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GEOLOGICAL SURVEY

LARGE-SCALE BEDFORMS IN THE PLATTE RIVER DOWNSTREAM FROM GRAND ISLAND, NEBRASKA: STRUCTURE, PROCESS, AND RELATIONSHIP TO CHANNEL NARROWING

By K. D. Crowley

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MATHEMATICAL SYMBOLS USED IN TEXT

C	Dimensional constant in equation 5b and 6 that expresses properties of the sediment.
D	Median grain size.
G_s	Specific gravity of sediment.
g	Acceleration of gravity.
H	Amplitude of macroform (fig. 13).
h_s	Stoss-side erosion depth.
h_s^o	Sufficient erosion depth.
ℓ	Macroform length, measured parallel to the channel banks (fig. 4).
q_b	Unit-volume rate of sediment transport.
s	Average channel slope.
t	Time.
U_*	Shear velocity.
w_c	Channel width (fig. 4).
w_f	Average macroform width, measured perpendicular to the slipface (fig. 4).
y	Flow depth over macroform.
λ_L	Distance macroform moves downstream (fig. 13).

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LARGE-SCALE BEDFORMS IN THE PLATTE RIVER DOWNSTREAM FROM GRAND ISLAND, NEBRASKA: STRUCTURE, PROCESS, AND RELATIONSHIP TO CHANNEL NARROWING

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K. D. Crowley

ABSTRACT

The Platte River channel in Nebraska, especially downstream from Grand Island, is characterized by large, periodic, and geometrically distinct bedforms called macroforms. Macroforms have dimensions commensurate with the width and depth of the channel and are emergent at all but the highest flow stages.

The encroachment of vegetation on macroforms and their consequent stabilization since the large-scale development of irrigation in the Platte River basin is the major cause of the reduction in channel width upstream from Grand Island, Nebraska. From simple geometrical considerations of macroform shape, an equation is developed to predict the depth and duration of flow required to erode the stoss sides of the macroforms to remove new vegetal growth each year.

The methods developed in this report to eliminate vegetal growth on macroforms may provide a useful management tool for controlling width of the Platte River channels. Although further testing is required to establish the validity of these methods at actual stream sites, a sample calculation for the Silver Creek, Nebraska, reach shows good agreement between the flow conditions predicted by the methods developed in this report and actual flow conditions.

INTRODUCTION

The channels of the Platte River in Nebraska are characterized by large, spatially-periodic deformations of the channel bed, which, considered collectively, constitute a series of periodic and geometrically distinct bedforms. These bedforms, here termed macroforms, have dimensions commensurate with the width and depth of the channel and are emergent at all but the highest flow stages. Macroforms are quasi-stable features, adjusted to prevailing flow regimes, that move at relatively slow rates through the channel during high flows; individual macroforms can be identified on aerial photographs taken during several decades.

Since the advent of large-scale irrigation in the Platte River basin (about 1880), hydrology of the Platte River has undergone several changes. In general, peak discharges, mean discharges, and ranges in discharges have decreased with time through most of the basin (Kircher and Karlinger, 1981).

Hence a new flow regime has been imposed on the river channels; channel features adjusted to previous regimes, such as macroforms, are no longer in equilibrium with prevailing flows.

The most immediate effect of these hydrologic changes has been to decrease the rate of movement of macroforms through the channel by decreasing the time during which the forms are submerged each year. As a result, vegetation has become established on the macroforms and several of the macroforms have been transformed into islands. Stabilization of macroforms by vegetation, caused by changes in peak-flow regime, appears to be the major mechanism that causes channel narrowing.

Encroachment of vegetation in the channels of the Platte River has created several management problems; the growth of vegetation in the channels increases hydraulic roughness, reducing channel capacities and increasing flooding hazards. Additionally, recent studies (U.S. Fish and Wildlife Service, 1980) indicate that encroachment of vegetation on the channels in central Nebraska has degraded the riverine habitat for several species of waterfowl, including sandhill cranes and whooping cranes, that use the river during the late winter and early spring each year.

Stabilization of channel width, with respect to increasing demands for water within the basin, presents a major challenge to land-use and wildlife managers. The purpose of this report, one of a series of reports resulting from a study of the Platte River basin by the U.S. Geological Survey, is to describe the structure of the macroforms and some of the basic relationships between macroform geometry and flow regime; these relationships can be used to develop useful criteria for maintaining riverine habitats.

Several U.S. Geological Survey personnel made important contributions to the report: L. E. Dobson, T. R. Eschner, E. M. Held, J. E. Kircher, D. J. Reynolds, and H. H. Stevens, Jr., ably assisted with one or more aspects of onsite laboratory, or office work. D. A. Baldwin, W. F. Curtis, G. E. Ghering, D. W. Hubbell, and C. F. Nordin, Jr., provided equipment and advice on its use and maintenance. Personnel of the Nebraska and Colorado Districts, provided the data shown in figures 2, 3, and 9.

ENVIRONMENTAL SETTING

The Platte River basin, a major component in the Missouri River basin, drains an area of approximately 222,000 km^2 (square kilometers) on the High Plains of Colorado, Wyoming, and Nebraska (fig. 1). The Platte River basin comprises three major subbasins: The North Platte and South Platte rivers with headwaters on the east side of the Continental Divide in Colorado, and the Platte River, which is formed by the junction of the North Platte and South Platte rivers in western Nebraska. In the western reaches of the Platte River basin, streams flow through valleys eroded into Precambrian crystalline rocks and Paleozoic and Mesozoic sedimentary rocks; on the High Plains, streams flow on reworked Quaternary sediments in shallow valleys of varying width eroded into Cretaceous and Tertiary sedimentary rocks.

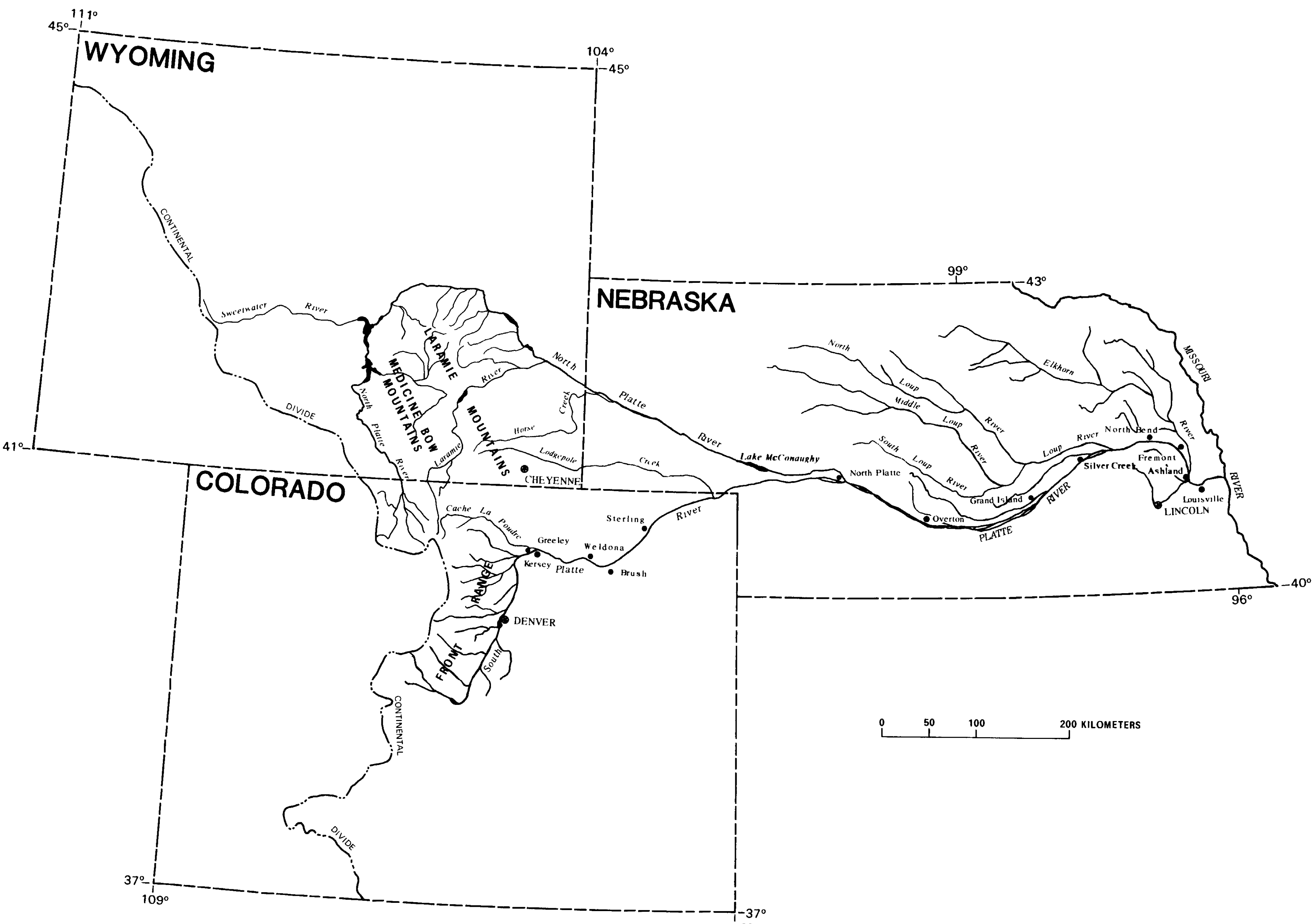


Figure 1.--Map of Platte River basin.

