of each new link are presented in Table 7.1, while locations of the sites are shown on Figure 7.9.

7.3.4. Summary

After cartographical and field examination, extension of the various drainage networks surrounding Stoney Cross Airfield can confidently be attributed to the construction of the airfield, and therefore as having developed since 1942. Channels have been initiated not only at the outlets of the underground airfield drains, but also at the base of concrete chutes and by runoff from the airfield surface resulting in both the extension of existing exterior links and the creation of new links.

Because the date of airfield construction can be fixed, the study is able to provide an example of the rate and extent to which a drainage network can respond to man-induced conditions. Such response by the drainage network to a changed pattern of runoff may have wider applications to many other forms of construction work. Because extensions of the drainage network can lead to higher peak velocities and to larger flood peaks downstream, similar proposals for the disposal of runoff in Britain should be carefully scrutinised before being implemented.

7.4 CONCLUSIONS FROM EMPIRICAL EVIDENCE

The use of repeated surveys for sites on Highland Water in the New Forest, Hampshire, and at Plynlimon, Central Wales has shown the usefulness of such empirical evidence in a study of network change. However, the potential of the technique was not fully realised because the time period over which changes were examined was too short. Consequently, the technique did not produce as much evidence about the processes of network extension as was originally hoped.

The role played by recent improvements to the A31 road in the extension of a drainage link on Highland Water, indicates the rapidity with which man's activities can affect drainage networks. Although little morphological evidence of change is apparent from select cross profile comparisons, field observations, together with pictorial coverage and vegetation changes, reflect the considerable physical change that has occurred to the drainage link in question over a period of 21 months. Similar conclusions of the rapidity with which man's activity can cause permanent network extension, together with the scale and extent that such changes may assume, are illustrated in a study of the disused airfield complex at Stoney Cross. Here, the considerable network extension that has occurred recently in the headwaters of Dockens Water, Highland Water, Coalmeer Gutter and King's Garn Gutter has been shown by field survey to be the result of the disposal of runoff by various means from the airfield surface, and has developed since 1942.

An examination of potential sites of natural drainage network extension was not as successful as those occurring as the result of human interference due mainly to the nature of the change; the slow build up to a sudden and catastrophic failure of perennial pipes requires a delicate balance of conditions. Unfortunately, the required combination of conditions did not occur during the restricted eighteen-month monitoring period which, instead, showed very little perceptible change except some downslope movement of loose material in the gully bottom of the Upper Wye Site and some opening and closing of peat pipes on the Gerig Flush. It is hoped that these sites may yield more productive information in the future.

Nevertheless, the considerable modifications of the drainage network shown to occur through man's activity may have far-reaching implications for downstream hydrographs. The increased efficiency of the passage of rainfall to the channel system should result in a sharper rising limb to the hydrograph as well as a greater peak, which may have a serious effect downstream. Consequently, the likely downstream effect of additional inputs of water should be carefully examined before similar storm runoff disposal from construction sites is authorised.

With the apparent frequency and possible extent of forms of man-induced extension to the drainage network established (albeit for a specific area in the New Forest, Hampshire,) there is perhaps a need to amplify recent modelling approaches (e.g. Beven and Kirkby 1976, Beven, Gilman and Newson 1979) so as to include consideration of network extension as relevant to areas of considerable human activity.

CHAPTER 8 ANALYSIS, AREAL COMPARISON OF DRAINAGE NETWORK CHANGES, AND CONCLUSIONS

Following substantiation of network change in Britain over the last 150 years and examination of the reasons for change by detailed investigation at selected sites it remains to review the general factors governing change at a basin level and hence to attempt to identify the most important variables controlling network change. The level of analysis is of necessity generalised, consisting of little more than an areal comparison of the eighteen basins, because it would be impossible to do otherwise without additional and extensive fieldwork. However suggested directions for future detailed research are presented in Section 8.3.2.

The object of this proposed general analysis is to explain extension and contraction within the drainage network in terms of the effects of individual, or of several, parameters expressing drainage basin characteristics and these parameters are selected in Section 8.1. The results of regression analysis, a provisional model for drainage network change, and suggested lines for further research are presented in Sections 8.2, 8.3.1 and 8.3.2 respectively.

8.1 SELECTION OF VARIABLES FOR ANALYSIS

In an attempt to explain network change four geomorphological variables were chosen as independent variables and three different expressions of network change were used as dependent variables. The independent variables were basin area (Ad), an index of basin relief, precipitation amount (SAAR) and precipitation intensity (M52D). The dependent variables were total stream lengths (ΣL), drainage densities (Dd) - these two variables corresponding to the early and recent surveying of the channel network - and finally the net amount of extension and contraction within the basin obtained as the difference between the two surveys.

Basin areas were derived from Second Edition 1:25000 maps or, where this was not possible, from the most recent Ordnance Survey map available. The minimum scale utilised was the 1:50000 series.

