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THE MEANDERING OF ALLUVIAL RIVERS

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To explain the formation of meanders, the author has synthesized relevant knowledge and utilized basic physical principles of flowing turbulent water and its interaction with the river bed.
Starting from an initially straight and smooth channel, one can argue that the most probable site of the first erosional scar will be lateral from the centre of the river. This scar will then develop into a cavity, which in turn will affect the streamline situation of the flow. In front of the cavity the streamlines will converge, and behind it they will diverge. The diverging streamlines, together with unaffected or less affected streamlines, will then create a new convergence zone behind the first cavity but on the opposite side of the river's centre line. The ultimate and most probable and stable result will be a meander.

The aim of this paper is to give a physically sound explanation of the initiation of meandering on alluvial beds.

No new experimental data have been obtained, but published data generally support the thesis presented. The discussion is intentionally descriptive, rather than quantitative, because no new mathematical developments are involved. Adequate references are cited for those wishing to pursue the development more thoroughly.

LITERATURE REVIEW

Geomorphologists for many years have tried to explain the geometric regularity of stream meanders. One of the first theories of meandering was based on the concept of the graded river. The term "graded" goes back to Gilbert (1877); a definition is given by Mackin (1948).

The rotation of the earth, which causes the Coriolis force, has been used as an explanation of meandering (Eakin 1910, Einstein 1926, Neu 1969). Dinga (1970) showed that the meander pattern is influenced by the rotation of the earth: in the Northern Hemisphere, the radius of a right-hand turn tends to be smaller than that of a left-hand turn.

Other theories of meandering have been based upon the existence of secondary, helicoidal flow in river bends. Helicoidal currents have been described by many researchers (Thomson 1877, Einstein 1926, Vogel & Thompson 1933, Wittman & Böss 1938, Shukry 1950, Prandtl 1953, Einstein & Harder 1954, Leliavsky 1955, Ananyan 1957, Einstein & Li 1958, Delleur & McManus 1959, Leopold & Wolman 1960, Ippen et al. 1960, 1962, Kondrat'ev 1962, Rozovskii 1963, Henderson 1966, Desaulniers & Frenette 1971, and others).

Helicoidal currents will cause erosion at the outer bank of a river and deposition at the inner bank. Prus-Chacinski (1954), Leliavski (1955), and others, argue that helicoidal flow is the basic mechanism that leads to meandering. The work of Bagnold (1960) indicates that helicoidal motion is a necessary consequence of flow through a curved channel. Einstein & Li (1958), from the concept of mean and fluctuating velocity components and the basic Navier-Stoke equations, concluded that one can expect secondary currents even in straight channels. This work does not, however, explain the initiation of secondary currents in a straight flow. Delleur & McManus (1959) have shown that the shear stress in a straight open channel can initiate the secondary flow. Chiu & Lee (1971) have given a method to calculate secondary flow in a straight channel. The theory of helicoidal flow thus explains why a meandering river continues to meander, but it fails to explain how meandering is initiated.

A completely different approach to explain meanders has been taken by Leopold & Langbein. The work of Leopold & Wolman (1960) and Leopold et al. (1964) suggests that meandering may be related to a condition of minimum energy expenditure in the channel. These ideas were later elaborated by Langbein & Leopold (1966) and Leopold & Langbein (1966). They propose that the most probable path of a river can be expressed in terms of a random walk. This is, however, a dubious approach, as the physical and dynamic properties of flowing water are neglected in favor of statistical considerations.

Other theories have been presented by Hjulström (1942, 1949), Fujiyoshi (1950), Speight (1965, 1967) and Werner (1951).

According to Scheidegger (1970) the Werner theory, although crude, is still the best one available to correlate meander wavelength with other quantities characterizing the flow. Werner's theory fails, however, in the physical deduction of the meander initiation.

The difficulty of giving a satisfactory theoretical explanation of meandering has prompted investigators to try empirical methods (Jefferson 1902, Tiffany & Nelson 1939, Inglis 1947, 1949, Friedkin 1945, Leopold & Wolman 1957, 1960, Shen 1961, Leopold et al. 1964, Carlston 1965, Dury 1965, Snyder & Stall 1965, Anderson 1967, Shen & Komura 1968, Ackers & Charlton 1970, Chitale 1970, Maddock 1970, Nilsson & Martvall 1972).