The character of the channels changes significantly along the length of the system. Channel width ranges from approximately 30 m (meters) in the western reaches to more than 400 m near the mouth. Channel gradient ranges from almost 2 m/km (meters per kilometer) to less than 1 m/km along the length of the system. Bed material is composed of a poorly-sorted mixture of coarse pebbles, sand, and silt in the western reaches and a moderately-sorted to well-sorted mixture of granules, sand, and silt in the eastern reaches.

Although the river traverses several climatic zones, streamflow is relatively unaffected by precipitation in the eastern two-thirds of the basin; most runoff is supplied by snowmelt in the Rocky Mountains during the spring and early summer (March-June). Occasionally, cloudbursts on the High Plains, particularly in the piedmont regions, contribute substantial runoff to the rivers. There are few important tributaries to the trunk rivers east of the piedmont region; two exceptions are the Loup River, which drains central Nebraska, and the Elkhorn River, which drains northeastern Nebraska.

Flow regime has been affected by construction of canals and water-storage facilities and transmountain diversions of water. Impoundment of water for irrigation has reduced flood peaks and mean discharges, and irrigation return flows have increased low flows (Kircher and Karlinger, 1981). Moreover, the channels have narrowed in response to the decrease in magnitude and duration of flood peaks with time.

Analysis of land-grant maps and aerial photographs taken by the writer show that relatively minor channel changes have occurred along the Platte River downstream from Grand Island, Nebraska since 1865; therefore, there has been little change in flow regime (fig. 2). The flow regime and channel geometry of the Platte River upstream from Grand Island and along the North Platte River have changed substantially since 1865 (Williams, 1978; fig. 2).

The flow regime and channel geometry of the South Platte River have changed little since the early 20th century (fig. 2). Historical data indicate that hydrology of the South Platte River, hence channel width, was affected by the construction of irrigation projects during the middle and late 19th century. There has been little new construction in the South Platte basin since 1900, and the channels have been stable during the 20th century.

Before the advent of irrigation, the Platte was an intermittent river upstream from the Loup River, characterized by peak spring flows and low summer flows. Because of irrigation returns, the channels now carry water throughout the summer months. Moreover, before the encroachment of vegetation on the channels, there is no historical evidence to indicate that overbank flows occurred regularly. During 80 years of written records from western exploration and migration, starting in 1820 with the Long Expedition, there are no reports of overbank flows along the Platte, even though the river was travelled mostly during the peak spring flows. Overbank flows, reported as typical by Blodgett and Stanley (1980), appear to be a recent phenomenon caused by bank stabilization and increased channel roughness from vegetation.

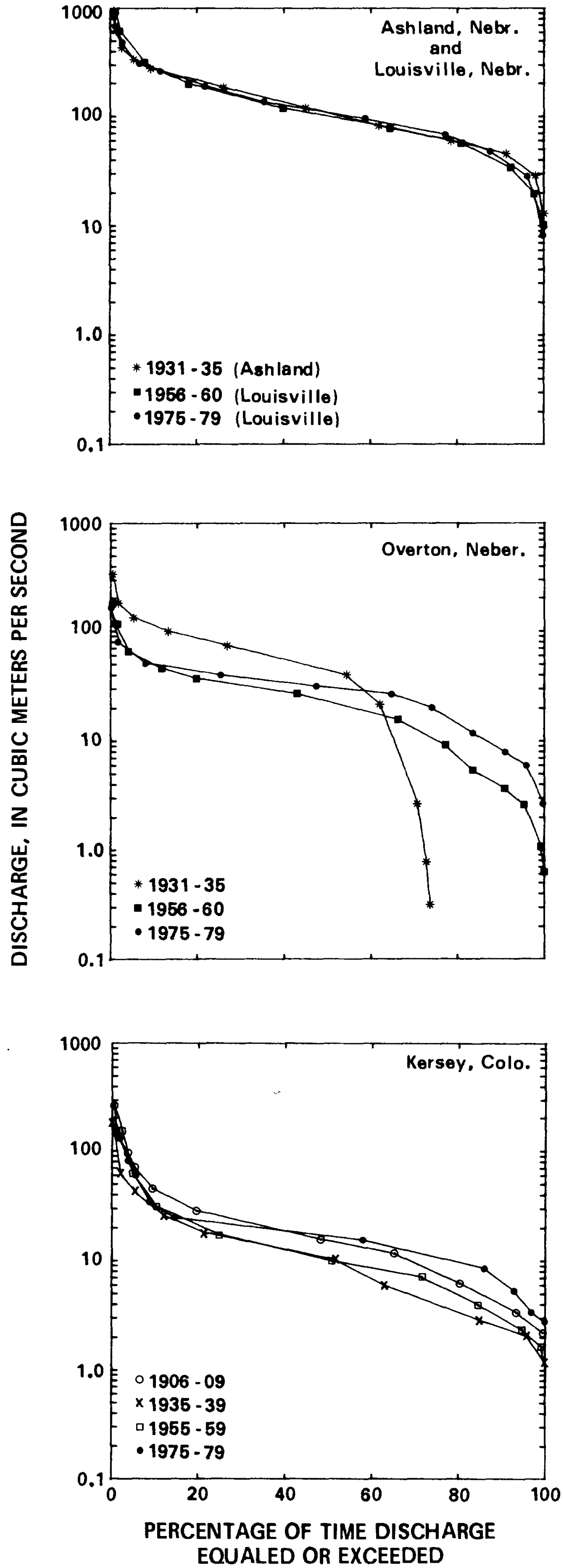


Figure 2A.-- Flow-duration curves for the Platte River near Ashland and Louisville, Nebr., Platte River near Overton, Nebr., South Platte River near Kersey, Colo.

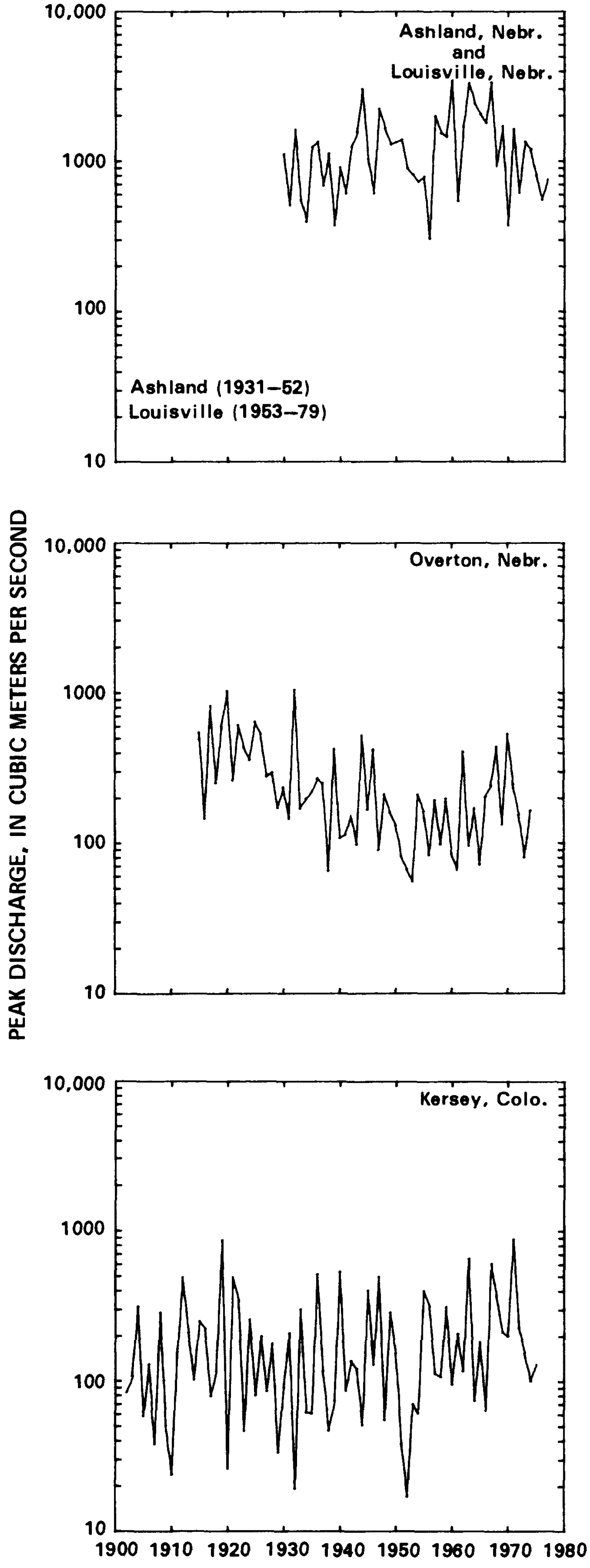


Figure 2B.-- Peak-discharge curves for the Platte River near Ashland and Louisville, Nebr.; Platte River near Overton, Nebr.; South Platte River near Kersey, Colo.

