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GEOMORPHOLOGICAL CHANGES AFTER RIVER-MEANDER SURGERY[1]

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ABSTRACT

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A meandering river, upon preliminary inspection, looks like a very inefficient system, in need of serious correction. That the contrary is the case is shown by geomorphological changes which occur when sets of river meanders are cut off and replaced by straight or curved channel sections. Subsequent to the meander cutting, the potentially available energy per metre of channel increases dramatically and the water velocity increases. The excess energy causes erosion of bed and banks, while eroded material is deposited in the downstream channel.

Before equilibrium can be reached again, a river bed must incise deeply for considerable distance upstream. Thereupon the river will start to make a new set of meanders not unlike the old meander pattern. The one-dimensional open-channel flow equation, when applied to river erosion (triggered by meander cutting), shows that the 'half life' of such man-made disturbances ranges from hundreds to a thousand years. Consequently, man-made interference with natural rivers represents a costly capital operation, which requires a long term (50-100 years) commitment for up-keep, improvement and replacement, if not in the short run, then in the long run (next 500 years).

INTRODUCTION

Rivers in most countries provide a water supply for people in channels, ready-made for exploitation. They provide the water demanded by a substantial number of cities, industries, towns and settlements. Those towns which are in the fortunate position to have a river nearby, must also live with some less desirable fluvial behaviour:

(1) erosion of river banks on which people have settled;
(2) flooding of land at high runoff;
(3) droughts at low flows, associated with lowering groundwater tables.

The problems, which the absence or presence of rivers have posed, have in turn precipitated solutions resulting in a hundred thousand cases of interference in the natural equilibrium of river systems, exemplified by practically any type of large construction project on rivers in the ± 200 countries in this world.

Interference with rivers through civil-engineering works may occur, temporarily or permanently, via changes of:

(1) river bed;
(2) the river discharge;
(3) the river-water level.

This report analyses geomorphological changes caused by river regulation of the first category, that is the modification of the river bed by cutting off river meanders to reduce flooding, improve navigation, or to permit land development.

The principles of conservation of mass, energy, and momentum are applied. The objective is to predict the future changes in river systems as a result of the man-made meander cutting.

The basic assumption is that the civil-engineering ethics of river surgery require to:

(1) create a stable condition on a river over a long period of time (50-100 years);
(2) which will serve the people in the area for 50-100 years;
(3) such that the investment pays off in a long-term benefit (50-100 years).

CLASSICAL MEANDER ENGINEERING TRIALS

The cutting of the meanders of rivers has been a terrain for some classical engineering trials. The reason is perhaps that a meandering river, upon preliminary inspection, looks like a

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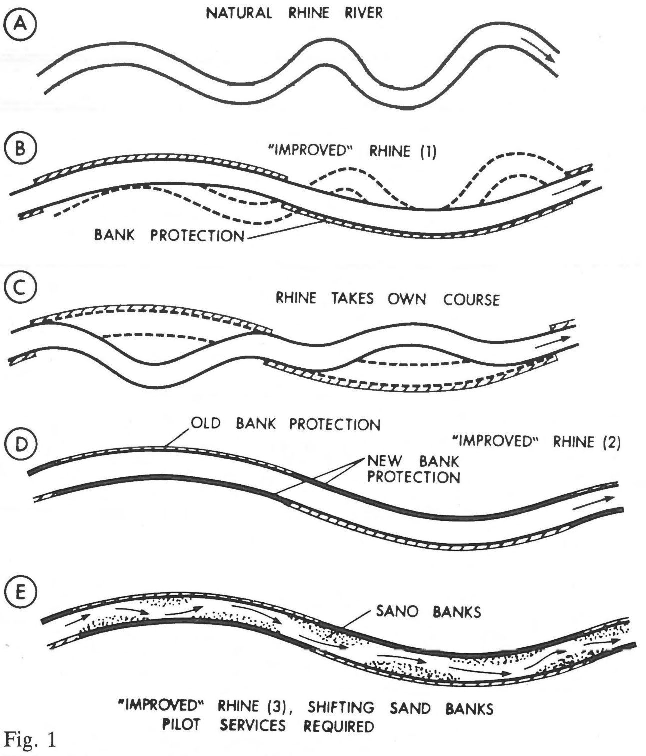


Fig. 1
Rhine River meander cut-off experience.

very inefficient system, in need of serious correction. That the contrary is the case, is obviously not obvious. For example, in 1800 the plans of Joh. Gottr. Tulla called for the shortening of the Rhine River meanders between Basel and Strassbourg by 14%. This was carried out by the construction of river bends which were given much greater radii than the radii of the previous natural Rhine meander bends (Fig. 1: A, B). Part of the engineering plan called for the construction of reinforced outer banks of a bend. Subsequently, however, the river had much more available energy in the shortened reach and the Rhine channel established a new set of meanders, similar to its previous natural meander pattern, with the exception of the reinforced outer banks (Fig. 1C). The only solution to the problem which would keep the old protection functioning, consisted of the protection of all banks and this was carried out, rather *gründlich* (Fig. 1D). The entire Rhine channel was now fixed in space and time, but a new unexpected problem arose (Fig. 1E). The river bed began to shift and is still moving, making this stretch of the Rhine so treacherous with sand banks, that a system of pilot services is required (VAN BENDEGOM, 1973).