These experimental studies have produced an indication of the factors involved in meander formation, if not a true explanation of the origin in terms of basic physical principles.

Recently Yang (1971 a, b) has published two papers on river meanders. He has proposed a theory based upon the concept of entropy which was introduced by Leopold & Langbein (1962). Leopold & Langbein developed their large scale landscape theory using analogies to thermodynamic principles. Yang's approach is very interesting, but as he bases his theory on the concept of entropy he works in a macro scale where it is no longer possible to follow the development of a single constituent, like a river. Another question mark in Yang's theory is that he does not start from the basic physical properties of flowing turbulent water and its interaction with the river bed. I think that, in the future, the stochastic models that will be of the greatest value are those that are founded on basic physical principles.

THE INITIATION OF MEANDERS

Assuming that the helicoidal theory correctly explains the maintenance of meanders, the problem of initiation still remains unsolved. Leopold et al. (1964) explain the initiation in this way: "The vagaries of nature provide endless opportunities for perturbations in the flow – local bank erosion, chance emplacement of a boulder, fallen trees – any one of which would alter the path of a straight channel. Thus one need hardly inquire why a channel is not straight." This, of course, is not an acceptable theoretical explanation, nor can it explain the meander development even in flume experiments. For example, Tiffany & Nelson (1939), Quraishy (1944), Friedkin (1945), Shen (1961) and Karcz (1971) have shown that meanders develop spontaneously in flume experiments with alluvial material. The key to the problem must be found in the dynamic properties of flowing water and their interaction with the stream bed.

The velocity distribution in a river has been investigated both theoretically and experimentally by numerous workers (Lane 1937, Matthés 1949, Sundborg 1956, Tracy and Lester 1961, Rozovskii 1963, Taffaleti 1963, and many others). The velocity distribution pattern in a transverse cross section in a channel is generally symmetrical as long as the section itself is symmetrical, but the morphological activity of a stream is not a simple function of the velocity distribution. Even if the cross section is symmetrical, the instantaneous maximum shear stresses may be asymmetrically distributed.

Laboratory tests by Ippen et al. (1962) and Yen (1965) have also shown that an asymmetric velocity distribution pattern is present in symmetrical sections downstream from bends.

A necessary but not sufficient condition for meander development is that the discharge and the grain size distribution are within certain definite limits. Werner (1951) has shown that no true meanders can develop in shooting flow. From Hjulström's (1935) and Sundborg's (1956) curves on the relationship between the particle size and the critical erosion velocity, one can deduce the necessary physical conditions for meandering.

The mechanism of entrainment of particles from the bottom have been studied thoroughly by Sundborg (1956) and more recently by Grigg (1970) using radioactive techniques. The force in action is the shearing force (boundary shear, shear stress, tractive force) for turbulent flow.

According to general theories, for example Prandtl (1926), the shear stress increases with the velocity gradient, other parameters (viscosity, eddy viscosty) being held constant.

Another aspect of utmost importance in the initiation of meanders is the site of the very first erosion on the river bed. The entrainment of the first particles will create a new flow (streamline) situation. A discussion of the concept of streamline is given by Allen (1968). A functional relation for sediment-pickup has been established by Lefeuvre et al. (1970). In the following, streamlines represent the actual path of fluid particles in a quasisteady state. Once the first scar has appeared on the bottom, this place will be the favoured location for intensified erosion.

According to Leighly (1934) the distribution patterns of velocity and of turbulence in a stream cross section may be quite different. He gives a theoretical explanation as well as experimental data which indicate the existence of zones of maximum turbulence flanking the central region of maximum velocity. A consequence of Leighly's results is that the most probable site of the first entrainment would be in or near the zones of maximum turbulence, that is, sideways from the centre line of the channel. Hjulström (1935) strongly supports Leighly's ideas. Even if Leighly's theories of flanking zones of maximum turbulence are not always valid, one can still argue that the most probable site of the first erosion would be near the banks rather than in the thalweg.

We can predict that the combined effect of decreasing depth and increasing transverse slope of the river bed will result in greater turbulence. The inclination of river banks also results in a dynamically more unstable environment for the river bed material, due to the force of gravity, than do plane beds. The theory of a basic instability in turbulent flow adopted by Einstein & Li (1957) and by Anayan (1959) supports the idea that the most probable site of the first entrainment would be lateral from the centre line of the channel.