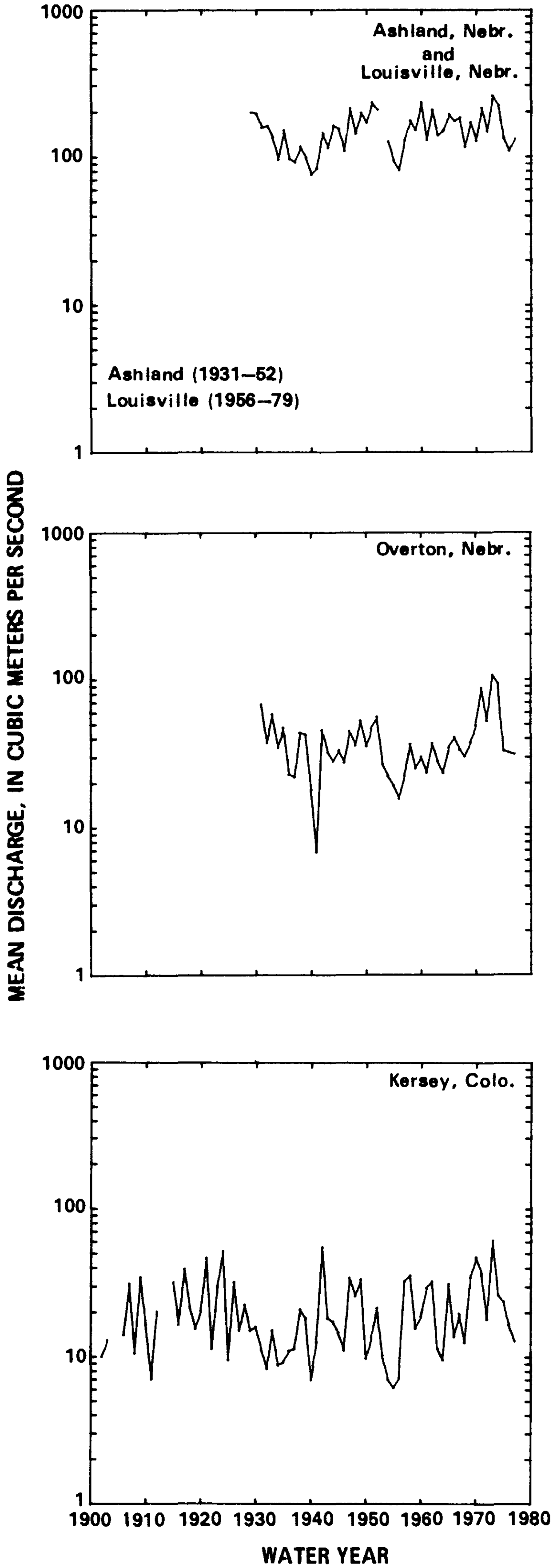


Figure 2C.-- Mean-discharge curves for the Platte River near Ashland and Louisville, Nebr., Platte River near Overton, Nebr., South Platte River near Kersey, Colo.

METHODS OF INVESTIGATION

Onsite investigations were made at high flow during April, May, and June, 1980, on the Platte River downstream from Grand Island, Nebraska (fig. 3). Investigations were confined to the river downstream from Grand Island for two reasons:

1. Flow patterns in the channel upstream from Grand Island are so altered by vegetative encroachment that bedform processes are difficult to interpret. Vegetated islands tend to split the flow into a series of channels that are irregular and complex in plan, so resulting bedforms show no distinct and regular pattern. Bedform morphology can be studied only in single channels, where flow patterns are not obscured by vegetation.
2. The unaltered channel downstream from Grand Island may be representative of the predevelopment Platte River channels upstream from Grand Island. Hence, the processes active downstream from Grand Island should be more representative of the processes that occurred upstream from Grand Island before irrigation development. There is no reason to conclude that these same processes would not occur in the Platte River channels upstream from Grand Island, if vegetation were cleared from the channels.

High-flow measurements were made from a small boat. Macroforms were mapped with the aid of a fathometer mounted in the centerwell of the boat. Continuous bottom profiles were collected with a high-frequency [500 to 2,000 kHz (kilohertz)], high pulse-repetition rate sounder with scale settings of 0 to 0.30 m, 0 to 1.52 m, and 0 to 3.05 m; accuracy was approximately 1 percent of full scale (Richardson and others, 1961). Low-level aerial photographs by the author supplemented ground observations (June 1, 1980).

Velocity and current-direction measurements were made with a bi-directional, direct-reading electromagnetic flowmeter mounted on a wading rod. Measurements were made on the macroforms by wading (at bankfull flows the macroforms were covered with 0.5 to 1.0 m of water), and in the channels by holding the wading rod off the side of the boat.

Stranded high-flow macroforms were trenched at low stage during the late summer. High-flow macroforms were relocated using maps drawn during spring runoff; the macroforms were resurveyed and remapped to determine rates of movement during spring flows.

MACROFORM MORPHOLOGY

Previous Work

Details of structure, form, and process of macroforms are not well-known, because macroforms are active only during the highest flows in rivers with coarse-grained channels and steep-gradient slopes. Macroforms cannot be studied in the laboratory, except by fairly sophisticated scale-modeling techniques (Southard and others, 1980). As a result, opinion on the origin of these features varies.

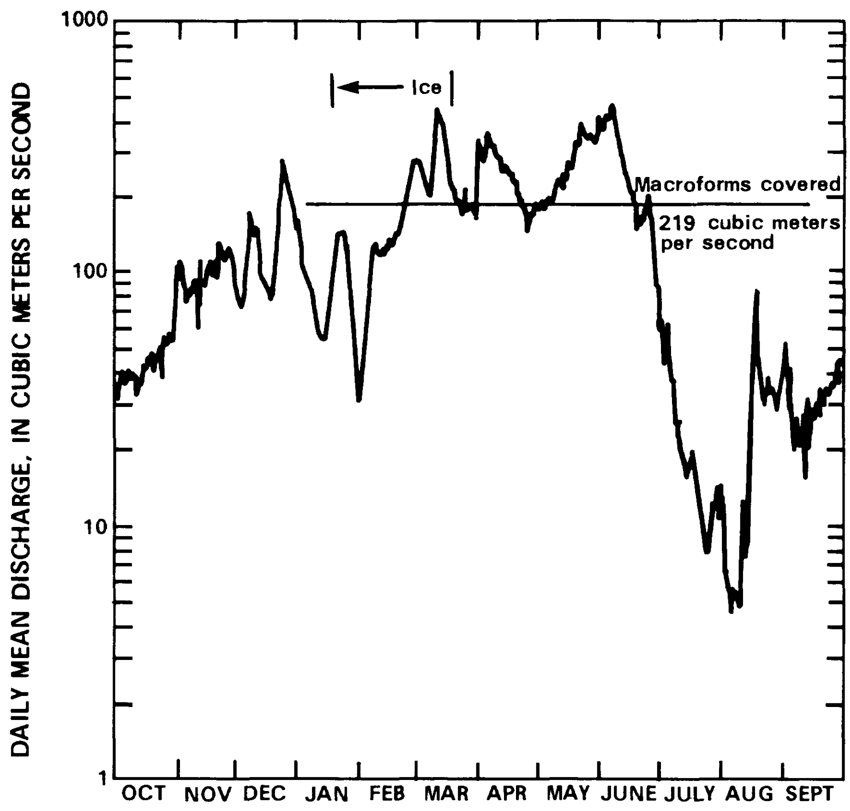


Figure 3.--Discharge hydrograph for the Platte River near North Bend, Nebr., 1980 water year.

For logistical reasons, most river studies are done at low flow; previous work on the Platte River was reported by Ore (1964), Smith (1970, 1971), and Blodgett and Stanley (1980). Platte River macroforms have been described variously as transverse bars or linguoid bars, depending on the river stage at which the features were observed. These bars generally are equated with the dune configuration of Guy and others (1966).

Geometrically similar bedforms also have been reported from the Tana River in Norway (Collinson, 1970), the South Saskatchewan River in Alberta (Cant, 1978; Cant and Walker, 1978), and the Loup River in Nebraska (Brice, 1964). These bedforms also are described as transverse bars or linguoid bars; they usually are equated with the dune configuration.

Recent work on bedform hierarchies by Allen (1968), Allen and Collinson (1974), and Jackson (1976) confirm interpretation of the large bars as hydrodynamic equivalents of the dune configuration. Allen and Collinson (1974, p. 177) assert that "*** large transverse forms *** are all dunes in a hydrodynamic sense ***;" hence, large bedforms reported in fluvial systems (such as the Platte River) are dunes formed at highest flows according to these authors.

In a separate paper (Crowley, 1981b), this author suggests that macroforms are not equivalent hydrodynamically to dunes, but, instead, comprise a unique hierarchial class of bedforms. Macroforms include not only bedforms of the Platte River; a type of bedform commonly known as a point bar also is included in this class of features.

