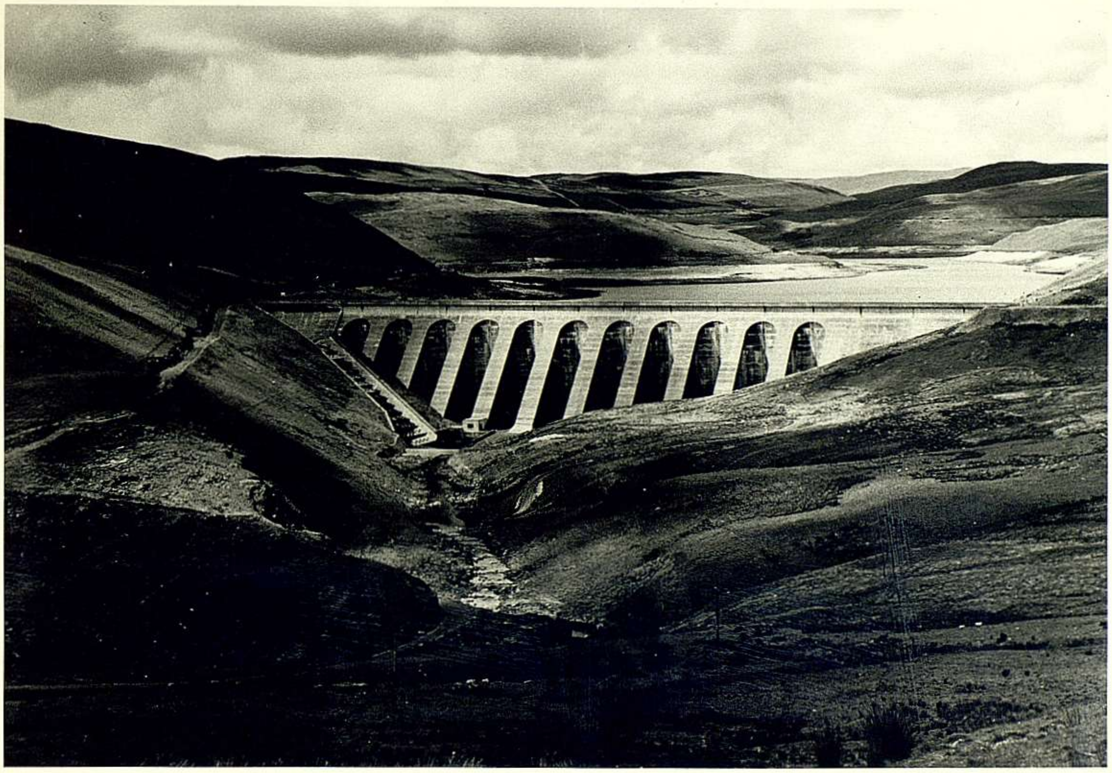

THE UPPER RHEIDOL BEFORE (TOP) AND AFTER (BOTTOM)
THE CONSTRUCTION OF THE NANT-Y-MOCH RESERVOIR.

UNIVERSITY OF SOUTHAMPTON

THE ADJUSTMENT OF RIVER CHANNEL CAPACITY DOWNSTREAM FROM RESERVOIRS IN GREAT BRITAIN

by

Geoffrey Eric Petts

This Thesis is submitted in fulfilment of the requirements
for the
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CONTENTS

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE

GEOGRAPHY

Doctor of Philosophy

THE ADJUSTMENT OF RIVER CHANNEL CAPACITY DOWNSTREAM FROM RESERVOIRS IN GREAT BRITAIN

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The variety of impacts that reservoir construction may have upon river channels in Britain are identified below fifteen dams located within diverse geomorphic and hydrologic areas. Channel changes are recognised by the comparison of field surveyed channel dimensions between regulated and non-regulated rivers. Regression analyses, relating the non-regulated channel dimensions to drainage area - a surrogate for discharge, provide an estimate of the pre-reservoir channel form. Sedimentological data, flow equations, and dating techniques are employed to corroborate this approach, and dendrochronology, applied to trees growing on channel sides and on floodplain margins, is demonstrated to be an effective technique for the dating of channel change in Britain.

Analyses of discharge records and theoretical flood-routing based upon methods advocated by the 'Flood Studies Report', 1975, indicate the variety of discharge changes that may occur consequent upon dam construction, and the significance of flood frequency changes for the channel form are evaluated. The dominant adjustment of river channels to river impoundment is demonstrated to be a reduction of channel capacity, but the observed spatial variation of channel response is complex. The factors influencing this complex response are illuminated and two primary mechanisms for channel adjustment are identified: the impact of reservoirs upon river flows, and the sediment introduced by tributaries are demonstrated to be significant factors. Major floods may be required for channel changes to be initiated, but the adjusted shape of the river channel will reflect the relative importance of sediment transport. Finally, a provisional model is presented to describe the complex adjustment of river channels downstream of reservoirs in Britain.

CHAPTER 1 INTRODUCTION

For more than two and a half thousand years man has sought to understand, to predict, and even to control nature in order to achieve the maximum benefits from available resources. Numerous examples exist of man's unintentional and sometimes deliberate alteration or destruction of natural systems due to ignorance of, or indifference to, the intricate balance existing between the numerous components of natural systems. Although researchers have for some time witnessed dramatic changes in the environment it is only since the turn of the century, and in particular during the past twenty years, that man has become aware of the problems which may arise through the unconsidered interference with the natural environment.

The fluvial system in particular may have been irreparably affected by man's desire for development and expansion. Early civilisations were concerned with controlling nature, and water supply and land drainage schemes were developed as early as 3200 B.C. (Drower, 1954). In Britain river works and land drainage schemes were certainly widely used by Domesday (Cole, 1976), so that today few rivers in Britain are truly natural. Indeed, Gregory (1976 a) cites the work of several researchers who, prior to 1920, described changes in channel characteristics, sediment loads, and flood frequency as a consequence of man's activities. However, the implications of these changes have not been further investigated until the last decade or so. This has been associated with the general lack of studies of fluvial landforms during the first part of the twentieth century (Gregory and Walling, 1973), a consequence of the paucity of field data, particularly streamflow measurements (Gregory, 1976 a). The past ten years have witnessed the rapid increase in both the number and variety of studies concerned with the identification of man's impact upon drainage basin processes. Accounts demonstrating the variety of impacts that man may have upon the hydrological cycle and upon river channels have recently been collected by Hollis (1978) and Gregory (1977) respectively. This thesis examines one aspect of man's interference within the fluvial system; the effect of reservoir construction upon river channels. However, before considering the specific aims of this thesis it is necessary to place the topic in the context of the development of fluvial geomorphology.

1.1. THE DEVELOPMENT OF FLUVIAL STUDIES WITHIN GEOMORPHOLOGY

The preoccupation of human geographers with spatial socio-economic factors since the turn of the century has been paralleled by a marked change of the definition of physical geography and of its position within geography as a whole. Geography continues to possess a 'physical basis' but this does not imply the classical man - land approach responsible for the development of regional studies during the first part of the century. Today, the 'physical basis' lies within the processes and characteristics of the natural environment which affect man.

The first attempts to understand the environmental systems were made during the sixth century B.C. (Biswas, 1967), but it was not until the seventeenth century A.D. that the teleological aspects, which dominated the research of the previous centuries, were replaced by experimental philosophy. This change, together with a resurgence of interest in practical hydraulic engineering at this time (Wolf, 1935) led to the rapid development of hydraulic research. Subsequent research was based upon the derivation of the concept of continuity by Castelli in 1628 although the idea, that discharge could be expressed in terms of cross-sectional area and velocity, was conceived by Hero of Alexandria in the first century A.D., and by Leonardo in the fifteenth century, but their works passed without recognition. In 1697 Guglielmini enunciated some of the basic concepts of open channel flow, and he has been viewed as the first important writer on fluvial geomorphology (Gregory, 1976 b; Lane, 1955). Prior to this time flow records were qualitative, based upon stage records alone, but the perfection of the current meter by Dr. Santorio Santorio revolutionised methods of evaluating river discharges (Frazier, 1969). The availability of data and the intellectual impetus provided mainly by the Italians (Biswas, 1968) led to a concerted effort to establish some of the fundamental principles of hydraulics through experimental investigations.

During the eighteenth century research concentrated upon developments within the field of surface water hydraulics, particularly with the calculation of velocity (Bernoulli, 1738) and discharge (Chezy, 1769). However, perhaps the most significant development during this century was by Brahms (1753) whose 'sixth-power law' focused attention upon the essential fact that the transporting and erosive power of a stream increases tremendously with velocity (Muir, 1968). This work was followed nearly one hundred years later by the formulation of the laws of erosion by Surrell (1841).

The roots of fluvial geomorphology lie not only in the works of early engineers but also in the later works of geologists. Until the late nineteenth century geologists were concerned with the primarily qualitative description of landform assemblages. However, the installation of the first continuous flow recorder by Powell in 1889 laid the foundations for the linking of form and process. Thus the works of Gilbert at the turn of the century (1887, 1914), based upon empirical observations and theoretical deductions, isolated many of the fundamental features of fluvial processes.

1.1.1. Early 20th century developments.

In Britain geomorphologists utilised the Davisian cycle of erosion for their basic methodology and the works of Gilbert were not followed by researches for half a century (Chorley, et al, 1964). During this time geomorphology became more diversified, particularly through the studies of the spatial variations of geomorphic process from continental Europe. Despite an increase in sedimentological studies with the formation of Hjülström's school of fluvial dynamics at Uppsala in Sweden during the 1930's, geomorphology maintained a qualitative framework.

In contrast, engineers attempted to relate velocity and discharge to channel morphology for design purposes. The efforts of British engineers in the design of stable irrigation canals in India led to the development of the essentially empirical, regime theory. Although the theory of regime was expounded within a large literature (Kennedy 1895; Lindley, 1919; Lacey, 1930) the principles embodied within it were generally ignored by geomorphologists, and it was not until Horton's 1932 and 1945 papers that a quantitative approach was re-introduced into geomorphological studies.

Horton's 1945 paper demonstrated how the problem of erosional morphology may be approached quantitatively and this work stimulated enquiry into the relationship between form and process. The development of a quantitative framework together with the availability of abundant hydrological and morphological data of rivers led to the application of the 'regime' approach to rivers, termed the hydraulic geometry of stream channels by Leopold and Maddock (1953). Their paper examined the temporal and spatial variations within the relationship between water and sediment parameters and channel form. Furthermore, the paper had an immediate impact upon geomorphology primarily because, together with Horton's (1945) earlier paper, a degree of order was quantitatively demonstrated to exist within the landform development.

1.1.2. The introduction of the quantitative and systematic frameworks.

Statistics were introduced into the Earth Sciences in the latter part of the nineteenth century (Charlier, 1968) but it was not until the 1950's that the broad foundations for quantitative research were laid within geomorphology. During the early 1950's Strahler produced a series of papers based upon mechanics and fluid dynamics (Strahler 1950, 1952). Strahler's 1952 paper introduced a dynamic approach to geomorphology which considered processes as forces within the environment producing a strain or failure within earth materials. Furthermore, the paper encouraged the formulation of mathematical models both by rational deduction and empirical analysis of observations data, to relate mass and time. Thus, the classification (Schumm, 1963), description (Strahler, 1957), and analysis of spatial variations among landforms (Melton, 1958) have been attempted within a quantitative framework. The importance of the quantitative expression of fluvial landform geometry has been discussed by Gregory and Brown (1966) who stressed the significance of technological developments facilitating the analysis of large amounts of data introduced by the multivariate nature of geomorphic studies.

The provision of a quantitative framework inspired the independent development of several fields of study within geomorphology. These fields not only spanned wide inter-disciplinary planes (Butzer, 1973) but also paralleled developments within related disciplines such as geology and hydrology. These developments provided new techniques and methods of study as well as additional data. Thus, within each individual field of geomorphology the range of specialisms became diversified, so that Gregory (1976 b) identified four particular fields of interest existing within fluvial geomorphology by 1960; basin characteristics, morphometry, channel patterns and channel geometry. However, the introduction of the systems approach (Chorley, 1962) to physical geography provided a common conceptual theme and served to re-unite the various disciplines.

The systematic approach attempts to rationalise physical geography which may now assume new significance and coherence. The establishment of an open system framework not only served to focus attention upon the possible relationships between form and process and the multivariate character of most geomorphic phenomena, but also to direct attention to the whole landscape assemblage. Furthermore, within fluvial geomorphology common elements contained in the specialised lines of research identified by Gregory (1976 b) became linked by theoretical developments involving entropy (Leopold and Langbein, 1962), stochastic or probability theory (Scheidegger and Langbein 1966), and the concept of dynamic equilibrium (Hack, 1960). Drainage basin studies, together with observations of runoff and sediment production, led to the realisation that the drainage basin was a dynamic rather than static unit. Thus, Hack (1960) viewed the physical landscape as composed of dynamic equilibrium conditions between form and process. The existence of equilibrium between form and process in studies of river channel geometry has been termed quasi-equilibrium (Langbein and Leopold, 1964) because the landforms may be adjusted to events of particular magnitude. The Davisian 'Cycle of Erosion' has been discounted by many in favour of dynamic equilibrium, but it is current practice (Schumm, 1973) to visualise dynamic equilibrium within the conceptual framework of geomorphological time as, in landform development, the distinction between cause and effect is a function not only of the size of the system in space but also of the length of time under consideration (Schumm and Lichty, 1965). In fact, the first two characteristics of a process-response system outlined by Chorley and Kennedy (1971, p.128) are conformed to by the Davisian model (1899).

1.1.3 The present status of fluvial geomorphology.

During the past decade an increasing number of equilibrium conditions have been recognised between form and process, both within the drainage basin as a whole and in its component subsystems. Any change over time may lead to an adjustment of basin characteristics in drainage basin process. Attempts to visualise this change within the landscape over time has given rise to a new approach within geomorphology. Palaeogeomorphology is directed at the interpretation of landform sequences and to the utilisation of this information for the prediction of future changes. Thus, Schumm (1969) identified the complete metamorphosis of river channels as a consequence of climatic changes from which equations were developed to describe the response of river channels to changes in discharge and sediment load.

The recognition of the drainage basin as the fundamental geomorphic unit (Chorley, 1969) resulted in the concentration of activity within geomorphology upon the subject of fluvial processes. Thus, following a period of consolidation and re-union of the various elements of geomorphology the past few years have witnessed a more fundamental and more theoretical appreciation for the basis of fluvial landform sequences. Furthermore, it has been suggested that fluvial geomorphology may now be regarded as potentially an applied science. A complete understanding of the nature and significance of channel geometry is, for example, required in order to improve water supply and land drainage schemes (Ackers, 1972). Indeed, one reason for the recent surge of interest in the measurement of geomorphic processes may stem from the need to utilize knowledge of processes in the interpretation of temporal change.

1.1.4 The fourth dimension.

The spatial variation of fluvial landform is particularly dependent upon the rate of change of the individual landforms with time. Traditional approaches to change require that the system be affected by an application of an external stimulus such as man or climatic change. However, Schumm (1973) has suggested that some geomorphic anomalies may be an inherent part of the erosional development of landforms, and that the components of a geomorphic system need not be in phase. This may therefore complicate the recognition of changes within the system to specific events or impacts. Nevertheless, numerous examples exist of changes within drainage basins to a variety of causes. The possibility of river channel changes consequent upon the interference by man through the modification of rates of water and sediment discharge was elaborated by Lane (1955), and the variety of impacts that man may have upon stream regimen have been reviewed by Mrowka (1974)as direct channel alteration, modification of watershed characteristics, urbanisation, inter-basin transfers, and water pollution. Despite the increase in awareness of the need to evaluate environmental impacts on the landscape (Emmett, 1974), upon continental waters (Unesco, 1972), and more specifically upon river channels (Einstein, 1961), one effect of man upon stream channels that has been virtually neglected is that of reservoir construction.

The literature is replete with examples of the degradation of river channels below reservoirs (Leopold et al, 1964), a result of the often complete abstraction of the sediment load available to reaches below the dam. Although the understanding of the relationships between form and process are, as yet, imprecise, it is generally agreed (Gregory, 1976 a) that the frequency of flood discharges and the magnitude of the sediment yield are dominant features. However, Nixon (1959) suggested that the sediment load of rivers in England and Wales is small so that the effect of the sediment discharge upon channel form may also be small. Thus, discharge may have the predominant effect in determining the channel capacity of British rivers and may be the dominant control of channel adjustment downstream from reservoirs in Britain.

1.2. THE AIMS OF THE THESIS

This thesis seeks progressively to achieve three aims:-

(a) To identify the variety of effects that reservoir construction may have upon river channels in Britain.

(b) To evaluate the significance of changes in the flood frequency distribution consequent upon dam closure, to the channel form.

(c) To illuminate the factors which control the magnitude and rate of river channel adjustment to an alteration of the flow regime.

The present state of knowledge of the adjustment of river channel form is reviewed in Chapter 2 together with a summary of the literature relating to the impact of reservoir construction upon channel form and process. An approach to the identification of channel changes downstream from British reservoirs is developed in Chapter 3 and, following a discussion of potential study areas and the data required, this approach is applied to the River Derwent, Derbyshire. This study demonstrates that the approach adopted may be applied to the detection of river channelchanges downstream of reservoirs in Britain. Thus, the variation of channel changes consequent upon reservoir construction within similar geomorphic and hydrologic regions (Chapter 4) and between individual locations (Chapter 5) is examined. Based upon the information provided by the preceding chapters, Chapter 6 seeks to determine the importance of changes within the flood frequency distribution to the adjustment of river channel capacity, and the factors which control and constrain the rate of channel adjustment are evaluated in Chapter 7.

The information provided by this study may not only be applied to the estimation of channel changes below future reservoirs but also to explain the spatial variation between and within individual systems at a particular point in time, and to illuminate the significance of specific discharges for the production and maintenance of river channel dimensions.

CHAPTER 2 THE ADJUSTMENT OF RIVER CHANNEL FORM

The definition of the drainage basin within a system's framework (Chorley, 1962) led to the establishment of the river channel as the fundamental component of the drainage basin. Moreover, within the open system a tendency toward a steady-state condition by self-regulation exists so that river channel morphology is adjusted to the input of water and sediment supplied by the drainage basin. Thus,

> "If equilibrium exists in a reach of a river, a change in only one condition at a single point which would upset the equilibrium at this point would, if no other factors changed, eventually upset the conditions of equilibrium throughout the entire reach and bring about a new condition of equilibrium in this reach."
>
> (Lane, 1955a, 185)

The examination of the response of river channels to sediment and water discharge impoundment consequent upon reservoir construction requires the determination of the factors controlling and constraining the equilibrium channel form. Section 2.1. outlines the development of studies concerned with the determination of the equilibrium form of river channels and identifies the factors which account for the spatial variation in river channel morphology. Temporal variations within channel form resulting from changes of one or more of the independent controls are reviewed in Section 2.2 and a literature survey from throughout the world has provided evidence of the impact of reservoir construction upon channel form and process (Section 2.3). The information derived from the reported temporal variations may then be applied to the examination of the effects of river impoundment upon river channels within Britain.

2.1. THE QUASI - EQUILIBRIUM CHANNEL FORM

The recognition of the existence of equilibrium between form and process within the drainage basin has provided a basis for subsequent channel studies concerned particularly with the spatial and temporal variations of fluvial landforms. The conception, and development of the fundamental principles of an equilibrium state existing between stream channel morphology and the supply of water and sediment from the drainage basin was however, inherent within earlier channel studies involving the design of stable irrigation channels by engineers and the study of the hydraulic geometry of stream channels by geologists.

2.1.1. The development of stable channel design.

During the eighteenth and nineteenth centuries many of the fundamental concepts of hydraulic research were formulated, so that by the beginning of the twentieth century engineers had attempted to define the conditions required for the designing of stable alluvial channels. Two independent theories were developed, the essentially empirical regime theory, and the more rational tractive force theory.

The Tractive Force theory developed from the work of Du Boys (1879) who examined the effect of channel slope upon channel stability. Du Boys made the first attempt at the formulation of a rational theory of bed-load transport, postulating that the bed-load discharge should be a function of the difference between bed-shear stress and the critical shear stress of the sediment particles on the bed, that is, a function of the excess tractive force. Nearly fifty years later the theory was outlined by Lane (1937) and applied to channels in both non-cohesive (Lane, 1952) and cohesive (Smerdon and Beasley, 1959) materials. However, the theory makes unrealistic assumptions for the evaluation of the shear at the interface between the flowing water and the bed-material. Within natural equilibrium channels the forces exerted on, and the stability of, the bed and bank material will vary (Simons and Albertson, 1960) and the channel bed will become 'live' during high discharges so that the threshold conditions will no longer apply (Richards, 1977). Thus, whilst the tractive force theory is generally adequate for the determination of an equilibrium channel form within coarse material, low sediment load discharges (Maddock, 1973) it fails with high concentration, sand bed channels within which sediment transport is complicated by the variation of bedforms and roughness with discharge.

Developing parallel to, and generally independent of, the tractive force theory the theory of regime in open channel hydraulics, though essentially empirical rather than theoretical, was based upon experimental and field evidence. Regime theory was initiated by Kennedy in 1885 who related velocity to a power function of channel depth, and although the first written definition was not published until 1919 by Lindley, the idea of regime was gradually elaborated and it was soon realised that there was probably an optimum channel design which would accommodate the discharge of water and sediment at a constant rate without the occurrence of aggradation or degradation. In 1933 Lacey published several ralationships, based upon Kennedy's original data and the hydraulic mean depth, to calculate the complete hydraulic data of stable channels. Field data were derived primarily from straight irrigation canals in India and the analysis of his data led Lacey to conclude that most canals would be described in respect of their regime dimensions by three equations, being functions of discharge, velocity shape, and a sediment factor. The applicability of the Lacey formulae has been elaborated by Blench (1957).

Subsequent advances in regime theory have been made by Inglis (1947, 1949a) who realised the importance of sediment transport (1947, 1949b), and examined the mechanism of change which controls and maintains a dominant state of equilibrium in regime channels. He attempted to identify the factors maintaining this state and to demonstrate the relationship between channel shape and slope, and the quantity and grade of sediment in transport. Although concluding that the shapes and dimensions of channels were produced by a dominant discharge he appreciated that the regime concept permitted variations in channel form about the mean due to seasonal variations in water and sediment discharge, and (1949a, 9) that the situation within river channels, rather than canals, was more complex owing to the variation of discharge and sediment loads over time. The constancy of sediment concentration and discharge throughout the length of canals of India and Pakistan avoided the problem of changing bed-form with discharge variation, and hence roughness, characteristic of natural rivers. Furthermore, the influence of variations in bank material on channel form was generally ignored. Several authors have considered that it is impossible to establish determinate relationships for the solution of the dual problems of flow resistance and sediment transport in alluvial channels (Vanoni and Brooks, 1957, Maddock 1970) due to the variable nature of the bed configuration and associated changein roughness as discharge varies. Nevertheless, it has been demonstrated (Grishanin, 1972) that the movement of channel bed forms does not interfere with the stability of a reach as a whole. Furthermore, regime theory only sets out to establish the conditions for the existence of equilibrium within open channels, it does not specify how the equilibrium is to be attained. However, the theory may be used to indicate the responses of river channels to change in the independent or even one of the dependent variables (Maddock, 1970). The problems lie not in using the general relationships, but in assigning numerical values to the coefficients and in choosing a formal equation (Laursen, 1958). Even though regime theories have generally diminished in popularity over the past decade or so, they have encouraged research into the mechanics of sediment transport and have initiated thought on the effect of changes in water or sediment discharge upon channel form.

2.1.2. The hydraulic geometry of river channels.

The empirical, experimental and theoretical studies of stable channel design indicated that relationships should exist between form and process within natural river channels. Thus, Leopold and Maddock (1953) examined the variation of channel form and flow parameters with discharge. The relationships developed, describing the 'hydraulic geometry' of river channels, were inspired by the introduction of quantitative framework within geomorphology (Horton, 1945) and utilised river data collected by engineers over a period of 70 years. Leopold and Maddock demonstrated that straight-line relationships of the logarithmic values described the variation of channel form and flow parameters with discharge both for particular cross-sections and along a river. These relationships indicated that channel width, channel depth and flow velocity variations could be expressed in the form of simple power functions. The sum of the exponents within the relationships being equal to unity in order to satisfy the condition of continuity. Furthermore, the study introduced the significance of discharge of constant frequency for determining along-channel relationships.

Utilising the discharge at the mean annual flood as the basis for study Leopold and Maddock (1953) determined the average values of the exponents for the south-west U.S.A. However, subsequent work has demonstrated that marked contrasts exist between values determined for different environments (Table 2.1). Park (1977) has collated the exponent values reported in the literature and categorised these according to the environmental conditions. Such studies are of value for the comparison of river channel geometry between areas, and provide opportunities for the analysis of the influence of basin characteristics. For example, the rate of increase of channel width is more rapid within channels having non-cohesive bank materials than those with cohesive banks.

TABLE 2.1. Hydraulic geometry variation between rivers.

Region	Width	Depth	Velocity	Bank[1] materials	Source
	Exponent Values				
Mid-West, U.S.A.	0.26	0.40	0.34	n	Leopold and Maddock, 1953
Ephemeral streams, U.S.A.	0.29	0.36	0.34	n	Leopold, Wolman, Miller, 1964
Cheshire, U.K.	0.29	0.40	0.31	n	Knighton, 1972
White River, pro-glacial.	0.38	0.33	0.22	n	Fahnestock, 1963
Norway, pro-glacial.	0.30	0.40	0.28	n.	Petts, 1974
Norway, pro-glacial.	0.12	0.40	0.45	c	Petts, 1974
Pennines, U.K.	0.09	0.36	0.53	c	Wilcock, 1971
Brandywine Creek, U.S.A.	0.04.	0.41	0.55	c	Wolman, 1955

[1] c = cohesive; n = non-cohesive

Similar studies have examined the variation of suspended load, slope, roughness and bed-material, as well as width, depth and velocity, with discharge.

The downstream variations of channel form and flow parameters and discharge contained a large amount of scatter. This has been recognised by Wolman (1955) from a study of Brandywine Creek to be the result of local variations in channel form. Thus, Knighton (1974) described variations of the width exponent in relation to the percent silt-clay of the banks, responsible for the bank angle. Similarly, Richards (1976) has observed variations in the exponents between riffle and pool locations, the flow geometry in the pool tending to be determined by the depth of flow over the downstream riffle. Furthermore, at any one particular section the hydraulic geometry exponents describing the cross-section will vary annually (Knighton, 1972, 1975) in response to natural short-term changes in discharge and sediment yield, channel migration, and during specific flood events if the bed and banks are modified. Thus, at-a-station scatter may be explained by variations in roughness and bed configuration with varying discharge and to scour at high discharges (Richards, 1977).

The development of bi-variate relationships between variables within systems inherent in Leopold and Maddock's (1953) paper provided geomorphological evidence for the existence of an equilibrium condition through the identification of significant correlations (Chorley and Kennedy,1971). Indeed a close response relationship between channel form and process is implied in the relationships developed within the hydraulic geometry approach. The relationships between channel width and depth, and discharge, both at-a-station and downstream, imply that channel geometry is adjusted to the independent variables of discharge and load.

2.1.3. The definition of equilibrium within river channels.

During the first half of the twentieth century geomorphologists were preoccupied with the Davisian Cycle of Erosion and the advances made by engineers in the development of the theory of stable channel design were generally ignored. It was not until Leopold and Maddock's (1953) classic paper that geomorphologists gained an appreciation of the relevance of the concept of equilibrium to river channels. The concept of grade inherent in the work of Davis (1902) was defined by Mackin (1948, 471):

> "A graded stream is one which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transport of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change."

Although expressing the concept of equilibrium grade assumes the maintenance of the equilibrium state to be uniquely determined by an adjustment of channel slope. In that respect, grade differed from the 'regime' condition within river channels as identified by engineers. Lindley (1919, 63) stated that:

> "the dimensions, width, depth and gradient of a channel to carry a given supply of water loaded with a given silt charge were all fixed by nature."

Regime theory considered that a river channel would not only adjust to the water and sediment discharge through a change of gradient but also by an alteration of its cross-sectional dimensions. Furthermore, Inglis (1949,2) considered that "channels which do not alter appreciably from year to year though they may vary during the year - are said to be 'in regime'." Thus,...

> "Regime suggests considerable freedom of individual behaviour within a framework of laws and has no short term connotation ... capable of acquiring regime, or equilibrium eventually by self-adjustment of its non-fluid boundaries, if the imposed conditions do not change on a long-term average."
>
> (Blench, 1961)

In 1952 Rubey (1952) demonstrated, from the analysis of Gilbert's (1914) experimental flume data, that an equilibrium condition within river channels may be maintained through changes in channel cross-sectional dimensions as well as channel slope. The link between engineering research and fluvial geomorphology was established by Lane (1955a) in a discussion of equilibrium in natural streams from both the geomorphological and engineering viewpoints. Field observations subsequently demonstrated the significance of self-regulation within river channels. Thus, Leopold and Wolman (1957) demonstrated that a river channel would adjust to variations of streamflow by changing its planform in order to maintain an equilibrium condition. Changes in planform however, require a relatively long time period. Wolman (1955) suggested from the study of Brandywine Creek, that a stream can effectively and rapidly adjust its cross-sectional form in order to absorb the effect of a change in the independent controls. Thus, Hack (1960) envisages that a stream or reach may be virtually always adjusted without developing the smooth longitudinal profile inherent in the Davisian Cycle, so that the geometry of stream channels (Leopold and Maddock, 1953) achieved significant correlations with contemporary processes.

Channel form variations are balanced about a constantly changing system condition which has a trajectory of unrepeated 'average' states through time. This state has been termed 'dynamic equilibrium' (Chorley and Kennedy, 1971), and the balance involving the existence of a steady state condition without involving any regularity of form has been termed quasi - equilibrium (Langbein and Leopold, 1964) with reference to river channels. Therefore, the quasi-equilibrium channel form, is directly comparable to the regime channels defined by engineers. Within a constantly changing energy environment and subjected to a definite set of constraints, river channels tend towards a steady state condition. Although absolute equilibrium is seldom actually present, river channels will adjust their gradient, planform, and cross-sectional dimensions to prevailing conditions and may retain no influence of previous conditons.

2.1.4. Quasi-equilibrium within river channels.

A system in quasi-equilibrium will represent the most probable state between two opposing tendencies encompassed in the theories of minimum variance (Langbein and Leopold, 1966: Scheidegger and Langbein, 1966) and minimization of work (Leopold and Langbein, 1962). Leopold and Langbein (1962) reasoned by analogy with thermodynamic entropy that the most probable distribution of energy in certain geomorphic systems could be derived by considering the geomorphic system as an open system in steady state. Thus, the most probable energy distribution would be a compromise or intermediate state between the tendencies toward a uniformly distributed rate of energy expenditure and minimum total work expended in the system. Therefore, in accommodating a change in stream power a channel changes so that each component of power changes as equably as possible (Langbein, 1964). However, because these tendencies are statistical, the theory shows that there are no unique solutions. Thus, Langbein and Leopold (1964, 793) defined the quasi-equilibirum condition within river channels as: "a mean or modal condition merely somewhat more probable than other possible conditions".

Probability concepts imply an assumption of randomness, and Scheidegger and Langbein (1966) proposed that river channels produced by flowing water may be dominated by random processes. The assumption of randomness permits the use of statistical concepts to describe the physical state of a river and its dynamic equilibrium. Thus, Langbein and Leopold (1966) have shown that the most probable random walk pattern describing river channel planform, a meander, satisfies the conditions of minimum variance. Field observations (Langbein and Leopold, 1966) demonstrated that the downstream spatial variance in shear and friction were lower in natural meandering channels than in otherwise comparable straight reaches of rivers.

The conception of the two theories describing the opposing tendencies toward minimum work and uniform distribution of work gives firm support to the hypothesis that the condition of quasi-equilibrium is reached and maintained very rapidly. Therefore, the river channel may remain in quasi-equilibrium with the controlling factors during the long term reduction of relief. Where the particle size distribution of the bank materials of a channel are known, regime conditions can be calculated by the solution of four equations, the equations of motion and continuity for water and sediment (Prins and de Vries, 1971). However, the prediction of the exact dimensions of river channels for a steady state condition to be attained is problematic (Maddock, 1970).

River channels possess five degrees of freedom (Langbein, 1964) being able to adjust their roughness, slope, width, depth and planform to maintain a quasi-equilibrium state. Thus, Langbein and Leopold (1966) demonstrated from field observations, that the channel properties of depth, velocity and slope will adjust so as to decrease the variance of shear and friction on the stream bed. Langbein (1964) considered that the quasi-equilibrium state requires the satisfaction of three physical relations - continuity, an hydraulic relation between velocity, depth, slope and roughness, and an hydraulic relation between stream power and sediment transport. Recently Hey (1974) advocated the use of five process equations to explain how a river adjusts to the independent variables - the input of water and sediment and valley slope - based upon the five degrees of freedom possessed by river channels. Although all five equations do not, at present, have solution, Hey (1974) suggested that the continuity, flow resistance, bed load, bank competence and meander equations could define the three dimensional geometry of alluvial channels. Thus, Knighton (1975) identified four ways in which a stream can adjust its channel form; by changes of planimetric geometry, channel bed-slope, cross-sectional dimensions or bed-configuration.

2.1.5. The significance of discharge in relation to channel form

The recognition of the existence of a quasi-equilibrium state between river channel form and process has demonstrated the importance of discharge frequency (Leopold and Maddock, 1953). Indeed, Inglis (1947) had suggested that river meanders are adjusted to a dominant discharge at which equilibrium is most closely approached and the tendency to change is least. Thus, Wolman and Leopold (1957) concluded that the channel dimensions at bankfaull stage on many rivers could be defined by the frequency of flooding. However, subsequent workers have demonstrated that it is difficult to formulate a measurable variable of discharge which characterises the system under investigation and satisfactorily provides a single, suitable discharge index. Whilst it is recognised that some standard definition of the discharge index to be used at each station is essential, for the comparison of river channel data, it has been demonstrated (Harvey, 1969, 1975) that a single discharge variable may not be equally representative of the discharge distribution at each station, and may vary in its channel forming significance.

A study of the mechanics of flood-plain formation by Wolman and Leopold (1957) revealed that a remarkable similarity existed in the frequency of bankfull stage on a variety of rivers of various scales and from diverse environments. An independent study by Nixon (1959) of rivers in England and Wales concluded similarly, that the frequency of the bankfull discharge was further expressed by the application of regime formula (Nixon, 1959) derived from the work of Lacey and Inglis. Subsequently, the existence of a common bankfull discharge was justified on the grounds of sediment transport rates by Wolman and Miller (1960) whose calculations equated the discharge at bankfull stage with the flow that collectively transports most sediment. Furthermore, Langbein (1964) demonstrated that flow resistance decreases as stage increases within the channel and reaches a minimum at bankfull stage (Hey, 1972). Thus, the channel operates most efficiently with regard to water conveyance at bankfull stage. Indeed, the laboratory analysis of meanders under varying discharges (Ackers and Charlton, 1970) provided evidence in support of the recommendation made by Inglis (1947) that the bankfull flow was the dominant condition for river channels. Thus, the channel forming discharge is accepted in part of the literature to be represented by the discharge at bankfull stage.

The equilibrium form of river channels has been demonstrated to be adjusted to a dominant discharge. This discharge has been defined in relation to channel pattern as "the steady flow that would yield the observed meander length in otherwise similar conditions" (Ackers and Charlton, 1970, 250) and is "usually taken to be the bankfull discharge in streams where the flow is variable", (Sellin, 1969). Whilst Bray (1975) defined the dominant discharge (p.143) as "the discharge which, when flowing continuously, would result in the water surface width and the cross-sectional area of a relatively stable natural channel", he recognised that:

> "The dominant discharge ... cannot be simply defined for a river reach. In most cases a representative discharge must be selected which is reasonably close to the true dominant discharge and which can be computed in an objective manner" (p.152).

Definitions of the dominant discharge determined from hydrological analyses have been expressed in terms of specific return periods or specified flow durations. Thus, in their pioneer study of river channel hydraulic geometry, Leopold and Maddock (1953) utilised the mean annual discharge as representative of the dominant discharge. Dury, Hails and Robbie (1963) preferred a statistical definition of the bankfull discharge, the 1.58 yr. flood on the annual series. This is similar to the value derived by Hey (1975) for upland, gravel bed rivers in the United Kingdom, based upon the comparison of field survey channel dimensions and gauged flow data. Furthermore, Woodyer (1968) produced evidence from field observations to substantiate the claim for a common bankfull frequency of between one and three years on the annual series. However, a series of papers by McGilchrist, Woodyer and Chapman (1968, 1969, 1970 1972) discussed the problems of determining recurrence intervals for non-seasonal rivers. The usual methods of analysing the frequency of exceedence of selected river levels (Chow, 1964) fail to consider the actual intervals of time between successive exceedences. Thus, McGilchrist et al (1968, 1969) utilised exponential, gamma and Markov models for the analysis of the probability of exceedence of a selected stage using daily maximum water levels in order to examine the discharge frequency at bankfull stage.

Examination of the degree of correlation between meander wavelengths and a variety of discharge indices (Carlston, 1965) indicated that wavelength is only poorly correlated with bankfull discharge. A much closer correlation with more frequent discharges, particularly the mean annual discharge, was demonstrated. Results obtained from laboratory analysis by Ackers and Charlton (1970) contradicted the conclusions of Carlston (1965), but indicated that the dominant discharge would have a different value for different channel form parameters. This view was supported by Harvey (1975) who demonstrated that whereas the overall adjustment of the gross form of the channels is primarily to rarer discharges, the adjustment or perhaps maintenance of the detailed configuration of small scale features - such as pools and riffles - appears to be related to more frequent discharges well below bankfull stage. Furthermore, Harvey (1969) demonstrated that for three rivers in south-east England the frequency of the bankfull discharge is dependent on the flow regime. As the baseflow portion of the annual discharge increases, the associated bankfull frequency is reduced. Similarly, Dury (1961) observed that a discrete event of fixed return period increases in duration, although it remains constant in frequency, along the length of the channel. Therefore, the decrease in flow variability downstream, resulting from flood wave attenuation, may be expected to affect the magnitude and frequency of the dominant discharge.

The definition of the dominant discharge has been attempted on a morphological basis as the bankfull stage of the river channel. This has received a great deal of attention and the problems of identifying the bankfull stage have been reviewed by Gregory (1976c). The first attempt at a morphological definition of the dominant discharge was made by Wolman (1955) who identified 'bankfull' as the stage at which the channel width-depth ratio is at a minimum. Subsequently, sedimentological (Nunally, 1967), vegetational (Leopold and Skibitzke, 1967), morphometric (Riley, 1972) and morphological (Brush, 1961) criteria have been advanced for the determination of the bankfull capacity of river channels. The applicability of these techniques to channel studies in Britain will be referred to later (Section 3.2.4.). However, the relation of a topographic definition of bankfull stage to an index of discharge for Piedmont streams (Kilpatrick and Barnes, 1964) demonstrated that the recurrence interval of the bankfull discharge increased as channel slope steepened. Thus, that the frequency of overbank flows should be consistently uniform among rivers (Wolman and Leopold, 1957, 1) appears to be unlikely. Nevertheless, Bray (1975), from a study of rivers in Alberta, utilised both hydrological and morphological evidence to determine the dominant discharge of river channels. The width-discharge area-discharge relationships developed had the highest correlation coefficients when the two-year flood was adopted as representative of the dominant discharge. The two-year flood is the median flood in the log-normal analysis and consequently is best defined for a given hydrological record. This frequency corresponds closely to other results cited herein and to data from American rivers documented by Leopold et al (1964, p.320).

Dominant discharge has also been defined as the range of flows which over a period of time, transports the most bed-material load or bed-load. Such a definition has been adopted by Marlette and Walker (1968) and Prins and de Vries (1971) whilst Benson and Thomas (1966) applied a similar definition incorporating the maximum suspended sediment transport. Thus, Pickup (1976) demonstrated for four Cumberland Basin stream channels that bed-load channels tend to adjust their cross-sectional form to become the optimum shape for bed-load transport at or close to the discharge at which the most bed-load transport is accomplished. However, the hitherto accepted tendency to equate the discharge at bankfull stage with the flow that collectively transports most sediment (Wolman and Miller, 1960) has been questioned (Pickup and Warner, 1976). Data from rivers within the Cumberland Basin indicate that the frequency of the most effective discharge for bed-load transport contrasts with the bankfull frequency. The most effective discharge for bed-load transport being more frequent. The amount of work effected by different discharges in transporting the sediment load is related to the flow variability. The more variable the flow is, the greater the duration of high flows and the greater part in transporting the load of the stream. Conversely, the less variable the flow is, the more important the lower and more moderate discharges become as long as they are competent. Thus, for the low flow variability Cumberland basin streams, most sediment is transported by very small flow (Pickup and Warner, 1976).

An exact correspondence between the discharge at bankfull stage and the optimum discharge for bed-load transport (Pickup, 1976) should not be expected as other energy expenditure conditions have to be simultaneously satisfied (Leopold and Langbein, 1962: Langbein and Leopold, 1964). In fact, Tanner (1977) considered that the equilibrium stream represents a compromise between three tendencies, to maximize grain size, to maximize the quantity of bed-load transported and to minimize bed shear stress representing water discharge among other things. Thus, whilst the most efficient channel for water conveyance, the channel with the maximum hydraulic radius has a semi-circular cross-section Lane (1957), Sundberg (1956) and Schumm (1963) have noted that bed-load channels tend to have a wider and shallower cross-sectional form. This may represent the maximum hydraulic radius the channels are able to attain under the conditions of character of bed, amount of load and other contributing variables. The often marked discrepancy between the bankfull discharge and the most efficient discharge for bed-load transport for the Cumberland Basin rivers have, however, been used to identify channels that are incised (Dury, Hails, Robbie 1963; Hickin, 1967), that is the channel form is not adjusted to the existing flow regime. Where the channel is non-mobile, having cohesive bank materials or banks stabilised by vegetation, occasional overbank deposition and channel bed-degradation may increase the channel capacity. Similarly, a decrease in the value of the bankfull discharge should, it has been suggested (Leopold and Wolman, 1957, 3), result in a reduction of channel width, determined by the balance between erosional and resistive forces, and that depth and velocity will adjust within that constraint. The reduction of channel width is, however, a slow process so that a time lag will exist between process change and channel form response, the length of time being dependent upon local environmental conditions.

Although the precise definition of the dominant discharge is, as yet, uncertain, and reference to the frequency scale has obvious advantages, the relationship between channel bankfull capacity and drainage area, a common surrogate for discharge, has been successfully employed in the United Kingdom. Thus, both the spatial (Park, 1976) and temporal (Gregory, 1976 a) variations of the equilibrium channel form have been identified.

2.1.6. Factors influencing channel form.

The quasi-equilibrium form of river channels is a result of the interaction between water discharge, quantity and character of the sediment load, and the composition of the bed and bank materials (Leopold et al, 1964). Independent variables other than water and sediment discharge are therefore of significance to river channel form particularly if analysis is conducted at a regional scale (Brush, 1961) where the probability of variation of bed and bank material is greater than in a single, small catchment. Thus, variations of channel hydraulic geometry, recognised by Leopold and Maddock (1953) reflect the influence of independent or semi-independent variables which affect the size and shape of channel cross-sections. The actual form of river channels will constrain the influence of both the tendency toward adjustment to quasi-equilibrium and the effect of lithology, structure and geologic history (Langbein, 1964) on a catchment scale, whilst within a single reach the channel form will be constrained by the nature of the bed and bank materials and variations in the role of vegetation.

(a) Slope

Stream profiles are adjusted to transport the products of erosion from their basins at rates determined by the initial relief, time and geology (Hack, 1957). However, changes in river channel slope, except for local adjustments, require a long period of time. Therefore, channel slope may be considered to be an independent variable. Brush (1961) in an examination of the spatial variation of river slopes within Pennsylvania, demonstrated that within an hydrologically similar area, valley slope may account for the observed variations in channel form parameters. Although the slope of the valley floor, often composed of inherited valley fill, is an independent control initially determining the rate of energy loss, channel gradient is also a function of planform. The river channel planimetric dimensions are adjusted to the prevailing load and discharge conditions, so that the channel gradient is partially dependent. Nevertheless, Park (1975) demonstrated the existence of an inverse relationship between slope and channel capacity based upon field data from the channel network of the river Dart in Devon. The net channel slope of an individual branch within the channel network is demonstrated (Park, 1975) to condition the rate of increase of channel capacity relative to drainage area in that branch. This relationship may be attributed to the influence of channel slope on flood routing and hence on channel form variations downstream. Thus, Kilpatrick and Barnes (1964) related channel depth at bankfull stage to the mean flood and channel slope. The introduction of a slope variable into the channel capacity - drainage area relationship for the Yorkshire Dales rivers having profiles inherited from glacial drainage channels, permitted

Gregory and Park (1976) to determine the drainage area required to support a specific channel capacity with a particular slope value under uniform geology but different annual rainfalls. Therefore, the variations of channel slope, a combination of valley slope and planform, may explain the variations of channel cross-sectional form.

(b) Bed-material.

The particle-size distribution of the channel bed-material influences channel roughness and the velocity distribution. Tanner (1977) recognised that an equilibrium stream represents not only a compromise between the tendencies to maximize the quantity of bed-load transport and to minimize bed shear stress, but also to maximize grain size. Thus, bed-material and discharge may be related. However, where immobile residual bed-material occurs, inherited from a palaeohydrological regime, channels have been identified (Wilcock, 1967) to be wider and steeper than normal given their discharge characteristics. However, Schumm (1960) observed high width-depth ratios within coarse bed-material streams resulting from lateral migration and undercutting. This widening may arise from flow diversion by riffles into which coarse material accumulates (Richards, 1976 a) rather than being a direct consequence of the bed-material. Therefore, high width-depth ratio channels may represent the equilibrium form of rivers having coarse bed-materials. Furthermore, the calibre of the channel bed-materials has been related to river gradient as well as to discharge. Hack (1957) demonstrated that, for rivers in Virginia and Maryland, at a given drainage area, the channel slope is directly proportional to a power function of the size of the bed sediments. Similarly, Cherkauer (1973) demonstrated the association of steep slopes, coarse bed-materials and high width-depth channels.

(c) Bank-material.

Where the valley fill is inherited from a former hydrological regime, that is where the valley floor deposits are not related to the contemporary flow regime, the composition of the bank material will be an independent variable and thus an important control upon channel form (Schumm and Lichty, 1965). Although the factors affecting channel shape are not fully understood, Schumm (1960) demonstrated that the channel shape is a function of the percent silt and clay within the bank sediment, and Glover and Florey (1951) related the bank material shear strength to the transverse bank slope. Thus, Pickup and Warner (1976) concluded (p.73) that "the strength of the channel perimeter material may ... completely modify the role of the hydrologic regime" in determining channel dimensions. If the resistance of the channel perimeter sediment is high, low frequency, high magnitude discharges may play an important part in channel development. Low resistance materials will be affected by small and more moderate flows. The dimensions of river channels may be a function of the strength of the channel perimeter sediment and the impinging fluid force.

(d) Non-fluvial factors :-

(i) Vegetation - within humid environments the bank resistance to erosion, which has been related to the soil shear strength (Glover and Florey, 1951), physico-chemical factors (Partheniades, 1970), and the percentage of organic matter (Smith, 1976), may be controlled by the relatively unquantifiable influence of bank vegetation. Lewis (1969) further demonstrated that in-channel vegetation may act to prevent bank erosion by increasing flow resistance and encouraging energy dissipation. Observations of the changes in floodflow characteristics of a rectified channel (Wilson, 1973) revealed that the channel capacity of earthen channels may be reduced by 50 percent as a result of only one year's growth of vegetation. The reduction of channel capacity was associated with the growth of in-channel vegetation which increased channel roughness affecting the stage-discharge relationship. The influence of bank vegetation upon stream channel morphology has been assessed by Zimmerman et al (1967) for reaches of the Sleepers River basin in Northern Vermont. They demonstrated that for small drainage areas, of less than 2.07 km^2 encroaching vegetation would eliminate the effect of the downstream increase in discharge, so that channel dimensions are primarily influenced by vegetation factors. However, the influence of vegetation decreases as drainage areas increase, and the largest channels having drainage areas greater than 10.3 km^2 are affected only to a marginal extent by vegetation.

(ii) Frost-action - the cross-sectional forms of river channels will be particularly modified by frost-action. In contrast to the effect of vegetation, frost-action will increase the susceptibility of bank material to erosion. Leopold et al (1964) observed that channel bank erosion was most rapid during winter months when freeze and thaw and moisture in the soil greatly lower the shear stress required for erosion. Thus, Hill (1973) concludes that the considerable variation in the rates of erosion both at a particular section and downstream is related to the differential susceptibility of sediment to frost action. This weakens correlation between channel form parameters and discharge either because of the direct effect of frost or because the banks are susceptible to significant erosion by relatively low flows.

2.1.7. The effect of high magnitude floods.

Although high magnitude infrequent events may be responsible for catastrophic changes in channel form, river channels rapidly readjust toward pre-flood dimensions (Schumm and Lichty, 1963), the rate of recovery generally being fast in comparison to the recurrence interval of the flood event (Gupta, 1975). Costa (1974) and Gupta and Fox (1974) have documented the impact of tropical storm Agnes which generated flooding with a recurrence interval much greater than 100 years in a Piedmont watershed. During the flood the river channels were widened by up to 160 percent (Costa, 1974). However, more frequent low and medium flows following the flood, reduced the channel width by enlarging existing bars and creating new ones, primarily along the channel margin but also as braids. Within one year of the flood, channel cross-sections were "well along recovery toward pre-flood dimensions" (Costa, 1974, 106). Active meandering reaches were observed to recover faster than the more stable straight channels. Furthermore, a channel-in-channel form may develop, that is, within the enlarged flood channel a smaller one adjusted to more regular flows might occur. (Gupta and Fox, 1974). Where repetitive floods of high magnitude occur within a relatively short period of time the channel may adopt a complex form in order to satisfy the conditions for equilibrium through the wide range of flows. However, a study of the persistence of landscape features formed by the 1952 Exmoor flood (Anderson and Calver, 1977) indicated that a degree of channel deepening may survive the mean recurrence interval of the flood in the absence of a larger intervening event.

> "When the landscape is viewed in terms of the establishment of dynamic equilibrium over medium length time spans, it is the probability distribution of occurrences of events of particular magnitudes over that span that relates to the general prevailing form, while the particular sequence of events define the degree of oscillation about that form."
> (P.253)

The effect of major floods will vary along a particular river (Galka, 1973) in relation to the strength of the bed and bank materials, and the condition of the pre-flood channel. The effectiveness of competent discharges is a function not only of the magnitude of the particular event but also of the form of the velocity distribution, and the spacing of flood peaks (McQueen, 1961) or rather the degree of flow variability. Thus, Knighton (1973) reported the rapid erosion along the Bollin Dean, Cheshire, associated with the complex multi-peaked flows of the winter months and Leopold (1973) concluded that major summer floods were not effective in lateral erosion. The high rate of erosion in winter, relative to the summer months, being related to the preconditioning of the bank materials by wetting. Thus, variations in the degree of correlation between channel parameters and the dominant discharge will reflect the time elapsed since the last major destructive flood as well as the constraints of slope and perimeter sediment strength.

2.1.8. Complex response of geomorphic systems

Consideration of a geomorphic system in a state of dynamic equilibrium requires that before change can occur an external stimulus such as man or climatic change must be applied to that system. All the components of dynamic equilibrium should respond to a stimulus in a similar way. Therefore, the effect of large magnitude floods should not be as variable as they appear. The concept of geomorphic thresholds and complex response of geomorphic systems (Schummn, 1973) may explain the occurrence of these geomorphic anomalies. The concepts view the variations between the components of the geomorphic system as an inherent part of the erosional development of landforms so that the components need not be in phase. Schumm (1973) conceived the existence of geomorphic thresholds, intrinsic to the system. Whilst external variables remain relatively constant, the progressive change of the geomorphic system itself through time renders it unstable and failure will occur; adjustment or failure will not occur however until the system has evolved to a critical situation. Thus, large floods will only be of significance when a geomorphic threshold is exceeded.

The infrequent event, although performing little of the total work within a river system (Wolman and Miller, 1960) may act as a catalyst causing the crossing of a geomorphic threshold and the initiation of a complex sequence of events, involving negative feed-back mechanisms (Chorley and Kennedy, 1971, 135), that will produce significant landscape modifications. However, a geomorphic threshold will not be exceeded simultaneously throughout a river system, and the processes of readjustment will vary spatially. Nevertheless, similar final states may be achieved. This mechanism was conceived by Schumm (1973) as the complex response of geomorphic systems. Most changes within the river system result from the gradual migration of zones of erosion or deposition as the system adjusts to a new steady state equilibrium. Thus, Pickup (1975) identified the presence of sediment transport discontinuities. These discontinuities represent the transition between channel sections adjusted to present conditions and those adjusted to a previous hydrological regime. The product of downstream changes in those channel characteristics which influence stream competence, sediment transport discontinuities result in the erosion or deposition which restore the system to equilibrium.

One impact of man upon river channels, that of river regulation, exemplifies the complex response of a river system through the crossing of an intrinsic threshold. An extrinsic threshold has been defined by Schumm (1973) as a threshold existing within a system which will not be crossed without the influence of an external stimulus. The removal of flood peaks within a mainstream will effectively lower tributary base level during times of flood and initiate tributary rejuvenation. The increase of the sediment supply to the mainstream results in deposition which will initiate feedback mechanisms affecting reaches upstream. As aggradation progresses channel slope will be reduced for upstream sections inducing further sediment deposition. However, as the depositional front develops, the downstream slope will steepen until a geomorphic threshold is crossed. That is until the threshold slope is exceeded when erosion will occur. The incision will migrate upstream producing a new channel in equilibrium with the existing flow conditions.

The concepts of geomorphic thresholds and complex response of geomorphic systems have been summarized by Schumm (1973, 309).

> "Readjustment of the system will be complex as morphology and sediment yields change with time. The timing of these changes unquestionably will be related to major flood or storm events, but such events may be only the catalyst that induces the change at a particular time. That is, it is the existence of geomorphic thresholds, and the complex feedback response of geomorphic systems, that permit high magnitude events to play a major role in landscape evolution".

The spatial variation of stream channel form will be related to the sources of sediment supply and of runoff, to the state of the drainage system in relation to the intrinsic threshold value, and to the length of time since the last high magnitude flood, constrained by the strength of the channel perimeter sediment. Discharge may be viewed as essentially a scale variable determining the absolute size of a river channel. The actual dimensions of the channel will be influenced by other variables. Thus, a multivariate approach may be required to identify the state of quasi-equilibrium within a river system.

2.2. CHANNEL RESPONSE TO AN ALTERATION OF AN INDEPENDENT VARIABLE

The self-regulating tendencies of natural river channels requires that the channel absorbs the annual fluctuations in the inflow of energy and sediment from outside by regulating its geometry. However, the application of an external stimulus, such as man, climatic change, tectonism, or isostasy, to the system in quasi-equilibrium may initiate channel processes affecting adjustments to a new equilibrium condition. Although the potential for change may exist within a river system, the river channel being in a state of dis-equilibrium with the independent controls, a large flood may be required for the adjustment to be manifested through the initiation of periods of erosion or deposition. Extrinsic thresholds (Schumm, 1973) must be crossed before channel change will occur. The precise definition of the extrinsic thresholds is still uncertain but they may be expected to differ between rivers in relation to the variation of the internal components of the system, particularly of the degree of human interference. Nevertheless, Lane (1955) identified six classes of stream profile changes resulting from a change of one or more of the factors controlling equilibrium. The changes were identified from the theoretical analysis of an equilibrium equation.

$$Q_s d \sim Q_w S$$

Q_s = sediment quantity
d = sediment calibre
Q_w = water discharge
S = stream slope

(Lane, 1955, 186)

Lane also provided field examples of each of the classes identified. Furthermore, Schumm (1969) produced a series of empirical equations based upon data from stable channels in semi-arid and sub-humid areas, describing the direction of change of channel width, depth, slope and planform to an alteration of the water discharge and sediment load.

2.2.1. Base-level change

A change of a river's base-level will result in an alteration of slope and hence the potential energy available within the system. The lowering of base-level effectively increases the river slope initiating channel incision not only of the mainstream but of the entire drainage network. Conversely, a rise of base level will result in channel aggradation until the river system again acquires a quasi-equilibrium state. Thus

Sonderegger (1935) observed the slow adjustment of the Whitewash River to the lowering of the Salten Sea, California; channel degradation took place primarily during rare large floods.

During the Quaternary, variations in the amount of water held in store within the ice-sheets resulted in significant fluctuations of sea level. Several researchers have recognised that the reduction of sea level by 150 metres some 15,000 years ago caused the lowering of the base level for the Mississippi system. This resulted in the entrenchment of the Mississippi River and its tributaries. During deglaciation the sea-level rose, decreasing base-level, and initiating a long phase of aggradation affecting the entire Mississippi drainage network. Evidence of river incision and aggradation may be expected to be widespread, associated with the variations of sea-level during the Quaternary period.

2.2.2. Climatic change

It is well established that relatively minor variations in climate may initiate major changes in the runoff-sediment yield relationship. The sensitivity of runoff volumes to potential evaporation, for example, has been demonstrated by Crawford (1966). A ten percent change in potential evaporation may lead to a thirty percent change in runoff. Furthermore, it is now accepted that some major erosional adjustments can be induced by rather insignificant changes in the magnitude and frequency of storm events (Leopold, 1951). Thus, several authors have identified sequences of aggradation and degradation as evidence of the adjustment of channels to changes in the magnitude of the bankfull discharge associated with long term climatic variations. Holmes and Moss (1955) identified a change of the Green Colorado and Platte - Missouri drainage system related to a post-glacial climatic change based upon sedimentogical & morphological evidence, and pollen profiles. Similarly, Hadley (1960) identified a terrace sequence along Fivemile Creek, Wyoming. The terraces developed during the Upper Pleistocene whilst the trenching of the valley and formation of the modern flood plain has occurred since 1920. Hadley related the sequence of deposits to a number of climatic changes. Although a major change in global climate occurred following deglaciation Schumm (1973) has indicated that a terrace sequence may form without a change of climatic conditions.

Evidence of former channel patterns dating from contrasted climates during the Quaternary have been recognised from a variety of areas. Thus, Dury (1964) identified deep buried channels within the flood plain deposits. Dury found that the contemporary meandering rivers had a lower wavelength than that of the river valley; a response to a drastic reduction of the dominant discharge. Such streams have been termed 'underfit' (Dury 1964). The degree of underfitness from studies of European, North American and Australian rivers suggest an average bankfall discharge some twenty times greater than the present. Dury visualised an increase in precipitation by a factor of 1.5 to 2.0 in early deglacial times to account for the increase in runoff. This has been supported by evidence from lake deposits and deep sea sediments (Dury, 1964).

The recognition of palaeohydrological regimes (Schumm, 1965) has provided evidence for the adjustment of channel cross-sectional form as well as of drainage network, and channel planform. Schumm (1968) identified palaeochannels on the alluvial plain of the sinuous Murrumbidgee river. The cross-sectional dimensions of the palaeochannels, as well as the sinuosity, are markedly different to the dimensions of the present river. These differences reflect the hydrologic regime of the period when each channel was functioning. The marked variation of channel shape, as indicated by the width-depth ratios of the palaeochannels of 67 and 13, compared to a value of 10 for the present channel, are related not only to changes in the water discharge, but also to the alteration of the quantity and type of sediment load.

The influence of changed climatic conditions upon vegetation growth appears to be the key to a river's behaviour (Schumm and Lichty, 1963). An increase in precipitation will increase runoff but may improve the vegetation cover reducing sediment yield. In contrast, a decrease in precipitation will decrease runoff but may also greatly increase the yield of sediment from the drainage basin by reducing the protective vegetation cover (Schumm, 1965). Thus, Pickup (1976a) observed that an increase in precipitation, for the Cumberland Basin rivers, resulted in higher discharges and a contemporary increase in vegetation cover which reduced the sediment supply resulting in channel degradation and an adjustment of channel slope (Pickup, 1976b). However, Pickup observed that drainage basin response to a variation of climatic conditions varies with soil type and vegetation cover. Therefore drainage basin response may be highly variable depending upon such factors as vegetation types, the sources and characteristics of the sediment load, the floodplain sediments and the effect of the change in regime on the magnitude and frequency of floods (Pickup, 1976, 192).

2.2.3 The impact of man.

> "He (man) has a set of gifts which make him unique among the animals: so that, unlike them, he is not a figure in the landscape - he is a shaper of the landscape."
> (Bronowski, 1973, 19)

Man has been intimately associated with river systems throughout his history, directly or indirectly altering the various components of the river system for his personal benefit. Today, a truly natural river is a rare phenomenon. However, it is only during the past century that the scale of man's impact upon river systems has become apparent. Mrowka (1974) has identified the effects of man upon the pattern of water and sediment production. These effects he categorised as direct channel manipulation, rural watershed alterations, the effect of urbanisation, and water pollution activities. Channel studies referred to so far have indicated that the river channel components will respond to changes in sediment yield and runoff. Therefore, changes of channel process through an alteration of one or more independent variables by man (Fig. 2.1.) may be anticipated to initiate an adjustment of the drainage network, channel form or channel cross-sectional dimensions.

(a) Alteration of the vegetation cover

Perhaps the most widespread impact of man upon the drainage basin in general, and stream channels in particular, is that of landuse change. Indeed, numerous accounts exist of the removal and conversion of the vegetation cover by man. The widening of the Cimarron River, initiated by a major flood in 1914 has been associated with the rapid growth of agriculture and subsequent abandonment (McLaughlin, 1947). Smith (1940) related the widening of the Cimarron River channel to the cutting of drainage ditches, the weakening of the grass cover by grazing and the destruction of the sod by ploughing. The reduction of the vegetation cover resulted in accelerated runoff, widespread soil erosion and gullying and an adjustment of the drainage system. Changes in the long profile and cross-sectional form of a South California stream resulted from the removal of the deep-rooted scrub vegetation and replacement by grass (Orme and Bailey, 1971). The changes of channel form were again initiated by a series of major storm events.

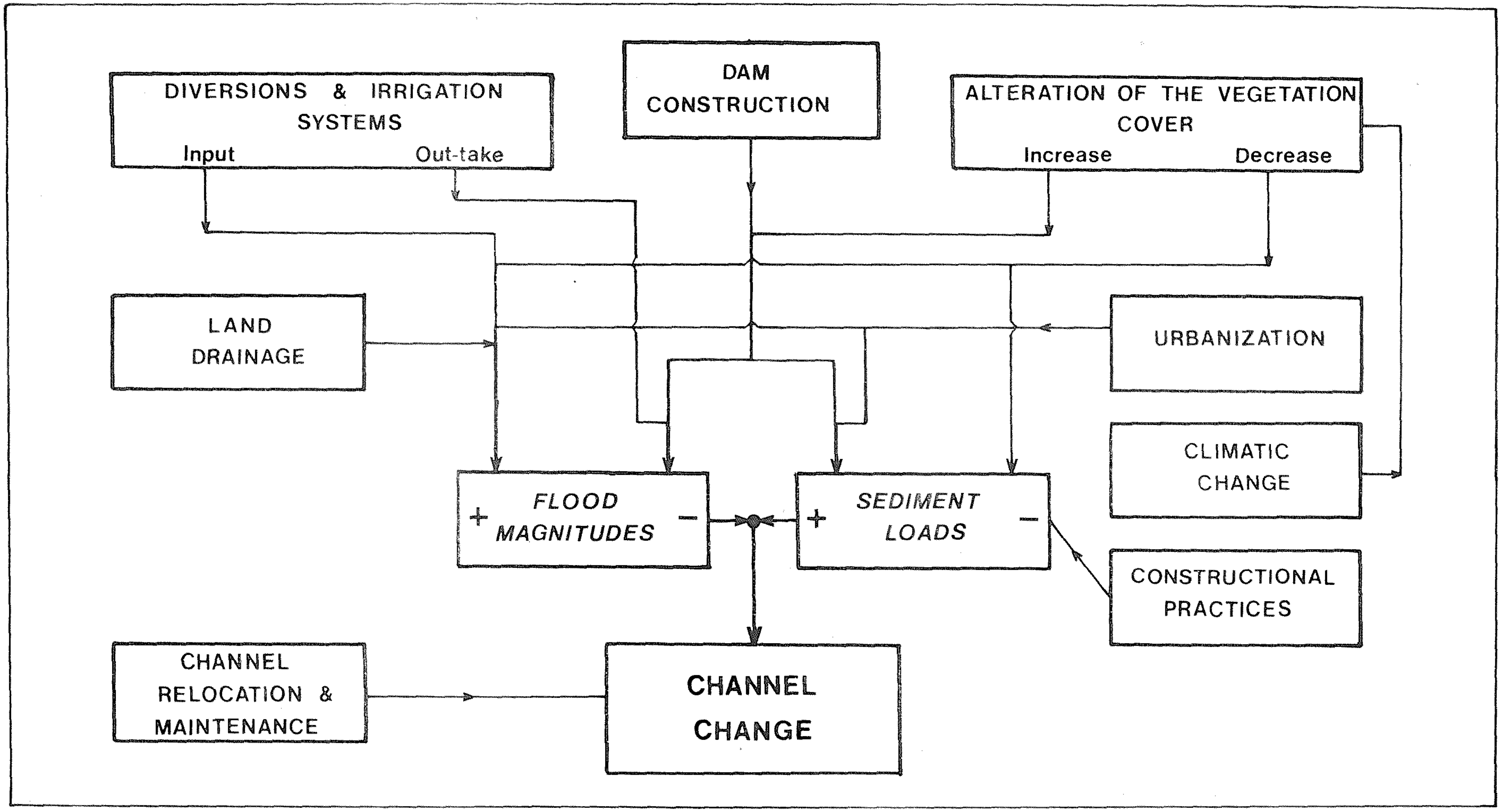

FIGURE 2.1 THE IMPACT OF MAN UPON CHANNEL PROCESS AND FORM.

The impact of agricultural practices and grazing upon drainage basins within the semi-arid regions of North America have been well documented (Bryan, 1928; Daniels, 1966; Schumm and Hadley, 1967). Bryan (1928) observed from historic evidence that the channel changes along the Rio Puerco were coincident with settlement and the introduction of livestock throughout south-west North America. The reduction of the vegetation cover resulted in the increase of sediment yield. A simultaneous increase in runoff initiated mainstream entrenchment, lowering tributary base-levels and initiating the headward extension of the drainage net increasing the sediment supply to reaches downstream. Thus, Daniels (1966) identified stream trenching and valley side gullying in western Iowa associated with increased runoff through cultivation - the removal of the vegetation cover reduces surface roughness - and regional changes in climate. Active valley-head and valley side gullies have also been identified within Medicine Creek drainage basin, Nebraska. (Brice, 1966). The incision and ramification of the drainage system here, was attributed to land use since settlement rather than to climatic change. However, the observed cause of channel change, be it a large flood or overgrazing need not necessarily be the primary cause, it may be only the most obvious cause (Schumm and Hadley, 1967). Nevertheless, restoration of the native vegetation to the heads of valleys may be effective in the control and prevention of valley-head gullies (Bryan, 1928). Gottschalk (1962) reported that within the United States nearly 440,000 acres of 'critical sediment source area' had been stabilized by the planting of grasses, legumes and trees in order to reduce erosion and sediment damages.

(b) Urbanisation.

Since the turn of the century the most widespread and dramatic impact of man upon the environment has been through urban development. Indeed, major changes in runoff and sediment yield have resulted from the conversion of, often agricultural, land to urban land-use. Over the past decade in particular the consideration of the changes in channel processes consequent upon urbanisation has received a great deal of attention (Walling and Gregory, 1970). The existence of impervious surfaces will reduce infiltration rates and surface roughness increasing the rate of runoff. The increased density and efficiency of the drainage network will further increase storm runoff intensity. Stream channel sediment supply will be reduced by the protection of the catchment surface and channel boundaries with resistant materials.

The spread of an impervious area, the reduction of surface roughness, and the introduction of a storm drainage system result in an increased runoff volume, reduction of the time of concentration, and increased peak discharges. Thus, Ramsey (1959) concluded that the floods in the Chicago area had increased at least 2½ times because of urban development, whilst Savini and Kammerer (1961) found increases of between two and five times for flood discharges in California. The increase in flood magnitudes may be associated with an increase in the frequency of flooding. Leopold (1968) calculated that a catchment being 50 percent sewered and 50 percent impervious would promote a four-fold increase in the number of floods equal to or exceeding bankfull. However, James (1965) Martens (1968) and Hollis (1975) have indicated that the dramatic increase in the magnitude of peak discharges with urbanisation becomes less significant for floods of increasing magnitude. For rare rainstorms of high intensity the differences in land surface permeability would become less significant. Furthermore, at high storm intensities the design discharge for the storm drainage system may be exceeded, reducing the efficiency of runoff conveyance. Thus, Martens (1968) for Charlotte, North Carolina, expected an increase of the mean annual flood by 58% whilst the 20 year flood would increase by only 17%. Summer floods being most significantly affected (Hollis, 1974).