Fifty years after the Rhine River works, meander engineering projects on the Mississippi River started in the 1850's with the aim of improved navigation. However, not until the 1880's was dredging used extensively to rapidly change the river bed and river banks on a major scale. Dredging was also used to mine gravel for construction material (LAGASSE & SIMONS, 1976).

As in Germany a century before that, the alignment of the Mississippi River was improved, starting in 1928, by (1) an extensive cutting off of meander loops; (2) a corrective dredging program to produce a gently sinuous river; and (3) fixing the alignment by bank protection. Between 1929-1945 the distance between the mouths of the White River and the Red River on the lower Mississippi was shortened by not less than 155 river kilometres. Consequently, for identical high floods, the specific water level in 1928 before cutt off, and in 1941, 13 years after cutt off, was reduced by 3-4 m along the entire reach, measured by 8 stations. However, in the downstream reach, water levels rose one metre initially, from 1928-1931. After 1931 water levels decreased sharply. After 1941 the water levels have been rising unsteadily and at least 1.5 metres from 1941, up to the present. Just as on the Rhine, it was found that the Mississippi cut offs increased water surface slopes and velocity, causing bank failure, disrupting the sinuosity and sequencing of pools and crossings. In analogy with the lower Rhine, it was found on the lower Mississippi that the configuration and alignment of dredged river cut-offs are only marginally stable. Similar to the Rhine, it was established on the Mississippi (LAGASSE & SIMONS, 1976) that dredging alone is rarely successful in obtaining and assuring navigation depth, unless combined with dikes; the latter to prevent lateral erosion and to keep the channel at depth and contracted. It was found that repeated dredging directly interrupts or retards downstream movement of bed-load sediment in the river, while it is as bed load that the bed material exercises its greatest influence on river meanders. Consequently dredging in the upper Mississippi contributes to the sediment deficiency in the lower Mississippi.

The Rhine and Mississippi Rivers are both large rivers, which sometimes leads to the assumption that small rivers are not as much affected by meander surgery. The following recent example from a small river is therefore instructive as it has not yet been reported in the literature.

In 1953 and during the period of 1968-1971 the meanders of the lower West (1200 km^2) and East (1500 km^2) Prairie Rivers and the South Heart River (1700 km^2) in Central Alberta, Western Canada (Fig. 2A) were cut off by straight canal sections (Fig. 2B). The new canal system bypassed swamps and its purpose was to reduce the effects of flooding. Flooding affected not only the town of High Prairie, but also farmland settlements downstream from the town.

During this operation the river course was shortened from 33 km to 20 km over the stretch from the town of High Prairie to the junction of the South Heart River with the East Prairie River. The canal extends another 1.5 km past that junction, but it stops some 15 km short of Buffalo Bay, the west arm of Lesser Slave Lake.

During and after the operation serious problems arose:
- erosion of farmland upstream from the town;
- erosion of industrial land in the town;
- erosion of farmland along the canal downstream from the town, new meanders are forming in the man-made straight canal sections;
- river-bed degradation of 1-6 m at the upstream end of the