Three types of evidence exist to support this conclusion. First, wavelength-depth ratios for macroforms (w_f/y) are an order of magnitude larger than the wavelength-depth ratio for dunes. Second, macroform geometry is proportional to the width of the flow system in a manner similar to the relation of point bar geometry to width. The ratios w_f/w_c and ℓ/w_c, where w_f is the width of the macroform, measured perpendicular to the slipface; w_c is the channel width; and ℓ is the wavelength of the macroform, measured parallel to the channel banks, are identical for the Platte River macroforms and point bars present on the South Platte River (fig. 4). Third, dune geometry is controlled by flow-separation processes active downstream of the dune crest. Experimental studies show that flow-separation processes control height and wavelength of dunes. However, Platte River macroforms are not controlled by flow-separation eddies; the eddies, if present, are barely measureable downstream of the macroform crests at high flow. Rather, rotational vortices were detected downstream of the Platte-type macroforms at bankfull flows. These vortices were alined parallel to, and just downstream of, the major slipface.

External Form

The Platte macroforms occur in a distinct and consistent geometry that can be identified along the entire length of the river. The major features of macroform geometry are reviewed in the following paragraphs; a more thorough treatment is given by Crowley (1981a).

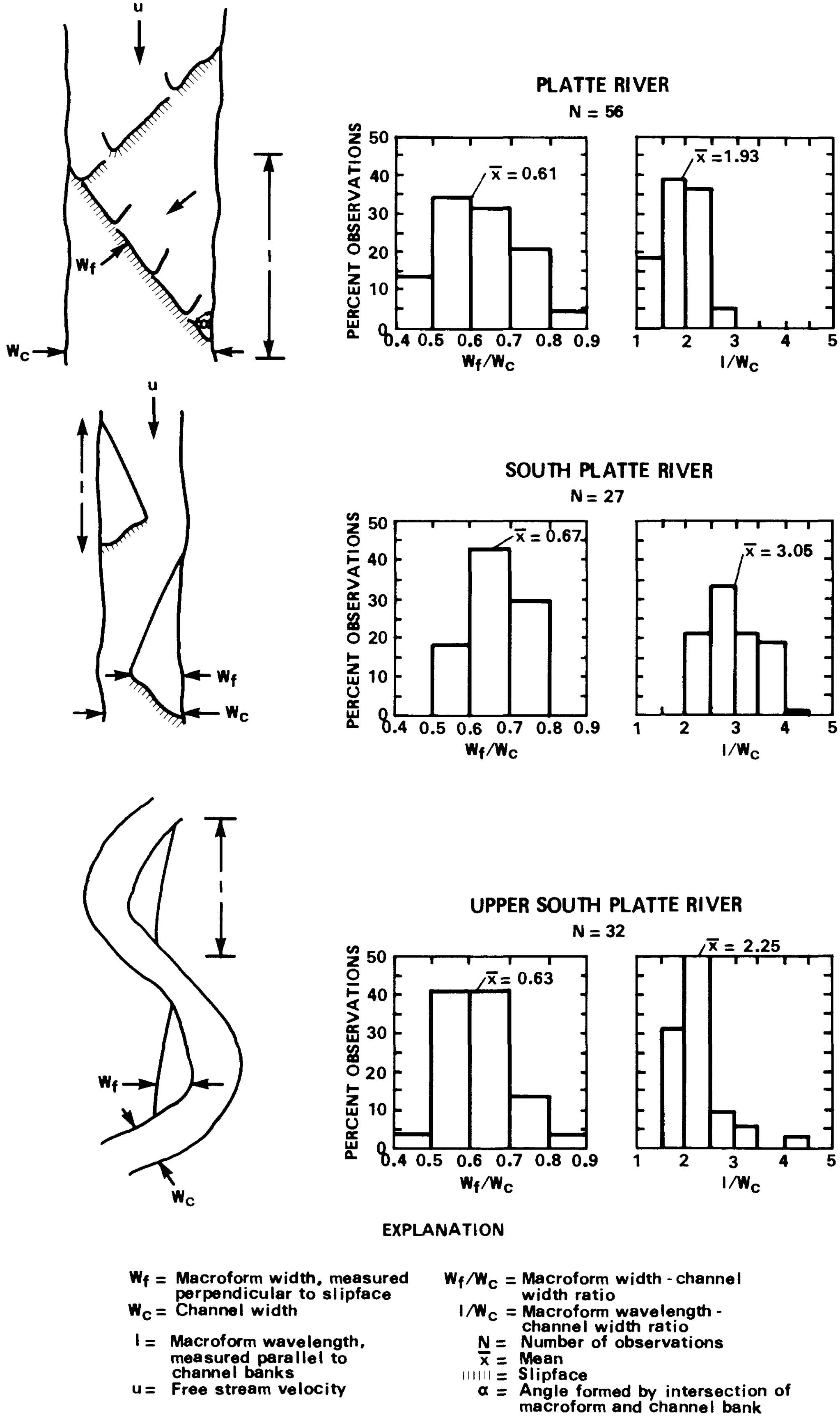


Figure 4.--Sketch showing macroforms in the Platte River basin.

In plan view, the Platte macroforms extend obliquely to the channel banks, across its entire width (figs. 4 and 5). Macroforms are present in all major and minor channels in the river; their length and width (fig. 4) are related to channel width by the relations:

$$\ell = 1.93\, w_c \;, \tag{1a}$$

and

$$w_f = 0.61\, w_c \tag{1b}$$

The acute angle formed by the intersection of the macroforms with the channel banks varies from 15 to 37.5 degrees, with a mean of 28 degrees.

Orientation of the macroforms with the channel banks assumes a regular alternating pattern, in a manner similar to point bars. This alternating pattern (fig. 6) reflects the meandering pattern of the major flow lines characteristic of the river at high flow.

The macroforms are disrupted by small channels that cut the forms at an angle perpendicular to the slipface and parallel to the flow lines. These channels are spaced in an approximately regular manner across the macroform; they may be formed during falling stages, when the flow over the macroforms becomes concentrated in narrow depressions. These depressions are transformed into channels by erosional activity; once formed, they seem to be maintained during the next high flow.

In cross section perpendicular to the slipface, macroforms have a triangular shape, similar to that reported for ripples and dunes, with long, gentle upstream or stoss slopes ($< 2°$) and short, steep downstream or lee slipfaces ($\sim 30°$). In the Platte River downstream from Grand Island, the macroforms have average widths (w_f) of about 300 m and average heights of about 2 m. Average height-width ratios are about 1:150.

The major high-flow channels in the river tract are located directly downstream of the macroform slipfaces. The river tract is defined here as the area between high-flow banks. Major high-flow channels are depressions in the river tract that convey the most discharge and are not channels in the sense of possessing well-defined banks. Flow is concentrated in these channels after moving over the macroforms, approximately perpendicular to the slipfaces. Where a major channel and a minor channel intersect, discharge tends to be deflected downstream, forming a region of slow-velocity water. These areas of slow velocity, here termed lobes, are illustrated in figures 5 and 6.

The sounding profiles made over the macroforms at bankfull flow are shown in figure 7; the plan view accompanying the figures shows general orientation of the profiles. The profile along A-A' illustrates gross geometry of the macroforms. The stoss sides of the macroforms are mantled with smaller bedforms, in this case dunes. Note the triangular shape of macroforms, height of slipfaces, and major channels directly downstream of the slipfaces.

Figure 5.--Oblique aerial photograph looking northwest downstream from Silver Creek, Nebr. (June 1, 1980), showing external geometry of the Platte River macroforms.

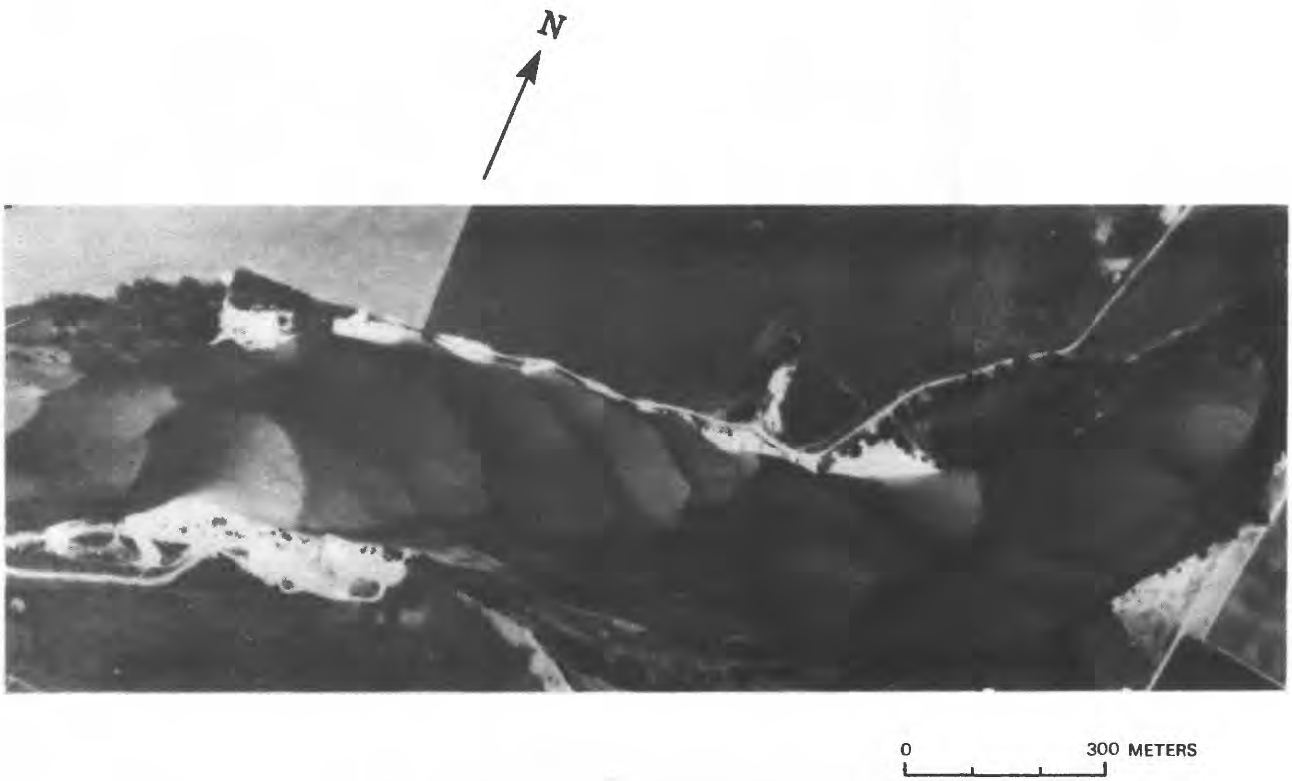


Figure 6.--Vertical aerial photograph showing external geometry of the Platte River macroforms, Platte River near Grand Island, Nebr.

