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Classification and Analysis of River Processes[a]

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Introduction

Rivers have fascinated generations of hydraulic engineers with their variety of form and behavior. The large potential benefits of successful river engineering works, combined with the dire consequences of failures, have provided one of the earliest and greatest challenges to the profession. Today this challenge continues to be met in research on river-related processes and by systematic collection of river data. Much progress has been made in both respects but it is the writers' contention that the bias of most engineers towards readily quantifiable topics has led to a serious gap in this work, the neglect of interpretive work on river-related landforms. Lane (15) made a similar plea 20 yr ago and although that paper is often quoted, its message seems to have been largely ignored. Publication of river data consisting of sets of numbers without descriptive notes (see, for example, Ref. 5), and general statements about river behavior made without proper qualifications as to the river type considered are evidence of this (Refs. 36, 38, and 42 are recent examples).

Rivers are one of the most active agents in shaping the surface of the earth and the landforms associated with a particular river therefore provide an account, which may be quite detailed, of the river's past and present activity. The records on riverine landforms are far more complete than any other type of river record. Stereo aerial-photograph coverage at several scales and at different times is available for virtually all rivers of North America and for many rivers throughout

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the world, whereas hydrometric data are available at only a limited number of sites.

Many river engineering problems unfortunately lie outside areas where research or routine observations are presently concentrated and thus have to be solved by a combination of intuition, past experience of sometimes dubious applicability, and interpretation of fluvial features as seen on aerial photographs and in the field. Included under "past experience" are the many purely empirical design rules and equations such as the so-called regime "theory" or the procedures for computing reservoir deposition proposed in the well-known manual on "Design of Small Dams" (37). Some examples of such river engineering problems are: Selecting locations for river crossings by highways, pipelines, or railways, and selection of the most appropriate method of crossing; location and conceptual design of water intakes, training works, and wharves; prediction of bank stability and lateral shift rates; prediction of the location of ice jams and ice scour; and prediction of mixing characteristics over the range of flows.

Even in situations where quantitative methods of computation and the necessary data are available, the engineer should check his results against geomorphological evidence as may be contained in differences between successive aerial photographs and maps, or in plant successions or in systematically shifting rating curves. Sediment transport computations can sometimes be checked against growth rates of alluvial fans and deltas or against point bar progression rates (23); maximum flood levels can be checked with evidence of silt deposition, ice scour trim lines, deposition of ice rafted material, or evidence contained in the vegetation. Mixing processes at tributary junctions are identical to those at effluent outfalls and often clearly identifiable on some types of aerial photographs or other remote sensing records. Local scour at natural constrictions or spurs is still one of the most reliable indicators of potential scour at proposed bridge crossings (24). If geomorphological evidence disagrees with computed values, as is not infrequently the case, most prudent engineers will give it precedence.

Interpretation of fluvial features is not a new study and an extensive literature exists. However much of it is oriented towards the interpretation of geological history rather than towards deriving present river process rates, hydraulic parameters, and the associated composition of bed, bank, and flood-plain materials, the parameters most frequently sought by engineers.

The present contribution presents a general consideration of fluvial morphology, including a brief review of literature dealing with river channel classification and interpretaion of fluvial features, emphasizing those contributions that appear most useful in normal river engineering practice. A classification of riverine features is proposed that may serve as a checklist in photo interpretation or field reconnaissance, and permit the concise and consistent description of large numbers of river sites that may be examined in a project such as a major pipeline or highway.

River Classification: Problem and Past Approaches

Basic Problem.—Despite the long-time interest of both geomorphologists and engineers in this subject, no definitive classification exists. Classification of a river should proceed by individual "homogeneous reaches;" i.e., channel reaches (of variable length) within which hydrological, geological, and adjacent watershed surface conditions remain sufficiently uniform so that a substantially uniform river morphology results.

The characteristics of a river channel will change wherever a change occurs in any of the conditions that govern fluvial morphology and reasonably detailed knowledge of these conditions is therefore an essential prerequisite to the proper planning of any engineering interference with a river. Evidence regarding the governing conditions and thus regarding the likely behavior of the channel may be deduced from channel morphology as displayed on aerial photographs. If, in addition, a field inspection of the reach is possible, much more can be deduced. The classification to be proposed herein should be viewed as one of several tools required to recognize these conditions and their relative importance at a particular site. The most important ones may be summarized as follows.