The measure of catchment relief used was that of $\frac{\text{basin relief}}{\text{area}}$, the values obtained being in metres of fall per km^2. Prior to the choice of $\frac{\text{basin relief}}{\text{area}}$ several alternative measures of slope were considered including the stream channel slope measured between two points, these representing 10% and 85% of the stream length from the gauge (S1085) and the Taylor-Schwarz slope of the channel (Tayslo). A comparison of figures obtained by S1085 and Tayslo methods for several basins contained in the 'Flood Studies Report' (N.E.R.C.1975) are presented in Table 8.1. All three slope measures rank identically but a marked similarity is evident between actual values obtained by the $\frac{\text{basin relief}}{\text{area}}$ and S1085 methods. Because the results

Catchment	S1085	Tayslo	Basin Relief / Area
Isla	13.12	13.02	13.13
Hodge Beck	30.64	20.98	30.49
Croasdale Brook	35.60	36.46	38.86
Dove	33.70	28.49	33.17
East Stour	3.20	2.90	2.91
Harpers Brook	3.79	4.32	3.10

TABLE 8.1 COMPARISON OF CHANNEL SLOPE MEASUREMENTS OBTAINED BY S1085, TAYSLO AND $\frac{\text{BASIN RELIEF}}{\text{AREA}}$ METHODS

obtained by S1085 and $\frac{\text{basin relief}}{\text{area}}$ methods of slope determination are so similar, and in spite of the geomorphological validity being by no means perfect (established slope measure such as Taylor-Schwarz are anyway difficult to interpret geomorphologically) it was decided to proceed with the $\frac{\text{basin relief}}{\text{area}}$ method of channel slope determination, enjoying a great saving in time and labour.

The rainfall variables of amount and intensity were arrived at much more simply and followed the example of the 'Flood Studies Report' (N.E.R.C.1975). Average annual precipitation 1916-1950 was used for rainfall amount with the rainfall intensity index being that of the 2-day maximum rainfall with an expected recurrence interval of 5 years (M52D).

8.1.1 Reasons Governing the Choice of Variables

It was considered necessary to employ three different expressions of the dependent variable. The first of these, considered for each basin in turn, were total stream lengths corresponding to the two surveys ($\Sigma L1$ and $\Sigma L2$) which were designed to illustrate the effects of changes in network extent when placed in the context of total stream lengths. In this form it was hoped to discover how $\Sigma L1$ and $\Sigma L2$ relationships varied when regressed with certain catchment parameters perhaps indicating whether network change over a period of at least 100 years gave improved or less significant relationships. Another form adopted as a dependent variable representing network change were total amounts of extension and contraction resulting in a separation of these two basic types in an attempt to see whether any simple explanation could be found for either category of change in terms of the independent variables. The last expression of the dependent variable was that of drainage density (corresponding to the two map editions used), and drainage density change chosen in order that some idea of amounts of change per unit area could be introduced thus allowing spatial comparisons. However, problems of multicollinearity arise in the regression of drainage densities with certain catchment parameters.

For reasons that will soon become apparent the independent variables of rainfall amount, rainfall intensity, slope and drainage area were considered both the most important and potentially the most rewarding in terms of the explanation of network change. Rainfall amount was considered a major factor because it has an important influence on the determination of the density of the drainage network, and because it determines in part the amount of potential runoff and therefore the number of drainage links available for change. The significance of rainfall intensity as a variable was appreciated largely as a result of work at Plynlimon and in the New Forest where it appeared that the threshold value of effectiveness of vegetation protection was most likely to be exceeded during a high intensity storm.

The use of slope as a variable was justified after visualising its apparent effect on channel types, particularly on the pipe-like channel initiation and flush metamorphosis extension categories as observed in the Croasdale Brook catchment. The flush metamorphosis type appears in general to occur upon the gentler slopes which may to some extent be a function of water being unable to rest on steep slopes. Additionally, slope may influence the development and efficiency of sub-surface water movement, particularly the development of pipes which have been suggested to be an important source of network extension (Jones 1971).

Drainage area was selected in order to qualify relationships so that the amount of network change within a catchment was put into the context of basin size. However where the dependent variable expressing network change was drainage density this was not necessary. The size of basin also produces some idea of the percentage of stream length accounted for by exterior headwater links and thus the proportion of the type of link that is most susceptible to change.

Once these variables had been selected and justified, logical combinations were examined in an attempt to explain drainage network change in terms of natural basin characteristics.

8.2 RESULTS

8.2.1. Correlation Matrix and Simple Regression

A correlation matrix is presented in Table 8.2 to give an indication of the strength and direction of associations between all possible combinations of the selected variables. Many can be disregarded because they are meaningless in geomorphological terms. The associations which appeared worthwhile pursuing, geomorphologically, and which were relevant to a study of drainage networks, are printed in italics in Table 8.2 and it is these that will be considered in the remainder of this section.

The high associations obtained between $\Sigma L1$ and $\Sigma L2$ with total extension and total contraction are as expected in that extension and contraction amounts are dependent upon the length of drainage network, in terms of the number of links available for change. Conventionally, relationships between total stream lengths and drainage areas are log-transformed and therefore, to facilitate comparison with studies by other authors these will be discussed later in such form. Wherever possible a basic rule was made not to transform the data, although care was taken to ensure a normal distribution before fitting regression models. Problems are introduced with data transformations because it is the transformed data that are interpreted and not the actual values. The positive associations between extension and contraction with area ($r=0.65$ and 0.63 respectively) strengthen the case for a significant part of change in the drainage network being controlled by the size of basin and therefore the length of drainage network considered. 'T' test values, relating whether or not the values predicted by the regression are from the same population as the observed values, are significant at the 0.01 level for both extension and contraction with area.