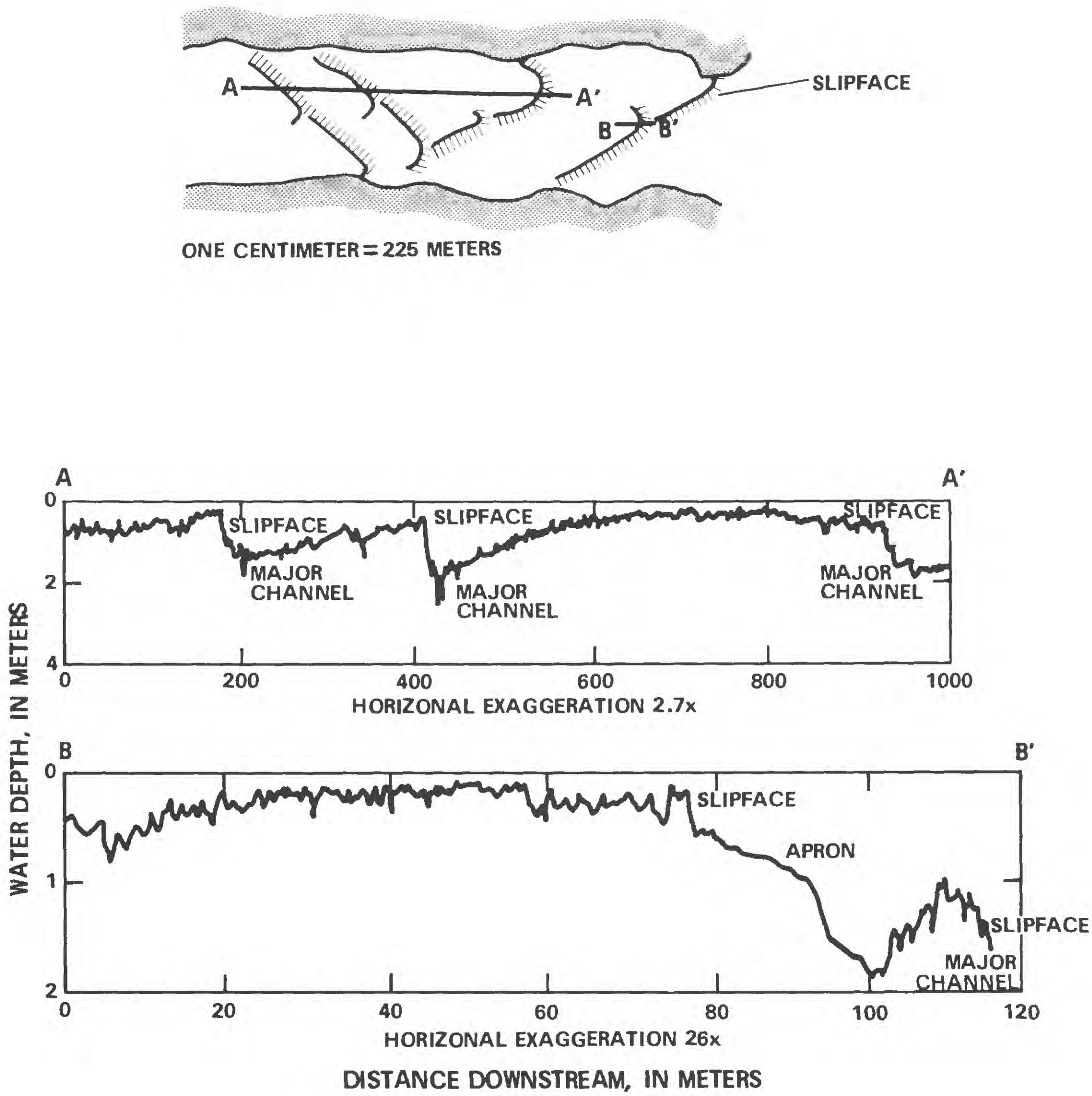


Figure 7.--Plan view and sounding profiles over the Platte River macroforms collected near peak flow near Grand Island, Nebr.

Profile B-B' illustrates the geometry of a macroform across a lobe. The flow directly downstream of the slipface in this region is characterized by decreased velocities that cause deposition of fine-grained sediments from suspension. An apron deposit is formed by deposition of these sediments directly downstream of the slipface. These apron deposits have thicknesses that in some instances exceed 1 m; as a result, macroform slipfaces tend to have a subdued expression or low relief. Note that even at bankfull flows, macroforms are covered by only 0.5 to 1.0 m of water, and that the deepest channels, directly in front of the macroforms, have depths of about 2.0 to 2.5 m.

Several velocity readings were made over macroforms during high flow; a typical flow field is shown in figure 8. Flow velocities increase over the crest of the macroform and are greatest in the channel directly downstream of the slipface. Additionally, flow in this channel is helical in nature, in a manner similar to velocity patterns in meander bends.

Grain size varies regularly over the macroforms. The coarsest grains [approximately 4 cm (centimeters) in diameter in the Platte River downstream from Grand Island] are confined to channels downstream of the slipface and the upstream end of the next downstream macroform. Grains with intermediate diameters (medium to coarse sand) are concentrated on the macroforms just upstream of the slipface. Finest materials (silt and fine sand) are concentrated on apron deposits at macroform lobes.

MACROFORM PROCESS

The origin of macroforms is uncertain because an observer never had the opportunity to see them develop in the natural environment. Macroforms in the Platte River are temporally stable features; although they move downstream each year, individual macroforms can be identified in aerial photographs taken throughout several decades.

Macroforms are active only at highest flows. For example, in the Platte River at North Bend, Nebraska, macroforms are covered only when discharge exceeds 219 m^3/s (cubic meters per second) (fig. 2). Moreover, macroforms do not move downstream at any detectable rate until they are covered with approximately 20 cm of water. At North Bend, the average macroform was covered with 20 cm of water for about 2 weeks during the 1980 water year (not including the period the macroforms were covered with water from ice jamming) (fig. 9). Hence, the Platte macroforms are active only during a few weeks each year.

Once the macroforms are inundated by flow, velocity fields are established on their stoss sides and cause development of smaller bedforms, usually dunes and ripples (fig. 7). Sediment is eroded from the stoss side of the macroforms and is transported to the macroform crest by smaller bedforms. At the macroform crest, sediment avalanches down the slipface and is covered by succeeding avalanches. The macroform is translated downstream by erosional and depositional processes.