Accordingly, one will get a converging streamline pattern on the side of the channel. A cavity will eventually develop and a new convergence zone will occur downstream from the first caving and on the opposite side of the channel. This will create a new scar, and so on. These arguments are supported by some of the results from flume experiments conducted by Shen (1961). He found that a series of alternating scour-holes developed, in a straight flume, along the flow direction.

Although based on physical reasoning, the deduction may be schematically summarized in the following manner.

1. The Initial Stage

The river bed material is assumed to be alluvial. As in most natural rivers, the cross section is supposed to be of a semielliptical type. The channel is straight and the streamline pattern is undisturbed by any irregularities on the river bed, aside from the natural roughness. According to the discussion above, the most probable site of the very first entrainment of a particle is lateral from the centre line of the river because of at least the following reasons: a) the existence of flanking zones of maximum turbulence, and b) the instability of particles resting on an inclined river bed.

2. The Developing Stage

I herein want to consider primarily the development of a meander from an initially straight, uniform channel, where rocks, tree roots, etc. cannot be the cause of the first disturbance. The first erosion scar might develop on either side of the river. The Coriolis force is thought to be negligible. When the very first erosion has occurred a new streamline pattern will develop. The streamlines will converege in front of the scar and thus create a zone of increased turbulent activity leading to an increased probability of further erosion on the same spot. The scar will grow and develop to form a larger cavity. In front of the cavity one will get a comparatively large converging streamline pattern, and behind the cavity the streamlines will diverge. For the further development I consider the following to be the most probable. The diverging streamlines behind the cavity sooner or later must of necessity converge with other straight or nearly straight streamlines which are relatively uninfluenced by the cavity. A new convergence zone will appear behind the first cavity but on the opposite side of the river (Fig. 1). That the second cavity will appear on the opposite and not on the same side of the river as the first cavity may be concluded on the basis of dynamic as well as geometric reasoning. The diverging streamlines behind the first cavity will thus participate and create a new convergence zone with increased turbulence in the zone of maximum turbulence behind and on the opposite side of the first cavity. The development of the second cavity must then lead to a third cavity behind the second one but on the same side as the first cavity. The process started in this way may then prolong itself down the river and perhaps also develop backwards. A slightly sinusoidal river with a helicoidal (secondary) flow finishes the Developing Stage.

3. The Mature Stage

The meander wavelength, the slope and all other meander characteristics will then eventually adjust themselves to the prevailing conditions of the actual river, and a steady state of equilibrium will be reached.

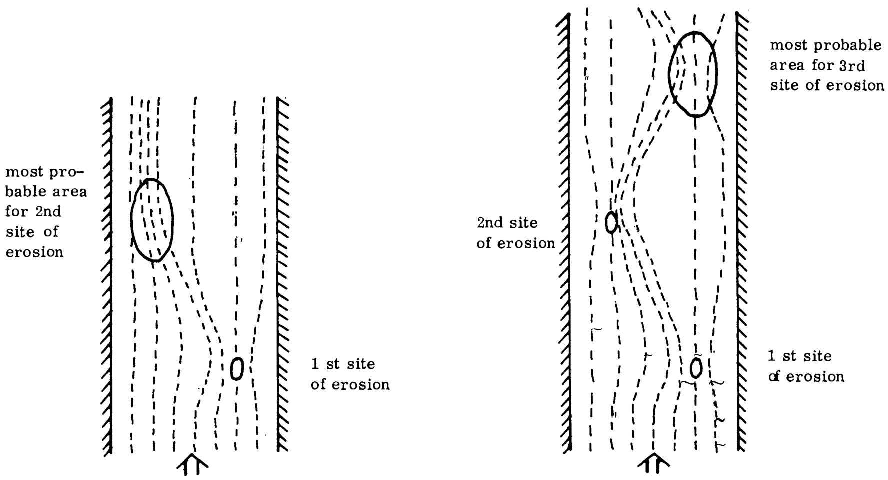

Fig. 1.
Schematic illustration of the development downstream of the first erosional scar.

If the bottom surface is rippled, Sundborg (1956) has argued that this is the only stable surface when the flow is smooth or transitional; the same type of argumentation on meander initiation should be valid. Yen (1970) has studied how the bed topography affects flow in a meander. His results do not seem to contradict this interpretation of meandering. Under given physical conditions a meander would be the most probable and most stable course for a river.

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