Supply of Water and Sediment from Upstream.—This determines the size of the river channel and many of its morphological features. Whereas sediment load in the short term is closely related to discharge, in the long run it is a largely independent consequence of upstream conditions (geology, climate, land use).

The temporal variability of discharge is important in the following two respects:

1. Rivers with extremely variable discharge from year to year (steep flood frequency plots) tend to look different from rivers with similar yearly floods, a fact that is easily confirmed by comparing the outlet channels of large lakes with nearby rivers of similar setting but unaffected by lake storage.

2. Long-term natural or artificial variations in flow or sediment supply lead to adjustments in river morphology. A storage and regulation project, for instance, will in due course convert a river with large flow variations into a much smaller typical lake outlet channel. Lane (15) gives many other examples. Stevens, et al. (36) examine changes in river size and form resulting from long-term natural variations in discharge and show that some rivers appear to be constantly changing channel form and dimensions.

Nature of Materials through which River Flows.—The materials through which the river flows influence channel form by determining bank strength and erosion thresholds. Schumm (27,28) has studied the influence of alluvial sediment character on channel shape and pattern for sand-bed channels in the mid-western United States. Recognition of the adjustement of channel form to materials is also a prominent feature of the Indian regime formulas (2,11).

While the importance of bed material type is widely recognized and authors on river-related topics rarely fail to pay lip-service to it, the implications remain widely ignored as the following examples show. Several case histories exist of degradation downstream from most dams. The exact opposite, aggradation, appears to be more likely in some gravel-bed channels downstream of large dams and has in fact been documented (12,34). Bars and bed forms in gravel-bed channels are distinctly different from those in sand channels, yet this does not seem to deter engineers from applying "sand-bed derived" sediment transport and roughness formulas to gravel channels and vice versa (40).

Geomorphological Setting and Geological History.—These conditions are frequently the most important ones and unfortunately also the most difficult ones to consider in a systematic manner. Most rivers, except for those set on deltas, fans, or broad alluvial plains, are affected significantly by structural or tectonic influences that may impose a slope or a plan form, or by other nonfluvial effects such as glacial activity or slumping valley walls.

Most rivers of the northern Great Plains region have clearly imposed slopes as evidenced by the close correspondence between the slope of the land and the slope of the rivers, irrespective of the widely varying nature of some of the major rivers (13). Generally these rivers follow pre-Pleistocene valleys, but occasionally they leave the old valley, and this occurrence is normally associated with distinct changes in river behavior.

In most of North America the geologically recent end of the last major glacial period (about 10,000 yr ago near the 49th parallel) remains a significant factor for understanding present river behavior. During much of the period since then, the rivers have been moving, sorting, and redepositing the major "slug" of glacially derived sediments; today many rivers flow over lag deposits of glacial till or outwash that they are not now competent to move. Adjustments to post-glacial crustal rebound and to changing sea levels are probably still in progress. Many lakes in northern North America more or less effectively regulate downstream flows, and are themselves a legacy of glaciation.

Besides these three major conditions, many other factors can affect rivers, e.g., winter ice conditions or permafrost dominate the appearance and form of many northern rivers, and the stabilizing effects of dense vegetation in humid regions are well known.

Past Approaches.—Early physiographic classifications of rivers were mainly concerned with the relationship between river channel patterns and geological history, or with river-valley relationships in a theoretical cyclical view of landscape development known as the "fluvial cycle" (see Ref. 39 for a recent view of this concept). Some notions encompassed by this line of reasoning remain useful under the heading of geomorphological setting.

The earliest attempts at river classification that are useful in the present context were concerned with the categorization of rivers on alluvial surfaces, and with the classification of the fluvial sediments themselves. Melton (21) presented an empirical classification of flood plains and noted the possibility of relating river morphology as displayed on aerial photographs to aspects of river behavior. Happ, et al. (9; see also 33) developed a classification of alluvial deposits which were grouped into several "associations" (normal flood plain, alluvial fan, etc.) which constitute geomorphological settings.