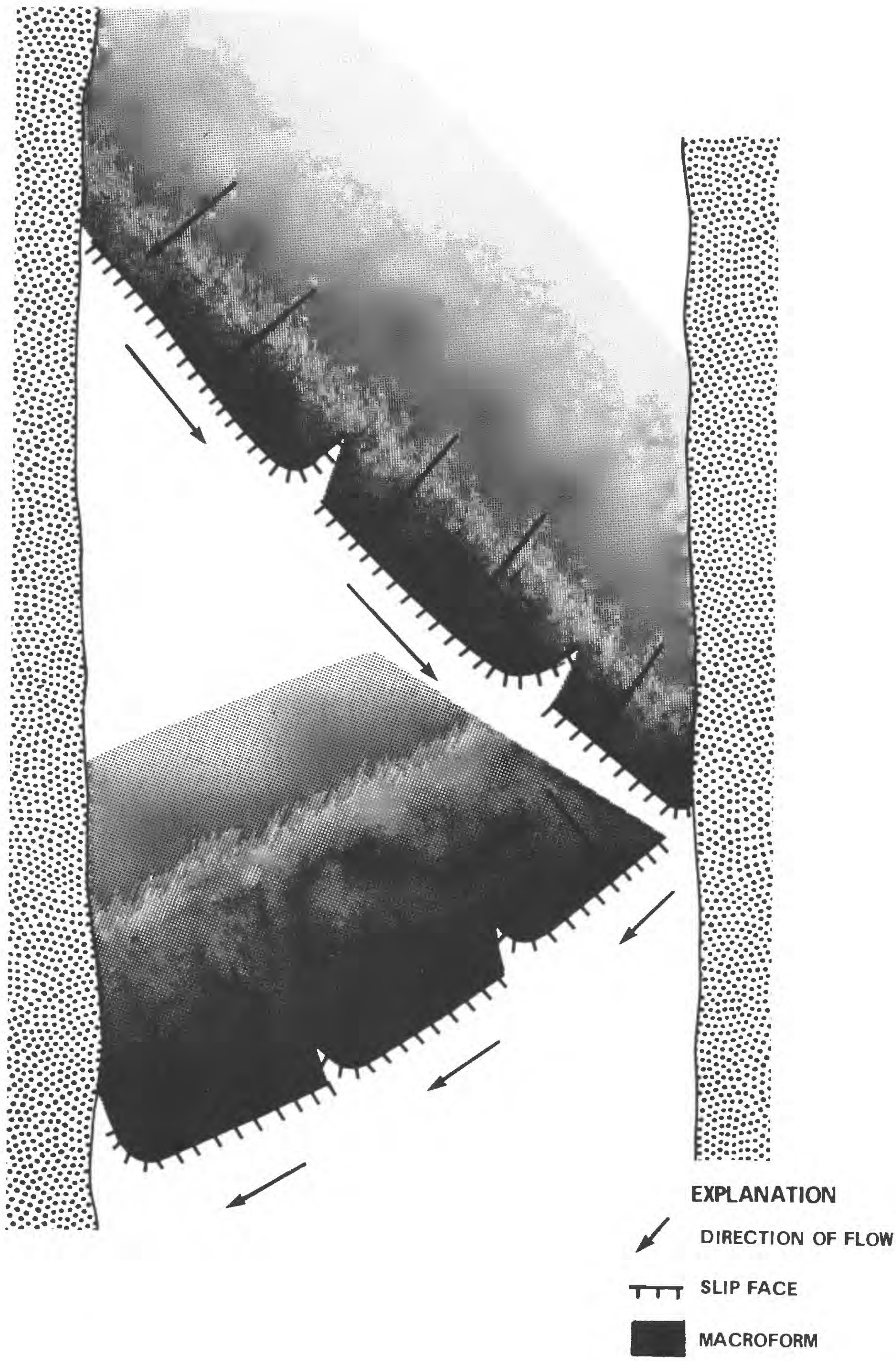


Figure 8.--Sketch showing generalized flow distribution over a macroform.

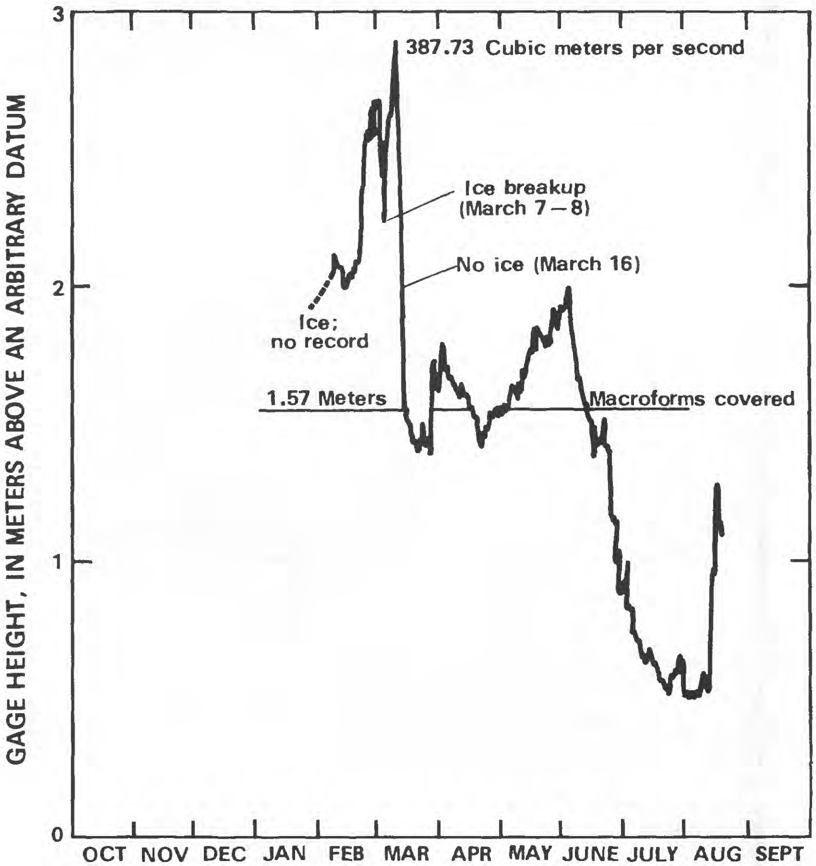


Figure 9.--Graph showing gage height curve for the Platte River at North Bend, Nebr., 1980 water year.

The rate of movement of the macroforms is variable. During high flows, fence posts were driven into several macroforms just upstream of the slipfaces; the posts acted as reference points from which downstream migration rates could be computed.

During the highest flows, macroforms migrated downstream at a rate of between 1.0 and 1.5 m/hr (meters per hour). However, migration rates decreased rapidly as flow diminished. In most instances, migration was undetectable when flow depth over the macroforms declined to less than 20 cm. Maximum observed migration distances of any macroform for the 1980 water year was less than 100 m.

Long-term migration rates were computed from aerial photographs taken during the period 1959-79 and from surveying data collected during 1980. Like short-term migration rates, long-term migration rates vary considerably. For example, long-term migration rates for macroforms at Silver Creek, Nebraska, average 10.1 m/yr (meters per year) (1971-81), whereas at North Bend, Nebraska, migration rates average 18.8 m/yr (1971-81). Migration rates at Fremont, Nebraska, average 24.0 m/yr (1959-65). These data indicate that migration rate increases downstream; this probably is correct, because discharge increases downstream, particularly downstream from the junction with the Loup River (fig. 1). However, a definite trend cannot be established because of insufficient data.

These migration rates are average rates; some years, the macroforms probably do not migrate at all. For the Silver Creek macroforms, approximately one-half of the total migration distance recorded between 1971 and 1981 occurred during spring runoff of the 1980 water year; only one-half of the total migration distance occurred in the preceding 9 years.

As river stage begins to decline at the end of spring runoff, the rate of sediment transport and rate of macroform migration decreases. Declining-stage flows modify the macroforms in two ways:

1. Finer sediments on the stoss sides of the macroforms are winnowed out by the flows. Finer sediments are transported to the crest of the macroform by small bedforms (ripples, dunes) and are stored on thmacroform slipface. As a result, the macroforms become armored with coarse material. From Grand Island to Fremont, Nebraska, this armoring material consists of granules and pebbles, with cobbles occurring locally. The stoss sides of the macroforms become armored in a few days; this armoring retards additional sediment transport.
2. Declining-stage flows tend to be concentrated within small areas of the macroforms where they erode channels. These channels act as conduits for the flow; they are active at low flow and give the river a distinctive braided pattern.

MACROFORMS AND CHANNEL NARROWING--THE GROWTH OF VEGETATION

The channels of the Platte River upstream from Grand Island, Nebraska, have narrowed considerably since the development of large-scale irrigation in the Platte River basin. Channel narrowing is chiefly the result of vegetation encroachment on macroforms in the river channel.

According to a recent report by the U.S. Fish and Wildlife Service (1980), establishment of vegetation along the Platte River requires a moist, unvegetated substrate. Two woody plants, cottonwood (*Populus deltoides*) and willow (*Salix*), are among the first to become established on such a substrate. Seeds from these species are released from early June to mid-July and are transported by high flows onto the substrate where they germinate in proper moisture conditions. Vegetation growth is not limited by availability of seeds; it also is dependent on availability of a suitable substrate.

From onsite work and analysis of aerial photographs, it is clear that macroforms are the major sites on which vegetation is established in the channel. The vegetation anchors the sediment on the macroform and prevents the macroform from moving downstream at high flow. Once anchored, the macroform is transformed slowly into an island.

Sedimentational evolution of the macroform from an unvegetated bedform to an island is affected by, and, in turn, affects vegetation development. An unvegetated macroform is invaded first by several annual herbaceous and woody species, including cottonwood and willow. Cottonwoods and willows have taproots that anchor them in the substrate, making them resistant to the effects of scouring currents. Once established, these species persist through large floods. For example, the cottonwood tree shown in figure 10 was inundated by high flow in the Mormon Island reach during spring runoff in the 1979 water year. High flow succeeded in knocking the plant over and burying it with a thin layer of sediment. However, by August 1979, the cottonwood had regrown above the substrate. The distinctive offset pattern of the cottonwood shown in figure 10 commonly is found on partly vegetated macroforms; it commonly is possible to find two or more offset patterns on a single plant.

Vegetation establishment also anchors the sediments on the stoss side of the macroform, impeding its downstream movement. As a result, the macroform builds vertically by deposition of sediment on its stoss side from smaller bedforms (fig. 11).

After the river recedes, the accreted sediment is invaded rapidly by new vegetation. For example, accreted sediment deposited during June, 1979, was covered completely by new vegetation by the end of August (fig. 11).