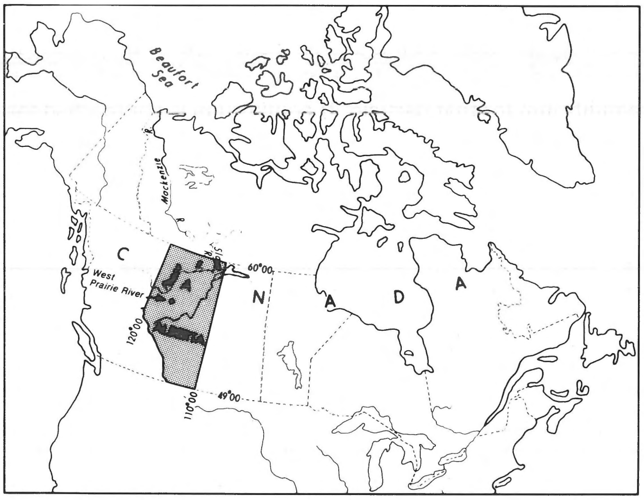


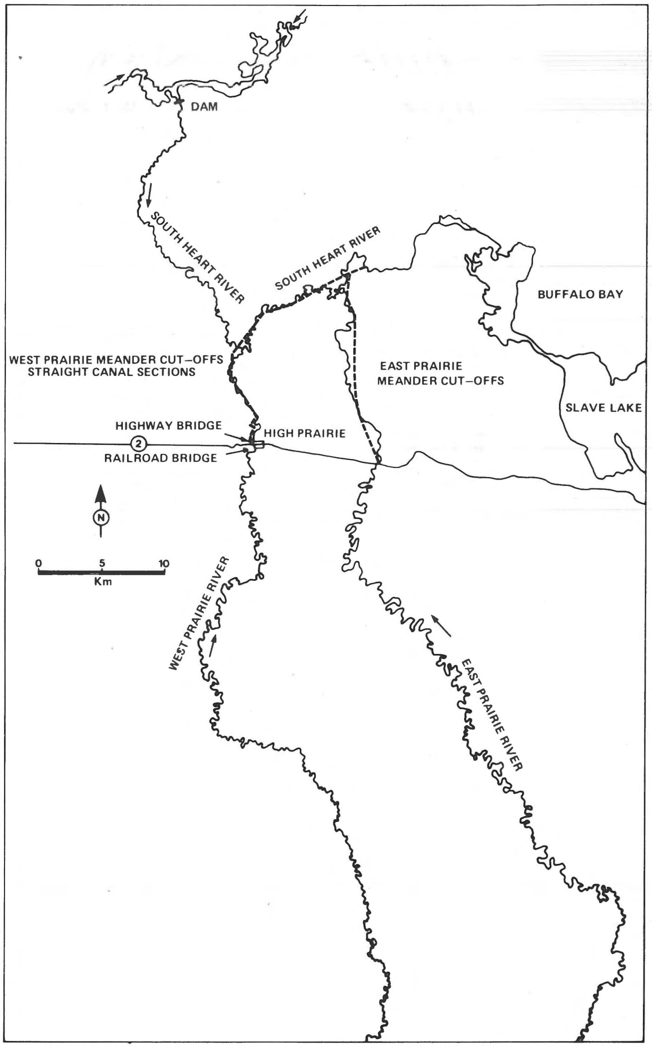
Fig. 2
Location map of the West Prairie River meander cut-offs.

canal;
- river bed aggradation of 0.5-2.5 m in the downstream portion of the canal, especially downstream from the confluence of tributaries;
- highway and railroad bridges scoured;
- siltation of downstream channel at river junctions under backwater conditions, deposition of sediment overbank on farmland;
- reduced flood protection when dikes for flood protection are overtopped and broken in the downstream canal;
- a growth of an extended delta in the west arm of Lesser Slave Lake;
- sedimentation of fine sediment in Buffalo Bay.

Problems are compounded at the downstream end of the canal by dam regulation on the South Heart River upstream from the West Prairie confluence and by meander cutting carried out on the East Prairie River.

KELVIN'S EXPLANATION OF MEANDERS

In all fairness to the engineers working on the Rhine River in the early 1800's, and to the engineers working on the Mississippi River in the 1850's, it must be stated that it was not until 1876 that J. THOMSON (1872), in a report communicated by W. Thomson, Lord Kelvin, for the Royal Society in 1876 described, perhaps as the first physicist to do so, the helicoidal flow mechanism of rivers. He stated that in a meandering river bend, the water pressure in a cross section must be increasing from the inner bend to the outer bend, on account of the centrifugal force of the water particles. Thus, he argued, the water surface of the river will have a transverse inclination. Thomson stated that the layer of water along the bottom, being by friction much retarded, has much less centrifugal



force, and consequently will flow sidewise along the bottom towards the inner bank. At the inner bank the bottom flow will, at least partly, rise up, deposit material and protect the inner bank. On the other hand, along the outer bank there will be a general tendency to descent of surface water which will have a high velocity, not having been much impeded by friction. This mechanism, Thomson stated, will wear away the bank and carry the worn substance down to the bottom of the river. The material worn from the outer bank may have to travel a long distance down stream before finding an inner bank of a bend on which to deposit itself. Thomson defined the helicoidal or spiral flow as *'oblique flow'*.

It is noteworthy that Thomson showed in his illustrations that oblique flow along the bottom towards the inner bank begins even upstream from the bend. In other words, Thomson noted that the spiral axis is offset with respect to the centre line of the meander. In his theory, the transverse movement of water, associated with oblique flow, is instigated by the abatement of pressure in the water along the inner bank, produced by centrifugal force. Now, more than a century later, it is sufficient to state that Thomson's theory still stands.

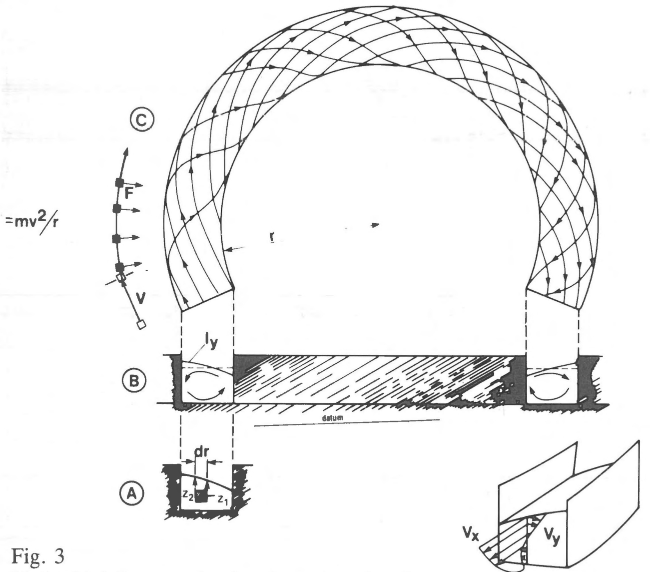


Fig. 3
Helicoidal flow mechanism in a river bend.