Several studies have measured the magnitude of changes in peak flows for individual or groups of catchments (Moore and Morgan, 1969). However, Hollis (1975) has further demonstrated that the increase in floodflows following urbanisation is related to the flood recurrence interval and the percentage of the basin paved. Hollis concluded that rare events may be markedly increased if the percentage of paved area is significantly large; a thirty percent paving of the basin may double the size of the 100 year flood. Nevertheless, the effect of urbanisation declines in relative terms as the flood recurrence intervals increase. Variations in the response of catchments to urbanisation will result from differences in the type and degree of urbanisation, the position of the development in the catchment, and the degree of improvement of the drainage network.

The impact of urbanisation upon sediment yields is dramatic yet completely transformed as the urban area develops. During construction the removal of the protective surface vegetation cover and the disturbance of the surface layers not only increases runoff but also increases the available sediment supply. Thus, Walling and Gregory (1970) observed a tenfold increase in suspended sediment concentrations following the onset of building setivity. Over very small areas constructional practices may increase erosion rates by more than 40,000 times the amount eroded from rural land in an equivalent period of time (Wolman, 1967). However, after construction the sediment supply will be reduced due to the protection of the catchment surface and channel boundaries by resistant materials and the increased runoff of relatively sediment-free water may flush the sediment released during construction from the system. Therefore, it would appear that urbanisation increases runoff without a concomitant increase in sediment supply.

Stream channels will tend to adjust their dimensions in order to maintain a quasi-equilibrium state with the altered flow regime. Thus, Wolman (1967), compared the bankfull width of urban channels with the bankfull width of non-urban channels and demonstrated that many urban channels exhibit greater width than their rural counterparts. In the United Kingdom Gregory and Park (1976) compared the channel capacities of natural and urban channels, and demonstrated that the urban channels within Catterick Garrison were enlarged to at least 1.7 times the capacity expected from non-urbanised channels. However, river channels below urban areas have also been observed to decrease in capacity. Emmett (1974) reported that the reduction of the cross-sectional area of Watts Branch, Maryland, to 66% of its former value consequent upon urbanisation. The progressive decrease of channel cross-sectional area has been attributed to the increased loads of suspended sediment resulting from constructional practices. Most of the reduction was achieved by the plastering of silt on channel banks. Leopold (1973) noted, however, that whilst the channel aggraded as a result of building activity increasing sediment loads, the subsequent development of an impervious surface led to an increase in the number of overbank flows resulting in channel degradation. Evidence from 78 small watersheds near Philadelphia (Hammer, 1972) indicates that the influence of urban development on channel size is related to the topographic characteristics of the watershed, to the location of impervious development within the watershed, to the man-made drainage alterations, and to the type of impervious surface. Large channel enlargement effects were found for sewered streets and areas of major impervious parcels such as car parks, and much smaller effects for for unsewered streets and impervious areas involving low density housing with gardens. Thus, the river channel below urban areas may be anticipated to observe a sequence of aggradation and degradation related to the initiation, completion, and extent of urban development.

(c) Land-drainage.

Because of the demands upon agricultural land, land drainage has been undertaken for thousands of years, indeed the origins of land-drainage are pre-Roman (Cole, 1976). In Britain, one quarter of the agricultural land requires improved drainage for maximum output. Since the passing of the Agricultural Act of 1937 the area of field drainage has increased annually. The effective increase in the drainage net will intentionally increase the rate of runoff and may increase peak discharges within river channels. Attempts to increase runoff rates have effected channel response which was probably not considered when the changes were made. The evidence suggests that man-made changes of a drainage system in south-east Nebraska about 1914 (Mundorff, 1967) may have caused channel erosion which increased sediment loads to reaches downstream. Similarly, the construction of a system of drainage ditches following road construction has resulted in the formation of a gully (Gregory and Park, 1976) associated with the changed runoff pattern. The increase of the drainage network will result in the decrease of the time of overland or throughflow and an increase in channel flow time, that is, a decrease in the period of concentration, increasing the magnitude of peak flows and initiating channel degradation.

(d) Diversions.

A characteristic of water resources, particularly within the United Kingdom is that the major sources of supply are located some distance from the centres of peak demand. Increasingly interbasin transfers are being planned in order to divert water to high demand/low supply areas. The hydraulic effect of diversions and their impact upon channel form have been detailed by Lindner (1952). In brief, a diversion will reduce the discharge without affecting the amount of bed-load delivered to the channel downstream. Deposition will occur and the cross-sectional area of the channel will be reduced. Aggradation will progress downstream so that slope increases until the stream is able to transport the bed-load at reduced flows. Smith (1940) observed that the diversion of river water for irrigation has, at least in part, resulted in the reduction of channel width, narrowing the Arkansas river in eastern Colorado and in western counties of Kansas. In the United Kingdom Dury (1973) reported the reduction in channel width with relatively little change of depth on the River Ouse downstream of mill leat offtakes, an adjustment to the reduction of discharge with little or no change of the sediment load.

The import of water into a river system may be anticipated to initiate contrasting adjustments. An increase of the discharge without a concomitant increase in sediment load may result in channel erosion, the increase of channel capacity and an increase of channel roughness. The scour will reduce the slope and, together with the increase of roughness, will reduce the erosive force, reducing the sediment supply, so that degradation proceeds downstream. The cross-sectional area and slope of the channel will increase and decrease respectively until a balance is reached between the transport capacity and the amount of material moved. Between 1971 and 1973 water imported to the River Tame catchment contributed to the increased flood peaks experienced downstream from an urban centre (Richards and Wood, 1977). A flow of 0.5 yr. return period is here increased by about 15% because of imported base flow. Hey(1975) examined the effects of diversions upon total sediment flow. Whether aggradation, degradation or a stable situation exists will depend upon the threshold for sediment transport. Study of a proposed intake/outfall point on the River Severn (Hey, 1975) revealed that whilst the reach immediately downstream of the intake/outfall was basically stable, between 4 and 8 km. downstream it was eroding, and further downstream evidence suggested depositional activity. Although the proposed residual flow (Hey, 1975) may be below the sediment transport threshold in the vicinity of the intake/outfall the operation of channel processes may be markedly altered further downstream.

(e) Channelisation.

The direct alteration of channel dimensions both in cross-section and planform is increasingly being undertaken in order to increase the efficiency of water conveyance, to decrease the 'flood hazard' and improve navigation. The Task Committee on Sedimentation (A.S.C.E., 1972) discussed the problems arising from man's interference with natural water courses. Although the South Grand River in Missouri maintained its alignment and cross-section after artificial straightening for more than 40 years the entire valley of approximately the lower one-mile of the straightened reach and several miles of unimproved reach downstream has been completely swamped because the flow conditions in the natural channel were not adequate to continue the transportation of the sediment. The shortening of river channels with straightening increases the gradient and hence local energy conditions. In order to reduce the rate of energy expenditure rivers will attempt to return to a meandering form, such as has occurred for example on the Mississippi (Fairweather, 1973). A change in the cross-sectional dimensions may occur rather than a change of planform so that the shortening and straightening of the Peabody River, New Hampshire (Yearke, 1971) has resulted in channel degradation both upstream and downstream of the straightened reach, increasing channel width and depth. Increasing channel width appears to inhibit meandering or at least reduce the rate of adjustment. Thus, for a comparison of the adjustments of some naturally meandering streams, consequent upon straightening, to improve flood control and tile drainage, with laboratory models, Noble and Palmquist (1968) concluded that the width-depth ratio is an important factor governing the rate of adjustment. Straightened channels dug to twice their pre-straightened width should inhibit future meandering.

2.2.4. Relevance to dam construction.

Within the constraints, unique to any particular drainage basin, river channels will adjust their gross dimensions to permit the most efficient removal of water and sediment supplied from the catchment upstream. The self-regulating processes operating within the river channels will operate so as to absorb fluctuations of the independent variables until a particular threshold condition is crossed when adjustments will be made to a new quasi-equilibrium state. Thus the alteration of the sediment and water discharge characteristics of rivers consequent upon dam construction may be expected to initiate processes which will serve to determine a new set of quasi-equilibrium dimensions.

2.3 THE IMPACT OF RESERVOIR CONSTRUCTION UPON RIVER CHANNEL FORM AND PROCESS: A LITERATURE REVIEW.

Dams were first constructed for the purpose of river regulation some 5,000 years ago (Smith, 1971). Since their first construction in Egypt the use of dams for a variety of water resource schemes increased dramatically. Solid dams were popular within the Mediterranean area by Roman times but in Western Europe dams did not proliferate until the common introduction of the overshot wheel in the late Middle Ages (Beckinsale, 1972). However, since the turn of the century the number of reservoirs has more than doubled. It is becoming clear that reservoirs have a considerable physical effect on rivers downstream, not only in terms of discharge and sediment characteristics but also on the river channels themselves. (Fig. 2.2)

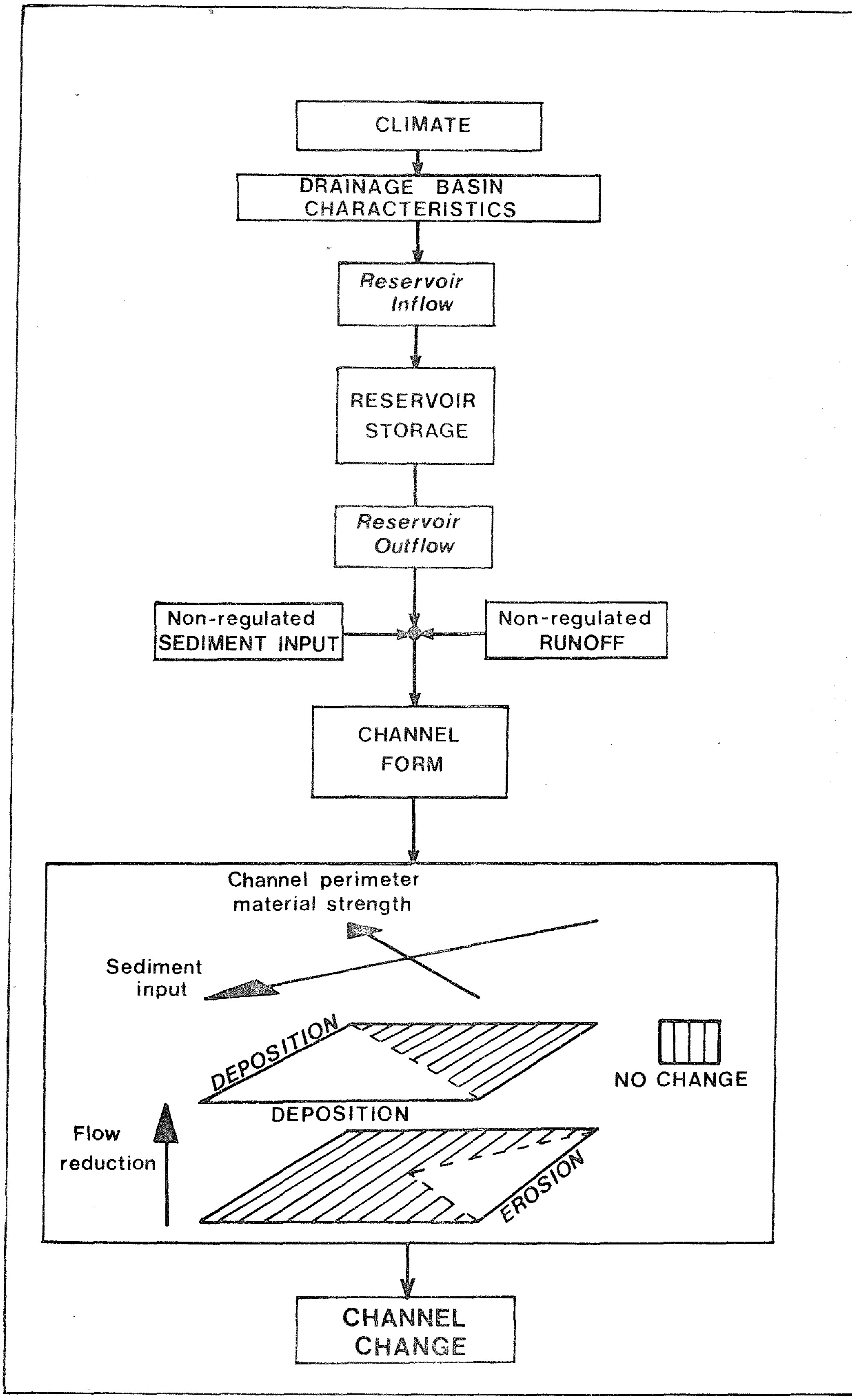

FIGURE 2.2 THE IMPACT OF RESERVOIR CONSTRUCTION UPON CHANNEL FORM.

2.3.1. Flow alteration.

The construction of a reservoir within a river system will markedly alter the flow regime (Fig. 2.3). De Coursey (1975) demonstrated from a literature survey that significant reductions in peak rates of flow will occur downstream from reservoirs. The retention of water behind a dam and its gradual release downstream results in the reduction of peak discharges and the regulation of the flow regime.

The variety of impacts that a single reservoir may have upon streamflow has been summarized by Rutter and Engström (1964). They stated the basic concept of flow regulation was 'empty space'. That is, the effect of a reservoir upon individual flood discharges is related to the content of the reservoir prior to the arrival of the flood wave. If the reservoir is empty the magnitude and timing of flood peaks will be reduced as the flood discharges are absorbed by the reservoir storage volume. The amount of storage available within the reservoir being dependent upon the water level - the amount of 'draw-down', the height of the dam, and the reservoir basin morphometry. When the reservoir is full, flood waves will be attenuated by storage above the spillweir. Indeed, the

> "balancing effect of the temporary storage of water in the reservoir above the crest level of the waste weir when the reservoir is full and overflowing, referred to as the reservoir 'lag', plays an important role in reducing the maximum rate of outflow from the reservoir". (I.C.E., 1933,10).

The effect of storage provided by the rise in water level about the spillweir-crest is related to the surface area of the reservoir, the hydraulic characteristics of the spillweir and the form of the inflow hydrograph (Fig. 2.3). The storage-head relationship is controlled by the reservoir surface area which is normally expressed as the retention factor (Lauterback and Leder, 1969) describing the attenuation of flood peaks routed through a reservoir, as a function of the quotient of the total reservoir surface area to catchment area. The Institute of Civil Engineers (1933) Report on 'Floods in Relation to Reservoirs Practice' considered (p.18) that

> "where the water area of a reservoir is 2% or upwards of the catchment area, the storage provided by the rise in water level about the weir has an appreciable effect in reducing the rate and head of overflow".

As the retention factor increases so the 'lag' effect becomes more marked.

The head-outflow relationship is controlled by the hydraulic characteristics of the spillweir. The length of the overflow weir

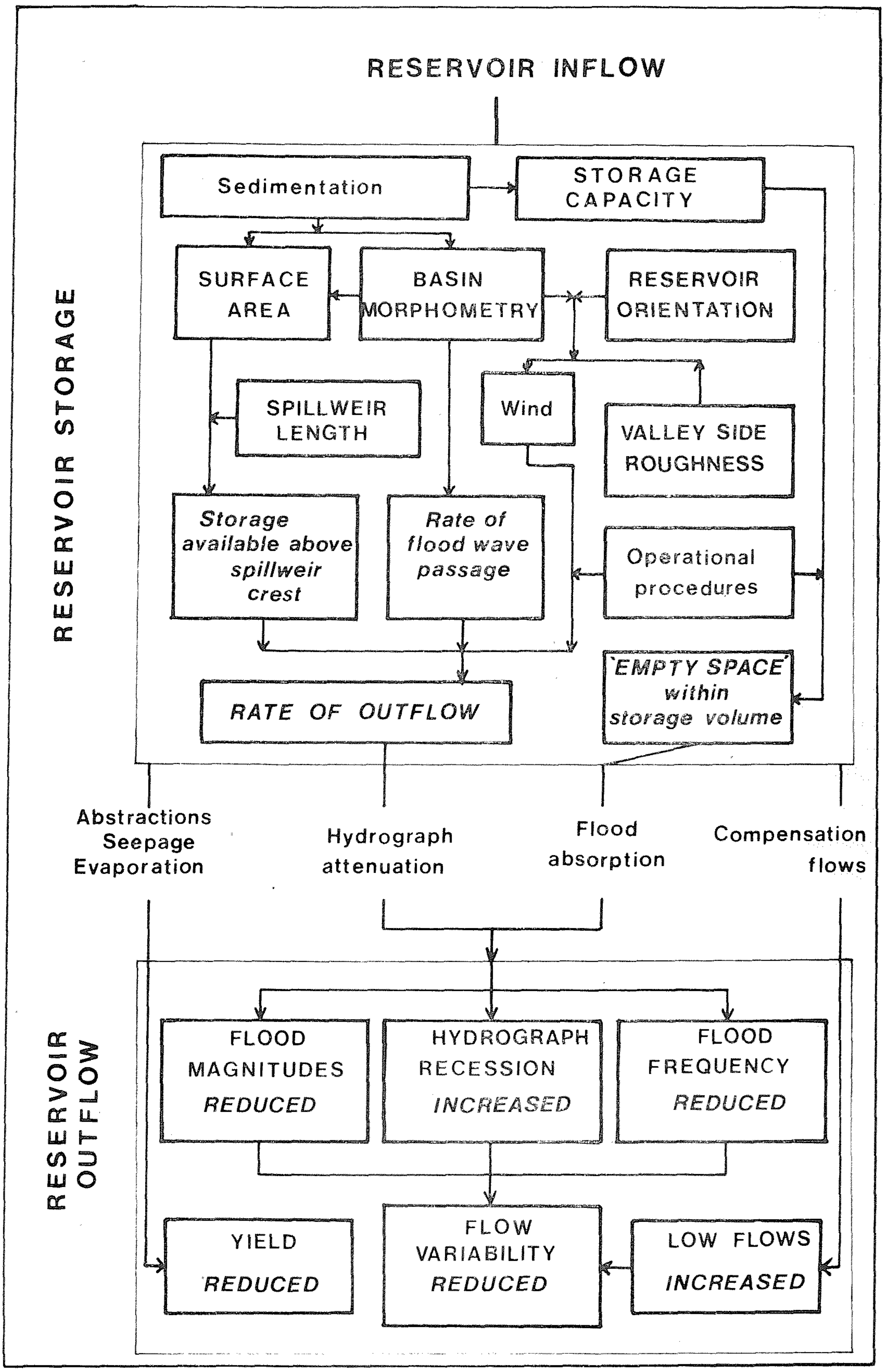

FIGURE 2.3 THE IMPACT OF RESERVOIR CONSTRUCTION UPON THE FLOW REGIME.

affects reservoir lag - the greater the head the greater the outflow control. However, today the length of the weir depends upon the reservoir surface area and the permissible head, determined during design. Where prolonged intense rainfalls occur, such as in Wales, the Lake District and the Scottish Highlands, persistent high runoff of more than 6 cm per day may occur (I.C.E., 1933). "This would be sufficiently long to neutralise the lag effect and to permit the overflow to become roughly equal to the inflow, even in reservoirs of relatively large areas", (I.C.E., 1933,20). The rate of flood wave passage through the reservoir is related directly to the water depth and to a lesser extent to the shape of the reservoir surface area.

The ratio between inflow and outflow discharge at the peak, often used to describe the 'effect of regulation', may be a function of the volume of flow, but more generally it is a function of the shape of the inflow hydrograph. Although a function of the magnitude, duration and location of the storm event, the shape of the inflow hydrograph characterises the rate of catchment response to a given storm rainfall. Minor variations in the outflow peak may occur as a consequence of persistent high velocity winds causing the pile-up of water and increasing the head above the spillweir crest. Winds may be of particular importance within open, treeless valleys. Under such conditions, Makkaveyev (1970) observed that wind speeds of 18-20 m/sec. produced waves of 3 metres in height within the Kuybysher Reservoir.

Whether the reservoir is full or empty flood peaks will be reduced (Table 2.2) and the recession parts of the hydrograph will be lengthened. Thus, Moore (1969) in a study of fourteen reservoirs in Texas found that routing through a reservoir with no available storage may reduce peak discharges by over 50%; the flow rate on small storms was reduced by as much at 98%. Summer events may be regulated more successfully than winter floods as during the summer storage space within the reservoir volume proper will likely be available. Hartmen et al (1969) used unit hydrograph analyses to examine the effect of flood control structures upon three high magnitude events on Sugar Creek, Oklahoma. They estimated that flood peaks would be reduced by between 25 - 70% depending upon the area controlled and the location of maximum rainfall. This compares with the 36% reduction of the mean annual flood on the Blue River (Huggins and Griek, 1974).

The reduction of the magnitude of peak discharges may be greater for smaller, more frequent events, and least for the larger, less frequent events, as the attenuating effect of storage is independent of the size of

Table 2.2 The effect of reservoirs upon peak flows

Location	Mean annual rainfall (mm)	Discharge Characteristics	Peak flow reduction (%)	Source
Clatworthy, Somerset U.K.	1150	mean annual flood	60	Gregory and Park, 1974
Central European rivers	1000	50 year flood	20	Lauterbach and Leder, 1969
Panchet Reservoir, India.	1000	design flood	80	Jain et al, 1973
High Aswan Dam, Egypt.	450	flood peaks	75	Kinawy et al, 1973
Glen Canyon Dam, Colorado U.S.A.	400	10 year flood	75	Dolan, et al 1974.
Willow Creek, Montana U.S.A.	350	highest discharge	45	Frickel, 1972
Elephant Butte, New Mexico, U.S.A.	300	mean annual flood	25	Wolman, 1967
John Martin, Colorado U.S.A.	400	mean annual flood	25	Wolman, 1967
Blue River, Colorado U.S.A.	550	mean annual flood	36	Huggins and Griek 1974
Sugar Creek, Oklahoma U.S.A.	785	high magnitude events	25 < 70	Hartman et al, 1969

the inflow events. A given storage at a given degree of emptiness might completely absorb a very small flood yet have an insignificant effect on a very large flood. Therefore, the outflow flood frequency curve may tend to be considerably below the inflow flood frequency curve for more frequent events, and to approach it more closely for rarer events. Thus, Lauterbach and Leder (1969) for a study of reservoirs in Central Europe analysed annual maximum and monthly maximum discharge data to determine the change in the value of the 10 year, 50 year and 100 year events consequent upon dam construction. They determined that although the effect of the retention factor decreases as the recurrence interval increases, the decrease was generally small and often constant.

Downstream of the dam the lag of mainstream peak discharges routed through a reservoir may de-synchronise the mainstream and tributary peaks. Conversely, the superposition of hydrographs may occur where the alteration of the timing of the event causes the mainstream and tributary peaks to coincide. However, the effect of impounding the headwaters will decrease as the percentage of non-regulated catchment area increases downstream. Comparison of discharges with specified frequencies for the River Tone below Clatworthy Reservoir with the regional pattern (Gregory and Park, 1974) suggested that peak discharges immediately below the dam (a drainage area of 18.2 km^2) are 34-40% of those expected. Downstream at a catchment area of 57.8 km^2 discharges are still less than half the expected values, but with a catchment area of 202 km^2 peak discharges approximate to the regional pattern.

The runoff yield may be altered by the abstractions and loss through evaporation, seepage and bank storage. Evaporation depends upon the surface area of the reservoir and the amount of potential evaporation. The total volume of flow may be reduced by the increase in time during which seepage and evaporation losses occur, possibly responsible for a loss of 25% annually (Gilbert and Sauer, 1970). On a study of Sandstone Creek, Oklahoma, Kennon (1966) attributed a water loss of about 175 cm. p.a. to evaporation. Reservoir seepage also increased groundwater levels and increased the baseflow component of the hydrograph along Sandstone Creek. The prolonged flow at downstream points increased transmission losses within the semi-arid channels. But Gilbert and Sauer (1970) concluded that channel transmission losses resulting from the change in stream flow regimen imposed by systems of floodwater-retarding reservoirs were not significantly different from those occuring in the passage of natural flood waves.

Identification of changes within the annual variation of runoff may be problematic as short term climatic changes may obscure the effects of flow regulation. Anderson (1975) utilised demodulation techniques to determine the changes in the amplitude of an oscillation of a given frequency within a precipitation and discharge time-series, and detected that the construction of a dam on the R. Blythe has resulted in a halving of the annual amplitude of the discharge.

Changes in the inflow hydrograph may occur consequent upon dam closure. Precipitation directly on to the reservoir surface may be important where the reservoir inundates more than 5% of the catchment area (I.C.E., 1975). The shortening of stream lengths following the inundation of tributaries by the reservoir may also be important. More commonly, an alteration of the inflow hydrograph may occur following a change in the landuse of the headwaters. Afforestation of the reservoir catchment, often undertaken to stabilise the valley side slopes and to reduce soil erosion, and hence sediment yields to the reservoir, may markedly alter the inflow hydrograph. Schneider (1969) observed that reforestation of 58% of a catchment may reduce winter and spring floods by up to 66%. However, recent studies of forested catchments (Newson, 1977) indicates that sediment yields may in fact increase. The extension of the drainage network by forest drainage ditches condenses flow rapidly into channels often running directly down-slope resulting in rapid erosion. The headwater streams of Lake Vyrnwy, mid-Wales exemplify this. The Cowny, a grass catchment, yields sediment at a rate of $2.5 m^3 km^{-2} yr^{-1}$ whilst the sediment yield from the forested Marchnant catchment is $30.9 m^3 km^{-2} yr^{-1}$. A continual change in the distribution of peak flows downstream from reservoirs may be anticipated as storage space is continually being lost through sedimentation (Table 2.3). However, the progressive change in the flood probability distribution below British reservoirs will be only small as storage loss appears to be low.

2.3.2. Sediment abstraction.

Reservoirs will permanently store practically the entire sediment load of river channels. However, the problem of reservoir sedimentation was not conceived until the mid-1920's. The reduction of flow velocities by lake storage results in the deposition of the sediment load transported by rivers feeding the reservoir. Part of the sediment storage occurs in the storage volume proper and part in the channel and valley bottom upstream by backwater effects. The bed-material load begins to deposit

Table 2.3 Rates of reservoir storage loss.

Location	Climate zone *	Storage loss per annum (%)	Source
Cropston Res., U.K.	marine West Coast	0.005	N.E.R.C., 1976
Burrator Res., U.K.	" " "	0.055	" "
Grand Res., California U.S.A.	mediterranean	2.306	Buttling and Shaw, 1973
Lake Mead, Arizona U.S.A.	mid-latitude desert	3.20	Thomas, 1973
Lake Austin, Colorado, U.S.A.	mid-latitude steppe	10.375 (failed after 7 years)	Buttling and Shaw, 1973
South-eastern reservoirs, USA	humid subtropical	0.31 < 2.82	Brown, 1944
120 reservoirs USA, India, Cyprus	-------	0.02 ≤ 14.33	Buttling and Shaw, 1973
Aswam High Dam, Egypt	tropical desert and steppe	0.002	Kinawy et al, 1973
Habra Dam, Algeria	subtropical steppe	2.636	Buttling and Shaw, 1973
Panchet Res., India	tropical savanna	6.400	Ditto ditto

* based on Trewartha, 1951

at the section in the river channel where the backwater from the reservoir first decreases the transport capacity. Deposition continues from this point into the reservoir. Depending upon the velocity of flow through the pool, the fine material held in suspension will often be deposited in the reservoir proper but may be carried through the reservoir. However, it is the, often total, abstraction of the bed load which has significance to the channel form, in most cases the quantity of the fine load of silt and clay sizes can change almost indefinitely without materially affecting the river channel downstream.

Reservoirs having a large storage capacity will trap in excess of 95% of the sediment load transported by the river (Leopold et al, 1964). The reservoir trap efficiency, the percentage of incoming sediment trapped and deposited in a reservoir, depends upon a number of factors, reservoir storage capacity, rate of inflow, reservoir age, shape of the reservoir basin, operational procedures, and sediment calibre. Brune (1953) found that the ratio of reservoir capacity to the average annual inflow was the most important parameter. This factor describes the average detention time of the stored runoff. In a preliminary report on the trap efficiency of 19 floodwater retarding reservoirs, Gottschalk (1964) showed that most of the measured trap efficiencies agreed reasonably well with the curve Brune developed for estimating trap efficiency. Variation in the calibre of the suspended load has little effect upon the trap efficiency (Gilbert and Sauer, 1970) which approaches 98% for sand and 97% for silt-clay loads. The percentage annual storage loss is inversely related to the original storage per unit of catchment area. That is, as the original storage volume increases per unit area the percentage annual storage loss decreases (Brown, 1944). Although sluicing and venting (Brown, 1944) may reduce the trap efficiency by as much as 10% the reduction of the water storage capacity of reservoirs by over one percent per year has been observed in Europe (Gvelesiani and Shmalkmzel, 1971) and America (Frickel, 1972).

The isolation of upland sediment sources may considerably reduce the sediment yield from a catchment as a whole. Thus, Grimshaw and Lewin (in press) observed that in two separate years the sediment yields determined from measured suspended sediment concentrations and the calculation of loads using sediment rating curves and flow frequency data for the Ystwyth were 7 and 16 times those on the Rheidol which has 54% of its catchment affected by impounding for hydro-electric generation. Yields based upon tracers and using Schoklitsch relationships (Graf, 1971, 136) indicated differences between rivers that were even more apparent.

The sediment load leaving the reservoir is usually nil or is restricted to very much reduced releases that have the purpose of flushing some of the sediment through the storage volume. Sediment loads available to reaches below the dam will be markedly reduced although sediment introduced to the river from release during construction may temporarily increase sediment yields. Thus, Nilsson (1976), for three rivers in Sweden, demonstrated that suspended load increased by up to 65% during construction, and reduced to 35% of the original value after dam closure. Headwater sediment sources will be isolated from the lower river and discharge regulation will affect the frequency with which bed sediments can be transported. Thus, it has been suggested (Petts and Lewin, 1978,7) that impounding may lead to a significant alteration in sediment yields and that the patterns of erosion and alluvial sedimentation in regulated rivers may in the long term become noticeably modified.

Reservoirs act as artificial sediment sinks within catchments, and several different methods are available for measuring accumulation amounts (Gregory and Walling, 1973, 165). Data on sediment accumulation rates in British reservoirs is sparse, and has generally relied upon single ground survey techniques undertaken at low water conditions (Petts and Lewin, 1978 table 3). Volumetric estimates of observed sediment accumulation depths may be both difficult to interpret and unreliable (Slaymaker 1972, 62 and Fig.11). Nevertheless, reservoirs in general are likely to be relatively efficient sediment traps and the loss of sediment load to rivers downstream may have a variety of consequences.

2.3.3. Channel response.

The marked reduction of the dominant discharge may have implications for the adjustment of the stream channel below the reservoir. However, studies of the impact of reservoir construction upon river channels have predominantly been concerned with the effects of scour immediately below the dams. Indeed, the literature is replete with examples of channel degradation below reservoirs associated with the often complete abstraction of the sediment load.

(a) Degradation

Degredation occurs where the outflow from a reservoir has sufficient tractive force to initiate the movement of sediment in the channel below the structure (Gottschalk, 1964). Leopold et al (1964) demonstrated that in the United States the average rate of degradation of the river bed over a period of between 10 and 15 years after dam closure was of the order of 3 cms p.a. Rates of more than 15 cms. per year have been observed both in the United States (Leopold et al, 1964) and Europe (Shulits, 1934).

Several theories have been advanced relating the rate of sediment transport to the many parameters involved, but tremendous difficulties have been encountered when predicting the total amount and the rate of degradation (Livesey, 1963). Early research concentrated upon homogeneous bed material channels. Utilising analytical procedures Tinney (1962) developed an idealised degradation relationship that incorporated the equations for continuity of sediment movement in alluvial channels, the Du Boys sediment transport equation, the tractive force equation, and the Manning discharge equation. However, field observations of channel degradation (Lawson, 1924; Lane, 1934, Borland and Miller, 1960) indicated that in most cases the degradation amounts and patterns could not be accurately predicted using an idealised approach alone. Few streams, if any, contain homogeneous bed sediments and Tinney (1962) recognised that numerous inter-related hydraulic, sedimentologic and biotic factors complicate the formulation of a theory of channel degradation applicable to all natural streams.

Heterogeneous deposits within channels below dams will, where flows remain competent, undergo selective erosion by the relatively sediment free discharges passing through the reservoir. The finer fractions of the bed material will be removed from the channel perimeter by sorting and transported downstream. The hydraulic sorting of the bed sediments occurs primarily through differential transport of sediment sizes forming the bed. As a result, the sorting procedure is affected by all the variables involved in the transport of sediment such as discharge, flow regime, fluid characteristics, energy slope and the characteristics of the channel form and channel perimeter sediment.

The phenomenon of channel armouring was identified by Harrison (1950) from flume studies. Subsequently, Mostafa (1955) observed that the median grain size of the bed sediment became coarser following the closure of Hoover Dam. A study of the Missouri River below Fort Randall Dam, S. Dakota (Livesey, 1963) demonstrated that a one-grain thickness of gravel accumulated over the entire channel bed surface for several miles downstream from the dam. This incomplete surface layer of coarse gravel particles effected total armouring and protected the underlying erodible sands. The depth of scour, therefore, is related to the percentage of non-moving particles within the bed-materials, and the number of particles required to form a single layer. Komura and Simons (1967) made the first attempt to incorporate the effect of the size of the bed-material theoretically into an analytical solution for the problem of channel degradation downstream from a dam resulting from the scouring tendency of sediment-free water released from the reservoir. The effects of armouring were estimated and a final equilibrium profile for river-bed degradation obtained from differential equations using the channel width, particle size distribution of the bed-material and bed and water surface slopes. Hammad (1972) calculated that the River Nile may in fact attain an armoured condition before an appreciable change of bed slope occurs.

Degradation may extend downstream at a rate of several kilometres per year in lowland streams and tens of kilometres in mountain streams (Fedorev, 1969). Indeed, Lawson (1924) identified channel bed degradation and the associated reduction of slope for over 150 kms below Elephant Butte Dam, U.S.A. A mathematical-graphical procedure for the prediction of the longitudinal extent of degradation with time has been presented by Hales et al (1970). Analysis of the channel bed-sediment before and after the construction of Garrison, Cavins Point and Fort Randall Dams (Hales et al. 1970) demonstrated a coarsening during the post construction period. Where a degree of coarsening was not apparent, local conditions such as meandering, tributary sediment injection, or the absence of size fractions large enough to enable coarsening were considered to be important controls. The profiles predicted were unique, indicating different rates of armouring, and approached the original profile asymptotically in the downstream direction. Degradation is initiated in an upstream section close to the dam, and maximum erosion usually occurs in the tail-water of the dam but may occur up to sixty-nine channel widths downstream (Wolman, 1967). The amount and extent of degradation will however be controlled by resistant rock outcrops. Under such conditions, the river channel may adjust its slope by an alteration of its planform; an increase in sinuosity would decrease slope. Nevertheless, where armouring does occur degradation will persist until the reduction of slope and the increase of channel bed roughness reduce velocity below the threshold for sediment transport. Similarly degradation will not occur where the channel slope is so low that the velocity of the water is not adequate to initiate sediment transport or where the channel bed and bank material are too large or too cohesive for the available stream power to move.

The majority of the examples of degrading channels below reservoirs cited in the literature are derived from rivers within areas of non-compact sands and low density vegetation, that is within highly mobile materials. Rivers having coarse bed-materials, channels lined by hard bed-rock, and banks stabilised by vegetation, may resist erosion as the reduction of the dominant discharge, caused by the removal of peak flows by storage, may counteract the affect of reduced sediment load. In an extreme case a single adjustment will occur whereby the regulated discharges are 'accommodated' within the pre-reservoir channel form. The examination of changes in channel form below reservoirs requires the complete analysis of the dynamics of natural rivers. The direction and rate of river channel response will not simply be controlled by changes of the sediment load, but also by changes in flow regime, and influenced by the injection of sediment and runoff from non-regulated sources (Fig. 2.4). Channel adjustment will be constrained by the form of the pre-reservoir channel, the strength of the channel perimeter sediment and the overall slope of the valley floor. Therefore, in detail a wide spectrum of channel adjustments may be anticipated consequent upon reservoir construction.

(b) Aggradation

River channel degradation below reservoirs will only be effective if the reduction in sediment supply is greater than that of the carrying capacity. Where discharges are reduced below the threshold for sediment transport the channel perimeter sediment will form a natural protective armour layer preventing erosion. Thus, Wolman (1967) suggested that the factor determining whether channel cross-sectional area increases or decreases following dam closure depends upon the ratio of pre- and post-dam closure discharges. Wolman determined that the threshold between the two states was within the range of 0.75 and 0.9; below a ratio of 0.75 no degradation occurred whilst at a ratio of 0.75 channel capacities ranged from 140% to 50% of the pre-closure value. The reduction of channel capacity below reservoirs has been identified in the U.K. associated with the changed frequency of peak discharges. In fact, the evidence from the literature suggests that the process of aggradation and degradation below reservoirs may be part of a single adjustment or metamorphosis. For example, Malhotra 1951, reported from work in India that the rapid degradation of the river channel subsequent to dam closure was only the first phase of adjustment. Degradation was followed within a period of between twenty and thirty years of dam closure by aggradation restoring the system to equilibrium. Further reports refer to the initially rapid degradation and the subsequent usual

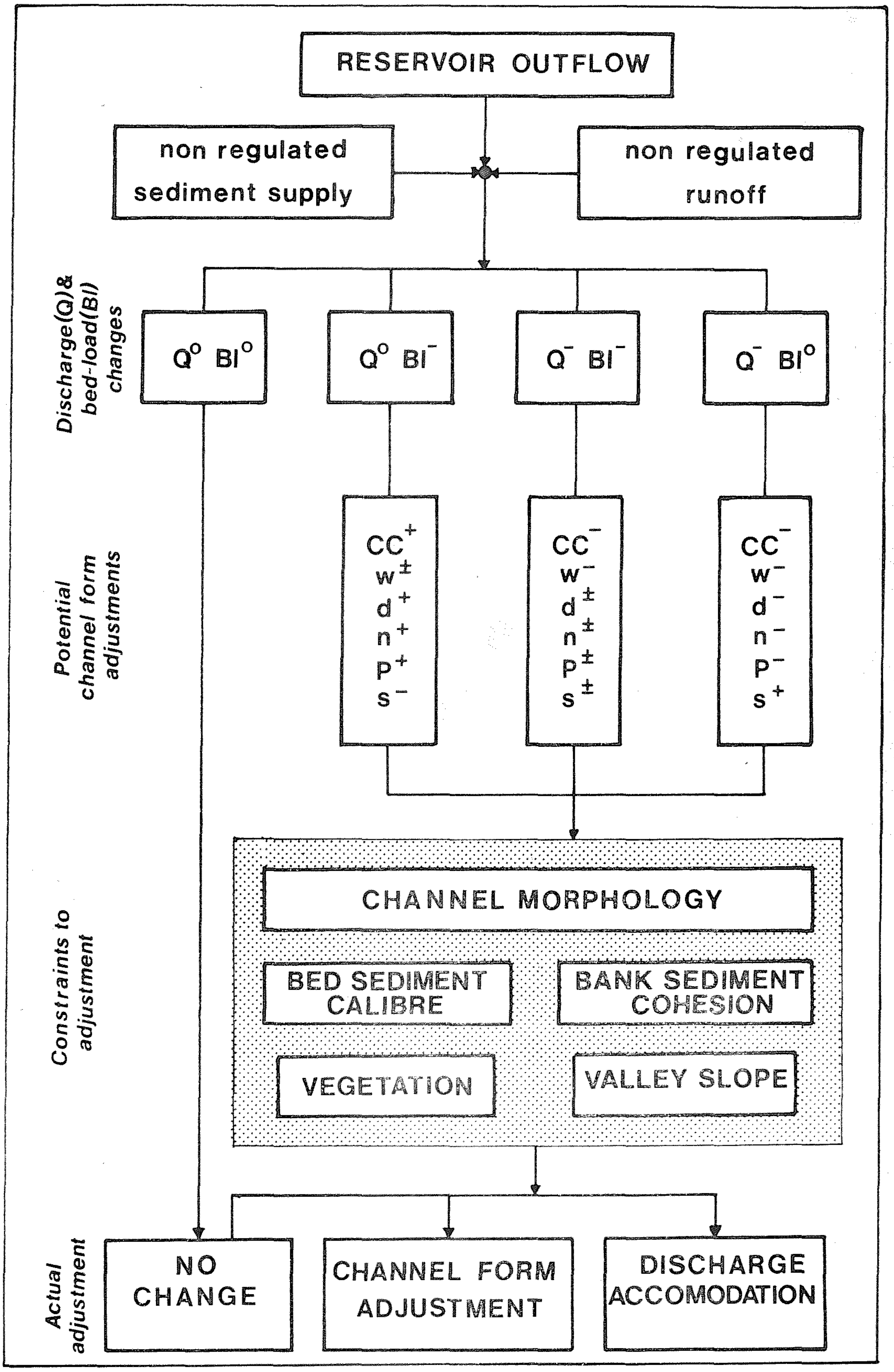

FIGURE 2.4 RIVER CHANNEL ADJUSTMENT CONSEQUENT UPON RESERVOIR CONSTRUCTION.

complete readjustment of the stream channel (Joglekar and Wadekar, 1951).

Although studies of the effects of reservoir construction upon stream channels have been dominated by channel erosion, the aggradation of river channels and the reduction of river channel capacity downstream from reservoirs has been recognised, albeit incidentally, for over half a century. However, few attempts have been made to relate the change of channel form to the degree of flow regulation. Nevertheless, the loss of at least 50% of the pre-reservoir channel capacity has been reported both from the United States and the United Kingdom (Table 2.4). River channels possess five degrees of freedom, being able to adjust their shape, roughness, width, depth and planform (Langbein, 1964) to maintain a quasi-equilibrium state, so that a direct relationship between the reduction of flood peaks and the reduction of channel capacity should not be expected. Furthermore, the channel response may be multi-directional. That is, in order to establish a quasi-equilibrium over time, several, often opposite adjustments may be made in the short term. Thus Wolman (1967) observed phases of aggradation and degradation of the channel bed below Fort Peck Dam on the Missouri River. A change in channel shape with a reduction in the width-depth ratio, without any major change in cross-sectional area, has been observed along Sandstone Creek, Oklahoma (Bergman and Sullivan, 1963) as a result of the regulation of the marked seasonal variation of streamflow and establishment of riparian vegetation. A combination of adjustments affecting channel shape, in cross-section and planform, and capacity may be anticipated in an attempt to satisfy the conditions for efficient sediment transport and water conveyance.

One of the first records of channel aggradation below reservoirs was made by Lawson (1924) relating to the affects of Elephant Butte Reservoir upon the Rio Grande. He concluded that the channel capacity will increase or decrease depending upon the relationship between flow and tributary sediment discharges. The adjustment to reduced flood magnitudes is a much slower process than degradation, involving the introduction or re-distribution of sediment forming depositional berms to narrow the channel, which, once vegetated resist erosion by future rare high magnitude events. The deposits may be composed of finer material than the pre-reservoir deposits due to the removal of bed-load and reduction in competence: these deposits would encourage a narrower section.

Observations of the reduction of channel capacity below a reservoir require consideration of the mechanism of capacity loss.

Table 2.4 Magnitude of channel capacity reduction below reservoirs

River	Dam	Reduction of channel capacity (%)	Reduction of mean annual flood (%)	Source
Republican	Harlan County	66	-	Northrup, 1965
Arkansas	John Martin	50	25	Wolman, 1967
Rio Grande	Elephant Butte	50	25	Wolman, 1967
Tone	Clatworthy	54	60	Gregory and Park, 1974
Meavy	Burrator	73	-	Gregory, 1976
Nidd	Angram	60	-	Gregory and Park, 1976
Burn	Burn	34	-	Gregory and Park, 1976

Two possibilities involve the redistribution of the channel perimeter sediment inherited from the pre-reservoir conditions, and the injection of sediment into the regulated channel. The literature of the past 50 years contains several suggestions for sources of sediment supply to reaches below the reservoir (Table 2.5). The importance of wind-blown sediment will be dependant upon the local environmental conditions, and material derived from bank collapse may be of significance for short reaches, or particular locations, where vegetation may stabilise the deposits. The neglection of the Republican River below Harlan County dam has initiated a reduction of channel capacity caused by the growth of willows within the channel and the formation of islands and a new floodplain (Northrop, 1965). Constructional practices may be responsible for the increase of sediment supply but this will only be temporary and will cease once the dam is complete. Prior to the closure of Granby Dam in September 1949 a large quantity of sediment was introduced into the Colarado River. Flows during the construction period were insufficient to transport material so deposition occured and some of the deposits still remain along the channel sides as terraces even after flooding (Eustis and Hillen, 1954).

Degradation immediately below a dam may act as a sediment source for reaches further downstream. Below Elephant Butte Reservoir on the Rio Grande degradation occurred immediately below the dam and extended for 150 km. downstream. However, the eroded material was deposited within a reach extending for a further seventy miles downstream (Lawson, 1924). Hathaway (1948) also observed shoaling and bar formation below eroded sections on the Ohio River. Where the regulated flow remains competent to erode and transport at least part of the channel sediment a reduction of channel capacity may be achieved through sediment redistribution. The net movement of material eroded from narrow sections to be deposited at wide sections was noted by Hathaway (1948) on the Arkansas River.

Sediment discharged by tributaries into a regulated mainstream, with a reduced frequency of peak discharges, reduced frequency of bed-load transport, will be deposited within the main channel. If the main river is unable to 'flush' the material, the deposit will form a single delta in the first instance. The form and composition of the deposit will depend upon the rate and size of distribution of the sediment supply from the tributary, and the affect of regulation upon the mainstream discharge. During high magnitude, infrequent events the deposit may be eroded, the sediment redistributed, or completely unaffected where vegetation has stabilised the material. The removal of flood peaks, or rather the reduction of the magnitude and frequency of peak flows along the mainstream, not only results in aggradation below the confluence

Table 2.5 Observations on channel capcity reduction below reservoirs

Location	Sediment Source						Aggradation induced/ assisted by vegetation encroachment	Source
	Upstream degradation	Tributaries	Redistribution of channel sediment	Wind blown	Bank Collapse	Constructional practices		
Arkansas R.			*	*			*	Hathaway, 1948
Colorado R.		*						Dolan et al, 1974
Colorado R.						*		Eustis & Hillen, 1954
N.Platte R.		*	*					Schumm, 1969
Ohio R.	*							Hathaway, 1948
Peace R.		*			*			Kellerhals & Gill, 1975
Republican R.							*	Northrup, 1965
S.Canadian R.		*						Hathaway, 1948
Trinity R.		*						Fraser, 1971
Wind River Basin		*					*	King, 1967
Rio Grande	*	*						Lawson, 1924
Trinity and Lewiston dams Central Valley California		*					*	Serr, 1972

but also in the reduction of the effective base-level of tributaries during times of flood. This may initiate tributary rejuvenation, degradation migrating upstream and further increases the sediment supply to the regulated main river. Tributary erosion resulting from the effective lowering of the base level by mainstream regulation may assume catastrophic proportions. In the first few years after closure of the Tsimlyansk dam (Makkaveyev, 1970) downcutting in the lower reaches of the N. Donets was so extensive that the river depth doubled and tripled and its dischage of sediment virtually extended across the entire channel of the lower Don.

Aggradation at a point on the main channel will reduce the energy slope upstream reducing the velocity of the peak discharge and inducing further aggradation. Indeed, the formation of the rapids along the Colorado River has been associated with the reduction of flood magnitudes following the construction of Hoover Dam, the material being derived from flash flooding tributaries (Dolan et al, 1974). Eventually the downstream slope of the deposits will steepen and incision will occur. Incision will also occur once the long profile of the mainstream and tributaries becomes adjusted and the sediment discharge is greatly reduced. This may have implications to coastal and delta maintenance. A rapid reduction in the sediment discharge to the delta of the Rioni River has resulted in shoreline erosion at a rate of 30 m.p.a. in this section of the Black Sea (Makkaveyev, 1970). Therefore, the complete metamorphosis of river channels may result from reservoir construction (Schumm, 1969) identified the reduction of the width and sinuosity of the N. Platte river consequent upon flow regulation and sediment abstraction.

> "With time, a complete transformation (metamorphosis) of river morphology may be a consequence of river regulation. That is, although the immediate morphologic result of dam construction is local and is manifested by channel degradation, geologic evidence suggests that the influence of regulatory and diversion structures may cause a complete alteration of channel morphology throughout the length of a river system"
>
> S.A.Schumm (1969, 255)

Changes of river channel form may be anticipated below reservoirs in Britain, adjustments being made to the changes in flow regime and sediment load. The examples of river channel adjustment from the literature indicate that the channel response to reservoir construction may be described by a single qualitative formula:

$$Q\ BL \underset{S \quad F}{\overset{C \quad B}{\rightleftharpoons}} w\ d\ p\ n\ s$$

Q = water discharge) BL= bed load)	controls	w = width) d = depth) p = sinuosity) s = channel slope) n = roughness)	channel characteristics.
S = valley slope) C = bank cohesion) B = bed sediment calibre) F = channel dimensions)	constraints		

The effect of reservoir construction upon river channels within Britain will be identified in an attempt to place this qualitative model within a quantitative framework and to examine the importance of the various constraints upon channel form. Moreover, the use of this simple model based upon experience from the literature, may permit some insight into the mechanism of river channel adjustment and provide information as to the significance of particular discharges to the channel form parameters. The following chapter will develop an approach for the identification of channel changes downstream from reservoirs within Britain.

CHAPTER 3. THE IDENTIFICATION OF CHANNEL CHANGE BELOW RESERVOIRS

The form of river channels will (Chapter 2.1) tend towards a quasi-equilibrium state, being maintained by the characteristics of runoff and sediment production of the drainage basin. The form of river channels in plan and cross-section will vary spatially in response to the variation in sediment supply and runoff and to local variations of lithological, vegetational and other drainage basin variables which constrain channel adjustment. Runoff pattern and stream behaviour are unique for each watershed, reflecting the interaction of all the factors which affect runoff (Black, 1970, p.156), but it is possible to identify environmental regions within which runoff conditions may be similar. Thus, Cole (1966) has divided England and Wales into a series of hydrologic areas based upon weather patterns and upon drainage basin characteristics. Similarly, whilst observing some variation in channel form characteristics between rivers within south-west England, Park (1976) demonstrated that regional relationships may be developed between channel form parameters and the controlling variables.

The sediment load of rivers plays an important role in channel processes. Although in Britain, measurements of sediment yield are few, the amounts of sediment transported by rivers within the United Kingdom have been considered to be generally low (Nixon, 1959), so that discharge may be the factor which has the predominant effect in determining the dimensions of the river channel. Nevertheless, the literature indicates (Chapter 2.3) that an alteration of the characteristics of runoff and sediment production within a drainage basin, as a result of man's interference with a natural system, will inevitably have feedback effects upon the river channel form, in plan and cross-section, and upon the network of channels within the drainage system. Thus, Gregory (1976a) cites several examples of the adjustment of British river systems, river channels and drainage basins, to alterations of the controlling variables. Indeed, several types of drainage basin response to specific impacts by man had been isolated prior to the turn of the century, but the implications of the observed changes were not realised for over fifty years.

In Britain the earliest reservoirs were either built by men like Capability Brown to beautify the estates of large landowners

(Kennard, 1972) or by canal engineers. The register of all dams greater than 15m in height (International Commission on Large Dams, 1973) records Coombs Dam as the first entry for Great Britain; it was completed in 1797. To 1970, 297 large dams had been constructed in England and Wales and a further 143 in Scotland. However, no absolute list of reservoirs exists. Nevertheless, the available data may be used to demonstrate the size distribution of reservoirs according to surface area within different regions (Table 3.1). The data is based upon a survey of all lakes and reservoirs marked on 1:250,000 maps of Great Britain undertaken by The Institute of Terrestrial Ecology (pers. comm). Reservoirs were distinguished from other natural water bodies except in the cases of water with an area of less than 0.25 km^2. The area represented in the count (1926 km^2) is approximately 78% of the total area of inland water in Great Britain. Although no precise criterion for including any water body on such maps exist (Ordnance Survey, pers.comm.), a complete population of large reservoirs, above an area of 1 km^2, may be identified, the uncertainty applying only to the smallest reservoirs.

Throughout this century the tendency has been to construct relatively fewer and larger reservoirs, often now used for river regulation and hydro-electric power generation rather than simply for direct supply by pipeline. The use of water in England and Wales and the developments required to meet the deficiency in supply expected by the end of the century have been examined by the Water Resources Board (1973). Within the study twenty-two new reservoirs with surface areas greater than 2 km^2 were considered, and ten existing dams were considered for enlargement. As reservoirs become more numerous and competition for water becomes greater, the alteration of drainage basin processes and the consequent changes of river channel form will become more important. The identification of river channel changes downstream of reservoirs may permit an evaluation of the impact of reservoir construction in Britain, which may illuminate the factors influencing the response of river channels to changes of flow regime.

3.1. AN APPROACH TO CHANNEL CHANGE.

Channel changes in response to the impact of man have been identified from various environments throughout the world, but few attempts have hitherto been made to identify channel response consequent upon reservoir construction within Britain. Nevertheless, an adjustment of the quasi-equilibrium channel form to the reduction of the sediment

Table 3.1 Distribution of reservoirs in Great Britain

Region	Distribution according to surface area (%)				Total number of reservoirs counted	Distribution according to region (%)
	< 1.0 km²	1-4 km²	2-16 km²	16 km² <		
Scotland	53	22	21	4	103	38
Upland England and Wales	81	17	2	-	121	44
Total Uplands	67	19.5	11.5	2	224	82
Lowland England & Wales [1]	70	22	8	-	50	18
Total England & Wales	75.5	19.5	5	-	171	62
Total Great Britain	64.25	18.25	13	2	274	100

1 Lowland England and Wales has been defined as those hydrometric areas whose solid geology consists largely of sedimentary rocks younger than the Permian.

load and alteration of the flow regime imposed upon river channels by reservoir construction may be expected. For several reasons study of such effects can be difficult, not least because observations are not available before dam construction. Data of river channel dimensions, discharges and sediment yields prior to dam closure are often non-existent, incomplete or of questionable accuracy. Certainly for future studies data should be collected from catchments where reservoir development is intended. Hey (pers.comm) has examined river channels before the implementation of the proposed Craig Goch scheme in mid-Wales and the Kielder scheme in Northumberland in an attempt to predict the effects of flow regulation and sediment abstraction upon the river channel following dam closure. The comparison of pre-existing physical conditions of study-reaches with those on the same reaches after reservoir construction will be possible provided that representative data covering satisfactorily comparable time-spans are obtained for both the calibration and the impounding phases. However, at present pre-reservoir channel form data is sparce. Nevertheless, four particular approaches to estimating the effects of reservoir construction upon river channel capacity are considered to be helpful in a British context, namely, theoretical modelling, empirical prediction, single catchment studies, and paired catchment studies.

3.1.1. Theoretical modelling

The theoretical modelling of discharges or sediment loads may be attempted to facilitate the determination of changes within river channel form. Whilst the routing of flood hydrographs through reservoirs is commonly dealt with in the modern texts on hydrology, particularly the Flood Studies Report (N.E.R.C., 1975), the determination of sediment loads is more problematic. Nevertheless, a number of relationships for predicting sediment transport from flow parameters have been derived (Graf, 1971); if discharges and flow frequencies before and after reservoir development can be deduced, then differences in sediment transport may be predicted, at least in so far as the prediction equations provide reasonable estimates when subjected to empirical testing. Grimshaw and Lewin (in press) successfully utilised Schoklitsch relationships (Graf, 1971, p.136) to estimate the effect of reservoir construction upon the sediment yield of the Rheidol.

The alteration of the flow regime and sediment loads of rivers consequent upon dam closure have been utilised by Hey (1975) to produce a model for the prediction of channel change. Five process equations were proposed to explain the mechanism of river adjustment to the independent variables - the equations of continuity, flow resistance, bed-load transport, bank collapse, and sinuosity. Although the equations were not actually specified, the simultaneous solution of all five equations would permit each dependant variable, velocity, depth, width, slope and planform to be uniquely defined.

The prediction of the equilibrium form of river channels is only one aspect of river channel adjustment to the impact of reservoir construction. The time required for an adjustment to occur is also a significant factor. A model for describing and evaluating the relaxation time - that period between the beginning of change and the establishment of the new steady state - of a geomorphic system to a man induced disturbance has been developed by Graf (1977). The model was based upon the rate law used to describe the decay of radioactive isotopes and mixture of solutions. As decaying isotopes approach new stable isotopes at continuously decreasing rates, so geomorphic components would tend toward equilibrium states at continuously decreasing rates. The rate law algebraically links the original amount of material with the amount remaining after a given period of decay (1)

$$\left(\tfrac{1}{2}\right)^{t/T} = At/Ao \qquad (1)$$

Where Ao = potential equilibrium form
At = amount of original material remaining at time t
T = half-life
t = time elapsed since disruption to the system

Other forms of the relationship utilised by Graf may be used to determine the amount of adjustment to occur (2) and the amount that has already occurred, Ax, (3)

$$At = Aoe^{-bt} \qquad (2)$$

$$Ax = Ao - Aoe^{-bt} \qquad (3)$$

The rate constant, b, may be interpreted

$$T = (\ln 2)/b \qquad (4)$$

or by the solution of equation (2) in its linear form where sufficient data are available.

$$\ln At = \ln Ao - bt \qquad (5)$$

Utilising these equations Graf (1977), for observations of gully development in the Colorado Piedmont, concluded that whilst the relaxation time varies between systems the rate law may provide a general framework for the prediction and comparison of geomorphic adjustments. The negative exponential form of the rate law achieved for gully development indicated a decreasing rate of adjustment with time, suggesting the operation of a negative feedback loop.

Although theoretical modelling may provide a general framework for the examination of river channel changes, the controls and dynamics of natural river channels are themselves only imperfectly understood and may be precisely indeterminate (Maddock, 1969), so that the general prediction of man induced changes will prove problematic.

3.1.2. Empirical prediction.

The problem of lack of data for quantitative estimates has led several researchers to attempt the qualitative and empirical analysis of stream morphology change. Lane (1955) derived a general expression (1) applicable to the qualitative analysis of stream profile change.

$$Qs\phi \sim QwS \qquad (1)$$

where Qw = discharge; Qs = sediment load;
ϕ = sediment calibre; S = slope

Lane's equation identified a channel equilibrium state so that a change in any one of the four variables will initiate changes within one or more of the other variables to restore equilibrium. The sediment transport factor only includes bed-load as this part of the sediment load is of primary importance to the channel form, the quantity of suspended sediment may change markedly without materially effecting the river profile. The equation qualitatively indicates the adjustments which will necessarily take place in a stream when a change of one of the variables occurs.

Schumm (1969) developed this type of analysis and produced a series of empirical equations to indicate the direction in which channels would adjust to a disruption induced by man. These suggest that for any change in water and/or sediment discharge, channel metamorphosis will occur, and the impact of impoundment upon river channel dimensions may be induced (2)

$$Qw^{-}Qs^{-} \quad \frac{W^{-}L^{-}F^{-}}{p\,+} \quad S^{\pm} \quad d^{\pm} \qquad (2)$$

where w = channel width; L = meander wavelength
d = channel mean depth; F = width-depth ratio
P = sinuosity

The recognition of the direction of channel adjustment may permit the determination of the magnitude of change of particular parameters. Several studies have attempted to predict river channel form from hydraulic geometry relationships (Ferguson, 1973: Richards, 1977).. The conventional hydraulic geometry approach (Leopold and Maddock, 1954) has the advantage of correlating a morphometric parameter to the process variable which is a measure of discharge. Thus, Ferguson (1973) produced an empirical equation (3) to predict channel width from the mean annual flood, Qm, and the percent silt-clay contained within the bank sediments, B.

$$W = 33.1\ Qm^{0.58}\ B^{-0.66} \qquad (3)$$

A direct attempt at utilising the hydraulic geometry approach to predict channel change was made by Richards and Wood (1977) who produced several equations in order to determine the change of channel form variables as the mean annual flood changed (4)

$$\Delta w = (\Delta Qm)^{b} \qquad \Delta d = (\Delta Qm)^{f} \qquad \Delta v = (\Delta Qm)^{m} \qquad (4)$$

$$\text{and } \Delta w . \Delta d . \Delta v = \Delta Qm$$

Thus, any change in discharge will require changes in the three degrees of freedom of the flow cross-section in order to maintain a steady state. Richards and Wood demonstrated that the change of channel width may not be as pronounced as expected, because depth and velocity also change. Nevertheless, a two-fold increase in the mean annual flood resulted in a width increase by 1.2 to 1.5 times, depending upon the state of the pre-existing equilibrium and geometry.

Inorder to determine the discharge of palaeochannels, Dury (1976) produced a sequence of empirical equations. The identification of numerical constants derived from data for unbraided channels facilitated the definition of a set of equations to describe the dimensions of a model stream for humid areas including the cross-sectional area, Ac, (5), the basis of reference being the discharge at the most probable annual flood (q), having a recurrence interval of 1.58 years.

$$Ac = 1.327q^{0.91} \qquad (5)$$

Although the empirical equations are based upon field data, changes in channel form induced by man have been considered to be analogous to climatically induced changes in fluvial systems. Whilst the direction of change may be comparable it is questionable as to whether the changes will be of a similar magnitude or will occur at similar rates. Furthermore, the general application of empirical equations based upon a few, possibly unrepresentative, case studies will prove somewhat hazardous.

3.1.3. Single catchment studies.

The empirical description of the spatial variations of the channel form parameters within a single catchment permits the identification of anomalies which may represent change. Evidence from the literature (Chapter 2.2) indicates that a simple relationship should exist between the channel cross-sectional dimensions and discharge, so that the channel form parameters may be expected to vary progressively downstream. Thus, the downstream variation of channel form of the 'natural' river above a reservoir may be used to predict the 'natural' dimensions of the channel below the dam; comparison of the predicted data with the actual channel dimensions permits the identification of channel change. However, flow records of sufficient quality or length to justify analysis are often unavailable. Thus, Park (1976) proposed that the relationship between channel form and drainage area - a surrogate for discharge - within a single catchment may be the most widely applicable, and effective approach for the examination of the spatial characteristics of river channels within Britain. The implications of drainage area for discharge both between catchments and along a single river have been summarised by Gregory and Walling (1973, Fig. 5.9)). Indeed, Gregory and Park (1974) successfully employed this technique to identify channel form changes along the River Tone, below Clatworthy Reservoir, Somerset. The channel capacities from locations above the reservoir were regressed against the corresponding catchment areas. The significant relationship developed was extended to predict the channel capacities of sites below the dam, and a maximum reduction of 54% of the expected value was demonstrated.

The use of a simple linear regression model to predict channel form data assumes that the rate of runoff is uniform throughout the catchment, and that a linear relationship exists between the downstream increase of drainage area and discharge. Thus, within catchments underlain by heterogeneous lithologies, containing a variety of landuses, or sub-catchments of varying relief, the assumed linear relationship may be invalid. However, for small or hydrologically homogeneous catchments the use of drainage area as a surrogate for discharge will be satisfactory.

3.1.4. Paired catchment studies

Paired or multiple catchment studies have been undertaken so that regulated and non-regulated rivers may be compared. Such studies are dependant upon the existence of hydrological similarity between catchments so that observed differences in hydrology or channel morphology can be genuinely ascribed to the effects of upstream impounding. In detail such identity is virtually impossible but in certain selected cases it may be sufficient to reveal gross differences in conditions. Thus Grimshaw and Lewin (in press) compared the impounded Rheidol and 'natural' Ystwyth catchments in mid-Wales inorder to determine the effect of reservoir construction upon suspended sediment yields. The analysis of the catchments, which are broadly comparable in size and general characteristics, revealed that sediment yields have been significantly altered, being markedly lower for the Rheidol, and that the patterns of erosion and alluvial sedimentation in regulated rivers may, in the long term, become noticeably modified.

The use of channel form data from above the reservoir within a single catchment study requires justification as it is statistically unsound to extend the regression beyond the extent of the data. The establishment of a regional trend between drainage area and channel form parameters based upon one or more neighbouring catchments may provide the justification required for the extension of the prediction equation. Paired catchments possessing like channel-form - drainage area relationships may justify the application of regression equations based upon non-regulated reservoir headwater channel data to the detection of channel change below the dam; if the range of the data is markedly increased by the 'neighbour' catchment then a paired relationship may be used directly to identify channel change.

The direct application of data from a neighbouring catchment to the identification of channel change must be treated with caution as prediction equations developed from one population and solved for another population that is removed either in space or time are never free from error. This error often arises from unwarranted assumptions concerning the degree of similarity between the original and the new groups of data. Inorder to determine whether a significant difference occurs in the groups the catchments should be examined in general for geomorphic and hydrologic similarity and in detail with reference to the specific criteria being predicted.

3.1.5. Channel change identification below British reservoirs.

The identification of channel change some time after dam closure requires information concerning the pre-existing equilibrium condition.

The approach adopted was based upon single catchment studies supported in every case by a paired or multiple catchment study. This approach does not make any assumptions as to the magnitude, direction or rate of change, but simply provides an estimate of the pre-dam channel dimensions. Regression equations based upon the downstream variation of non-regulated channel form parameters permits the identification of channel change when compared with the surveyed dimensions of impounded river channels. For specific channel form parameters the ratio of the actual value to that predicted is hereinafter termed the 'channel change ratio'.

The degree of interaction of the various channel form parameters combine to make the statistical detection of change extremely difficult. Nevertheless, Lee (1977) concluded that, where supported by quantitative data and field observations, regression equations may be useful in predicting the changes a river will undergo in response to a change in its regime. Confidence limits, incorporating the standard errors of the regression constant and coefficient, calculated in the conventional manner (Gregory S. 1963) may be used to detect significant discontinuities within the relationship. Nevertheless, the satisfactory identification of channel changes using regression analysis requires that the degree of variation inherent within the relationship be reduced to a minimum.

The identification of channel response to flow regulation will be complicated by superimposed local, and long-term, changes. Annual random fluctuations in channel morphology (Wolman, 1959; Knighton 1975) and long-term changes in response to climatic trends reflecting dynamic equilibrium rather than a steady state (Schumm, 1968; Dury, 1970) may render the determination of the significance of flow impoundment problematic.

3.1.6. The significance of impoundment to channel change.

The establishment of a statistically significant relationship between two variables does not establish beyond doubt that the independent variable causes the observed change in the dependant variable. Both may vary in response to the influence of one or more unidentified variables. Furthermore, the predictive techniques employed are dependant upon simplifying the relationships. In reality adjustments are complex so that the rate, magnitude, and direction of response may vary both with regard to time and to different parts of the stream channel. Changes may occur so slowly that it may be impossible to correlate the observed effects with reservoir regulation (Leopold and Maddock, 1954). Inorder to identify the significance of reservoir construction for the initiation of channel change further evidence may be required. Three approaches may be employed to corroborate the evidence provided by the regression analysis: the application of discharge equations, sedimentological evidence, and dating techniques. These methods may assist not only in the determination of the direction of change, but also the magnitude and rate of channel response.

(a) The application of flow equations.

Flow equations facilitate the estimation of bankfull discharge from field measurements of channel form. The values of the derived bankfull discharges from regulated reaches may be compared with 'natural' flow data inorder to determine the magnitude of change in the water conveyance capacity of the channel, and to the regulated flow data for comparison with expected bankful frequencies. Hey (1975) demonstrated that the average bankfull discharge for stable, gravel bed upland rivers in the U.K. has a return period of 1.5 years on the annual series. The application of flow equations may enable the determination of the effect of flow regulation and sediment abstraction upon the frequency of the bankfull discharge.

The determination of channel capacity, the cross-sectional area at bankfull stage may be determined from field survey (Chapter 3.2.3.) The flow equations are required for the prediction of mean velocity. Velocity may be calculated by dividing velocity (v) into its components on the basis of a modified Chezy equation for uniform flow.

$$v = C \sqrt{\bar{d}\, S} \qquad (1)$$

For many natural channels the hydraulic radius (R), area (A) divided by wetted perimeter (Wp) is almost equal to the mean depth ($\bar{d}$) of the channel. Where slope (S) data are unavailable the Chezy coefficient (C) may be expressed in terms of the Mannings roughness coefficient (n)

$$C = \frac{1}{n} \cdot (\bar{d})^{\frac{1}{6}} \qquad (2)$$

Although the Chezy Equation takes into account the varying stream geometry, the $C\sqrt{S}$ function is not a constant. The Manning formula depends upon hydraulic principles and is more reliant upon field observation.