Much of the pre-existing vegetation, covered by newly accreted sediment, dies and decays, forming a thin, organic-rich layer. These layers are distinctive and usually can be identified in trenches. Three or four layers in the Mormon Island reach are shown in figure 12. Each couplet consists of a layer

Figure 10.--Photograph showing offset in small cottonwood tree caused by inundation and burial during the spring flood, 1979 water year, near Grand Island, Nebr.

Figure 11.--Photograph showing vertical accretion on the stoss side of a macroform by the action of smaller bedforms, near Grand Island, Nebr.

Figure 12.--Photograph showing couplets of organic-rich and sandy sediments representing an annual cycle of vertical accretion on the macroforms, near Grand Island, Nebr.

of aggraded sediment and an organic-rich layer; it probably represents an annual cycle of aggradation and vegetational growth.

As the stabilized macroform builds above the channel bottom by bedform accretion, it reaches an elevation where it largely is immune from the erosive effects of rapid-velocity currents. The stabilized macroform then continues to enlarge vertically by the deposition of fine sediment from suspension. The macroform, now an island, presumably can enlarge vertically in this manner until it reaches the elevation of the channel banks.

The time required to develop an island from a macroform is unknown and probably varies from reach to reach. However, based on analysis of aerial photographs, it is reasonable to expect that islands can be developed from macroforms within a decade or two. It is not clear why vegetation has become established on macroforms in the Platte River upstream from Grand Island, Nebraska, while macroforms downstream from Grand Island largely have remained free of vegetation. This difference can be attributed in part to changes in flow regime of the Platte River upstream from Grand Island caused primarily by regulation of the North Platte River (fig. 2; Kircher and Karlinger, 1981). However, translation of these changes into vegetative encroachment is uncertain. One or two causes may explain the encroachment of vegetation on the macroforms upstream from Grand Island: (1) River flows have declined, due to regulation, to the point where macroforms are uncovered during the critical germination period, allowing vegetation to become established; or (2) river flows have declined to the point that vegetation, established during a preceding year, no longer is scoured off the macroform during spring peak flows.

The first explanation is not entirely satisfactory. Historical accounts of the Platte River channels and few hydrologic records available for the river since 1900 indicate that peak flows never have persisted through the critical germination period (mid-May to mid-August). Periods conducive to vegetation germination probably always have existed. Since the first historical accounts of the river, vegetated islands in the channels have been reported indicating that periods conducive for germination were common.

The second explanation may be more satisfactory. Peak flows have declined along the Platte River upstream from Grand Island, but have remained relatively stable downstream from Grand Island. Vegetation has the opportunity to be established on the macroforms upstream from Grand Island, because annual peak flows no longer are capable of clearing vegetal growth from macroforms each year. Downstream from Grand Island, peak flows inundate macroforms often enough to maintain the original width of the river.

MAINTENANCE OF CHANNEL WIDTH

If the reasonable assumption is made that macroforms are kept clear of vegetation by the scouring action of peak flows, then it is possible to predict the magnitude and frequency of flow required to maintain a given channel width. Methods for making such predictions are outlined in this section.

Vegetation can be scoured from macroforms in two ways: (1) By the reworking of sediment by smaller bedforms on the stoss side of the macroform; and (2) by the transport of sediment, with a concomitant lowering of the sediment surface with respect to the channel bed, in a downstream direction involving the movement of the entire macroform. Both interrelated processes contribute to the removal of vegetation from the macroforms.

Effects of these processes can be described quantitatively. In cross section, a macroform can be represented as a triangular element (fig. 13). If geometry of the macroform is in equilibrium with prevailing flows, it moves downstream while maintaining this triangular geometry. Movement of the macroform in a downstream direction involves erosion of sediment from the stoss side of the macroform and deposition on the lee side.

The distance λ_L through which the macroform moves in the downstream direction is given by the equation:

$$\lambda_L = \frac{h_s}{H}\left(\frac{w_f}{\sin\alpha} - \frac{H}{\cos\theta}\right), \tag{2a}$$

where

h_s is the depth of erosion on the stoss side of the macroform;

H is the amplitude of the macroform;

w_f is the macroform width;

α is the acute angle formed by the intersection of the macroform with the channel banks (fig. 4); and

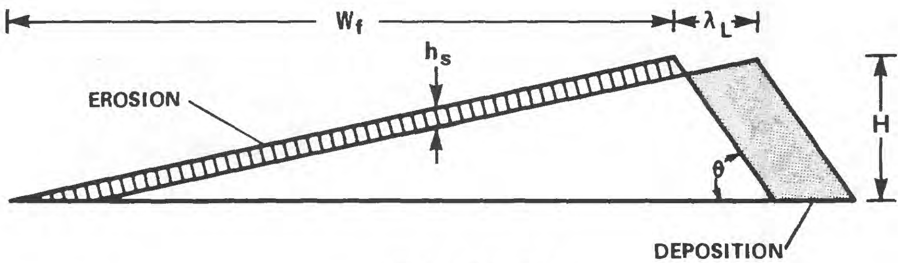
θ is the acute slipface angle with the horizontal.

Equation 2a can be simplified to

$$\lambda_L = \frac{h_s\, w_f}{H \sin\alpha}, \tag{2b}$$

because the value of $\frac{H}{\cos\theta}$ is negligible in comparison with the factor $w_f/\sin\alpha$.

Equation 2b shows that wavelength of the macroform is related to distance through which it moves downstream by the amplitude and depth of erosion on the stoss side. Alternatively, depth to which sediment is eroded on the stoss side of the macroform is a function of the distance through which it moves in a downstream direction. Therefore, if the depth to which sediment must be eroded from the stoss side of the macroform to remove vegetative growth is known, the approximate distance could be predicted through which a macroform of known dimensions must travel in a downstream direction to remain free of vegetal growth. To remove all vegetative growth, the bed should be eroded below the deepest penetrating plant roots. Data on rooting depths are not available. However, a range of erosion depths can be defined on the unvegetated macroforms



EXPLANATION

$$\lambda_L = \frac{h_s}{H}\left(\frac{W_f}{\sin \alpha} - \frac{H}{\cos \theta}\right)$$

λ_L = net movement in downstream direction

h_s = erosion depth on stoss side

H = amplitude

W_f = macroform width

α = angle formed by intersection of macroform and channel bank

θ = slipface angle

Figure 13.--Sketch showing macroform geometry.

downstream from Grand Island; assuming that these erosion depths are sufficient to keep the macroforms clear of vegetation, an average sufficient erosion depth, h_s°, can be computed.

As discussed previously, the average rate of downstream movement of macroforms downstream from Grand Island ranges from 10 to 24 m/yr. Defining the macroform width by the equation $w_f = 0.61\ w_c$ (equation 1b), and assuming a value of 2 m for H; a value of 28° for α; and a value of 300 m for w_c, equation 2b yields stoss-side erosion depths of between 3 and 8 cm. For lack of better data, the sufficient erosion depth (h_s°) is taken to be the largest of these numbers, or approximately 8 cm. It is assumed then that the stoss sides of the macroform will remain free of vegetation as long as the stoss sides are eroded to a depth of 8 cm each year.

The sufficient erosion depth is only an average; the actual depth of erosion required to remove vegetation is unknown. Moreover, it is assumed that this erosion must occur each year. The rigidity imposed on the analysis by these assumptions probably is unrealistic, but, in lieu of more substantial data on which to build the model, this approach is used.

Given a sufficient erosion depth of 8 cm, what are the flow conditions necessary to move the macroforms the requisite distance to achieve this erosion? Referring again to figure 13, rate of movement of the macroform is related to average rate of tranport of bedload sediment by the equation:

$$\lambda_L = \frac{2\ q_b\ t}{H} \tag{3}$$

where

q_b is the unit-volume rate of bedload sediment transport; and

t is the time in seconds required for the macroform to migrate a distance λ_L.

The rate of bedload sediment transport can be approximated by any of several equations. A modified version of the Kalinske equation (Raudkivi, 1967) is suitable, because river slope and water depth, characteristics that are measured easily onsite, are used to determine transport rates; the equation is given by:

$$q_b = 10\ U_*\ D \left[\frac{U_*^2}{(G_s - 1)\ g\ D}\right]^2 \tag{4}$$

which, when substituted into equation 3, yields:

$$\lambda_L = \frac{2\ t}{H} \left[10\ U_*\ D\ \frac{U_*^2}{(G_s - 1)\ g\ D}\right]^2 \tag{5a}$$

or

$$\lambda_L = \frac{U_*^5 \, C \, t}{H} \tag{5b}$$

where

U_* is shear velocity;

D is median grain diameter;

G_s is specific gravity of sediment;

g is acceleration of gravity; and

C is a dimensional constant that varies with the properties of the sediment.

Equation 5b can be used in the following manner to predict flow conditions required to obtain optimal erosion depth. Rearranging equation 5b,

$$t = \frac{\lambda_L \, H \, U_*^{-5}}{2 \, C} \quad . \tag{6}$$

Equation 6 shows that the time required to move the macroform a distance λ_L to obtain the sufficient erosion depth is a function of flow conditions, as given by shear velocity and a number of other factors that are constant at any given reach. Shear velocity ($U_* = (g\ y\ s)^{\frac{1}{2}}$) contains two important variables; average channel slope, s, which also is constant at a reach, and flow depth over the macroform, y.