SPIRAL FLOW IN MEANDERS WITH CONSTANT FLOW

After THOMSON'S (1872) work on meanders, some more recent sediment-fluid flow experiments with river meanders have been carried out by FRIEDKIN (1945) at the Vicksburg Station, by IPPEN ET AL. (1962) at MIT and by MARTVALL & NILSSON (1972) at the Uppsala (Hjulström) laboratory. These authors present also extensive literature reviews. A review of spiral flow in meanders is necessary to understand why interference with meanders is a difficult task. For this purpose, the work of VAN BENDEGOM (1969, 1973) of the Delft laboratory has been used. Van Bendegom starts with the basic laws, which state that at a given location the total energy head of a particle of water in a river equals its potential energy head with respect to mean sea level, plus the hydrostatic head of the column of water above the particle plus its kinetic energy, added to the atmospheric pressure. The imaginary plane representing the total energy head is located a distance of $(\overline{v})^2/2g$ above the water surface where $\overline{v}$ equals the average velocity in a vertical, while g represents the acceleration caused by gravity. Conservation of energy dictates that, at locations of increased velocity, the water level should be depressed with respect to a constant energy head plane. Accelerations and decelerations of the water cause depressions and, respectively, mounds in the water surface. In a sloping prismatic circular channel, a water particle of mass m, density ϱ, width dr and of unit length and unit depth, will describe a circular path of radius r, if a centripetal force $F = m.a$ acts perpendicularly to its direction of movement, where $a = v^2/r$ and $m = \varrho dr$. This force F is related to the difference in hydrostatic pressure: $\varrho g z_2 - \varrho g z_1$. In a cross section of the channel (Fig. 3A) the centripetal head becomes: $z_2 - z_1 = (v^2/gr)\ dr$ (1). The cross slope I_y of the water surface becomes $I_y = (z_2 - z_1)/dr$ (2); consequently, $I_y = v^2/gr$ (3).

In a vertical and horizontal direction of a river cross-section each river-water particle has its characteristic velocity. Each particle's path in the plane of the cross section is influenced by a centripetal acceleration and characterized by its particular hypothetical cross slope I_y which would be required to reach equilibrium for that particle. If equilibrium is not reached for a number of particles, river-level oscillations may occur. In a bend of a prismatic channel the water cross-slope $\overline{I}_y$ curves from the high outside to the low inside bend (Fig. 3B). Consequently v^2/gr increases to the inside of the bend and decreases near the outside of the bend. The cross slope $\overline{I}_y$ of the water surface in a river bend represents an equilibrium condition, associated with an average velocity $\overline{v}$ in a vertical line. Near the surface of the river the actual velocity v exceeds $\overline{v}$ and the centripetal acceleration associated with $\overline{v}$ is not sufficient to ensure that the surface water follows the bend; near the bottom the actual velocity is less than $\overline{v}$. A streamflow tube near the surface will be centrifuged outward since the average cross slope $\overline{I}_y$ does not provide a large enough acceleration to keep the streamflow tube in the track of the bend. Near the bottom of a river bend, the streamflow tubes are curved inward because $\overline{I}_y$ provides too much of a centripetal acceleration. The result is called spiral or helicoidal flow (Fig. 3C), although it has first been described by THOMSON (1872) as oblique flow.

The helicoidal flow explains the existence of some types of bars under an oblique angle with the inner bank. They may be explained by the upwelling flow which exerts bed shear stresses parallel to streamlines up the slope of the inner bank, but the upslope force is counterbalanced by the body force of the sediment travelling slowly over and in continuous contact with the channel bed. Since force times the distance represents energy, it is the available energy, which determines whether no movement, ripples, sand waves or dunes, plane beds or antidunes will form. Ripples are found to represent the normal transport form at low flow velocities. Transverse bars are the most common form at high velocities, whereas ripples are formed on transverse bars. Transverse bars are formed on point bars. The point bars, having dimensions of a dune, are the final morphological result of the sedimentation of bed load and suspended load. Point bars are created (MARTVALL & NILSSON, 1972) by the successive deposition of materials on the inner banks. As the channel is displaced laterally and downstream, new point bars are formed outside each other (Fig. 4). In time they grow higher and are covered with vegetation and look like curved levees.

A factor often mentioned in meander flow, is the Coriolis force. This force acts on any flowing water particle. For example, as the water flows south in a meander bend on the northern hemisphere, it moves farther away from the earth's axis and therefore must increase its rotational velocity to match that of the solid earth. The necessary acceleration is provided by pressure from the west bank of the river, causing the water to pile up there. For a north flowing river bend the water level should rise on the east bank. For a latitude of 50° (the horizontal) component of the Coriolis force per unit mass amounts to only a few percent of the centripetal force per unit mass.