The low and insignificant 'T' values, obtained when $\Sigma L1$, $\Sigma L2$, extension and contraction were each regressed in turn with rainfall amount, possibly reflect the complex interaction of variables responsible for network

	ΣL1	ΣL2	Ext.	Cont.	Ad	SAAR	M52D	Relief	Dd1	Dd2	Dd Change
ΣL 1	1.0000										
ΣL 2	0.9661	1.0000									
Extension	0.7238	0.8700	1.0000								
Contraction	0.8875	0.8117	0.6027	1.0000							
Ad	0.7686	0.7873	0.6460	0.6252	1.0000						
SAAR	0.3003	0.2871	0.1999	0.2872	-0.1048	1.0000					
M52D	0.4855	0.5002	0.4297	0.4291	0.0832	0.8752	1.0000				
Relief	-0.1459	-0.1334	-0.0495	-0.0947	-0.4392	0.3711	0.2083	1.0000			
Dd1	0.5031	0.4154	0.2020	0.5094	-0.1115	0.6373	0.6028	0.5363	1.0000		
Dd2	0.1424	0.2453	0.4557	0.1791	-0.3214	0.4383	0.4534	0.5054	0.5338	1.0000	
Dd Change	-0.2410	-0.0506	0.3661	-0.2035	-0.2833	-0.0057	0.0396	0.1538	-0.1878	0.7303	1.0000

TABLE 8.2 CORRELATION MATRIX FOR SELECTED DRAINAGE BASIN PARAMETERS

changes. However, the relationship of rainfall intensity with the same variables does demonstrate that intensity of rain is a better variable to explain stream length, with 'T' values for ≤L1 and ≤L2 that are significant at the 0.05 level and extension and contraction at the 0.1 level.

Basin relief, considered alone and in the context of an inter-basin comparison, is shown not to have any influence on length, extension, or contraction of the drainage network. The association of area with both rainfall variables and drainage densities is poor although an expected inverse association is seen with relief (r = -0.44).

The earlier drainage density values have a strong and interesting positive relationship with both rainfall variables as seen in the 'T' values from the regression which are significant at the 0.05 level. The association decreases significantly when correlated with the present drainage density with a 'T' value significance level of only 0.1. The implication of the better relationship of early drainage density with rainfall amount and intensity is that a new influence has been brought to bear on drainage density, upsetting the natural balance; the effects of human activity could provide a possible explanation.

The final untransformed coefficient considered is basin relief which has a positive association of between r=0.51 and 0.54 with the two drainage density values.

The correlation coefficients of the logged values of stream lengths 1 and 2 with area show positive associations of r=0.80 and 0.69 respectively. A 'T' test on the regression residuals confirms an apparent decay in this relationship over the period between the surveys with the significance level falling from the 0.001 to the 0.01 level. An examination of the regression lines, relating to these two sets of values of total stream length regressed with area, show that the change in the relationship does not represent a total shift in the position of the regression line, but a marked decrease in the slope of the line (Figure 8.1). The inference of this slope decrease is that drainage