An alternative approach is to directly examine the hydraulic character of river channels. This has been done empirically by adherents to "regime theory" methods with the most extensive classification exercise being that of Simons and Albertson (35). They recognized six classes of channels (subdivided on the nature of bed and bank materials) for the purpose of varying the parameters of their equations. Closely related studies of river channels by means of "hydraulic geometry" (16) have not, however, revealed any widely evident consistent variation in channel dimensions attributable to specific imposed conditions. The third writer (3,4) in particular attempted directly to detect effects of geomorphic setting and bed and bank materials on hydraulic geometry, with mainly negative results.

Direct discrimination amongst braided and single thread channels was made by Leopold and Wolman (17) and by Henderson (10), using discharge, slope, and bed material size as discriminating variables. Recently, Schumm and collaborators (31,32) have examined sediment load in this context as well. Neill and Galay (25) made an attempt at placing river regime evaluation on a systematic basis but they did not consider channel morphology except by classifying plan form in the conventional manner. The only general inventory of channel plan forms is one given by Dury (6), directly from observation. He recognized eight types: Meandering, braided, straight, straight-simulating, deltaic-distributory, anabranching, reticulate, and irregular. Chitale (5) gave some analysis on channel patterns. A recent classification of the plan form of rivers in the Zaire basin (26) is interesting in recognizing that braiding and meandering are not mutually exclusive.

On the basis of his studies of river sinuosity and alluvial sediments, Schumm (29,30), presented the first genetically oriented classification of river channels. He chose channel stability (in the sense of degrading/stable/aggrading) and mode of sediment transport as his classification criteria. Allen (1) recast Schumm's work in terms of lateral stability of channels and presented a diagrammatic classification that implied a continuum of channel forms. Mollard (22) and Galay, and the first and third writers (7) have developed this notion further and are the first authors to clearly emphasize the continuum of river channel types. Mollard's classification is based on plan form of the channel and is restricted to alluvial reaches with flood plains. Being one-dimensional, the classification neglects or simplifies many aspects of river morphology. Nevertheless it permits useful qualitative deductions on the following factors: (1) Discharge variability; (2) sediment supply and character; (3) ratio of bed material load to total sediment load; (4) textures of flood-plain sediments; (5) channel gradient; (6) channel sinuosity; and (7) channel stability. Mollard's analysis is keyed to aerial-photograph interpretation: His main purpose is to use observed channel pattern and associated features to make deductions about various parameters required in engineering studies, with particular emphasis on flood-plain materials. This remains the most comprehensive work of river channel classification to date.

Standing apart from all these works is a channel classification by Matthes (20). He defined as "primary channel types" mountain streams, "hard-bed" streams, erodible-bed streams, alluvial (meandering) rivers, braided rivers, delta channels, estuaries, bayous, salt-marsh channels, and lake outlets. In this list, some regard for geomorphological setting, an aspect missing from most attempts at classificaion since the early physiographic ones, is implied.

Classification System for Fluvial Features

The system to be presented herein is intended mainly as an aid to summarizing descriptive field data gained through aerial-photograph and map interpretation and through field inspection. It can also serve as a checklist if a large number of river sites have to be investigated. The system originated with an attempt to make generally available the results of 108 surveys of river reaches in Alberta (13). It soon became apparent that tables of hydrologic, hydraulic, and bed material size data gave only an incomplete account of the useful information that had been assembled. A classification system with associated coding sheets was therefore developed to permit the systematic and consistent tabulation of

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TABLE 1.—Classification of River Valley Features

Reach Name: *RED DEER RIVER, nr. Sundre* Reach No: ______ Date of Analysis: *Feb. 1976* Analysis By: *RK/MC*

Scale of Air Photos: *4 in. to 1 mi. (1:15,840)* Scale of Map: *1:50,000, NTS 82-O/10*

NOTE: Complete codes by circling the appropriate number (s). Use '-1' for 'unknown' and '0' for 'not applicable'.

