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CONTRIBUTION TO A GENERAL THEORY OF MEANDERING VALLEYS

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ABSTRACT. Systematic valley windings have often been taken as homologues of river meanders, and ascribed to erosion by powerful ancestral streams. River capture and the decay of ice- or snowfields are among the agencies variously credited with the implied reduction of discharge. Alternatively, the windings have been referred to peculiarities of rocks or structure. None of the several hypotheses explains the wide distribution of winding valleys, or their development on a regional scale.

Recent experiment and observation indicate that meandering can be wholly independent of external obstacles, and that the size of the loops is closely related to discharge. Furthermore, the alluvium in a number of winding valleys is shown, for the first time, to occupy large channels which meander, with appropriate bed form, round the valley bends. It is therefore concluded that the bends were in fact cut by streams, which were larger than those which now flow.

The discharge of the large channels at bankfull stage can be approximately determined from well-known formulae. It is found that present-day precipitation, however much the runoff might be concentrated in a single season, would be inadequate to supply discharges of the required order. Formulae for flood discharge are used to indicate the rates of rainfall per hour capable of nourishing the large former streams.

Although much work remains to be done on problems of dating, it appears likely that the high rates of rainfall and the resulting high river discharges obtained at various times during the Pleistocene. Certain implications concerning processes and modes of landscape evolution in the areas affected call for detailed investigation.

INTRODUCTION

The problem discussed in this paper is that of the combination of river meanders with equally systematic but far more ample windings of the valleys in which the river flows. In certain parts of the world such a combination is widely observed. It has naturally stimulated enquiry from time to time, mainly on the part of physical geographers, but as yet no single explanation has been exclusively accepted.

Logical reasoning about the problem is hampered by the nature of the terms in current use, for these are not merely descriptive but also embody genetic implications, as if the questions at issue had already been resolved. Thus the expression *meandering valley* is applied where the pattern of valley windings broadly resembles the trace of a meandering stream and where successive windings are for the most part of the same general order of size. Similarly a *valley meander* is an individual member of the series of windings. Now it is evident that each of these terms can be taken to imply that valley windings of the kind in question are homologous to river meanders, the difference being merely one of size. Many works indeed contain the tacit assumption that the two groups of features have originated in identical fashion. On the basis of evidence and reasoning which are presented later in this account, the writer considers homology to be in fact proved, but until the data have been considered it is proposed to use the noncommittal descriptive terms *winding valley* and *valley bend*. The assumption of homology is also implicit in the expression *underfit stream* (often also called *misfit stream*), by which is meant a stream too small for the valley in which it flows. It is quite clear that Davis, to whom these two terms are due, did not intend to suggest that for a given size of stream there is an appropriate size of valley, but only that certain valleys show signs of having been cut by streams far larger than those which now flow in them. The evidence adduced by Davis as indicating an underfit condition consists precisely of the combination of valley windings and river meanders. His interpretation has prevailed to the extent that underfit stream has passed into the literature as connoting a stream meandering within the limits of the bottom of a winding valley.

A second assumpion on which the use of the term underfit must depend, and which is also implicit in Davis' interpretation of valley bends, is that the dimensions of meanders are related to amount of stream discharge. Here is the deductive basis—as opposed to induction from the analysis of landform —of the inference that valley windings were shaped by rivers far more powerful than the rivers now observed, and that streams described as underfit have at some time been greatly reduced in volume. None of the geographers and geologists who alone seem to have considered the problem of valley windings appears to have checked or tested this second assumption, where it has been implied. Clearly, however, it is the essential premise to a certain line of reasoning, and as will be seen, supports a whole group of hypotheses. Its unquestioning acceptance (mainly by writers in English) may be unfortunate but is not altogether surprising; for the critical data must come from physical and mathematical investigations of the general problem of meandering currents. This work is still in its early stages, and the necessary information is only now becoming available. At the same time, it is of first importance to recognize the assumption for what it is, in order to evaluate the worth, force, and validity of the views summarized in the next section, and to understand how an authoritative group of writers could commence with very different postulates.

As with valley meander, the debatable term underfit will be avoided as far as possible in the discussion which follows.

PREVIOUS HYPOTHESES

Existing hypotheses of the origin of winding valleys fall into two groups: those which require stream discharges formerly higher than the present, and those which do not. The first group is summarized in the first four sections below, the second in the fifth. The summary is followed in the next section by a statement of the need for a general hypothesis, together with reasons for rejecting the hypotheses listed here.

The capture hypothesis.—This is the principal hypothesis of the group where changes in stream discharge are assumed or inferred. It was formulated by W. M. Davis (1895, 1896, 1899) with reference to valley features in the Cotswold Hills of England, the scarplands of the Paris Basin and Lorraine, and the South German Scarplands. In all these areas, boldly winding valleys containing small meandering streams occur on the dip slopes of strong geological formations. Davis quite properly identified the spurs between successive valley bends as similar in form to the meander lobes of many incised meandering rivers; for the spurs are often trimmed on the upstream side, as if by a large river, while at the extremity of valley bends the outer valley side is frequently very steep, in marked contrast to the gentle descent opposite (fig. 1). If, then, valley bends were the work of former great streams, the problem became merely one of accounting for the loss of water. The mechanism seemed ready to hand in the river capture to be expected in landscapes of this kind. Davis was at the time concerned with elaborating the

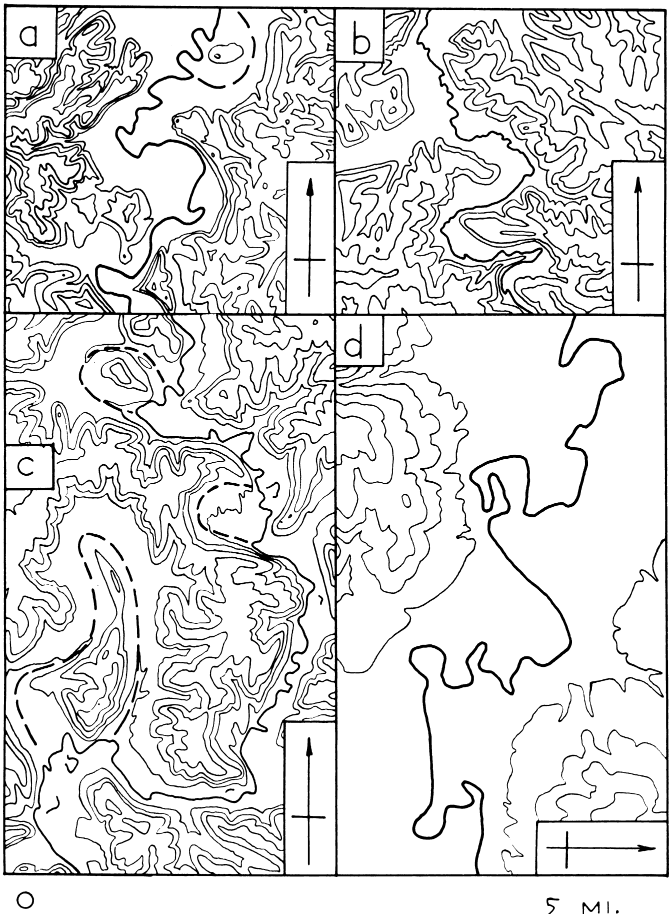


Fig. 1. Examples of winding valleys in the U. S. A.
a, Tygarts Creek, Kentucky (Greenup Quadrangle);
b, Fennimore Fork, Wisconsin (Boscobel Quadrangle);
c, Kickapoo River, Wisconsin (Wauzeka Quadrangle);
d, Tualatin River, Oregon (Tualatin Quadrangle);
Contour interval throughout, 100 ft. Pecked lines indicate abandoned valley bends. Tributary streams omitted for clarity.
Based on the maps of the U. S. Geological Survey.

scheme of the normal cycle of erosion and with presenting it in Europe. The uniclinal structure of scarpland country is especially well adapted for reference in discussing the evolution of drainage systems, and the river capture which is likely to occur frequently in the course of the normal cycle; many of the dip streams of the scarplands mentioned do, indeed, head in or near gaps in the scarp crest, and there is every reason to conclude that they have been beheaded by more successful competitors working along the weaker outcrops. It was an obvious step to conclude that the valley windings were cut before capture occurred, at a time when more extensive headwaters provided a greater flow.

In this conclusion Davis was followed by S. S. Buckman (1899, 1902) and later by many others. His own observations of anomalous facts, and his later expressions of a limited dissatisfaction with the simple capture hypothesis have, on the other hand, attracted little attention. In the three early papers cited, he noted that near the Cotswolds the Avon, supposedly a leading captor stream, also describes small meanders within a winding valley, and has, therefore, also presumably suffered a loss of flow, whereas it should have gained in volume to the extent that the beheaded dip streams lost. In the Swabian Alb also, a dip stream classed as underfit seems not to have been beheaded. In the classic instance of the capture of the upper Moselle from the Meuse, the latter seems too small for its valley both above as well as below the point of capture, for valley windings and river meanders occur in both reaches alike. Davis was impelled to postulate in addition to capture a loss of water doubtless due to "some climatic change of external and obscure origin." The main hypothesis still stood, however, and he restated it in 1923, apparently with approval.