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

Both methods are however subject to errors arising from the alteration of the form of the cross-section due to scour and fill during flood discharges. Nevertheless, current U.S. practice (Sokolov, et al, 1976) utilises a conveyance - slope method based upon the equations for steady flow of Chezy and Manning

$$Q = kS^{\frac{1}{2}} \qquad (4)$$

The conveyance factor

$$K = CAR^{\frac{1}{2}} \quad \text{in the Chezy equation}$$

and

$$K = \left(\frac{1}{n}\right) AR^{\frac{2}{3}} \quad \text{in the Manning equation}$$

The Manning equation may be criticised because of its dependance upon the value of n. Problems may arise in the selection of a value for n, which may vary with discharge 'at-a-station'. Nevertheless major channel form changes may be anticipated so that a high degree of precision will not be required. Values of Mannings 'n' were evaluated from observations of the calibre of the bed material, the uniformity of the channel form and the abundance of vegetation. Utilising the base values for 'n' according to bed material calibre together with data from India, U.S.S.R. and U.S.A. (Sokolov, et al, 1976, 7.3.5.1) a basic framework was developed (Table 3.2) to assist in the determination of channel roughness. Whilst cross-sectional irregularities such as rock outcrops may increase the value of 'n' by as much as 0.02, the increase in roughness coefficients caused by curves and bends is generally considered to be less than 0.003. However, vegetation such as trees, bushes and weeds may cause an increase of 'n' by as much as 0.04 depending on the degree to which the cross-section is occupied, type and density of growth, and height of growth in relation to the depth of flow. For relatively steep-bank, narrow channels common within lowland Britain, dense bank vegetation overhanging the channel may cause a large increase in the roughness coefficient, however for coarse bed material channels in upland areas the influence of vegetation is usually minor.

(b) Sedimentological evidence

The recognition of sequences of sedimentation and erosion have been often used to imply changes in drainage basin conditions. Stratigraphic evidence from recent superficial deposits have been studied as 'alluvial morphology' and 'alluvial chronology' (Gregory and Walling, 1973), and Dury (1964) has identified infill, buried channels beneath the contemporary valley floors of many valleys of lowland England and elsewhere. Similarly, Schumm (1968, a) recognised deposits and channels representing several phases of development within the contemporary

Table 3.2 Values of Mannings 'n'

Sediment calibre / Slope	Sands & gravels	Alluvium	Coarse Gravels	Cobbles	Boulders	Large boulders	Channel Characteristics	
Low slope	0.020	0.025	0.028	0.030	0.040	0.060	Uniform channel	No vegetation
	0.030	0.035	0.040	0.040	0.050	0.070	Pools & riffles	No vegetation
	0.050	0.055	0.055	0.055	0.065	0.075	Pools & riffles	Some vegetation
	0.040	0.045	0.045	0.045	0.055	0.075	Uniform channel	Some vegetation
	0.080	0.085	0.090	0.090	0.100	0.120	Highly irregular channel	High vegetation
High slope	0.035	0.030	0.035	0.040	0.050	0.070	Uniform channel	No vegetation
	0.045	0.040	0.045	0.050	0.060	0.080	Pools & riffles	No vegetation
	0.060	0.055	0.060	0.060	0.065	0.085	Pools & riffles	Some vegetation
	0.050	0.045	0.050	0.050	0.055	0.075	Uniform channel	Some vegetation
	0.055	0.050	0.055	0.060	0.070	0.090	Highly irregular channel	No vegetation

Murrumbidgee river channel, Australia. Examination of the relations existing between the morphologic and hydrologic characteristics of river channels demonstrates that fluvial sedimentary deposits are significantly different depending upon the nature of the sediment load moved through the channel. Thus, Schumm (1968a) classified alluvial channels according to the type of sediment load.

The abstraction of environmental information from the grain size analyses of sediments has received consideration attention but conflicting opinions are held as to the environmental sensitivity of textural parameters used (Sevon, 1966; Friedman, 1961; Miola and Weiser, 1968). Nevertheless, Royse (1968) developed the application of textural parameters to differentiate diverse products of a single system such as fluvial regime. Evidence from the northern Great Plains suggested that although fluvial deposits constitute a depositional continium, C.M. diagrams (Passega, 1957, 1964) may be very useful to delimit fluvial facies. Passega (1957, 1964) related the minimum competence of the transporting agent, the smallest particle size in the coarsest 1 percentile (C), to the total range of sizes undergoing transport, a function of the median grain size (M). The dispersal of sediment particles within a fluvial system is clearly related to their mode of transport so that from the identification of textural types inferences may be made as to the mode of transport. Royse (1968) differentiated between floodplains and channel deposits from the genetic interpretation of C.M. diagrams. Changes in facies abundance within a sedimentary sequence or between several sequences may indicate fluvial adjustments related to changes in the independent controls. Richards and Wood (1977) envisaged that berms composed of fine sediment fractions may form after reservoir construction as a result of the reduction in the magnitude of peak discharges.

Soil surveys may be used as an aid in the identification of floodplains. Alluvial soils have unique properties due to the fact that they are periodically inundated. Because they receive periodic deposits of fresh sediment from overbank discharges, alluvial soils lack the distinctive horizons sequence characteristic of soils on stable land surfaces. Thus, McCormack (1971) evaluated the frequency of flooding and depth of flood waters on alluvial soils and soils on stream terraces in Ohio. This revealed that the frequency of flooding could be determined, albeit in general terms, so that terraces could be distinguished from the active floodplain. Thus the examination of deposits may provide an insight into the changes in hydrologic regime which occur consequent upon dam construction. In particular, sedimentological analyses may aid in the interpretation of compound channel forms.

(c) The dating of fluvial forms and deposits.

Techniques available for dating fluvial deposits include radiocarbon dating (Goede, 1973), dendrochronology (Helley and LaMarche, 1973), lichenometry (Gregory, 1976, d), the study of historical records (Leopold and Snyder, 1951), and archaeological evidence such as pottery (Miller and Wendorf, 1958) and other artifacts, including beer cans (Beaumont and Oberlander, 1973), and car number plates (Costa, 1975). However, archaeological evidence may produce grossly eroneous dates as fluvial deposits represent only temporary storages within the drainage basin system so that evidence much older than the depositional form may be found. Furthermore, radiocarbon dating for practical purposes has a reliable range of between 2,000 and 20,000 years and is therefore of little use in the detection of recent changes in channel form. The application of historic records is becoming increasingly important as records improve and surveys become more complete. Evidence from maps, plans or photographs record the precise state of a channel at a particular point in time and may be used not only to determine the amount of change, but also to provide a limiting date for a particular change, permitting the establishment of a minimum rate of operation. However, at present the amount of historical evidence is sparce, but where available may provide valuable information. In Britain dendrochronology and lichenometry may prove most useful in the analysis of river channel change.

(i) Dendrochronology; during the past two decades dendrochronology has become rapidly established as a dating technique with a high potential accuracy (Plate 3.1). Dendrochronology (Douglass, 1914), has been used to calibrate the decay rate of radiocarbon and for the dating of post-glacial events to 7,500 B.P. The technique may be defined as 'the systematic study of tree rings applied to dating past events and evaluating climatic history' (Fritts, 1966).

The technique is based upon the recognition, counting and correlation of annual growth rings exposed in transverse sections or in cores taken with an increment borer (Plate 3.2). The differential seasonal growth rates of new wood produced by the cambial layer enables the recognition of distinct annual layers appearing as rings in transverse section. The density of wood within a single species is influenced by site conditions - soil type, slope, groundwater

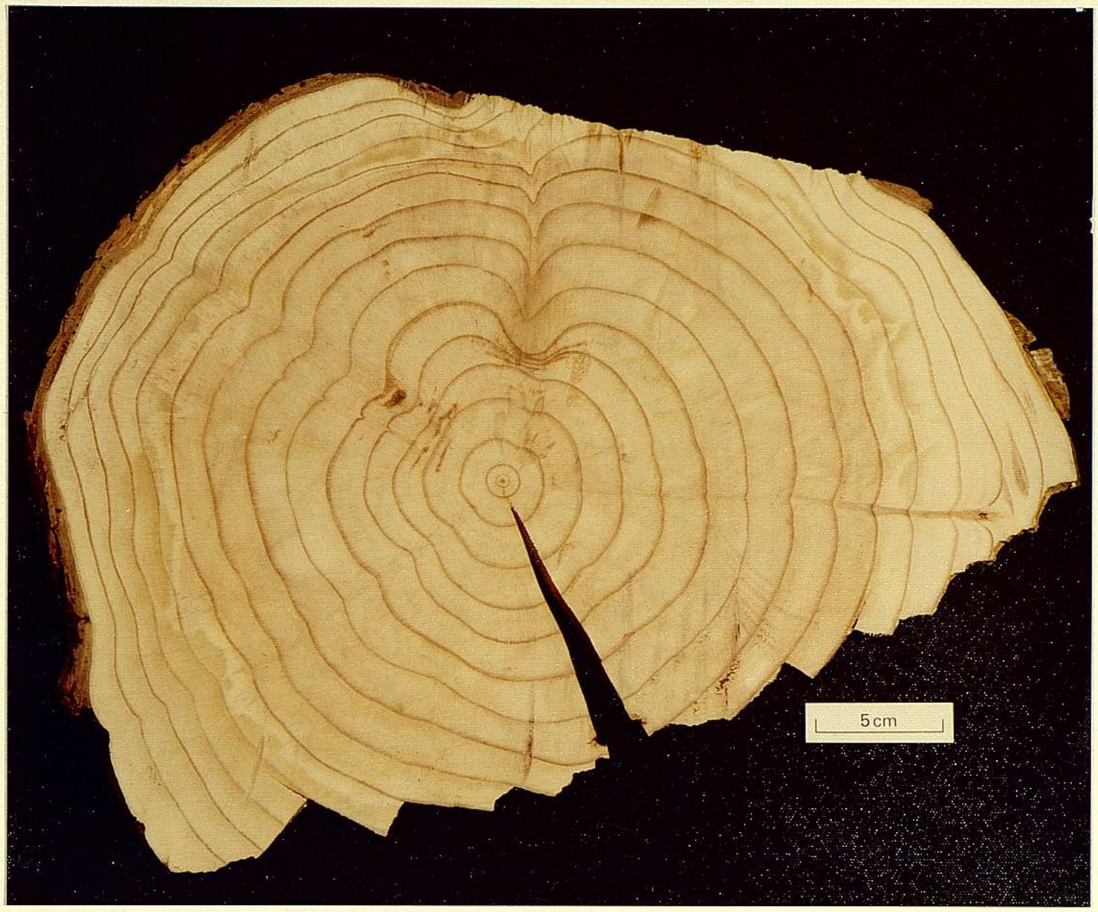

PLATE 3.1 ANNUAL GROWTH RINGS DEVELOPED WITHIN A 19 YEAR OLD CANADIAN REDWOOD.

PLATE 3.2 A TRANSVERSE SECTION AND CORE OF A 22 YEAR OLD ASH, DEMONSTRATING PROBLEMS OF 'ANNUAL RING' IDENTIFICATION.

availability, and climate. Although the technique has a high potential accuracy, variations in growth rates may cause problems of resolution.

During periods of extremely slow growth rings of only a few cells thick may be added and resolution of individual rings will be poor. Also, double or multiple rings consisting of two or more false rings, caused by serious interruptions to growth during the growing period may cause errors in analysis. Growth rings may not be continuous nor concentric about the axis, not uniform in width around the layer - especially problematic if cores are used for spatial correlation. Furthermore, the decay of the central old wood may require the estimation of the "missing" time span as inferred from an average growth rate. Random variation in growth between trees may be reduced by using a large sample.

Dendrochronology is best utilised in areas of marked climatic seasonality. In Britain, because of generally adequate ground-water supplies the response of tree growth to short-term climatic fluctuations has a poor degree of sensitivity. However, this is advantageous for the dating of depositional forms as the problem of false and missing rings is reduced. The establishment and maturation of trees on a floodplain are the result of an interrelated sequence in the timing of the seed dissemination and germination, suitable environmental conditions, and the flow regime of the river. Because the age of each tree provides a minimum date for the establishment of the surface upon which it grows, trees provide a convenient dating machanism with which to analyse the development of compound channel forms. Thus the minimum ages and rates of development can be established and compared with man's activities within the area. Everitt (1968) determined the rate of channel migration from a dendrochronological survey of the cottonwood. The colonizing habits of the cottonwood indicated that germination and growth are intricately related to the discharge of the river, movement of the channel, and development of the floodplain. Although the height and diameter of the cottonwoods varied by as much as a factor of five, ages varied by no more than 10% in any one grove. For a study of episodic erosion producing gully-in-gully form within the Colorado Piedmont, (Graf, 1977) dendrochronological evidence from ponderosa pines confirmed that obscured benches are substantially older than the present gully floors. The tree ring evidence indicated that the protogully system began its development in 1824 and that by 1880 the headcut had eroded to 85% of its ultimate length. Thus, dendrochronology may provide an accurate method for dating channel changes downstream from reservoirs.

(ii) Lichenometry; the technique (Beschel, 1950; translated Beschel, 1973) permits the dating of rock surfaces by comparison of the diameter of lichen thalli on undated surfaces with an established growth curve for the lichen species. Growth curves may be obtained by direct measurement of a single lichen thalli at regular time intervals (Beschel, 1961) or from thalli diamaters measured on dated surfaces. Beschel (1973) observed that lichens may establish themselves immediately after the exposure of a rock surface in crevises and hair cracks or on irregularities of the rock surface. Lichens may therefore provide an accurate date for rock surface exposure. The growth rate tends to be rapid at first but then to decrease (Carrara and Andrews, 1973). However, the rate of growth of a particular lichen species depends primarily on the micro-climatic environment and the nature of the substrate is very important in species selection. Immobility and permanence are further pre-requisites, external mechanical disturbances having a disrupting effect.

Lichenometry contains many potential problems (Webber and Andrews, 1973). The method demands the a cceptance of certain primary assumptions which may create a considerable source of error. Beschel's fundamental assumption was that only the lichen thallus with the maximum diameter is an indicator of surface age. The largest, and hence optimal growing, individual lichen thallus will give the minimum age of substrate. Criticisms (Jochimson, 1966) have been concerned with the numerous sources of potential error, arising from environmental factors, not yet fully understood. Furthermore, the growth of the lichen, which forms the basis of lichenometry is still open to question from its beginning both in its physiological fundamentals, and in the influences exerted upon it by its local environment. Problems also arise in the identification of individual species in the field and in the measurement of thalli diameter for non-circular individuals. For the latter Andrews and Webber (1964) recommended that the minimum diameter of the largest thalli in each location should be measured.

In the light of Jochimson's (1966) challenging paper Andrews and Webber (1969) re-evaluated and re-affirmed the use of lichenometry as a dating technique. Whilst the assumptions inherent within the technique of lichenometry create a considerable potential source of error, especially as it is more desirable to have absolute rather than relative dates, Andrews and Webber (1969) concluded that the assumptions are often correct. However, each geographical area must be assessed separately with respect to suitable species, their growth rate, and reliability of results.

Beschel envisaged many applications for lichenometry (1961) and made general reference to the dating of dry river channels. However, the optimal water supply within the spray zone will result in lichens growing much faster than those without this abundant water supply. Problems may be anticipated to arise in the comparison of river bank species with the same species from less favourable environments such as gravestones. Nevertheless, Gregory (1976 d) applied lichenometry to the regulated channel below Dumaresq Dam. The dam was built in 1898 and reference to a growth curve derived from tombstones for the *Parmelia conspersa* group suggests a date of pre-1910 for this surface. Therefore, lichenometry may be employed to indicate dates of channel modification due to the reduction of peak flows subsequent upon dam closure, for bedrock channels in Britain.

3.2. DATA COLLECTION.

The analysis of channel response to impoundment requires either the long-term study of a particular catchment or the identification of channel changes downstream of a number of reservoirs of different ages. Time constraints and the desire to examine the variety of changes in channel form that may occur necessitated the adoption of the second method. The approach utilised (Chapter 3.1) permits the identification of changes in channel dimensions below reservoirs. Furthermore, the reservoirs selected from a variety of environments may permit the determination of the rates, magnitudes, and directions of response under varying constraints.

3.2.1. Selection of catchments.

This was based upon two requirements. Firstly, the variety of catchments selected should permit the examination of reservoir effects within a variety of hydrologic and geomorphic regions. Secondly, sufficient reservoirs within particular regions should be examined inorder to determine the influence of reservoir age and size upon river channel form. The selection was constrained by the need for neighbouring catchments having like environmental qualities to permit comparison. For regulated tributaries sufficient channel length should be available between the dam and the mainstream to justify analysis.

Britain has been recognised as being composed of two main landform zones (Fig. 3.1 a). A more detailed division of England and Wales has been made by Cole (1966) who identified six hydrologic categories based upon the regional analysis of flood frequency data, particularly the mean annual flood (Fig. 3.1 b). Although the regions have a general correlation with rainfall (Fig. 3.1 c), and the hydrologic divide - between high and low discharge areas - coincides approximately with the relief division of Britain (Gregory and Brown, 1975), the

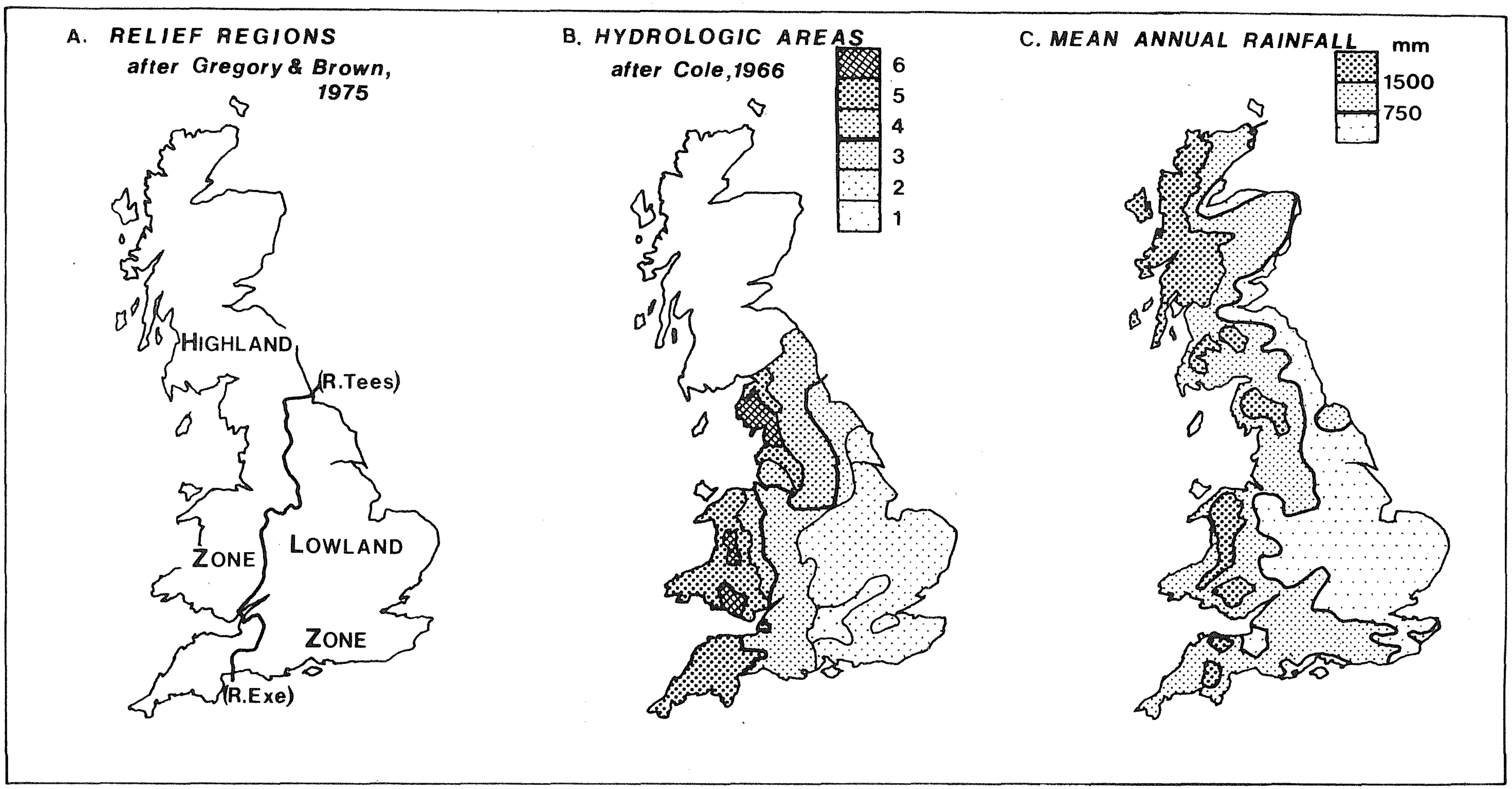

FIGURE 3.1. THE ZONATION OF BRITAIN ACCORDING TO RELIEF (A), HYDROLOGY (B), AND RAINFALL (C).

hydrologic areas devised by Cole demonstrate the effects of ground permeability also. The development of a fluvial system is not only related to hydrometeorologic and relief factors, but also to geology. Hack (1957) and Brush (1961) demonstrated the influence of rock type on the morphologic properties of a drainage basin and on the morphometric characteristics of stream channels. Indeed, the geology of a basin may markedly influence the manner in which fluvial variables interact within a drainage system. Cole's (1966) hydrologic divisions may, although only provisional, provide a basic framework for the selection of catchments. The primary data for each of the reservoir catchments studied (Fig. 3.2) is summarised in Table 3.3 Each reservoir is either paired with a neighbouring catchment or is compared with regional data to enable the identification of channel change.

3.2.2. Determination of independent controls.

In the absence of adequate flow records a variety of parameters have been used to examine the spatial variation of river channel form. Drainage area has been most frequently employed (Gregory and Walling, 1974; Park, 1976). Indeed, drainage area has often been used to estimate stream discharge and has been correlated both with frequent runoff events of low magnitude (Hack, 1957) and with infrequent runoff events of high magnitude (Patton and Baker, 1975). In addition to area, Horton (1932, 1945) suggested that stream slope and drainage density should be highly correlated with maximum flood discharge per unit area. The significance of slope has been dealt with previously (Chapter 2.1.6.) but Gregory and Park (1976) emphasised the importance of slope in an examination of the channel capacity of a small N.W. Yorkshire stream. Because of glacial interference during the Quaternary the profile of Swinney Beck, north of the Burn basin is convex upwards so that many of the largest channels occur in the headwaters. Thus a multiple regression combining channel capacity and slope was required to explain the variation of drainage area.

Several authors have used other morphometric variables in relation to discharge such as mainstream length (Dury, 1967: Chang and Toebes, 1970). Drainage density is controlled by the numerous variables affecting the hydrologic response of a drainage basin so that drainage density may be viewed, in simplistic form, as a measure of the basin efficiency in removing excess precipitation inputs. One problem of using drainage area as a surrogate for discharge centres upon the non-linear catchment response to rainfall inputs. Differences in

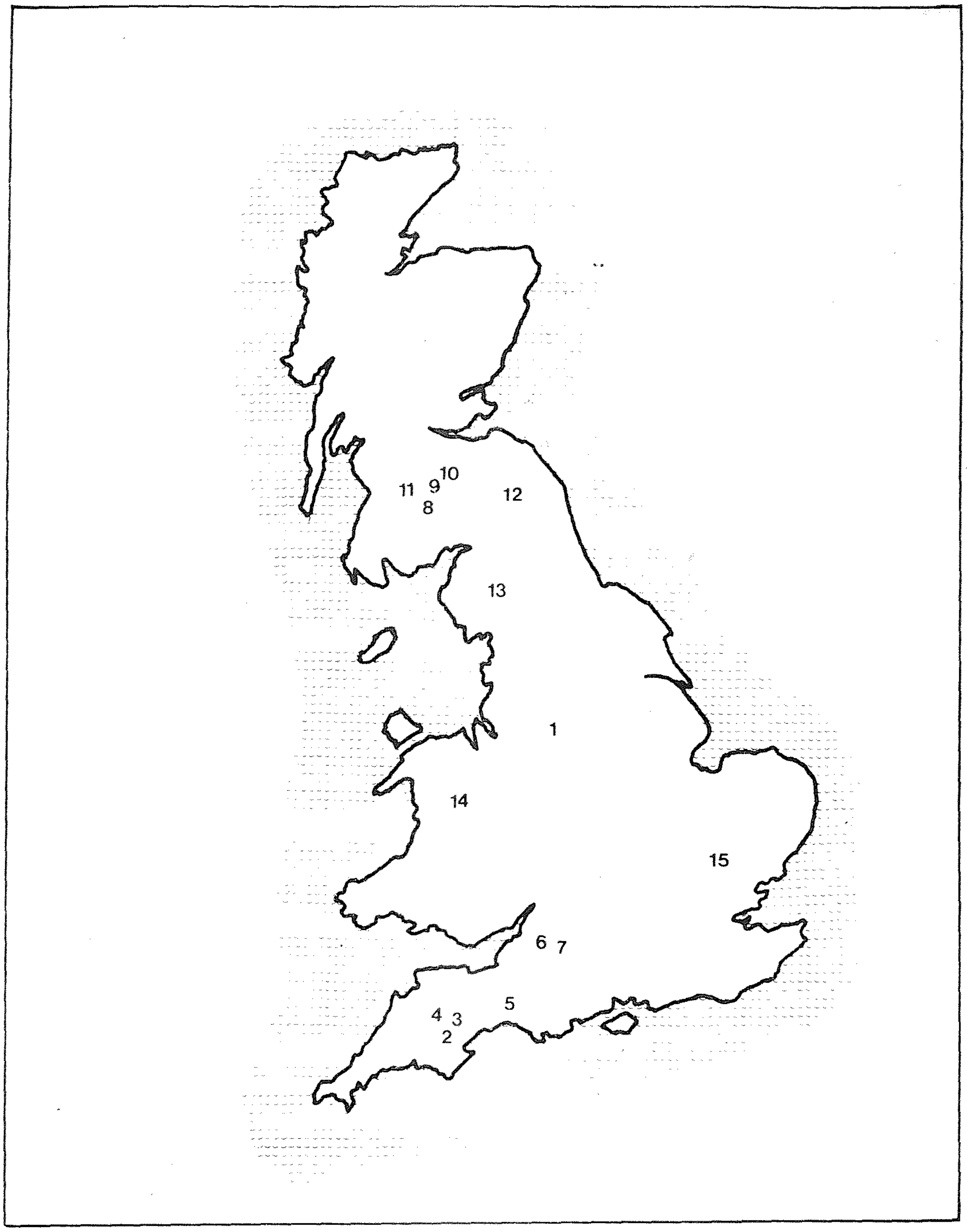

FIGURE 3.2 THE LOCATION OF THE RESERVOIRS STUDIED.

1. The Derwent Reservoirs
2. Avon Dam
3. Fernworthy
4. Meldon
5. Sutton Bingham
6. Blagdon
7. Chew Valley
8. Daer
9. Camps
10. Cowgill
11. Leadhills
12. Catcleugh
13. Stocks
14. Vyrnwy
15. Leighs

Table 3.3 Summary of impounded catchments studied

Relief zone[1]	Relief region	Hydrologic[2] area	River	Reservoir	Catchment area (km^2)	Date of closure
Highland	mid-Wales	6	Vyrnwy	Lake Vyrnmy	73.87	1891
Highland	north Pennines	6	Hodder	Stocks	37.45	1932
Highland	Dartmoor	5	Avon S.Teign W.Okement	Avon Fernworthy Meldon	12.03 9.95 16.83	1958 1942 1970
Highland	Southern Uplands	5	Daerwater Camps Water Cow Gill Elvan Water	Daer Camps Cowgill Leadhills	47.33 24.59 3.50 3.40	1956 1925 1904 pre-1900
Highland	Cheviots	4	Rede	Catcleugh	39.90	1905
Highland	south Pennines	4	Derwent	Ladybower	126.21	1945
Lowland	Wessex Downs	3	Yeo	Sutton Bingham	30.22	1955
Lowland	Mendips	3	Chew Yeo	Chew Valley Blagdon	58.03 26.62	1953 1900
Lowland	East Anglia	2	Ter	Leighs	30.9	1964

[1] Based upon Gregory and Brown, 1975

[2] Based upon Cole, 1966

the catchment characteristics may result in varying relationships between rainfall and runoff for different parts of the same catchment. Lithology is one important control governing both the amount and timing of surface runoff (Gregory and Gardiner, 1975). As drainage density is associated with the most efficient removal of flood runoff (Carlston, 1963), total stream length may be a more pertinent surrogate for discharge than is drainage area within catchments of diverse geology. The examination of two catchments in Pennsylvania and New York States (Smart and Surkan, 1967) further revealed that the mainstream length does not appear to be a very useful parameter in characterising drainage basins. Smart and Surkan suggested however, that total stream length in a basin should be more closely correlated with dependant factors, both geomorphic and hydrologic. Therefore, inorder to determine the most suitable surrogate several variables were measured - drainage area, total stream length, mainstream length and the number of forks within the drainage network.

Due to cartographic generalisation (Maling, 1968) measured values of drainage basin parameters are affected by the topographic map scale. Maps of consistent scale must therefore be adopted for data abstraction. In Britain the Ordnance Survey 1:25,000 (Provisional Edition) maps contain the most complete and conveniently depicted rivers and contours. Furthermore, Werritty (1972) in an examination of the lengths of exterior links for three catchments in Devon and Somerset demonstrated that although the degree of correspondence between field survey data and data for the provisional edition of the 1:25,000 map appeared to be poor, statistical analysis failed to reveal any major differences. Areal measurements were made with a polar planimeter and linear measurements determined with a map sheet. Channel slope was calculated from maps rather than in the field in accordance with the recommendations of Park (1976) who, for a study of channel slopes on Dartmoor concluded that field measurement did not significantly improve the accuracy of the slope value. The 'blue lines' on the 1:25,000 Ordnance Survey (Provisional Edition) maps (Gregory, 1966) were used for the measurement of stream lengths. Although researchers have called attention to the limitations of measuring stream lengths from maps (Chorley and Dale, 1972; Drummond, 1972) for this study the precision of stream delineation was considered less important than the use of a consistent mapping convention. The Ordnance Survey depict streams at their 'normal winter level' on the 1:25,000 maps so that the spatial variation of drainage density may be examined.

3.2.3. Field investigation.

The selection of suitable study reaches is one of the most important elements in the determining of channel data for use in the detection of channel change. An ideal reach from the standpoint of hydraulic principles is virtually non-existent in natural channels, and consequently the problem is one of selecting the best reach available. The need to ensure that the data being analysed are sufficiently accurate and conform to the assumptions made in the analysis requires that the investigation procedure be standardised. Obviously it is expedient to examine the total stream network. It is therefore necessary to observe the fundamental sampling requirement that the channel sections analysed are representative of the river channel and are randomly selected inorder to provide an unbiased estimate of the parameters required.

Because uncertainty exists concerning the magnitude of energy losses caused by local disturbances of the streamlines attempts were made to ensure that straight uniform reaches were selected for the determination of the channel cross-sectional dimensions. The reaches were of such a length so as to include a morphological pair of channel elements consisting of a pool and riffle. Where possible longer reaches incorporating a number of morphological sequences were employed. Sharp bends caused by heteromorphic formations were avoided where possible because their influence on channel roughness may be highly variable and difficult to evaluate,and reaches having tributary inflow or diversions were avoided as unsteady flow conditions may occur at those points. The study reaches were free from major obstructions by rocks and vegetation, and had simple geometric shapes. Channels of compound cross-section however, were included where the compound section was uniform throughout the reach. Locations on mountain streams were free of abrupt drops in water-surface elevation caused by waterfalls, rapids or constructions, because the abrupt change in elevation may result in channel instability.

Channel cross-sections were surveyed at two or three locations within each reach for the purpose of computing the cross-sectional dimensions. Channel cross-sections were consistently located just upstream of riffle crests. Standard surveying procedures were used to define the cross-sections. Bankfull cross-sectional form was measured by stretching a tape horizontally across the channel and measuring verticals with a calibrated staff at frequent intervals. To avoid unnecessary error, sections greater than 10 metres in width were surveyed using a Hilgar and Watts Quickset level. When surveying the cross-sections the survey was carried beyond the recognised bankfull level to incorporate, when possible, levels for lateral correlation. The cross-sectional parameters derived from the survey are described in Table 3.4. The regression procedure for channel change identification requires that the parameters used are free from correlation. The use of interrelated variables may lead to spurious correlations. That is, although two variables may appear independent the incorporation of the same variable on either side may lead to a spurious correlation; dimensionless ratios containing common random elements must therefore be avoided. A second assumption is that the data used in the analyses are substantially homogeneous. Homogeneity may be achieved by using a consistent definition.

3.2.4. A standardised measure of channel bankfull dimensions.
A consistent method for the identification of channel capacity is required as a basis for the detection of changes revealed by spatial analysis. The obstacles to be overcome in the determination of channel capacity have been documented by Gregory (1976, c). The observation of a simple, uniform channel cross-sectional form, having a plane bed bounded by two single element banks intersecting the flood plain at a sharp angle, is uncommon in natural channels. Gregory (1976, c) classified the problems of identifying the 'active' channel as arising from three sources.

The problems of utilising a standard morphologic definition of the channel cross-section have been reviewed by Dury, (1961). These arise from the difficulty in determining the precise elevation of the bankfull stage. The valley floor bordering the main channel may be of different elevations, the banks may be convex upwards so that the contact between the channel banks and the valley floor may not be sharply defined, or levees may occur raising the observed bankfull stage above the level of the floodplain.

Compound channel cross-sections introduce irregularities into the cross-section which render the definition of a consistent bankfull level problematic, particularly where a well developed floodplain is absent. These irregularities may be the result of heterogeneous bank materials, of channel incision below the floodplain level, the

Table 3.4 Channel-form parameters derived from field investigation

Variable	Notation	Description
Cross-sectional area	A	Fundamental variable describing channel size
Channel capacity	CC	Cross-sectional area or bankfull stage
Channel width Channel mean depth	W) d) at bankfull stage	Appear to be functions of energy expenditure within a channel (Maddock, 1969) and are significantly related to the boundary sediment and sediment discharge (Leopold, et al, 1964)
Wetted perimeter	Wp	Length of channel perimeter
Width-depth ratio	W/d	A measure of channel shape apparently related to sediment transport (Schumm, 1968) and boundary material (Schumm, 1960)
Hydraulic coefficient	n	Roughness coefficient (see Table 3.2)
Conveyance factor	k	Modified form of the conveyance factor cited previously (3.1.5 a) $K = CC.R^{0.66} = CC^{1.66} \div Wp^{0.66}$

deposition of channel side benches, or of the existance of several groups of channel forming discharges. The latter source of difficulty for the consistent definition of the channel bankfull stage is contained within the third group of problems (Gregory 1976,c), as uncertainty exists as to the significance of particular discharge frequencies to the channel form (Chapter 2.1.5.). Because of the problems of using a discharge of specific frequency a consistent morphologic definition of the channel cross-section at bankfull stage was employed to obtain channel form data for the determination of channel change.

3.2.5. Criteria for the identification of channel capacity.

Whilst the problems of identifying the bankfull capacity of river channels, including along - and between - channel variations in channel form, have been reviewed by Gregory (1976, c) various criteria have been advanced for the determination of the bankfull capacity of river channels. Kilpatrick and Barnes (1964) suggested that the profile of bankfull stage elevations should plot approximately parallel to the long profile of the water surface at a given discharge through the reach. Similar morphological criteria were recommended by Leopold et al (1964) who determined bankfull stage as the vertical difference between the average floodplain profile and channel bed profile in the vicinity of the study cross-section. This technique does not however permit the distinction between terraces, floodplains and benches within compound sections. Evidence from recent high magnitude discharges however, may be used to indicate the approximate elevation of the bankfull stage. Flood debris may be employed to trace the flood level, and standardise channel capacity determination, downstream (Leopold and Skibitzke, 1967). However, magnitude-frequency data must be used in conjunction with flood elevation data inorder to determine the significance of a particular level.

Vegetation limits have also been used in conjunction with channel form observations inorder to determine contemporary bankfull levels (Gregory and Park, 1974). The establishment and maturation of plant species on a floodplain are the result of an interrelated sequence in the timing of seed dissemination and germination, environmental conditions, the magnitude and frequency of flood events and the sediment content and quality of the flood water. Hence, vegetation characteristics may offer a potentially valuable basis for the identification of channel capacity. Changes in vegetation type may reflect variations in the rates of colonisation of different parts of the cross-section by different species demonstrating the tolerance of individuals to the frequency of innundation. Thus, Leopold and Skibitzke (1967) suggested that the lower limit of herbs and forbs may aid the identification of channel capacity. The channelward limit of perennial woody plants represents either the level of the maximum discharge during extended periods of low flow or the edge of the channel that is encroaching on a floodplain as a result of lateral corrasion. Sigafoos (1964) used the channelward limit of trees to determine the junction between the channel and floodplain. Floodplain trees were identified to the approximate level of the two-year flood within actively meandering systems.

The presence of mosses and lichens growing on rock surfaces may indicate a level above low water within alluvial (Leopold and Skibitzke, 1967) and bedrock (Gregory 1976, d) channels. The analyses of lichen limits on the sides of rock channels in New England, Australia (Gregory, 1976, d) indicated that the lowest lichen limit was maintained by peak discharges which occur on average at least once or twice each year. The relationship of lichen limits to discharge records enabled Gregory to identify three discharge levels within the bedrock channels. Within alluvial channels however, sedimentological evidence may prove more informative as to the significance of particular morphological levels.

The construction of floodplain segments to a particular elevation serves to maintain the stream channel in a state of quasi-equilibrium, so that the surfaces of point bars, within actively meandering systems, will occur at various elevations up to the general level of the flood-plain surface (Wolman and Leopold, 1957). Similarly, a newly formed bench appears to undergo a sharp reduction in its rate of aggradation when it defines a channel whose size bears a certain relationship to streamflow (Hammer, 1970). Furthermore, the surface deposits of mature point bars may be of a different texture to the deposits at depth (Nunally, 1967) and the frequency with which a surface is innundated, and the velocity of flow across the surface, will be reflected in the characteristics of the surface. Sedimentological evidence may therefore provide a basis for distinguishing between channel and floodplain deposits, and may assist in the determination of the significance of particular morphologic elements within compound sections.

In an attempt to improve the precision with which the bankfull stage may be identified Wolman (1955) and Riley (1972) advanced a qualitative methodology. Both methods were based upon water-depth coordinates derived from the field survey of the channel cross-section. Wolman (1955) recognised the bankfull level as the stage at which the ratio of channel width to depth is at a minimum. However, within irregular cross-sections - and particularly for compound channels the ratio does not always indicate the floodplain-channel junction. Thus, Riley (1972) observed that whilst the minimum width-depth ratio may produce satisfactory results for rectangular profiles,for channels with shallow profiles and gently sloping banks the technique may produce erroneous results. Inorder to resolve this problem Riley (1972) developed the 'Bench Index' which considers segments of the channel profile rather than the whole profile. The 'Bench Index' is based upon values of width and maximum depth calculated for each coordinate and ranked in order of decreasing depth. Whilst the accuracy of the 'Bench Index' depends on the spacing of coordinate points defining the profile, the relationship between the 'Bench Index' and depth displays a marked peak value near the actual bankfull stage. Although less dependant upon subjective measurement, subjective judgement is still required to define the approximate bankfull channel inorder to locate the transverse limits. Hence compound sections and incised channels remain problematic.

By definition channel capacity is the channel cross-sectional area at the stage above which discharge commences to flow over the floodplain. The problem arises in the identification of the channel-ward limit of the active floodplain - the floodplain-channel junction. The approach (Chapter 3.1.5.) assumes that a reasonably close relationship exists between the channel area and streamflow. It is necessary to define a standard framework for the determination of channel bankfull capacity inorder to maximise the possibility of association between channel area and streamflow through the minimisation of "noise" arising from the pecularities of individual streams. Whilst it is recognised that channel cross-sectional area may bear a more complicated relationship to streamflow, as a general guide the flood having a recurrence interval of 1.5 years (Hey, 1975) was assumed to represent the bankfull discharge where flow data were available. Bankfull capacity was consistently observed as the level

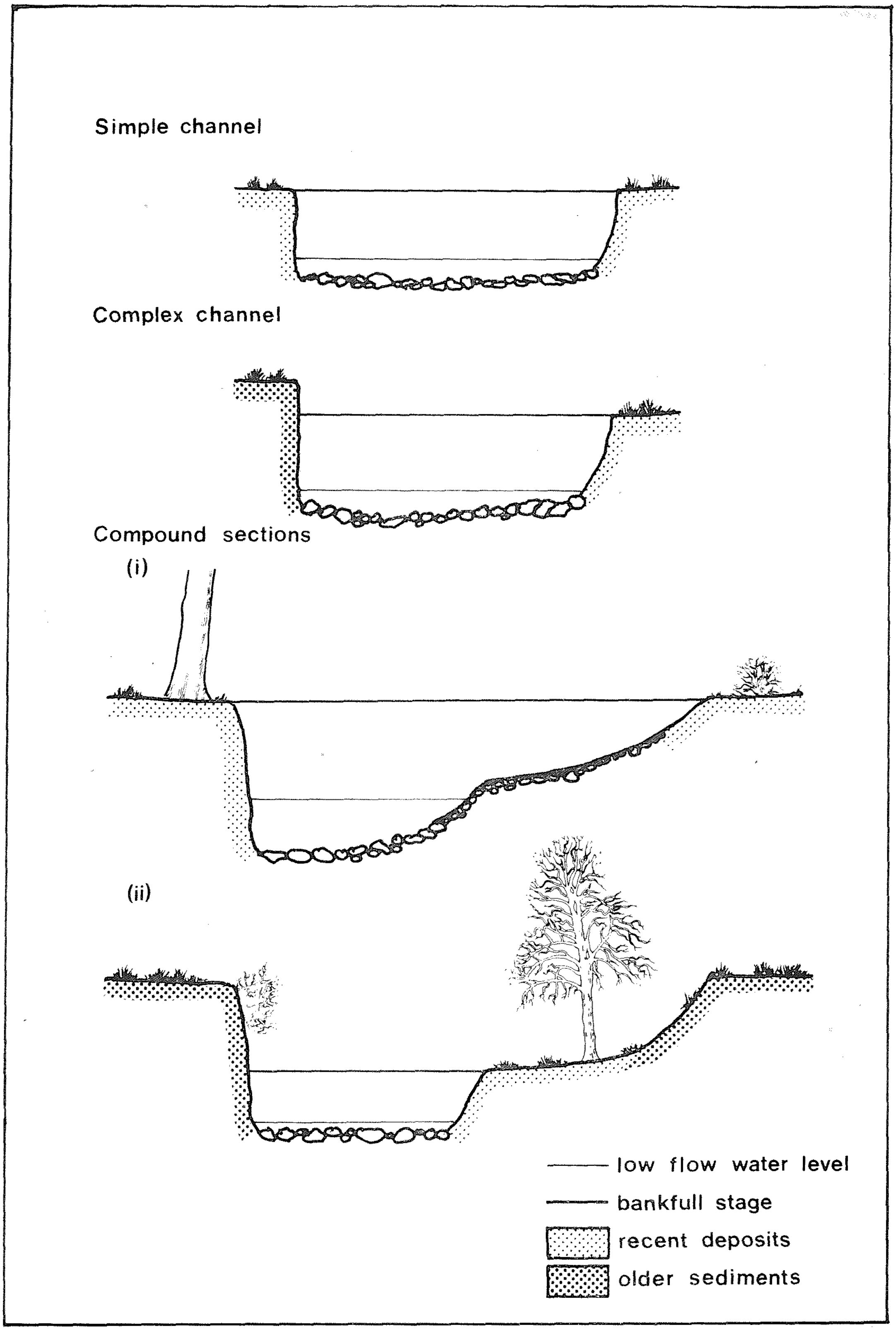

FIGURE 3.3 THE RECOGNITION OF BANKFULL WITHIN SIMPLE, COMPLEX, AND COMPOUND CROSS-SECTIONS.

of a major break of slope separating a well defined channel from a mature floodplain or bench. Hammer (1970) has described the characteristics of "newly mature" berms indicating the existence of quasi-equilibrium with streamflow. Compound sections were interpreted by referece to vegetational limits and sedimentological evidence (Fig.3.3) whilst the downstream correlation of the bankfull level was assisted by wash lines and lichen limits. The selection of a consistent measure of the bankfull capacity of river channels enables the assumption of a downstream steady-state condition to be satisfied.

3.3. FEASIBILITY STUDY: THE RIVER DERWENT, DERBYSHIRE.

The suitability of the approach (Chapter 3.1@3.2) to the identification of the effect of reservoir construction upon river channels in Britain was examined with reference to the Derbyshire Derwent. The regulation of the river was authorised in 1899 and the masonry, crest-weir overflow dams of Howden and Derwent, constructed in sequence to impound the runoff from the headwaters, were closed in 1912 and 1914 respectively. However, it was the construction of the Ladybower dam, begun in 1935 and completed in 1945, that had the major impact upon the River Derwent. The earthfill, bellmouth overflow dam was constructed downstream of the Ashope confluence so that the runoff and sediment supply from a catchment area of 127 km² has been affected. During construction, however, tunnels later to be used for the bellmouth overflows, were effectively employed for dealing with flood discharges (Hill, 1949). Subsequent to the completion of the Derwent and Ladybower dams the water supply to the reservoirs was augmented by the construction of diversions from the neighbouring Ashope, Alport, Noe and Jaggers Clough.

3.3.1. Catchment characteristics.

The River Derwent rises at an elevation of over 575 m.O.D. on the northeast side of Bleaklow Hill, falls rapidly to below 200 m.O.D. within the first 30 km of its length, and subsequently at a decreasing gradient to 44.4 m.O.D. at Longbridge Weir, Derby (Fig.3.4). The 74 km long catchment encompasses an area of 120 km². Mean annual rainfall generally decreases in relation to altitude (Fig. 3.5a) from over 1600 mm on the High Moors around Bleaklow to under 800 mm in the extreme south and east, so that the catchment average is 1080mm.

Geologically, the area may be divided into three main units (Fig. 3.5b). The most extensive, the Millstone Grit series of alternating sandstones and shales, provides a broad area of outcrop

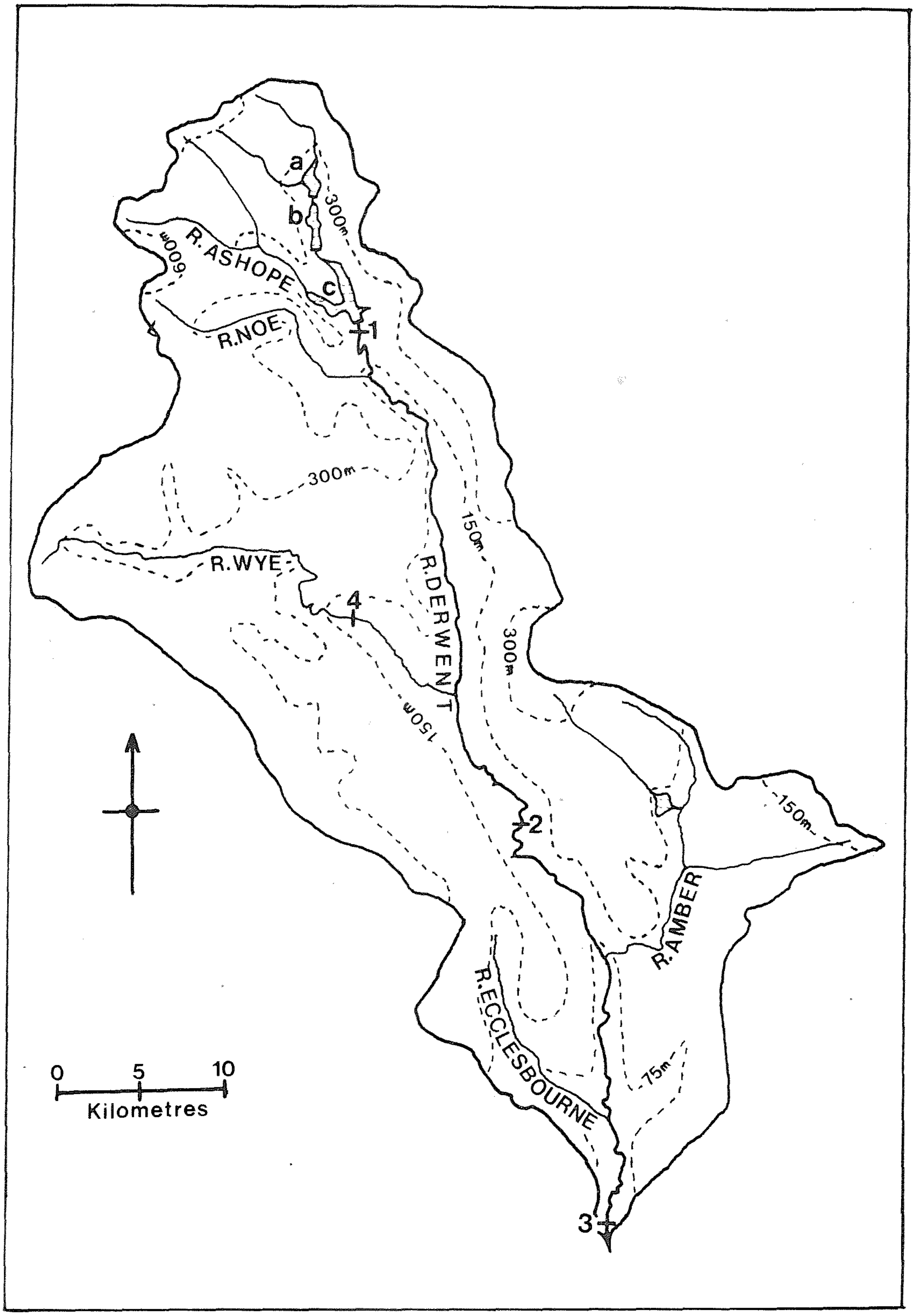

FIGURE 3.4 THE CATCHMENT OF THE DERBYSHIRE DERWENT ABOVE LONGBRIDGE WEIR.

Reservoirs

a) Howden
b) Derwent
c) Ladybower

Gauging Stations

1. Yorkshire Bridge
2. Matlock Bath
3. Longbridge Weir
4. Ashford

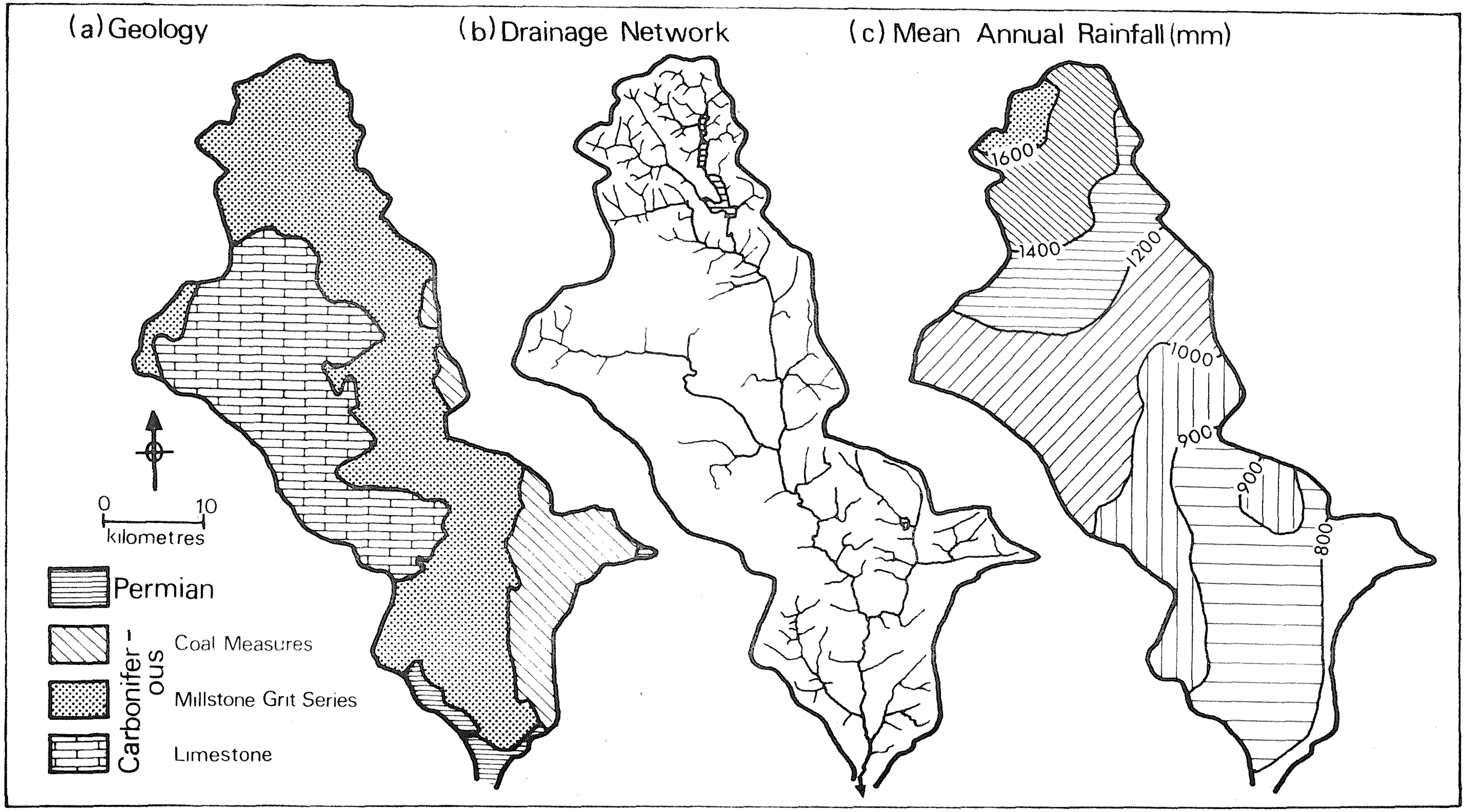

FIGURE 3.5 PHYSICAL CHARACTERISTICS OF THE DERWENT BASIN.

in the north, narrowing southwards to separate the carboniferous limestone from the Coal Measures. The frequent beds of shale within the generally permeable grits ensure the impermeability of the Millstone Grit Series as a whole and results in the formation of perched water tables, responsible for frequent springs along the valley sides. In the north, peat often overlies a weathered, fractured gritstone surface, and this provides some regulation of runoff and tends to balance the seasonal irregularities in the rainfall.

The Carboniferous Limestone Series of the Derbyshire Dome dominate the west of the catchment. The series, composed predominantly of pervious limestone with interbedded basaltic lavas and tuffs, typically has little channelised flow in contrast to the remainder of the catchment (Fig. 3.5c). Mudstones and sandstones of the Coal Measures in the south and east have an undulating topography with summits up to 180 m.O.D., and restricted outcrops of Permian limestones with mudstones and Bunter sandstones occur in the extreme south of the area. The valley fill is composed of terrace, alluvial fen, and head deposits, and glacial material occurs in rare, scattered patches on the higher slopes (Straw and Lewis, 1962). Rock outcrops at several points along the river channel and although the valley is generally wide, at Matlock the river enters a narrow gorge cut in Carboniferous Limestone. The river channel is often tree lined with birch, ash, oak, elm and willow which, together with the outcrops of bedrock and the several weirs and mills, tend to stabilise the slope and planform of the river.

3.3.2 The alteration of channel processes.

From the literature (Chapter 2.3) it may be expected that the reservoirs of the River Derwent will trap a large percentage of the sediment load and significantly alter the discharge hydrograph of flows downstream. Indeed, the significant percentage of reservoired surface area, some 2.7% of the regulated catchment area, indicates that there would be an appreciable reduction in the rate of outflow to reaches below the reservoir (I.C.E., 1933). Nixon (1962) estimated that successive flood peaks in 1960 at Yorkshire Bridge were reduced by over 50 $m^3/_s$. However, the effective reduction of peak discharges decreased downstream as a progressively small fraction of total catchment is reservoired. Although streamflow records have been maintained for a number of years at the three main gauging stations on the River Derwent (Fig. 3.4), the length of record available prior to reservoir construction in insufficient to enable comparison with the present flow regime.

The reservoirs may be expected to trap and store the sediment yield from the headwaters and deposition has been observed at several locations. The capacity-inflow ratio of 0.239 indicates a high trap efficiency of the order of 80 - 90% (Brune, 1953), and with a storage capacity of 37.2×10^4 m^3/km^2 a reduction of reservoir capacity of significantly less than 0.3% per annum may be anticipated (Brown, 1944).

3.3.3. Channel change below Ladybower Dam.

The reduction of peak flows and the virtually complete abstraction of the sediment load may have initiated an adjustment of channel capacity downstream of Ladybower Dam. Measurements of channel cross-sectional dimensions at bankfull stage were made at 110 sites on the River Derwent, above and below the reservoirs, and on the major tributaries. Drainage area and the channel form variables were related by simple regression analysis of log-transformed values. A significant relationship exists for the data from the non-regulated Upper Derwent and Ashope rivers (Table 3.5). However, it is statistically unsound to extend the regression beyond the extent of the data. The incorporation of the Ecclesbourne, Amber, Noe and Wye data (Fig.3.6) significantly increases the range of the regression to twice the drainage area of the Ladybower dam but the standard error of the regression equation is also considerably increased (Table 3.5). The scatter of points reflects the presence of varied lithologies within the Derwent catchment, so that neither the addition of channel slope, nor of the percentage of silt-clay of the banks, into a multiple regression achieved a significant improvement in the explanation.

Not only does the rate of runoff vary markedly between the limestone and sandstone-shale areas (Table 3.6) but there is also difficulty in delineating drainage divides. Several square kilometres of limestone to the north of Peak Forest Village in the Wye basin drain to Castleton in the Noe catchment (Fearnsides, 1932). As the relationship between rainfall and runoff may be expected to vary within the Derwent catchment total stream length may be a more pertinent surrogate for discharge than is drainage area. The linear regression relating total stream length to channel capacity decreases

Table 3.5 Summary of regression analysis of channel capacity on drainage area and total stream length

Date source	Independent variable	Number of data points	Correlation coefficient	Two standard errors	Regression constant	Regression coefficient
Upper Derwent and Ashope	Drainage area	31	0.98	0.1752	-0.1507	0.8860
Upper Derwent and Ashope	Total stream length	31	0.97	0.2083	-0.7010	0.9870
All non-regulated streams	Drainage area	77	0.81	0.3837	-0.0040	0.5746
All non-regulated streams	Total stream length	77	0.94	0.2242	-0.5360	0.8532

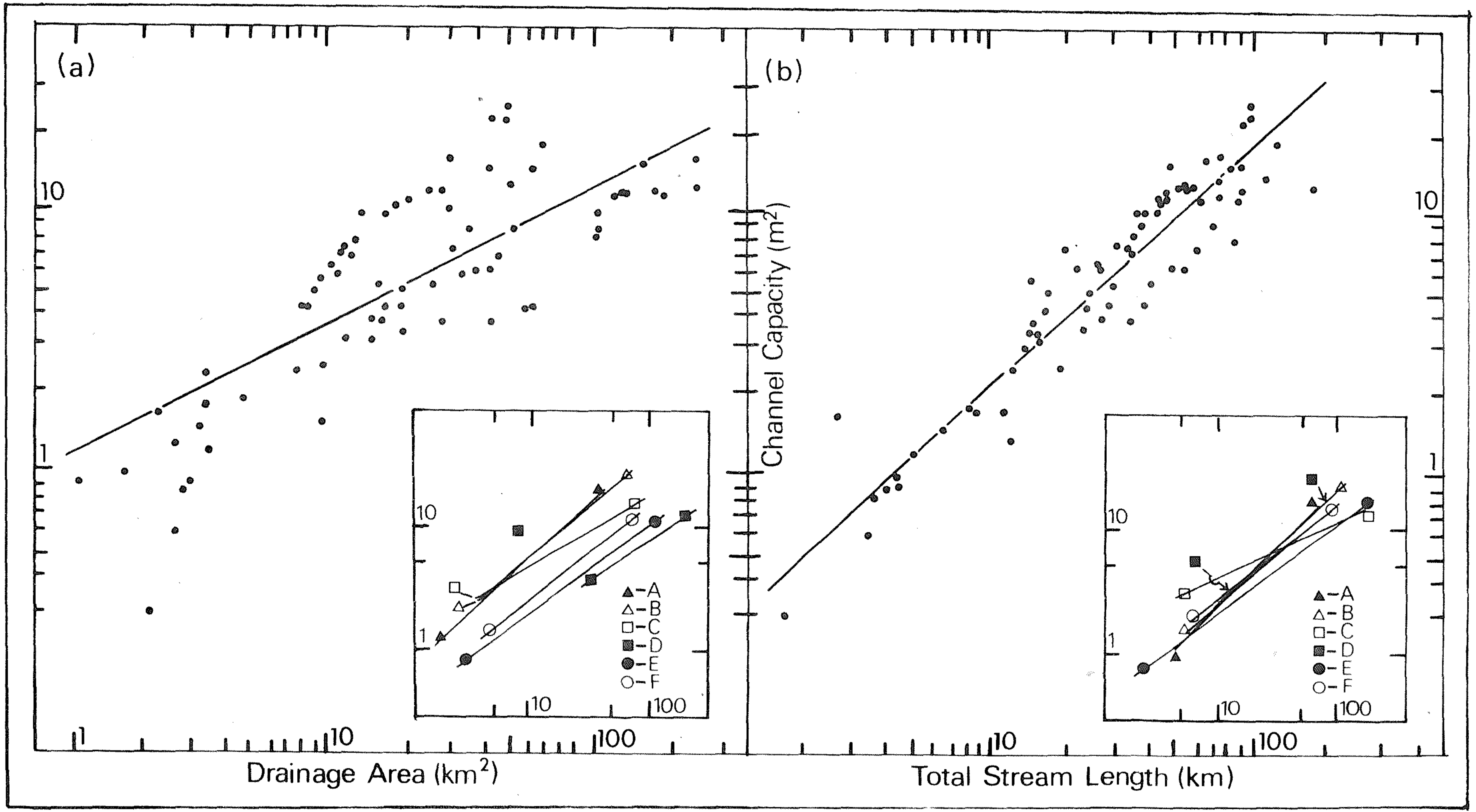

FIGURE 3.6 THE REGIONAL REGRESSION BETWEEN DRAINAGE AREA (a) AND TOTAL STREAM LENGTH (b) AND CHANNEL CAPACITY.

Table 3.6 Comparison of the discharge records of the sandstone-shale and limestone regions

River, gauging station and geology	Drainage area (km^2)	Average Rainfall (mm)	Gauged flows		
			Mean	Maximum	Minimum
Derwent, Yorkshire Br., sandstone and shales	127	1220	3.80	150.60 (9.12.65)	0.47 (often)
Wye, ashford limestone	154	1150	3.96	37.8 (9.12.65)	1.05 (2.11.69)

the standard error (Table 3.5), but the range of the data is insufficiently large to enable the prediction of channel capacities downstream of the Derwent dams. Nevertheless, the variation of peak discharge downstream may be illustrated by relating total stream length, which at any point reflects the characteristics of the drainage basin upstream, to drainage area.

The examination of the scatter of points above a drainage area of 100 km^2 suggests that more than one regression line would give an improvement in explanation. A test employed by Thornes (1970) was utilised to determine points of inflection minimising the combined error sum of squares. A sequence of regressions, calculated by grouping the data beginning at the lowest value for drainage area, indicated the presence of two inflection points (Fig. 3.7). A regression incorporating these points gives a significant (0.5% level) improvement in the standard error from the 'F' statistic and the segments reflect the occurrence, increase, and decrease of the percentage of catchment area underlain by Carboniferous limestone, The application of the inflection points to the relationship between drainage area and channel capacity downstream from Ladybower Dam (Fig. 3.7) demonstrates only a poor degree of correlation. However, classification of the sections according to the nature of the site is revealing. Erosional, compound, obstructed (influenced by man-made structures), and normal sections (simple, stable sections, isolated from structures) were identified. Examination of the 'normal sites', assumed to represent 'pre-dam' conditions, indicates that the inflection points derived above appear to be valid for this relationship (Fig. 3.7). Channel capacities derived from compound sections appear to be reduced so that they lie outside two standard errors of the 'normal' relationship. This conservative estimate of pre-dam conditions indicates a marked change in channel form prevailing along a reach between 4 and 9 km downstream from the Ladybower Reservoir. However, inorder to associate this channel change with the impoundment of the headwaters further evidence is required.

A comparison of channel form surveys before and after reservoir construction is desired but suitable surveys or large scale maps are not available for the River Derwent. Furthermore, the occurrence of trees bounding long reaches of the channel inhibit the use of available air photographs. Nevertheless, comparison between

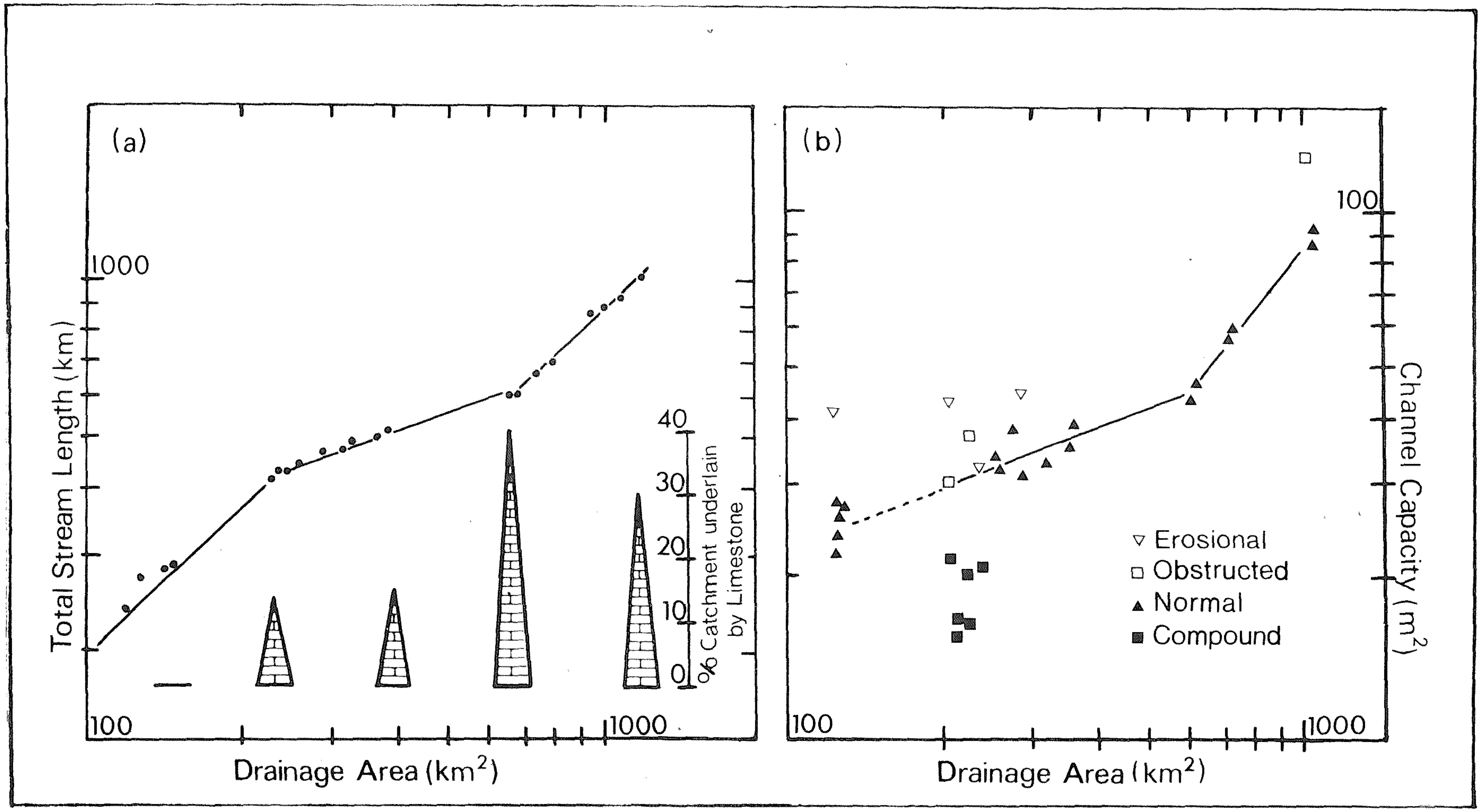

FIGURE 3.7 DOWNSTREAM VARIATION IN THE RATE OF INCREASE OF TOTAL STREAM LENGTH (a) AND CHANNEL CAPACITY (b).

air photographs taken during 1972 at a 1:12,000 scale, and the 1:2,500 Ordnance Survey (2nd edition) maps surveyed in 1879 for a short reach some 8 km downstream from the Ladybower Dam indicates the development of a marked bench since this time. Sedimentological analyses revealed that the benches are formed of coarse sand and gravel, often with a coating of finer sand and silt. This contrasts with the terrace materials which have between 16 and 45% silt-clay, similar to the bank materials of simple sections both upstream and downstream. A certain amount of bank collapse is also evident and on occasion this material has become stabilised and incorporated into a bench form.