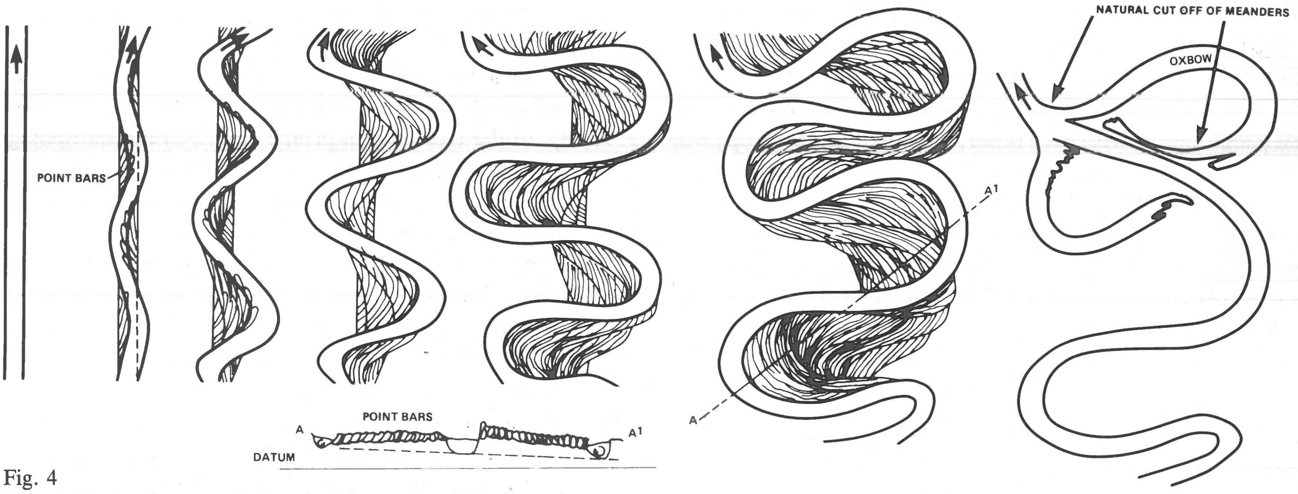


Fig. 4
Development of a meandering river from a straight channel.

SPIRAL FLOW IN RIVERS WITH CHANGING FLOW

Natural rivers experience daily, seasonal and annual run-off cycles associated with changes in channel slope and sediment transport. For instance, at low river flows, small meanders form in large meanders. If two different water levels z_1 and z_2 dominate or occur in an annual cycle, each water level being associated with a characteristic type of sediment transport, different gullies form in the river channel. Each typical gully in a channel, meanders. At high water level z_3 these gullies break through, causing the downstream shifting of the new gullies, while lateral erosion of banks may set in, counterbalanced by sedimentation in unused gullies in the channel. Regulation of a natural river will therefore consist of making a choice between giving a desired stable slope to the low-water or high-water bed in a vertical or horizontal sense over short or long distances.

Geological deposits of different strengths can temporarily constrict the boundaries of the valleys of meandering rivers. In a river valley each meander becomes unique due to a combination of time variable conditions such as semi-permanent obstacles, obstacles caused by sedimentation, bottom or bank friction, bottom topography of a given reach in a river, angle and stability of bank slope, strength of bank and bed deposits, depth of channel, flow separation, local oscillations of water levels, eddy zones, local gradients of mounds in the water surface, turbulent flow memory effects, typical cycles of water levels, water discharge, water viscosities and sediment load. The development of meanders starting from a straight river reach to a meander break through is shown in figure 4. The step between the stages just before and after natural cut off of meanders (Fig. 4) often represents about a century of river development.

JOULE'S LAW, ENTHALPY AND ENTROPY OF A RIVER SYSTEM

It is a time-consuming task to use a deterministic approach to model waterflow, sedimentation, and the implications of man-made changes for a meandering river system. Thus, thermodynamics may have to be called on. Thermo-dynamics transcends in this case the domain of analytical physics, yet describes river meandering phenomena in a classical manner. The fact that this can be done is based on the laws governing the coupling of natural processes.

For an open river system, Joule's law of conservation of energy states that the net amount of energy added to the system as heat and all forms of work, plus the stored energy of mass leaving the system, equals the net increase in stored energy of the river system. Also, the energy of a river system adjusts itself in such a way that the entropy is as large as possible, such that the system is in its most random macrostate.

For reversible cyclical hydrologic processes in which the elevation z of a particle of water varies during the energy absorption and energy rejection Q, (for instance in an ideal pumped peak storage scheme), the entropy for any reversible cycle Q_{rev} is zero (BAUMEISTER, 1967):

$$\text{entropy } S_{1,2} = \int_1^2 \frac{dQ_{rev}}{z} = S_1 - S_2 = 0 \qquad (4)$$

For any irreversible hydrologic process which cannot be returned to its original state, the net entropy change is positive. Natural hydrologic processes are irreversible and therefore occur with a decrease in the amount of energy available for doing work, i.e. with an increase in unavailable energy. The increase in unavailable energy is the product of two factors, z_o and S_{net} where z_o represents the lowest available elevation for energy loss, while S_{net} represents the net change in entropy, proportional to the size of the system.