Hypothesis of overspill of glacial meltwater.—Davis reopened the question of winding valleys in the Cotswolds after an interval of ten years (Davis, 1909), suggesting that small ice-dammed lakes might have discharged through the cols to provide powerful streams in the valleys of the dip slope. A similar view appears in Arkell's detailed studies of the same piece of country (1947a, 1947b). A variant opinion is that glacial meltwater or snowmelt, without the intervention of a lake, formerly provided high discharges.

Hypothesis of underflow.—In a paper of 1913 Davis admitted the inadequacy of river capture as a general explanation of stream shrinkage but was little inclined to substitute climatic change. He suggested that water might be lost to deep percolation and to shallow underflow through alluvium. As is well known, his views on graded waste slopes and the wastage of divides logically demand some infilling of trunk valleys during the mature stage of the cycle; this aggradation seemed capable of promoting powerful underflow.

Hypothesis of erosion by floodwater.—Certain writers (Engelmann, 1922; Flohn, 1935) have thought that rivers in flood might be capable of eroding valley bends. This view refers to former as well as to contemporary floods, and is related to the postulate of snowmelt already mentioned.

Structural hypotheses.—Under this head come those interpretations of valley windings which depend on the supposed influence on a downcutting meandering river of lithology, lithological succession, attitude of strata, or earth movements. French and German writers have been especially prominent in this connection. Thus Vacher (1909) considered that a river cutting in weak rock would, on encountering more resistant strata, develop more ample curves. A diametrically opposite view appears in Blache (1939, 1940) who regards small meanders (sc. river meanders) as a response to weaker rock in the valley bottoms. Musset (1928) identified more than one "generation of meanders" on the Loire, separating them in time by episodes of downcutting and slope reduction whereby he thought to account for the smaller amplitudes of the later curves. Cole (1930) related river meanders to the structure of the bedrock. Masuch (1935) also noted some relation between rock structure and the enlargement of meanders during downcutting (ingrowth of meanders), but considered valley windings characteristic of antecedence and superimposition rather than a response to structure. For reasons which the present writer does not find convincing, she did not regard as essential a genetic connection between river meanders and valley windings [talmaänder]. A useful survey of earlier work appears in Flohn (1935) who, while rejecting structural hypotheses and favoring flood flow as a cause of valley bends, concluded that these features are morphological convergences which can originate in different ways.

Miscellaneous hypotheses: The question of inheritance.—Wright (1942) ascribed valley bends to the fact that the loops of an incised stream are unlikely to suffer cut-off, with the result that they undergo progressive enlargement: this is the concept of "auto-underfitness." Bates (1939) thought that the development of river meanders is a response to aggradation, and Baulig (1925) had previously maintained that underfitting is a proof of aggradation in progress. It should be noted that Baulig later modified his opinion, stating in a more detailed study (1948) that the present condition of rivers is abnormal, and postulating a formerly much greater flow simultaneously reduced throughout the length of a stream. Nevertheless he was unwilling to accept climatic change as the basic cause, on the ground that such change should make all the rivers of a vast region underfit, and appealed to steepened slopes in the lower courses as a means of provoking more powerful currents.

The debate on winding valleys has been complicated from time to time by confusion between river meanders and valley bends, and by contradictory views on whether or not valley bends are necessarily inherited from a previous cycle of erosion. The question of inheritance is relevant not only to the problem of origin but also to the matter of dating.

Lehmann (1915), although reluctant to lay down a fixed rule, thought incised meanders unlikely to develop in a single cycle. With Flohn and Hol, he is among the critics of Davis' well-known scheme of the evolution of an incised meandering stream. Lehmann wished to take into account the wide range of variation found in nature, for example, in the relation of valley side to valley floor. Hol (1938, 1939), commencing by a penetrating critique of earlier work, concluded that all true incised meanders result from two cycles of development. The opposite view appears in Blache (1939, 1940), who identifies a valley bend on the Moselle as having originated in the present cycle, and also in Baulig (1948).

THE NEED FOR A GENERAL HYPOTHESIS

Not all the hypotheses referred to above can be valid for they are contradictory among themselves. A leading objection to most is that they demand special circumstances, such as local or regional particularities of structure, the incidence of river capture, or the former presence of glacial lakes or of snowfields. It seems highly unlikely on general grounds that any of these can account for the widespread occurrence of winding valleys in country which is lithologically and tectonically varied, and within as well as outside the former limits of ice.

When large areas are inspected in the field, or on large-scale maps and air photographs, valley bends are seen to be as common on captor streams

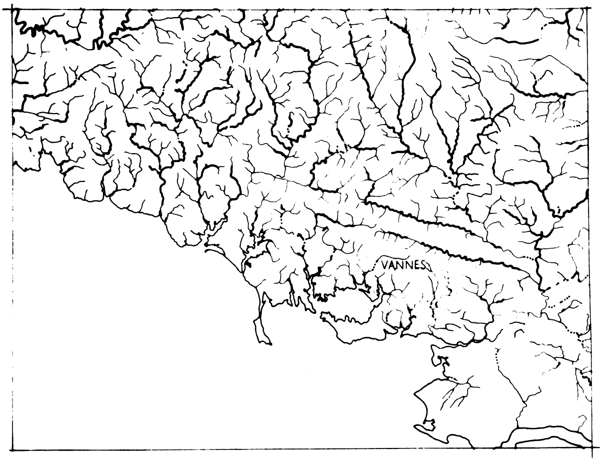


Fig. 2. The drainage net of part of Brittany, showing underfit streams (heavy lines). The map represents an area approximately 80 x 100 miles.

as on those which have been beheaded. The ratio of dimension between valley bends and river meanders is known to be comparable on opposite sides of certain watersheds, even when one group of streams is gaining and the other losing ground (Dury, 1951). A map of the distribution of winding valleys in France, part of which is reproduced here as figure 2, leaves no doubt that they are in fact regionally developed despite Baulig's statement to the contrary. The fact that some valleys are without valley bends is no more surprising than the absence of meanders from certain rivers. Moreover, allowance must be made for the suppression of river meanders in those parts of incised winding valleys where there is simply not room in the valley bottom for them to develop, with the result that the only trace shown on the map is that of the valley bends.

The classic instance of the Toul capture, where the Meuse has lost the upper Moselle (Davis, 1896), has probably served more than any other to support the view that valley bends are the former meanders of streams now diminished by beheading. But the disproportion between valley bends and river meanders on the Meuse is the same both above and below the point of capture, and the capturing Moselle shows similar inferential evidence of shrinkage. Thus the undoubted occurrence of capture may well have no connection with the problem of a general diminution of stream flow. Now de Martonne (1935, p. 598) has shown that since the capture the Moselle has had time to cut down some 40 meters, developing a valley bend in the process (Blache, 1939, 1940). Any shrinkage of the Moselle has taken place since the cutting of the valley bend, which in turn postdates the capture.

Many other instances of the supposed effect of capture can be disposed of by similar appeals to the elements of simple chronology. It can readily be shown that the gaps at the heads of some streams in the Cotswolds and neighboring hills already existed before the onset of the last local ice, and that the scarp face had already retreated almost to its present position by that time. All but the last minor reductions in the length of the dip streams had already taken place. But as will be shown later, the valley bends were still being eroded after the ice had disappeared. The most convincing single illustration that valley windings are not related to river capture is provided by the Stratford Avon, which is known not to have suffered capture since its initiation on a great spread of drift (Shotton, 1953). Any reduction in the discharge of this river must clearly have occured independently of capture, and also late in the day; for the forms of the valley leave no doubt that the valley bends continued to evolve, at least from time to time, until the river had cut down to its present level.

Postulates of discharge from temporary ice-dammed lakes or from the ice front are readily seen to be irrelevant to the general problem of winding valleys, when it is observed that these can occur well outside the extreme limits of Pleistocene glaciation. This fact appears strikingly on the map of France mentioned above and is also evident in the English Weald, where streams were selected for detailed study. In the broad view, too, it is difficult to imagine a system of lakes or glaciers which could have provided large rivers in all the winding valleys known to occur within the area formerly ice-covered.

The supposed efficacy of underflow through alluvium has been strongly criticized, for instance, by Wright (1942) and Baulig (1948). The process is not usually considered very seriously nowadays, but it may be noted in passing that if valley bends were cut by large streams the reduction of discharge far exceeds anything that underflow could explain. It is pertinent to remark here that certain winding valleys, including some of those described in a later section, are cut in impermeable bedrock and lined with fine-grained alluvium. In these cases, not only can underflow through the alluvium be disregarded but also it is obvious that losses to deep percolation are nil or negligible.