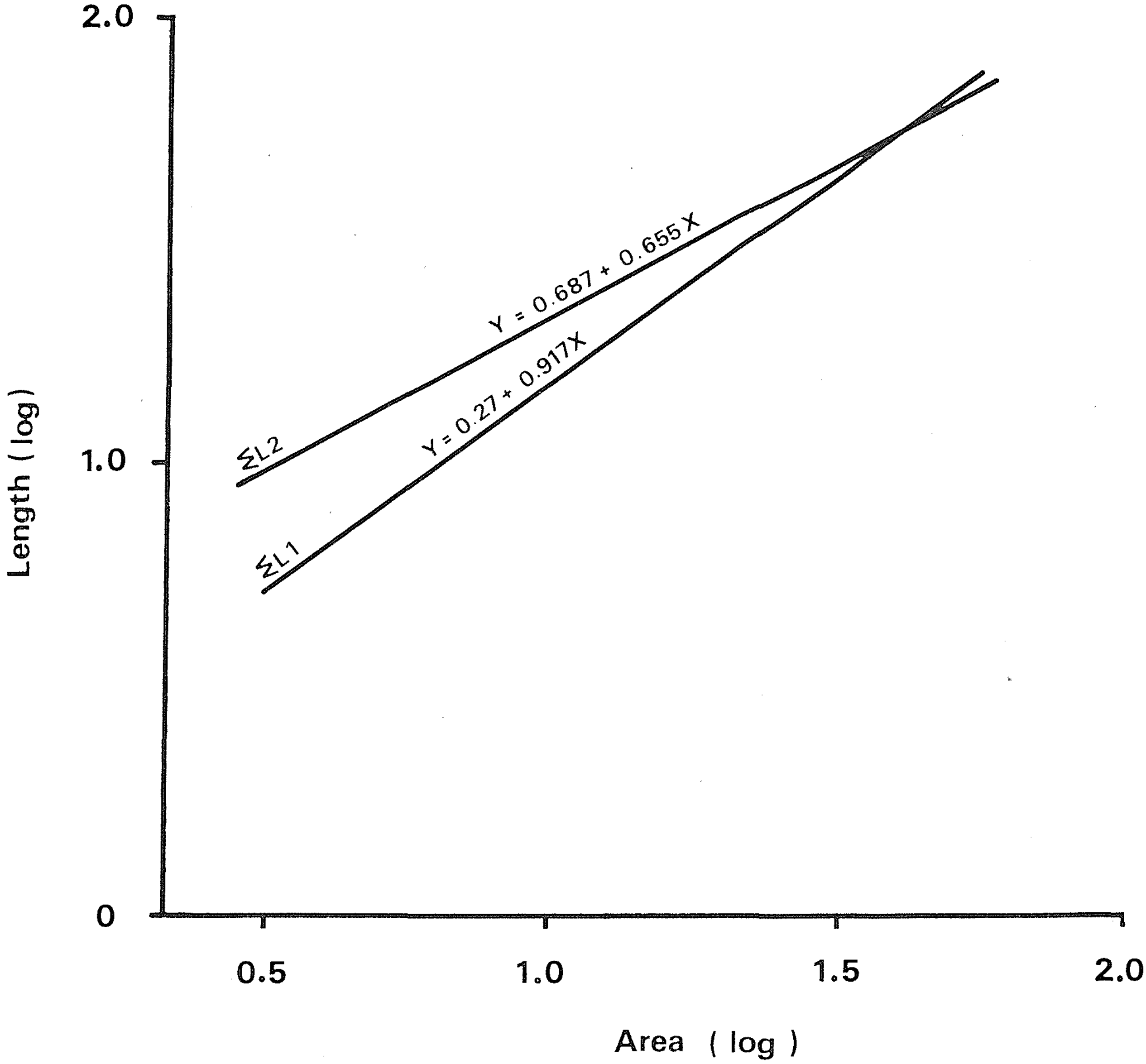


FIGURE 8.1 RELATIONSHIPS BETWEEN DRAINAGE NETWORK LENGTH, CORRESPONDING TO FIRST (ΣL1) AND REGULAR OR METRIC MAP EDITIONS (ΣL2), AND DRAINAGE AREA.

network extension is greater in the smaller catchments, or is concerned with the type of links (for example the headwater streams) that are abundant in the smaller basins. The relative importance of small first-order exterior links in the context of total stream length declines as the catchment size increases and it is these links that fieldwork has shown to be most susceptible to change.

8.2.2. Multiple Regression

Several multiple regression analyses were examined in an attempt to find if these models had any advantages over the simple regression analyses already discussed in terms of a better explanation of drainage network change. To this end the various expressions of network change (dependent variable) were used with independent variables of area and SAAR, area and M52D, area and basin relief, SAAR and relief and finally M52D and relief. The results of these analyses in the form of the variance accounted for by the various regression models, the value and significance level of the 'F' statistic, and the significance levels of the 'T' statistic (relating to the slopes of the independent variables in the regression equations) are presented in Table 8.3. Because an attempt to explain or model network change is being made in terms of particular morphometric variables, the significance of the contribution of each of the independent variables, as indicated by the associated 'T' statistic, is of greater importance than the 'F' statistic which examines the significance of the whole relationship.

However the values of both the 'F' and 'T' statistics are important in assessing the validity of the regression model and are thus both presented in Table 8.3. The relevant 'T' test associated with each independent variable tests a null hypothesis that the associated slope coefficient is zero. If this null hypothesis can be rejected, it indicates that the particular variable under consideration offers some explanation of the observed variation in the dependent

Variables for Multiple Regression Analysis. Dependent	Independent (i)		Independent (ii)	Variance Accounted For	'T' Statistic Significance Level For Independent Variables. (i)	(ii)	'F' Statistic. Value	Significance Level
Length 1	Ad	+	SAAR	70.2	0.001 level	0.02 level	21.07	0.001 level
Length 2	Ad	+	SAAR	72.6	0.001 level	0.01 level	23.49	0.001 level
Extension	Ad	+	SAAR	42.2	0.01 level	*	7.19	0.01 level
Contraction	Ad	+	SAAR	45.2	0.01 level	0.1 level	8.01	0.005 level
Dd 1	Ad	+	SAAR	32.9	*	0.01 level	5.17	0.05 level
Dd 2	Ad	+	SAAR	17.1	*	0.1 level	2.76	0.1 level
Length 1	Ad	+	M52D	73.9	0.001 level	0.01 level	25.06	0.001 level
Length 2	Ad	+	M52D	78.5	0.001 level	0.01 level	31.99	0.001 level
Extension	Ad	+	M52D	50.1	0.01 level	0.05 level	9.53	0.005 level
Contraction	Ad	+	M52D	47.2	0.01 level	0.05 level	8.60	0.005 level
Dd 1	Ad	+	M52D	30.8	*	0.1 level	4.79	0.05 level
Dd 2	Ad	+	M52D	24.7	*	0.05 level	3.78	0.05 level
Length 1	Ad	+	Relief	58.8	0.001 level	*	13.12	0.001 level
Length 2	Ad	+	Relief	63.2	0.001 level	*	15.63	0.001 level
Extension	Ad	+	Relief	41.7	0.01 level	*	7.07	0.01 level
Contraction	Ad	+	Relief	35.5	0.01 level	*	5.68	0.05 level
Dd 1	Ad	+	Relief	21.4	*	0.05 level	3.31	0.1 level
Dd 2	Ad	+	Relief	17.0	*	0.1 level	2.74	0.1 level
Length 1	SAAR	+	Relief	5.6	*	*	1.50	*
Length 2	SAAR	+	Relief	3.6	*	*	1.31	*
Extension	SAAR	+	Relief	-6.8	*	*	0.46	*
Contraction	SAAR	+	Relief	1.3	*	*	1.11	*
Dd 1	SAAR	+	Relief	44.5	0.02 level	0.01 level	7.98	0.005 level
Dd 2	SAAR	+	Relief	23.9	*	*	3.67	0.1 level
Length 1	M52D	+	Relief	20.6	0.05 level	*	3.21	0.1 level
Length 2	M52D	+	Relief	21.7	0.05 level	*	3.36	0.1 level
Extension	M52D	+	Relief	9.9	0.1 level	*	1.93	*
Contraction	M52D	+	Relief	11.5	0.1 level	*	2.11	*
Dd 1	M52D	+	Relief	47.8	0.02 level	0.05 level	8.80	0.005 level
Dd 2	M52D	+	Relief	30.0	0.1 level	0.1 level	4.64	0.05 level