Availability of a quantity of energy B is defined as:

$$B = h - z_o S + v^2/2g + (g/g_c)\, z \qquad (5)$$

where h is the enthalpy of the river system, g the acceleration due to gravity, v the velocity, g_c a dimensional constant (mass^{-1}) and z the distance above or below reference level. Entropy has the dimension of energy and it is a logarithmic measure of the degree of randomness of the system. In a statistical sense, the entropy is a measure of increased disorder. When two river bends are placed in energy contact, as in the case of a meander break-through, so that they are free to exchange energy with each other, then their total entropy will be maximized at equilibrium. The total energy, however, is always conserved. If an amount of energy Q is added to the river system (rain, snowmelt), the average energy in the system is increased by h, the enthalpy. Enthalpy represents the energy content at constant pressure. The energy of a river system adjusts itself in such a manner that the entropy of the total isolated system is as large as possible, that is, such that the system is in its most random macrostate.

APPLICATION

These principles will now be applied to the shortening of the West Prairie River, which occurred during the cutting of its meanders. The average annual runoff rate of the West Prairie River near High Prairie amounts to 4.64 m^3s^{-1}, equivalent to 146.10^6 m^3 per year, while the difference in elevation between the total energy head of the river at High Prairie and the confluence with the East Prairie River is 10 m. The distance between upstream and downstream points before man-made meander cut-off was about 32,700 m; after the cut-offs the distance was reduced to 19,500 m. The potential energy in the system between those two points, immediately before and after cutting, was $4.64 (10^3) (9.81) (10) = 4.55.10^5$ Joule (Ws). Per metre of channel there used to be an average potential energy of 14.2 Joule available, but immediately after cut off that was increased to $4.55.10^5/19{,}500 = 23.8$ Joule per metre, an increase of 68%.

The average velocity in the new channel has initially increased by the square root of the new slope, divided by the square root of the slope of the old channel, which amounts to a velocity increase of 29%. The 'Hjulström diagram' shows that erosion will take place in the river stretch under consideration. Because of the increased velocities (just as on the Mississippi River) the sediment, eroded from the upstream part of the new channel, has piled up at the downstream end of the man-made river reach. Once this has been carried away, additional erosion will take place. This erosion will continue to a level well below the present river bed. This conclusion could be reached from the drawing of a new equilibrium river profile of the shortened river, using a spline solution for the profile, parallel to the 1967 profile. Based on the 1967 river bed elevation at the confluence of the East and West Prairie, which serves as a common point of the equilibrium for the new and old channel, the new profile of the shortened river indicates that erosion will continue to a level 6-8 m below the pre-1968 river bed.

The West Prairie River profile before the man-made meander cut offs, was in a state of long-term dynamic equilibrium. This conclusion is derived from an analysis of evolution of some 200-300 year old meanders near High Prairie. The amplitude and wavelength of the old meanders is nearly similar to those of the present day meanders before man-made interference took place.

That a meander cut-off results in river-bed lowering, is shown in figure 5. The meander is shortened from A to B (Fig. 5: A, B). In the river length profile (Fig. 5C) the shortening represents a shift from B to B^1 (Fig. 5D) and from C to C^1. Point A remains at the same location. When erosion sets in upstream from A (Fig. 5E), the bed at A is temporarily covered by eroded bed material until transported by the river at a later date. The bed is ultimately lowered by an amount Δz, (Fig. 5F), where Δz equals (or exceeds) the length of the old meander AB times the old bed slope before meander cut off. The bed level at B^1 decreases by Δz to establish the river profile in equilibrium with the level at A, where the extra available energy upstream from A is partly expended to erode the bed so as to maximize the entropy of the system. Development of the incising river cross section at B^1 and C^1 is given in figure 5 (C, D, E and F).

DURATION OF EROSION CAUSED BY CHANNEL SHORTENING

The question is posed, how many years it will take before at a location $x = L_m$ on a degrading river, the river bed will be lowered by a given amount as a result of bed degradation triggered by man-made cutting of meanders and shortening of the river. DE VRIES (1975) has addressed this question for rivers in general, starting out from the one-dimensional open-channel flow equation. In his equation (6) the celerities (v) of the water-level changes are assumed to be much larger than those of the river bed changes, in other words, $\delta v/\delta t \simeq o$:

$$v(\delta v/\delta x) + g(\delta H/\delta x + \delta z/\delta x) = -gv|v|/C^2h \qquad (6)$$