Erosion of valley bends by floodwater in the present climatic regime can also be readily dismissed. It is a matter of observation that "normal" floods (using the term in the hydrological sense) fail to erode the sides of most meandering valleys or to disturb all the alluvium of the valley floor. The spreading of floodwater over a floodplain is well known to reduce the peak flow; but erosion of valley bends can scarcely begin until the mode of flow over the floodplain is comparable to the violent motion which occurs in the main channel. Presumably there is for each valley a critical depth of water at which the floodplain alluvium would begin to move bodily, but this depth is not attained in present conditions even with exceptional floods. Probability analysis provides exactly the information required in calculations of the height of the centennial flood, the greatest flood to be expected in a randomly selected 100-year period—Pickels (1937) showed that for streams in Illinois the centennial flood is only of the order of two to three times the mean flood. More recently, it has been calculated that the exceptional floods of spring 1947 on the Northamptonshire Nene reached or even exceeded the level of the centennial flood (Crocker, 1952), while on the Severn the centennial level was closely approached in the same year (Rhodes, 1952). It appears safe to conclude that even the highest flood discharges now experienced are inadequate to account for the erosion of valley bends.

Although incised winding valleys are commonly associated with resistant rock, it is a mistake to suppose that the association has the force of a rule, as is usually done by those who seek the origin of valley bends in some response to lithology or structure. The only necessary connection seems to be the ability of strong rock to develop, sustain, and preserve steep slopes. Moreover, valley bends are not entirely confined to resistant outcrops or to incised reaches. The Stratford Avon has already been mentioned as having been initiated upon drift, in which it developed and incised a series of well-formed valley bends. One of its tributaries, the Warwickshire Itchen, has cut a winding valley through the moderately resistant outcrop of a limestone-shale series, but also describes valley bends as well as river meanders in the flat strike vale carved from the weak overlying clays. In the Weald of southeastern England, valley bends are numerous on the Weald Clay, a formation noted for its low resistance to denudation. Observations of this kind suggest that the low frequency of valley bends on weak rocks may be due to the tendency for the wide valley floors to be even and formless, and to the speed with which changes in the stream are reflected here in changes in the whole landscape.

The various special cases of the possible influence of structure or earth movements which certain writers have discussed again fail to carry conviction in view of the presence of winding valleys in homogeneous as well as in heterogeneous rock, in horizontal as well as in folded strata, and on weak as well as on strong outcrops. Since many of the valleys occur in tectonically stable areas, it must be concluded that local earth movements have no necessary bearing on the problem of their origin.

Attempts to explain valley bends as river meanders enlarged in especially favorable circumstances must also be regarded with doubt. Some workers seem to have overlooked the fundamental distinction between windings of two orders of size, perhaps because of the suppression—mentioned above—of river meanders in some confined reaches of winding valleys. The tendency of many rivers to enlarge their loops during incision is widely recognized but should not be permitted to obscure the fact that valley bends are usually very much more ample than the curves of the river. It is also necessary to bear in mind the possibility that stream discharge and dimension of meanders may be related. The final, and definitive, objection to the interpretation of valley bends as hypertrophied incised meanders is, however, provided by the evidence described in a later section that some winding valleys can be proved to contain filled stream channels much larger than those in use at the present time. Thus, there can be no doubt that two sets of features are in question.

Aggradation in progress cannot be accepted as a cause of small-scale winding unless it can be demonstrated. But as far as investigation of selected cases shows, mean down-valley gradient has changed very little since the present river meanders came into being, and in one instance at least excavation not infilling can be shown to be going on. Thus, although diminution of stream discharge should lead to valley filling (other things being equal), both should be looked on as the effects of a common cause.

The view that valley windings are necessarily inherited from free meanders at a higher level implies that they are not genetically related to outcrops of resistant rock, except of course to the extent that rock resistance has promoted their lateral enlargement during incision. But if inheritance has occurred, it follows (as pointed out by Hol) that the interval between the valley bends was determined before incision commenced. It is also implicit here that the valley bends originated as stream meanders. Since very many valley bends have in fact undergone lateral enlargement—have become *ingrown*[1]—it might be thought that earlier and less sinuous traces could be reconstructed for the higher levels, in order to show if a straight course existed when incision began. In practice the matter is very difficult, and inferential evidence must be relied on. The writer accepts the evidence of Blache (1939, 1940) that the Moselle has cut a valley bend in the course of a single cycle, and has himself recorded the development of meanders in a small gully, *pari passu* with incision (1951). It is concluded therefore that although many series of valley bends may well have originated in the incision of free meanders, inheritance is not essential. Consequently it is not permissible to date the initiation of every incised series to a time before their incision.

For all these reasons, it seems desirable to treat the general problem of valley bends as distinct from the specific problems of external influences on a given stream and to look for agencies which can operate independently of local circumstances. If it can be shown that the size of stream meanders is related to the size of stream, and if convincing evidence can be produced that valley bends are truly homologous to stream meanders, there is a strong case for concluding that in certain areas stream discharge was once higher than it is now, and that a general diminution has occurred. The best method of approach seems to be through a summary of recent views on the cause of meandering, which will serve to indicate the form of a meandering channel and to suggest that a mathematical relation between stream size and meander size actually exists.

RIVER MEANDERS: BED FORM AND SILT TRANSPORT

The mode of flow round bends has attracted the attention of physical scientists for a good many years, and considerable progress has been made in theoretical and experimental research. Physiographers, however, have tended as a group to accept the occurrence of meanders on natural streams

[1] The term is due to Rich (1914).

and to rest content with the postulates that helicoidal flow occurs at bends and that meanders are generated by solid obstacles in the bed. In consequence, much information has been overlooked that is of great use in the interpretation of winding valleys.

As is well known, the bed of a meandering stream is characterized by deeps or *swales* below the outer banks of curves, by shallows or *crossings* at the inflections between successive loops, and by constructional *scrolls* at the inner curved bank. Thus a meandering channel is typically asymmetrical in cross-profile. This description holds good whether the stream is incised or not.

The typical bed form has often been ascribed to or associated with the helicoidal flow which is supposed to take place at bends. The water surface is said to be superlevated at the outside of the curve, so that secondary descending currents are set up near the outer bank and are continued by transverse flow across the bottom towards the inner bank. This interpretation long seemed to account satisfactorily for the channel form, the formation of scrolls, and the lateral enlargement of bends, as well as to explain how meanders could originate in the deflection of the stream: it appears widely in geographical literature. There are, however, serious objections to it. Experiments on natural and on laboratory streams have shown that where bank erosion occurs little material is carried from one side of the channel to the other; instead, it is carried downstream and deposited *on the same side as the eroded bank.* Some authorities maintain that observable secondary flow may be described in terms of a complex of helices rather than of filaments. Moreover, experiments with dyed material and with injected dyes suggest that bed-load movement is not necessarily parallel to flow lines.[2] Leighly in particular has stressed the importance of taking turbulence into account. He finds by analyzing the distribution of eddy conductivity that in an unsymmetrical channel the concentration of force on the deeper parts of the bed is disproportionately large in comparison to the depth of water. Also he holds that maximum turbidity should occur at the bottom of the swale, with deposition lateral to some thread of maximum velocity and its flanking threads of maximum turbulence. On these grounds it is easy to suppose that mere asymmetry of the channel could account for the lateral enlargement of a bend, without appeal to centrifugal force. Once a bend and the associated deep were in being, turbulent transfer of material towards the inner bank would occur, until some kind of equilibrium was achieved between the forces tending to move material towards the inner bank and the gravitational pull towards the bottom of the swale.

As will appear, an interpretation of this kind accords with the results of recent work on the initiation of meanders. It will be noted that the forces at work are thought of as operating generally throughout the stream. This in itself opposes the view that meanders are due to external obstacles, but a few additional points may be noted in passing. As Hjulström (1942, 1949) remarks, meandering is usually least developed precisely where natural streams

[2] It will be realized that this review is presented in the most summary form. It has been necessary to refer to the results, without discussing the evidence, of the following authors: Blue et al. (1934), Claxton (1927), Eakin (1935), Einstein (1926), Friedkin (1945), Leighly (1932, 1934), Matthes (1941), Quraishy (1942), Russell (1936), Tiffany and Nelson (1939), Vogel and Thompson (1933).

are most easily deflected and where obstacles are most numerous, that is, near the sources. The truth seems to be that obstacles impede the initiation, development, and propagation of meanders; supporting evidence comes from the experiments of Friedkin, and from the field observations of Russell (1936), Matthes (1941), Fisk (1944), and Strahler (1946).

In this connection also, it may be stated that geographical (and other) literature contains many references to the supposed influence of gradient in the initiation or modification of meanders. Some hold that meandering increases the length of a stream, so that energy is reduced by the lessening of gradient and dissipated by the attack on the banks. A grave weakness in this argument is that it seems to impute finality to the stream; it has been used, however, in attempted explanations of the ample curves of valley bends. The opposite opinion is also to be found, that meandering occurs only on slight gradients: the stream is held to be easily deflected because of its low velocity. Thus meanders are rather remarkably ascribed either to an excess or to a deficit of stream energy. In actuality, meanders can form on very steep slopes, for example, the slope of 1:12 in the meandering gully mentioned above. It does seem likely, however, that meandering in natural streams is promoted by low gradients and small discharges, for both Matthes and Friedkin have observed that lines of flow become straighter with increased discharge, while Friedkin and Quraishy find that increased slope tends to increase the meander wave length. The logical ultimate consequence of increased volume and velocity is described by Mathes, who concludes that if velocity could be coordinated with bed resistance by adjustment of bed width, a straight and wide but very shallow channel could theoretically result. Friedkin draws a similar inference. Chatley (1940) has developed the mathematical argument, starting with the Manning and similar flow formulae, and using the Kennedy-Lacey rule for bed stability. He considers that rectification of a meandering course would lead to a great reduction of velocity and hydraulic radius and a great increase of wetted perimeter.