The calculation of the bankfull discharges for the compound sections from the Manning equation permits a comparison to be made with flow data. The 1.5 year flood at each gauging station was determined from instantaneous peak flow data, and values for intermediate reaches were estimated from a linear relationship developed between the 1.5 year flood and drainage area. The results (Table 3.7) indicate that although a close similarity exists between the calculated bankfull discharge and the 1.5 year flood for three of the reaches cited, the channels having compound sections are either adjusted to a more frequent event or have not had sufficient time to reach equilibrium with the new flow regime. Sedimentological and vegetational evidence suggest that the former is the case here.

The lack of historical records has been referred to earlier but the numerous trees lining the channel of the River Derwent allows the use of dendrochronology to determine the minimum age of the bench features. Some 200 trees dated along a reach between 5 and 7 km downstream from the Ladybower Dam. Each tree was classified according to situation as terrace top, degraded slope, bench form, or stranded. An inferred ground surface level related to height above water level (low flow was observed throughout) was recorded for each tree and related to dates obtained from cores (Table 3.8). This indicates that all 'bench'forms of up to 1.5m above water level (a.w.l.) are less than 51 years old. Furthermore a former bank level at approximately 2.0 m a.w.l. is suggested by the 'stranded' forms. For 'stranded' forms the ground surface elevation was taken as the level of the highest root, not as the point of inflection of the basal flare which has commonly been misidentified as representing the original ground level. The inflection point will migrate upward with respect to even a static ground surface as a consequence of increasing stem and root diameter LaMarche, 1968). The exposure of the root systems of many terrace top

Table 3.7 Comparison of bankfull discharges derived from the Mannings equation and flow records.

Reach	Drainage area (km^2)	Range of channel capacities	Value of Manning's 'n'	Bankfull discharge derived from Manning's equation ($m^3/_s$)	1-5 year flood determined from flow records ($m^3/_s$)
Yorkshire bridge to Bamford	127 132	22.2 28.2	0.037	28.79 49.47	38.70
Noe confluence to Hathersage	205 235	16.4 21.4	0.035	17.29 29.37	50.00
Allestree, Derby	1104 1108	84.3 91.3	0.030	145.96 185.80	133.83

Table 3.8 Summary of tree-ring evidence

Form	Height above water level (m)	Maximum age (years)
Bench	1.0 < 1.5	51
Stranded	1.75 < 2.25	65% greater than 70 years.
Degraded slope	1.5 <	82
Terrace top	generally 2.5 +	101 +

forms may indicate a former period of erosion. It would be expected that the rapid exposure of a large proportion of a tree's root system due to bank erosion would lead to a suppression of growth (LaMarche,1968). Although the evidence is sparse and growth curves of individual species and climatic data need to be considered, cores from 'terrace top' forms subjected to massive root exposure show a marked reduction in growth rate at about 50 years ago.

A reduction in channel capacity has occurred on the River Derwent for 5 km below the Noe confluence (Table 3.9). Above this the channel bed is composed of gravel and small boulders which provide a natural armoured layer preventing degradation; also, the absence of a sediment supply results in an accommodation of the water discharge within the pre-dam channel. That a bench is not evident until the tributary has joined the mainstream implies that the introduction of sediment by the River Noe into the regulated mainstream may be the significant factor triggering channel adjustment. The reduction of channel capacity from the segmented regression indicates a reduction of over 50%, however, the conveyance factor (K) has been reduced to 66% of the value expected, reflecting a change in channel shape. The post-dam channel, adjusted to a flow event of greater frequency than the 1.5 year flood, may be adjusted to the more efficient transport of sediment at moderate flows. Dendrochronology provides a date for the formation of the bench of 1926. Thus the post-dam channel has adjusted to the impoundment of the headwaters by a reduction of its dimensions and alteration of shape.

3.3.4. Conclusion.

Four approaches to the identification of channel change have been isolated (Section 3-1) but the general applicability of 'theoretical modelling' and 'empirical prediction' to river channel change below reservoirs will be problematic not least because of the imperfect understanding of the controls and dynamics of natural river channels. Nevertheless, the application of single catchment studies supported by multiple or paired catchment studies may be readily applicable to the examination of channel response to flow regulations in Britain. The recognition of systematic spatial variations of channel form parameters has permitted the identification of channel form changes downstream of the Derwent reservoirs. The regression model enables the prediction of pre-reservoir conditions and its flexibility allows the examination of non-linear trends between discharge and drainage

Table 3.9 Interpretation of compound sections

Summary of the evidence for channel change consequent upon dam construction at a single channel section

Details of the channel section

Post-dam capacity from Field Survey	$21.4 m^2$
Pre-dam capacity from Field Survey and identified from level of stranded trees	$43.9 m^2$
Ratio of pre-dam to post-dam capacity	0.49
Drainage area	$210 km^2$
Total stream length	430.2 km

Age of Post-dam channel (River Derwent first regulated in 1914)

From historical evidence - maximum age 97 years
From dendrochronological evidence - minimum age 51 years.

Comparison of the post-dam channel capacity with the pre-dam capacity predicted from regression analyses of regional data

Source of data	Independent variable	Ratio of predicted capacity to the Post-dam capacity	Direction of change
Upper Derwent and Ashope	Drainage area	0.27	Reduction
	Total stream length	0.55	Reduction
All nonregulated channels	Drainage area	1.00	No change
	Total stream length	0.42	Reduction
Segmented regression	Drainage area	0.64	Reduction

Comparison of bankfull discharges estimated from Flow Records and Manning's formula

1.5 yr. flood estimated from flow records	$50 m^3/s$
Ratio of 1.5 yr. flood to the pre-dam bankfull discharge	1.20
Ratio of 1.5 yr. flood to the post-dam bankfull discharge	0.59

Conclusion:

Channel response to impoundment of headwaters is to reduce channel capacity. The post-dam channel is adjusted to a more frequent event.

area, and channel form parameters; total stream length may prove a valuable parameter for the identification of discontinuities within this relationship.

The application of this approach to the Derbyshire Derwent has permitted the identification of channel form changes along a reach extending for 5 km downstream of the River Noe confluence. Within this reach the formation of a bench has reduced channel capacity to less than 60% of the expected value; upstream of the confluence channel form changes are not apparent. The study demonstrated that sedimentological evidence may aid the interpretation of compound sections, and suggested that tree-ring dating may be widely applicable to the dating of fluvial deposits. The classification of trees according to location within compound sections revealed that the bench (Section 3.3.3.) was at least 51 years old - the headwaters of the Derwent were first regulated 64 years ago. The application of the Manning equation permits the calculation of the contemporary bankfull discharge which may be compared with gauged flow data to illuminate the significance of specific discharge frequencies to the maintenance of channel morphology. Estimated bankfull discharges for the 'changed' reach of the River Derwent below the River Noe confluence suggested that the channel was adjusted to a flow event of greater frequency that the 1.5 year flood which may suggest a tendency toward the maximisation of efficiency for sediment transport.

The approach adopted successfully identified channel form changes consequent upon reservoir construction within the headwaters of the Derbyshire Derwent. Within the following two chapters the approach is applied to the identification of channel form changes within (Chapter 4) and between (Chapter 5) hydrologic and geomorphic regions. The identification of spatial variations in the magnitude, rate and direction of channel adjustment to flow regulation may illuminate the factors which influence channel changes.

CHAPTER 4. VARIATIONS OF CHANNEL CAPACITY ADJUSTMENT WITHIN SIMILAR GEOMORPHIC AND HYDROLOGIC REGIONS.

The variety of impacts that reservoir construction may have upon river channel morphology may be identified by the examination of several impounded catchments within similar geomorphic and hydrologic regions. The examination of reservoirs of different age and size may illuminate the factors which influence the rate and magnitude of channel adjustment within a particular area. Previous studies undertaken to identify the effects of reservoir construction upon upland river channels in Britain have been confined to impounded rivers draining Exmoor (Gregory and Park, 1975) and Dartmoor (Gregory, 1976). However, south-west England contains two 'populations' of reservoirs, those situated within the upland areas, and the lowland reservoirs draining the clay vales of Somerset and Avon. The impact of reservoir construction upon peak discharges may be expected to differ between the upland and lowland regions (Chapter 2.3) and the rate of adjustment may also vary, reflecting differences in the stability of the channel perimeter sediments, and the quantities of sediment introduced by tributaries.

The greatest development of water storage reservoirs in Britain has been in Scotland which contains some 50% of the eighty-four reservoirs having a capacity of greater than 10×10^6 m^3. Within the Southern Uplands of Scotland the upper Clyde catchment contains a collection of reservoirs which are suitable for examination. Indeed, the reservoirs provide a variety of scales at which to examine the variation of channel response to flow regulation. In contrast to the upland streams of south-west England the channels are characterised by reaches of active meanders which migrate across dominantly gravel floodplains constrained only infrequently by vegetation and bedrock outcrops.

Three separate regions of Britain have been identified for the examination of the variation in the magnitude, direction and rate of river channel adjustment subsequent to river impoundment. The evidence from within each of the upper Clyde, upland and lowland south-west England, regions are considered in turn, and a comparison between the regions is made in section 4.3.

4.1. THE UPPER CLYDE RESERVOIRS.

Numerous sources for water supply both in the form of surface water storage and groundwater developments exist within southern Scotland. The upper Clyde catchment contains a number of mainstream and tributary reservoirs of different ages and impounding a variety of catchment areas (Table 4.1). Situated within the central southern uplands of the upper Clyde system is bounded on the west and south by the Lowther Hills rising to 732 m. at Green Lowther, and to the east by a line of hills rising to 748 m. at Coulter Fell dividing the upper Clyde catchment from that of the river Tweed (Fig. 4.1). Within the catchment numerous smooth, rounded peaks rise to a common elevation probably representing a pre-Cretaceous surface.

The area is dominated by highly deformed Ordovician and Silurian sediments which are traversed from north-west to south-east by a series of volcanic dykes of Tertiary age. Although the major valley systems post-date the Tertiary intrusions they were probably in existance prior to the onset of the Quaternary. Today the valleys contain thicknesses of glacial and fluvio-glacial deposits which will influence the hydrology of the catchments. Much of the higher ground is vegetated by grasses, heathers and summit mosses, and large tracts of peat occur which may attain thicknesses of up to 6 m.

Mean annual rainfall is in the order of 1500 mm but the occurrence of sands and gravels covered by thicknesses of peat, particularly within the numerous small upland basins, may be expected to reduce the rate of runoff. A relatively low degree of flow variability may be anticipated when compared for example to the rapid time to peak, high magnitude Dartmoor events. Therefore, the rate of increase of channel capacity along a single river may be anticipated to be markedly slower than that determined for the upland rivers upon Dartmoor (Section 4.2.1.).

The analysis of channel form data collected from the field survey of channel cross-sections from the non-regulated headwaters of the river Tweed, Water of Ae, Meggat Water, and Daerwater (Table 4.2) reveal that a consistent relationship exists between the downstream variation of drainage area and channel capacity for the four populations. It was therefore considered justifiable to adopt the regional relationship, based upon the maximum available data, to predict channel dimensions below the dams. Furthermore, the range of the independent variable, drainage area, of nearly 100 km^2 more than doubles the catchment

Table 4.1 Characteristics of the Upper Clyde Reservoirs

Reservoir	River	Date of closure	Impounded catchment area (km^2)	Reservoir surface area (km^2)
Leadhills	Elvan Water	Pre 1900	3.40	0.15
Cowgill Upper	Cow Gill	1904	3.33	0.18
Camps	Camps Water	1925	24.59	0.77
Daer	Daerwater	1953	47.33	2.05

Table 4.2 Channel-capacity-drainage-area relationships for non-regulated channels within the Southern Uplands

River	Drainage area range (km^2)	Number of locations surveyed	Regression constant	Regression coefficient	R^2
Daerwater	1.98 - 16.98	14	-0.1299	0.6802	0.98
Tweed	1.20 - 30.90	12	-0.1577	0.7286	0.94
Water of Ae	13.10 - 97.80	15	-0.1835	0.7161	0.90
Meggat Water	5.13 - 58.50	12	-0.1448	0.7359	0.94
Regional Relationship	1.20 - 97.80	53	-0.1384	0.6983	0.90

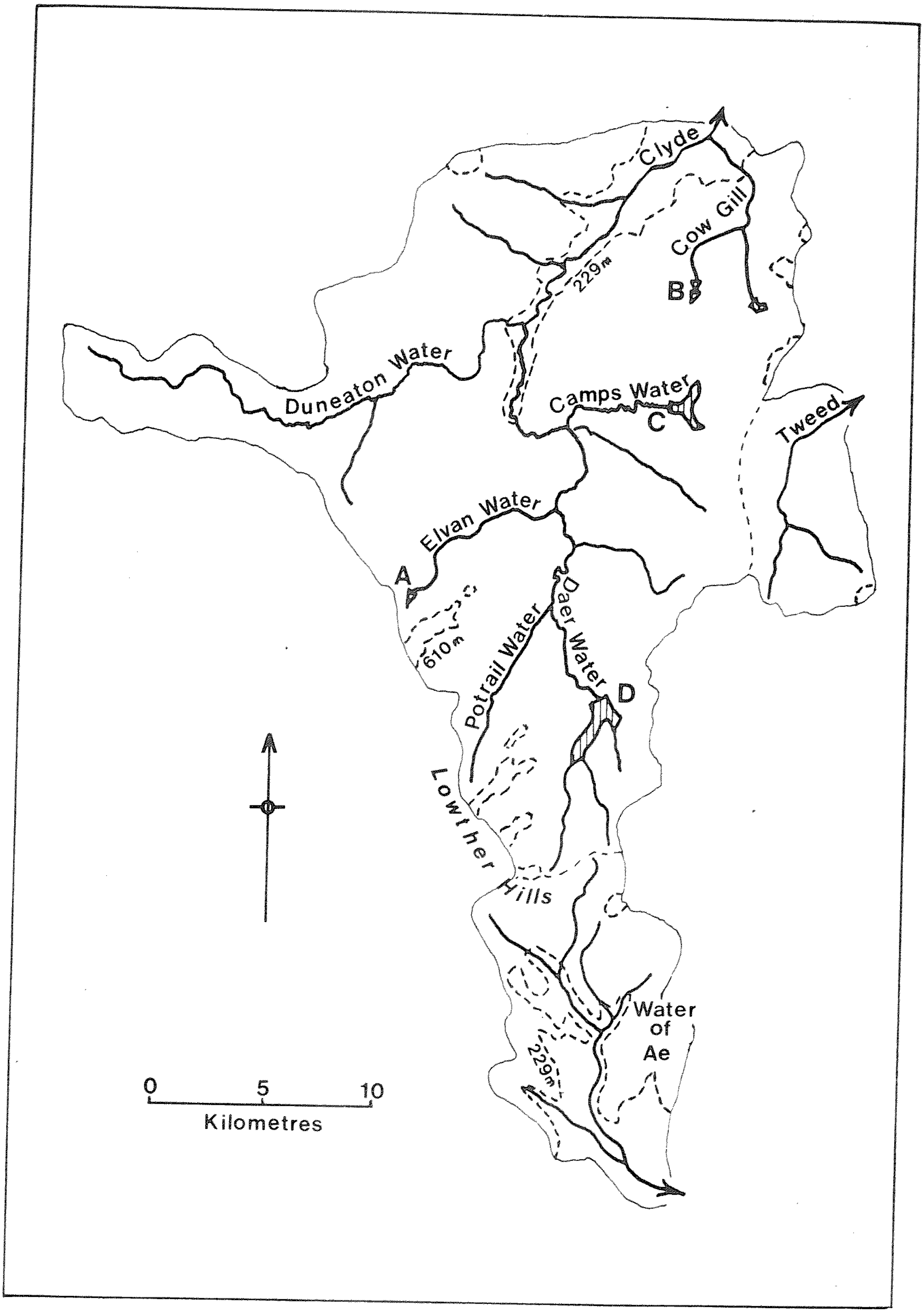

FIGURE 4.1 THE CATCHMENT OF THE UPPER CLYDE.

A. Leadhills Reservoir
B. Cowgill Reservoir
C. Camps Reservoir
D. Daer Reservoir

area of the largest reservoir and avoids the problems inherent in the extrapolation of the individual headwater relationships to predict channel dimensions below the dams. However, the application of the combined standard error of the regression constant and exponent for the determination of the magnitude of channel change was found to be insufficiently rigorous. That is the spread of the confidence bands reflecting the scatter of the data within the drainage area - channel form relationships, was found to be too large to detect changes in channel form. Nevertheless, the comparison of channel dimensions downstream from the dam with the predicted values from the regional relationship identicated major changes of channel form below the reservoir.

a) Leadhills reservoir.

The small reservoir at Leadhills is almost certainly the oldest reservoir within the upper Clyde catchment, although the actual date of construction is uncertain. The Shortcleugh stream was impounded by two earthfill dams to provide water for the lead mining industry which operated here until 1939. In recent years however the spillweir has fallen into disrepair and is at present undergoing erosion during times of flood. Nevertheless it is probable that the sediment and runoff from the reservoired catchment have been impounded for more than 100 years.

Immediately below the dam the channel capacity of Shortcleugh is comparable to that predicted by the regional relationship (Table 4.3). Downstream however, the channel capacity has been reduced so that immediately upstream of the first tributary confluence the channel capacity is only 46% of the predicted value. Below the tributary channel capacities are commonly between 45 and 50 percent of the values predicted but the introduction of a second tributary has had a contrasting effect. Downstream of the second tributary channel capacities are within 15% of the predicted values. That is, the introduction of a tributary having a catchment area equal to 40% of the catchment area above the confluence, and 60% of the regulated headwater area, has reduced the effect of impoundment upon channel processes. The pattern of the downstream variation in channel capacity is paralleled by the conveyance factor 'k', which has been reduced to less than 50% of the predicted value along the reach between the two tributaries.

Table 4.3 Summary of channel form changes below Leadhills Reservoir

Drainage area (km)	Percentage of catchment regulated	Mean channel change ratios				
		Channel capacity.	Width.	Mean depth.	Width/depth ratio	Conveyance factor
3.40 - 3.60	98 - 92.5	1.14	1.18	1.00	1.10	1.15
3.61 - 3.75	92 - 88.8	0.51	0.48	1.02	0.48	0.50
4.75 - 5.10	70 - 65.3	0.56	0.74	0.76	0.98	0.46
7.10 - 21.85	47 - 15.2	0.94	0.78	1.21	0.66	1.02

Upstream of the first tributary confluence the reduction of channel capacity has been achieved by the reduction of channel width, whilst the mean depths of individual cross-sections are comparable to the predictedvalues. Downstream of the tributary both width and depth have been reduced and this may indicate the deposition of bed-material transported by the tributary during times of flood. These changes are reflected in the variation of the width-depth ratio which is markedly lower than the predicted values for sections above the tributary and of similar magnitude to those of the regional relationship below the confluence.

The channel of Shortclough downstream from the Leadhills reservoir has, over a period of at least 100 years, adjusted to the imposed regulation of runoff by reducing the channel width and capacity to 50% of the expected values. However, once the catchment area of the reservoir is exceeded by the area of non-regulated catchment the impact of impoundment upon channel processes does not have an effect upon channel form.

b) Cowgill Reservoir

Cow Gill flows northwards below Whitelaw Brae (Fig. 4.1) and is regulated by two small reservoirs constructed at the turn of the century. Three kilometres downstream from the reservoir Cow Gill joins Culter Water which is itself regulated by the Culter Watershed reservoir. However, this reservoir has recently been overtopped by a major flood which resulted in the erosion of the spillweir and channel immediately below the dam, so that the examination of channel form was restricted to the Cow Gill. The two Cow Gill reservoirs are separated by a short 0.7 km reach permitting the examination of the effects of single and multiple reservoirs upon channel form.

Downstream from the Cowgill Upper Reservoir the channel capacity has been reduced to less than 20% of the value predicted by the regional regression relationship. The average channel change ratio for the reach (Table 4.4.) is 0.242 but the omission of the first and last sites reduces this value to 0.16. The first site immediately below the dam is comparable in capacity to the predicted value, but shows evidence of having an unstable position. There is an absence of vegetation and evidence of former channels; at high flows the channel may be braided. The last site may be affected by backwater from the Cowgill Low Reservoir which may account for the channel capacity being larger than sections immediately upstream.

Table 4.4 Summary of channel form changes below Cowgill Reservoir

Drainage area (km²)	Percentage of catchment regulated	Mean channel change ratios				
		Channel capacity	Width	Mean depth	Width-depth ratio	Conveyance factor.
3.33 - 3.68	99 - 90	0.24 0.16[1]	0.39 0.31	0.61 0.55	0.66 0.62	0.20 0.10
5.50 - 7.13	60.5 - 46.7	0.23	0.29	0.78	0.38	0.18
10.08 - 11.53	33.0 - 28.9	0.51	0.37	1.38	0.29	0.58
26.04 - 29.25	12.8 - 11.4	0.73	0.65	1.12	0.59	0.73

[1] excluding two locations (see text)

The reduction of the channel capacity is associated with the complete change in the form of the channel and has resulted in the reduction of the conveyance factor to 10% of the predicted value. Channel width has been reduced to an average of nearly 30% and mean depth to less than 40% of the expected values. The preferential reduction of width to depth at this small catchment area may be related to the stabilisation of sediment by vegetation. Although difficult to quantify, the encroachment of vegetation appears from field observation to have facilitated the reduction of the width-depth ratio. This may be a response to the reduction of peak discharge magnitudes and to the reduction of the calibre of the sediment load consequent upon reservoir construction.

Below the Cowgill Lower Dam the values of the channel change ratios (Table 4.4) are similar to those above the reservoir. The values of channel capacity obtained are markedly lower than those predicted from the regional relationship. Furthermore, the channel shape has been sufficiently altered so that the efficiency for water conveyance, as indicated by the 'k' factor, has for individual sections been reduced to one-tenth of the predicted value. The effect of impoundment decreases downstream and at a catchment area of 29.25 km² - 2.3 times the regulated catchment area - the channel capacity is within 20% of the predicted value.

Since the chosure of the Cowgill reservoirs seventy years ago the channel capacity has been reduced to less than 20% of the value expected. At catchment areas of less than 5 km² vegetation may play the dominant role in the adjustment of river channels consequent upon reservoir construction. The colonisation of deposits by vegetation may effectively confine the flow, reducing channel width. However, as for the Leadhills reservoir, at a catchment area which is greater than twice the area of the regulated catchment channel form changes have not occurred.

c) Camps Reservoir.

The analysis of the Camps Water channel data enables the examination of the effects of reservoir construction upon channel form within an actively migrating meander system. At a catchment area over 20 km² the riparian vegetation, of grasses and heathers, is unable to stabilise the channel planform. However, downstream the channel becomes progressively less sinuous, the valley being constricted and slope controlled by a rock bar some 4 kms below the dam.

The channel reach immediately below the spillweir flume has experienced degradation which has increased the channel capacity by over 80% of the predicted value at individual cross-sections, (Table 4.5). The amount of degradation decreases rapidly away from the dam so that within 250 m. the channel capacity is reduced to less than 50% and the conveyance factor to nearly 30% of the values expected at individual cross-sections. The reduction of channel capacity is maintained until the contribution of the non-regulated catchment area equals 25% of that draining to the reservoir; below this point the channel capacities progressively approach the values predicted by the regional relationship. At a catchment area 50% greater than the impounded catchment area the channel capacities are closely comparable to those predicted. The reduction of channel capacity at nearly all the sites surveyed has been achieved through the reduction of channel width associated with only minor changes in mean depth. At individual locations channel width has been reduced to 50% of the values expected whilst degradation immediately below the dam has increased channel width to over 140% of the predicted value. Throughout this short reach the preferential erosion of the channel banks may indicate that the bed materials have formed a natural armour layer deposit, so that sediment entrainment has been achieved by the differential erosion of the bank sediments. The processes of erosion, differential sorting, and sediment redistribution during degradation and downstream meander migration has achieved a reduction of channel width by the deposition of channel-side berms and the formation of point bars. The post dam closure migration of the channel indicates that for infrequent events, at least, the regulated discharges are competent to transport the existing channel and floodplain sediments.

Downstream from the belt of active meanders the channel dimensions progressively approach the values predicted by the regional relationship. Therefore, it is considered that the reduction of channel capacity is dependant upon the deposition of sediment derived from differential erosion within the actively migrating meander system. Below this system channel capacities become increasingly comparable with the predicted values as the supply of sediment is reduced. Thus the apparent effect of a 50% increase in catchment area noted earlier may not be a causal factor. It may therefore be anticipated that the downstream migration of the meander system with time would initate the adjustment of the downstream reaches through the redistribution of the channel and floodplain sediments.

Table 4.5. Summary of channel form changes below Camps Reservoir.

Drainage area (km^2)	Percentage of catchment regulated	Mean channel change ratios				
		Channel capacity	Width	Mean depth	Width/depth ratio	Conveyance factor
24.6 - 26.1	98 - 92	1.31	1.12	1.14	0.97	1.48
26.2 - 30.5	92 - 78.7	0.46	0.58	0.80	0.76	0.40
30.6 - 35.9	74.4 - 66.9	0.75	0.76	0.98	0.78	0.66
36.0 - 37.5	66.7 - 64	1.02	0.98	1.04	0.94	1.04

d) Daer Reservoir

The largest and youngest of the reservoirs of the upper Clyde is the Daer Reservoir. Closed in 1956 the reservoir impounds the runoff from the 47 km² headwaters of Daerwater which drains the embayment formed by the Lowthers (Fig. 4.1.). The reservoir has a surface area of 2.05 km² - some 4.33% of the impounded catchment area, and may therefore be anticipated to have a significant effect upon the magnitude of peak flows downstream.

Inorder to determine the impact of reservoir construction upon channel form below Daer Reservoir the channel was divided into a series of reaches based upon the qualitative description of channel stability on planform (Table 4.6). The analysis of channel form data below Camps Reservoir indicated that channel mobility was important for adjustment to occur. The data for the identified reaches below Daer Reservoir has been summarised in Table 4.7a, which illustrates the mean reduction ratios between the actual and predicted values for the individual site within each reach.

Immediately below the dam the channel has a compound form and the data for the outer bankfull level is closely comparable to the values predicted by the regional relationship. This level most probably represents the bankfull stage of the pre-reservoir channel. The inner level however, may represent the contemporary bankfull stage; certainly it is clearly defined and traceable for 0.65 km downstream. The engineers report following dam construction indicates that boulders and concrete blocks were deposited within the channel following construction to prevent erosion but the similarity between the predicted channel data and the former channel dimensions indicated by the outer bankfull level, indicates that this did not have a significant effect upon channel dimensions. The increase of channel bed roughness may, however, have affected the formation of the inner bench. The bench delineating the contemporary bankfull stage appears to have been formed by bank degradation and subsequent vegetation growth, rather than fluvial deposition. Nevertheless, assuming that the bench represents a physical adjustment to the altered flow regime, then reservoir construction has resulted in the reduction of channel capacity to one half of the expected value at individual sections together with a reduction of the conveyance factor to less than 30% of the value predicted. The increase of the width-depth ratio through the reach has been achieved by the primary reduction of channel mean depth. Although channel capacities below this reach

Table 4.6 Channel reaches identified below Daer Reservoir

Reach	Drainage area (km^2)	Distance downstream (Km)	Description
I	47.84 52.02	0.35	Straight, stable channel, gravel banks, gravel-boulder bed, poorly vegetated
II	52.22 53,22	1.00	Straight, stable channel, silt-clay banks, gravel bed, well vegetated.
III	62.50 65.77	1.41	Meandering, stable channel, gravel bed and banks, poorly vegetated.
IV	73.54 73.59	4.51	Straight, stable channel, mixed bank sediments, gravel bed, well vegetated
V	106.99 125.60	6.50	Meandering, mobile channel, gravel bed and banks, poorly vegetated.
VI	158.20 364.80	11.72 26.80	Generally stable channel controlled by bedrock and vegetation; mobility increases downstream.

Table 4.7a Summary of channel form changes below Daer Reservoir

Reach	Percentage of catchment regulated	-------- mean channel change ratios --------				
		channel capacity	width	mean depth	width/depth ratio	conveyance factor
i.	99 - 91	0.54	0.98	0.57	1.86	0.36
ii	90.8 - 88.9	0.96	0.98	1.00	0.99	0.94
iii	75.7 - 72	0.78	0.88	0.91	1.06	0.72
iv.	64.4 - 64.3	0.93	0.96	0.99	1.00	0.90
v.	44.1 - 37.7	0.68	0.73	0.92	0.77	0.62
vi.	29.9 - 13.0	0.97	0.75	1.28	0.60	1.13

approach the values predicted by the regional relationship, reduced channel capacities are evident downstream of the first major tributary confluence. The tributary Portrail water, has a catchment area equal to 70% of the area draining to the reservoir and increases the drainage area of the channel to 2.26 times the impounded area. Through this reach channel capacities are commonly between 60 and 70% of the predicted values. Once again this adjustment has been achieved by a reduction in channel width within the actively migrating meander system. Below this reach the channel pattern is stabilised by vegetation and bedrock and even though channel mobility increases downstream channel change is not evident.

Throughout the reach between the dam and the confluence with Portrail Water discharges are generally accommodated within the pre-existing channel form. Although sediment sorting and redistribution may have occurred immediately below the dam there is no evidence of channel adjustment further downstream. The contemporary discharges, regulated by the reservoir, may be incompetent to transport the pre-existing channel sediments. Downstream of Portrail Water the flows will be reduced by the absorption and attenuation of peak flows within the reservoir but discharges are competant to erode and transport the channel and floodplain sediments. Differential sorting has occurred during meander migration and sediment may have been introduced by the tributary. These processes have resulted in the reduction of channel capacities along a reach between 6.50 kms and 11.70 kms downstream from the Daer Reservoir.

e) Adjustment of channel capacity downstream of the upper Clyde reservoirs. The adjustment of channel form below the dams, described by the magnitude of change of pertinent channel parameters, demonstrates that channels in mobile materials adjust their capacities by a reduction of channel width. The reduction of channel width, and the reduction of channel capacity, occur at locations where the channel has an actively meandering planform. However, at catchment areas of less than 5 km^2 vegetation encroachment may be the dominant control of the direction, magnitude and rate of adjustment; at larger catchment areas the higher discharges will reduce the effect of vegetation.

The adjustment of channel form will not be uniform throughout the length of the river as the form of the pre-existing channel in particular will affect the rate and direction of adjustment. The channel mobility and supply of sediment will also affect the adjustment of particular channel reaches. Nevertheless, evidence from the upper Clyde reservoirs (Fig. 4.2) indicates that the impact of reservoir

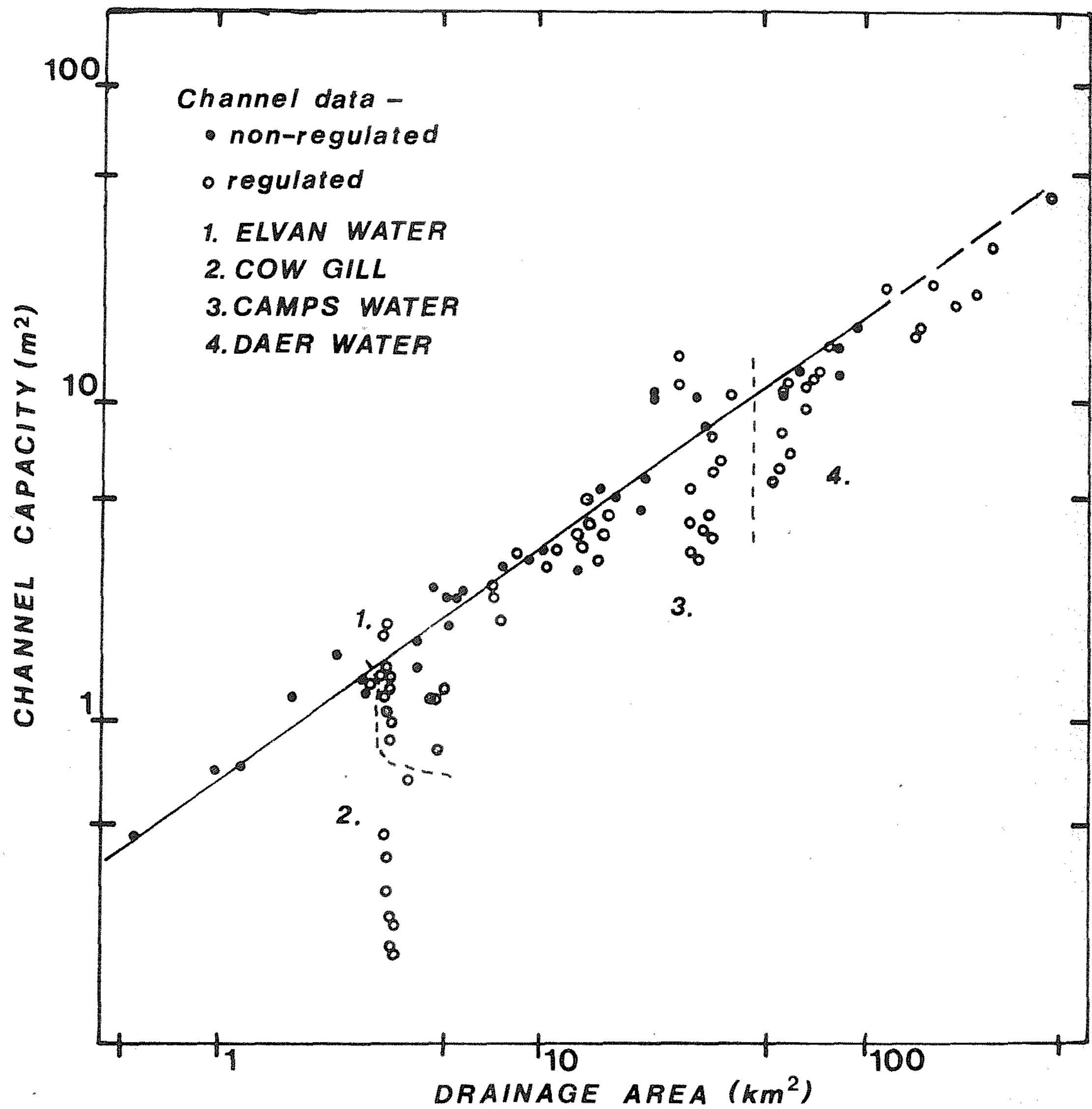

FIGURE 4.2 CHANNEL CAPACITY VARIATION DOWNSTREAM FROM THE UPPER CLYDE RESERVOIRS.

construction upon channel form may be greater for small catchments and moderate size reservoirs. The construction of a large reservoir on a river may sufficiently reduce the magnitude of peak discharge downstream so that the flows are incompetent to erode the channel perimeter sediments. This results in the accommodation of contemporary discharges within the pre-existing channel form. Under these conditions an infrequent event may be required to initiate an adjustment of the channel form by the redistribution of the channel and floodplain sediment. The rate of adjustment will therefore be dependant upon the magnitude and frequency of competent discharges downstream from the dam.

4.2 SOUTH-WEST ENGLAND.

Within south-west England a major demand upon water supplies occurs during the summer months arising particularly from the requirements of tourism. Mean annual rainfall varies from below 750 mm within the Somerset 'levels' to over 2000 mm within central Dartmoor, but this is concentrated in the winter season. Much of the region is underlain by rocks including clays, marls and slates which are of low porosity and permeability, but the Carboniferous Limestones of the Mendips and Cretaceous chalk of south Dorset and Somerset provide important groundwater resources. Furthermore, small and often discontinuous yields are obtained from fissures developed within the granite aureole and floodplain gravels, and some supplies in mining areas are drawn from old shafts and adits. However, the general unavailability of significant aquifers has necessitated that water resource schemes depend upon the construction of river intakes and storage reservoirs. Furthermore, the physiography of the area is such that water is best supplied from a series of small reservoirs rather than a single major source.

4.2.1. Upland reservoirs.

The scope for further study on Exmoor is limited by the lack of suitable impounded catchments, but several regulated rivers are available within Dartmoor (Fig. 4.3.). The water resource potential of Dartmoor was recognised in the 16th century by Sir Francis Drake and one of the earliest water resource developments within the area was the construction of a 24 mile leat constructed in 1585 to convey water from Dartmoor to Plymouth. However, the first major reservoir, Burrator, was not completed until 1898, impounding the headwaters of the Meavy. This was soon followed by the construction of Vennaford reservoir on Holne Moor in 1907 and since 1940 three more reservoirs have been added

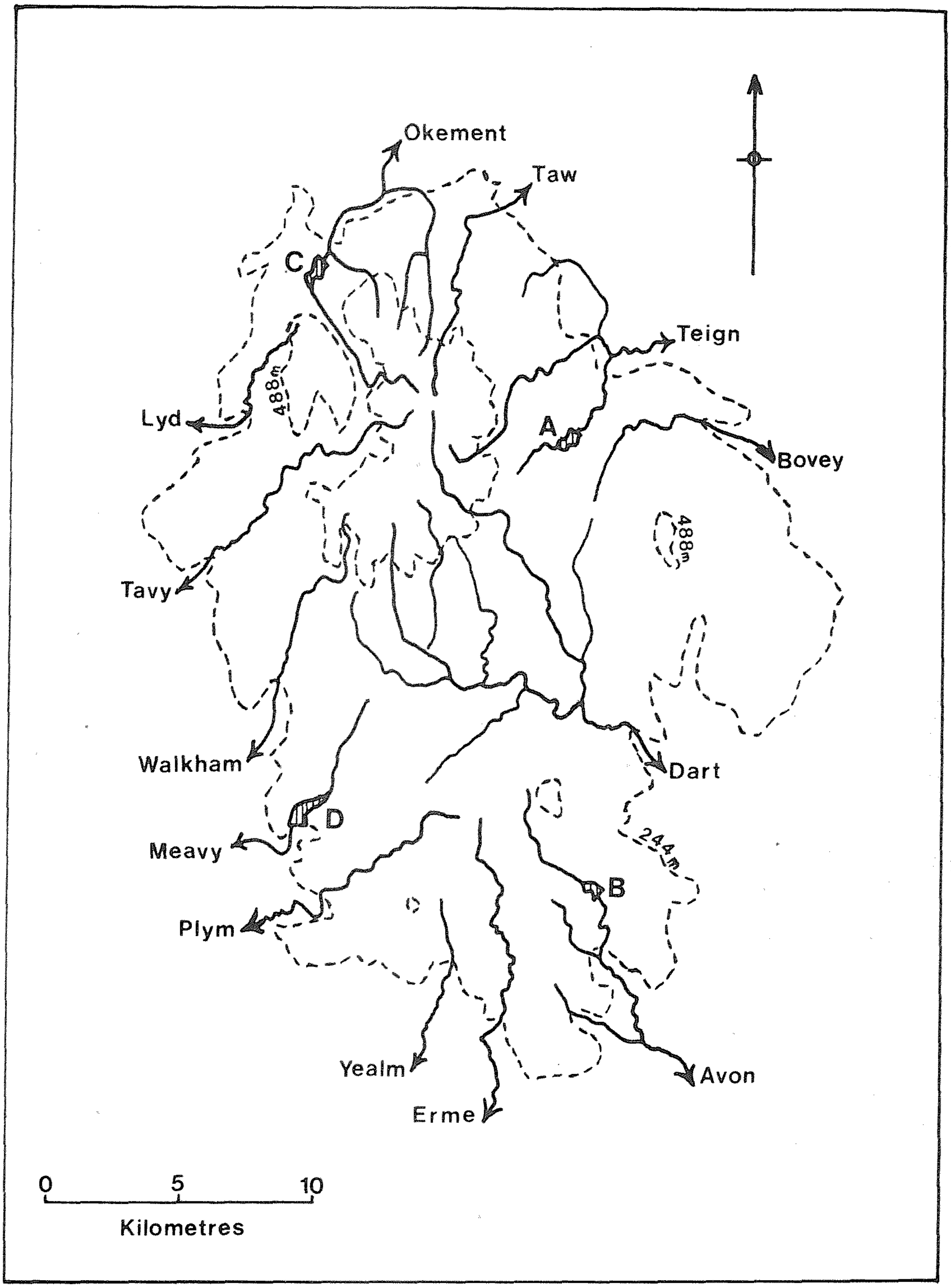

FIGURE 4.3 THE LOCATION OF THE DARTMOOR RESERVOIRS.

A. Fernworthy Reservoir
B. Avon Dam Reservoir
C. Meldon Reservoir
D. Burrator Reservoir.

Fernworthy, Avon, and most recently Meldon (Table 4.7b)

The area is dominated by the granite boss of Dartmoor which represents the surface exposure of one of six cupolas of a single Armorican batholith. The intrusion deformed the country rocks up to 4 miles from the contacts. Rivers radiate from the upland area and all but the Taw and Torridge flow southward; the Taw and Torridge flow northwards to Bideford Bay. The surface of the moor is generally flat but at the edge of the granite the rivers often enter steep wooded gorges and many are incised below the floors of wider old valleys.

Dartmoor lies within one of the highest rainfall intensity areas within the United Kingdom having an estimated maximum 24 hour rainfall of over 400 mm (Flood Studies Report, 1975). This, and the absence of substantial thicknesses of superficial deposits overlying the impervious granite, explains the rapid response of the Dartmoor streams to storm rainfall. The "flashy" nature of the river regimes and the generally steep slopes has led to the occurrence of coarse lag deposits on the river beds. The introduction of an artificial runoff store into the headwater reaches of the Dartmoor streams may be anticipated to markedly alter the flow regime and to reduce the supply of coarse sediment for reaches below the dams. Furthermore, the existence of only coarse channel bed deposits and the outcrop of bed-rock, may produce a natural armoured layer restricting channel degradation. Evidence from the upper Clyde reservoirs indicates that in the absence of a sediment source and in the presence of controls upon channel planform the rate of response to flow regulation may be very slow.

Channel form data was obtained from rivers running parallel to and adjoining the impounded catchments, and from the headwaters of the regulated rivers. This information was supplemented by data collected for Dartmoor streams by Park (1976). The data derived from the regression of channel form variables against drainage area indicates that the rate of increase of channel capacity in relation to drainage area generally decreases from south-east to north-west (Table 4.8). Therefore, paired catchments rather than a regional relationship for the whole of Dartmoor were used to predict channel form variables for reaches below each of the dams.

a) Fernworthy reservoir.

The south Teign river has been regulated since 1942 and is the largest reservoir - in terms of surface area as a percentage of the impounded

Table 4.7b Characteristics of the Dartmoor reservoirs studied

Reservoir	River	Date of closure	Catchment area (km^2)	Surface area (km^2)	Weir length (m)
Fernworthy	S. Teign	1942	9.95	0.29	45.72
Avon	Avon	1958	12.03	0.17	45.00
Meldon	W.Okement	1970	16.83	0.22	64.00

Table 4.8 Variation of channel-capacity-drainage area relationships for non-regulated channels upon Dartmoor

River	Number of locations surveyed	Regression constant	Regression coefficient	R^2	
W. Okement	16	-0.2900	0.7081	0.69	*
W. Okement	15	-0.2885	0.7874	0.92	
E. Okement	22	-02784	0.8377	0.90	
N. Teign	14	-0.2874	0.8991	0.90	
E. Dart	19	-0.4237	1.0223	0.95	*
W. Dart	18	-0.3653	0.8954	0.93	*
Meavy	23	-0.4577	0.9993	0.86	*
Avon	15	-0.3206	1.0303	0.92	
Erme	14	-0.3214	1.0209	0.96	

* Park, 1976.

catchment area - upon Dartmoor (Table 4.7b). The reservoir impounds the 9.95 km^2 headwater area of the South Teign which flows north-eastwards for 7.5 kms before joining the North Teign river (Fig.4.3) and turning southwards to the sea north of Torbay. The impounded catchment contains one of the major coniferous plantations on Dartmoor so that the utilisation of the North Teign channel data to predict the channel form of the South Teign below the dam may prove problematic.

The capacity of the channel below Fernworthy Reservoir is generally considerably smaller than that predicted from the North Teign data. However, within any particular reach the maximum channel capacity is closely comparable to the predicted value (Table 4.9). Therefore it was considered that the North Teign channel form data could be justifiably used to determine channel change below Fernworthy reservoir.

Immediately below the dam a marked, although longitudinally short, bench occurs bordering the river channel. This has effectively reduced the channel capacity to 33% of the predicted value (Table 4.9). The bed material is composed of coarse cobbles and occasional small boulders forming a natural armour layer preventing channel degradation by the relatively sediment-free discharges from the reservoir. Downstream the channel capacity rapidly approaches the predicted value so that within 0.4 kms of the dam the ratio between the actual and predicted channel capacity reaches a value of 0.99. However, although individual cross-sections are described by the dimensions predicted for the North Teign data channel capacities at 70% of the locations surveyed between 0.4 km below the dam and the confluence of North Teign river - a distance of 35 kms, were significantly different from the predicted values. The division between the two reaches, above and below 0.4 kms downstream from the dam, coincides with the first tributary confluence, but channel slope may also be employed. Channel slope has been demonstrated (Chapter 2.1) to play an important role in the determination of channel dimensions and the South Teign river below Fernworthy reservoir may be divided into three reaches on the basis of channel slope (Table 4.9). The division between the two reaches identified above is also related to the change of channel slope from 33.83 m/km to 16.92 m/km. Throughout the 'middle' reach individual locations contain evidence of active channel migration, albeit on a small scale. Cross-sections surveyed at these locations

Table 4.9 Channel capacity variation below Fernworthy Reservoir

Drainage area (km^2)	Distance downstream (km)	Slope (m/km)	Number of locations surveyed	Channel change ratio range	mean
9.62 - 11.07	0 - 0.4	33.83	5	0.33 - 0.99	0.62
12.53 - 13.49	0.4 - 0.8	16.92	7	0.35 - 0.87	0.62
13.90 - 19.70	0.8 - 4.1	30.08	12	0.43 - 1.04	0.64

differed markedly in their dimensions whilst the form of sections at stable sites, with wooded banks, was comparable in several cases to the predicted values. Although the average value of channel capacity relative to the predicted capacities remain almost constant throughout the length of the river, the maximum reduction of channel capacity at any one location decreases downstream. The channel capacity of the South Teign river has been reduced to less than 33% of the predicted value, and the conveyance factor to 16%, in response to the absorption and attenuation of peak flows within the reservoir.

The reduction of channel capacity below Fernworthy reservoir has been achieved through the complete alteration of channel shape (Table 4.10). Considerable variation in channel shape exists between individual locations and more generally between the three reaches due to the influence of bank sediment and vegetation, and channel slope. Furthermore, adjustments at particular locations will depend in part upon the nature of the pre-reservoir channel form. Nevertheless, the data indicate that downstream of the reservoir channel mean depth has been reduced preferentially to width so that the width-depth ratio has increased. This is even more pronounced, through the second reach, identified previously (Table. 4.9) and may be a response to the relatively high reduction of peak discharge with little change in the calibre of the sediment load downstream of the tributary. Indeed, channels within coarse bed sediments have been demonstrated to adopt high width-depth ratio forms (Schumm, 1963), and evidence of channel aggradation exists at several locations downstream from the tributary confluence.

The third reach identified (Table 4.9) is markedly different from the two upstream reaches in that channel width and the width-depth ratios are generally lower than the values predicted from the North Teign data. This may reflect the marked increase in slope through the reach which through the increase in velocity would permit a reduction of the cross-sectional area. Indeed, individual sections may be degrading at the present time.

The occurrence of a complex channel form (Fig 4.4) at several sections along the South Teign river requires not only the identification of the contemporary bankfull stage, but also the downstream correlation of the channel forms. Whilst the inner bench, which has been used to define the contemporary bankfull stage, has a varied sedimentological structure along the river, the analysis of the bank materials suggests a decrease in particle size downstream (Fig.4.5). The higher level

Table 4.10 Summary of channel form changes below Fernworthy Reservoir

Drainage area (km²)	Percentage of catchment regulated	Mean channel change ratios				
		channel capacity	width	mean depth	width-depth ratio	conveyance factor
9.62 - 11.07	99.8 - 86.7	0.62	0.83	0.73	1.29	0.57
12.53 - 13.49	76.6 - 71.2	0.62	0.86	0.72	1.42	0.52
13.90 - 19.70	69.1 - 48.7	0.64	0.74	0.89	0.91	0.61

Table 4.11 Dendrochronological evidence for channel change below Fernworthy Reservoir.

Distance downstream (km)	-	0.2	0.4	0.43	0.45	0.5	0.7	0.72
Age of inner bench surface (yrs)	-	22	16	20	19	15	28	23
Age of valley floor (yrs)	-	49	24	38	53	80 +	47	33

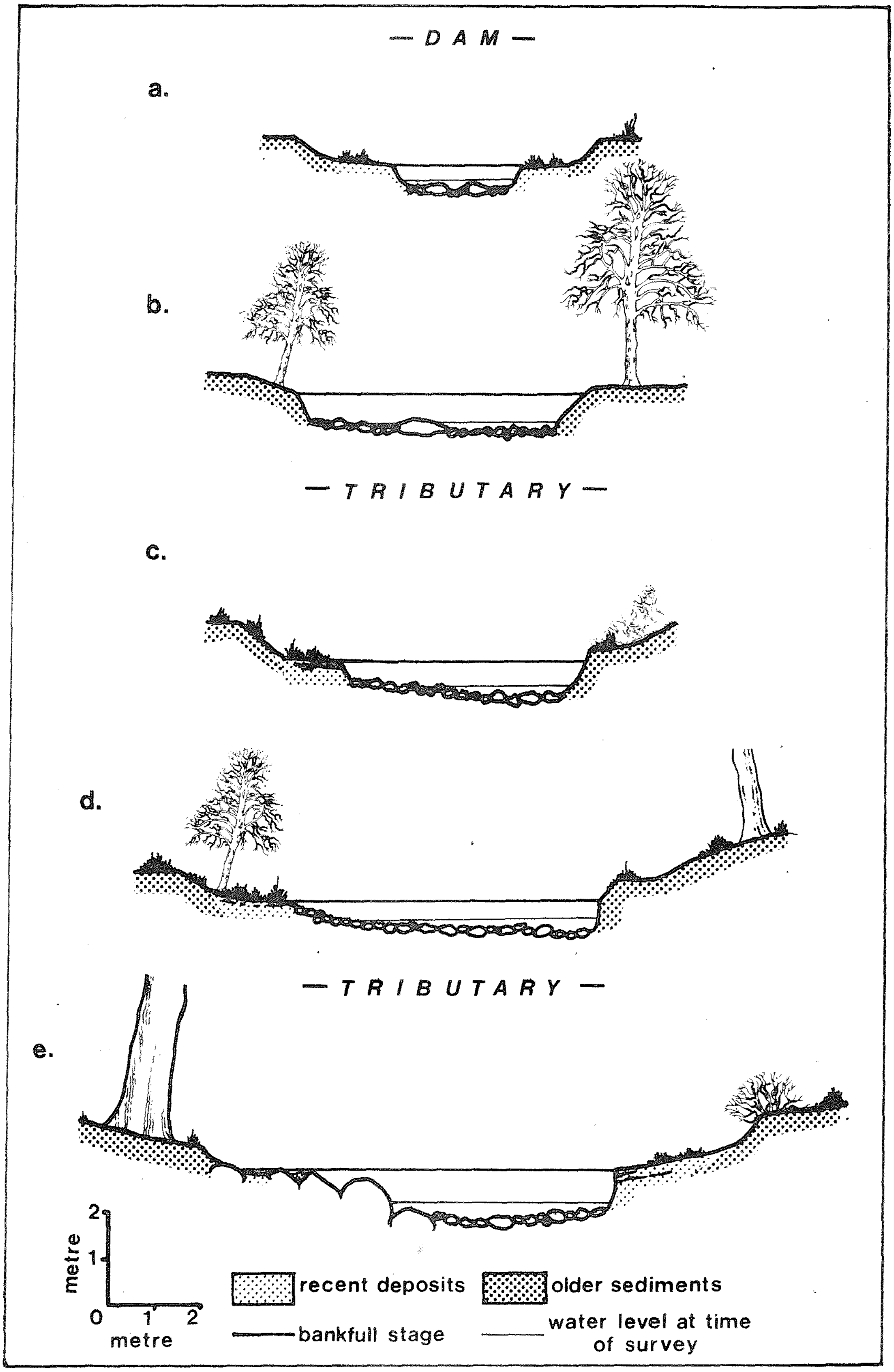

FIGURE 4.4 CHANNEL CROSS-SECTIONAL FORMS DOWNSTREAM FROM FERNWORTHY RESERVOIR.

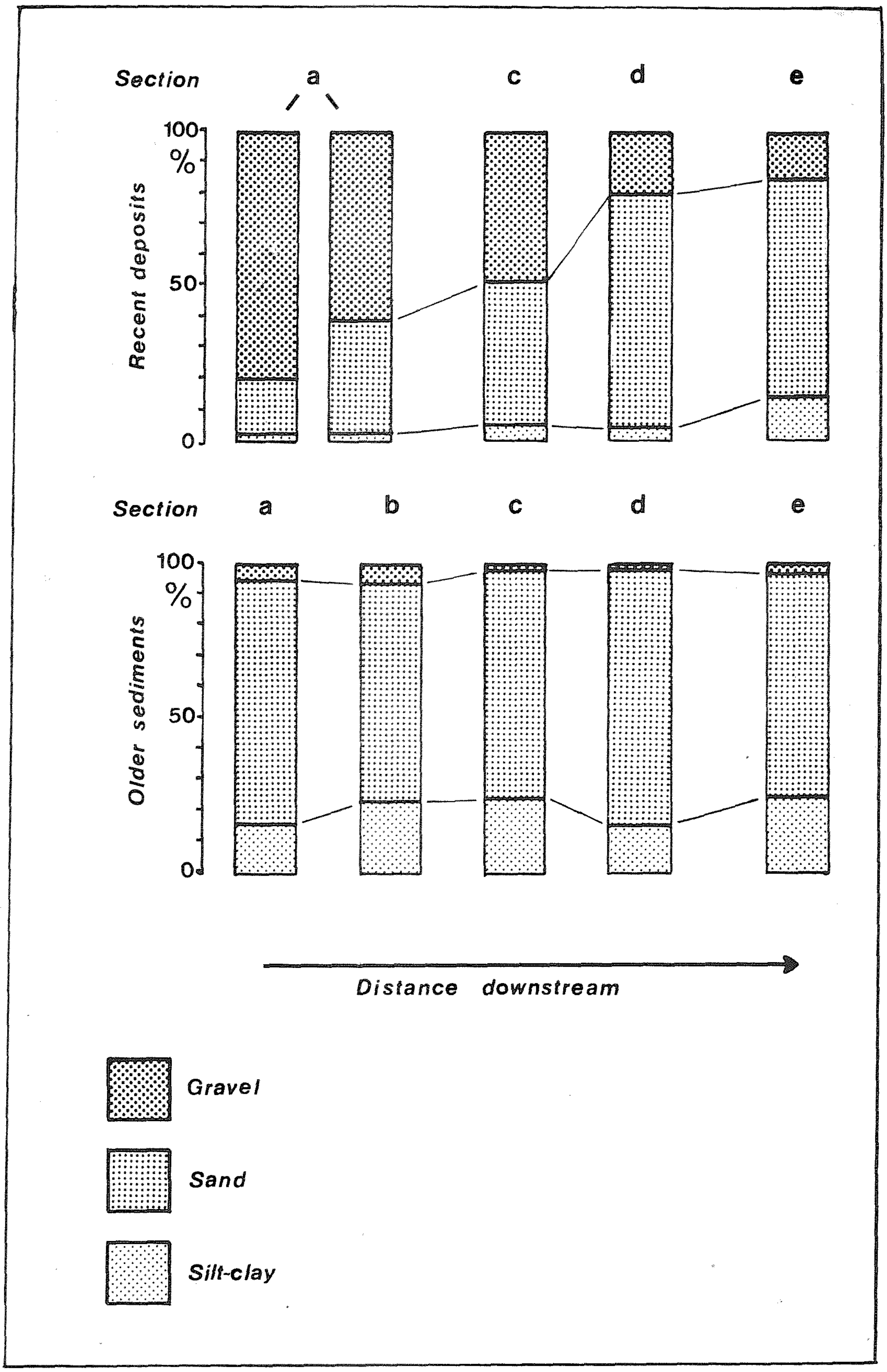

FIGURE 4.5 SEDIMENTOLOGICAL VARIATIONS BETWEEN DEPOSITS OF DIFFERENT AGE AND WITH DISTANCE DOWNSTREAM FROM FERNWORTHY DAM.

which is coincident with the general level of the valley floor, is related to sediments which demonstrate a reasonably consistent particle size composition at the various locations. Datable material along the South Teign river is sparse but the tree cores taken from the surfaces of the river bench and the valley floor (Table 4.11) tend to confirm that the inner bench defines the limits of the contemporary channel, and has been formed since the closure of Fernworthy reservoir.

b) Avon Dam Reservoir.

The river Avon rises at an altitude of 465 m below Ryder's Hill (Fig. 4.3) and flows southwards parallel to the neighbouring River Erme to the west which rises at a similar altitude of 451m. Whilst the river Avon is impounded by the Avon Dam controlling the 12.03 km² headwater area, the river Erme is a relatively natural channel. Channel form data from the river Erme have been used to extend the relationships developed between the independent catchment and dependant channel form variables for the 560 km long river Avon above the reservoir: the river Erme above Harford has a drainage area of 21.05 km².

Drainage area was again utilised as the independent variable of the regression relationships describing the downstream variation of channel form utilising 'natural' channel form data. A closer degree of correlation between the independent and dependant variable was achieved using drainage area rather than a measure describing the drainage network such as total stream length or main stream length (Table 4.12). The problems of measuring the drainage network from maps have been outlined (Chapter 3.2) and data from a variety of sources for Dartmoor rivers illustrate these (Table 4.13). Variation of the measured parameters occurs between different data sources and for the same source between rivers. The regression coefficients describing the variation of channel capacity with drainage area for the river Avon above the reservoir and the river Erme are similar but the application of the standard error of the equation to the identification of channel changes was again found to be problematic (Table 4.14) indicating a range of channel capacities between 12.8 and 48.9 m² at a drainage area of 50 km².

The distribution of the channel capacity values for sections below the Avon Dam indicates that channel capacities have been reduced to less than 60% of that expected. The reduction of channel capacity and the change of channel slope has resulted in a reduction of the conveyance factor to less than 40% of the predicted value. However, downstream from the dam the channel dimensions rapidly approach the

Table 4.12 Correlations between channel capacity and different independent variables.

Dependent variable	Independent variable	Data source	R^2
Channel capacity	Drainage area	R.Avon	0.92
Channel capacity	Drainage area	R.Erme	0.96
Channel capacity	Drainage area	R.Avon & R. Erme	0.95
Channel capacity	Total stream length	R.Avon	0.88
Channel capacity	Total stream length	R.Erme	0.90
Channel capacity	Total stream length	R.Avon & R.Erme	0.81
Channel capacity	Mainstream length	R.Avon	0.87
Channel capacity	Mainstream length	R.Erme	0.89
Channel capacity	Mainstream length	R.Avon & R.Erme	0.84

Table 4.13 Variation[1] of stream lengths derived from different sources for two Dartmoor rivers[2]

R.Avon / R.Erme	O.S.Map 1959 1:25,000	O.S.Map 1907 1:10,560	O.S.Map 1954 1:10,560	Air Photograph 1940 1:10,000
O.S.Map 1959 1:25,000		3.6 (6.8)	1.2 (6.9)	8.8 (23.3)
O.S.Map 1907 1:10,560	2.2 (16.1)		2.4 (0.14)	5.5 (17.8)
O.S.Map 1954 1:10,560	2.2(16.1)	1.3 (0.4)		7.7 (17.6)
Air Photograph 1940 1:10,000	30.4 (36.1)	21.9 (23.5)	28.8 (23.8)	

[1] variation described as a percentage.

[2] catchment areas = 5 km² (10 km²)

Table 4.14 Channel capacity variation within non-regulated data.

Drainage area (km^2)	----- Predicted values of channel capacity ------			
	Mean (m^2)	Range within two standard errors (m^2)		
2.0	0.951	0.632	-	1.431
5.0	2.411	1.487	-	3.911
10	4.873	2.838	-	8.368
30	14.864	7.909	-	27.935
50	24.964	12.787	-	48.931

predicted values so that in a catchment area of 18 km^2 channel change is not apparent. This coincides with the occurrence of a bedrock channel some 2 kms downstream from the dam so that an adjustment of the channel form may not be expected. Downstream of the Bala Brook confluence, 3 kms below the dam, channel capacities have beeen reduced to 60% and the 'k' values to 50% of the values expected. The Bala Brook is the first major tributary, having a catchment area equal to 50% of the impounded catchment area. However, once the catchment area has reached a value equal to 2.5 times that of the regulated headwater area, some 7.75 km downstream, the channel form parameters are predicted by the regression equation. Downstream from this point channel change is not apparent even at individual locations downstream from tributaries. It is interesting to note that whilst the channel capacity and conveyance factor values are related to the variation of drainage area - a surrogate for discharge - channel shape as described by the width-depth ratio may be related to the particle size distribution of the bank materials, reflecting variations of lithology. (Table 4.15). The channels on granite outcrops have bank sediments composed primarily of coarse and medium sand whilst the bank materials of channels within the aureole contain approximately 60% of fine sand, silt and clay.

The extensive outcrop of bedrock within the reach between 1.8 and 3.5 kms below the Avon Dam has prohibited the physical adjustment of the channel form, but an indication of the affect of reservoir construction may be achieved by an examination of lichen limits (Gregory, 1976). Lichens occur on the granite surfaces along the channel margins and two populations of individuals may be identified (Fig. 4.6). The lower population contains individuals whose thalli are smaller than 40 mm in diameter. This population is separated from the higher population whose individual thalli range up to 81 mm by a clearly defined limit. Comparison of the individual thalli diameters with a growth curve for the particular species permits the determination of an absolute age for the change of hydrologic regime.

Although the identification of individual species was problematic, species of the groups *Parmelia* and *Lecarora* were observed and compared with growth curves based upon thalli diameters derived from gravestones. However, the proximity of river bank species to an abundant water supply may favour more rapid growth and so lichen thalli from weirs and bridges were also measured, and a significant difference in the rate of growth between riparian and cemetary lichens was revealed. Nevertheless, the lichen thalli diameters from the lower population

Table 4.15 Summary of channel form changes below Avon Reservoir

Drainage area (km^2)	Percentage of catchment regulated	Mean channel change ratios				
		Channel capacity	Width	Mean depth	Width-depth ratio	Conveyance Ratio
13.15 - 14.18[1]	91.5 - 84.8	0.65	0.91	0.70	1.41	0.54
14.19 - 15.37[1]	84.8 - 78.3	0.72	0.99	0.72	1.48	0.61
15.38 - 17.70[1]	78.2 - 68	0.90	1.01	0.93	1.19	0.88
23.90 - 29.00[1]	50.3 - 41.5	0.70	1.05	0.66	1.61	0.57
32.00 - 35.00[2]	37.6 - 34.4	0.97	0.88	1.13	0.69	1.07
44.00 - 52.00[2]	27.3 - 23.1	0.94	0.86	1.09	0.87	0.99

[1] granite lithology, bank materials contain up to 10% silt-clay

[2] meta-Devonian lithology, bank materials contain up to 20% of silt-clay.

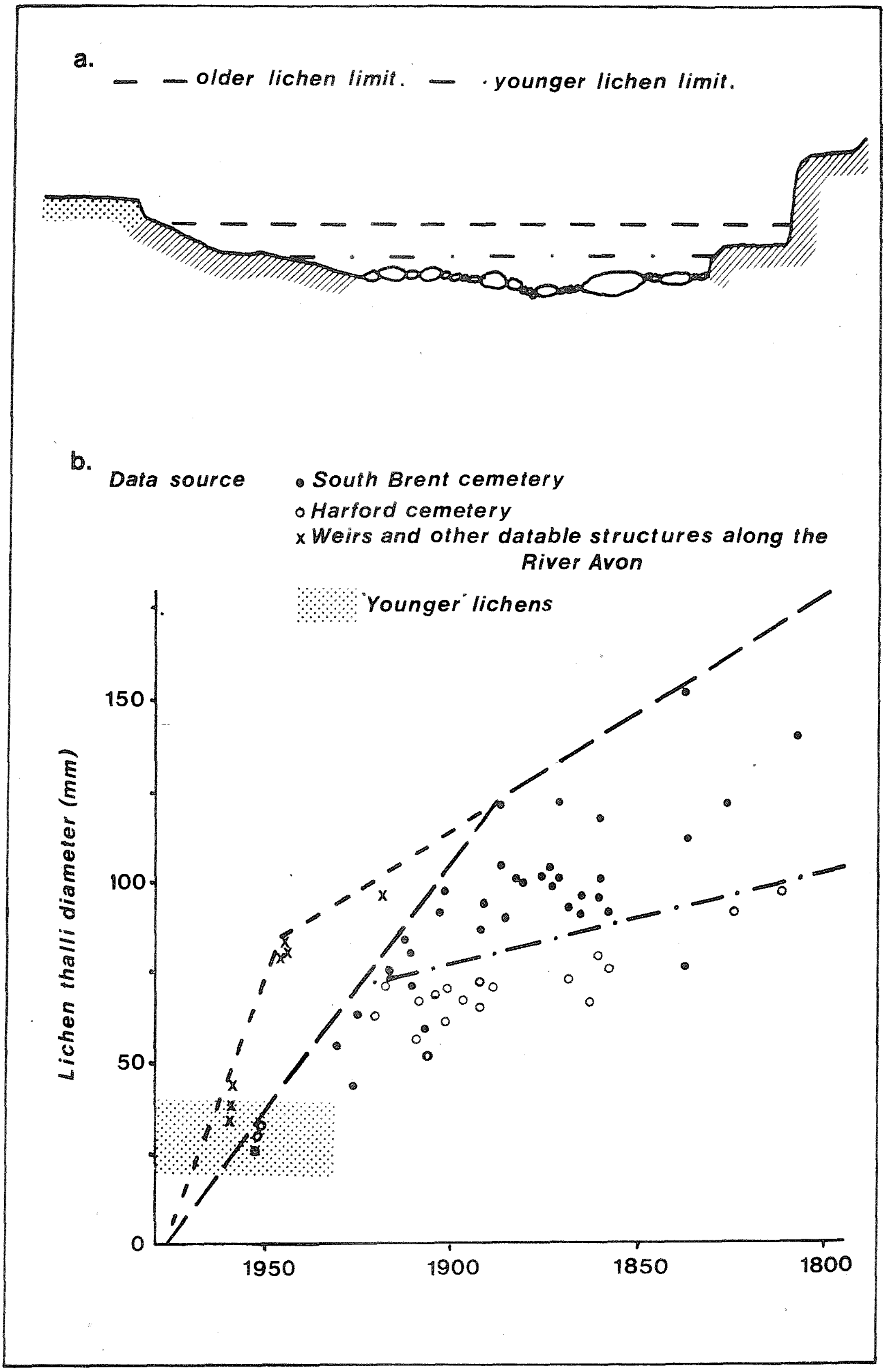

FIGURE 4.6 THE APPLICATION OF LICHEN LIMITS (a) AND LICHENOMETRY (b) TO THE IDENTIFICATION OF DISCHARGE CHANGES WITHIN BEDROCK CHANNELS BELOW AVON DAM.

(Fig. 4.6) indicate that an abrupt change in the flood frequency distribution occurred between approximately 5 and 15 years ago - the dam is 17 years old.