* Indicates 'T' or 'F' Statistic is not Significant

TABLE 8.3 VARIANCE, AND 'T' & 'F' STATISTIC SIGNIFICANCE LEVELS FOR MULTIPLE REGRESSIONS variable. However Table 8.3 reveals that in a number of cases the multiple regression models represent no improvement on the simple regression relationships. This is largely the case with the explanation of network change (dependent variables) by the independent variables of Ad and relief, SAAR and relief and M52D and relief.

More successful were the models explaining network change (dependent variable) in terms of the independent variables of Ad and SAAR, and Ad and M52D (Table 8.3). In general the models which use rainfall intensity (M52D) as one of the independent variables account for higher variances, and sometimes higher significance levels for both 'T' and 'F' statistics than the models where rainfall amount (SAAR) is used as one of the independent variables.

Of the various transformations of the dependent variable, the models using length 1 or length 2, as dependent variables, proved consistently better than those using the other transformations of the dependent variable (i.e. extension, contraction Dd1, Dd2), as demonstrated in the higher variance and significance levels attained for these models (Table 8.3). Additionally the variances obtained by the multiple regression models of

$$\left.\begin{matrix}\text{Length 1}\\ \text{Length 2}\end{matrix}\right\}\text{(dependent)}:\ \begin{matrix}\text{Area +}\\ \text{Area +}\end{matrix}\left\{\begin{matrix}\text{Rainfall}\\ \text{Indice}\end{matrix}\right\}\text{(independents)}$$

were substantially higher than those obtained by the simple regression models of

Length 1/2 (dependent): Area (independent)

Thus the use of a rainfall variable as an independent variable in these multiple regression models does significantly assist the explanation of the dependent variable.

8.2.3. Thresholds

Due to disappointing, but largely expected, results of the attempt to explain drainage network change exclusively in terms of natural drainage basin parameters, it was decided to examine briefly the possible existence of a threshold between extension and contraction sites.

Schumm and Hadley as early as 1957 suggested the possible existence of a threshold or a critical value governing whether or not a valley slope in semi-arid valleys would be subject to erosion. Schumm (1973) drew attention to the importance of geomorphic thresholds in the evolution of erosional and depositional landforms. Patton and Schumm (1975) using drainage basin area as a surrogate for discharge, related slope to drainage basin area for 57 basins in the Piceance Creek and Yellow Creek drainage basins of N.W. Colorado. By distinguishing between gullied and ungullied valley reaches, the authors were able to draw a line through the lower limit of scatter of gullied points, arriving at a critical value for valley slope above which entrenchment should occur for any given drainage area.

In view of Schumm's (1973) comments it was hypothesised that such a threshold value of slope may determine whether extension or contraction of the drainage network was occurring. It was not feasible to relate the existing measure of basin relief to drainage area for the 18 basins analysed due to problems of multicollinearity, and therefore a new measure of basin relief not incorporating area would be required. However an inter-basin comparison of this nature would be unsatisfactory due to the consideration of average values of slope and area rather than actual values relating to specific sites of extension or contraction, Additionally the data set is somewhat unsuitable with 16 basins showing net extension of the drainage network and only two demonstrating contraction. Such a regression would do little more than highlight the coincidence of basins in which a high percentage of extension to the drainage network is accounted for by natural processes (e.g. flush metamorphosis by pipe burst) with those possessing the highest basin relief (as evident from the data contained in Table 5.5 Section 5.4.2.). Consequently the relationship between basin relief and drainage area was not examined for all eighteen basins but a similar type of analysis was attempted with specific slope and area values for a single catchment, the chosen basin being that of the Ellen, in the Lake District. This choice was mainly because of the Ellen's small and manageable catchment area together with the variety and even numerical distribution of contraction and extension sites occurring within its area. Slope values, measured as metres of fall per kilometre over the length of each of the change sites, were plotted against the drainage area above each change site and a distinction was made between sites of extension of the drainage network and sites of contraction. Drains confirmed during field survey (Sites 15, 16 and 17) were not considered due to an obvious direct human influence, nor were the two unchanged drainage links at Sites 14 and 20. This left 22 exterior links on which change could be considered, and the results of these are plotted in Figure 8.2. Clearly apparent are the groupings of extension and contraction sites (ignoring three 'erratic' points) and a line drawn through the upper edge of scatter of the contraction points conveniently divides the majority of the extended links from the contracted ones. The figure does very little to help the explanation of extension or contraction in terms of the slope of the drainage links in question, but there does appear to be some form of relationship because the extension of the drainage network is confined to the larger drainage areas (in excess of 0.08 km^2). Although it is not possible to draw any meaningful conclusions after the examination of a handful of sites in one particular basin, there is the possible inference of the role played by contributing area generating a sufficient enough volume of water to exceed a certain threshold level allowing extension of the drainage network to occur. Such a concept is presented by Bunting (1961) who states

> *'While the supply of moisture obviously comes from an upslope direction, the extension of incipient drainage or seepage lines into crestal areas must gradually cease when the crestal area, reaching some minimum width, can no longer yield sufficient moisture to the adjacent seepage hollows or cusps for the process of corrosion to continue.'*

Subsequent authors have taken the Patton and Schumm (1975) threshold concept and examined the influence of other variables such as the effects of vegetation (Graf 1979).