Now these several conclusions are of the greatest importance in the present discussion. Their converse is that if a straight channel becomes more sinuous, the hydraulic radius and mean velocity increase, while the wetted perimeter is reduced. Thus a deeper channel with more stable banks can be maintained and a more efficient runoff occur than with a straight course. If this is so, it can easily be seen why a meandering course, once established, remains in being, and why also the dimensions of the curves are likely to be related to other dimensions of the channel.

MEANDERS IN RELATION TO STREAM SIZE

The initial cause of meandering has been investigated by a number of laboratory workers. It is probably a fair summary of the available results to state that meandering appears to originate primarily in the bed, with the simultaneous formation of shoals throughout the length of the channel. As White remarks (1939), "two distinct stages can be recognised, one in which the bed controls the banks, and another in which the banks control the bed, as in fully developed meander in nature." The initiation of meanders in nature can be witnessed only in such conditions as those of tidal flats: the wave length of most valley windings was determined long since. Nevertheless it should be noted that meanders have been produced in laboratory streams, where the initial channel was straight, uniform in cross-section, and shaped in uniform and incoherent bed material, and where, moreover, the entrance was straight. Meandering is due to, or is at least related to, shoals which form for reasons not yet fully understood. Their development suggests a connection between the causation of meanders and the presence of a silt charge in the stream, especially since the shoals seem to be affected by the amount of load.[3] However this may be, it seems reasonably safe to state that in laboratory streams the amplitude and wave length of meanders have been found to be related most closely to discharge. Although Friedkin emphasizes the difficulty of description in mathematical terms on the grounds that the several variables form a circle of dependency, his own experiments produced uniform bends in constant conditions of slope and discharge. He accepted the general relationship between stream and meander size indicated by Quraishy and verified by Fisk.

Work based on field or map measurements of natural streams is likely, for obvious reasons, to take account of fewer variables than are considered in laboratory work. The values most easily determined are those of bed width W, depth D, wetted perimeter P, and values calculated from these; slope S; catchment area M; width of meander belt M_b and meander wave length (or interval) M_1. A group of important formulae make use of velocity V and discharge Q. For the purpose in hand it is necessary to consider whether a relationship exists in natural streams between Q, W (or P) and D on the one hand, and M_b and M_1 on the other.

Quraishy's experimental work led to the equation:

$$M_1 = \frac{32.6\ W}{(W/D)^{0.222}} \qquad (1)$$

in which it is clear that changes in bed width would have much greater proportional effects than changes in depth. Inglis (1941) has reanalyzed the data on natural streams presented by Jefferson (1902) and Bates (1939) and has found a statistical relationship connecting bed width, meander amplitude, and meander wave length. The equations relate only to rivers flowing in flood-plains in open valleys—*alluvial rivers*. The original figures show a much greater amplitude of curves for incised rivers than for rivers not incised, part of which may be due to the ingrowth of curves; but since it is likely that river meanders have not always been separated in the measurements from valley meanders, the equations referring to incised rivers are not repeated here.

[3] Certain workers, whether explicitly or by implication, deny the necessity for a silt charge; some would compare stream meanders to the looped pattern of atmospheric jet streams and certain ocean currents. The matter cannot be pursued here, but reference may be made to the works listed below, by Baschin (1916), Exner (1919, 1924, 1928), Flohn (1952), Hjulström (1942, 1949), Kaufmann (1929), and van Rheden (1941).

From Jefferson's data Inglis finds that

$$M_b = 18.65\ W^{0.99} \qquad (2a)$$

$$\text{or} \qquad 17.38\ W \qquad (2b)$$

Bates' figures give

$$M_b = 10.9\ W^{1.04} \qquad (2c)$$

$$\text{or} \qquad 14\ W \qquad (2d)$$

These results may be compared with those of de Geer (1911) and with de Martonne's acceptance of $M_b = 18\ W$ for European rivers (de Martonne, 1935).

Inglis' analysis gives meander wave length as

$$M_1 = 6.06\ W^{0.99} \qquad (3a)$$

$$\text{or} \quad = 6.06\ W \qquad (3b)$$

from Jefferson's figures.

Some difference between formulae derived from different sets of data is not surprising, in view of the distortion to which individual meanders or meander trains are liable in nature, and considering also that bed width is not the only variable. It seems, however, that a fairly close relationship may be claimed, and the writer is prepared to accept a connection of the order given in equations (2a) to (2d).

SIZE OF MEANDERS, BED WIDTH, AND DISCHARGE

Inglis would go further and relate the width of meander belt directly to discharge (in cusecs) approximately as follows:

$$M_b = 57.8\ Q^{0.54} \qquad (4a)$$

$$\text{or} \qquad 84.7\ Q^{1/2} \qquad (4b)$$

An equation of this type depends on the assumption that bed width is related to discharge, and is, therefore, in accord with the work of Lacey, to whom a number of important channel formulae are due. Lacey concurs (1930) with the Lindley theorem that for a given discharge and silt factor the cross-sectional area, wetted perimeter, and slope of a stable channel flowing in and transporting its own silt are uniquely determined. Although in natural streams variations occur in silt factor, there is good reason to suppose that for a given value of S, discharge is by far the most important variable.[4] Lacey concludes that for stable channels in alluvium

$$P = 2.67\ Q^{1/2}, \qquad (5)$$

where P is the wetted perimeter in feet and Q the discharge in cusecs. This equation is claimed to be independent of silt grade (Lacey, 1938). Since in alluvial rivers W is approximately equal to P, it follows that $W \propto Q^{1/2}$. Inglis (1941) obtained a different constant, as follows:

$$W = 4.88\ Q^{1/2} \qquad (6)$$

but agrees, as has been noted, that P (or W), as also M_b and M_1, vary roughly as $Q^{1/2}$, and supports his contention by the analysis of various groups of data.

[4] The silt factor has been much debated, cf. White (1938), Schnackenberg (1951), and the discussions to Lacey's papers.

An equation of similar form, in which bed width is related to total annual discharge, is derived by Schoklitsch (1920) from a mass of data related to European rivers. Rewritten with the symbols used here, it becomes

$$W = \beta\ (CRM)^{0.6} \qquad (7)$$

where W is in feet, M the catchment area in square miles, R the annual rainfall in inches, C the coefficient of runoff, and β a bed coefficient ranging from 0.300 to 0.375. The advantage of this equation, for practical purposes, is that M may be obtained by planimetry, R from published data, and C from gauging records, or, if necessary, from rainfall records treated in the manner of Penman (1950) or Thornthwaite (1948).

CHANNEL FORM IN WINDING VALLEYS

Although there is clearly much room for additional work, the facts set out in the foregoing section are taken to verify a relation between discharge and bed width and between bed width and size of meanders. That is, a relation between discharge and size of meanders is taken as established. This conclusion appears to provide the required theoretical support for the view that valley bends are the work of former large streams—always supposing that the bends are identical in kind with stream meanders.

Mention has already been made of the evident similarity between the slopes developed at valley bends and the slopes eroded by an ingrowing meandering stream. It seemed to the writer that if the features were truly homologous the similarity ought also to appear in bed form. If large rivers had once occupied the winding valleys, it seemed possible that traces of their channels might still remain beneath the present alluvium, and that the bottom contours might be those typical of the bed of a meandering channel.

Six valleys have been investigated to date. Two lie in a formerly glaciated part of the English Midlands; one in the Cotswolds is a valley described by Davis, (1899); two in the Weald of southeastern England are outside the extreme limits of Pleistocene ice, and the sixth is in the Welsh Border country. In each valley the bed of the large river which cut the valley bends has been identified. The bottom contours are exactly appropriate to the channel of a meandering stream, very much larger than the existing river.

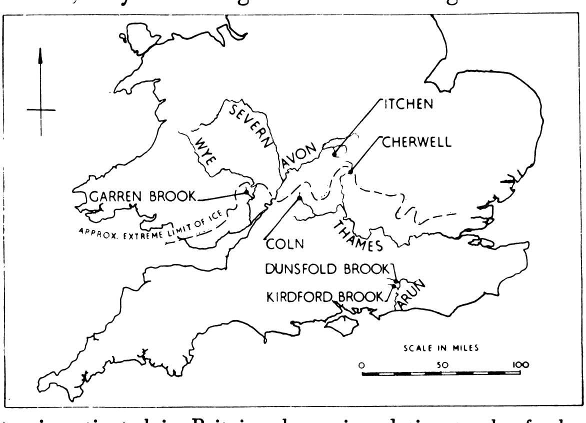


Fig. 3. Sites investigated in Britain, shown in relation to the farthest limit of ice.