Equation 6 has two degrees-of-freedom <u>at a</u> reach, y and t. A plot of t and y in the form of U_* (fig. 14) indicates the relative time required at any given flow depth (or shear velocity) to move the macroform downstream a sufficient distance to obtain sufficient erosion depth.

Time increases exponentially (fig. 14), and it is not unreasonable to expect that some minimum U_* exists, at which the relationship is invalid. It was suggested previously that large dunes on the stoss sides of macroforms aid in uprooting vegetation. Dunes are developed in flows, with gradients similar to those on the Platte River, at $U_* \sim 5$ cm/s (centimeters per second). The value $U_* \sim 5$ also corresponds to the depth of flow at which the macroform becomes inactive because of armoring of the bed. Hence, $U_* = 5$ cm/s is defined here as the lower limit of the relationship in figure 14.

Equation 6 can be used in a management plan to maintain the channel in a given reach of river, in which criteria for minimum acceptable widths have been established, in the following manner:

1. Given a design channel width, an average macroform width is computed from equation 1b.
2. Annual macroform-migration distance, λ_L, required to achieve an optimal erosion depth of 8 cm is computed from equation 2b. If actual rooting depth is known, this value can be substituted in the equation for h_s°.

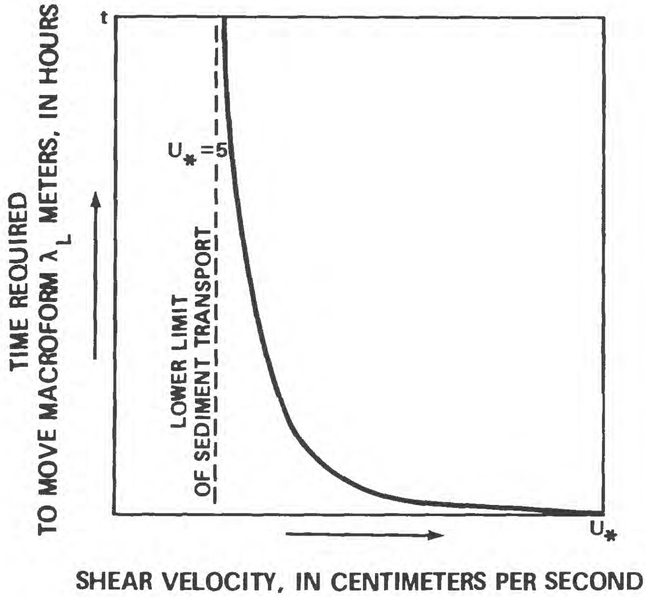


Figure 14.--Generalized shear-velocity diagram.

3. A shear-velocity diagram (fig. 14) is constructed by solving equation 6, using the computed value of λ_L; channel slope and median grain size are determined from onsite studies.
4. Shear velocity, or flow depth, from the shear-velocity diagram, can be related to river stage by surveying crests of the macroforms into a datum common with a stage-discharge curve; discharge in turn can be determined from the stage-discharge relationship.
5. The shear-velocity diagram is used to determine the length of time various flows must be sustained to obtain sufficient erosion depth.

The shear-velocity diagram is an effective management tool that indicates not only the range of depths to which macroforms must be inundated each year, but also the time during which that depth must be maintained to achieve required erosion to remove vegetation from the macroform. This method is applied to a reach of the Platte River near Silver Creek, Nebraska, as follows.

Present width of the channel just downstream of Silver Creek is approximately 240 m; width of the average macroform in the reach (eq. 1b) is approximately 146 m. Average amplitude of the macroforms (determined from onsite studies) is approximately 2 m. Slope of the reach measured from topographic maps is 0.00127; median grain size on the macroforms (from onsite studies) is 0.025 cm; the angle α is approximately 28°; G_s = 2.65; and g = 980 cm/s^2 (centimeters per second squared).

To achieve a sufficient erosion depth of 8 cm, the macroform must move downstream approximately 12.4 m each year (eq. 2b). By substituting this value with the other values listed, into equation 6, a shear-velocity diagram can be constructed (fig. 15). As discussed previously, the lower limit of this diagram is defined by U_* = 5 cm/s. Because slope is constant, the shear-velocity axis in the diagram can be replaced with depth of flow over the macroform.

Flow depth and the time over which this depth must be maintained to achieve sufficient erosion is shown in figure 15. The macroforms become inactive at flow depths less than 20 cm. In the Silver Creek reach, flows above 80 to 90 cm will result in overbank flooding. Therefore, a range in depth of 20 to 80 cm represents flow conditions that can remove vegetation from the macroforms.

At y = 20 cm, the flow must be maintained for 72 hours to achieve sufficient erosion; whereas, at y = 80 cm, the flow must be maintained for approximately 2 hours. The initial period during which the system establishes an equilibrium is not included in the time estimate. This period varies with flow conditions and could constitute a significant percentage of the time indicated by figure 15. For very large flow depths, this initial time probably exceeds the time indicated by the figure. Figure 15 was constructed with the assumption that flow causing sufficient erosion depth occurs during one period of flow. However, it should be possible to divide total flow into a number of lesser periods of flow. With each additional period of flow, the total time that the flow must be maintained increases, because equilibrium must be established for each flow period.

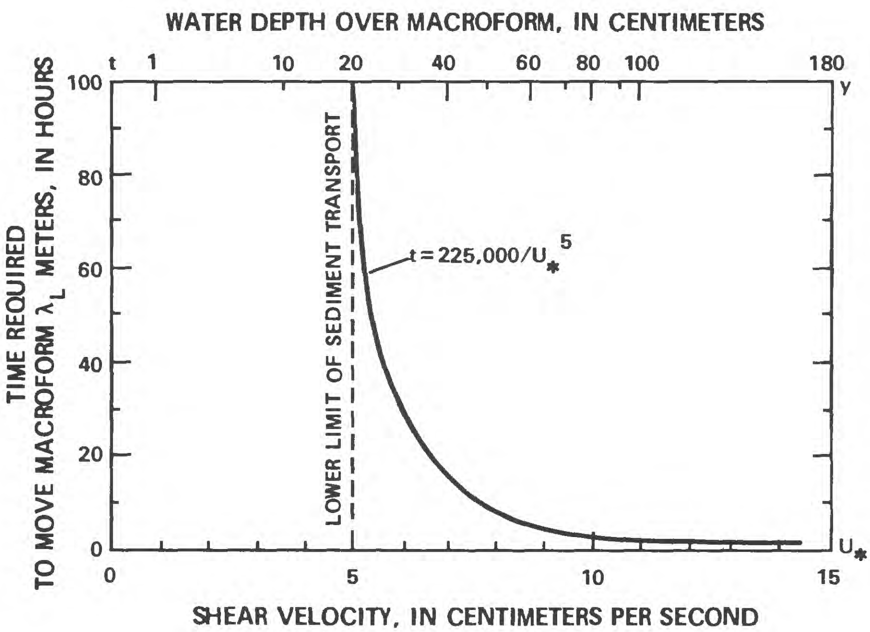


Figure 15.--Shear-velocity diagram, Platte River near Silver Creek, Nebr.

SUMMARY AND CONCLUSIONS

The bed of the Platte River in Nebraska is characterized by large, periodic, and geometrically-distinct bedforms, here termed macroforms. Macroform length and width are related to channel width (fig. 4). The macroforms are emergent at all but the highest flow stages. Macroforms are temporally stable features; single macroforms can be recognized in aerial photographs taken during several decades.

Macroforms are active only at the highest flows. After a macroform is covered to a depth of about 20 cm by the flow, sediment transport occurs over the stoss side of the macroform through the migration of smaller bedforms, such as ripples and dunes. Sediment eroded from the stoss side of the macroform is transported by smaller bedforms to the macroform crest and subsequently is deposited on the slipface. This erosion and deposition causes the macroform to move in a downstream direction. Average rates of movement of several macroforms, calculated from aerial photographs and onsite surveys, ranged from 10 to 24 m/yr, and generally increased in downstream direction from Grand Island to Fremont, Nebraska.

Encroachment of vegetation on macroforms, and their consequent stabilization, caused by changes in peak-flow regime, since the large-scale development of irrigation in the Platte River basin, is the major cause of channel width reduction upstream from Grand Island. Apparently, vegetation has become established on the macroforms, because spring flows are no longer capable of removing new vegetative growth by scouring.

From simple geometrical considerations of macroform shape (fig. 13), an equation (eq. 6) can be developed to predict the depth and duration of flow (figs. 14 and 15) required to erode the stoss side of macroforms to a sufficient depth to remove new vegetal growth. By eroding the macroform to this depth each year, new vegetative growth should be eliminated.

Methods developed in this report to predict flow conditions required to achieve sufficient erosion depths may provide useful management tools for controlling vegetation growth along the Platte River channels. Although further testing of these methods is required to establish their validity with actual macroforms, a sample calculation for the Silver Creek, Nebraska, reach shows good agreement between the flow conditions predicted by the methods outlined in this report and actual rates of movement and flow conditions observed in the reach.

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