Above and below the bedrock lined channel the capacity of the river Avon channel has been reduced by the deposition of a channel-side bench (Fig. 4.7) and the process may still be in operation at some locations where immature berms exist within the former channel form. However, the origin of the sediment producing the berms within reaches above the confluence with the Bala Brook is uncertain. Whilst there is no evidence of degradation below the dam or of channel migration, the sediment may represent lag deposits derived from the flushing of sediment during, and subsequent to, the construction of the dam. The berms may require a long time period to reach maturity in the absence of a sediment supply; future deposition will be related to the occurrence of discharge competent to erode, transport and redistribute the channel perimeter sediments. Below the Bala Brook confluence the rate of maturation will be related to the degree of peak flow reduction and the quantity and calibre of the sediment load transported by the Bala Brook. However, the mature benches display typical sedimentary structures of fluvial deposition (Fig. 4.7) notably fining upward sequences broken by flood deposits, and a marked discontinuity occurs at the junction between the terrace and the contemporary 'floodplain'. Although immediately below the Avon Dam the channel has adjusted to the altered flow regime the rate of adjustment along the channel appears to be dependant upon the availability of sediment and the frequency of competent discharges to sort and redistribute the material.

c) Meldon reservoir.

Situated within the West Okement valley on the north of Dartmoor, (Fig.4.3), Meldon reservoir is the most recent of the water resource development schemes. The evidence from the regulated South Teign and Avon rivers has indicated that the rate of adjustment will be dependant upon the availability of sediment and upon the magnitude and frequency of post-dam closure peak discharges. Although the dam was closed only five years ago a major sediment supply exists some 750 metres below the reservoir, so that channel response may be expected to be relatively rapid. At this location the West Okement cuts into the toe of an active alluvial fan produced by a tributary draining the Meldon Quarry. Immediately downstream from the toe of the fan the river enters a short gorge before meandering over a wide floodplain at a low slope of 10 m/km. Thus, the channel downstream from Meldon Dam may be divided

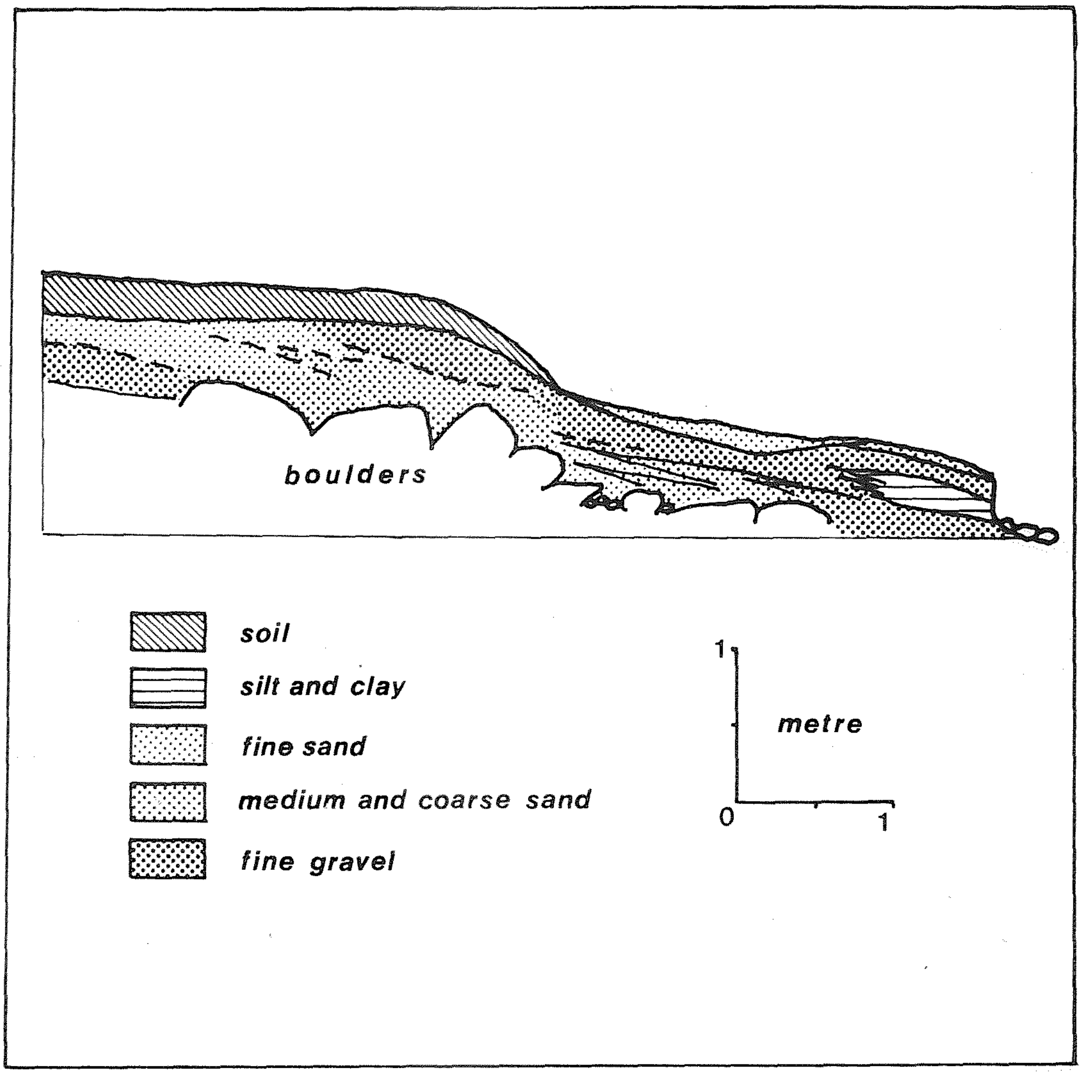

FIGURE 4.7 THE SEDIMENT SEQUENCE WITHIN A CHANNEL-SIDE BENCH AND TERRACE DOWNSTREAM OF THE AVON DAM.

into two reaches, one experiencing reduced sediment loads and discharges, the other, downstream of the gorge, experiencing reduced flows with little change of the sediment load.

Determination of the effects of dam closure upon the channel of the West Okement reguires the production of a regression equation based upon 'natural' data. Data from the headwaters of the West Okement above the reservoir and the neighbouring East Okement revealed different rates of channel capacity variation with drainage area when analysed separately (Table 4.8), but the regression of the combined data sets against discharge produced an exponential function similar to that derived for the headwaters of the West Okement. It was therefore, considered justifiable to extend the headwater regression to predict channel dimensions for locations downstream of the dam.

The reach between Meldon Dam and Meldon Quarry does not appear to have adjusted to the alteration of the flow regime imposed by reservoir construction, although at a single location the channel capacity is less than 60% of the value predicted (Table 4.16). Throughout this reach discharges are simply accommodated within the pre-reservoir channel form. Downstream of the gorge, deposition has occurred within the channel, and channel capacity has been reduced to one-half of the expected value. However, with distance downstream from the sediment source the channel capacity values approach those predicted. With time the gradual redistribution of sediment downstream may be anticipated until the river channel has become adjusted to the new flow regime. The reach immediately below the dam may change little in the absence of a sediment supply, and the attenuation of peak flows will have reduced the probability of channel sediment redistribution.

Inorder to determine the significance of the depositional bench crest stage recorders were emplaced along the West Okement at four locations, and one on the East Okement for comparison, so that peak discharges could be monitored and traced downstream with the aid of debris lines. The simple gauges successfully recorded the maximum flow stage during a single or multiple event and on several occasions the flood level could be traced with relative ease downstream. The data (Table 4.17) indicate that the changed channel sections may be adjusted to a different flow frequency to that at the stable sections. The channel forms below the dam belong to the same population as other stable sections further downstream (Fig.4.8). Although the period of observation was short, six months, the highest flow on the West Okement was also the highest recorded on the East Okement for the period of record. The flood

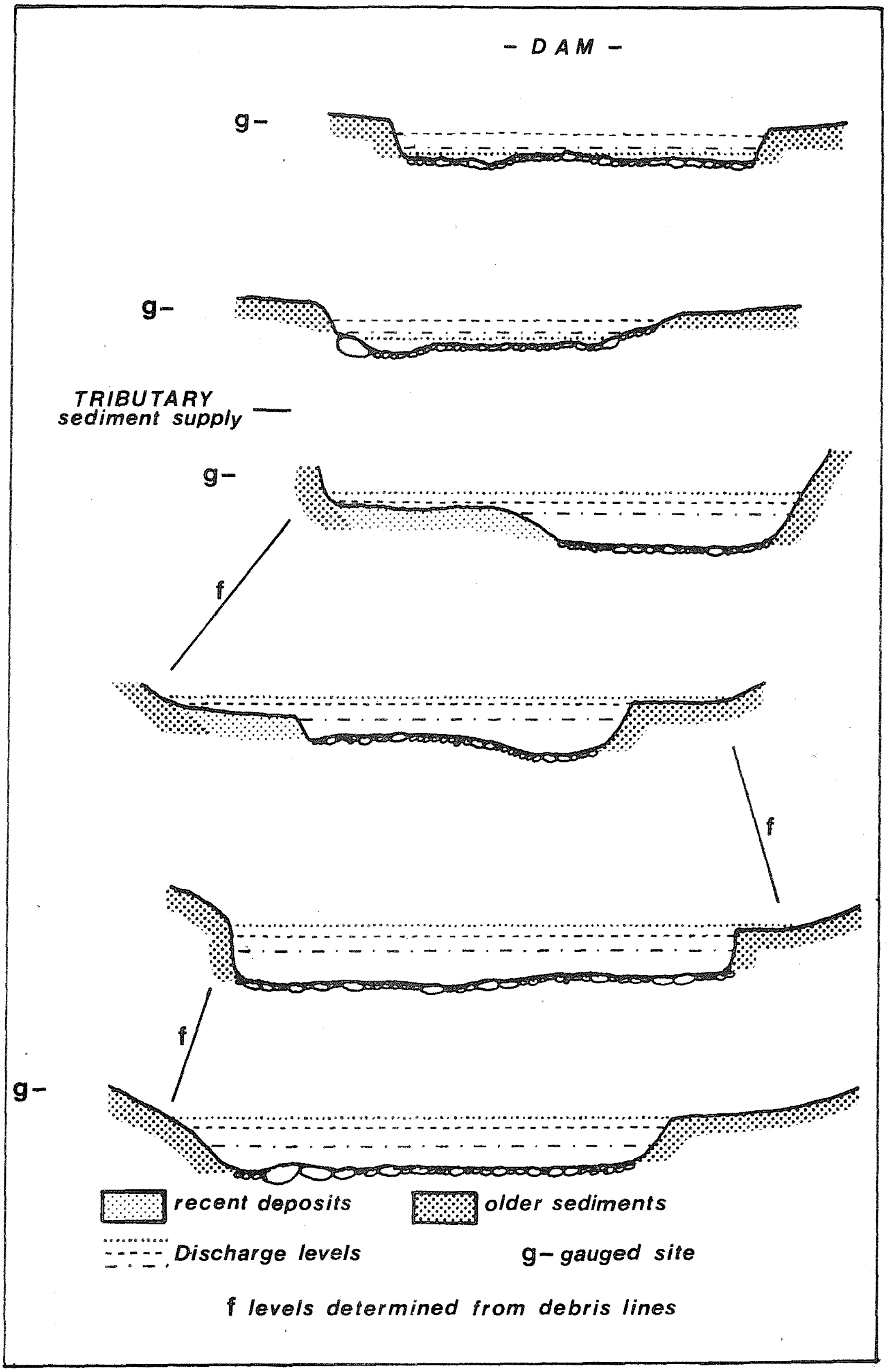

FIGURE 4.8 THE DOWNSTREAM VARIATION OF STAGE LEVELS FOR THREE INDEPENDANT HIGH FLOWS BELOW MELDON RESERVOIR.

Table 4.16 Summary of channel form changes below Meldon reservoir

Drainage area (km²)	Percentage of catchment regulated	Mean channel change ratios				
		channel capacity	width	mean depth	width-depth ratio	conveyance factor
16.9 - 17.29	99.6 - 97.3	0.96	1.10	0.88	1.34	0.95
23.52 - 25.75	71.6 - 65.4	0.60	0.75	0.80	0.95	0.52
25.80 - 30.25	65.2 - 55.6	1.07	1.00	1.08	0.94	1.08

Table 4.17 Discharges[1] calculated from stage records for three independent high flows

Drainage area (km²)	16.5	23.52	27.41	30.25
Flow A	9.32	12.08	12.78	13.98
Flow B	1.03	12.74	15.17	19.85
Flow C	2.82	4.68	5.74	6.18

[1] discharges in cumecs.

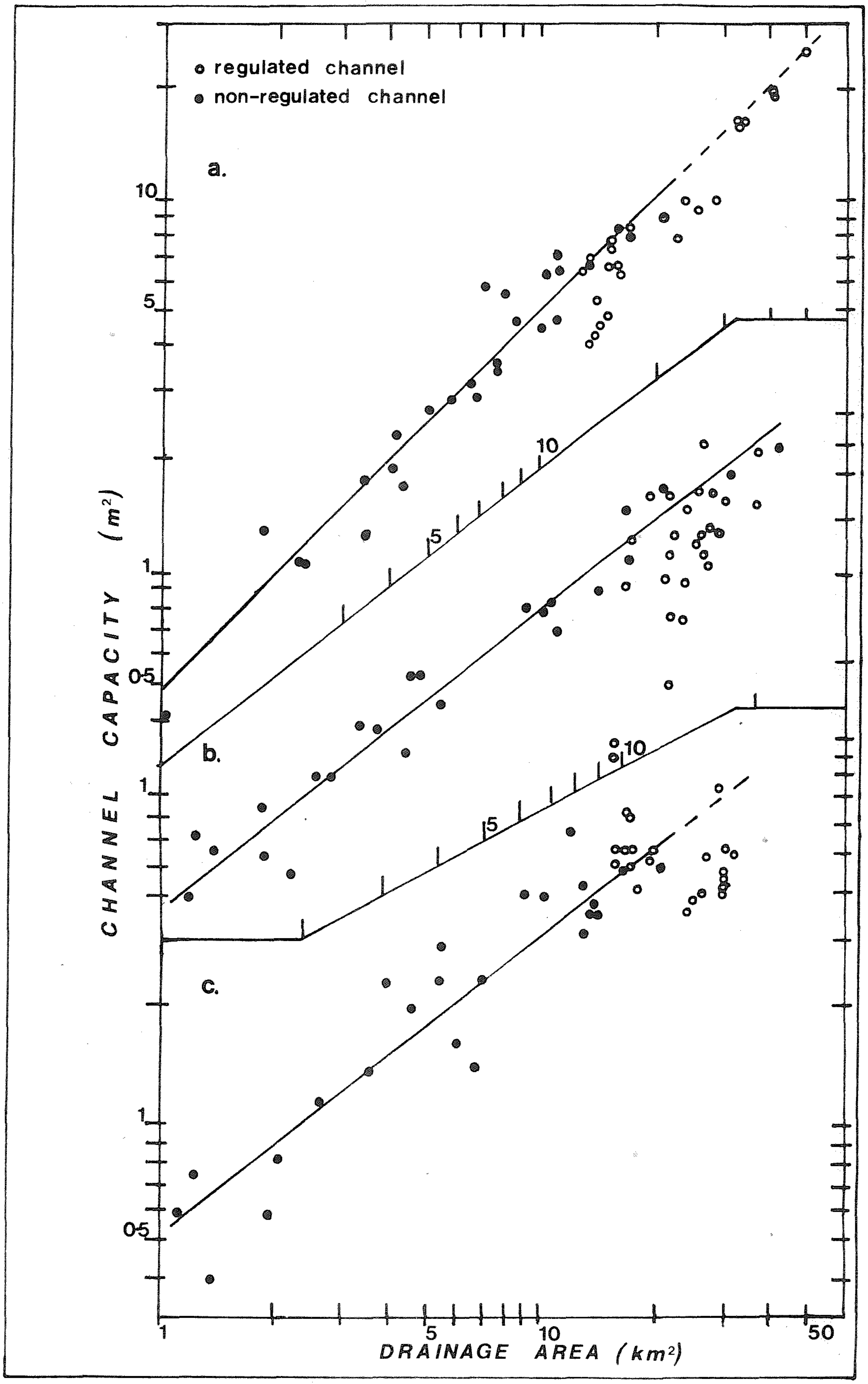

FIGURE 4.9 THE VARIATION OF CHANNEL CAPACITY DOWNSTREAM FROM AVON (a), FERNWORTHY (b), AND MELDON (c) RESERVOIRS. (regressions based upon the non-regulated data).

discharge did not appear to increase greatly downstream indicating that the lag of the flood peak introduced by the reservoir may have desynchronised the mainstream and tributary flood peaks. The reduction of channel capacity to 53% and the conveyance factor to 40% of the expected value may be a response to the reduction of peak flow magnitude which has resulted in the deposition of sediment supplied by the Meldon Quarry fan. The deposition has preferentially reduced channel width, wich at any particular location has been reduced to two-thirds of the expected value.

d) Channel capacity adjustment to flow regulation within Dartmoor rivers. The evidence of channel adjustment downstream of Fernworthy, Avon and Meldon reservoirs (Fig. 4.9) has revealed that the rate of channel adjustment is particularly dependant upon the input of sediment from tributaries within channels which have a planform stabilised by bedrock outcrops and vegetation. The introduction of a tributary sediment supply into a mainstream experiencing reduced peak flows may result in the formation of depositional berms which migrate downstream and result in the reduction of channel capacity. The mean depth is generally reduced preferentially to width so that the width-depth ratio is increased, a response to the changed relationship between sediment supply and water discharge.

4.2.2. Lowland reservoirs

The reservoirs of the Somerset and Avon clay vales contrast with the upland areas of Dartmoor and the upper Clyde. Water supplies within the area have been largely derived from groundwater sources, the Carboniferous Limestone, Upper Greensand and Chalk being the primary aquifers. During the mid 1800's Chew Mendip springs were tapped and the water supply stored in the Barrow Lakes to the north. Since that time supplies within the Mendips have been supplemented by two major storage reservoirs at Blagdon (1900) and Chew (1953). The reservoirs have their headwaters within the Mendip Carboniferous Limestone but their valleys are underlain by impermeable marls. In 1955 a third reservoir was constructed to the south to augment the supply for the Yeovil district (Fig. 4.10). Sutton Bingham reservoir is smaller than either Blagdon or Chew but regulates the runoff from a drainage area of similar magnitude (Table 4.18). Also in comparison with the Mendip reservoirs the catchment is composed of permeable and porous lithologies in the headwaters and impermeable lithologies in the vales. The Cretaceous Upper Greensand and Chalk form the southern catchment divide and clays with subordinate sandstones and limestones in the valley bottoms. Although the catchments

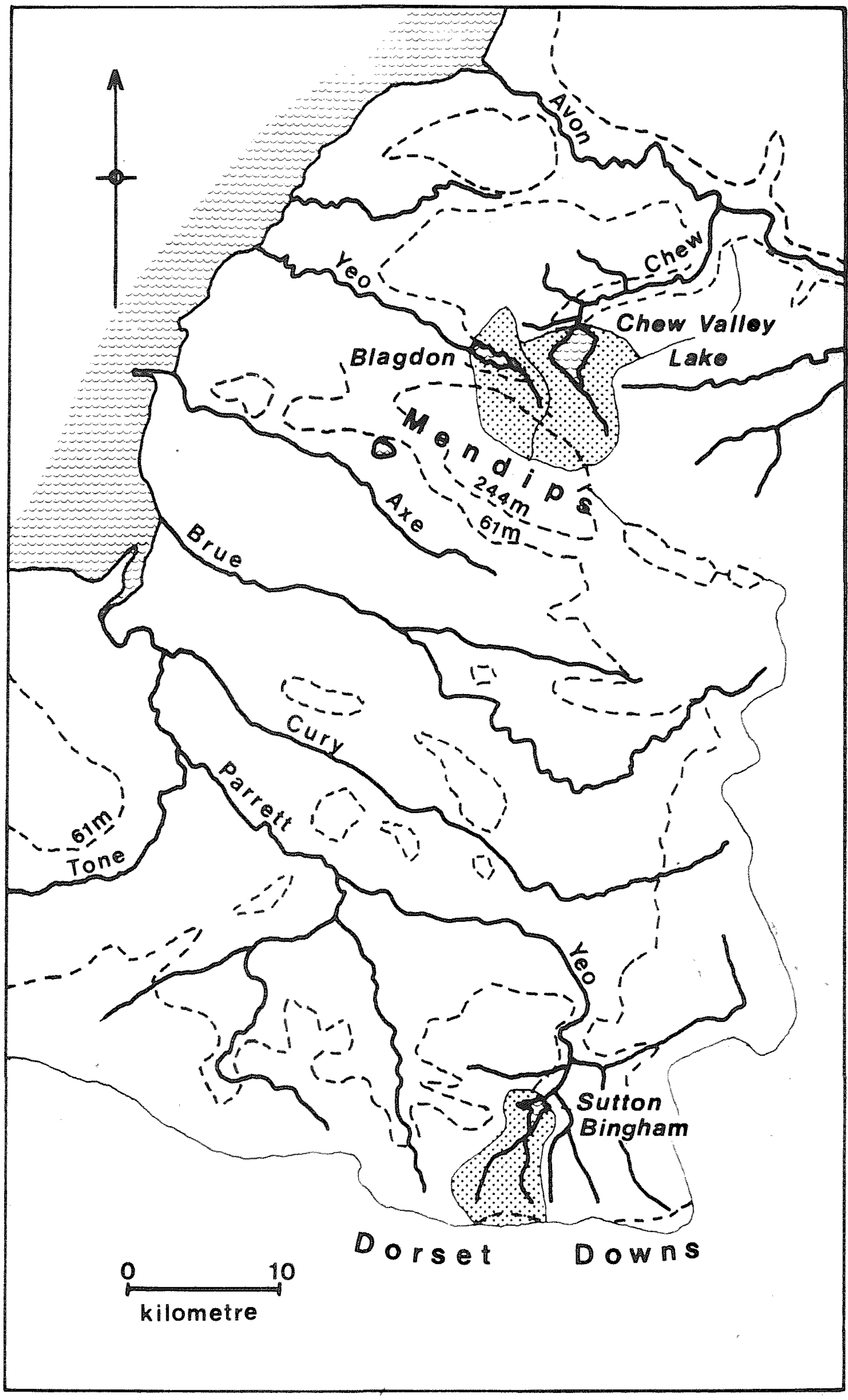

FIGURE 4.10 THE LOCATION OF THE RESERVOIRS WITHIN LOWLAND SOUTH-WEST ENGLAND.

Table 4.18 Catchment characteristics of the lowland reservoirs.

Catchment	Mean annual rainfall (mm)	Mean annual runoff (mm)	Maximum 24-hr rainfall (mm)	Mean annual flood cumecs/1000 km²	Mean channel slope (m/km)	Drainage area-channel capacity	
						regression coefficient	capacity at 1 km²
Chew Blagdon	1050	530	30	200	7.43	0.5783	0.47 m
Sutton Bingham	965	512	30	350	4.125	0.7508	0.53 m

Table 4.19 Summary of channel form changes below Sutton Bingham reservoir

Drainage Area (km²)	Percentage of catchment regulated	Mean channel change ratios				
		channel capacity	width	mean depth	width-depth ratio	conveyance factor
30.3 - 30.4	99 - 98.7	0.83	0.71	1.09	0.69	0.95
30.5 - 30.7	98.5 - 97.7	0.57	0.66	0.78	0.84	0.55
52.79 - 54.00	56.8 - 55.6	0.46	0.56	0.71	0.86	0.43
54.10 - 57.27	55.4 - 52.4	0.62	0.73	0.76	0.60	0.63
57.25 - 67.57	52.4 - 44.4	0.68	0.70	0.83	1.11	0.72

appear to be similar at first, a marked difference exists in the magnitude of the mean annual flood. This may be reflected in the variation of the channel form data downstream. Analysis of river channel capacities from the headwaters of the impounded catchments and from neighbouring streams revealed a marked variation in the increase of channel capacity with drainage area (Table 4.18), although the intercept values are of the same order of magnitude. Therefore, the Chew-Blagdon reservoirs are considered separately from the Sutton Bingham reservoir.

a) Sutton Bingham Reservoir

The Sutton Bingham earth-fill dam impounds the runoff from the 30 km^2 headwaters of a tributary of the river Yeo, itself a south-bank tributary of the Parrett. During construction a tunnel was built to take floods, and this is now incorporated into a bellmouth type overflow. Inorder to predict channel form dimensions in the absence of a suitable neighbouring catchment of sufficient size a regional relationship was developed based upon channel form data from the impounded catchment, Gallica Brook, the headwaters of the river Parrett to the west and of the Yeo to the east. Although a large scatter exists within the data this was considered preferential to the extension of a relationship developed from the data of the impounded headwaters alone.

The relationships developed demonstrate that below the Sutton Bingham dam channel capacity progressively decreases to reach a minimum immediately below the confluence with Gallica Brook, a tributary having a catchment area equal to 70% of the impounded catchment area. Downstream of the confluence the channel capacities gradually approach the values predicted by the regional relationship. The channel bed is paved with gravel and whilst immediately above and below the confluence with Gallica Brook evidence of channel aggradation occurs, the primary adjustment has been through a reduction of channel width (Table 4.19). This has resulted in the reduction of channel capacity to 50% and of the conveyance factor to less than 40% of the predicted value at individual locations. The sections immediately below the tributary however, have a mean depth which is equal to only 45% of the predicted value. Nevertheless, the channel width-depth ratios have been consistently reduced.

The channel is commonly incised within the valley bottom sediments and although channel side deposition has been observed at sites below the Gallica Brook confluence, at several locations channel narrowing has been caused by bank slumping. The valley floor is commonly between 4 and 5 metres above the channel bottom and the width of the 'channel' at the valley floor level is in excess of 12 metres. Nevertheless, since dam closure the reduction of flood discharge appears to have resulted in the deposition of sediment introduced by the Gallica Brook tributary. This,together with the erosion and redistribution of the slump deposits,has enabled the reduction of channel capacity to less than one-half of the predicted value at individual locations.

b) Blagdon and Chew reservoirs.

These regulate a combined area of 85 km^2 draining the north facing slopes of the Mendips (Fig.4.10). The surface areas of the reservoirs are large being equivalent to 8.33 and 7.84 percent of the impounded catchment areas for the Chew and Blagdon reservoirs respectively. Discharges downstream may therefore be anticipated to be markedly reduced. Indeed the 1968 Mendip Floods having a recurrence interval of 100 years did not overtop the Chew Valley Lake although Blagdon and a small reservoir at Chew Magna were overtopped. The rise of the water level in the Chew Valley Lake indicated a runoff of 2.14 million m^3 (37mm) within less than 24 hours. The identification of channel changes consequent upon the alteration of the flow regime following dam construction requires the collection of non-regulated channel data inorder to predict the channel dimensions for reaches below the dams. As with the case of the Sutton Bingham reservoir the lack of a suitable single neighbouring catchment necessitated the collection of data from a number of channels within the region.

The regression equations produced permit the determination of the magnitude and direction of channel change below the reservoirs. Blagdon reservoir constructed in 1900 impounds the headwaters of the river Yeo which becomes tidal some 7 kms below the dam at Congressbury. Immediately below the dam a depositional bench, colonised by vegetation, has reduced the channel capacity to 30% of the predicted value. However, within 250 metres of the dam the channel dimensions are closely comparable to the predicted values (Table 4.20), and the dimensions of the surveyed cross-sections are generally comparable to the values predicted until the river enters the tidal zone. However, the occurrence of low channel capacities immediately upstream and downstream of a tributary 5 km^2 below the dam may represent an adjustment to flow regulation. The bench immediately below the dam has been formed of sediment containing some 45% silt clay overlying gravel and this has effectively reduced channel width to 70% and channel mean depth to 40 % of values determined from the regional relationship.

Table 4.20 Summary of channel form changes below Blagdon reservoir.

Drainage area (km²)	Percentage of catchment regulated	Mean channel change ratios				
		channel capacity	width	mean depth	width-depth ratio	conveyance factor
33.1 - 33.5	99.7 - 98.5	0.29	0.73	0.39	1.88	0.15
33.6 - 44.0	98.2 - 75.0	1.03	0.96	1.07	0.91	1.03
72.5 - 89.6	45.4 - 37	0.58	0.58	0.84	1.35	0.54
90.0 - 94.5	36.7 - 34.9	0.93	0.93	1.01	0.93	1.03

Table 4.21 Summary of channel form changes below Chew Valley Lake.

Drainage area (km²)	Percentage of catchment regulated	Mean channel change ratios				
		channel capacity	width	mean depth	width-depth ratio	conveyance factor
60.3 - 60.6	99.9 - 99	0.50	0.73	0.67	1.09	0.46
60.7 - 60.9	98.9 - 98.5	0.90	0.94	0.97	0.97	0.89
73.6 - 73.8	81.5 - 81.3	0.54	0.76	0.80	0.96	0.49
73.9 - 75.4	81.2 - 79.6	1.09	1.08	1.01	1.02	1.16
98.9 - 152.4	60.7 - 39.4	0.99	1.10	0.92	1.52	1.08

Chew Valley Lake was closed in 1953 and impounds a catchment area of 58 km^2. The channel bed along a reach extending for 1.5 kms below the dam is composed of fine sediment and a high proportion of organics. The only coarse material revealed on the bed occurs at the confluence of the Chew Stoke Brook, which has a catchment area equal to 20% of the regulated drainage area. Immediately downstream of the dam and above the compensation outflow some 150 m. downstream, the channel capacity has been reduced to 50% of the value expected (Table 4.21), but below the outflow no change is evident. Downstream from the confluence of the Chew Stoke Brook the channel capacity has once again been reduced to 50% of the predicted value. However, the channel capacity of individual cross-sections progressively approaches the values predicted by the regional relationship downstream from the confluence.

The reach between 3 kms and 12 kms below the dam is incised into alluvium and at individual locations deposition has occurred resulting in the reduction of the channel capacity to 40% of the expected value. The sediment at the location appears to have been derived in part from the erosion and redistribution of material which has slumped into the channel, similar to that identified below Sutton Bingham reservoir. In contrast the reduction of channel width below the Chew Stoke Brook confluence has been partly achieved by the plastering of fine sediment onto the banks during channel migration. A minor reduction of channel depth may also have occurred following the deposition of coarse material immediately below the confluence. Furthermore, the complete lack of a pool and riffle sequence may indicate that the pools have been refilled by fine sediment during the persistent low flows consequent upon dam closure. Datable material along the channel was rare but young trees growing on the surface of the bench within the reach between the dam and the compensation outflow yielded a maximum age of 12 years. This gives the bench a minimum date of 1955 and indicates that the bench may have been formed since dam closure.

The evidence for channel change downstream from Blagdon and Chew reservoirs is inconclusive. However, evidence from the upland reservoirs has indicated that under certain conditions the rate of channel response may be slow. Both reservoirs have large surface areas, relative to their catchment areas, so that the absorption and attenuation of peak discharges may markedly reduce the magnitude of peak flows. This may result in discharges which are simply accommodated within the pre-existing channel. That is the

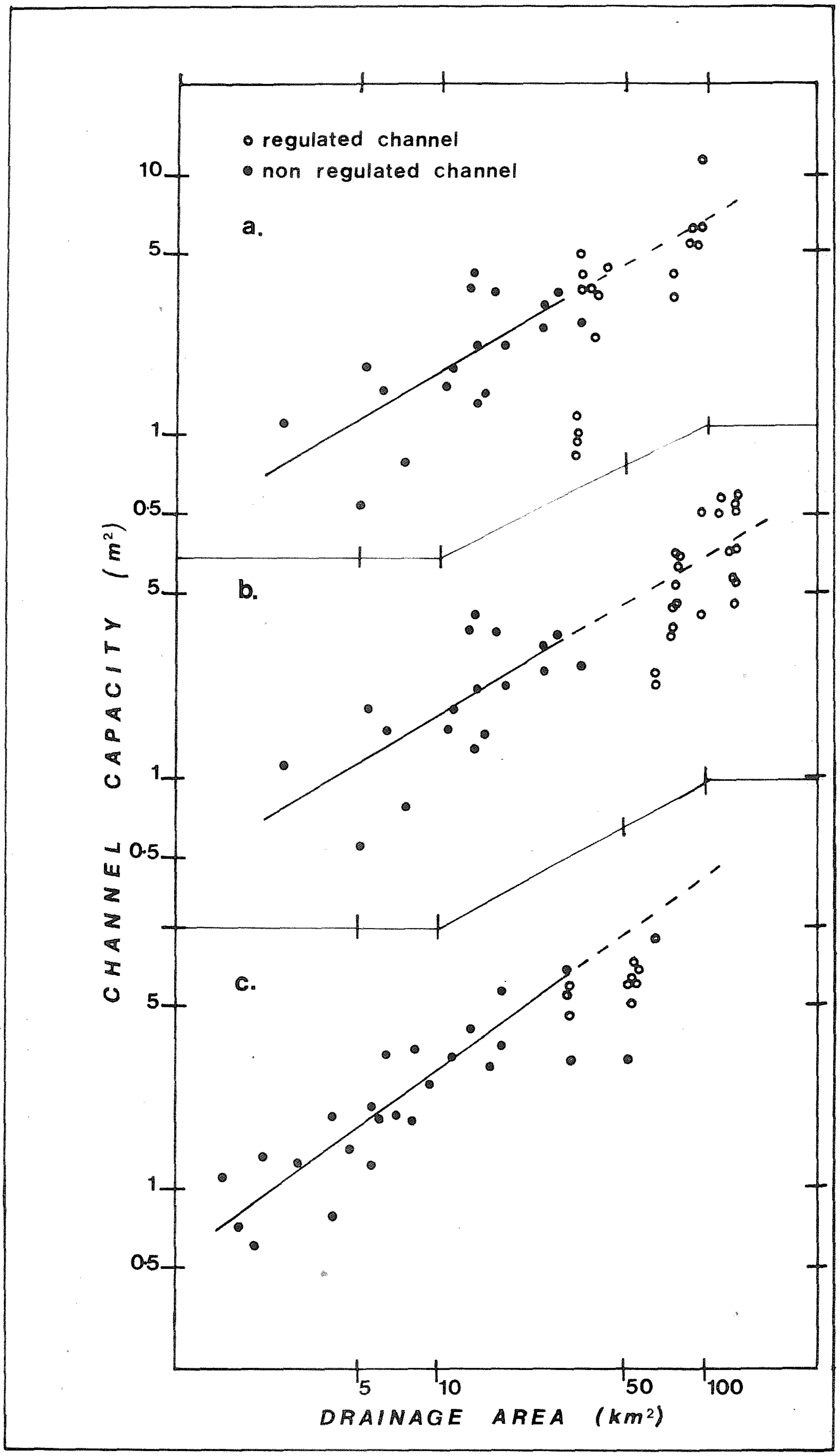

FIGURE 4.11 THE VARIATION OF CHANNEL CAPACITY DOWNSTREAM FROM BLAGDON (a), CHEW VALLEY (b), AND SUTTON BINGHAM (c) RESERVOIRS.
(Regressions based upon the non-regulated data).

regulated discharge may not be competent to transport the bed sediments nor to erode the cohesive bank materials. Where flows are incompetent to erode and redistribute the channel and floodplain sediments a sediment input is required to initiate channel adjustment. Downstream from Blagdon and Chew reservoirs no such sources exist so that the rate of channel response will be dependant upon the frequency of competent discharges released from the reservoir.

c) Channel capacity adjustment below lowland reservoirs.

The analysis of channel form data downstream from lowland reservoirs (Fig. 4.11) has revealed that the rate of adjustment is dependant upon the capability of flows to erode and redistribute the channel perimeter sediment and the mobility of the channel in planform. The cohesive bank sediments within the three catchments examined prohibit bank erosion but sediment derived from tributaries or from bank slumping may be redistributed and result in the reduction of channel capacity. The higher rate of adjustment below Sutton Bingham compared with the Chew and Blagdon reservoirs may indicate the importance of sediment introduced by the Gallica Brook or the higher frequency of competent discharges. The latter is most probable as the reservoir surface area - and therefore the effect upon the flood frequency distribution, is much lower than that of the Mendip reservoirs.

4.3. THE IMPACT OF RESERVOIR CONSTRUCTION UPON CHANNEL CAPACITY.

The evidence derived from within the three selected regions (Fig. 4.12) has revealed several factors which may control the magnitude, direction, rate and spatial distribution of river channel response to impoundment. Indeed, certain factors were characteristic of each of the cases examined. Where discharges below the dam were competent to erode, sort and redistribute the channel perimeter and floodplain sediments channel adjustment occurred relatively rapidly. The competence of the flows depends not only upon the particle size distribution of the sediment but also upon the effect of reservoir absorption and attenuation upon peak flows. Further constraints may be applied by bank vegetation prohibiting channel migration. However, at small catchment areas the encroachment of vegetation and the stabilisation of sediments may initiate a very rapid adjustment.

In the absence of active sediment transport the regulated flows will be simply accommodated within the pre-reservoir channel form. However, the introduction of sediment by tributaries and by bank slumping may initiate channel adjustment. Nevertheless it is the magnitude and frequency of competent discharges which appears to

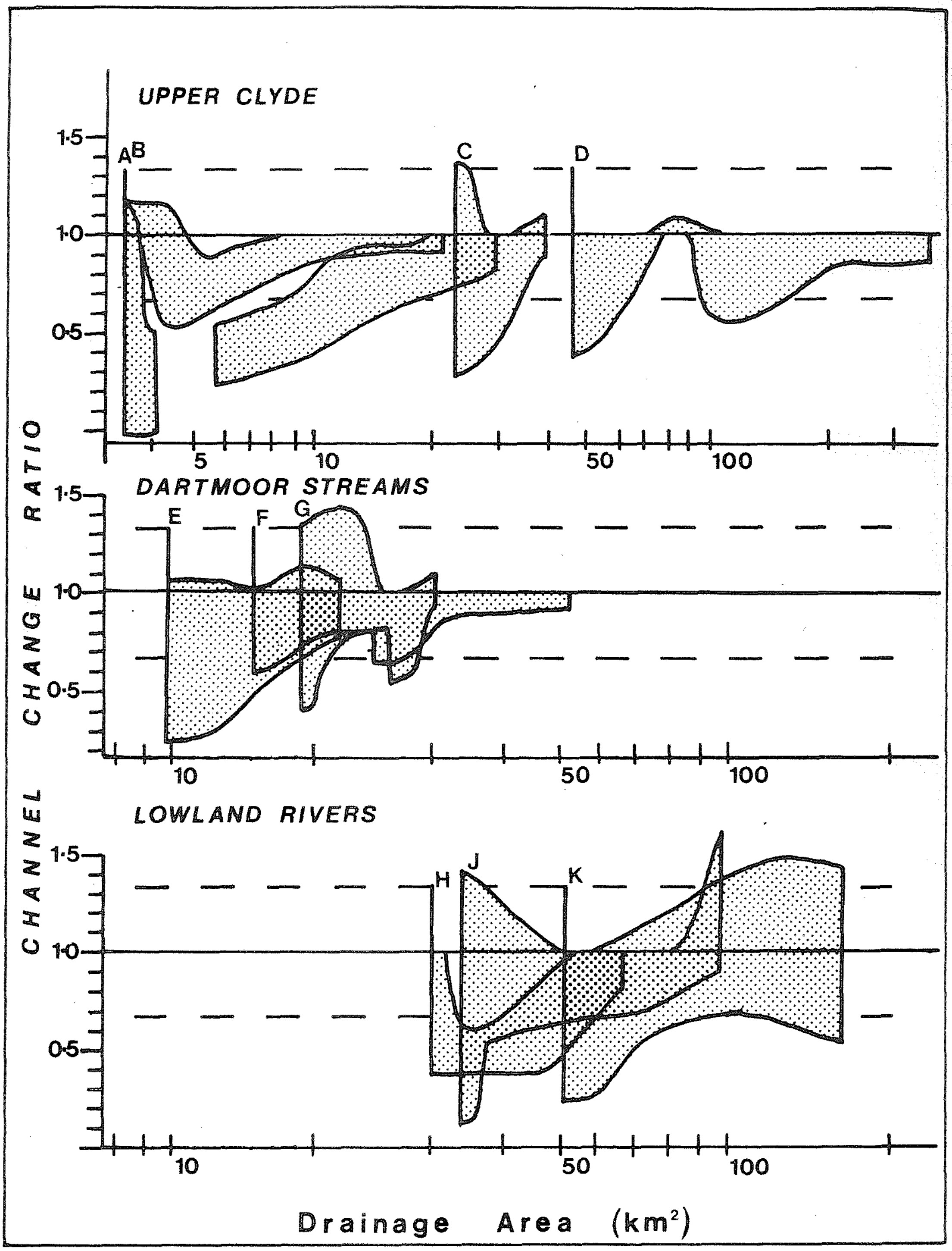

FIGURE 4.12 CHANGES OF CHANNEL CAPACITY DOWNSTREAM FROM RESERVOIRS WITHIN THE UPPER CLYDE BASIN, DARTMOOR, AND LOWLAND SOUTH-WEST ENGLAND.

A. Cowgill
B. Leadhills
C. Camps
D. Daer

E. Fernworthy
F. Avon
G. Meldon

H. Sutton Bingham
J. Blagdon
K. Chew Valley.

fundamentally determine the rate of channel capacity adjustment below reservoirs. Whether channel width or depth are preferentially adjusted similarly appears to be a function of the relationship between peak flow reduction and the calibre of the existing channel sediment.

The following chapter seeks to examine the significance of these factors to the adjustment of river channel capacity downstream from four individual reservoirs, Lake Vyrnwy in mid-Wales, Stocks reservoir in the Forest of Bowland, Catcleugh reservoir in the Cheviots and Leighs reservoir, a small lowland site on the river Ter in Essex.

CHAPTER 5. VARIATIONS OF CHANNEL CAPACITY ADJUSTMENT BETWEEN REGULATED CATCHMENTS

The information derived from the analysis of channel form data downstream from reservoirs within the three selected regions (Chapter 4) illuminated several factors which may control the adjustment of channel capacity. Consequent upon reservoir formation the rate of river channel response, to the alteration of the flow regime and the abstraction of the sediment load, may be dependant upon the frequency of competent discharges, whilst the magnitude of response may reflect the degree of peak flow reduction for discharges of particular frequency. Furthermore, the downstream extent of channel adjustment may be related to the effectiveness of flow regulation.

Within actively meandering channels the reduction of channel capacity will be achieved by the reduction of channel width caused by the redistribution of channel and floodplain sediments. However, within channels having a stable planform, or where competent discharges are very infrequent, the rate of channel response to flow regulation will be dependant upon the supply of sediment derived from a non-regulated source. The reduction of the flow variability resulting from the absorption and attenuation of peak flows within the reservoir may alter the stability of bank materials and the susceptibility of the sediments to erosion at high flows.

Inorder to evaluate the importance of these factors to the adjustment of river channel form four reservoirs were selected from different areas of Britain (Table 5.1.) Lake Vyrnwy and Stocks reservoir are situated within high rainfall areas but differ both in size and age. The river channels downstream of the two reservoirs have planforms which have been stabilised by riparian vegetation and bed-rock outcrops so that the rate of adjustment in each case will be related to the supply of sediment from non-regulated sources. The differences in age and size may be expected to be reflected in the rate of channel response, the magnitude of adjustment, and the extent of channel change downstream.

Downstream of Catcleugh reservoir the channel is initially highly sinuous, unlike the previous two reservoirs, meandering within gravel floodplain sediments. Further downstream the channel becomes

Table 5.1 Characteristics of the reservoired catchments.

Location	River	Reservoir	Date of closure	Surface area	Drainage area (km²)	Mean annual rainfall (mm)	Mean annual runoff (mm)
Mid-Wales	Vyrnwy	Lake Vyrnwy	1888	6.14	73.87	1,908	1,437
Bowland Forest	Hodder	Stocks	1933	3.70	37.45	1,656	1,195
Cheviots	Rede	Catcleugh	1905	2.72	39.90	1,255	1,026
Essex	Ter	Leighs	1964	P	29.90	587	100

P = pumped storage reservoir

Table 5.2 Downstream channel form variations between the Afon Banwy and Afon Tanat

Dependant variable	Independent variable	Regression coefficients Afon Banwy	Regression coefficients Afon Tanat
Drainage area	Channel capacity	0.7964	0.6067
" "	width	0.5505	0.3732
" "	mean depth	0.2465	0.2146
" "	width-depth ratio	0.3045	0.1421
" "	conveyance factor	0.9716	0.7793

stabilised so that a sediment input may be required to initiate channel adjustment. Evidence from the previous chapter indicated that the rate of adjustment may be more rapid for moderately sized reservoirs as the channels downstream may experience more frequent competent discharges. Thus the rate of adjustment may be expected to vary between the three reservoirs for several reasons, related to the frequency of competent discharges and the quantity and calibre of sediment derived from tributaries.

The Leighs reservoirs on the river Ter are unique for this study but provide an example of the effects that a pumped storage, flow regulation scheme may have upon channel form. Water is stored within the two small reservoirs during winter and released during summer to augment the low flows. Whilst the reservoirs have little or no effect upon peak flows the increase of discharges during periods of low flow may affect the stability of the bank materials. The reservoirs are situated within lowland England, associated with low mean annual rainfalls and high evapotranspiration. However, the occurrence of large areas of boulder clay render the catchment largely impermeable so that the flow regime is 'flashy'. Thus, the preconditioning of the bank materials during summer following flow augmentation may have increased the susceptibility of the sediments to erosion by high magnitude discharges resulting from summer storm rainfalls. The cross-sectional dimensions at a number of locations along the river Ter had been surveyed prior to reservoir construction by Dr. A. D. Harvey to whom I am indebted for his assistance both in the location of the sections and for the provision of data.

5.1. CHANNEL CHANGES DOWNSTREAM OF LAKE VYRNWY.

The Afon Vyrnwy, a tributary of the Severn, drains the southern extremity of the Berwyn mountains of mid-Wales. The impoundment of runoff from the headwater region of the river was first considered during the 1860's and the construction of the Lake Vyrnwy dam was begun in 1880. The reservoir which was to supply water to Merseyside by a 68 mile aqueduct was the largest lake in Europe at the time of construction. Furthermore, the dam was to be the first masonry dam in Britain and the first large dam to have a crest overflow weir rather than a by-wash channel cut into the undisturbed bedrock at the end of the dam. The dam was closed in 1888 and the reliable yield of the system was later augmented by the construction of two small diversion dams and tunnels to transfer the waters of the Marchnant and Cowny (Fig.5.1) to the reservoir.

The area is underlain by Ordovician Caradoc beds and the Wenlock series of the Silurian. These are dominated by shales and grit lithologies interspersed with volcanics, the whole acting as a relatively impermeable formation. However, the valleys often contain thicknesses of glacial and fluvio-glacial deposits which may reduce the rate of storm runoff; the Vyrnwy dam is sited on a rock-bar which maintained a natural lake during the post glacial period. The mean annual rainfall of the area exceeds 1,908 mm of which 75% goes to surface runoff. Furthermore, the estimated maximum 24 hour rainfall exceeds 300mm so that high magnitude floods may be expected. Indeed, the mean annual flood has a magnitude equal to approximately 1050 cumecs per 1000 km^2. However, the reservoir has a surface area representing an inundation of 6.1% of the direct catchment area and together with the physiography of the lake basin may be expected to have a marked attenuating effect upon peak flows.

The marked reduction of peak discharges downstream of the dam together with the coarse nature of the bed-material may have produced a natural armour layer resistant to degradation. The bed materials are predominantly cobbles and pebbles although an eight kilometre reach some twelve kilometres below the dam is incised, often into bedrock, and the bed-material here is of boulders. It has previously been suggested (Chapter 2.3) that under these conditions the rate of adjustment may be slow, being dependant upon the frequency of discharges competent to erode and redistribute the channel and floodplain sediment. Active meanders occur at only two isolated locations. Furthermore, two of the larger tributaries, the Marchnant and Cowny which may have provided a supply of sediment, are dammed. Nevertheless, active deposition was observed at the confluence of several small tributaries with the mainstream and the redistribution of sediment from these sources may have initiated channel changes along the Afon Vyrnwy.

The inundation of the headwater tributaries has reduced the stream length above the reservoir available for field survey so that the headwater channel form data may not be applied to the prediction of channel dimensions for reaches downstream of the dam. However, the Afon Vyrnmy has two major tributaries (Fig 5.1), the Afon Tanat and the Afon Banwy. The three rivers are derived from a similar source area and flow approximately parallel so that a similar relationship between drainage area and channel form variables may be expected for each river.

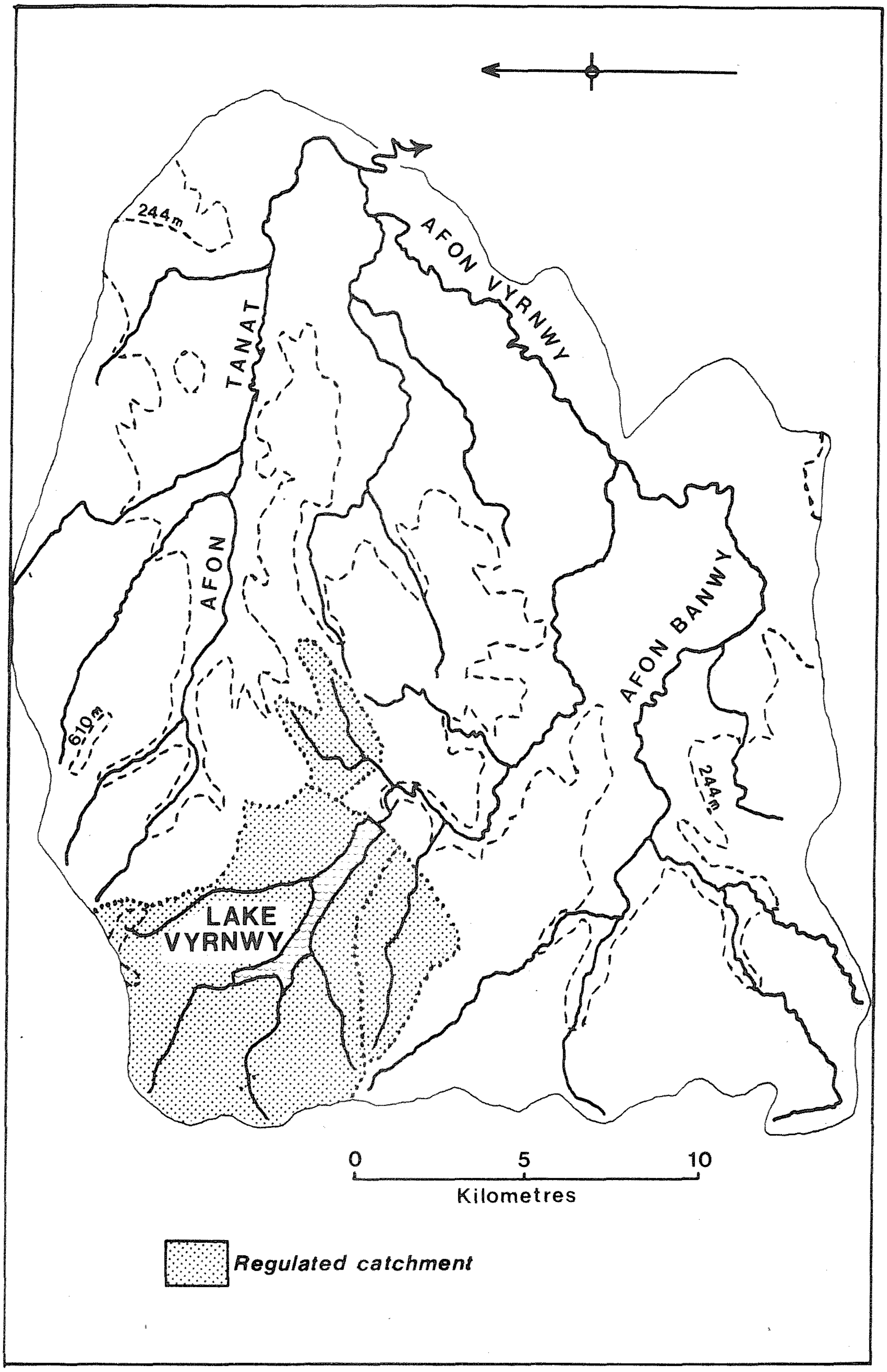

FIGURE 5.1 THE CATCHMENT OF THE AFON VYRNWY ABOVE THE AFON TANAT CONFLUENCE.

The analysis of field data revealed (Table 5.2) however, that the downstream variation of channel dimensions differed for the Afon Banwy and Afon Tanat.

Inorder to determine the applicability of the two populations to the prediction of channel form data for the Afon Vyrnwy, parameters describing the drainage network were regressed against drainage area. Measured values of total and main stream length derived from the Afon Vyrnwy were then compared with those predicted from the tributary data (Table 5.3). The data clearly indicates a close similarity between the Afon Banwy and the Afon Vyrnwy data, and a marked difference between these and the Afon Tanat. Although not indicating the cause of the channel form variation between rivers within one region, the spatial variation of total stream length may describe the variation of channel form parameters. This was also noted within the river Derwent study (Chapter 3.3).

The regression equations derived for the Afon Banwy describing the downstream variation of channel form parameters predicted the headwater channel form dimensions of the Afon Vyrnwy upstream of the reservoir (Fig. 5.2). Thus, channel dimensions downstream of Lake Vyrnwy were predicted by the regression equations derived from the Afon Banwy channel form data. Downstream of Lake Vyrnwy channel capacity has been markedly reduced although at individual locations the values are comparable to those predicted. The difference between the predicted and reduced channel capacities remains approximately constant downstream. That is the magnitude of the apparent channelchange does not decrease rapidly downstream as has been observed elsewhere. Examination of the data describing the downstream variation of the conveyance factor (Fig. 5.2) indicates a similar pattern. The estimated values of the conveyance factor for sections downstream of the reservoir varies markedly from the predicted values so that at a catchment area of 185 km^2 the conveyance factor is less than half of the expected value. The distribution of the conveyance factor and channel capacity values suggests the existence of two populations of channel forms downstream from the Vyrnwy dam. One population contains individuals whose dimensions are comparable to those predicted, the other is composed of individuals having channel capacity and conveyance factor values markedly lower than those expected. The examination of individual reaches of the Afon Vyrnwy tended to confirm this observation.

Table 5.3 The variation of total stream length (1) and mainstream length (2) between the Vyrnwy, Banwy and Tanat catchments.

Catchment	Drainage area		Stream length values (km) at drainage areas of 1 km²	100 km²	175 km²
Vyrnwy	187.74 km²	(1)	1.94	159.30	270.20
		(2)	1.20	20.76	35.44
Banwy	215.54 km²	(1)	2.06	165.96	282.75
		(2)	1.17	21.45	30.54
Tanat	264,71 km²	(1)	1.38	98.38	165,29
		(2)	0.74	14.91	21.48

Table 5.4 Channel changes downstream of Lake Vyrnwy

Reach	Distance downstream (km)	Percent of catchment regulated	Channel change ratios: Channel capacity	Conveyance factor	Width	Mean depth	Width-depth ratio
1	0 - 0.2	99.6	0.78	0.72	0.90	0.88	0.96
2	0.8	97.3	0.62	0.49	0.86	0.73	1.20
3	1.0	96.9	0.88	0.86	0.92	0.98	1.00
4	1.6	95.4	0.58	0.43	0.95	0.62	1.56
5	2.5	85.4	0.91	0.94	0.87	1.03	0.86
6	6.2	84.0	0.52	0.42	0.77	0.71	1.13
7	8.7	69.4	0.68	0.49	0.95	0.65	1.37
8	10.9	64.9	0.71	0.60	0.97	0.79	1.12
9	12.1	63.7	1.09	1.13	0.86	1.15	0.83
10	12.3	56.3	0.64	0.52	0.92	0.75	1.15
	19.7	G	0	R G	E		
11	22.2	44.1	0.96	0.99	0.82	1.17	0.76
12	25.0	40.0	0.59	0.51	0.69	0.84	0.84

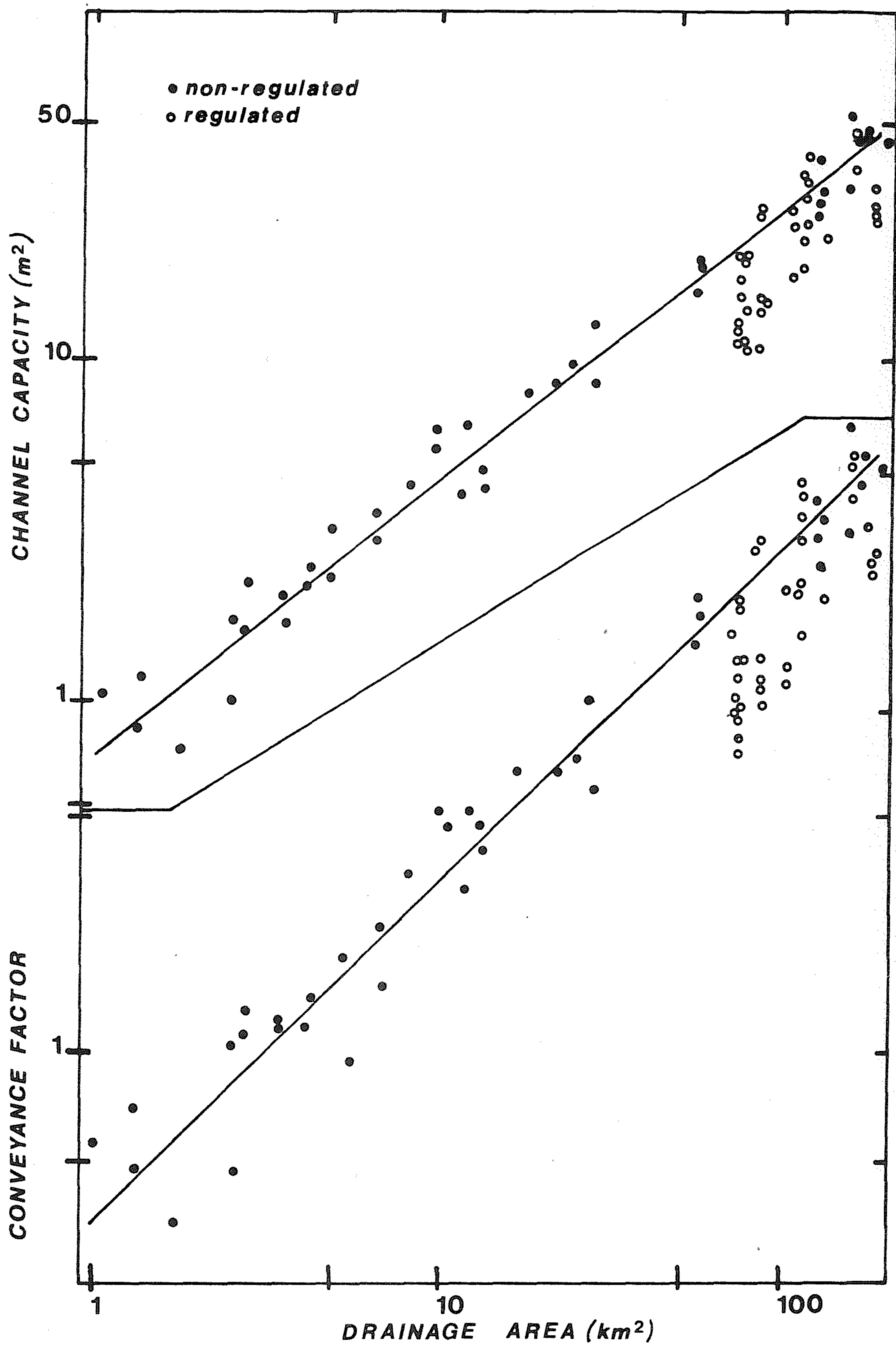

FIGURE 5.2 THE VARIATION OF CHANNEL CAPACITY AND THE CONVEYANCE FACTOR DOWNSTREAM FROM LAKE VYRNWY. (Regressions based upon non-regulated data).

The division of the channel into a series of reaches was based upon channel form characteristics and the occurrence of tributary confluences. The data for individual locations within each reach were combined to produce average channel dimensions which were related to the values predicted from the Banwy data (Table 5.4). Thirty-five percent of the locations surveyed have channel capacities within twenty percent of the predicted values, but forty percent of the sites had capacities equal to less than sixty percent of those expected. Of the twelve reaches surveyed, seven have channel change ratios varying from the predicted by greater than forty percent, and of the remaining five reaches, four have values closely comparable to those expected. The latter sites are characterised by being incised, bedrock outcrops, stable banks and locally steep slopes. Those having reduced channel capacities are often situated downstream of a tributary or as in the case of reach 12 within active meanders.

The deposition of sediment by a non-regulated tributary into the mainstream which is experiencing reduced flows was evidenced at several locations. Two hundred metres below the dam a right bank tributary having a catchment area of less than 0.5 km^2 had deposited gravel to form a delta within the channel of the Afon Vyrnwy (Plate 5. l,a,b.) The deposit may have been reworked during times of high flow within the main channel thereby providing sediment to reaches downstream. Indeed channel capacities within the reach extending for six-hundred metres downstream of the confluence are less than one-half of those expected. The form of the deposits and the redistribution of sediment downstream will be a function of the relative magnitudes and frequencies of competent tributary and mainstream discharges. Below the confluence of a right bank tributary some 6.2 km downstream of the Vyrnwy dam sediment has been deposited over the entire channel bed for some distance. The tributary has a catchment area of 6 km^2 and the larger discharges emanating from this tributary have led to the more widespread deposition of sediment over the regulated mainstream channel (Plate 5·2, a, b) compared to the simple delta produced by the smaller tributary. Channel capacities within the reach immediately below the confluence have been reduced to forty-three percent of those predicted, but within two kilometres the channel capacities approach the expected values.

The sediment discharge from the two major tributaries entering the Afon Vyrnwy downstream of the dam may be reduced by the trapping of the sediment load behind the diversion dams. Nevertheless the introduction of sediment from the non-regulated tributaries and the redistribution

PLATE 5.1 A DELTA FORMED BY A SMALL TRIBUTARY, HAVING A DRAINAGE AREA OF 0.5 km^2, WITHIN THE CHANNEL OF THE REGULATED AFON VYRNWY.

PLATE 5.2 AGGRADATION WITHIN THE CHANNEL OF THE REGULATED AFON VYRNWY BELOW THE CONFLUENCE OF A TRIBUTARY HAVING A DRAINAGE AREA OF 6 km^2, LOOKING UPSTREAM (TOP) AND DOWNSTREAM (BOTTOM).

of the sediment downstream at high flows has effectively reduced the channel capacity of the Afon Vyrnwy to forty percent, and the conveyance factor to fifty percent, of the predicted values. The channel changes are associated with a reduction of channel mean depth to approximately thirty percent of the expected values, which has resulted in an increase of the width-depth ratio. However, within reach 12, immediately above the Banwy confluence, channel capacities have been reduced consequent upon a reduction of channel width; an adjustment which has been shown to occur commonly within active meander systems. The reduction of channel capacity to sixty percent of the predicted value at a catchment area of 185 km^2 - 2.5 times that impounded by Lake Vyrnwy - may be related to the major reduction of peak discharges resulting from the absorption and attenuation of flows within the large surface area reservoir .

The examination of the frequency distribution of the channel change ratios for the various channel parameters may indicate the adjustment of the Afon Vyrnwy to a new equilibrium condition (Fig. 5.3), suggested by the two populations of channel forms identified perviously. The distribution of channel change ratios indicates a marked peak at a value of 0.55 for channel capacity and 0.45 for the conveyance factor. Both distributions have a marked positive skew. This form of the frequency distribution may be expected for a population which has been derived from a former population related to independant controls of different magnitude. The comparison of these distributions to those derived for the Afon Banwy data suggests that the contemporary Afon Vyrnwy data may be derived from a pre-reservoir distribution. The contemporary distribution may reflect the progressive adjustment of the Afon Vyrnwy to the flow regime imposed by reservoir construction.

Consequent upon dam construction the Afon Vyrnwy has adjusted its channel capacity to a new quasi-equilibrium condition. The reduction of channel capacity to fifty-five percent of the expected values has been achieved by the reduction of mean depth associated with the deposition of sediment by tributaries in the main channel experiencing reduced flood magnitudes. However, within an active meander system channel width may be reduced preferentially to depth. The change of channel shape and the increase of the wetted perimeter in relation to channel capacity has resulted in a reduction of the conveyance factor to forty-five percent of the expected values. Downstream the magnitude of channel adjustment is maintained at

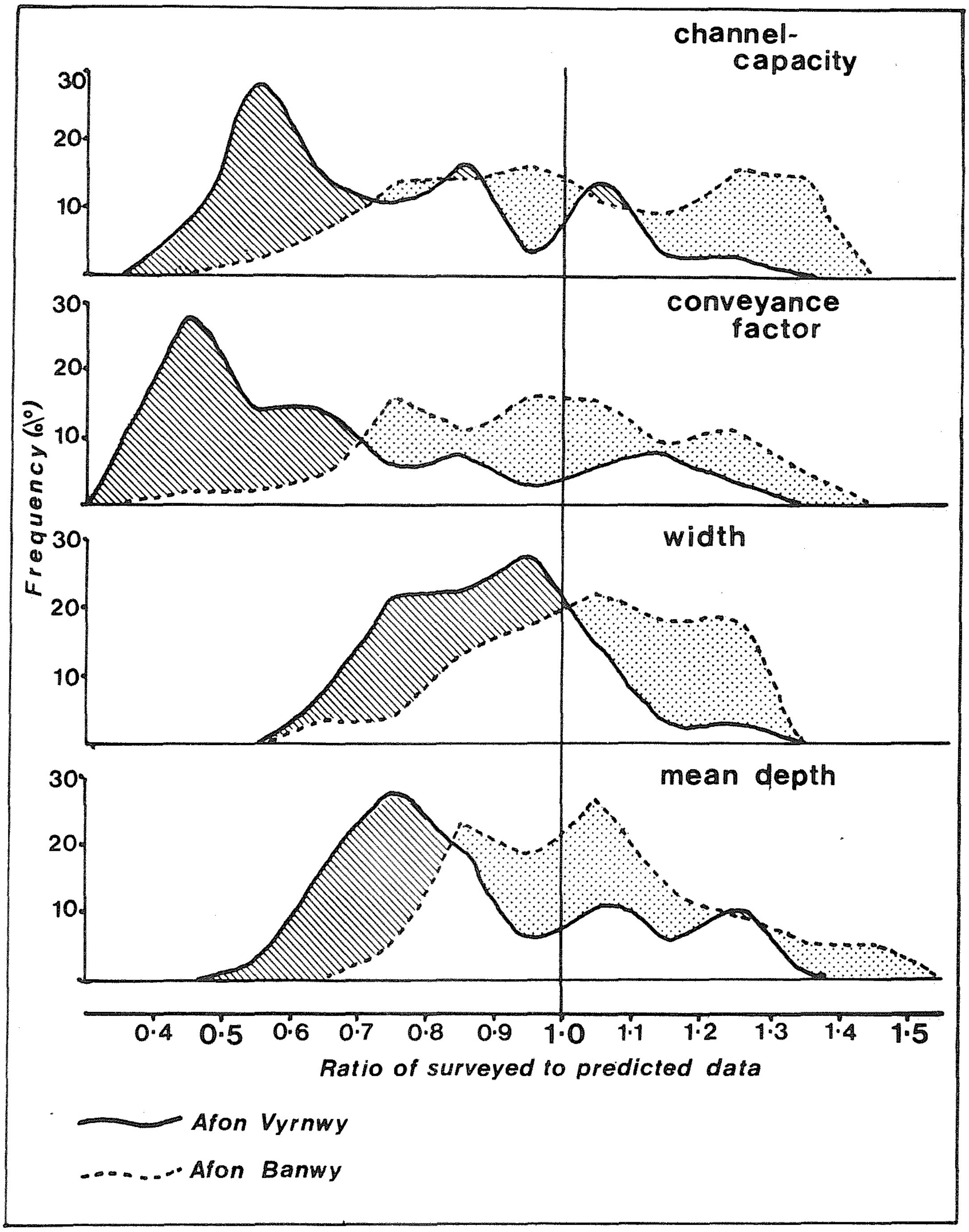

FIGURE 5.3 THE DISTRIBUTION OF CHANNEL CHANGE RATIOS FOR PARTICULAR CHANNEL PARAMETERS DOWNSTREAM FROM LAKE VYRNWY.

least until the catchment area has reached 2.5 times that draining to the lake Vyrnwy. The introduction of the Afon Banwy reduces the percentage of catchment impounded to eighteen percent and the channel size at a catchment area of over 400 km² prohibited further investiagation. Nevertheless, the downstream extent of channel change may reflect the magnitude of change of the flow regime consequent upon dam closure.

5.2 CHANNEL CHANGE BELOW STOCKS RESERVOIR.

The river Hodder drains the Forest of Bowland and flows southwards for 41 kilometers before joining the river Ribble. First considered for water resource development at the turn of the century the construction of Stocks dam commenced in 1925. The dam, an earth embankment with a puddle core and a side channel spillweir, was closed in 1933 storing runoff from the 37.45 km² headwater area of the river Hodder. During a prolonged dry spell the Broughton boreholes are used as an auxilliary supply.