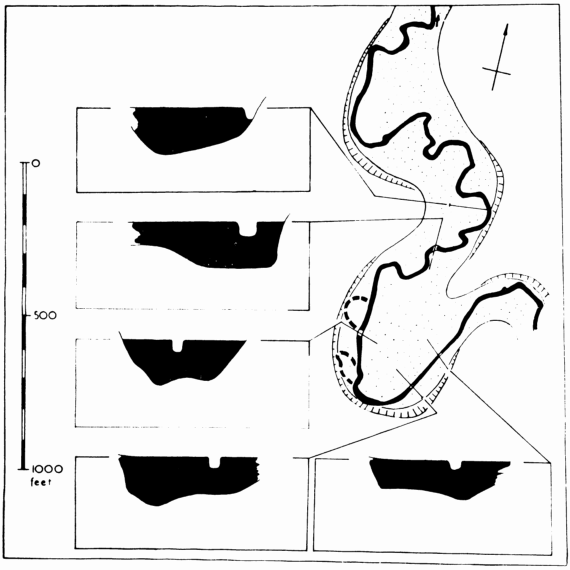


Fig. 4. Profiles of the filled channel on the Itchen, Warwickshire, England; catchment area approximately 9 square miles. Stipple on this and subsequent figures shows the present floodplain. Alluvium in solid black.

The Warwickshire Itchen has been best studied (figs. 3, 4, 5, 6). It is tributary to the Leam which in turn flows into the Stratford Avon. The valley was selected for investigation as containing impermeable alluvium underlain by impermeable solid rock, as not having been extended or reduced by divide migration since the last local glaciation, and as being tectonically stable. In part the valley is incised and winding, in part open and of very feeble relief but still with valley windings. On these counts none of the ad hoc explanations of valley bends, which were listed at the outset, could be postulated for the Itchen.

The windings are best displayed where the valley is incised into a limestone-shale series near the base of the Jurassic succession. The ribbon of alluvium which lines the valley bottom is for the most part sharply bounded in this reach by the base of the valley walls. The type features of winding valleys are well developed throughout—sinuosity on a large scale, steep slopes at the outside of valley bends, and gentle slopes on the inside, together with the small meanders of the existing stream. The latter, as is commonly observed, are mostly not in contact with the valley walls at many points but instead are described in the alluvium.

A number of auger holes were put down through the alluvium to the solid rock beneath, records of sample cores being kept, and the lines of working fixed by plane table on a base map of 1:2500 or 1:1250. The resulting data make it possible to draw sections through the valley bottom and, for some reaches, to construct contour maps of the base of the alluvium, as shown in the figures; these diagrams demonstrate the presence of a large *meandering* channel. It is seen that in the Itchen valley the former channel, now filled by alluvium, underlies the whole flood plain. It is asymmetrical at valley bends, being deepest at the outside of curves and shallowing towards the inner side. Where the valley is inflected between one bend and the next, the floor of the old channel rises: here are evidently the former crossings, and the crescentic deeps at bends are the former swales.

It is not proposed to discuss in detail the nature of the alluvial fill, either in the Itchen or in other valleys, since the constitution of the alluvium varies greatly from one valley to another. In consequence it seems best to leave detailed local descriptions to local journals, where some accounts have already appeared (see References). It may be remarked, however, that in all the valleys it was possible broadly to distinguish two kinds of material. The flood-plains are underlain by tenacious clay with impeded profile drainage; this in turn is underlain at many points by softer, moister material, which tends to become coarser in caliber at the base, and contains (or is much discolored by) plant debris. The former deposit appears to have settled out of floodwater, for all the valley bottoms are subject to flood, while the latter may well represent in part the former bed load but some of the characteristics noted belong to the development of a gley horizon in the soil. In most boreholes the junction between the alluvium and the solid rock beneath was very well defined. The solid, where consisting of limestone bands, was impenetrable; where argillaceous, it was dry, compact and tough, laminated in places, bright in color, abundantly micaceous but free of plant debris. In all these respects it contrasted with the alluvium. In other valleys solid rocks of different characteristics were found, but the junction in question was again clearly marked. The depths recorded in the diagrams are therefore looked on as wholly reliable.

It is important to observe that three different reaches of the Itchen were investigated, necessarily at different distances from the present source of the stream. It was found that the dimensions of the filled channel diminish headwards in about the same proportion as those of the existing channel. Hence the ratio between the respective widths of the two channels is the same throughout, as nearly as can be determined. Measurement is of course subject to a number of uncertainties, for the present banks are liable to be trodden down by cattle, while the filled channel seems to have shifted outwards at the bends; but the ratio of width can be roughly defined, by means of measurements at the respective crossings, as of the order of 10:1.

Now the same ratio appears in a comparison of the radii of curvature of the valley bends and the existing stream meanders in a group of streams in the English Midlands (Dury, 1951).[5] It also relates the widths of present and former channels near the head of the Cherwell (figs. 3, 7). What has affected the Itchen seems to have affected the Cherwell also, and to the same degree. Since the two streams are in competition, their loss of discharge cannot be due to capture.

[5] The writer is aware that the comparison of radii of curvature is not very satisfactory, and would recommend Leighly's paper of 1936 to fellow-investigators.

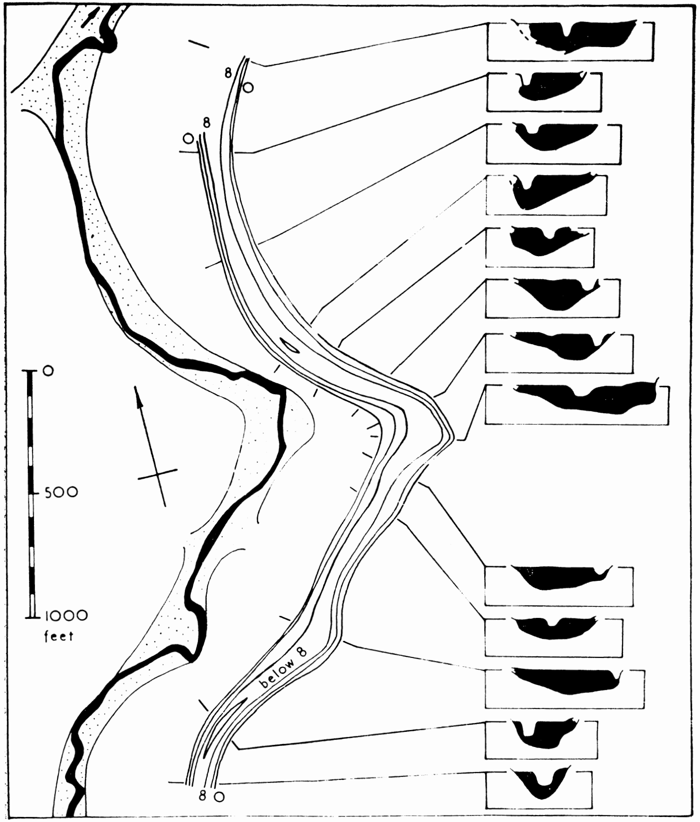


Fig. 5. Profiles of the filled channel on the Itchen: catchment area approximately 23 square miles. Contours show depth of channel floor below surface of floodplain, in feet. Map of present stream added for comparison.

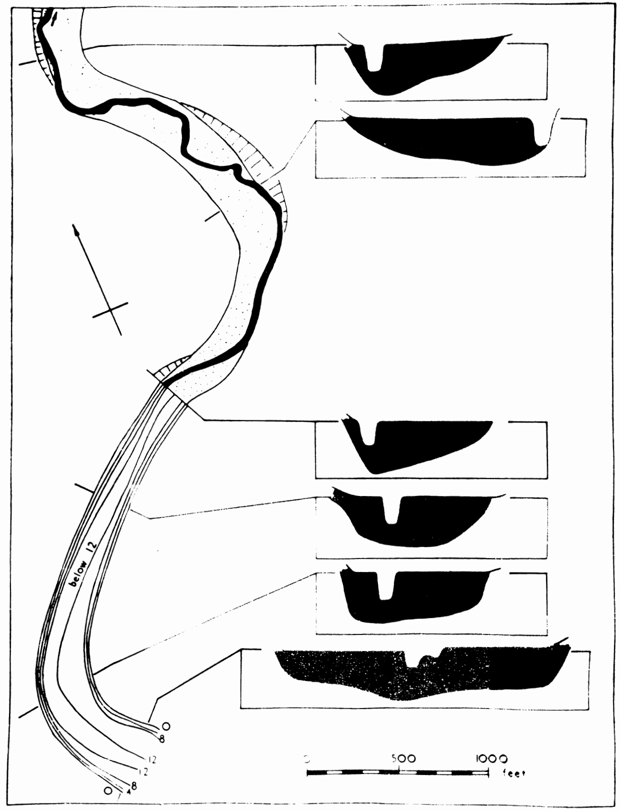


Fig. 6. Profiles of the filled channel on the Itchen: catchment area approximately 42 square miles. Contours in lower half as in figure 5; valley meander scars shown in upper half.