The water movement is uniform during the non-steady process of the change of the river bed, hence (6) reduces to:

$$-v|v|/C^2h = \delta z/\delta x = -v^3/C^2q \qquad (7)$$

In (6) and (7) v represents the flow velocity, g the acceleration due to gravity, H the water depth, z the river bed level, x the ordinate in the flow direction, q the discharge per unit width and C the Chézy coefficient. Differentiation of (7) with respect to x yields:

$$\delta^2z/\delta x^2 = -3v^2/C^2q\,(\delta v/\delta x) \qquad (8)$$

Conservation of mass implies:

$$\delta z/\delta t = -\delta s/\delta x \qquad (9)$$

Where s represents the sediment-transport bulk volume, including pores:

$$s = av^b \qquad (10)$$

in which a and b contain all sediment-transport parameters, except v. Substitution of (9) and (10) in (8) yields the diffusion equation:

$$\delta z/\delta t = K(t)\,\delta^2z/\delta x^2 \qquad (11)$$

where the time-dependent diffusion coefficient K(t) is defined as:

$$K(t) = C^2\,(qds/dv)\,/3v^2 = (ds/dv)v/3i \qquad (12)$$

In equation (12) the slope of the river bed is represented as i. The solution of the diffusion equation (11) for a rapid drop Δz of the river bed level is given by the analytical solution:

$$z(z,T) = \Delta z \ \mathrm{erfc}\left[\frac{x}{2\,{}_{o}\!\int^{t} K(t)dt}\right] \qquad (13)$$

As a result of the man-made river disturbance, created by meander cutting and river shortening, a degradation process has been triggered which lasts until the river bed is ultimately lowered by an amount Δz over its entire length. In analogy with radio-active decay, the number of years (N_{50}) required to lower a river bed over 50% of the final amount (Δz) at an upstream location at $x = L_m$ is given by the 'half life' of the man-made river disturbance (Fig. 5F):

$$N_{50} = L_m{}^2/{}_0\!\int^{1\,\mathrm{year}} K(t)dt = \frac{L_m{}^2}{\frac{1}{3}\frac{b}{B} i_0\!\int^{1\,\mathrm{year}} S(t)\,dt} \qquad (14)$$

In equation (14), b, B and i are independent of time. If this is not the case, then b, B and i must be left under the integral. In equation (14), S represents the sediment transport over the entire width of the river. For example, for a point $x = L_m = 30$ km, upstream from High Prairie, the half-life value N_{50} has been computed as 500 years, determined from the annual sediment load. The load S(t) is estimated at 100,000 m^3 per annum. The width B of the river is taken at the average effective sediment-transport concentration, which occurs at a high runoff rate exceeded 20% of the time, but this will vary from river to river.

Substitution of typical values for different rivers around the world shows that man-made interference has a half life ranging from less than one hundred to a thousand years. DE VRIES (1975) gives specific examples of half lives for the Rhine River (The Netherlands), Magdalena River (Colombia), Danube River (Hungary), Tana River (Kenya) and the Apure River (Venezuela). The half lives range from 30-1000 years for L_m = 200 km.

NEW MEANDERS IN STRAIGHT CHANNEL

The man-made cuts of meanders in a river, without the provision of bank protection, leave the bottom and the banks of the new straight channels free to find a new equilibrium. Equation (5) shows that a river system works to obtain a maximum energy expenditure in order to maximize entropy. Shear forces perform work on the river bed; therefore, bed transport represents an energy loss, where the energy is derived from the total energy in the river system. The total available energy in straightened river sections increases usually considerably, coupled with velocity increases. This makes the straightened river sections unstable and leads to erosion by river incision. In addition, disturbances occur at several locations in the straight channel, whereupon the helicoidal flow mechanism initiates erosion and sedimentation. This starts a new meandering process in the incised channel. It is observed that, when the river flow leaves the first meander bend to arrive into a straight channel, the water flows in a counter curve. That is where the next bend originates. In this fashion (Fig. 4) meanders can be observed to propagate downstream. It takes time to develop a new meander system, because the transverse velocity which sets up a convective transport, is considerably larger in the bends than in the straight reaches of a river (Fig. 3). The reason is that the pitch of the spiral path of a water particle changes rapidly in each bend, but decreases in a straight river section.

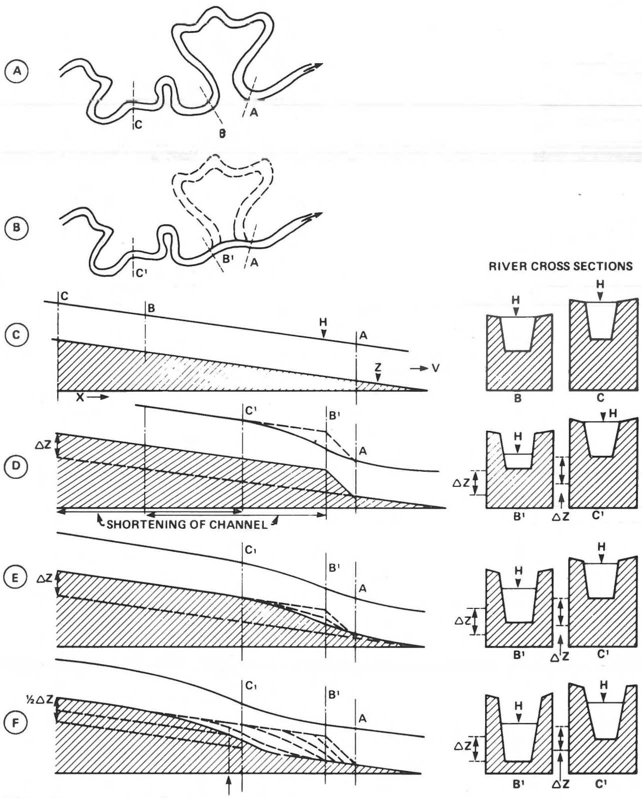


Fig. 5
Cutting of one meander changes the river profile and cross sections.