The area is one of high mean annual rainfall of 1,656 mm and the generally impermeable lithologies underlying the catchment produce a mean annual runoff of 1,195 mm. Although the catchment is crossed by a band of Carboniferous Limestone the major part is underlain by the Borland Shales and Pendle Grits. The latter is a massive sandstone but contains numerous bands of subordinate shales, and is underlain by well bedded laminated black shales producing an impermeable formation. The estimated maximum 24 hour rainfall is in excess of 300mm. Thus from the qualitative assessment of the catchment characteristics a flow regime containing high magnitude floods may be expected. Indeed, the mean annual flood for the Bowland streams has a value of approximately 1300 cumecs per 1000 km². However, the area has been extensively glaciated and the valleys contain thicknesses of glacial and fluvio-glacial deposits which may locally reduce runoff rates. The headwater area is covered primarily by moorland although some 25% of the catchment is given over to afforestation and pockets of peat occur within the higher basins.

At top level the reservoir inundates 3.7 % of the impounded catchment area. Thus flood magnitudes downstream of Stocks reservoir may have been markedly reduced subsequent to dam closure. In 1967 a severe storm produced a catastrophic flood in the neighbouring Dunsop valley and in the river Hodder headwater area,

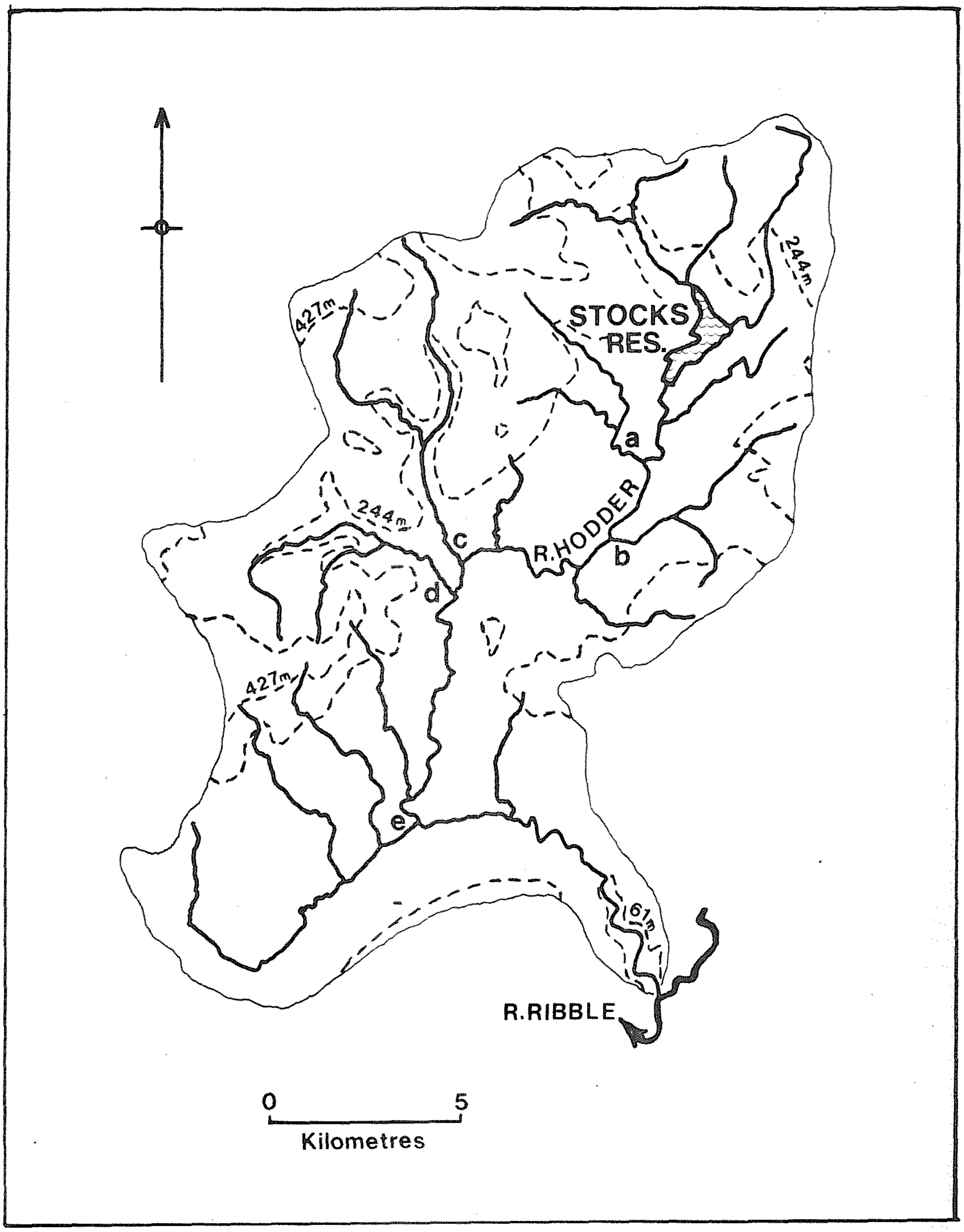

FIGURE 5.4 THE CATCHMENT OF THE RIVER HODDER.

a) Croasdale Brook
b) Skelshaw Brook
c) River Dunsop
d) Langden Brook
e) River Loud

but the attenuation of the flood peak within the reservoir reduced the magnitude of the flood downstream. Subsequent to the flood, proposals were accepted for the enlargement of Stocks dam and for the improvement of the overflow weir so as to increase the regulating capacity of the reservoir. Although the proposed enlargement did not commence immediately the normal water level within the reservoir was reduced by 1.22 m. inorder to permit the absorption of subsequent flood discharges - further reducing the magnitude of flood peaks downstream.

Downstream from Stocks reservoir the channel slope is controlled at several locations by the outcrop of bedrock and, except for a short reach downstream of the confluence with Langden Brook (Fig. 5.4) which is actively meandering, the planform of the channel is relatively stable. The bank materials commonly contain in excess of thirty percent silt-clay and are frequently stabilised by woody vegetation. Evidence from the previous studies has indicated that the rate of channel adjustment will be related to the frequency of competent discharges and to the quantity and calibre of sediment introduced by non-regulated tributaries. Whilst discharges may be markedly reduced downstream of the dam the changes of channel form may result from the deposition of sediment transported by the several tributaries during high flows. Furthermore, the downstream extent of channel adjustment to the altered flood frequency distribution may be related to the magnitude of flood peak reduction consequent upon dam closure.

The field survey of channel dimensions from the headwater area of the river Hodder above Stocks reservoir together with data derived from the neighbouring river Dunsop may provide information as to the downstream variation of channel dimensions for the prediction of the pré-reservoir channel form at locations downstream of the dam. However, a marked variation between the rate of increase of channel form parameters with drainage area was revealed for the two catchments (Table 5.5). The previous studies indicated that the examination of the drainage network may provide information inorder to justify the application of one data set to the prediction of channel dimensions downstream of reservoirs. Thus total stream length has been employed to determine whether the channel form-drainage area relationships derived from the headwaters of the river Hodder could be justifiably extended to predict channel dimensions for reaches below the dam. The data (Table 5.6) revealed that total stream length downstream of Stocks reservoir varied with drainage area in a similar manner to the river Hodder headwater relationships. Thus, the

Table 5.5 Downstream variation of channel form parameters within the Hodder and Dunsop catchments

Independent variable	Dependant variable	Regression coefficients Hodder	Dunsop
Drainage area	Channel capacity	0.7620	0.5772
" "	width	0.4977	0.4278
" "	mean depth	0.2672	0.1491
" "	width-depth ratio	0.2058	0.2780
" "	conveyance factor	0.7937	0.7247

Table 5.6 Downstream variation of total stream length

Drainage area (km²)	Total stream length (km)			
	----Predicted data----			
	River Hodder headwater	River Dunsop	Combined data	River Hodder below Stocks reservoir
38.0	70.3	57.7	60.9	63.41
49.2	90.7	72.4	76.8	88.32
74.5	134.5	104.6	111.7	136.81
106.2	194.8	142.9	153.5	186.83
142.3	259.1	185.1	199.8	253.21
178.8	324.6	226.4	245.3	350.84
258.0	466.2	313.0	341.1	516.00

regression equations produced for this catchment were used for the identification of channel changes downstream of Stocks reservoir.

Immediately downstream of the reservoir overflow inlet the channel capacity of the river Hodder has been enlarged to nearly twice the value predicted by the headwater regression equation. Within three hundred metres however, the channel capacity has been reduced to less than 50% of that expected. Downstream the magnitude of channel change decreases progressively (Fig. 5.5), as the proportion of the catchment regulated by the reservoir decreases. At a catchment area equal to five times the impounded headwater area, channel change is not evidenced. Similarly, the conveyance factor is reduced to 40% of the expected value some 250 m below the dam but increases with drainage area so that the values are comparable to those predicted at a catchment area of greater than 200 km^2. Within the reach immediately downstream of the dam degradation has increased channel capacity by the erosion of the channel bed materials and is reflected by channel mean depth which is 50% greater than expected. The differential sorting and transportation of this material downstream has produced a bench within the former channel containing less than ten percent silt-clay by weight. The permanency of this feature is indicated by the colonisation of the sediments by woody vegetation. The compound channel form occurs at several locations downstream until the catchment area has reached a value equal to three times the area of the impounded headwater. However, the composition of the bench varies and bank collapse and sediment deposition downstream of tributary confluences may determine the location of this feature.

The adjustment of river channel form at individual cross-sections will be related to the dimensions of the channel prior to dam closure so that considerable variation may occur within a single reach at any point in time. Further variation may be expected to result from local, short term, controls inherent within the river channel system. Inorder to examine the general pattern of adjustment downstream of Stocks reservoir the channel was divided into a number of reaches separated by tributary confluences and bedrock outcrops (Table 5.7). The latter will constrain the rate of channel adjustment upstream by inhibiting channel slope change.

The data derived for each reach indicates (Table 5.8) that for a distance of six kilometres downstream of Stocks reservoir the channel

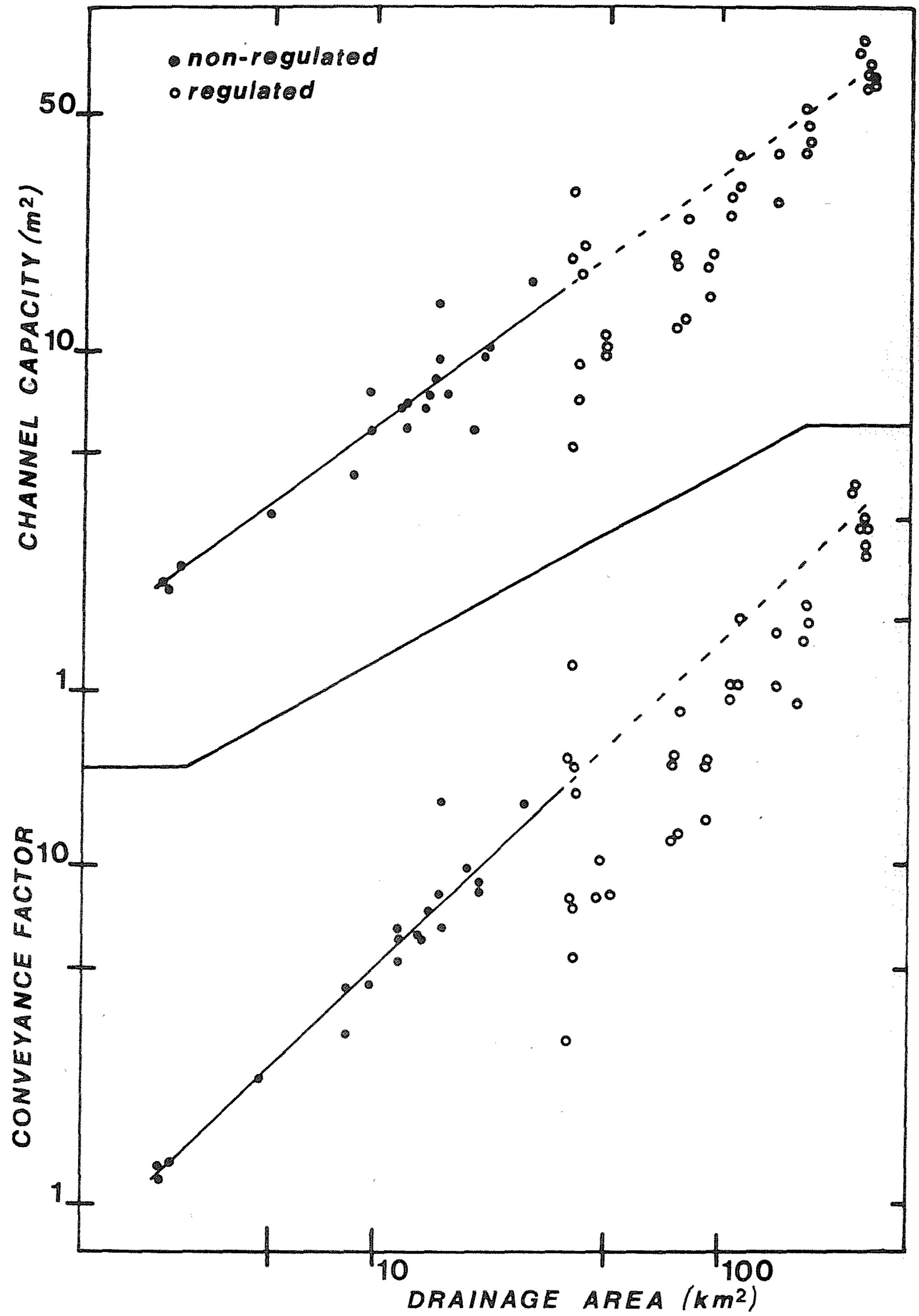

FIGURE 5.5 THE VARIATION OF CHANNEL CAPACITY AND THE CONVEYANCE FACTOR DOWNSTREAM OF STOCKS RESERVOIR.

(Regressions based upon the non-regulated data).

Table 5.7 Channel reach characteristics below Stocks reservoir

Reach	Drainage area	Distance downstream		% impounded catchment area
1	38.0 < 39.77	0 < 0.3	end of degraded reach	99
2	39.8 < 40.00	0.3 < 0.5	bedrock outcrop incised channel	94
3	40.01 < 40.12	0.5 < 0.9	Barn Gill	94 > 93
4	47.32 < 49.15	1.9	Croasdale Brook	79 > 76
5	74.28 < 78.20	4.5	Skelshaw Brook	50 > 48
6	92.73 < 93.83	6.1	bedrock outcrop/weir	41 > 40
7	106.20 < 111.70	8.75	Dunsop river	35 > 34
8	142.10 < 142,80	9.4	Langden Brook	26
9	170.90 < 178.80	13.7	River Loud	22 ≥ 21
10	241,90 < 263.40	30.29	River Ribble	16 > 14

Table 5.8 Summary of channel change below Stocks reservoir

Reach	cc	Mean k	channel w	change $\bar{d}$	ratio $w/\bar{d}$
1	1,42	1,66	1,18	1.36	0.90
2	0.51	0.39	0.73	0.65	1.20
3	1.10	1.31	0.83	1.31	0.68
4	0.52	0.39	0.80	0.69	1.19
5	0.62	0.54	0.76	0.81	0.99
6	0.53	0.45	0.70	0.75	1.02
7	0.83	0.81	0.87	0.95	0.95
8	0.72	0.65	0.86	0.84	1.04
9	0.84	0.63	0.99	0.84	1.25
10	0.98	0.95	0.98	1.02	1.13

capacity of the river Hodder has been reduced to approximately 50% of the predicted values. Throughout this section the bankfull stage was identified at a level below that of the valley floor except within reaches 1 and 3 within which evidence of an inner level was absent. Reach 1 has been degraded whilst the channel within reach 3, situated downstream of a bedrock outcrop, is incised within the valley floor sediments. The adjustment of channel capacity has been achieved by the reduction of channel width and depth producing width-depth ratios which are generally comparable to the predicted values.

Downstream from reach 6 the reservoir impounds runoff from less than forty percent of the drainage basin and the channel dimensions approach those predicted by the regression equations. That is, at a drainage area of greater than 100 km^2 changes in channel capacity are insignificant. However, within reach 8 and 9 the mean conveyance factor values are appreciably below those predicted. The former reach contains active meanders whilst reach 9 has a high width-depth ratio. Thus, although channel capacity has not markedly reduced within these reaches the change of the hydraulic radius has reduced the conveyance factor to two-thirds of the expected value. However, at catchment areas greater than 180 km^2 - 4.5 times that of the regulated headwater area - channel change is not evident.

The location of channel change often coincides with the introduction of a tributary into the regulated mainstream. Reaches 4 to 6 in particular may have undergone a reduction of channel capacity consequent upon the deposition of sediment transported by a tributary into a mainstream experiencing reduced flood magnitudes. Generally, channel capacities immediately downstream of the confluence are reduced to 45% of the expected values and, although considerable variations occur at individual locations the magnitude of channel change appears to decrease downstream of the confluence. The reduction of the conveyance factor downstream of the Dunsop river and Langden Brook may reflect the deposition of coarse material during the 1967 catastrophic flood. The magnitude of the mainstream flood was markedly reduced by the absorption and attenuation of the flood discharge within the reservoir so that the competence and capacity of the mainstream discharge may also have been reduced.

A dendrochronological survey was undertaken to provide a minimum date for bench formation and for the reduction of channel capacity. The evidence obtained (Table 5.9) indicates that bench formation and the associated reduction of channel dimensions may have occurred since reservoir construction. The tree cores suggest that the banks of the contemporary channel were sufficiently developed to support the development of tree species approximately thirty-two years ago - some thirteen years after dam closure.

The river Hodder downstream of Stocks reservoir has, over the past 45 years, adjusted its channel dimensions to the imposed flow regime. Although considerable variation exists between individual cross-sections the channel capacity within four of the reaches identified has been reduced to less than 60% of the expected value. Channel adjustment has been achieved by the deposition of sediment derived from channel degradation immediately below the dam and supplied by non-regulated tributaries, assisted by bank degradation and vegetation encroachment. Although constrained by bedrock outcrops within the channel the adjustment of the river Hodder channel to flow impoundment may be observed for 13.7 kilometres below the dam until the catchment area has reached a value equal to nearly five times that draining to the reservoir.

5.3. CHANNEL CHANGES DOWNSTREAM OF CATCLEUGH RESERVOIR

The river Rede rises below Carter Fell within the southern Cheviots (Fig. 5.6), and flows southwards for some 58 kilometres to join the north Tyne below Bellingham. The runoff from the headwaters of the river Rede have been impounded since 1905 by the Catcleugh dam providing a reliable yield of 45.5 $10^3 m^3$/day for supply to Newcastle. The masonry dam having a side channel overflow weir controls an area of approximately 40 km^2. The majority of the catchment is underlain by the Fellstone and Cementstone groups of the Lower Carboniferous. The former is a massive sandstone, but the underlying series of shales with innumerable thin bands of impure, compact limestone renders the formation impervious. Within the higher areas the Lower Carboniferous sediments are overlain by peat whilst much of the lower land, particularly downstream of the reservoir, is covered by thicknesses of boulder clay. Toward the foot of the catchment Carboniferous Limestone outcrops occasionally through the covering of boulder clay. Although the catchment surface is relatively impermeable and the catchment has an extensively branching stream network the low relief of the catchment and the low rainfall amounts compared with the Vyrnwy

Table 5.9 Dendrochronological evidence of channel change below Stocks reservoir

Age of trees	Location of trees sampled			
	Single channels channel change ratio		Compound channels	
	< 0.6	> 0.6	bench surface	terrace surface
Maximum age (yrs.)	32	67	27	84
Compared to reservoir age (yrs.)	- 13	+ 22	- 18	+ 39

Table 5.10 Regression equations derived from Kielder Burn and river Rede headwater data.

Independent variable	Dependant variable	Regression constant	Regression coefficient	R^2
Drainage area	channel capacity	0.0365	0.5737	0.81
" "	width	0.3980	0.4189	0.86
" "	mean depth	- 0.3713	0.1545	0.68
" "	width-depth ratio	0.7593	0.2644	0.44
" "	conveyance factor	- 0.2571	0.6896	0.80

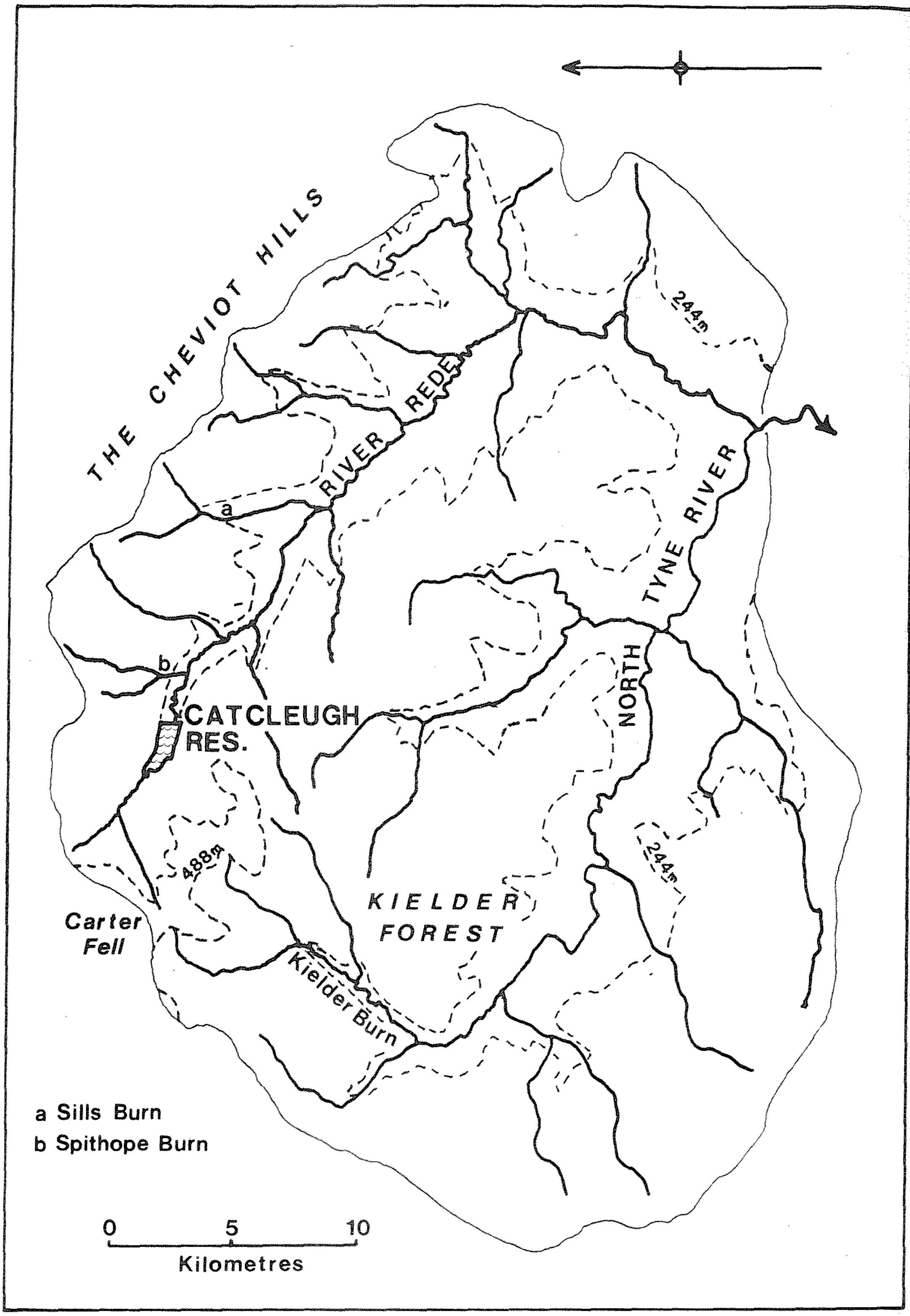

FIGURE 5.6 THE RIVER REDE AND KILDER BURN CATCHMENTS.

and Hodder catchments may produce lower rates of storm runoff and a slower increase of channel form dimensions with drainage area. Indeed the mean annual runoff of 1026 mm accounts for 82% of the mean annual rainfall but, although the estimated maximum 24 hour rainfall is over 300mm, the mean annual flood has a value of only 800 cumecs per 1000 km^2.

Records of peak discharges flowing into and being discharged from the reservoir are unavailable but the reservoir at top water level inundates an area of 1.1 km^2, some 2.72% of the catchment area, so that the storage provided above the level of the spillweir may be anticipated to have a marked effect upon the magnitude of peak flows downstream. Furthermore, the coarser fractions of the sediment load transported by the streams entering the reservoir will be deposited within the pool. Indeed the reservoir effectively traps the sediment load so that to 1960 sediment to an average depth of 4.7 mm had been deposited over the whole of the reservoir basin annually (Hall, 1967). Deposition had occurred to thicknesses of eight metres in deltaic areas around the inlet streams, but in the deeper parts of the reservoir sediment accumulations were small and adjacent to the dam itself very little material was found to be deposited.

The reduction of peak discharges and the abstraction of the sediment load for reaches downstream of the dam may, during the seventy years since dam closure, have caused an adjustment of the channel form. However, the previous studies have demonstrated that channel adjustment will not be uniform along a single river. At any location the rate and direction of channel change will reflect the frequency of discharges competent to transport the channel boundary material and floodplain sediment. Furthermore, channel adjustment will be constrained by riparian vegetation, bedrock outcrops and cohesive bank sediments so that an input of sediment may be required for channel change to occur. Nevertheless, the final 'equilibrium' form will be a function of the relationship between pre- and post-dam closure sediment and water discharges.

The river Rede below Catcheugh reservoir provides an opportunity to examine the importance of several control variables to channel change suggested within the previous studies. The planform of the river immediately downstream of the dam is stabilised by vegetation and bedrock outcrops but within 200 metres the channel forms a series of right meanders lacking any obvious constraints upon the planform. However, downstream the channel becomes straighter and the banks are once again stabilised by woody vegetation and cohesive bank materials. Indeed, short reaches of the channel are incised into the superficial covering of boulder clay. Within such stable channel forms previous studies have suggested that channel adjustment to an altered flow regime involving reduced flood magnitudes may require the introduction of sediment from a non-regulated source. Downstream from the meandering reach the river Rede is joined by numerous tributaries and although four serve to increase the drainage area by over 20%, evidence from the Afon Vyrnwy indicated that the smallest first order tributary may supply significant amounts of sediment to the regulated mainstream. Thus,the river Rede permits the examination of channel change within a meandering channel and the evaluation of the significance of a tributary sediment supply to channel form adjustment within straight stable reaches.

The identification of channel changes downstream from Catcleugh reservoir was achieved by the application of a series of regression equations relating channel form parameters to drainage area based upon data derived from the field survey of the river Rede above the reservoir and Kielder Burn (Fig. 5.7). The two catchments rise at similar elevations below Carter Fell and are underlain by comparable lithologies whilst the vegetation of coarse heath grass, heather and coniferous plantations are common to both. Furthermore, the incorporation of the Kielder Burn data into the regressions more than quadruples the range of drainage areas available when compared to that provided by the headwaters of the river Rede alone. Thus, there is a considerable overlap between the control data and the channel form date derived from reaches below the dam.

Changes of channel form have been identified by comparison of channel dimensions with those predicted from the regression equations based upon the control data (Table 5.10). Downstream of the overflow inlet the channel of the river Rede is wide and poorly defined with coarse, boulder bed-material. However, within 100 metres the channel planform and cross-section are clearly defined but vegetation has encroached into the channel. Sediment has been trapped by the vegetation and the deposit has reduced the channel capacity to forty percent of that expected (Fig.5.7). Downstream the magnitude of channel change increases so that the channel capacity has been reduced to one-fifth of the predicted value at individual locations within

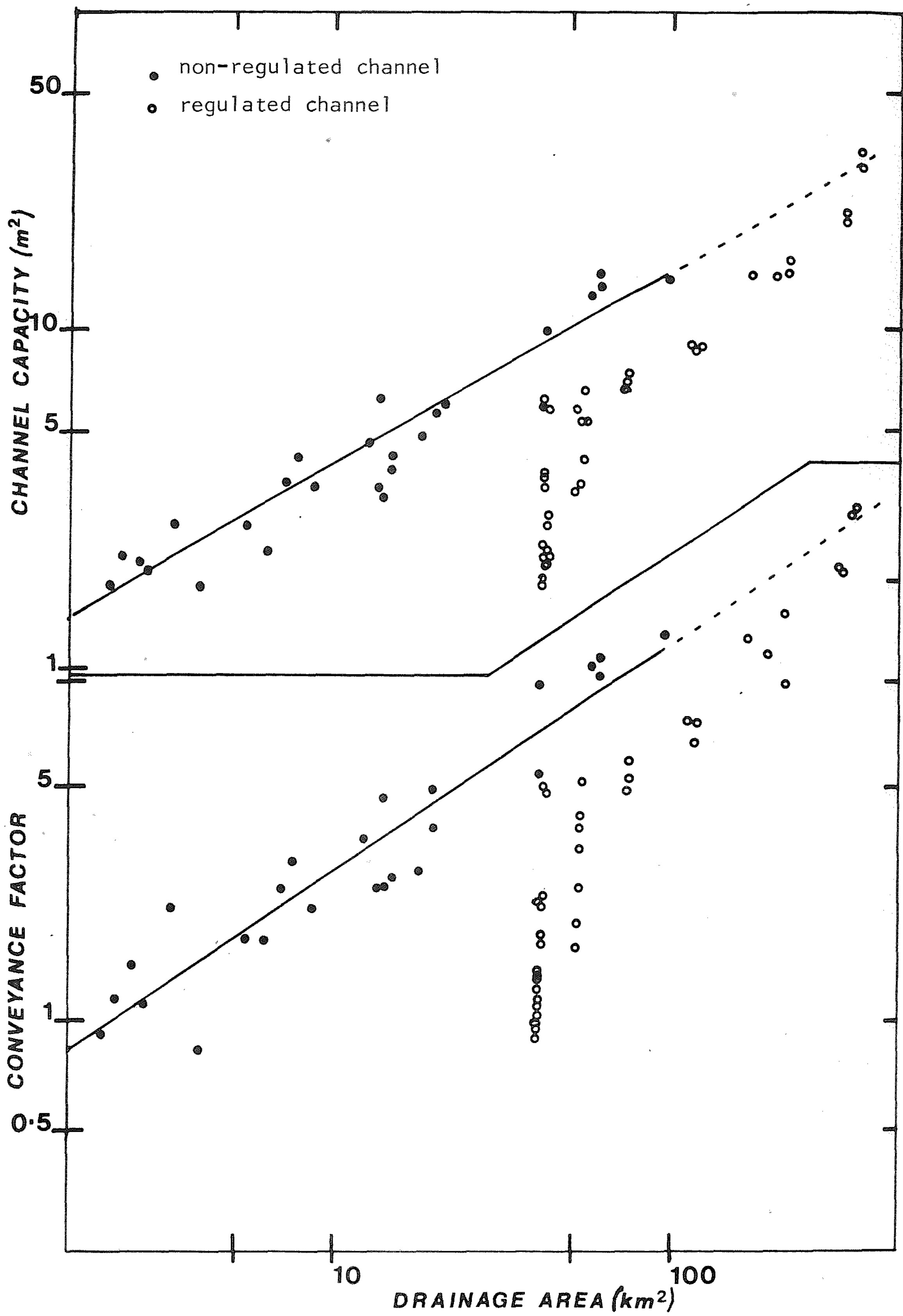

FIGURE 5.7 THE VARIATION OF CHANNEL CAPACITY AND THE CONVEYANCE FACTOR DOWNSTREAM OF CATCLEUGH RESERVOIR. (Regressions based upon the non-regulated data)

a reach between 0.2 and 1.63 km below the dam. Farther downstream the magnitude of channel change decreases progressively so that at a drainage area equal to four times the impounded catchment area, the channel capacities of individual sections along the river Rede are commonly within thirty percent of the predicted values.

Downstream from Sills Burn (Fig. 5.6) the precentage of the catchment underlain by Carboniferous Limestone rapidly increases so that the rate of increase of channel capacity with drainage area may reflect the reduction of the runoff rate. Therefore the deviation of the river Rede channel capacities from the predicted values at catchment areas greater than 136 m^2 may be over estimated. However, the superficial covering of impermeable boulder-clay may reduce the impact of the Carboniferous Limestone upon the runoff rate. Nevertheless, upstream of the Sills Burn confluence the channel capacities are commonly less than one half of the expected values.

The division of the river Rede downstream from the dam into discrete reaches may enable the identification of the factors which have influenced the rate and direction of channel adjustment. Ten reaches were identified on the basis of planform, and separated by major tributaries (Table 5.11). 'Major' tributaries were defined as those having a drainage area equal to, or greater than, 10% of the catchment area of the main stream immediately above the confluence.

The data (Table 5.12) suggests that the rate of channel adjustment is highest within the meandering reach. The erosion and redistribution of sediment during meander migration may have facilitated the reduction of channel capacity to 25% of the predicted value. The floodplain produced by channel migration is markedly lower than the general level of the valley floor from which it is separated by a definite, although small, bluff. The meander system appears to have stabilised, that is there are no signs of active erosion or deposition, so that the contemporary channel dimensions may represent a quasi-equilibrium form adjusted to the post dam closure flow regime. During the meander migration the channel sinuosity appears from the downstream situation of the bluff separating the valley floor from the contemporary floodplain, to have increased. The evidence from the literature (Chapter 2.3) suggests that this may be a response to the reduction of the calibre of the sediment load. The primary adjustment within the meandering reach has been a reduction of channel width and a decrease in the value of the width-depth ratio. This is consistent with channel changes consequent upon reservoir

Table 5.11 Identified reaches of the river Rede below Catcleugh reservoir

Reach	Drainage area (km^2)	Distance downstream (km)	Planform[1]	Tributary	Drainage area	% catchment regulated
1	41.29	0 - 0.21	s			
2	42.8	0.22 - 1.63	m			
3	43.24	1.64 - 2.50	s	Spithope Burn	9	92
4	52.44	2.51 - 3.0	s			76
5	56.15	3.01 - 6.0	s	Cottonshope Burn	16	71
6	72. - 75.24	6.01 - 8.1	s	Blakeshope Burn	18.5	55 - 53
7	95 -117	8.11 - 13.0	s	Sills Burn	19	42 - 34
8	136 -168.6	13.01 - 17.9	s	Durtrees Burn	22	29 - 24
9	190 - 219	17.91 - 27.0	s	Elsdon Brook	46	21 - 18
10	265 - 346	27.01 - 42.0	s	N. Tyne river		15 - 12

[1] s - stable m - mobile

Table 5. 12 Channel changes downstream of Catcleugh reservoir

Reach	Channel change ratios				
	Channel capacity	Conveyance factor	Width	Mean depth	Width-depth ratio
1	0.37	0.31	0.54	0.65	0.83
2	0.25	0.18	0.40	0.62	0.60
3	0.50	0.47	0.60	0.85	0.77
4	0.35	0.19	0.56	0.56	0.99
5	0.58	0.39	0.65	0.76	0.92
6	0.50	0.45	0.60	0.84	0.72
7	0.52	0.45	0.65	0.80	0.82
8	0.69	0.70	0.72	0.96	0.76
9	0.64	0.57	0.70	0.92	0.77
10	0.88	0.83	0.99	0.93	1.11

construction observed elsewhere within meander systems (Chapter 4.1). The small channel capacities and the alteration of the channel shape has resulted in conveyance factors which are less than one-fifth of those expected.

The magnitude of the observed channel change decreases downstream (Fig. 5.8) possibly in response to the increasing stability of the channel planform. In plan the channel becomes straight and the banks are well vegetated with coniferous woodland. However, immediately downstream of the Spithope Burn confluence the channel capacity is only 35% of the predicted value. The values of mean depth are lower than those within the meandering reach possibly reflecting channel aggradation effected by the deposition of sediment derived from the tributary. This is also suggested by the progressive decrease in the magnitude of channel change downstream of the confluence. Between six and twenty-seven kilometres downstream of the dam several tributaries join the mainstream and sediment derived from these sources, together with local channel migration and bank collapse, particularly within the incised sections, serve to maintain the reduced channel capacities until the catchment area has reached three times that draining to the reservoir. Downstream from the confluence of Sills Burn the contribution of runoff from the non-regulated catchment is such that the effect of impoundment upon the magnitude of peak flows may not be effective in the initiation of channel change.

Changes in the form of the channel of the river Rede downstream of Catcleugh reservoir, resulting from the alteration of the flood frequency distribution and the abstraction of the sediment load, has produced a contemporary channel whose capacity is only one-quarter of the predicted value. The evidence suggests that the rate of river channel adjustment is dependant upon the mobility of the channel in planform and the frequency of competent discharges. Previous studies indicated that the rate of channel response to runoff impoundment may be related to the surface area of the reservoir so that reservoirs of moderate size may initiate the most rapid changes of channel form. Peak discharges will be significantly reduced but not to the extent that sediment transport does not occur. Thus, although Catcleugh reservoir has a smaller surface area, in terms of the precentage of catchment area inundated, than Lake Vrynwy and Stocks reservoir, channel adjustment appears to have taken place more rapidly since dam closure. Within more stable reaches however, the rate of adjustment is slower requiring the input of sediment from non-regulated tributaries, bank collapse, and

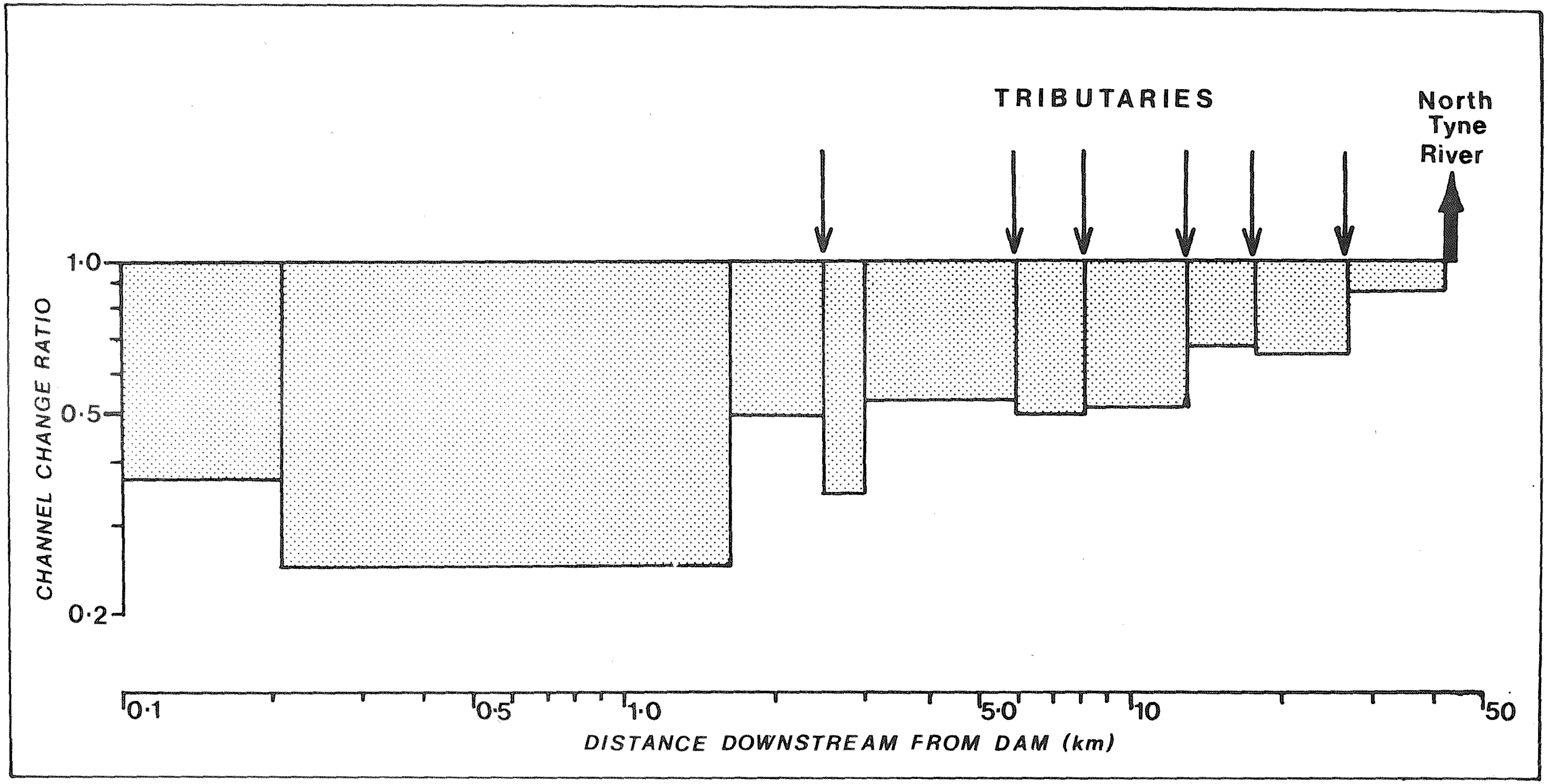

FIGURE 5.8 CHANGES OF CHANNEL CAPACITY DOWNSTREAM FROM CATCLEUGH RESERVOIR

minor planform changes during rare high discharges. Nevertheless, during the 70 years since dam closure channel adjustment has progressed downstream to a point where the non-regulated catchment area accounts for 70% of the drainage area of the river Rede.

5.4 CHANNEL CHANGES DOWNSTREAM OF LEIGHS RESERVOIR.

The studies hitherto have involved the examination of channel changes downstream from 'line of the valley' water storage reservoirs, that is reservoirs retained by a dam impounding the catchment runoff. In each case the peak flows will be reduced by reservoir lag and the attenuation of the hydrograph. However, within much of lowland England pumped storage reservoirs are often constructed, which are filled by water diverted or pumped from river and groundwater sources. Many pumped storage reservoirs are used for direct supply whilst others are designed, at least in part, to supplement the natural river discharge during summer. Pumped storage reservoirs have little or no effect upon the magnitude and frequency of peak discharges but the increase of summer low flows may have implications for the channel form. The augmentation of the natural baseflow discharge during the summer months may encourage bank erosion and channel capacity enlargement, as the rate of erosion has been related to the degree of pre-conditioning (Leopold, 1973). The examination of the river Ter downstream of the Leighs reservoir in Essex may provide evidence as to the effect of baseflow augmentation upon channel form and may illuminate the factors which constrain channel erosion.

The catchment of the river Ter is everywhere below 100 metres O.D and the river flows at a mean valley gradient of 2.78 m/km to join the Chelmer below Hatfield Peveral (Fig. 5.9). The catchment is underlain by impermeable boulder clay and although fluvio-glacial sands and gravels outcrop along the valley sides the river alluvium is bounded by the Eocene London Clay so that the catchment is an impervious unit. However, the water balance within the catchment is dominated by evapotranspiration. Indeed, Green (1970) included the catchment in one of the highest potential transpiration areas within the British Isles. The potential transpiration based upon lysimeter observations for the period between April and September 1967 exceeded 505 mm. Thus, mean annual runoff accounts for only 100 mm of the mean annual rainfall having a value of 587 mm, and the area requires irrigation in nine out of every ten years (Pearl, 1954). Nevertheless, the estimated maximum 24 hour rainfall exceeds 27.5 mm, and the mean annual flood has a value of approximately 100 cumecs per 1000 km². Furthermore, the river Ter,

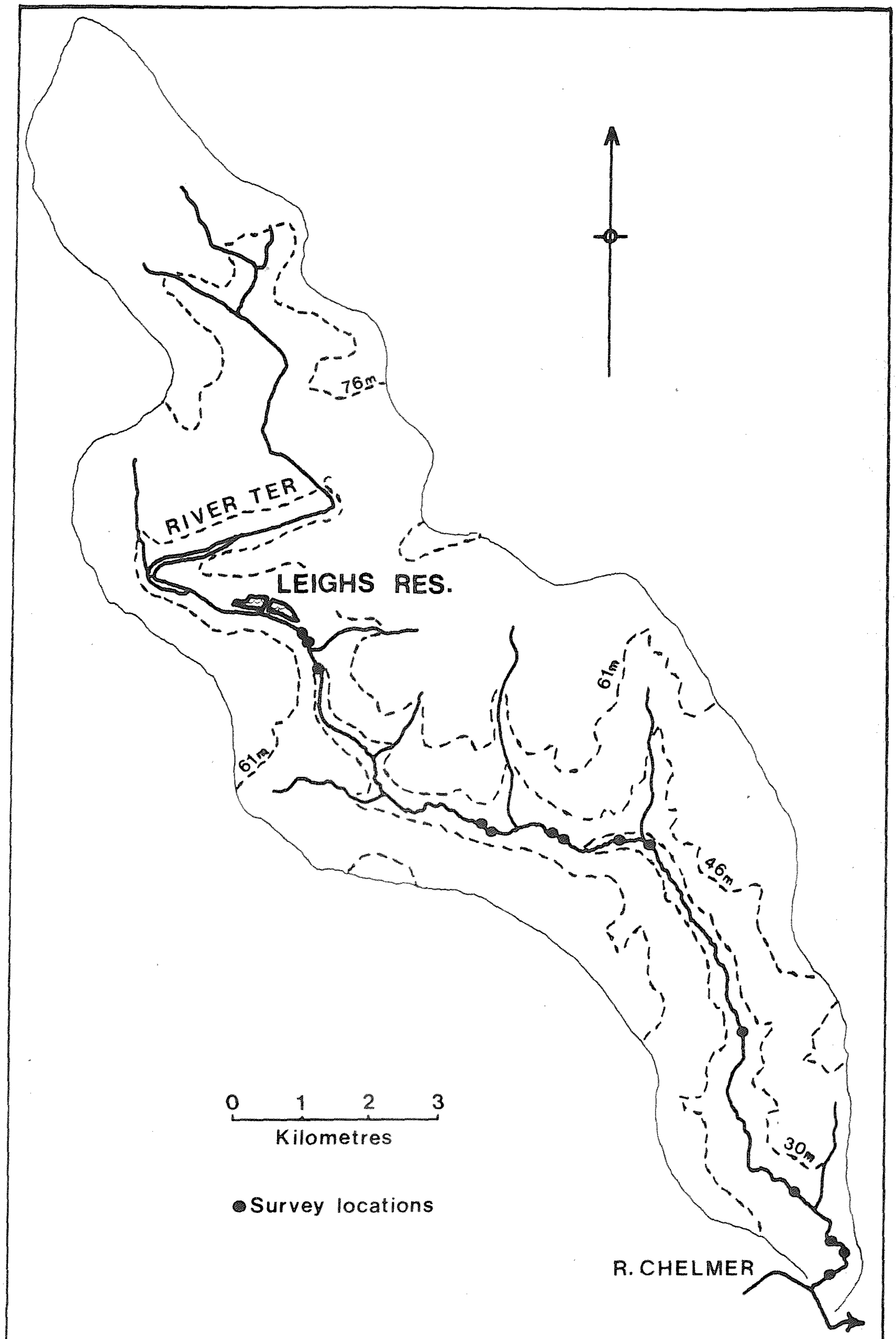

FIGURE 5.9 THE RIVER TER CATCHMENT.

draining a predominantly boulder-clay catchment, has an important peak flow component in the hydrograph, and Harvey (1969) demonstrated that under such conditions the balance between channel capacity and discharge is maintained approximately at the level of the mean annual flood. During the ten years since reservoir construction the artificial increase of summer baseflow levels may have affected bank stability and increased the susceptibility of the bank materials to erosion. The enlargement of channel capacity would occur until the fluid force is reduced to a level below that required for erosion, that is until the channel form has adjusted to the imposed regime.

The identification of channel changes along the River Ter downstream of the Leighs reservoir has been facilitated by the availability of a survey of channel cross-sections prior to reservoir construction. The channel cross-sectional form of the river Ter was surveyed during the early 1960's so that the comparison of the contemporary channel form at the same locations with the pre-reservoir forms would provide direct evidence of channel change. Although over one hundred cross-sectional surveys were included in the first survey, problems of locating these precisely and channel training along short reaches, reduced the sample to only fifteen sites. Nevertheless, the comparison of the 'before and after' data revealed major changes of channel form immediately below the reservoir.

Immediately downstream of the outlet the channel capacity has been enlarged to twice that of the pre-reservoir channel (Table 5.13), but further downstream the occurrence of channel form changes varies in magnitude between an increase of channel capacity of 107% to a decrease of 21%. Within the enlarged sections bank erosion has increased channel width by up to one metre at individual locations and mean depth is commonly more than thirty percent greater than the pre-reservoir value (Fig.5.10). The marked local variation in both the magnitude and direction of channel change downstream of the Leighs reservoirs has produced an inconsistent variation of the width-depth ratios between the different locations. However, the ratios derived from both surveys are small, ranging from between 3.9 and 7.5. Nevertheless, the alteration of channel form has increased the conveyance factor by over 150% at individual locations.

Downstream from the reservoir the magnitude of channel change generally decreases (Fig.5.11a) although considerable variation occurs between individual locations. Two factors may be of primary importance in determining the magnitude and rate of channel change

Table 5.13 Channel changes downstream from Leighs reservoirs

Distance below reservoir (km)	Channel change ratios[1]				
	channel capacity	width	mean depth	width-depth ratio	conveyance factor
0.28	1.56	1.18	1.32	0.90	1.88
0.34	2.05	1.30	1.57	0.83	2.82
0.73	1.82	1.12	1.62	0.69	2.12
5.10	1.22	1.15	1.05	1.10	1.29
6.02	1.07	1.13	0.96	1.17	1.06
7.31	1.31	1.11	0.95	1.68	1.25
7.50	2.07	1.49	1.38	1.08	2.78
8.47	0.79	0.98	0.80	1.22	0.70
8.89	1.15	0.96	1.19	0.80	1.19
12.84	1.41	1.15	1.22	0.94	1.51
15.84	1.11	1.04	1.07	0.97	1.15
16.96	1.04	1.01	1.04	0.97	1.15
16.99	1.43	1.16	1.23	0.95	1.58
17.03	0.90	0.93	0.97	0.94	0.84
17.14	1.22	1.00	1.21	1.20	1.36

[1] channel change ratios - $\frac{\text{1975 survey value}}{\text{1964 survey value}}$

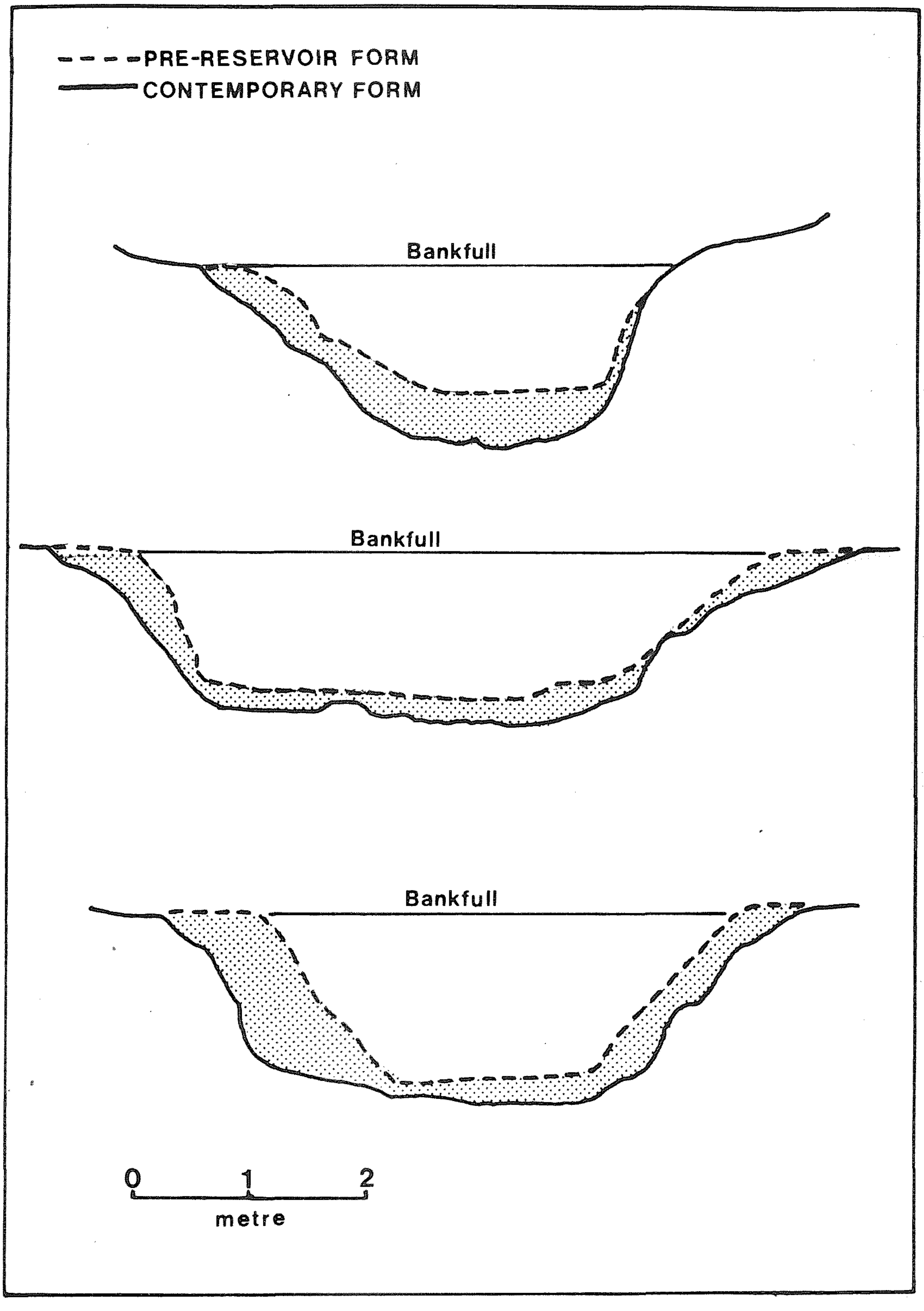

FIGURE 5.10 EXAMPLES OF CHANGES IN CHANNEL CROSS-SECTION CONSEQUENT UPON THE CONSTRUCTION OF THE LEIGHS RESERVOIRS.

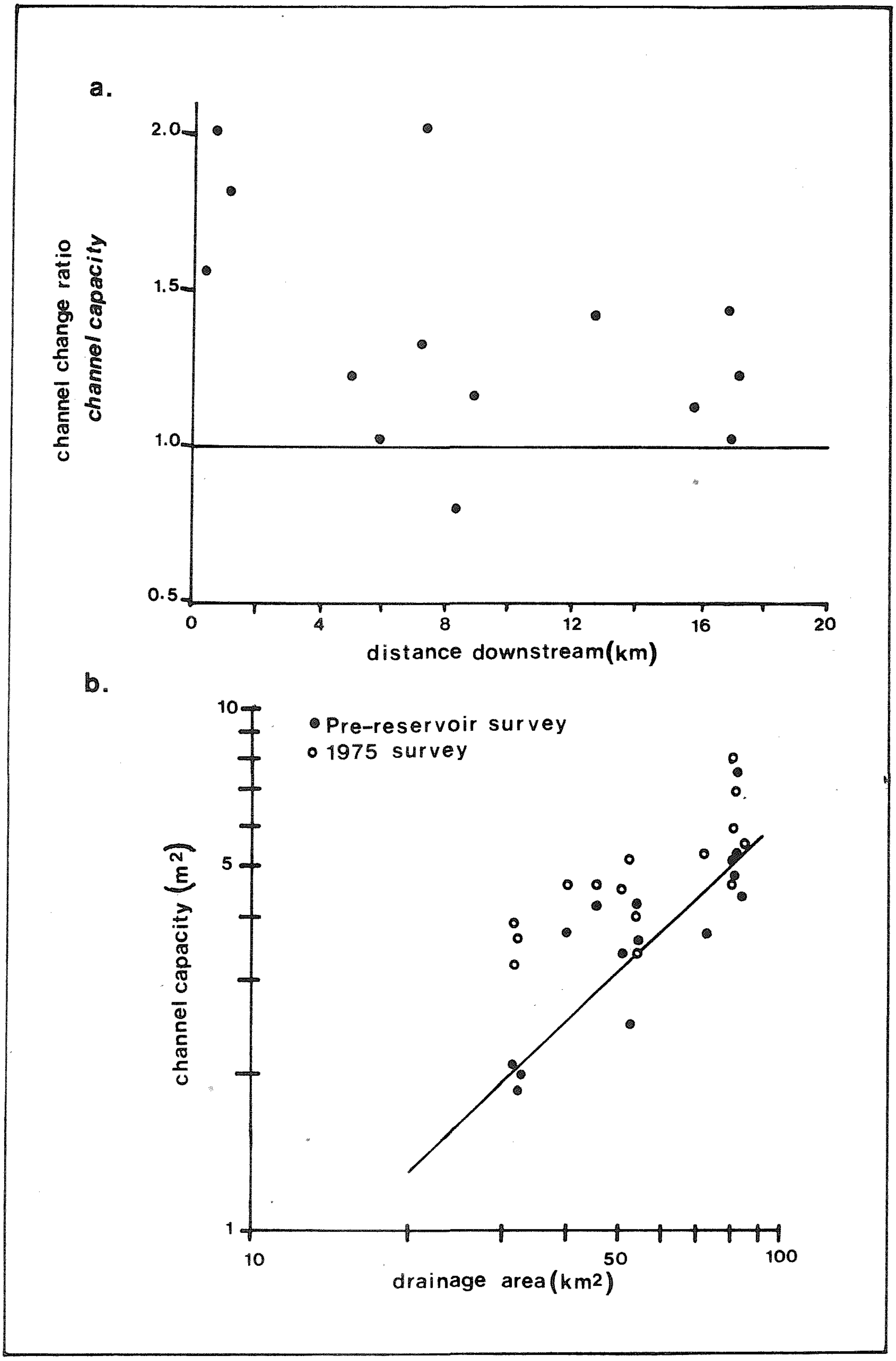

FIGURE 5.11 CHANGES OF CHANNEL CAPACITY DOWNSTREAM FROM THE LEIGHS RESERVOIRS RELATED TO MAINSTREAM LENGTH (a), AND DRAINAGE AREA (b).
(Regression based upon the pre-reservoir survey).

downstream of the Leighs reservoirs; the pre-reservoir channel dimensions and the strength of the bank materials. The strength of the bank sediments may be reflected by the percentage of silt and clay within the deposits and the insitu shear strength measured by the shear vane. Thus sediment samples were collected at each location together with three measures of shear strength, the mean being recorded. The results indicated that only a crude relationship exists between the magnitude of channel adjustment and both the shear strength and the percent silt-clay of the bank materials. Whilst the shear strength may be expected to be related, at least in part to the percent silt-clay of the bank materials the insitu shear strength of the sediments will also be related to moisture content, compaction and the occurrence of root systems. Nevertheless, the data suggests that the magnitude of channel enlargement at individual locations may be tentatively related to the strength of the bank sediments to resist erosion.

The effect of channel form variations, prior to reservoir construction, upon the rate of change may be examined by relating the channel dimensions to the general trend, that is by examination of the deviation of channel capacities at individual locations from the value predicted by a regression relationship describing the variation of channel capacity with drainage area. The comparison of these deviations with the channel change ratios for channel capacity (Fig. 5.12) indicates that, as may be expected, the smallest channel capacities prior to reservoir construction have generally undergone the greatest amount of change whilst locations having channel capacities greater than the predicted value have undergone only minor changes. However, this simple relationship is complicated by the possible division of the sites into two groups, depending upon the percentage of silt-clay within the bank materials. Locations having bank-materials containing more than 25% silt-clay demonstrated the least amount of change.

The augmentation of the natural baseflow of the river Ter during the summer months appears to have caused an increase in the channel capacity. The enlargement of the channel capacity initially by over 50% has resulted from an increase of channel width and depth. The magnitude of channel change decreases downstream as the impact of flow augmentation is reduced (Fig. 5.11b). However, the variation in the rate of adjustment may vary widely between individual locations depending on the channel dimensions prior to impoundment and possibly

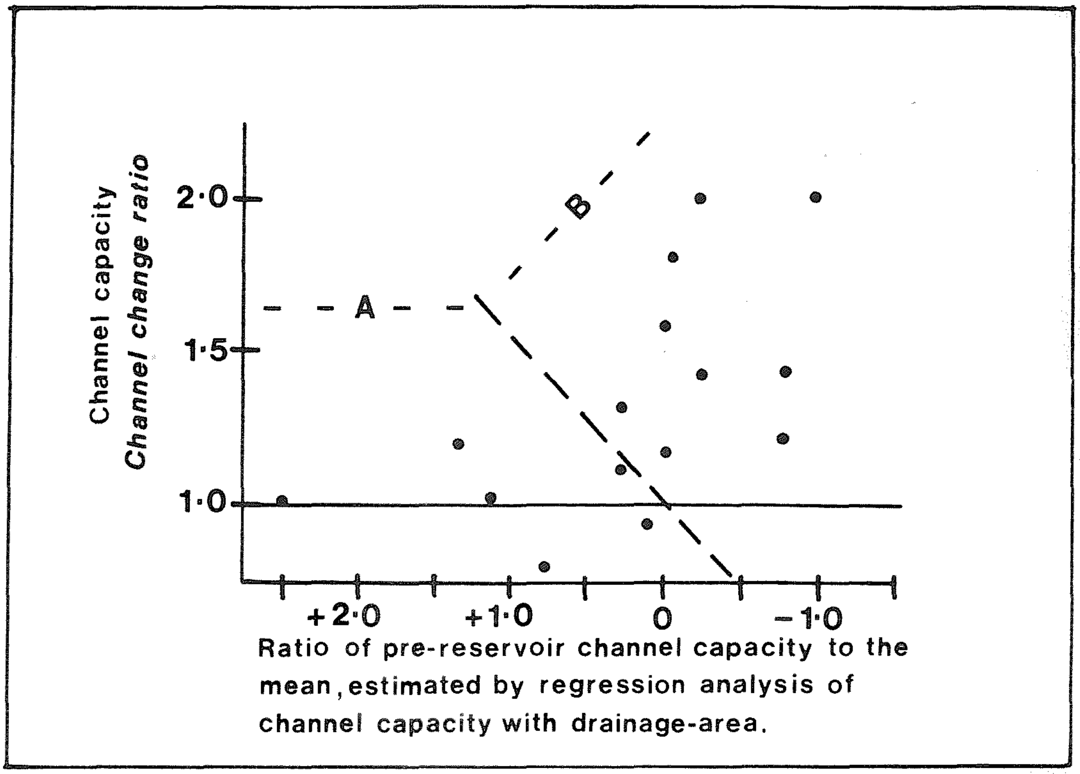

FIGURE 5.12 THE EFFECT OF PRE-RESERVOIR CHANNEL CAPACITY AT INDIVIDUAL LOCATIONS UPON THE MAGNITUDE OF CHANNEL CHANGE.

A ≑ < 25% silt-clay

B = > 25% silt-clay

the strength of the bank materials. Certainly the rate of channel enlargement is more rapid for initially narrow cross-sections as may be expected. The results suggest that the preconditioning of the bank materials by flow augmentation during the summer months increases the susceptibility of the bank materials to erosion. Although requiring further investigation this has implications for channel change downstream of the 'line of valley' regulating reservoirs. Although peak flows will be reduced by the attenuation and absorption of flood discharges within the reservoir, the release of water to augment low flows may influence the susceptibility of the bank materials to erosion at high discharges.

5.5. SUMMARY.

The information derived from the identification of channel changes downstream of Lake Vyrnwy, Stocks, Catcleugh, and Leighs reservoirs has provided evidence in support of several suggestions, introduced in Chapter 4, as to the factors which control the magnitude, direction and rate of channel response to impoundment. The quantity and calibre of sediment introduced from non-regulated sources, the stability of the channel in planform, and the dimensions of the channel form at individual locations immediately prior to dam closure have been illuminated as important variables. Furthermore, the studies provide support for the application of regression equations based upon control data to the identification of channel form changes in response to the alteration of the flow regime.

Downstream of the three 'line of the valley' reservoirs channel capacity has been markedly reduced (Fig. 5.13) in response to the lag and attenuation of peak flows within the reservoir. However, the magnitude of channel change identified at the time of survey does not appear to be directly related to the size of the reservoir. Channel capacities downstream of Lake Vyrnwy and Stocks reservoir are approximately 50% of the respective predicted values but Stocks reservoir inundates a smaller area of the catchment so that the reduction of peak discharges may not be as great. Furthermore, the river Rede downstream of Catcleugh reservoir has channel capacities equal to only one-third of the expected values but the reservoir inundates only 2.7% of the catchment area.

The data derived from the river Ter downstream of the Leighs reservoirs suggests that relatively subtle changes in the flow regime may initiate major changes of channel form. The channel capacity of the

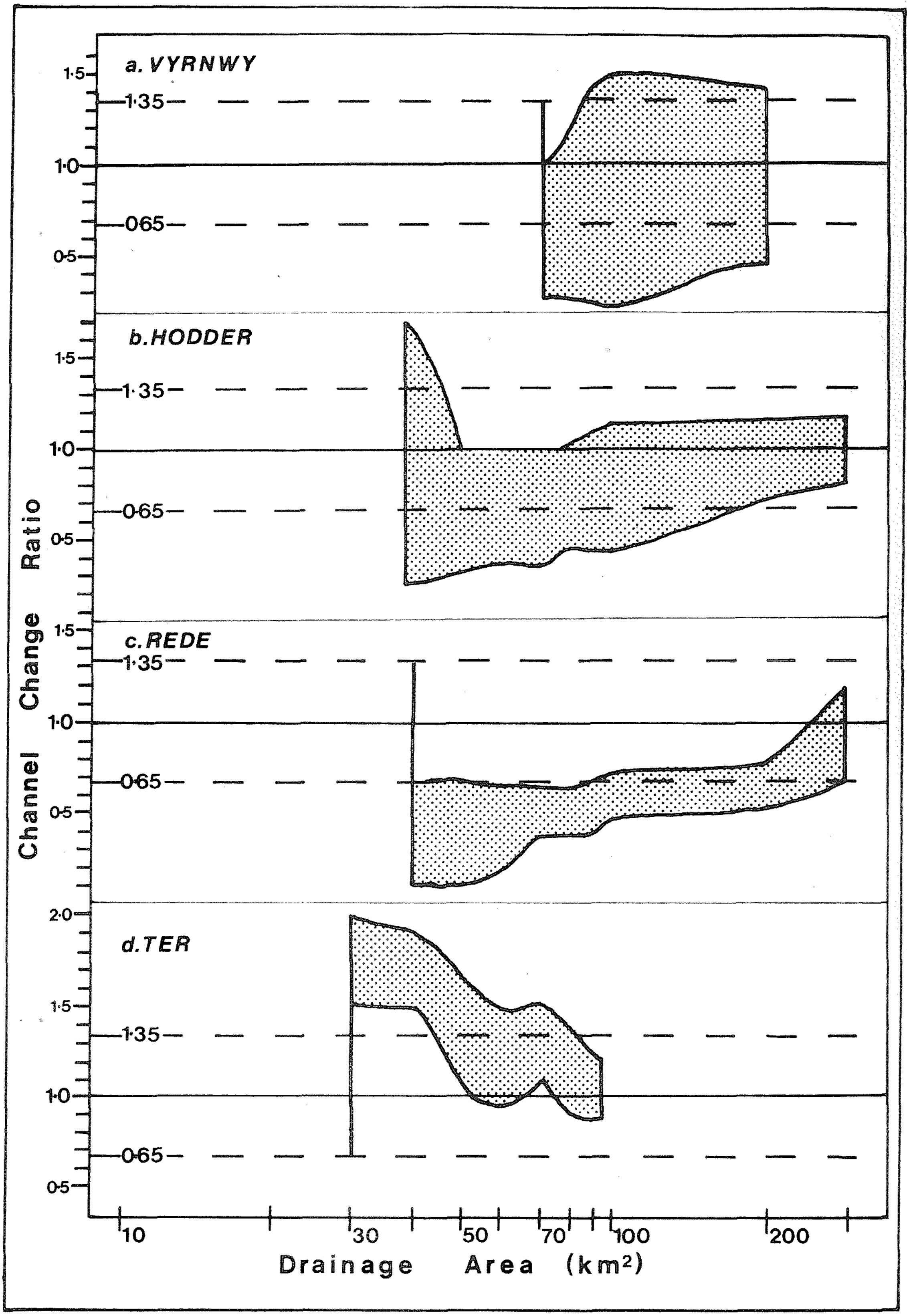

FIGURE 5.13 CHANNEL CAPACITY CHANGES DOWNSTREAM FROM LAKE VYRNWY (a), STOCKS RESERVOIR (b), CATCLEUGH RESERVOIR (c) AND THE LEIGHS RESERVOIRS (d).

river Ter has increased by 100% at individual locations since the initiation of baseflow augmentation during the summer months. Thus, the evidence tends to support the suggestion made previously (Chapter 4) that the construction of moderately sized reservoirs may have the most dramatic impact upon the channel form downstream. Although the 'threshold' reservoir size will depend upon the natural flow regime of the catchment, in general terms the larger the area of catchment inundated, the greater the reduction of peak flows, and the lower the frequency of competent discharges to erode and redistribute the channel perimeter, floodplain and introduced sediment, facilitating the adjustment of channel form.