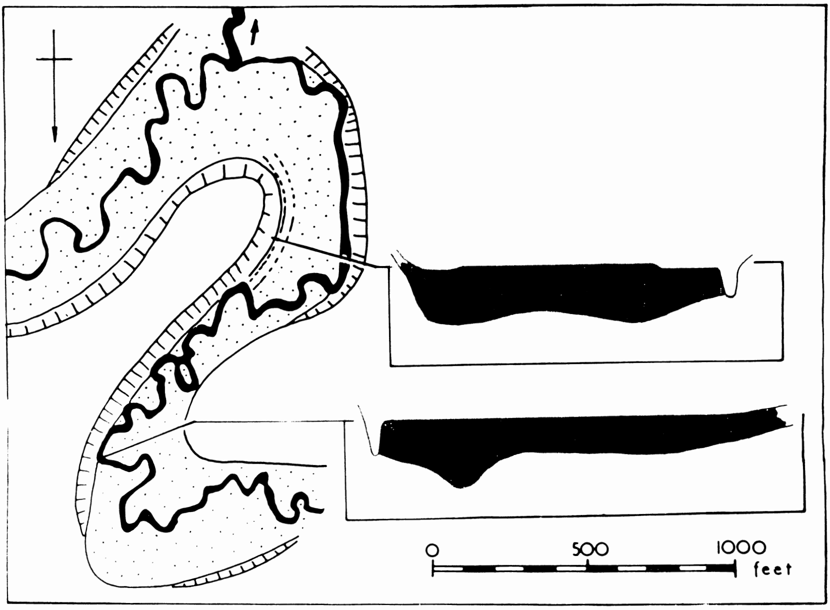


Fig. 7. Profiles of filled channel on the Cherwell, Northamptonshire, England. Form of valley walls indicated by symbols.

The Cotswold Coln (figs. 3, 8) is especially interesting in view of its use by Davis and Buckman to support the hypothesis of shrinkage through capture. Re-examination of the relevant reach of valley shows that both writers erred in identifying two sets of valley bends, which they took to indicate two successive captures. In fact there is only one set, in addition to the actively evolving loops of the present Coln. The field evidence is therefore wholly in accord with that of other localities, although there are complications. It is known that some water percolates into the subjacent oolitic limestone, so that the two channel widths can be less reliably compared. A knickpoint occurs in the middle of the reach investigated, and downstream from it the rejuvenated present stream has swept over much of the fill, planing off the solid floor beneath at some points. Nevertheless the general circumstances are similar to those known in the other valleys, and useful additional evidence is provided by local sludge gravels of Pleistocene age which demonstrably antedate the final cutting of the filled channel. The diagram shows that here too the present alluvium is contained in the channel of a former large meandering stream.

Percolation cannot have affected the two tributaries of the Sussex Arun (figs. 3, 9, 10) whose basins are largely underlain by Weald Clay, one of the great argillaceous formations of the Secondary succession. These streams moreover lie outside the limits of the Pleistocene ice sheets, and cannot have been affected by glacial meltwater or the discharge of proglacial lakes. The evidence secured in their valleys, however, closely resembles that from valleys in formerly glaciated parts. The filled channel is again present and is again

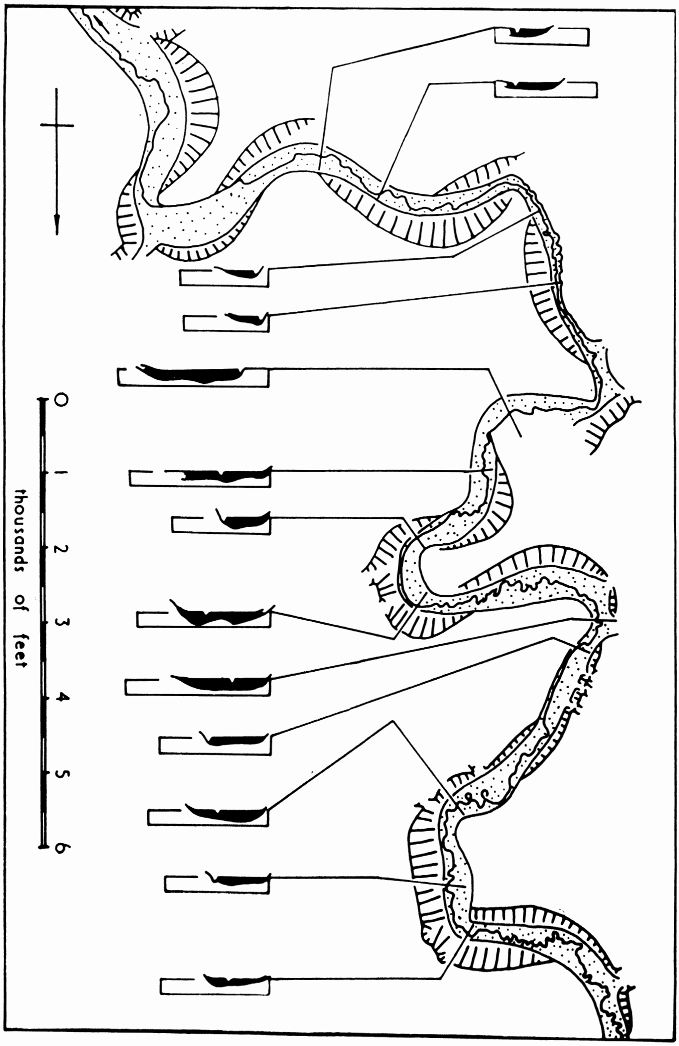


Fig. 8. Profiles of filled channel and form of valley walls on the Cotswold Coln.

asymmetrical at bends. It appears larger in proportion to the present stream bed than, for instance, the channel in the Itchen valley, but this is probably because the lines of augering run across valley bends where the old channel is laterally developed. The Garren Brook (figs. 3, 11), a tributary of the Wye, also drains a basin which is not thought to have been entered by ice. Here again a former channel encloses the alluvium. It will be seen that whereas the Itchen, Cherwell, and the two Sussex streams are not in contact with the solid rock except at the valley sides, and the Coln is eroding it only below the knickpoint, the Garren Brook has cut through the alluvial fill of the old channel and is becoming incised into the floor.

CHANNELS IN RELATION TO RUNOFF

In the writer's opinion, the qualitative results of field investigation are satisfactory and convincing as far as they go. It remains to be seen whether similar results will be obtained in other areas, particularly outside Britain, and it is hoped that the present account will stimulate others to join in the work. If the views advanced here are correct, comparable results are to be expected, although it need hardly be said that much variety of detail is likely to be found in practice. The matter need not, however, be left as it stands. Much additional light is thrown on the origin of the filled channels when their dimensions are compared with those of existing channels, and when they are considered quantitatively in relation to stream discharge and to size of drainage basins.

Data of bed width for both filled and present channels are given in table 1, together with areas of catchment. The length of wetted perimeter is stated only for the present channels, as it is difficult to determine bank level for the filled channels. The cross-sections show, however, that W and P were subequal in the latter.

In the small present channels matters are different. Depths are greater here in proportion to width, partly perhaps because the tenacious alluvium resists erosion and favors deepening at the expense of widening, but very largely because all the streams (except perhaps the Garren Brook) have been cleared in the course of drainage work. It may be noted in passing that the greater proportionate depths in the small channels have nothing to do with the principle of planimetric distortion (Lacey, 1934; Allen, 1947). According to this, depth in stream models [and in small streams] should be exaggerated in proportion to bed slope; but since the beds of the present streams are sensibly parallel to the known parts of the beds of the filled channels, there has been no significant increase in bed slope since the filled channels were in use. Indeed, when allowance is made for the greater tortuosity of the present streams, it appears that in some parts bed slope has actually been reduced.

Despite the uncertainties due to drainage works and to the difficulties of accurate and representative measurement, it is possible to obtain a rough relationship between the wetted perimeters or bed widths of the present streams, on the one hand, and stream discharge on the other. The linear measurements are made as at bankfull stage. Gauging records of flow are not plentiful in Britain, and in any event are not available for these small streams, but the mean annual discharge can easily be calculated from figures of rainfall minus losses.