In some cases attempts are made to mitigate the geomorphological changes resulting from meander surgery. In that context it is sometimes proposed to construct an upstream flood reservoir. Equation (5) can be used to show that a flood reservoir upstream from a degrading river section does not decrease the potential energy (conservation of energy), change the runoff volume (conservation of mass) nor change the slope of a degrading channel downstream from such reservoir. The useful function of flood reservoirs consists of dampening irregular high flow rates and catching the sediment load.

MINIMIZING GEOMORPHOLOGICAL CHANGE

A conceptual model of how a meandering river is shortened with minimal geomorphological change (VAN BENDEGOM, 1973) from points A to B is shown in figure 6 (A and B). The course of the river is changed by a series of new meandering curves of 45°, since 30° is usually too small. After shortening the river profile (Fig. 6C), a point A is transposed to A^1 (Fig. 6D). Without dredging and bank protection, a river is left free to degrade its bed and banks. In that case the increased available

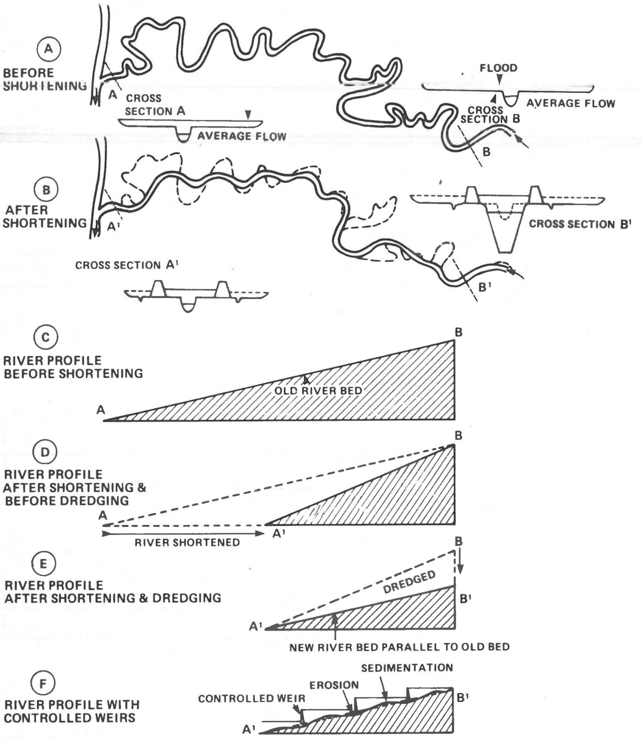


Fig. 6
Conceptual model for meander cutting.

energy causes incision of a new riverbed. Incision takes place over a vertical distance Δz, where Δz approximates the river shortening times the original channel slope. The reason is that, after shortening, more water becomes concentrated in the river channel, increasing the ratio of the runoff and slope. In order to avoid the deep natural incision followed by free meandering, a meander cut-off channel can be dredged so as to lower the bed immediately by an amount Δz over the entire length of the river, upstream from the starting point of meander cut-off. If the new equilibrium profile is not dredged all the way upstream, the river will carry this out until equilibrium is reached. The old river cross profiles at A and B are shown in figure 6A, the new profiles are shown in figure 6B.

New dikes are required to protect the land from flooding during the 1:100 year flood and special areas must be set aside with special dikes, which can be overtopped during the higher floods. Special works are required to ensure that the 1:2 year flood can drain from the tributary ditches and creeks, in spite of the dikes. The construction of a dredged channel, dikes, and bank protection is completed with an integrated series of controlled weirs, which regulate the flow according to a complicated regulation program. One or two isolated weirs, instead of an integrated series of weirs, create problems of their own. An uncontrolled weir presents an obstacle during floods, when it creates its own inundated area. Upstream from the weir sediment is trapped behind the structure. When the upstream area is filled in, the river can erode the banks, and meander around the weir. Special bank protection is thus needed to keep the upstream river in its designated course over the weir. Below a weir the flowing water has excess available energy, which results in erosion. A controlled weir results in deepening of the river bed section near the weir. If the weir bottom is constructed at the old river-bed level, it can be left hanging above the new equilibrium river bottom. In the case of a single, uncontrolled weir located on a degrading river section, the downstream river will continue to degrade, unaffected by the weir. This constitutes the reason for an integrated series of controlled weirs (Fig. 5). Continuous dredging programs form an integral part of this conceptual model for meander cutting.

CONCLUSIONS

In attempt to correct natural, but unruly river behaviour, interference with the natural rivers has taken place, and will take place in the future in all countries all over the world. However, some classical examples of river meander surgery make it clear that man-made interference with natural rivers, whether small or large, represents a costly capital operation, which requires a long-term (50-100 years) commitment for up keep, improvement and replacement, if not in the short run, then in the long run (next 500 years). In this respect and at present, most countries have a narrow tax base and many other competing priorities.

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