The rate and direction of channel change at a single location will be dependant upon factors other than the magnitude of peak flow reduction. The size and shape of the pre-reservoir construction channel form in particular will be an important factor although channel slope and the calibre of the bank-sediment may also be significant. The enlargement of channel capacity and associated channel erosion along the river Ter generally occurred most rapidly at locations having the smallest channel capacities prior to reservoir construction, and the converse may be expected downstream from the 'line of the valley' reservoirs. That is, the reduction of channel capacity in response to peak flow reduction may occur most rapidly at the locations having the largest dimensions prior to dam closure and hence, lowest velocities. However, the reduction of channel capacity requires the redistribution of channel perimeter and floodplain sediments, or the introduction of sediment from a non-regulated source.

River channels having a mobile, meandering planform appear to be more sensitive to a change of the flow regime than straighter and more stable channels. Consequent upon the impoundment of the river Rede channel adjustment has occurred more rapidly within meandering sections than within the straighter, less mobile reaches, and 25 km downstream from Lake Vyrnwy channel migration has effectively reduced the channel capacity to 60% of the expected value. The rate of adjustment within straight reaches and channels having stable planforms will be related to the quantity and calibre of sediment introduced by tributaries during times of flood to a mainstream experiencing reduced flows. Although direct evidence of channel aggradation at tributary confluences has only been observed downstream from Lake Vyrnwy, this may reflect the relative magnitudes of peakflow reduction.

A high percentage of the Afon Vyrnwy headwater catchment areas is inundated and peak flows may be markedly reduced so that the mainstream discharges may not be competent to transport the sediment. Below Catcleugh and Stocks reservoirs the evidence, albeit coincidental, suggests that sediment introduced by tributaries may also initiate channel adjustment although the suspected higher frequency of competent discharges permits the differential sorting and more rapid redistribution of the sediment than downstream of Lake Vyrnwy. Chapter 6 seeks to determine the effect of the reservoirs studied upon their respective flow regimes inorder to examine the relationships between flow regulation and the magnitude, rate and downstream extent of channel form changes.

CHAPTER 6. THE IMPACT OF FLOW REGULATION UPON CHANNEL CAPACITY.

Information derived from the examination of river channel dimensions downstream of reservoirs (Chapters 4 & 5) has demonstrated that changes of channel capacity have occurred since dam closure at each of the fifteen locations throughout Britain. Changes of channel form, identified by the comparison of field data with channel dimensions predicted by the regression analysis of 'natural' control data, have reduced channel capacities to less than one-half of the expected values. Furthermore, the change of channel dimensions has reduced the water conveyance factor at individual locations to forty percent of the predicted value. The dimensions of a river channel are adjusted to the characteristics of the water and sediment discharge supplied by the drainage basin (Chapter 2.1). Reservoirs will abstract virtually the entire sediment load and the flow regime will be markedly altered. Thus, the river channel changes identified may be related to changes of the controlling variables, water and sediment discharge, consequent upon dam closure.

6.1. THE CONTROLS OF CHANNEL CHANGE BELOW RESERVOIRS IN BRITAIN.

It is generally accepted that within a drainage basin, channel size, cross-sectional shape, and planform are dependant upon flood hydrology, and the quantity and calibre of the sediment load. However, within the river system particular phenomena will reflect the influence of different independant controls at different time-scales (Schumm and Lichty, 1965). Although the separation of the time-continuum into discrete phases is impossible, in the long-term the river must be considered as an evolving system, within which the rate of downcutting, that is slope, may be the dominant control variable upon channel morphology. However, over shorter, medium-term time-spans, of several decades, slope may be viewed as being constant so that the river channel form will adjust to the runoff and sediment load provided by hillslopes and tributaries within the catchment. Despite the possible existence of equilibrium forms at moderate time scales, the morphology of alluvial channels continually responds to varying hydrological and sedimentological conditions, so that within very short time spans the river may transport sediment selectively, initiating phases of local aggradation or degradation. Thus, channel form changes consequent upon dam closure must be viewed over moderate time scales during which slope may be considered to remain constant, and channel form adjustments may be anticipated to reflect the magnitude of flow regulation and sediment abstraction.

An examination of the literature (Chapter 2.2) has revealed that several parameters describing the river flows and sediment load may be significant for the maintenance of river channel form. Those parameters relevant to river impoundment are summarised in Table 6.1. Several authors have suggested that river channel form will be adjusted to discharges of particular frequency, and Hey (1975) has demonstrated, from the field survey of the Wye, Severn and Tweed, that channels within upland gravel bed rivers in Britain may be adjusted to a discharge having a frequency of 1.5 years on the annual series. Thus, an alteration of the magnitude of the 1.5 year flood may initiate an adjustment of the river channel form. However, the operation of processes responsible for the maintenance of the channel dimensions may occur preferentially according to season (Wolman, 1959) so that the seasonal variation of flow regulation may influence channel change. Furthermore, the flow variability has been demonstrated to effect the frequency of the bankfull discharge (Harvey, 1969) so that the increase of base-flow together with the attenuation of peak discharges may also affect channel change. Harvey's observations suggest that the decrease of flow variability consequent upon reservoir construction may initiate channel adjustment to less frequent events, so that the magnitude of channel change may be less than anticipated from observations of the reduction in magnitude of high discharges of specific frequency.

The sediment load available to reaches below the dam will be markedly reduced (Chapter 2.3.2.); all the bed-load and virtually all the suspended load transported by the headwater streams will be trapped and stored within the reservoir. Furthermore, the transportation of sediment has been viewed (Kirkby, 1977) as the limiting process for channel form, so that the channel will tend towards a form which will maximise the bedload transport efficiency, both in terms of the quantity and calibre of the sediment. Thus, the frequency of the dominant discharge for channel dimensions consequent upon dam closure will depend upon the quantity and calibre of the sediment load.

Table 6.1 The effects of dam construction upon the controls of river channel morphology.

Control variable	Effect of impoundment	Relevant reservoir characteristics.
Peak flow	Reduced magnitude - individual events - annual maxima - seasonal variations	size and shape of the reservoir basin
	Altered frequency - specific events - above threshold - seasonal variations	area of impounded catchment inundated - reservoir surface area
Flow variability	Base-flow increased Reservoir 'lag'	outflow coefficient - length of spillweir
Sediment load	Reduction of sediment calibre and quantity	operational procedures

Following impoundment the nature of the sediment load will have changed so that suspended load may predominate and the frequency of the dominant discharge for sediment transport will increase. Thus, the observed variation of channel changes downstream from reservoirs in Britain may be related to a number of hydrologic and sedimentologic parameters. Data describing the variation of sediment transport with discharge for rivers prior to dam construction is generally non-existent. However, it has been suggested (Nixon, 1959) that rivers in Britain transport relatively low sediment loads so that channel forms may be primarily adjusted to the water discharge.

6.1.1. Changes of flow regime consequent upon reservoir construction. The impoundment of rivers within Britain will result in the alteration of the flow regime in response to the reduction and redistribution of annual runoff, the decrease of flow variability, and the reduction of peak flows. These changes may initiate an adjustment of the river channel form below the dams. The effect of flow regulation upon peak flows, particularly the bankfull discharge, has the dominant, or most apparent significance to the operation of channel processes downstream. However, the evidence from the river Ter has suggested that the augmentation of summer flows may significantly alter the effectiveness of channel processes at particular discharge magnitudes.

Consequent upon dam closure a reservoir will exert an immediate effect upon the river discharge downstream. During the period that the reservoir is filling the entire runoff volume will be impounded by the dam so that only compensation flows will be available downstream. Once the permanent reservoir storage volume has filled, the reduction of total runoff will be related to the direct abstraction for water supply and to the increased time available for evaporation and seepage. Indeed, significant reductions in the volume of runoff available to reaches below a dam may occur during the summer months. This immediate impact upon the flow regime is exemplified by the variation of the cumulative rainfall-runoff relationship before and after the closure of the Sutton Bingham dam (Fig.6.1a). Subsequent to the filling of the permanent reservoir storage volume the cumulative rainfall-runoff relationship approached that characteristic of the pre-dam-closure situation, but during the following summer the runoff yield was again markedly reduced, reflecting the availability of storage for runoff absorption. However, the magnitude of the impact will be dependant upon local environmental and particularly climatic factors. Inorder to examine the variation of the impact of reservoir construction upon

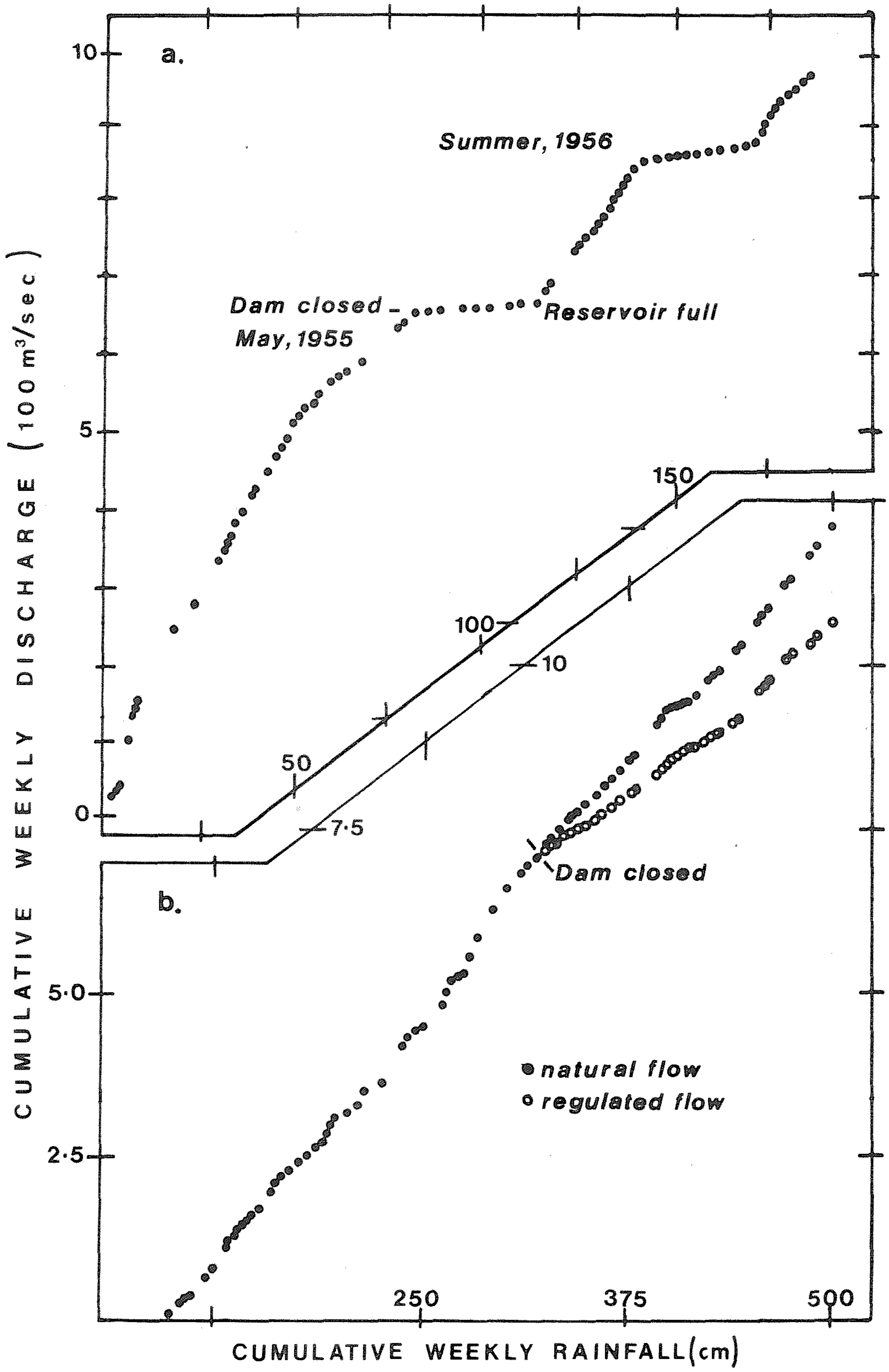

FIGURE 6.1 CHANGES OF THE CUMULATIVE RAINFALL-RUNOFF RELATIONSHIP AFTER THE CLOSURE OF SUTTON BINGHAM DAM (a), AND AVON DAM (b).

runoff yield to reaches below the dam, the impact of the lowland Sutton Bingham reservoir was compared with that of the Avon dam reservoir upon Dartmoor. Although within a similar mean annual evapotranspiration zone the mean annual rainfall upon Dartmoor is more than twice that for the Sutton Bingham catchment. Furthermore, the mean annual soil moisture deficit upon Dartmoor is less than 12mm compared to between 75 and 150 mm for the Yeovil area. The cumulative rainfall-runoff relationship for the river Avon (Fig. 6.1b) indicates that the seasonal variation of the runoff yield is less apparent for the upland catchment, reflecting the higher volumes of summer runoff maintaining the reservoir storage volume at or near top water level.

The seasonal distribution of mean daily discharges will also be altered and the evidence from the catchment studies has suggested that the increase of summer low flows may have implications for channel change downstream of the reservoirs. Examination of the difference between the estimated 'natural' discharges and the gauged flows downstream of the Avon, Sutton Bingham and Leighs reservoirs (Fig. 6.2) indicates that the baseflow discharges are increased in each case. This reflects the regulation of low flows by the provision of a compensation discharge which is generally greater than the natural low flow discharges. Although the frequency of peak discharges is reduced the magnitudes of the rare events are comparable. The evidence suggests that the effective increase of the magnitude of low flows will permit the more rapid operation of channel processes at high discharges, and may thus be an important factor for channel change downstream of reservoirs. Indeed, within semi-arid environments the initiation of a perennial streamflow has resulted in the reduction of the width-depth ratio of the Sandstone Creek channel, Oklahoma (Bergman and Sullivan, 1963). However, it is the reduction of the magnitude and timing of flood peaks which may be the major 'cause' of river channel change downstream of the 'line of the valley' reservoirs in Britain.

The alteration of the flood frequency distribution for reaches downstream of a reservoir will be effected by the permanent storage of flood discharges by 'empty-space' within the reservoir volume proper and temporary storage above the spillweir. Within a similar hydrologic and geomorphic region the storage available within the reservoir volume for flood absorption will depend primarily upon the magnitude of abstractions. Within the Mendips water for supply is abstracted preferentially from the Chew Valley Lake rather than from Blagdon 'reservoir' so that the storage available may be expected to be greater within Chew Valley Lake, and frequency of peak discharges may be

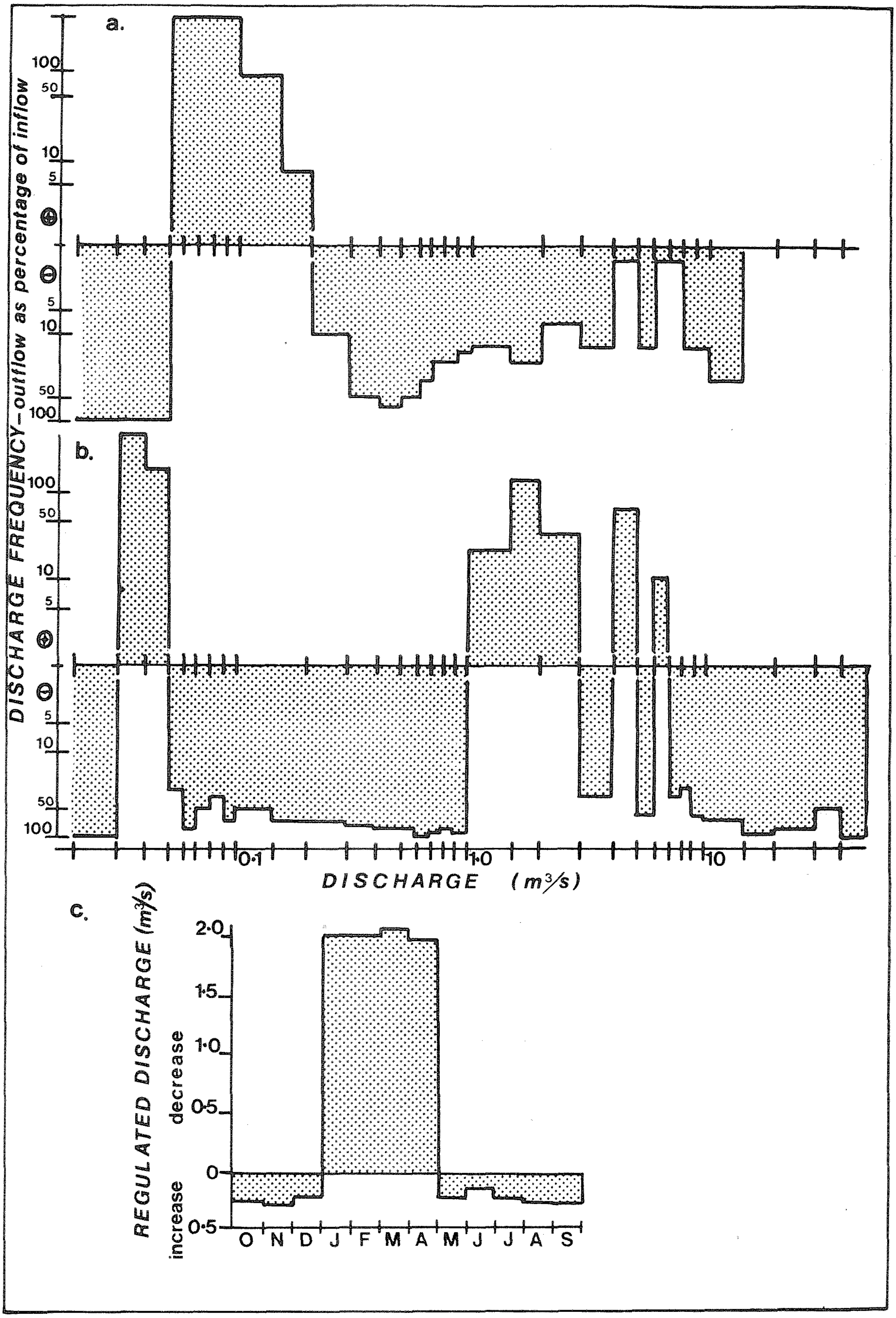

FIGURE 6.2 VARIATIONS BETWEEN THE 'INFLOW' DISCHARGES AND GAUGED 'OUTFLOWS' FROM THE AVON (a), SUTTON BINGHAM (b), AND LEIGHS (c) RESERVOIRS.

more greatly reduced. Examination of sixteen years of monthly flow data from the two reservoirs (Fig. 6.3.) indicates that Chew Valley Lake has a much greater impact upon downstream discharges than does Blagdon reservoir. Summer discharges are particularly affected. The draw-down of the water level within Chew Valley Lake during the months July to September is such that all high magnitude discharges have been absorbed by the reservoir throughout the period of record. Indeed although the storm of July 10th, 1968, caused catastrophic flooding throughout the area and Blagdon reservoir overflowed, Chew Valley Lake absorbed the flood discharge. The Lake was 0.9m down prior to the flood and rose 0.5 m, an inflow of 2.14 $10^3/m^3$, equal to 37 mm of runoff. Thus, reservoirs may be expected to have a marked effect upon peak discharges, particularly those resulting from summer storms. However, even when storage is unavailable within the permanent storage volume, peak flows may be markedly reduced.

Temporary storage above the spillweir plays an important role in reducing the maximum rate of outflow from a reservoir (I.C.E. 1933,10). The attenuating effect of temporary storage will be related to the surface area of the reservoir in particular, to the hydraulic characteristics of the spillweir and to the shape of the reservoir inflow hydrograph (Fig. 6.4). However, even reservoirs having large surface areas may have little effect upon low frequency, high magnitude storms produced by persistent high runoff (I.C.E. 1933, 20). Thus, whilst the magnitude of the more frequent flood discharges may be markedly reduced, the effect of impoundment upon less frequent, higher magnitude events may be less significant, and this may have implications for channel changes below the dam. Furthermore, the regulation of peak flows will become less effective downstream from the reservoir as the proportion of nonregulated catchment area increases, so that the magnitude of channel change may also decrease downstream. However, the evidence for channel form changes below reservoir s incorporated within this study has suggested that the rate of channel adjustment may be related to the frequency of competent discharges. Thus, below large reservoirs the rate of channel change may increase downstream, even though the magnitude of change may decrease, in response to the higher frequency of competent discharges.

The identification of changes in the magnitude and frequency of peak flow events may be readily achieved, either by the comparison of 'inflow and outflow' or 'before and after' discharge records. Problems in the interpretation of these records may arise from climatic

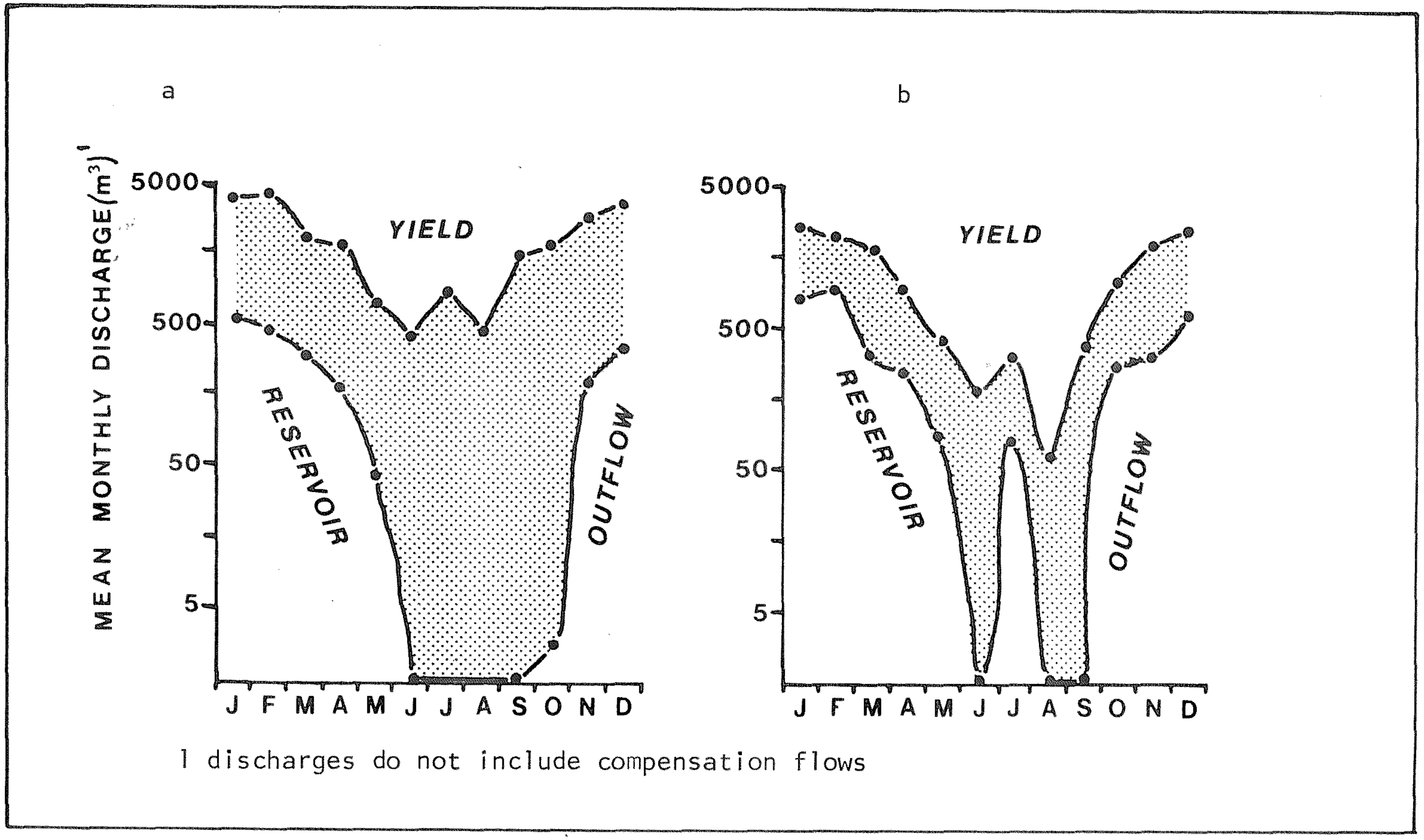

FIGURE 6.3 SEASONAL VARIATIONS IN THE CATCHMENT YIELD - RESERVOIR OUTFLOW RELATIONSHIP FOR CHEW VALLEY LAKE (a) AND BLAGDON RESERVOIR (b).

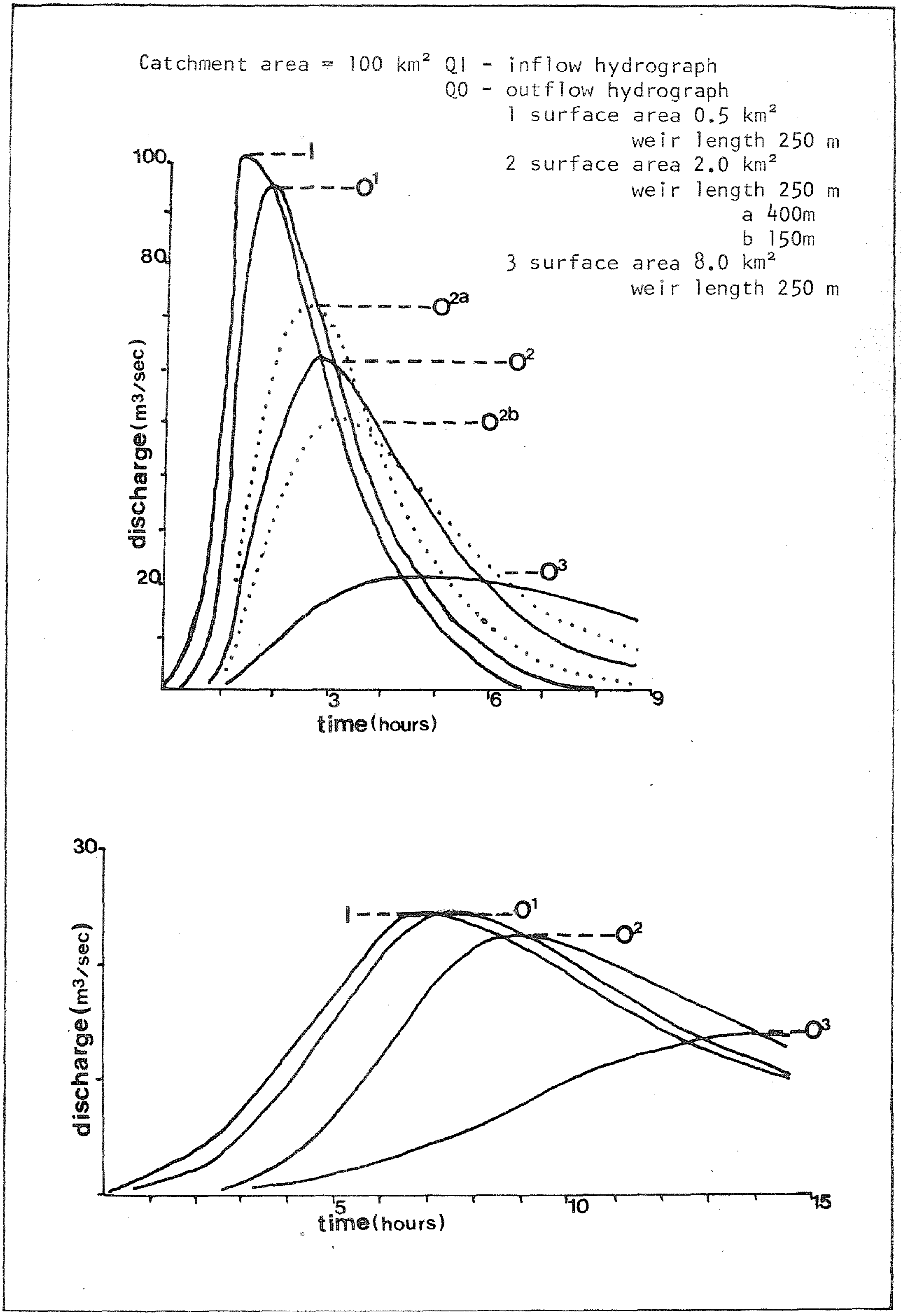

FIGURE 6.4 HYDROGRAPHS ROUTED THROUGH RESERVOIRS OF DIFFERENT SURFACE AREA AND WEIR LENGTH, WITHIN CATCHMENTS HAVING DIFFERENT FLOOD HYDROLOGY.

variations during the period of record and from changes of the catchment characteristics which control the rate of storm runoff. These problems have been detailed previously (p. 41), but the adoption of the 'inflow and outflow' comparisons may reduce the problems of interpretation.

Although adequate data describing the instantaneous variation of discharge below the reservoir are generally unavailable, flow records from three of the reservoirs included within this study may be employed to identify changes within the flood frequency distribution consequent upon reservoir construction. Detailed flow records exist for the river Hodder below Stocks reservoir, and the Dartmoor Avon in upland areas, and for the Sutton river downstream of Sutton Bingham reservoir within lowland Britain.

The comparison of inflow and outflow hydrographs for Sutton Bingham reservoir demonstrates the variations in the magnitude of flow reduction for individual flood hydrographs that may occur depending upon the volume of permanent storage available for flood-wave absorption (Fig. 6.5). In hydrograph (a) a considerable permanent storage volume was available prior to the first discharge peak so that the high flows were absorbed and spillweir discharge did not occur until the recession limbs of the third peak flow. However, under conditions of higher antecedent runoff (Fig. 6.5b) the reservoir storage was at spillweir level prior to the arrival of the flood-wave so that the magnitude of peak flow reduction was related to reservoir 'lag'. The third hydrograph (Fig. 6.5c) describes the effect of one operational procedure adopted to improve flow regulation. The operation of scour valves, inorder to reduce the level of permanent storage within the reservoir, produced a higher discharge peak than under natural flow conditions. Nevertheless, the absorption and attenuation of flood discharge may markedly reduce flow variability downstream of the reservoir.

The analysis of discharge data from the river Hodder may prove to be particularly revealing as records of river flows and rainfall are available for periods before and after reservoir construction. The data (Fig. 6.6.) demonstrate that the frequency of discharges above 5 m^3/sec has been reduced since dam closure. Furthermore, the data suggest that the frequency of rain-days above 20 mm has increased together with the natural flow variability during the post-dam-closure period. Thus, the detailed examination of changes in the flood-frequency distribution was based upon the comparison of reservoir inflow and outflow records.

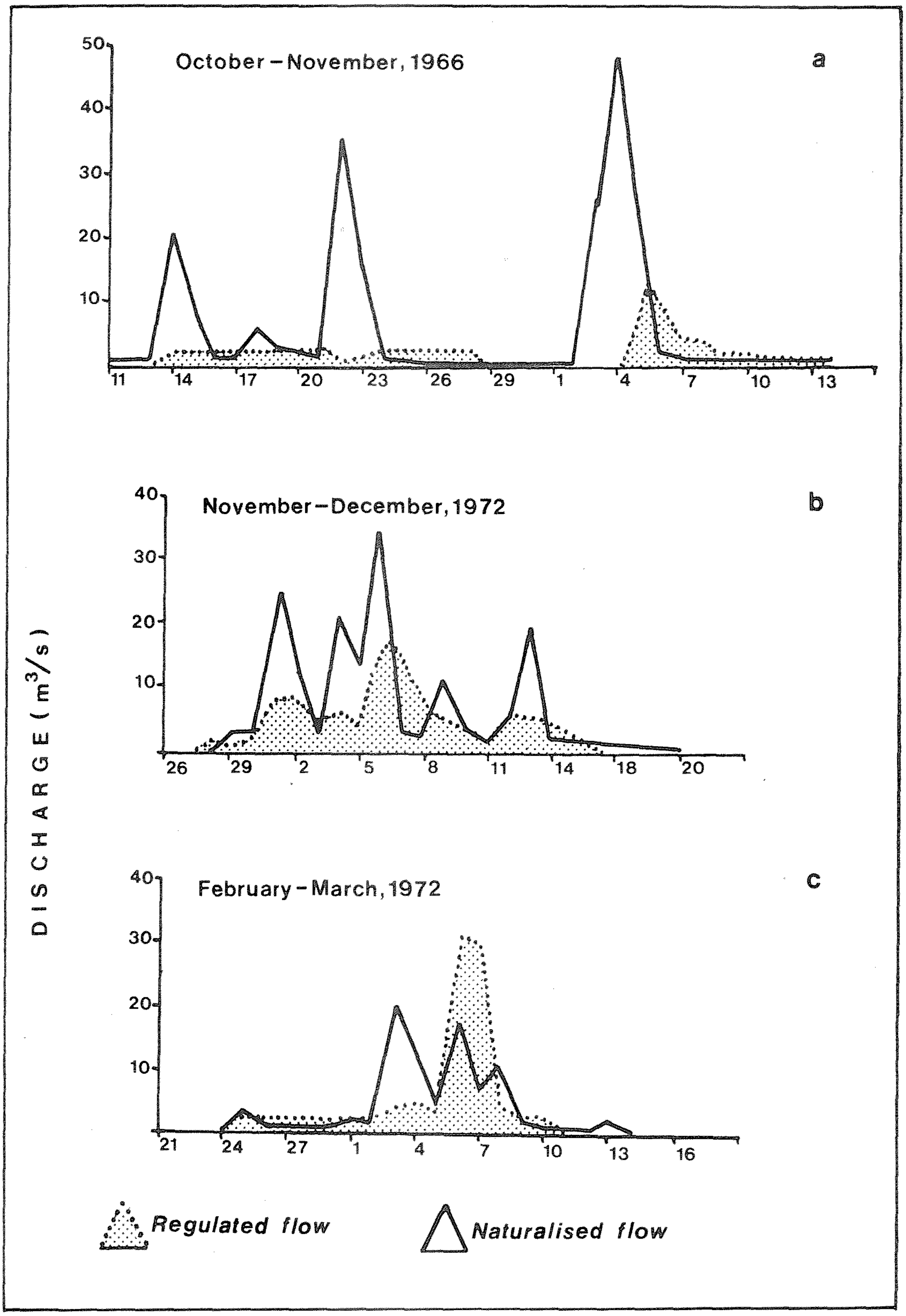

FIGURE 6.5 EXAMPLES OF NATURALISED AND REGULATED FLOW HYDROGRAPHS BELOW SUTTON BINGHAM RESERVOIR

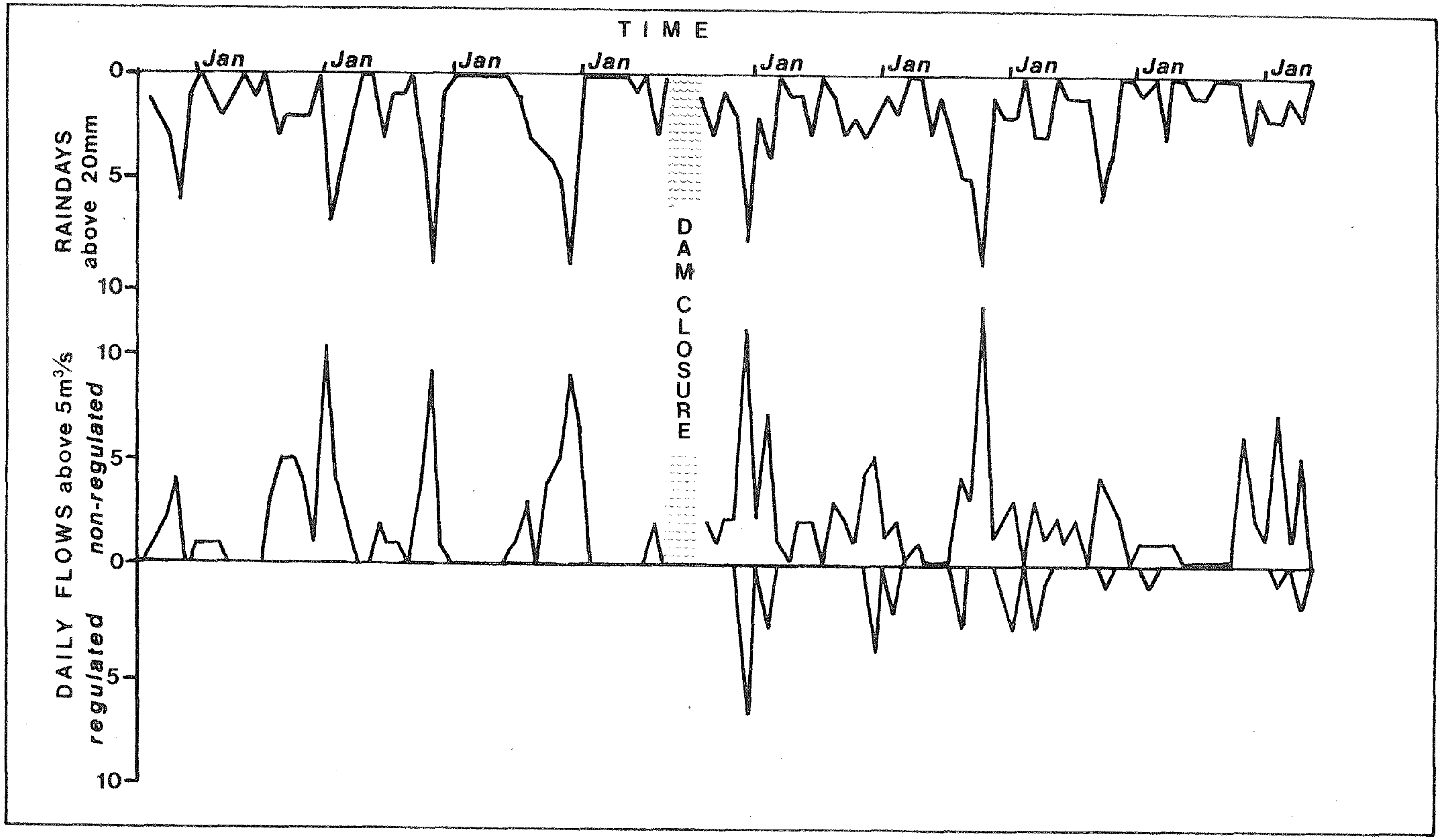

FIGURE 6.6 THE CHANGE OF THE 5 cumecs DISCHARGE FREQUENCY CONSEQUENT UPON THE CONSTRUCTION OF STOCKS RESERVOIR.

The frequency of discharges above the selected threshold since reservoir construction suggests that the summer peak discharges in particular have been reduced. Inorder to examine the effects of reservoir construction upon the flood frequency distribution. The annual exceedance series (Chow, 1964) was used, rather than the annual series, so that several independent exceedances may be included within one year. The separation of the flood frequency distribution may reveal the different effects of flow impoundment upon winter and summer discharges. Comparison of the reservoir inflow and outflow data (Fig. 6.7) demonstrates that the frequency distribution produced for the winter months are closely comparable, but the magnitudes of summer flows of particular frequency differ considerably. The magnitude of the 5 year flood downstream of Stocks reservoir, from the winter records, is reduced by only 8%, but the reduction of the flood indicated by the summer data approaches 50%. During the summer, often the period of most intense rainfalls, a volume of permanent storage is often available within the reservoir permitting the absorption of flood discharges. During the winter, however, the reservoir may be at or near spillweir capacity so that the reduction of peak flows will be dependant upon the attenuating effect of storage above the spillweir, although the draw-down of reservoir storage may be deliberately achieved inorder to increase flood control.

The apparent seasonality of peak flow reduction may influence the effectiveness of channel processes (Wolman, 1959) and may therefore be significant for channel change. Indeed, Richards and Wood (1977) suggest that since the effect of the reservoir on flood magnitudes is less apparent in winter, channel changes downstream may be less than anticipated. However, downstream of the 'line of the valley' reservoirs included within this study the dominant change of channel form has been a reduction of channel capacity associated primarily with the deposition of sediment supplied by non-regulated tributaries and channel migration generally within gravel floodplain sediments. Thus, the preferential occurrence of factors influencing the erosion of bank sediments containing a high percentage of silt and clay in winter may not be an important factor for changes in channel form downstream of 'line of the valley' reservoirs. Nevertheless, downstream of pumped storage reservoirs, which have little effect upon flood magnitudes, the augmentation of low flows may increase the moisture content of the bank-sediments permitting increased bank erosion and higher rates of channel migration.

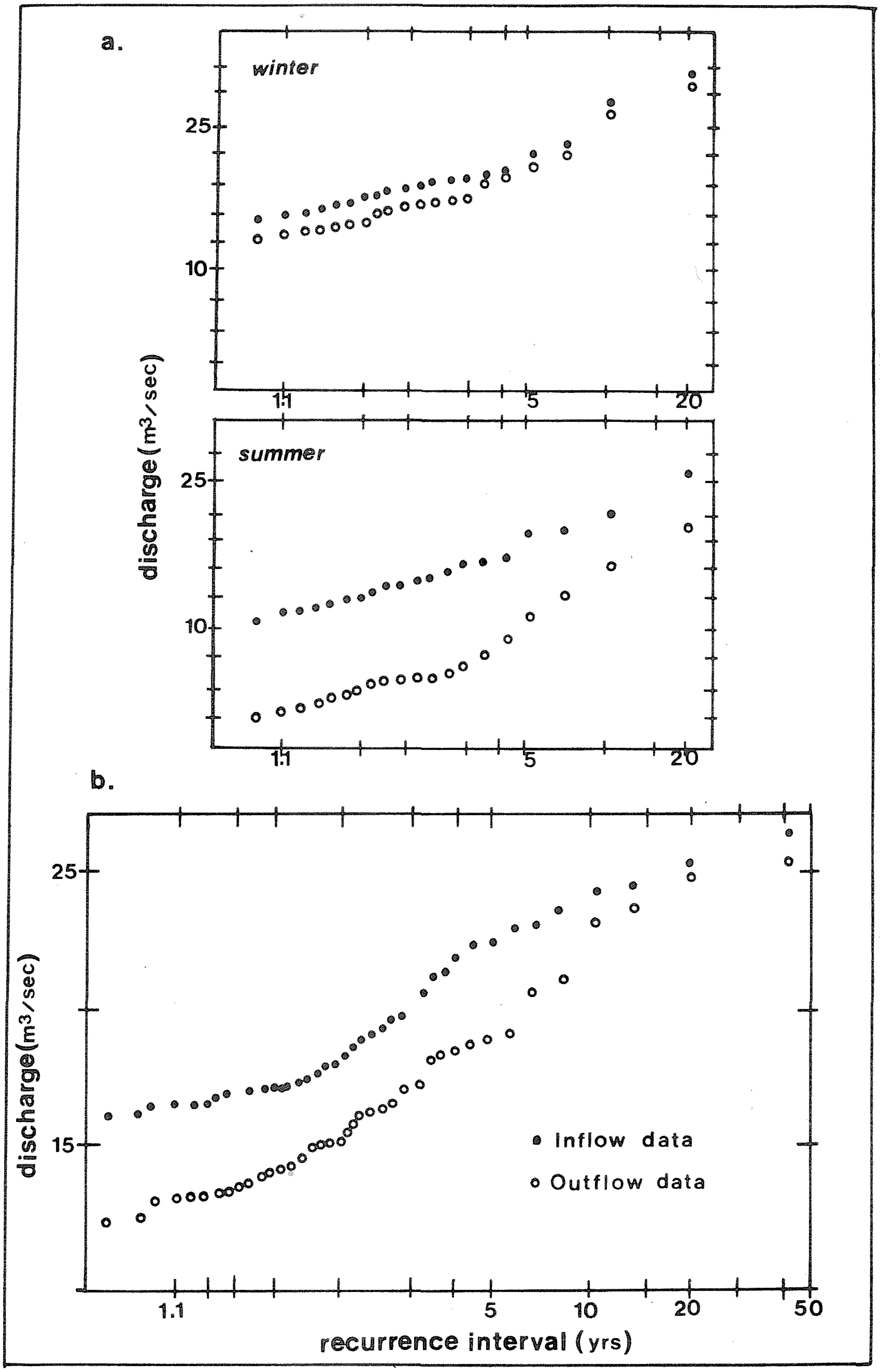

FIGURE 6.7 SEASONAL (a) AND ANNUAL (b) FLOOD FREQUENCY DISTRIBUTIONS OF THE INFLOW TO, AND OUTFLOW FROM, STOCKS RESERVOIR.

River channels downstream of reservoirs in Britain may be expected to adjust to the reduction of the frequency of peak discharges. However, the examination of the annual flood frequency distribution for the river Hodder (Fig. 6.7c) indicates that the magnitude of the more frequent flood events will be markedly reduced but the regulation of the rarer events will be less effective. That is, as the flood frequency decreases so the magnitude of the discharge to the river downstream of the reservoir approaches the value of the reservoir inflow peak. This trend is supported by the examination of discharge records from the Dartmoor Avon and Sutton river below Avon dam and Sutton Bingham reservoirs respectively (Fig. 6.8). A given storage at a certain degree of emptiness might completely absorb a low magnitude, more frequent events, yet have an insignificant effect upon a rarer event of higher magnitude. Therefore, the reservoir outflow flood frequency curve tends to be considerably below the inflow flood frequency curve for more frequent events, and approaches it more closely for the rarer events.

Downstream from a reservoir the reduction of peak flows decreases as a progressively smaller fraction of the total catchment is impounded. Spatial variations of the catchment permeability, relief, and the form of the drainage network are also important. Smith (1972) has described the effect of the January, 1960 flood peaks upon the Derbyshire Derwent. Three floodpeaks caused by heavy rainfall were absorbed by the reservoir before overflow occurred. Immediately below the dam the two largest flows were reduced by a total of 94.1 m^3/s whilst at Matlock, approximately 30 km downstream, the reduction was only 57.5 m^3/s. Nevertheless, had the proposed flood drawdown curve for Ladybower been operated in 1965 the flooding of Matlock to a depth of 1.8 m would have been prevented (Richards and Wood, 1977). Thus, although the tributary catchments of the river Derwent are underlain by permeable lithologies, the evidence suggests that flood regulation may be achieved for some distance downstream from reservoirs.

The determination of the variety of effects that reservoir construction may have upon instantaneous peak discharges within the catchments studied, required, in the absence of universally compatible discharge records, the theoretical routing of flood hydrographs. For each catchment characteristic hydrographs for comparable short duration storm rainfalls following a prolonged period of precipitation, that is under conditions of near minimum soil moisture deficit, were routed through the reservoirs. The computation of the reservoir outflow hydrographs was based upon the Fortran Flood Routing Programme outlined

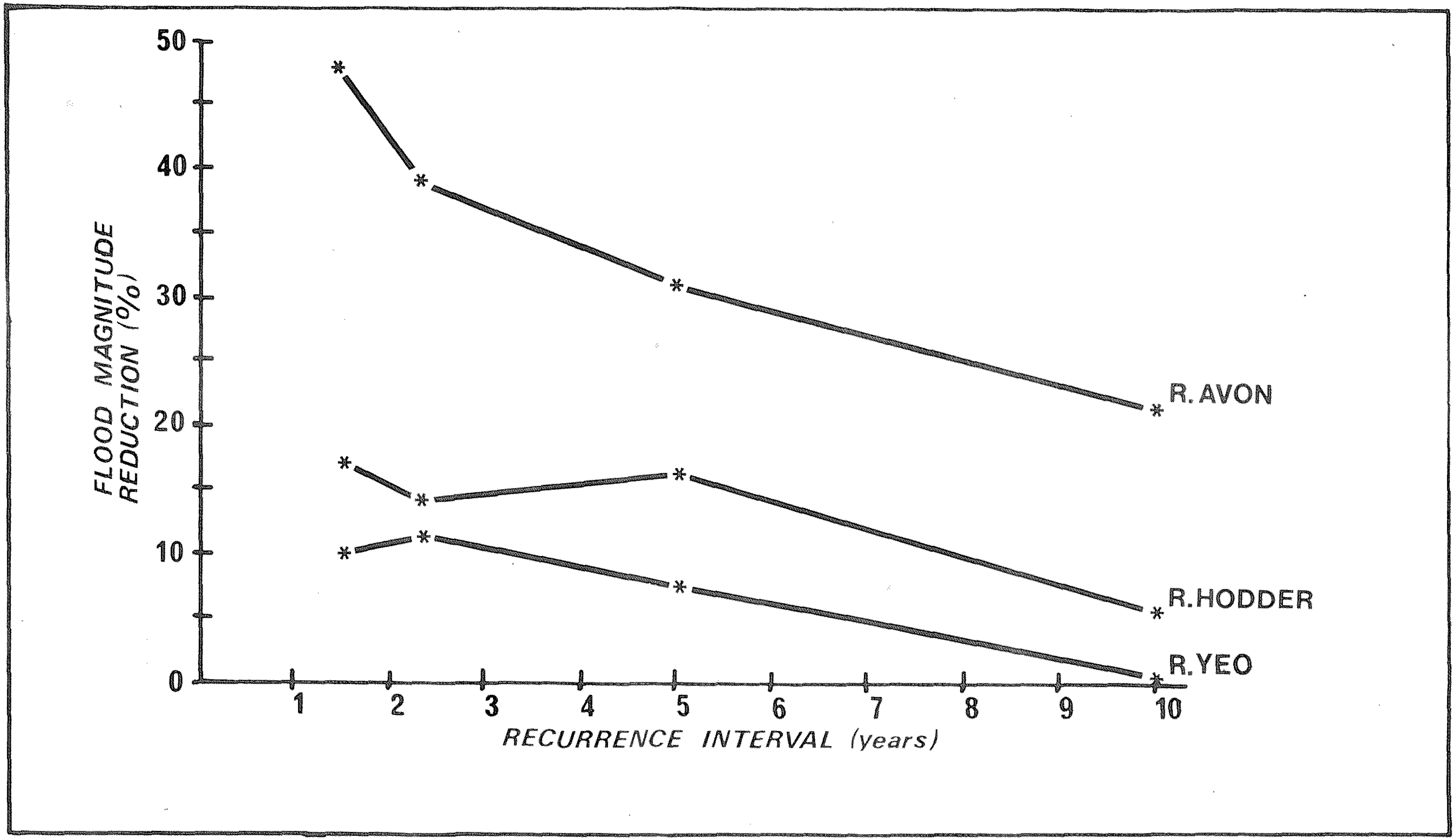

FIGURE 6.8 THE VARIABILITY OF PEAK FLOW REGULATION ACCORDING TO THE RECURRENCE INTERVAL OF THE EVENT.

in the 'Flood Studies Report' (N.E.R.C., 1975, vol.1. Section 7.4.2.). The comparison of the reservoir inflow and outflow hydrographs (Table 6.2) demonstrates the variety of effects that a reservoir may have upon the magnitude of peak flow, and upon the time to peak of the hydrograph when zero permanent storage is available. Thus hydrograph changes may be related to temporary storage above the level of the spillweir. The variation in the magnitude of impact between the individual reservoirs arises primarily from differences in the proportion of the catchment inundated by the reservoirs, and the shape of the inflow hydrograph: the weir length was found to have a relatively minor effect. Thus, within similar geomorphic and hydrologic regions the variation in the magnitude of channel form changes may reflect the different surface areas of the reservoirs; between regions the different rates of catchment response to storm rainfall may be the dominant factor. Furthermore, for individual floods within a single catchment, the magnitude of flow reduction will be dependant upon the antecedent conditions, which influence the shape of the inflow hydrograph. Operational procedures and the availability of storage space below the level of the spillweir will further reduce peak flow magnitudes for reaches downstream. Nevertheless, the data (Table 6.2) may provide a basis for the examination of the variation in the magnitude of channel change between impounded catchments.

6.2 CHANNEL CAPACITY ADJUSTMENT TO FLOW REGULATION

The construction of a reservoir will alter the flow regime for channel reaches downstream and the analysis of discharge records has revealed that the magnitude of individual flood peaks may be reduced to less than thirty percent of the expected value by temporary storage above the level of the spillweir. Particularly during the summer months storage available within the reservoir volume proper may completely absorb flood discharges. Although data as to the effect of impoundment upon the quantity and calibre of the sediment load are unavailable, the variety of impacts that the selected reservoirs have upon peak flows can be utilised to examine the factors influencing channel change.

6.2.1. Hypothetical relationships for channel change below reservoirs.

The subjective assessment of the evidence for channel change downstream of reservoirs in Britain (Chapters 4 & 5) has permitted the development of several hypotheses describing the adjustment of river channel capacity to impoundment. These hypotheses may provide a basic framework for the examination of the factors which control and constrain river channel change, in terms of the rate, and magnitude of response.

Table 6.2 Regulation of flood discharges downstream from selected British reservoirs

Reservoir	Proportion of catchment inundated (%)	Spillweir length. length for catchment of 1 km² (m)	Ratio of inflow-outflow hydrograph time to peak	Peak flow as % of inflow peak	Estimated peak flow reduction (%)
Fernworthy, Dartmoor	2.80	4.59	1.86	72	28
Avon, Dartmoor	1.38	3.74	1.57	84	16
Meldon, Dartmoor	1.30	3.80	1.36	91	9
Camps, S.Uplands	3.13	2.48	1.82	59	41
Daer, S.Uplands	4.33	1.42	2.21	44	56
Cowgill, S.Uplands	5.4	2.20	1.82	42	58
Leadhills, S.Uplands	4.4	1.67	2.13	53	47
Blagdon, Mendips	6.84	1.84	1.69	49	51
Sutton Bingham, Somerset	1.90	1.41	1.41	65	35
Chew Valley Lake, Mendips	8.33	0.75	2.89	27	73
Catcleugh, Cheviots	2.72	2.37	2.88	29	71
Ladybower, Peak District	1.60	1.21	2.38	58	42
Stocks, Forest of Bowland	3.70	2.44	2.09	30	70
Vyrnwy, mid-Wales	6.13	3.00	3.20	31	69

(a) Within a single hydrologic and geomorphic region, the larger the surface area of the reservoir in relation to its catchment area, that is the greater the volume of temporary storage available above the spillweir, the greater the reduction of peak flows and the greater the magnitude of channel change downstream of the dam. This relationship (Fig. 6.9a) will affect both the magnitude of channel response 'at-a-station' and the downstream extent of change.

(b) The variation in the magnitude of channel change downstream of reservoirs inundating a similar proportion of their catchment area, but within different hydrologic and geomorphic regions, will be dependant upon the shape of the natural flood hydrograph (Fig. 6.9b). As the time to peak of the natural flood hydrograph increases the effect of flow regulation by temporary storage above the spillweir decreases, so that the magnitude of channel change decreases.

The two hypotheses presented above may explain the gross variations between the magnitude of channel changes downstream from reservoirs both within and between hydrologic and geomorphic regions. However, the rate of adjustment may also vary between catchments and along individual rivers.

(c) The rate of river channel response to flow regulation and sediment abstraction will be dependant upon the frequency of competent discharges after dam closure (Fig. 6.9c). Thus, downstream of large surface area water storage reservoirs, or dams operated so as to maximise flood regulation, the rate of channel adjustment to the imposed flow regime may be markedly slower than below smaller reservoirs having a less significant effect upon the frequency of competent discharges. By implication from hypothesis (c):-

(d) Downstream of major flow regulation reservoirs the rate of river channel adjustment will increase in response to the increased frequency of competent discharges reflecting the input of non-regulated runoff. Thus, although the magnitude of channel change may be less, the rate of channel response to flow regulation may be most rapid some distance downstream of the dam (Fig. 610b). Furthermore, as the magnitude of 'at-a-station' channel change decreases and the rate of the response increases downstream, the channel may first attain a new equilibrium form at a downstream location (Fig. 610a).

The predominant channel change identified below reservoirs in Britain has been a reduction of channel capacity, supplemented within free meander systems by an increase in sinuosity. The occurrence

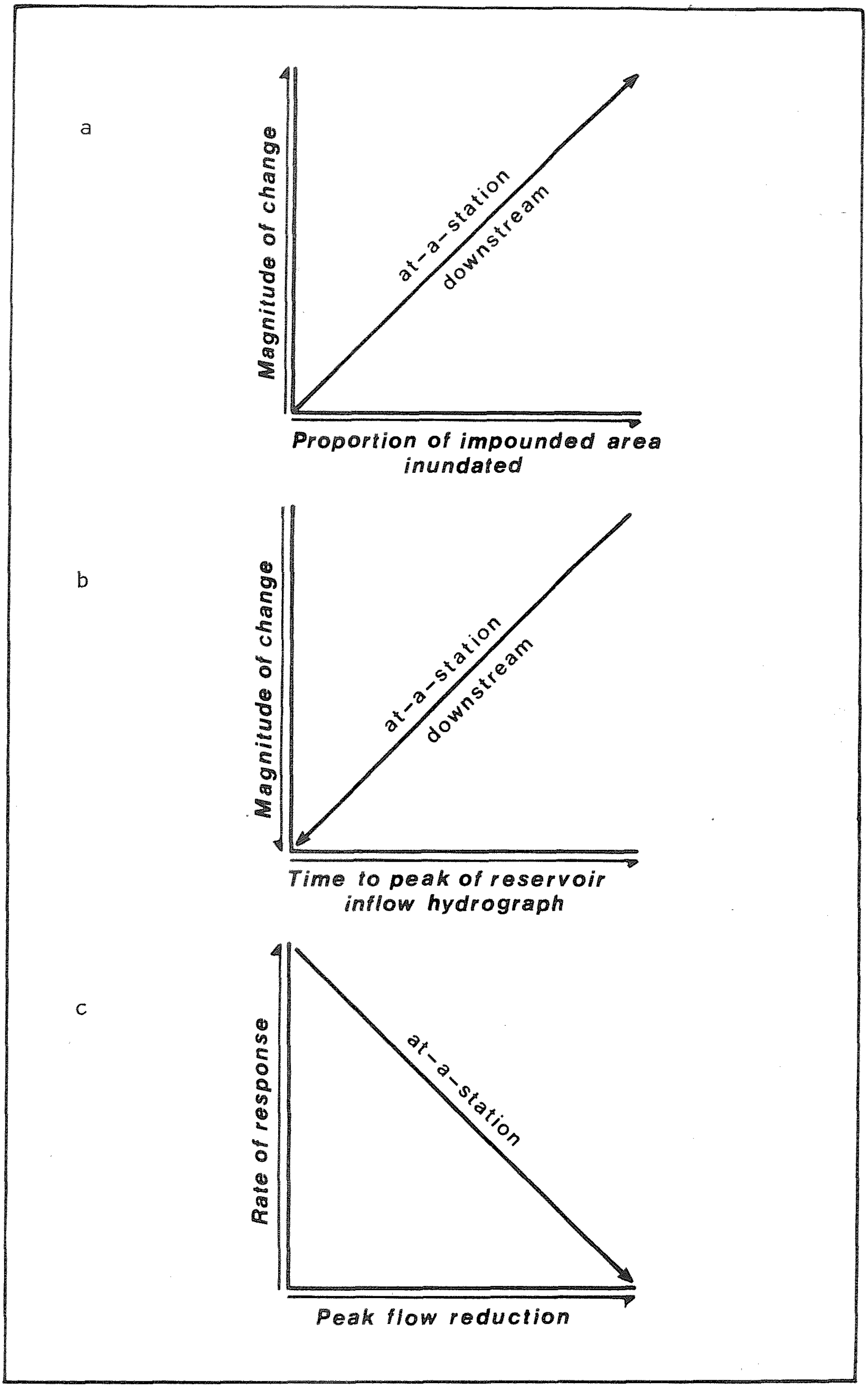

FIGURE 6.9 HYPOTHETICAL RELATIONSHIPS FOR CHANNEL CHANGE BELOW RESERVOIRS DEMONSTRATING THE EFFECT OF THE PROPORTION OF THE IMPOUNDED CATCHMENT INUNDATED (a) AND THE TIME TO PEAK OF THE INFLOW HYDROGRAPH (b) UPON THE MAGNITUDE OF CHANNEL CHANGE, AND THE IMPACT OF PEAK FLOW REGULATION UPON THE RATE OF RESPONSE (c).

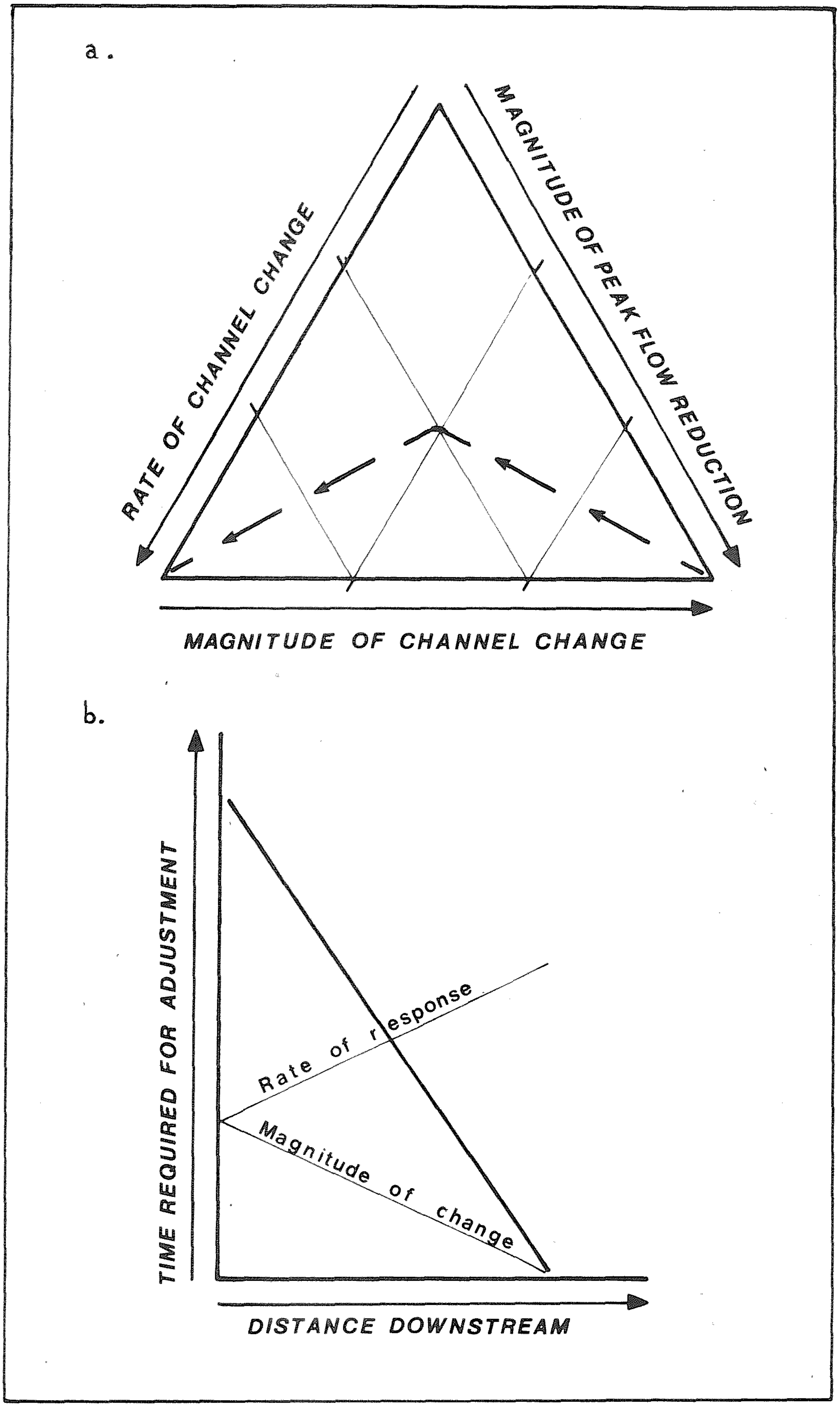

FIGURE 6.10 HYPOTHETICAL RELATIONSHIPS FOR CHANNEL CHANGE BELOW RESERVOIRS DEMONSTRATING THE EFFECT OF FLOOD MAGNITUDE REDUCTION UPON THE MAGNITUDE AND RATE OF CHANNEL CHANGE (a), AND THE DOWNSTREAM VARIATION IN THE TIME REQUIRED FOR AN ADJUSTMENT TO OCCUR (b).

of these changes at a point downstream may reduce channel slope and induce deposition upstream. Thus, the simplest case of channel response to flow regulation will involve the achievement of an equilibrium channel form by the progressive migration of a depositional front. However, in the real world situation the magnitude of channel change and the rate of response to impoundment will be controlled by geomorphic thresholds (Schumm, 1973), the state of the system prior to dam closure, and the nature of the constraints, such as channel perimeter sediment calibre, vegetation, bedrock outcrops and the quantity of sediment and runoff introduced by tributaries. Examination of the channel form data from below British reservoirs in the light of the hypotheses stated above, may illuminate the significance of these factors to channel change.

6.2.2. Parameters describing channel change below reservoirs.
Within the moderate time-span adopted for the observation of channel change downstream of reservoirs in Britain, the river channel may adjust its cross-sectional dimensions, planform dimensions and roughness. Data describing the change of channel roughness consequent upon reservoir construction are unavailable. However, evidence from the literature (Chapter 2.3) demonstrates that the channel perimeter sediment may undergo differential sorting, producing an armoured layer, and increasing the median grain size of the channel bed sediment. Thus, the lack of evidence as to changes of channel roughness may be expected to introduce a degree of unexplained variance within the relationships developed (6.2.3.)

The planform dimensions of the channels incorporated within this study are often unknown for the pre-reservoir period so that changes of channel morphology may be considered in terms of the cross-sectional form alone. Nevertheless, changes of channel capacity and shape may be anticipated to reflect the alteration of the control variables consequent upon impoundment. However, a uniform adjustment within a single reach may not be observed as short term changes of the control variables for channel form will initiate local periods of erosion and deposition. Variations of channel form from the expected will also occur as the rate and direction of response of river systems will differ between drainage basins, as channel response is complex (Schumm,1973). Thus, the examination of river channels downstream of reservoirs having different ages, at a single point in time, may complicate the isolation of the significant factor influencing channel change. Nevertheless, several parameters may be derived from the data within Chapters 4 & 5, to test the hypotheses stated previously (Chapter 6.2.1.), and these have been defined in Table 6.3.

The magnitude of channel change in response to flow regulation may be viewed in two ways; the adjustment of channel dimensions at a single location, and the downstream extent of channel change. Inorder to reduce the problem of local variations of channel form the 'at-a-station' magnitude of channel change was described by the maximum mean channel capacity change within a reach composed of three or more individual cross-profiles, hereinfafter termed REACHMAG. The downstream extent of channel change was recorded as a linear distance (DISTMAG) and as a function of the area of the catchment impounded (MAGAREA). The latter may prove to be the more significant as the downstream extent of channel change may reflect the contribution of runoff from the non-regulated catchment. Furthermore, the location of the REACHMAG was recorded in terms of the distance downstream (REACHLOC) and the percentage of changed channel length, having channel capacities reduced to less than 65% of the expected values, within the DISTMAG was determined(DOWNMAG). These latter two variables may provide evidence to support the hypothesis that channel change may occur more rapidly downstream than immediately below the dam. Also, CHANMAG, the mean channel change per unit of DOWNMAG, provides an estimate of the total amount of channel change, incorporating both 'at-a-station' changes and the downstream extent of channel adjustment.

6.2.3. Channel capacity changes downstream of British reservoirs.

The identification of the controls of river channel adjustment has suggested that downstream of reservoirs in Britain channel changes may be primarily related to the efficient removal of runoff rather than to the sediment loads which are relatively low. Examination of the relationships between the channel change parameters identified within the previous section, and variables describing the effect of flow regulation upon peak flows, may provide an insight into the validity of the hypotheses stated in Section 6.2.1.

Flow data analyses (Chapter 6.1) revealed that although suitable discharge records are unavailable for the three-quarters of the catchments investigated, three parameters are available for the description of the impact of reservoir construction upon the flow regime. Firstly, the proportion of the catchment area inundated by the reservoir may be used as a surrogate for the temporary storage available above the spillweir crest, and may provide an estimate of the potential minimum peak flow reduction for a single, short duration flood event. This parameter is easily obtainable and may explain channel change variations within individual hydrologic and geomorphic regions.