It is interesting to observe the result of substituting *the mean annual discharge* for Q in Lacey's equation ((5) *supra*). Values for wetted perimeter P are obtained, which are about half the observed values, except for the Garren Brook; here the observed length of P is over four times that calculated. Although Lacey's equation is designed to apply to channels of constant discharge, and although its use in this way largely ignores the effect of fluctuations in Q, the similarity of results for all but one of the several basins is worthy of note. It suggests that the equation has a measure of validity in the

TABLE 1

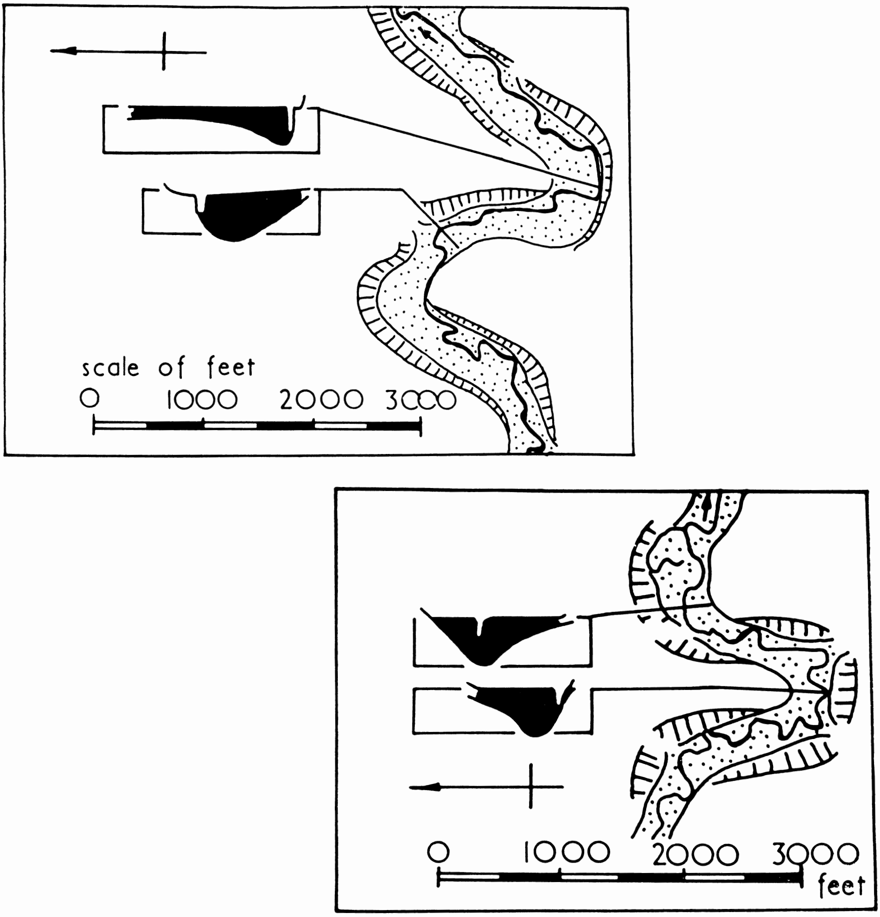
STATISTICS

BASIN	Catchment area M, square miles	Present annual rainfall R in.	Present annual runoff, r in. of rainfall	Coefficient of annual runoff, r/R	Present bed width, W_p ft. approx.	Bed width calculated from Schoklitsch's equation, (7)	Correcting factor	Present wetted perimeter, P_p feet approx.	Wetted perimeter calculated from Lacey's equation, (5), using mean annual value of Q.	Correcting factor	Bed width of filled channel, W_f feet; approx. equals wetted perimeter P_f	Ratio of bed width between filled and present channels, W_f/W_p	Discharge of filled channel at bankfull stage if $Q = \left(\frac{P}{2.67}\right)^2$, in cusecs	Rainfall intensity, in./hr., required to fill large channels with water if i = Q/640M
Itchen (i)	8.7	25.0	9	0.36	8	5	1.6	13	6.5	2.0	100	12.5	1400	0.25
Itchen (ii)	23.2	25.0	9	0.36	15	9	1.7	20	10.5	1.9	150	10	3165	0.21
Itchen (iii)	42.3	25.0	9	0.36	20	13	1.5	32	14	2.3	200	10	5610	0.21
Cherwell	13.3	25.0	9	0.36	10	6.5	1.5	21	8	2.6	125	12.5	2180	0.26
Coln (i)	13.2	30.0	9	0.30	10	6.5	1.5	14	8	1.8	140	14	2750	0.33
Coln (ii)	16.9	30.0	9	0.30	12	7.5	1.6	16	9	1.8	130	11	2315	0.21
Dunsfold Brook (to Arun)	37.0	28.5	11	0.39	18	14	1.3	34	14.5	2.3	275	15	10600	0.45
Kirdford Brook (to Arun)	20.8	30.0	12.5	0.42	15	10.5	1.4	26	11.5	2.3	200	13	5600	0.42
Garren Brook (to Wye)	4.1	33.0	13	0.39	15	4.0	3.8	23	5.3	4.3	75	5	780	0.30

Note: Certain apparent slight discrepancies in the calculations are due to the rounding-off of some figures.

climatic regimes concerned, for a correcting factor of 2 is alone required roughly to relate bed width to mean discharge. The value of the correcting factor could usefully be compared with the values relating to other climates, always supposing that a simple relationship of this kind were found to exist.

Similarly, Schoklitsch's equation, ((7) *supra*), which is derived from measurements of actual rivers and relates channel size to area of catchment, gives values of bed width smaller than those actually found in the present stream, even when the constant β is taken at the maximum value of 0.375. The necessary correcting factor here is of the order of 1.5, again excepting the Garren Brook, for which the factor is 3.7. Schoklitsch's work relates to rivers under the influence of continental rather than maritime climates, and also to larger catchments; it is likely that these small English rivers are very sensitive to heavy falls of rain, for in their short courses there is no time for flood peaks to be smoothed out. The high observed values of P and W for



Figs. 9, 10. Profiles of filled channels and forms of valley walls on two tributaries of the Arun, Sussex, England.

the Garren Brook are especially noteworthy, as belonging to a stream with a much steeper gradient and hillier basin than any of the others.

As has been already stated, the bed widths of the filled channels are some ten times those of the present channels in the same localities (see also table 1). If it be supposed, for the sake of argument, that the relationship between the dimensions of the filled channels and the runoff of the time can be expressed by the Lacey or Schoklitsch equations, with the same correcting factors applied as in existing conditions, it appears that former discharges were equivalent to 300, 400, or more inches of rain per annum. There is no reason to suppose a priori that any such totals of precipitation occurred, but the figures are worth mentioning in order to emphasize that present totals, even without loss, could not provide the runoffs needed to cut the filled channels. It is evident that no concentration by snowmelt could explain the high runoffs which once took place, for according to Lacey's equation, the present total annual runoff could have been delivered by the filled channels, flowing at bankfull stage, in two days or less. The whole of the present annual precipitation, with no loss to percolation or to evaporation, could similarly have been run off in no more than five days. It is necessary therefore to postulate a former precipitation greater, and probably considerably greater, than that which is now recorded.

FORMER INTENSITY OF RAINFALL

The information available is not sufficient to indicate what in fact was the scale of annual precipitation when the large meandering channels were in use by streams. Enquiry may be more profitable directed to the probable former intensity of rainfall, i.e. rate of fall per unit of time. The rate is necessarily expressed here as the equivalent of runoff.

Admittedly the characteristics of individual drainage basins vary considerably. Too little is known of those investigated for use to be made of hydrograph analysis, even if the responses to very heavy falls could be accurately predicted. But simple flood-discharge formulae may be employed to show the *minimum* runoff equivalent needed to produce streams capable of filling the large channels to bankful. The best known is probably the Rational Formula:

$$Q_{max} = 640\ CiM \qquad (8)$$

where Q_{max} is the greatest expectable flood discharge past a given point, M the area in square miles of the catchment above that point, C a coefficient of runoff, and i the intensity of rainfall in inches per hour. Assuming a total (and extremely rapid) runoff, C becomes unity. The intensity of rainfall required to produce a given discharge is then given by

$$i = \frac{Q_{max}}{640\ M} \qquad (9)$$

Now the rates of discharge for the large channels can be found by means of Lacey's equation (5). When they are substituted for Q_{max} in equation (9), values of i are obtained as shown in table 1, column 15. The runoff equivalents correspond to rainfall intensities ranging from 0.20 to 0.33 inches per hour.

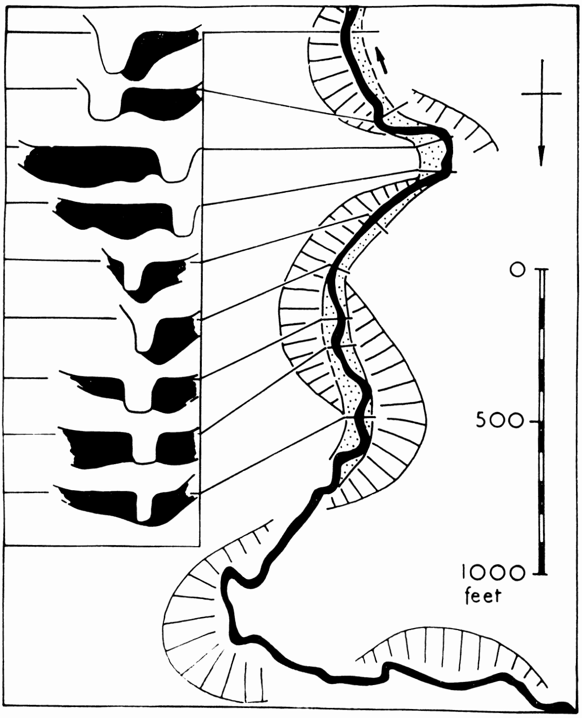


Fig. 11. Profiles of filled channel and form of vallev walls on the Garren Brook, Herefordshire, England. Note incision of stream into the solid rock.