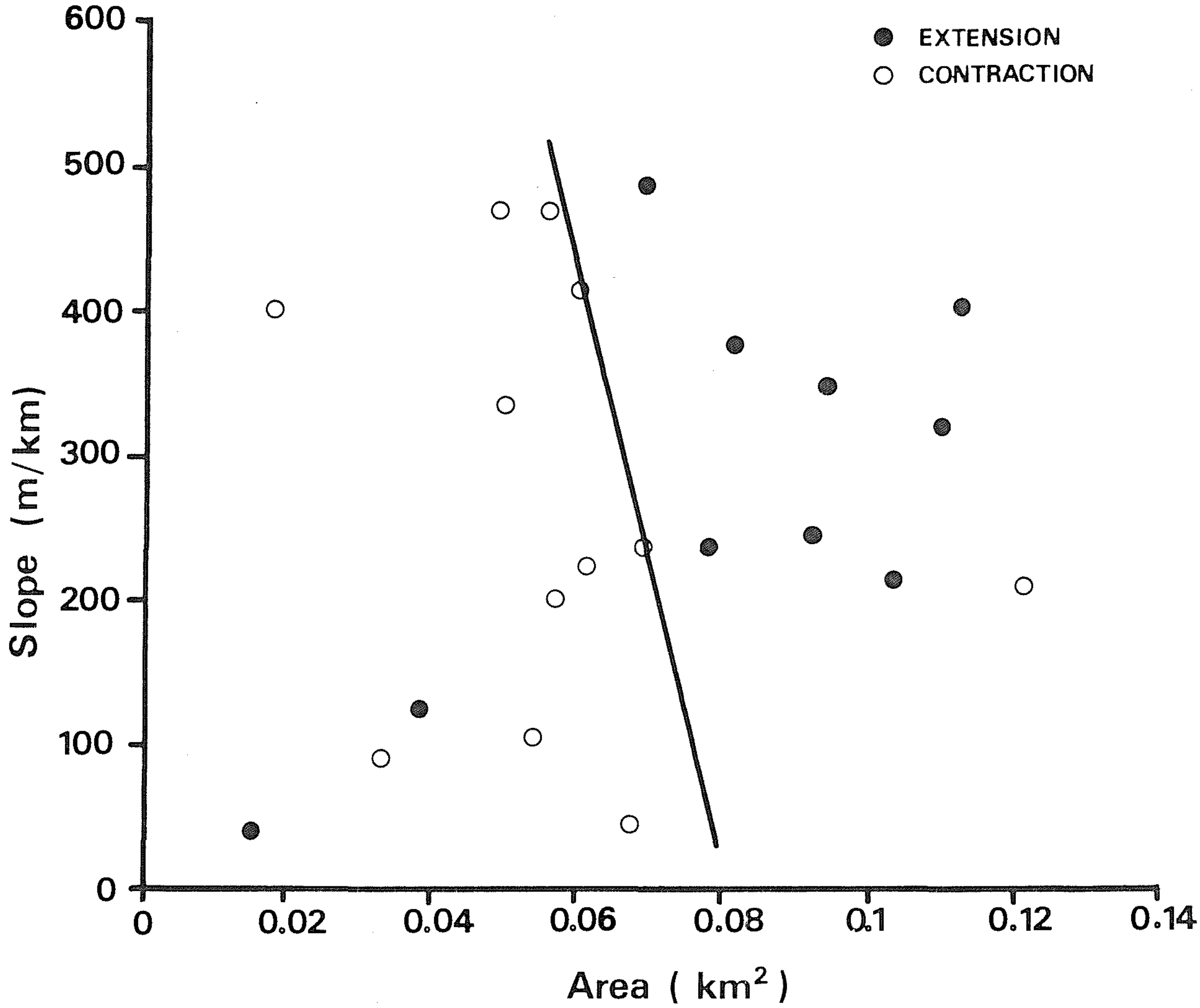


FIGURE 8.2 SLOPE AGAINST AREA, PLOTTED FOR 22 EXTERIOR LINKS DEMONSTRATING NETWORK CHANGE OVER THE PERIOD 1862-1976, WITHIN THE ELLEN CATCHMENT.

It was found that similar thresholds exist for the resistance of vegetation which could be an extremely important consideration due to its being much affected by both natural and human activities. However, it was not possible to examine the effect of vegetation in the Ellen Catchment with existing data.

Once again, these tentative conclusions from threshold analysis support those obtained by regression analysis in that even the most likely natural factors cannot, alone, explain changes in the drainage network. Similar thresholds to Patton and Schumm (1975) are not found in the Ellen Catchment and they probably do not exist in Britain. The existence of a threshold in the Patton and Schumm study area is possibly due to the greater simplicity of the semi-arid landscape. Uniform vegetation cover, cohesiveness of materials, less variable and sometimes higher slope values, and the intensity and seasonal distribution of rainfall all help to make fluvial landforms, and the processes acting upon them are more clear-cut than those acting upon drainage links in a temperate landscape.