Table 6.3 Summary of available independent variables

Reservoir	Hydrologic region	Age (yrs)	Area of impounded catchment inundated (%)	Time of peak of inflow hydrograph	Estimated peak flow reduction %
Fernworthy	5	33	2.80	7	28
Avon	5	17	1.38	7	16
Meldon	5	5	1.30	11	9
Camps	5	50	3.13	12	41
Daer	5	22	4.33	14	56
Cowgill	5	71	5.4	13	58
Leadhills	5	100 +	4.4	16	47
Blagdon	3	75	6.84	39	51
Sutton Bingham	3	20	1.90	13	35
Chew Valley Lake	3	22	8.33	27	73
Catcleugh	4	70	2.72	9	71
Ladybower	4	61	2.70	7	42
Stocks	6	42	3.70	11	70
Vyrnwy	6	77	6.13	6	69
Leighs	2	11	-	-	-

The observed variation of channel response to flow regulation may be related to the shape of the natural inflow hydrograph which will effect the magnitude of peak flow reduction by temporary storage above the level of the spillweir (Chapter 6.1.1.). Thus, the time to peak of the natural hydrograph and the estimated reduction of flood-peaks derived from similar storm events (Table 6.2) were employed to examine the channel change variations between catchments.

The initial examination of the control and dependant variable data, summarized in Table 6.3 and Table 6.4 respectively, demonstrates the variation in the magnitude of change that has occurred at individual locations with the reach of maximum change for each of the catchments. Whilst within several catchments the variation is small, for example below Catcleugh reservoir the reach of maximum change has an internal variation of only 9%, downstream of Stocks reservoir the channel change ratios range from 0.16 to 0.58. Considerable variation also occurs between the REACHMAG values for the individual catchments. Channel capacities have been reduced to between 65% and 16% of the expected values below the 'line of the valley' reservoirs. Furthermore, the DISTMAG values range from just 250 metres below Blagdon reservoir to approximately 30 kilometres downstream of Lake Vyrnwy.

Examination of the relationship between the proportion of the impounded catchment inundated and the REACHMAG values (Fig. 6.11a) indicates that whilst in general terms the magnitude of channel change increases as the reservoir size increases considerable scatter exists. Indeed, the correlation coefficient for the relationship indicates that only 21% of the variation of the REACHMAG values is explained by the variation in the area of impounded catchment inundated. However, part of the variation may be explained by differences in flood hydrology between the catchments, and use of the estimated magnitude of peakflow reduction (EMPR) as the independant variable increased the correlation coefficient to 0.639 so that

$$\log \text{REACHMAG} = 1.3141 + (\log \text{EMPR}.\ 0.2439)$$

Thus, the classification of the sites within the former relationship according to hydrologic region may illuminate the significance of differences in natural runoff rates to channel change consequent upon impoundment. The data (Fig. 6.11a) tentatively suggests that the REACHMAG value may be greater within the lower runoff regions, that is, as the time to peak of the natural hydrograph increases the REACHMAG value increases. Whilst this appears to conflict with the hypotheses stated previously (Chapter 6.2.1.) two explanations are

Table 6.4 Summary of channel change data.

Reservoir	Channel capacity						Conveyance factor	
	REACHMAG %	MAGAREA	DISTMAG (km)	REACH LOC (km)	DOWNMAG (%)	CHANMAG	REACHMAG %	CHANMAG
Fernworthy	38	3.00	5.00	0.03	100	1.85	48	2.40
Avon	35	2.40	4.00	0.40	68	0.84	46	1.14
Meldon	40	1.54	6.00	4.88	20	0.48	48	0.58
Camps	54	3.27	3.80	0.25	79	1.15	60	1.57
Daer	46	2.63	11.00	0.25	45	1.63	64	2.67
Blagdon	71	1.02	0.25	0.10	100	0.18	85	0.21
Sutton Bingham	54	2.60	3.0	0.63	90	1.35	57	1.32
Chew Valley Lake	50	1.23	1.50	0.30	75	0.53	54	0.61
Catcleugh	75	3.32	13.00	0.21	32	2.46	82	2.95
Ladybower	50	1.90	9.00	4.00	56	2.40	56	2.75
Stocks	49	2.79	6.10	0.30	89	2.28	61	3.15
Vyrnwy	48	5.00	30	2.50	32	4.22	58	5.28
Cowgill	84	2.03	5.50	0.30	100	3.74	90	4.68
Leadhills	49	2.12	1.50	0.40	87	0.59	54	0.68
Leighs	58	2.00	10.0	0.34	56	3.25	85	4.90

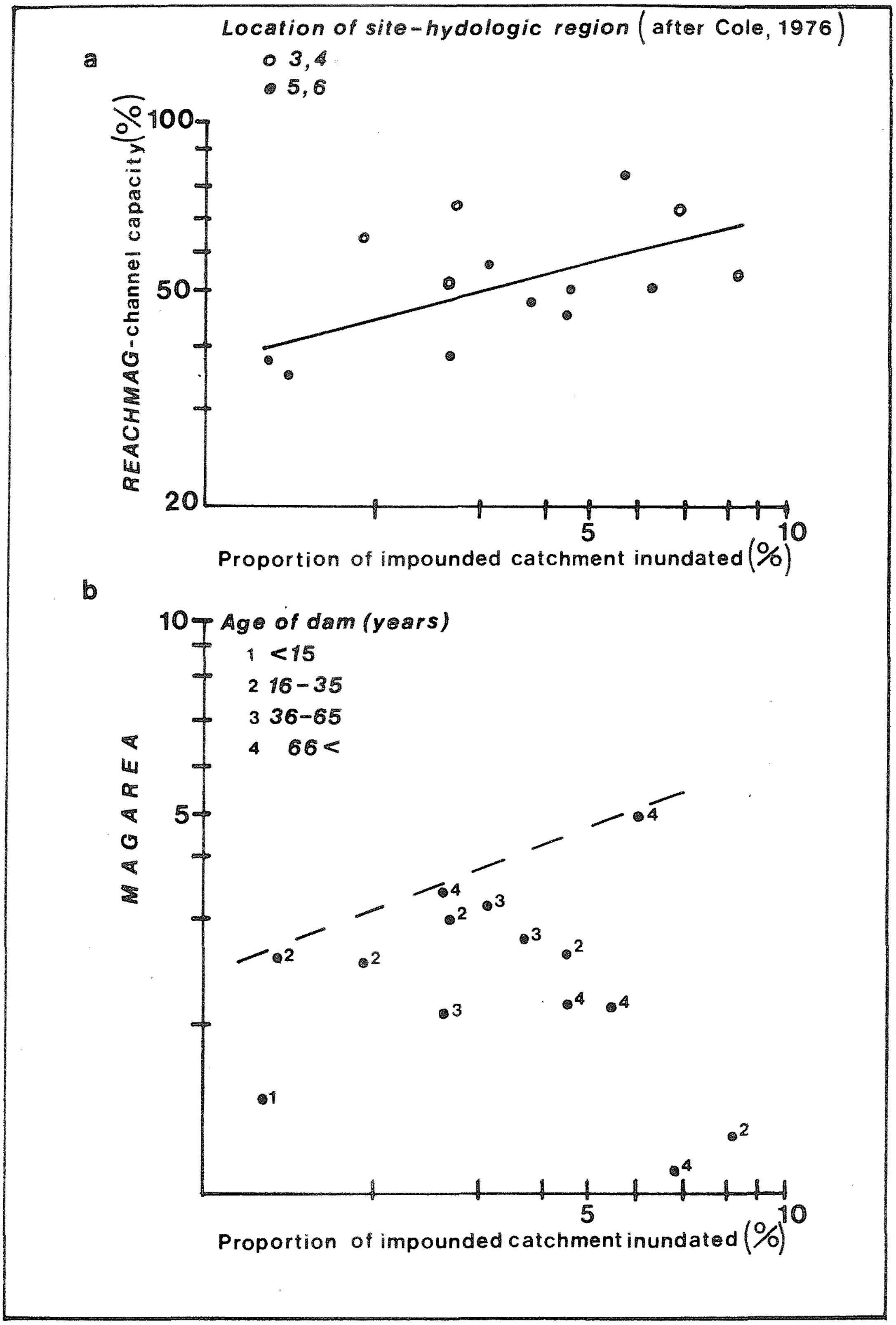

FIGURE 6.11. THE IMPACT OF RESERVOIRS INUNDATING DIFFERENT PROPORTIONS OF THEIR CATCHMENT AREAS UPON THE MAGNITUDE OF CHANNEL CAPACITY REDUCTION WITHIN INDIVIDUAL REACHES (a), AND THE DOWNSTREAM EXTENT OF CHANGE (b), DEMONSTRATING THE INFLUENCE OF AGE, AND CATCHMENT HYDROLOGY.

available. Firstly, within the lower runoff areas the reservoirs are maintained at spillweir capacity for a relatively short period of time so that a larger storage volume may be available for flood absorption than within reservoirs having a higher runoff yield. Secondly, the variation may reflect a difference in the frequency of the discharge responsible for maintaining the channel form. It has been argued (Hey, 1975) that the dominant discharge for sediment transport for rivers having a low flow variability regime may have a higher frequency than for more 'flashy' regimes. The analyses of the discharge records (Chapter 6.1.1.) revealed that the magnitude of peak flow reduction increased simultaneously with discharge frequency. Thus, natural channels adjusted to more frequent events may undergo a greater degree of change 'at-a-station' in response to flow regulation, than channels maintained by rarer events.

The limit of channel change downstream will reflect the magnitude of flow regulation, the impermeability of the catchment and the form of the drainage network in particular. Thus, the REACHMAG values were related to the MAGAREA for each catchment. The variation between sites is less pronounced than that observed using the DISTMAG values, and half of the catchments have MAGAREA values between 2.0 and 2.99, whilst the mean value is 2.49. That is, once the contribution of the regulated catchment area has been reduced to 40% the effect of impoundment on peak flows is insufficient to initiate channel change.

In detail, the downstream effect of flow regulation upon channel form is dependant upon the proportion of the impounded catchment inundated (Fig. 6.11b); as the surface area of the reservoir increases in relation to the catchment area impounded, so the extent of channel change increases downstream. The variation of the MAGAREA values may be related to differences in the rate of adjustment between the catchments. The limiting line indicated suggests the maximum downstream extent of channel change in terms of the area impounded for a particular 'size' of reservoir. Thus, over time the scatter of points may be seen to reduce as the channel progressively adjusts to the reduced discharge magnitudes. Furthermore, the classification of the data according to age (Fig. 6.11b) suggests that the rate at which a complete adjustment is achieved may be most rapid for reservoirs having relatively small surface areas. As the volume of temporary storage above the spillweir increases so the 'lag' time between the initial stimulus and the adjusted form may increase. However, the relationship will be complicated by the various impacts that reservoir construction may have upon flood hydrographs of different shapes.

The examination of the CHANMAG data which combines the magnitude of change 'at-a-station' with a measure of the downstream extent of change may permit the discrimination of the data. Indeed the relationship between the CHANMAG values and the relative surface areas of the reservoirs (Fig. 6.12a) reveals that the correlation between the two variables is affected by the shape of the natural flood hydrograph. Downstream of a reservoir having a known surface area the CHANMAG will increase as the time to peak of the natural hydrograph is reduced. Similarly, within the same hydrologic and geomorphic region, an increase of the reservoir surface area will produce a greater 'magnitude of change'.

Inorder to examine the effect of the rate of channel response, the CHANMAG values were related to the estimated value of peak flow reduction which incorporates the reservoir surface area and the time to peak of the natural hydrograph. The relationship (Fig. 6.12b) confirms the observation made previously that the achievement of an equilibrium condition will be most rapid within rivers subjected to relatively minor alterations of the flow regime. That is, for a reservoir of known age the lag time, between the crossing of an extrinsic threshold and the completion of the adjustment, will increase as flow regulation becomes more effective. Furthermore, the REACHLOC data indicates that whilst the reach of maximum change is commonly located within 500 metres of the dam, the reach is situated some distance downstream within the three catchments (Table 6.4). Downstream of the Derwent and Meldon reservoirs the REACHMAGS are the only reaches that have changed so that constraints to channel adjustement (Chapter 7) may control the location of the reach. However, below Lake Vyrnwy, inundating over six percent of the regulated catchment, the REACHMAG is located 2.5 kilometres downstream, and the reaches between the dam and this point have changed. This may provide evidence to support the hypothesis that the increase of the frequency of competent discharges downstream may initiate the most rapid response of channel form some distance below the dam. However, river channels may not only adjust their capacity but also their cross-sectional form in response to flow regulation. Thus, changes of channel shape may explain part of the variation within the developed relationships. Whilst the width-depth ratio has commonly been employed to describe channel stage, it is the length of the wetted perimeter which has the greater significance for the efficient

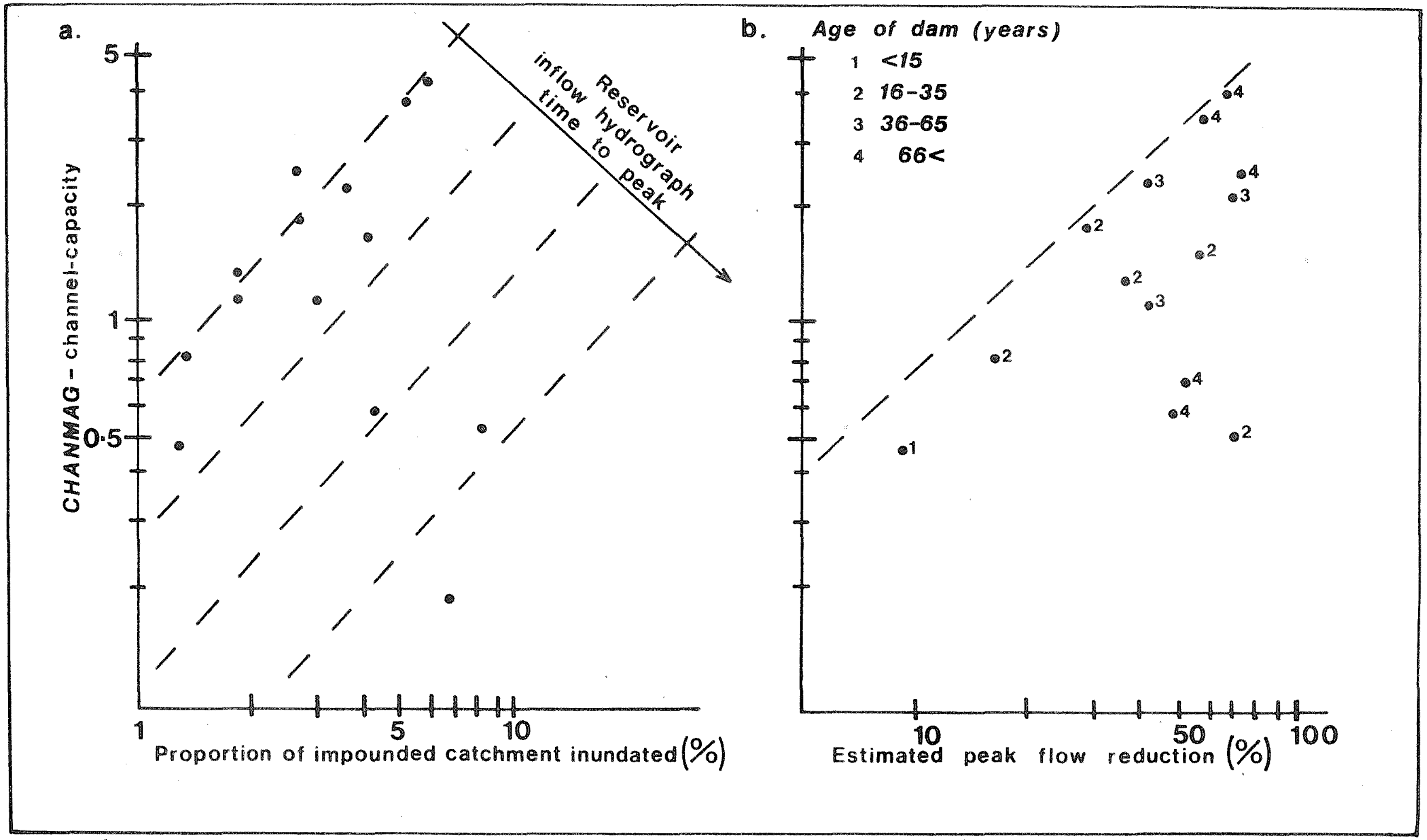

FIGURE 6.12 THE VARIATION OF CHANNEL CAPACITY CHANGES WITH THE PROPORTION OF IMPOUNDED CATCHMENT INUNDATED AND THE TIME TO PEAK OF THE INFLOW HYDROGRAPH (a), AND WITH THE ESTIMATED PEAK FLOW REDUCTION AND AGE OF THE DAM (b).

removal of runoff supplied by the catchment upstream. The examination of changes in the conveyance factor (Chapter 3.2.4.) values may, therefore, not only illuminate the significance of changes in channel shape to the maintenance of a quasi-equilibrium channel form, but also demonstrate the impact of channel changes upon the channel efficiency for water conveyance.

6.2.4. Flow regulation and channel efficiency.

The conveyance factor 'k' is a function of the channel cross-sectional area and the wetted perimeter of the channel, and, in the absence of data describing changes of channel slope and roughness, may provide the best estimate of channel efficiency changes, in terms of water conveyance, consequent upon dam closure. Indeed, the REACHMAG 'k' values (Table 6.4) indicate a higher degree of change than that demonstrated by the channel capacity data. Downstream of Cowgill, Blagdon and Catcleugh reservoirs the conveyance factor has been reduced to less than twenty-percent of the predicted values, whilst below seventy-five percent of the dams the 'k' values are less than half of those expected. Thus, the channel efficiency for water conveyance has been markedly reduced, but channels adjusted to more frequent discharges may experience an increased duration of overbank flows. The discharge records analysed indicated that whilst frequent high discharges may be greatly reduced the regulation of rarer events will be less effective.

As the conveyance factor includes a measure of channel shape as well as size the relationship between the 'k' values and parameters describing the impact of reservoir construction upon peak flows may be better defined than those relationships based upon channel capacity alone. However, the relationship between the REACHMAG 'k' values and the estimated reduction of peak flows is described by an exponent having a value insignificantly different to zero. Nevertheless, examination of the relationship between the CHANMAG 'k' values and the area of impounded catchment inundated (Fig. 6.13) tends to confirm the suggestion that for reservoirs of a given age the lag between dam closure and final adjustment will be greater as the size of the reservoir increases. This trend is particularly noticeable for channels in lowland areas having cohesive bank materials and lacking major sediment inputs, such as below Blagdon reservoir and Chew Valley Lake.

Although the relationships may have been improved if suitable discharge records were available for each of the reservoirs studied, in general the evidence presented here tends to support the hypotheses stated earlier (Chapter 6.2.1.). Within the natural environment river

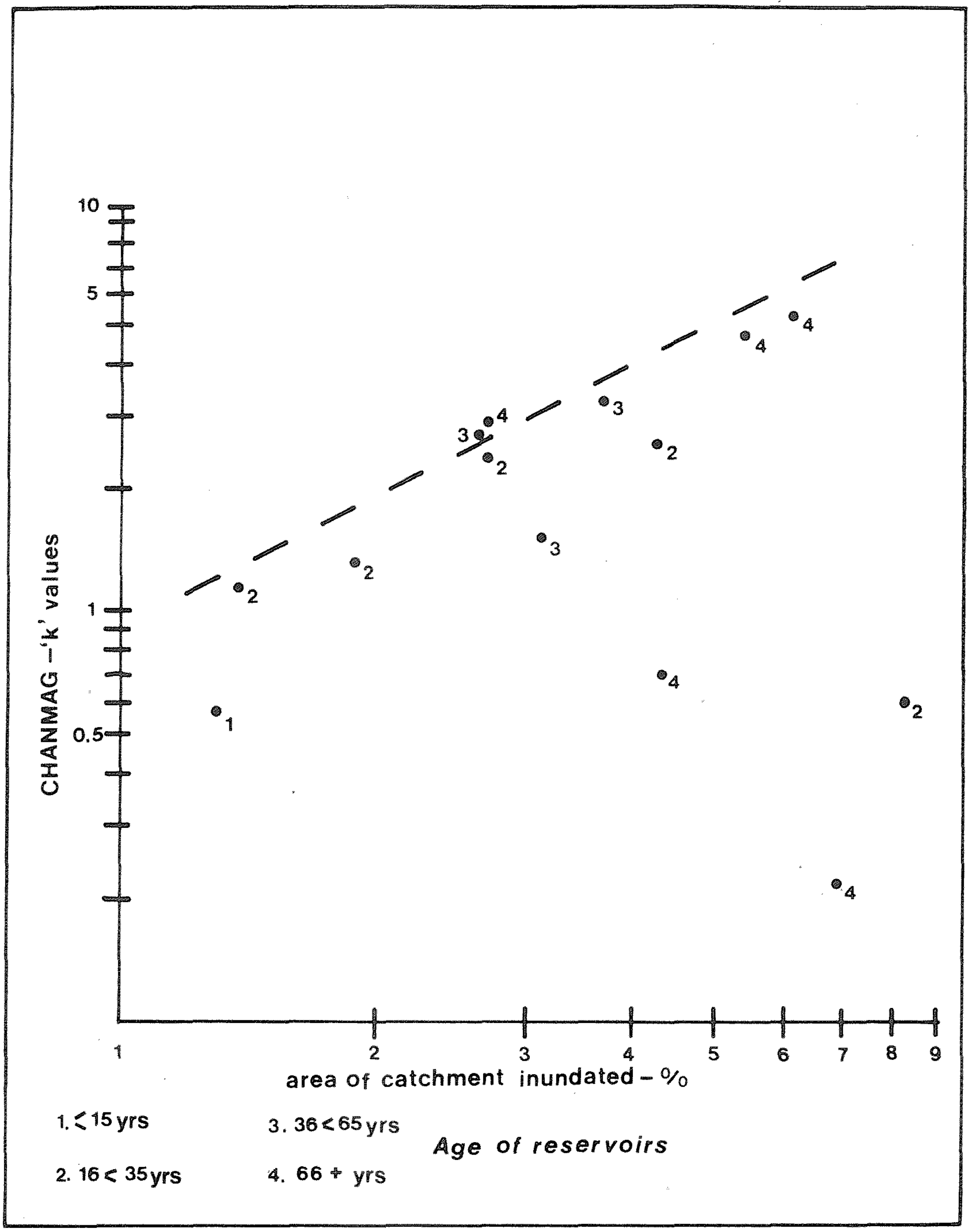

FIGURE 6.13 THE VARIATION OF CONVEYANCE FACTOR CHANGES WITH THE AREA OF CATCHMENT INUNDATED AND RESERVOIR AGE.

channels are subjected to numerous constraints which may affect the rate, direction, and magnitude of response to flow regulation. Indeed, the constraints may be such that a channel may 'adjust' to a condition dissimilar to the potential quasi-equilibrium form. For example, the channel below the seventy-five year old Blagdon reservoir may never attain its potential form suggested by the data (Fig. 6.13) as the flows appear to be incompetent to erode the channel perimeter sediment and a non-regulated sediment source is unavailable. Furthermore, the bankfull discharge, or rather the discharge responsible for maintaining the quasi-equilibrium channel form may vary both between and along individual rivers.

6.2.5. The significance of specific discharge frequencies to channel form. The evidence from the literature has suggested that the channel morphology of natural, upland, gravel bed rivers in the U.K. may be adjusted to the discharge having a frequency of 1.5 years on the annual series (Hey, 1975). However, it has also been suggested that the bankfull discharge will have a relatively lower frequency for regimes having a major base-flow component (Harvey, 1969), whilst the dominant discharge for sediment transport will increase in frequency as the calibre of the sediment load decreases (Hey. 1975). Comparison of bankfull discharges, computed by the Manning equation (Chapter 3.1.6.) at changed locations below reservoirs, with discharge records may illuminate the significance of specific discharges to the maintenance of channel form: suitable discharge records are available for six of the catchments studied (Table 6.5).

Downstream of Lake Vrynwy, the Derwent reservoirs and Sutton Bingham reservoir the river channel has adjusted to a discharge having a frequency greater than the 1.5 year flood on the annual series, whilst below the other three reservoirs the magnitude of the bankfull discharge is greater than that having a frequency of 1.5 years. The variation between the values of the bankfull discharge may reflect the relative importance of sediment transport.

The exact correlation between the bankfull discharge and the optimum discharge for bedload transport will not occur as the tendency to minimise boundary shear stress for water conveyance must also be satisfied (Chapter 2.1.5.). Downstream of Lake Vyrnwy, the Derwent reservoirs and Sutton Bingham Reservoir, the frequency of the bankfull discharge of less than 1.5 years may reflect the relatively higher rates of sediment transport than along the Avon, Hodder, and Daer rivers which may have adjusted to the abstraction of the sediment load by adjusting their channel form preferentially to maximise the capacity for water

Table 6.5 Comparison of gauged flow data with the bankfull discharge estimated by the Manning equation based upon the field survey of changed reaches below the selected dams.

Catchment	Estimated bankfull discharge (m^3/sec)	Recurrence interval (yrs)	Magnitude of gauged 1.5 yr. flood (m^3/s)
Avon	10.80 < 12.26	4.7 < 5.5	7.84
Hodder	15.67 < 19.07	3.6 < 8.0	11.10
Vyrnwy	50.20 < 60.24	1.11 < 1.26	65.79
Daer	10.94 < 14.22	2.0 < 4.0	8.6
Derwent	17.29 < 29.37	less than 1 yr.	50
Sutton Bingham	8.33 < 9.37	1.38 < 1.4	13.0

conveyance. This conclusion may be supported by reference to the location of channel change along the various rivers. Whilst the location of the REACHMAG downstream of Stocks, Avon dam, and Daer reservoirs is within 0.5 kilometres of the dams, below the remaining three sites the REACHMAG is situated some distance downstream. The former changes may be related (Chapter 7) to the redistribution of the channel perimeter sediment producing an armoured channel, whilst the latter three sites are associated with the deposition of sediment downstream of a tributary confluence and a readjustment of the channel form in an attempt to maximise the transport of the sediment downstream.

6.3 CHANNEL CAPACITY ADJUSTMENT TO AN IMPOSED FLOW REGIME.

The detailed examination of channel capacity changes consequent upon reservoir construction ideally requires a 'before and after' study involving hydrologic, sedimentologic and channel morphologic data. Although data for this type of study are generally unavailable, the application of spatial relationships has enabled the identification of a variety of channel changes to flow regulation. The analyses of the discharge records has demonstrated that peak flows will be reduced and the flow regime will be markedly altered subsequent to dam closure. However, the effect of flow regulation is reduced as the discharge frequency decreases. Nevertheless, individual flood events may be reduced for several kilometres below the dam.

Within similar hydrologic and geomorphic regions the magnitude of channel response may be related to the surface area of the reservoir, a surrogate for the temporary storage above the spillweir crest. Between region variations for reservoirs of similar size may reflect differences in flood hydrology. Furthermore, the rate of channel response will depend upon the frequency of competent discharges so that the introduction of tributary runoff may initiate a more rapid adjustment than immediately below the dam.

The adjustment of river channels to flow regulation may require a long period of time as sediment must be made available for the reduction of channel capacity. Considerable variations of channel morphology have been observed below reservoirs in Britain and differences in the magnitude of channel change exist between catchment and along individual rivers. Chapter 7 attempts to identify the primary mechanisms for river channel adjustment below reservoirs in Britain inorder to illuminate more clearly the controls of adjustment and to investigate the complex response of river channels.

CHAPTER 7. MECHANISMS OF CHANNEL ADJUSTMENT TO FLOW REGULATION

The adjustment of channel capacity downstream of reservoirs in Britain has been demonstrated (Chapter 6.2) to lack uniformity both along individual rivers and between catchments. The magnitude of channel form changes generally decreased downstream, but the reaches of changed morphology along a single river were often isolated, separated by river sections displaying no evidence of change, or of variable form. This chapter seeks to identify the factors which influence the spatial variation of channel change in response to flow impoundment.

The construction of a reservoir will reduce the magnitude and frequency of peak discharges and abstract virtually the entire sediment load. However, the relatively low sediment loads of British rivers together with the generally coarse nature of the bed-materials has initiated phases of channel capacity reduction in response to flow regulation. The deposition of sediment will be required to effect the reduction of channel capacity, but the often complete abstraction of the sediment load and the reduction of the frequency of competent discharges may require a long period of time for an adjustment to occur. Nevertheless, the examination of the detailed spatial variation of channel capacity changes along and between rivers may illuminate the different mechanisms of river channel adjustment.

7.1. FACTORS INFLUENCING THE SPATIAL VARIATION OF CHANNEL CHANGE BELOW RESERVOIRS.

The previous chapter has revealed that the reduction of channel capacity downstream of reservoirs in Britain is primarily related to the effect of impoundment upon the flood frequency distribution, although the frequency of the bankfull discharge subsequent to channel adjustment may be dependant upon the quantity and calibre of the sediment load. Although the magnitude of flow regulation, reflecting the storage available within the reservoir and the flood hydrology of the catchment, explains, in part, the variation in the magnitude of change between individual catchments - both in terms of the 'at-a-station' change and the downstream extent of change - considerable variation exists between individual reaches along a single river.

The variation of the magnitude of channel change downstream of the individual 'line of the valley' reservoirs has been summarised in Table 7.1. Downstream of Camps and Stocks reservoirs the channel capacity has enlarged as a result of channel degradation whilst immediately below Cowgill and Blagdon reservoirs the channel capacity has been reduced to less than thirty-percent of the expected values. The reaches immediately below Meldon and Ladybower dams show no signs of change resulting from either aggradation or degradation. Furthermore, the variability of channel response to flow regulation within reaches immediately below the dams is paralleled by variations in the magnitude of channel change within particular reaches downstream.

Channel capacity reduction in response to flow regulation requires the redistribution of channel perimeter sediment or the deposition of sediment derived from a non-regulated source. Thus, variations of the frequency of competent discharges, of bank-stability, and of the quantity of sediment and water discharge may affect the rate and direction of channel response. Furthermore, the state of the river system in general and individual channel sections in particular prior to dam closure will influence the rate and magnitude of channel adjustment, but the final state of the river system may display no evidence of former conditions.

(a) Constructional practices - a sediment source for channel change ?

During the construction of a dam considerable volumes of sediment may be released into the river system. Although the data does not provide any direct evidence as to the significance of this sediment source, the reduction of channel capacity has occurred immediately downstream of several reservoirs studied (Table 7.1). Immediately below Fernworthy reservoir the channel capacity has been reduced to one-third of the expected value at individual locations. Sediment may have been derived from channel degradation at the outfall of the reservoir overflow channel or from bank collapse, but in the absence of a non-regulated tributary supply, sediment introduced during construction may appear to be the most probable source. Consequent upon dam closure the temporary increase of the sediment supply will cease, and the generally sediment-free discharges may erode and redistribute the material downstream.

Table 7.1 Summary of channel change data (channel capacity)

Reach / Reservoir	1		2		3		4		5		6		7		8		9		10		11		12	
Blagdon	0.29	-	X	T	0.58	-	X																	
Chew Valley Lake	0.50	-	X	T	0.54	-	X	T	X															
Sutton Bingham	X	-	0.57	T	0.46	-	0.62	-	X															
Ladybower	X	-	0.52	-	X	-	X																	
Catcleugh	X	-	0.37	-	0.25	-	0.50	T	0,35	-	0.58	T	0.50	T	0.52	T	X	T	X	T	X			
Leadhills	X		X		0.51	T	0.56	T	X															
Daer	0.54	-	X	T	X	-	X	T	0.66															
Camps	1.31	-	0.46	-	X																			
Cowgill	0.16	T	0.23	T	0.51	T	X																	
Fernworthy	0.62	T	0.62	-	0.64	/																		
Avon	0.65	-	X	-	X	T	0.70	-	X															
Meldon	X	T	0.60	-	X																			
Vrynwy	X	T	0.62	T	X	-	0.58	T	X	T	0.52	-	0.68	-	X	-	X	T	0.64	-	X	-	0.59	/
Stocks	1.42	-	0.51	-	X	T	0.52	T	0.62	T	0.53	T	X	T	X	T	X	T	X					

X = no change (Ratio 1.0 ±0.3): T = tributary: - = arbitrary division: / = survey terminated by major tributary

(b) The significance of channel degradation as a sediment source for reaches downstream.

The erosion of the channel perimeter sediment immediately below a dam may provide a source of sediment for downstream reaches. Immediately below Stocks reservoir the channel capacity has been increased to double the expected size at individual sections, but within 300 metres the channel capacity has been reduced to fifty-percent of the predicted value. The reduction of channel capacity has been achieved by the deposition of coarse gravels which have subsequently been incised to form a new channel. However, the reduced channel capacity extends for only 200 metres downstream. Thus, although initiating major changes of channel morphology, the degradation and subsequent downstream deposition of coarse sediment within channels below reservoirs in Britain may have only local significance.

(c) The introduction of sediment from bank collapse.

Channel bank degradation may provide an important local source of sediment, particularly within channels incised into sediments having a high silt-clay content. Downstream of Sutton Bingham reservoir the river channel is commonly incised to a depth of four metres below the valley floor and the channel has been narrowed considerably by bank-slumping. Prior to reservoir construction the slumped material may have been eroded by high magnitude discharges, but since dam closure the reduction of the frequency of competent discharges may permit the stabilisation of the sediment by vegetation and the establishment of the deposit as a 'permanent' feature. Furthermore, even if the material is eroded the reduction of flood magnitudes may result in the deposition of the coarse sediment fractions as a lag deposit. Aggradation will occur until the downstream slope has increased above a threshold value when channel incision will occur producing a channel of smaller cross-sectional area. Thus, along a reach between three and twelve kilometres below Chew Valley Lake the channel capacity has been reduced to less than one-half of the expected value at individual, isolated locations.

(d) The effect of tributary sediment discharge upon channel capacity below reservoirs.

The examination of the channel change data (Table 7.1) suggests that the reduction of channel capacity is often greater for reaches downstream of tributary confluences. Immediately below Meldon dam the channel of the West Okement river has not changed its form or capacity since dam closure. However, downstream a major sediment supply is introduced by a tributary and the channel capacity has been reduced to less than one-half of the predicted value. Similarly, downstream of the Ladybower reservoir channel change is not apparent downstream to the confluence of the river Noe, a major tributary having a drainage area equal to fifty percent of the main stream catchment above the confluence. Below this tributary a marked depositional bench has formed along the channel margin reducing the channel capacity to approximately fifty percent of the expected value.

The isolation of individual channel cross-sections immediately above and below tributary confluences tends to support these observations. Although only coincidental evidence, the data (Table 7.2) indicate that the reduction of the regulated channel capacity is more effective downstream of a tributary confluence. The tributaries considered here have drainage areas equal to or greater than twenty percent of the catchment area of the mainstream immediately above the confluence. In the case of the river Hodder below Stocks reservoir the tributary merely serves to maintain the reduced channel form, but downstream of the Avon dam, on Dartmoor, and Catcleugh, in the Cheviots, the channel capacities below the isolated tributary confluences have been markedly reduced. However, the survey of the Afon Vyrnwy (Chapter 5.1) revealed that relatively minor tributaries may introduce significant amounts of sediment. Two hundred metres below the Lake Vyrnwy dam a small tributary having a drainage area of only 0.5 km^2 has deposited a delta of coarse gravels within the mainchannel. Further downstream a larger tributary draining approximately 6 km^2 has deposited sediment which has reduced the channel capacity to less than one-half of the expected value. Above the confluence the contemporary channel capacities are within five-percent of the predicted values. Similarly, downstream of Fernworthy dam channel capacities have been reduced to less than forty-percent of the expected values downstream of a tributary having a catchment area of 1.5 km^2; immediately upstream of the confluence the channel capacities are within ten percent of those expected.

The magnitude of channel change commonly decreases with distance downstream from a tributary confluence, that is with

Table 7.2 Channel change below tributaries along regulated rivers.

River	Reservoir	Tributary catchment area % catchment above confluence	Channel change ratio (channel capacity) Above confluence	Below confluence
Clyde	Daer	44.1	0.87	0.77
Rede	Catcleugh	20.8	0.60	0.31
Rede	Catcleugh	30.3	0.60	0.47
Chew	Chew Valley Lake	20.8	0.90	0.60
Yeo	Sutton Bingham	72.3	0.70	0.47
Avon	Avon	35.1	0.97	0.57
Hodder	Stocks	44.8	0.65	0.61
Derwent	Ladybower	52.5	1.02	0.66
W.Okement	Meldon	24 (3 tributaries)	1.01	0.53

distance away from the apparent sediment source. Below Lake Vyrnwy downstream of the confluence of the fourth recorded tributary (Table 7.1.) the channel capacity has been reduced along a three kilometre reach. However, the magnitude of change decreases progressively downstream from a reduction of nearly one-half to within ten percent of the expected values. Downstream of the first major tributary of the river Rede below Catcleugh reservoir the channel capacity has been reduced to less than forty percent of the predicted value, but the magnitude of channel change decreases progressively downstream until the second tributary confluence, downstream of which the magnitude of channel change is once more increased. Thus, the variation of the quantity and calibre of the sediment load between tributaries and differences of the frequency of tributaries between rivers may explain, in part, the spatial variation of the magnitude and rate of channel adjustment to impoundment.

Sediment discharged by tributaries into a regulated mainstream, experiencing reduced flows and unable to 'flush' the material, will be deposited within the main channel, often as a single delta initially. The regulation of the mainstream discharges may effectively reduce the base level for tributaries during times of flood so that tributary degradation may occur. The sediment supply from the tributary will be increased as the erosional front migrates upstream until the slope of the tributary has adjusted to the imposed 'base-level'. Within the main-channel the form of the deposit will depend upon the calibre of the sediment, the magnitude of the tributary discharges and the frequency of competent mainstream flows. Where competent mainstream discharges are infrequent vegetation may colonise and stablilse the sediment, protecting the deposit from erosion. Nevertheless, the erosion and redistribution of the sediment may be anticipated, at least during the infrequent, high magnitude events, so that channel change may occur progressively downstream. However, the aggradation of a river channel below a tributary confluence may also induce deposition upstream as the flow velocity will be reduced. Once the downstream slope of the depositional front has reached a critical threshold value the river channel may become incised into the sediments. But, observations made downstream of tributaries below Lake Vyrnwy tended to suggest that this process occurred simultaneously with deposition. That is, below the larger tributaries, producing higher magnitude discharges, sediment may be deposited as channel-side berms. The deposition of gravel served to narrow the channel and to confine the flow, increasing velocity and permitting sediment transport through the reach. Thus, the hitherto conceived discrete depositional and and erosional phases, separated by a threshold slope, may infact occur simultaneously, facilitated by a change of channel shape.

(e) Adjustments within stable channels.

Downstream of many British reservoirs the channel bed materials contain coarse sediments and the regulated discharges may be below the threshold for sediment transport so that a natural protective armour layer is produced. Outcrops of bedrock often occur which serve to resist erosion and to control the channel slope for reaches upstream. Furthermore, the bank materials frequently contain high proportions of silt and clay so that, together with the 'binding' effect of vegetation, the channel banks may also resist erosion. Thus, although the entire sediment load may have been trapped by the reservoir the reduction of the discharge magnitudes and the strength of the channel perimeter sediment may resist degradation.

In the absence of channel perimeter sediment erosion , or an input of sediment from a non-regulated source the morphology of the river channel will not change, but discharges will simply be accommodated within the existing channel form. The only evidence of 'change' being a reduction in the frequency of overbank flows. This 'accommodation' adjustment has been observed immediately below Ladybower and Meldon dams in particular (Table 7.1), and within isolated reaches at locations further downstream below Stocks reservoir and Lake Vyrnwy. However, consequent upon dam closure the potential for channel change may exist but within stable channels a rare, high magnitude flood may be required to initiate channel change. That is, within stable channels a major flood may be required for an intrinsic threshold-reflecting the resistance of the channel perimeter sediment - to be crossed and channel adjustment to occur. Thus, the rate of response will be complex depending upon the forces resisting erosion and the effectiveness of flow regulation. Nevertheless, once the intrinsic threshold has been crossed, the redistribution of the channel perimeter and floodplain sediments may initiate a rapid phase of channel adjustment.

(f) Channel response within active meander systems.

The reduction of channel capacity may result from the differential erosion of the channel perimeter sediment and the redistribution of the floodplain deposits. Within gravel deposits channel migration, often associated with the development of meanders, may produce rapid rates of channel adjustment providing that competent discharges have a moderate frequency. Thus, 25 kilometres downstream from Lake Vyrnwy the channel capacity has been reduced to sixty percent of the expected value within a meandering reach. Furthermore, downstream of Catcleugh reservoir the channel of the river Rede has adjusted most rapidly to the reduction of flood magnitudes within a meandering reach. The sorting and redistribution of the floodplain sediment during meander migration has produced a new floodplain separated from a terrace by a marked break of slope. Channel capacities have been reduced to one-quarter of those predicted and channel migration appears to have increased the sinuosity of the reach - possibly a response to the reduction of the calibre of the sediment load. The stability of the reach, however, increases downstream where the planform of the channel is confined by riparian, woody vegetation and the channel capacities approach the predicted values. Nevertheless, sediment eroded from, and transported through the meandering reach may be deposited within the less mobile reaches and the data (Table 7.1) suggests that this process may have reduced channel capacities to fifty percent of the predicted values along the river Rede.

Downstream of Camps reservoir, within the Southern Uplands, the post-dam closure migration of the channel indicates that the regulated discharges are competent to transport the existing channel and floodplain sediments. This suggestion is supported by the occurrence of a degraded section immediately below the dam. Within 250 metres of the dam the river enters a series of active meanders within which the channel capacity has been reduced to less than thirty percent of the expected values at individual locations (Fig.7.1). However, as the channel pattern becomes stabilised downstream the magnitude of channel change decreases and channel capacities approach the predicted values, although the trend is complicated by the introduction of a tributary. Nevertheless, the progressive migration of the meanders may provide sediment for the adjustment of reaches further downstream.

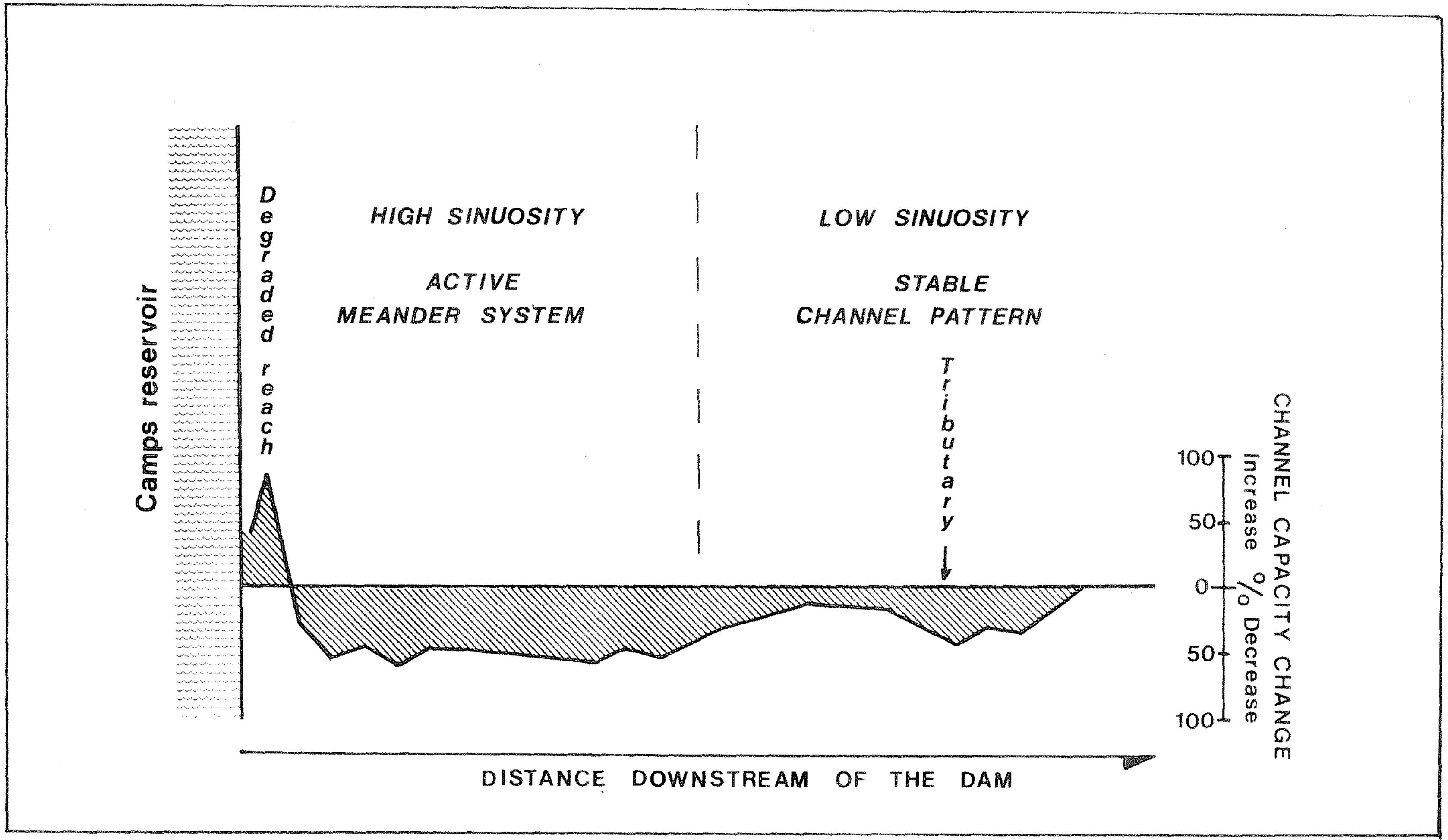

FIGURE 7.1 THE VARIATION OF CHANNEL CAPACITY CHANGES DOWNSTREAM FROM CAMPS RESERVOIR, ASSOCIATED WITH THE MOBILITY OF THE CHANNEL PLANFORM.

Within the meandering reaches the channel adjustment is often more uniform than that observed for less mobile channels. Indeed below Camps reservoir the mean channel change ratio is 0.46 and the values for individual locations within the meandering reach range between 0.39 and 0.52. Similarly, downstream of Catcleugh dam the channel change ratios have values of 0.25 ± 0.05. Thus, within mobile materials active channel migration may initiate a relatively uniform channel adjustment which will migrate progressively downstream when the main channel is not joined by a tributary. The channel perimeter and floodplain sediment will undergo differential erosion and redistribution during meander shifting: a new floodplain will be produced by the construction of point bars having surfaces lower than the surrounding valley floor.

(g) The influence of vegetation upon channel change.

The adjustment of river channel capacity along and between rivers will be complicated by differences in the significance of vegetation. Riparian vegetation may prohibit channel migration and increase the resistance of the bank materials to erosion. Also, the colonisation of sediment deposits within a regulated main channel may stabilise the material and protect the deposit from erosion during subsequent high discharges. Furthermore, where discharge magnitudes are markedly reduced the encroachment of vegetation may stabilise existing bank sediments, trap further sediment, and confine the flow to a definite, small, relatively deep channel. Thus, downstream of Cowgill reservoirs channel capacities have been reduced to one-fifth of the predicted value, and, at this small catchment area - of less than 5 km^2 - vegetation appears to play the dominant role in the adjustment of river channels consequent upon reservoir construction.

(h) Summary

The magnitude and rate of channel response to flow regulation may be related to the frequency of competent discharges, related to the magnitude of discharges and to the calibre and cohesion of the channel perimeter sediment, to the quantity and calibre of the sediment derived from the various sources considered above, and to the rate of sediment colonisation and stabilisation by vegetation. However, it may be anticipated that variation in the adjustment of channel shape may also be related to the different mechanisms of channel change.

7.2 FACTORS INFLUENCING THE SPATIAL VARIATION OF CHANNEL SHAPE BELOW RESERVOIRS.

Channel response to reservoir construction within Britain has generally involved the reduction of channel capacity although considerable variation exists both along and between rivers. However, the way in which channel capacities are reduced - that is, by an alteration of channel depth and/or width - also varies between locations having similar REACHMAG values. The reduction of channel capacity requires the redistribution of the channel perimeter and floodplain sediment, or the deposition of sediment derived from a non-regulated source, and the different changes of channel shape observed may reflect the relative importance of these two processes.

Immediately downstream of the dam the changes of channel shape vary widely (Table 7.3). Whilst below four of the reservoirs changes of channel shape have not occurred, elsewhere changes range from an increase of width and/or depth, reflecting degradation, to a decrease in one or more of the parameters in response to the deposition of sediment derived from constructional practices, or from the redistribution of the channel perimeter sediment. Downstream of Stocks reservoir channel bed degradation has provided a sediment source for reaches downstream where the deposition of the coarser fraction of the bed-material load has reduced channel depth preferentially to width. Indeed, it may be anticipated that the deposition of coarse sediment, derived from one or more of the sources identified previously, may result in the primary reduction of channel depth. Channel migration, involving the differential erosion and redistribution of channel and floodplain deposits, or bank collapse, may preferentially reduce channel width. The evidence from meandering reaches and locations below tributary confluences tends to support this suggestion (Table 7.3).

Within meandering channels the reduction of channel capacity has been preferentially achieved by a reduction of channel width. The redistribution of the channel perimeter and floodplain sediments will provide an initial sediment source for the reduction of channel capacity. However, once the channel form has become adjusted or the channel perimeter has become armoured - a result of the differential erosion of the sediments - the supply of sediment

Table 7.3 Changes of channel width (w) and mean depth (d) downstream from reservoirs in Britain .

Reservoir	Hydrologic region	Immediately below dam	Downstream reaches: Meandering channels	Downstream reaches: Below tributary confluences
Chew Valley Lake	3	$w^{-}\ d^{-}$	$w^{-}d^{-}$	$w^{-}d^{-}$
Blagdon	3	$w^{-}d^{=}$		w^{-}
Sutton Bingham	3	no change		$w^{=}d^{-}$
Catcleugh	4	no change	$w^{=}d^{-}$	$w^{-}d^{-}$
Ladybower	4	no change		$w^{-}d^{=}$
Leadhills	5	w^{+}	w^{-}	$w^{-}d^{-}$
Daer	5	d^{-}	w^{-}	d^{-}
Cowgill	5	$w^{=}d^{-}$	$w^{=}d^{-}$	w^{-}
Camps	5	$w^{+}d^{+}$	w^{-}	
Fernworthy	5	d^{-}	w^{-}	d^{-}
Meldon	5	no change		$w^{-}d^{-}$
Avon	5	d^{-}		d^{-}
Stocks	6	$d^{+}\ \ w^{-}\ d^{=}$	w^{-}	d^{-}
Vyrnwy	6	no change	$w^{=}d^{-}$	$w^{-}d^{-}$

will cease so that the channel form may reflect a tendency toward the maximisation of channel efficiency for water conveyance.

Below reservoirs in lowland England the encroachment of vegetation onto the channel banks may trap fine sediment, effectively reducing channel width. Indeed, channel bank 'plastering' by fine sediment was observed below Chew Valley Lake. Furthermore, the encroachment of vegetation has been suggested to be the dominant control of channel adjustment within small regulated catchments. Downstream of Cowgill reservoir the colonisation of the gravel deposits by vegetation, which has subsequently trapped fine sediment, has effectively reduced channel width.

The deposition of the tributary bed-load within the main channel experiencing reduced flow and unable to 'flush' the deposits has generally resulted in the primary reduction of channel depth. However, occasional competent mainstream discharges may sort and redistribute the sediment along the channel so that channel width may also be reduced. Furthermore, once the downstream slope of the depositional front has exceeded a threshold value, channel incision may occur, again producing a reduction of width as well as depth. The reduction of depth alone may reflect either the coarse nature of the deposit or the marked reduction in the frequency of competent mainstream discharges. Nevertheless, the adjusted channel form within reaches downstream of 'continuous' tributary sediment sources may reflect the tendency toward maximising the efficiency of sediment transport preferentially to water conveyance. Thus, the shape of the channel maintained by the regulated flow regime may reflect the relative importance of sediment transport.

7.3. CHANNEL ADJUSTMENT MECHANISMS BELOW BRITISH RESERVOIRS.

The reduction of channel capacity in response to flow regulation consequent upon reservoir construction in Britain will be a complex adjustment varying in magnitude, rate and direction both between rivers and along individual channels. Channel capacity reduction requires the deposition of sediment which may be derived from a number of sources, but in Britain two primary mechanisms for channel adjustment have been identified.

Channels formed in mobile sediments and experiencing competent discharges of moderate frequency will adjust their channel capacities by the differential erosion and redistribution of the channel perimeter and floodplain sediments. The rate of adjustment will be dependant upon the frequency of competent discharges, but the data suggest that channel capacity reduction may be achieved most rapidly within active meander systems. Whilst the primary adjustment will be a reduction of channel width, achieved by berm and point-bar formation, the evidence tentatively suggests that the channel sinuosity may also increase in response to the reduced calibre of the sediment load.

Within channels constrained by vegetated banks, cohesive bank sediments, coarse bed-materials or bedrock outcrops, the channel morphology may not change in the short term. The discharges will be accommodated within the pre-existing channel form so that the only evidence of impoundment is an alteration of the flow's hydraulic geometry. However, a rare, high magnitude flood may provide a stress above the threshold imposed by the resistance of the channel perimeter sediment and a phase of adjustment will be initiated. Moreover, the presence of a non-regulated sediment source may initiate a phase of adjustment within the stable channel form.

The deposition of sediment by non-regulated tributaries within a regulated mainstream has been demonstrated to be of primary importance to channel adjustment below reservoirs in Britain; even small tributaries may introduce significant quantities of sediment over time. The reduction of the frequency of competent discharges will result in the deposition of the tributary bed-load within the main channel reducing channel depth. However, the occurrence of competent mainstream discharges, or high magnitude tributary floods, may redistribute the sediment along the channel so that the reduction of channel width and depth may be achieved simultaneously

The primary mechanisms identified above may occur independently or simultaneously and will be complicated by local factors. Sediment may be derived from constructional practices, upstream degradation or bank collapse; vegetation may stabilise deposits, trap fine sediments and effectively confine the flow; and the dimensions of the channel prior to dam closure will influence changes at individual locations. Changes of channel form will occur initially at isolated locations along the channel and adjustments may occur progressively downstream from these loci. However, aggradation at a downstream point will effect the energy slope for reaches upstream. This will induce further aggradation if a sediment load is available, but within mobile channels a reduction of the water slope may reduce the competence of flows and the rate of adjustment. Thus, the reduction of channel capacity to flow regulation may require a long time period. Nevertheless, the rate, magnitude, and direction of channel response to a similar stimulus will vary between catchments and along individual rivers reflecting the relative importance of the different mechanisms for channel adjustment.

CHAPTER 8. CONCLUSION: A PROVISIONAL MODEL FOR CHANNEL ADJUSTMENT TO FLOW REGULATION IN BRITAIN

The past decade has witnessed the increased awareness of the variety of impacts that man may have upon drainage basin processes, and the identification of relationships between form and process stimulated the examination of landform adjustments to changes of the control variables at particular time-scales. However, the literature has been dominated by studies concerned with the causes and consequences of induced erosion; land use changes and urbanization in particular have attracted detailed research. Evidence of landform changes consequent upon a reduction of the magnitude and frequency of peak discharges is relatively sparce, possibly a reflection of the less dramatic short term consequences.

Studies of the impact of reservoir construction upon river channels have predominantly been concerned with the effects of scour immediately below the dams, a response to the abstraction of the sediment load. The impact of flow regulation upon channel form has only infrequently, and often coincidentally, been reported. However, river channel degradation below reservoirs will only be effective where the reduction in sediment supply is greater than that of the carrying capacity. In Britain, the sediment load of rivers is relatively low and the channels are often lined by coarse sediments so that consequent to impoundment river channels may adjust primarily to the alteration of the hydrologic regime.

The review of the literature concerned with the evaluation of the controls of river channel morphology (Chapter 2.1), and the illumination of changes resulting from an alteration of one or more of the control variables (Chapter 2.2), permitted the assessment of the consequences that river impoundment may have upon channel form in Britain. Furthermore, the detailed examination of the literature describing the impact of reservoirs upon hydrological and sedimentologic factors (Chapter 2.3) enabled the evaluation of the variety of changes that may occur consequent upon dam closure.

Although the recognition of channel changes below reservoirs is problematic owing to the lack of direct evidence as to discharges, channel geometry, and sediment yields prior to dam construction, changes of river channel form have been determined from the comparison of channel dimensions between regulated and non-regulated rivers. Park (1976) demonstrated that channel form dimensions vary along 'natural' stream channels in a systematic manner so that significant morphometric relationships can be established, for example, between channel capacity and drainage area. Thus, the identification of channel changes downstream of reservoirs was based upon the establishment of relationships for unmodified areas which were compared with actual, field surveyed, channel dimensions. However, the identification of anomalies within the relationships below reservoirs does not establish that flow regulation was the cause of change. Thus, three further approaches (Chapter 3.1) were employed to illuminate the cause of channel change.

Fifteen reservoirs throughout Britain were selected (Chapter 3.2), incorporating dams of different age and reservoirs of different size. The application of observed spatial trends to the identification of temporal changes of channel form proved to be an effective technique for the identification of channel changes below reservoirs in Britain (Chapters 4 and 5). Channel capacities downstream of the 'line of valley' reservoirs have been reduced to between sixteen and sixty-five percent of the expected values. Furthermore, downstream of six reservoirs the water conveyance factor was reduced to less than forty percent of the predicted values.

The reduction of channel capacity downstream of reservoirs in Britain has been associated with a changed frequency of peak discharges (Chapter 6). Indeed, the flood frequency distribution of a river subsequent to dam closure may be markedly altered. Flood discharges will be partly or completely absorbed within the reservoir volume, and storage above the spillweir crest, related to the proportion of the impounded catchment inundated by the reservoir and the hydraulic characteristics of the overflow weir, will have an attenuating effect upon peak flows, so that the hydrograph time to peak will be increased and the flood magnitude decreased. However, river channel changes consequent upon reservoir construction in Britain will not only be a function of the degree of peak flow reduction, but also of the sediment introduced by tributaries, and of the particle size distribution, cohesion and vegetation, influencing the susceptibility of the channel perimeter sediment to erosion.

The evaluation of the significance of spatial patterns in the magnitude, rate, and direction of channel response along a single river has enabled the illumination of several factors influencing the complex response of a fluvial system to river regulation (Chapter 7). However, three general statements may be advanced to describe the adjustment of channel capacity (Chapter 6.2).

Firstly, the magnitude of channel change within a single geomorphic and hydrologic region will be directly related to the area of the impounded catchment inundated by the reservoir. Downstream, channel adjustments will occur until the catchment has reached an area equal to approximately 2.5 times that of the impounded drainage area.

Secondly, variations of channel response to flow regulation downstream of reservoirs inundating the same proportion of their catchment areas may be related to differences in flood hydrology, particularly the shape of the reservoir inflow hydrograph.

Thirdly, the rate of channel response will reflect the frequency of competent discharges subsequent to dam closure. Thus, the rate of adjustment will be inversely related to the effectiveness of flow regulation. River channel adjustment may, therefore, operate more rapidly downstream of smaller reservoirs having a relatively insignificant effect upon the magnitude and frequency distribution of flows. Furthermore, as the frequency of competent discharges increases and the effectiveness of flow regulation decreases downstream, so the lag between dam closure and channel adjustment may decrease. That is, for a reservoir of known age the lag time will increase as flow regulation becomes more effective.

The regulation of peak flows and the reduction of the quantity and calibre of the bed-material load consequent upon reservoir construction may be anticipated to initiate the complete readjustment of the channel dimensions. However, where flows are no longer competent to erode, transport and redistribute the channel perimeter materials, an input of sediment may be required for an adjustment to occur. In the absence of a sediment supply the channel form may not change but the discharges will simply be accommodated within the existing channel form. Thus, although the potential for an adjustment of channel form is provided by the reduction of peak discharges, a major flood may be required to initiate channel change.

Examination of the channel form data downstream of the reservoirs revealed considerable variation both along and between regulated rivers. These variations reflect, in part, the relative importance of two primary mechanisms for channel adjustment to flow regulation.

Firstly, channels experiencing competent discharges and bounded by mobile sediments will adjust their channel capacity by the differential erosion and redistribution of the channel perimeter and floodplain sediments producing channel-side berms and point-bars which will preferentially reduce channel width.

Secondly, the reduction of discharges below the threshold for sediment transport will result in the deposition of tributary sediment loads within the main channel, reducing channel depth.

The redistribution of the channel perimeter sediment and the input of sediment from a non-regulated tributary has particular significance for regulated river channels in Britain (Chapter 7), although vegetation may also be important as the colonisation of deposits will stabilise the sediment so as to resist erosion by subsequent rare high discharges. Furthermore, the data suggests that the frequency of the bankfull discharge subsequent to channel adjustment will be dependant upon the significance of sediment transport. Within the mobile channel sediments, channel migration will supply sediment for an adjustment to occur, but once the adjustment or an armoured coat has been achieved the supply of sediment will cease so that the adjustment may reflect the tendency toward maximisation of the efficiency for water conveyance. Downstream of tributaries however, a permanent sediment supply will be available so that the adjustment of channel form may reflect a tendency to maximise the efficiency of bed-load transport.

Consequent upon reservoir construction changes of channel form may be initiated at discrete loci along a river. Local factors such as bank collapse or sediment introduced by constructional practices and upstream degradation may initiate adjustments but the dimensions of the channel prior to dam closure will also be important. Moreover, major adjustments will be initiated by the two primary mechanisms identified above. However, changes of channel form at a single location will have implications for the rate of adjustment within upstream and downstream reaches. Changes of channel morphometry must be interpreted not only in relation to changes of flow regime and competence, but also considering the reduction of the sediment load and the input of water and sediment from tributaries. The complex response of river channels to flow regulation may produce a variety of channel forms both along and between river channels. Nevertheless, the progressive adjustment of a single river channel over time may be described in terms of a simple model (Fig.8.1).

In the short term the reservoir may effectively reduce discharge magnitudes so that the reservoir outflows are below the threshold for sediment transport. Channel change will not occur within reaches A, B and C and the flows will be accommodated within the existing channel form. The regulation of the mainstream discharges will result in the deposition of sediment downstream of tributaries. Thus, immediately downstream of a minor tributary, reach D, the channel capacity has been reduced. Moreover, within reach E, the maintenance of competent discharges, although of reduced frequency, downstream of a major tributary has reduced the channel capacity by the deposition of the coarser fractions of the sediment load and the differential erosion and redistribution of the channel perimeter sediment. Further downstream the increase in the proportion of non-regulated catchment has reduced the effect of flow regulation so that channel change does not occur within reach F.

As the scale of observation increases the probability of competent discharges increases. Thus, within reach A, degradation may occur immediately below the dam and the eroded material will be sorted and redistributed downstream. Furthermore, within the actively meandering channel, reach B, the adjustment of channel capacity may be rapid, associated with the differential erosion and redistribution of the channel perimeter sediment. Sediment deposited downstream of tributary confluences will also be redistributed along the channel so that the adjustment of channel morphology within reaches D and E may become progressively more uniform. Thus, over the long term the downstream variation of the magnitude of channel capacity reduction will tend towards uniformity and the concept of equifinality may be satisfied. However, the same magnitude of channel capacity change may be achieved in different

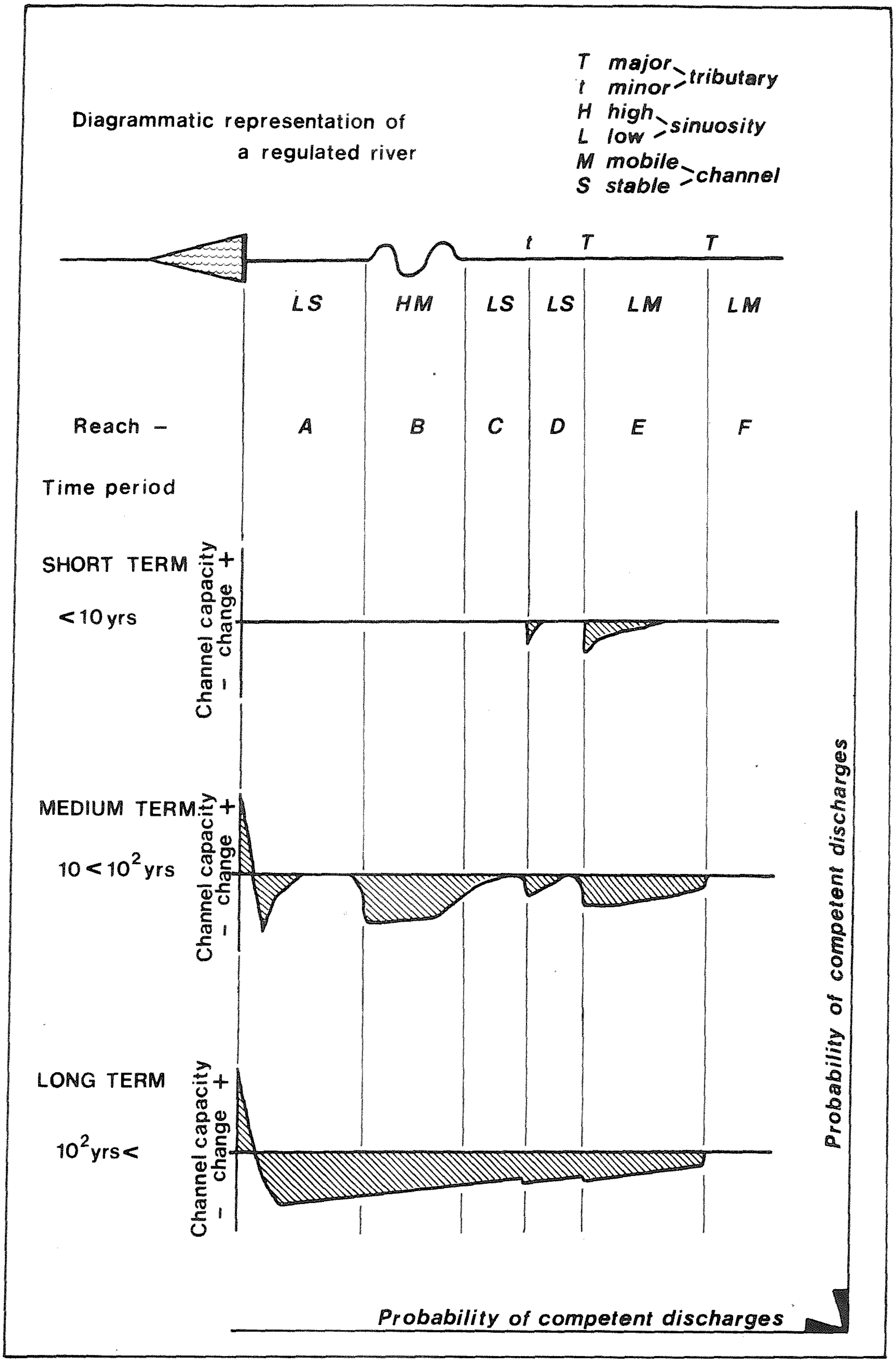

FIGURE 8.1 THE ADJUSTMENT OF RIVER CHANNEL CAPACITY TO FLOW REGULATION DOWNSTREAM FROM RESERVOIRS IN BRITAIN: A PROVISIONAL MODEL.

ways, by the preferential reduction of width within meandering systems, and of depth below tributary confluences, so that in detail considerable variations may occur between rivers and along individual channels.

The construction of large dams may also cause major, and often adverse,ecological changes within river systems (Turner, 1971). Indeed the alteration of the quantity and calibre of sediment loads, and the metamorphosis of river channels consequent upon reservoir construction, may affect the biota of freshwater and estuarine or marine environments. The migration of salmonids for example, may be adversely affected by flow regulation (Alabaster, 1970). Whilst much discussion has been concerned with the setting up of residual flows and the allowance of freshets inorder to 'protect downstream interests' (I.C.E., 1972,3), there is enough evidence to suggest that this concern should be paralleled by one for changes in channel form.

In Britain today few significant streams exist without some form of conscious or unconscious disruption by human activity. Man's dependance on dams for flood control and water storage is such that more dams are being planned and more rivers are being controlled. The construction of reservoirs within a river system will markedly alter the magnitude and frequency distribution of flows and significantly reduce the sediment load available to reaches below the dams. Over time the complete alteration of channel morphology will be a consequence of these changes, and the reduction of channel capacity may adversely affect the efficiency of flood-water transmission downstream; although the more frequent floods are markedly reduced, it has been demonstrated that the affect upon rarer events may be negligible. Thus, the successful operation of flow regulation schemes, necessary for both flood control and water supply, requires the consideration of the geomorphological consequences.

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