It may well appear significant that the values thus calculated are of the same order of magnitude in every case, although such a result might have been expected from the rough relationship of channel size to size of catchment.

It will be clear that the assumed connection between bed width, size of basin, and rainfall intensity expressed by the equations (5) and (9) can be used in a nomogram of the form shown in figure 12. Given values of M. and of W for the filled channels, the values of i can be read off directly.

At the present day, rainfalls of 0.20 in./hr. are to be expected in the basins studied on about 10 days a year, while the expectable frequency for falls of 0.35 in./hr. is only about 2 days. The scanty records available seem to indicate that the existing streams rise to, or above, bankfull stage on perhaps 10-20 days in an average year. This fact appears to confirm the implication in the foregoing, that the present channels are inadequate to cope with discharges produced by a rainfall intensity which was formerly usual rather than exceptional. The particular line of reasoning followed here further suggests that the large channels could have been cut when the total annual fall was considerably less than the 300 inches referred to above, but an actual figure cannot be derived without assuming some relationship between the rainfall intensity and the annual total. It should be noted, however, that if the large channels are to be associated with the compression of storm tracks

Table 2

Correlations: Based on the Work of Arkell. Flint, Shotton and Zeuner

	North America	Alps	Continental Europe	English Midlands	Midland Rivers—Nene, Ouse and Avon	Oxford Rivers—Cherwell and Windrush	Oxford Rivers—Evenlode
Postglacial					↑ Valley bends of Avon eroded as far as postglacial time		↑ Valley bends of Evenlode evolve into postglacial time
Glacial	Wisconsin	Würm	Warthe, etc.	Welsh re-advance (Cymrian of Arkell) Irish Sea Glaciation (Cornovian of Arkell)			
Interglacial	Sangamon	R/W				Floodplain gravel in valley-bends Taplow gravel in valley bends	
Glacial	Illinoian	Riss	Saale	Great Chalky Boulder Clay (Catuvellaunian of Arkell)	Warwickshire Avon Initiated		Evenlode gorge initiated
Interglacial	Yarmouth	M/R			Great Ouse valley meanders incised	Boyn Hill gravels in valley bends	
Glacial	Kansan	Mindel	Elster	Older Drift, Northern Drift (Berrocian of Arkell)			
Interglacial	Aftonian	G/M			? Nene valley already cut?		
Glacial	Nebraskan	Günz					

in parts of the Pleistocene, the highest rainfall intensities may not have departed greatly from the modal intensity, and that 300 inches could have fallen in less than 900 hours at a rate of 0.35 in./hr.

DATING THE EPISODES OF GREAT DISCHARGE

A discussion on climatic change cannot be initiated here, but two facts may be remarked in passing. Recent studies (Hoyt et al., 1936) indicate that rivers are extremely sensitive to changes in precipitation, while a number of well-known authorities postulate increased rainfall in mid-latitudes during the Pleistocene, often associated with the displacement of storm tracks (Willett, 1949, 1950).

For the time being it seems more important to consider the dating of winding valleys. There is good reason to place the inception of some, at least, well back in the Pleistocene, while the filled channels so far studied all seem to have been in use in Holocene time. A few significant examples must serve to illustrate the progress, admittedly limited, made to date in drawing up a

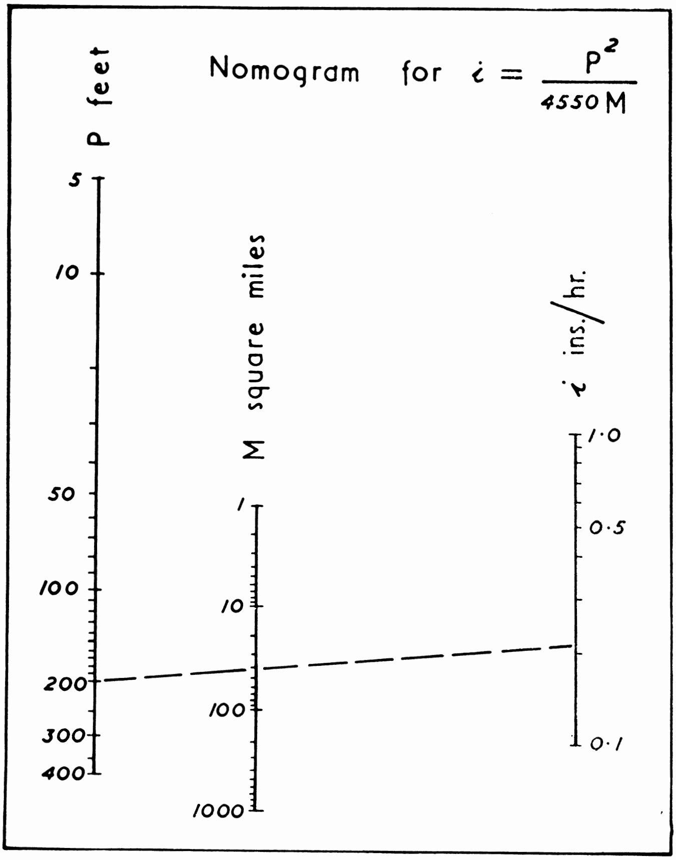


Fig. 12 Nomogram relating bed width of filled channels to minimum rainfall intensity required to produce adequate streams.

time scale. The results are summarized in table 2, where they are tentatively referred to the North American chronology recognized by Flint (1947).

The great abandoned loops of the Wye lie well above the river, in one instance about 400 feet (Davies, 1923; Miller, 1935). In the Oxford District, valley loops include, and therefore cannot postdate deposits of gravel *in situ* ranging in age from Boyn Hill to Flood Plain (Yarmouth to Sangamon) (Davies, 1923; Arkell, 1947). The great loops of the Stratford Avon seem to have swept out a meander trough at the no. 2 Terrace stage (Dury, 1951: Tomlinson, 1925). On the Seine, the train of valley bends from Rouen to Chizier seems to have appeared at the end of the Tyrrhenian [sic] glaciation (Cholley and Firmin, 1945). Valley bends of the Great Ouse are plugged by till of an ice sheet correlative probably with the Riss of the Alps (Dury, 1952). In the Fenlands of eastern England, old channels are known which describe loops more ample than those of the existing stream. Pollen analysis shows (Godwin, 1938, 1940) that the channels were cut at least as early as the preboreal period, by large streams which underwent a reduction of volume at least as early as 7500 B. C.

The evidence could be multiplied by reference to well-studied terraces, but perhaps enough has been said to indicate the interconnection of winding valleys and Pleistocene climates. A leading principle for future work on the chronology must obviously be that a winding valley is later than an erosion platform into which it is cut, and at least as early as the deposits which it contains. The most difficult task, however, appears to be the dating of the latest use of the filled channels; here radiocarbon dating and pollen analysis might help in fixing the age of the fill, but it is highly desirable to locate examples of valley bends incised into rocks as young as possible.

IMPLICATIONS

If valley bends are indeed the meanders of great streams, and if these were fed by rainfalls of the intensity inferred here, a number of further problems at once arise. The question of stream grade and of valley gradient in the areas affected needs to be re-examined. It follows from slope-discharge formulae and from the theory of stream models that a general reduction of discharge should lead to an increase in slope. But since aggradation seems to have made little headway in the valleys studied, the valley gradients seem to be related to former rather than to present discharges. Therefore the present streams cannot be graded in the Davisian sense. It necessarily follows from this conclusion that attempts to relate long profiles to present discharges are based on a false assumption.

The problem of dry valleys, especially in Chalk country, must also be considered anew. It is widely held (although not universally) that the valleys have been left dry as the water table was lowered by excavation of the water-retaining beds below the Chalk. But since the occurrence of valley windings has been shown to be independent of movements of the water table, it must be asked what would be the effect on dry valleys of frequent and heavy falls of rain. Even today, when underground circulation is presumably better organized than ever before, temporary streams appear in some dry valleys in unusually wet seasons. It is at least permissible to suggest that, when large rivers were eroding the valley bends, many valleys of Chalk tracts were occupied by streams, and that a return to former climatic conditions would again produce surface flow in areas now dry. On this view, lowering of the water table is due primarily to climatic change rather than to erosion.

A third important topic is that of process. Climatic change necessarily involves change in the relative effectiveness of erosional processes, and many recent studies suggest that small changes in climate may well bring additional processes into play. Increased rainfall intensity should favor the operation of sheet flood and sheet erosion in areas where rainwash, rillwash and creep are now dominant. This subject again is far too complex to be dealt with here, even in summary, but the suggestion made may seem to point the way to a solution of certain refractory problems of landscape evolution in humid as well as in arid climates.

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