8.3 CONCLUSIONS

8.3.1. Preliminary Model for Drainage Network Change

The dominant conclusion from the work of Section 8.2 is that an attempt to explain changes in drainage networks exclusively in terms of either single or combinations of natural basin parameters is not completely successful. Consequently, there is a need to combine man-induced and natural factors selected during field survey by direct observations, with the most successful variables from regression analysis. The most important variables singled out during the course of field survey of networks are summarized in Table 5.5 (Section 5.4.2) and include man-induced forms resulting from ditching, urbanisation, storm water disposal and construction work, and natural factors that field observation suggested might affect the categories of flush metamorphosis and pipe burst. An attempt to combine these variables with the

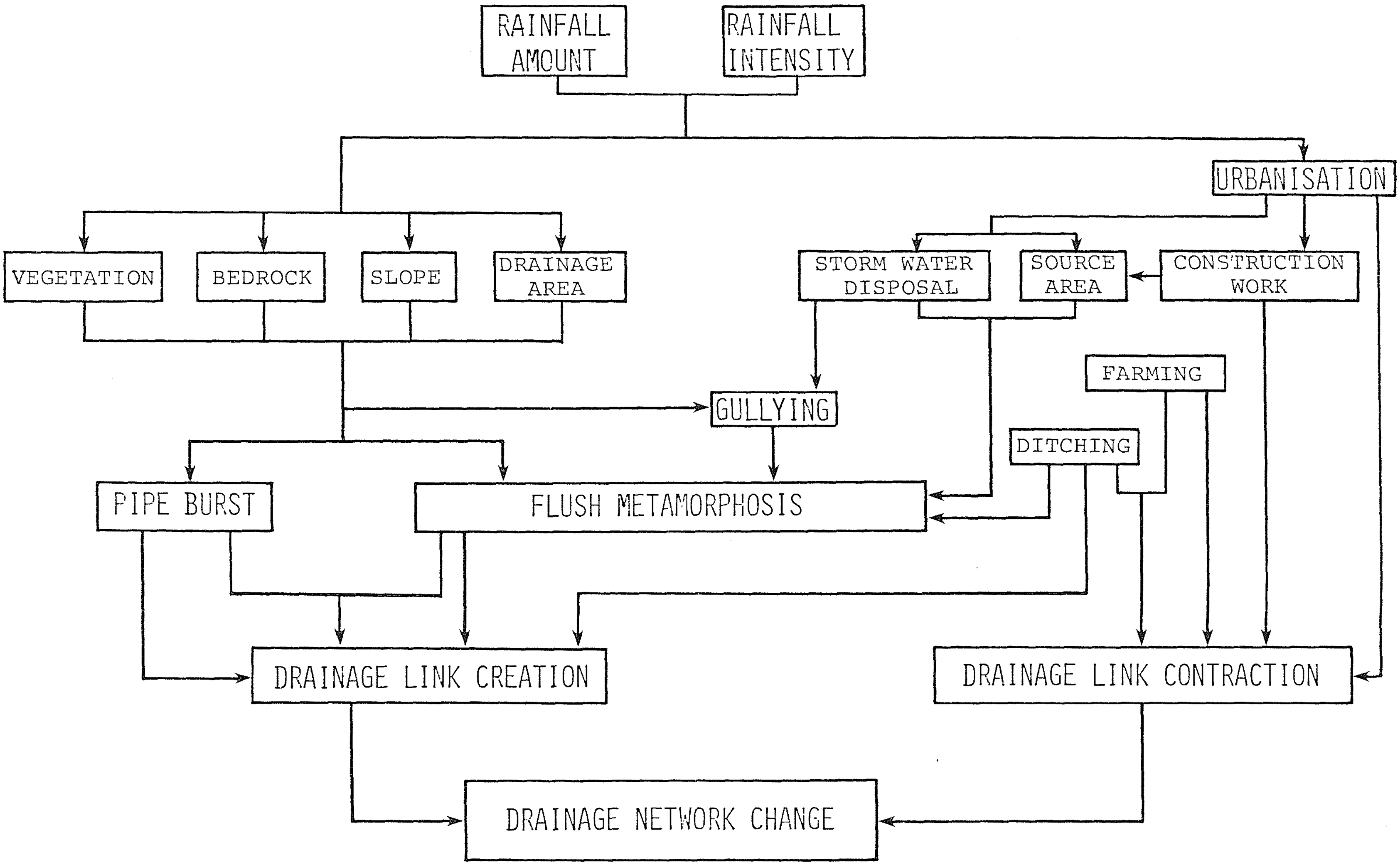


FIGURE 8.3 A PROVISIONAL MODEL FOR DRAINAGE NETWORK CHANGE

most successful natural parameters in explaining network change (namely rainfall intensity and rainfall amount) is produced in Figure 8.3 as a provisional model for drainage network change. This model defines rainfall intensity and amount as the initial inputs into the system and then routes these through natural (diagram left) and man-induced (diagram right) controls upon drainage network change in order to explain drainage link creation and contraction.

The diagram emphasises flush metamorphosis, by both natural and man-induced processes, as a major form of drainage link creation, while pipe burst is emphasised as a natural process of network extension. Additionally man-created factors are considered in a role where they act directly on drainage network components rather than in a situation where they influence form through processes as is the case with the mechanisms of pipe burst and flush metamorphosis just mentioned. This is seen in the form of ditching and the effects of urban areas on drainage network components.

This model, occurring at the end of what is essentially a preliminary study of changes in drainage network extent, summarises in a simplied form the conclusions reached concerning the forms that network change may frequently adopt as well as highlighting some of the processes and causes that most commonly appear to affect the change procedure.

8.3.2. Implications and Relevance of Drainage Network Changes

During the course of this study there has been confirmation that permanent changes to the drainage network occur and are widespread throughout a variety of British Drainage Basins.

All eighteen drainage basins that were examined showed some degree of change in the drainage network. 89% represented a positive increase in stream length over the period of the two surveys and 11% showed a very slight decrease in total stream length, although fieldwork in Dorback Burn (one of the basins demonstrating apparent net contraction of the drainage network) did not confirm some of this contraction in the field. The actual percentage increase in stream length for the 16 catchments that show a net extension of the drainage network varies widely from a 2.68% increase in the Plym basin to a 438% increase in the catchment of Hodge Beck. If this cross-section of drainage basins is representative of the true British situation, then network change is a very real process and one of considerable importance and relevance to many aspects of hydrology and fluvial geomorphology. Therefore in all morphometric analysis using stream length or any derivative, the possible time-dependence of the drainage network should not be overlooked. Consequently the date of survey assumes a new role of importance equal to that already held by map scale, map convention and the drainage network data source (i.e. whether map, remote sensing, or field survey).

An awareness of the possibility of changes to the drainage network over time, other than changes relating to the response of the drainage network to a specific climatic event, has not been previously reported in the literature. Consequently, this new concept of drainage network change does have implications in relation to previous research as well as providing new possibilities for a variety of types of conventional approach to studies of drainage networks.

From any such preliminary study several possible directions for further research in fluvial geomorphology should present themselves, and from this work is proposed a six-fold approach for future research relating to drainage network change. These approaches may be summarised as studies of network topology, morphometric analysis, process prediction, changing process, network modelling and landform evolution (Table 8.4). Network topology provides an instance where the potential of this type of data derived from map network comparisons may be utilised for investigations of drainage network development over time, thus obviating the need to assume that relationships through time are reflected in relationships

Type of Study	Objective	Implication of Network Change
1. Network Topology	Investigation of topological properties of networks and their development over time using space-time substitution e.g. Abrahams 1977.	Networks for an area derived from maps of specific dates can be the basis for investigation of the ways in which network topology changes.
2. Morphometric Analysis	Analysis of inter-relationships between morphometric properties of drainage basins and their controls.	Networks depicted on maps may vary with scale and map convention and also with date of survey which reflects the network at a particular date.
3. Process Prediction	Use of drainage network as one variable in a model constructed to predict water discharge or sediment yield.	Because network extent varies with date of map need to ensure that network data is compatible with years of discharge record.
4. Changing Processes	Demonstration of the way in which changes of the stream network induce changes in water discharge (and flood frequency) and sediment production.	Data may be available from maps of different date to relate to hydrological observations or to be used for modelling runoff response or sediment production.
5. Network Modelling	Routeing of water, falling as precipitation, through the drainage network and out of the system.	The effect of artificial source areas on the rapidity of conductance of runoff and resultant modification to channel forms should be considered.
6. Landform Evolution	Identification of short term stages of landscape change.	Changes of networks in historic times may be related to geomorphological change.

TABLE 8.4 POSSIBILITIES FOR FUTURE RESEARCH RELATING TO DRAINAGE NETWORK CHANGES

over space as has been used by space-time substitution in the past (Abrahams 1976, 1977, Abrahams and Campbell 1976). The consideration of drainage network change in morphometric analysis is of major importance. Map-derived data have frequently been used in fluvial geomorphology and hydrology with insufficient regard for the dates of survey or for the compatibility of sections of a particular drainage network which are represented on different map sheets. Once network change has been shown to occur, then map edition and date of survey assume new roles of paramount importance in morphometric studies.

Stream density is a parameter often employed for the estimation of river channel processes especially peak discharge (e.g. Flood Studies Report, N.E.R.C.1975, Newson 1978), and, assuming that drainage networks extend, great care must be exercised to ensure the compatibility of discharge records with the corresponding extent of the drainage network. This is of particular importance for smaller basins where drainage density values are more sensitive to change (i.e. Hodge Beck Catchment).

For some time it has been suspected in the literature that changes of flood frequency may have been induced by alterations to the drainage network (Howe, Slaymaker and Harding 1967) but except in areas for which recent ditching has occurred (Painter, et.al.1974) it has been impossible to quantify the precise relationship between extensions to the drainage network and flood frequency. Precise measurements of extensions to the drainage network, obtained from successive editions of large scale Ordnance Survey maps, provide a basis for examining such relationships.

Recent modelling approaches (Beven Gilman and Newson 1979, Beven and Kirkby 1976) have concentrated on flood routeing and contributing area models for which certain mechanisms, forms and processes of network extension illustrated in Figure 8.3, have much relevance, and should be considered in future models.

Finally, it is increasingly necessary to appreciate that several types of stream channel landforms are inadequately generalised as a 'blue-line' on maps. By developing a process-based classification of channel types comprising the drainage network, historic changes in the drainage network can possibly be related to geomorphological changes such as those inspired by past patterns of climate. With this relationship understood, the prediction of drainage network change becomes a possibility.

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