General Description of the Terrain in the Vicinity of the Surveyed Reach, above Valley

Terrain:
1 mountainous
(2) foothills
3 uplands
4 hills
5 plains
6 lowlands

Vegetation:
0 0 0 not applicable
1 1 1 almost none
2 2 2 grass
3 3 3 shrubs
4 4 4 sparsely forested, 0-25%
(5) 5 5 moderately forested, 25-75%
6 6 6 heavily forested, 75-100%
7 7 7 swamp or muskeg

Forest type:
0 0 0 not applicable
(1) 1 1 deciduous
2 (2) 2 coniferous
Comments: ______

Land use:
(0) 0 no cultivation or built-up area
1 1 partly cultivated
2 2 mainly cultivated
3 3 partly built-up
4 4 urbanized

Surficial geology:
1 1 1 bedrock
(2) 2 2 ground moraine
3 3 3 hummocky moraine
4 4 4 lacustrine deposits
5 (5) 5 glacio-fluvial dep.
6 6 6 fluvial deposits
7 7 7 aeolian deposits

Valley Characteristics above Valley Flat

Valley measurements:
___ within reach
✓ within reach and immediate vicinity
depth: *0* ft.
top width: *0* mi.
bottom width: *0.5* mi.

Slumping of valley walls:
(0) none
1 occasional
2 frequent

Length of reach with slumping valley walls (contact length in percent of total length of banks): ______

Vegetation on valley wall:
0 0 not applicable
1 1 almost none
2 2 grass
3 3 shrubs
(4) 4 sparsely forested
5 (5) moderately forested
6 6 heavily forested

Forest type on valley wall:
0 0 not applicable
(1) 1 deciduous
2 (2) coniferous

Comments: *south side forested, north side mostly in grass*

Terraces

Terrace presence:
0 none
1 indefinite
2 fragmentary
(3) continuous

Number of levels:
0 not applicable
1 one level
2 two levels
_ ___ levels
(9) several levels

Comments (in particular land use and vegetation): *1 prominent, high terrace, 30 ft above river, partly cleared; several low terrace levels*

Relation of Channel to Valley

Valley type:
0 not applicable
1 stream cut valley
2 stream cut valley in wide valley
(3) wide mountainous valley

If no valley:
(0) valley present
1 on alluvial fan
2 on alluvial plain
3 in delta
4 in old lake

Underfit:
(0) not applicable or not obviously underfit
1 obviously underfit

Local lateral constriction:
(0) none
1 one
2 two
_ ___ cases
9 several cases

Relation of channel to valley bottom (vertical):
0 not applicable
(1) not obviously degrading or aggrading
2 partly entrenched
3 entrenched
4 aggrading

Relation of channel to valley walls or to high, resistant terraces (lateral):
0 not applicable (no valley or free)
1 occasionally confined
(2) frequently confined
3 confined
4 entrenched

Comments: *could be "partly entrenched"; confined mainly by high terrace but occasionally by valley wall (beyond stereo view)*

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TABLE 2.—Classification of Valley Flat and Channel Features

Reach Name: *RED DEER RIVER, nr. Sundre, Alberta* Reach No: ________

Description of Valley Flat

Presence:
- 0 none
- 1 indefinite
- 2 fragmentary
- (3) continuous

Extent:
- 0 none
- 1 narrow (< 1 Ws)
- (2) moderate (1-5 Ws)
- 3 wide (> 5 Ws)

Average width *0.1* mi.
Maximum width *0.15*
Channel length with valley flat on left *100* %
on right *60* %

Vegetation:
- 0 0 not applicable
- 1 1 almost none or bare
- (2) 2 grass
- 3 3 shrubs
- 4 (4) sparsely forested
- 5 5 moderately forested
- 6 6 heavily forested
- 7 7 swamp or muskeg

Forest type:
- 0 0 not applicable
- (1) 1 deciduous
- 2 (2) coniferous

Land use:
- (0) 0 not cultivated, not built-up
- 1 1 partly cultivated
- 2 2 mainly cultivated
- 3 3 partly built-up
- 4 4 mainly built-up

Comments: *valley flat consists of small genetic flood plains and at least 2 low terrace levels*

Channel Description (near long-term mean)

Channel pattern:
- 1 straight
- 2 sinuous
- 3 irregular
- 4 regular meanders
- (5) irregular meanders
- 6 tortuous meanders

Islands:
- 0 none
- 1 occasional
- 2 frequent
- (3) split
- 4 braided

Type of flow:
- 1 uniform water surface
- 2 uniform with rapid in reach
- (3) irregular
- 4 pool and riffle sequence
- 5 tumbling flow

Bar type:
- 0 0 0 none
- 1 1 1 channel side bars
- 2 2 2 point bars
- 3 3 3 channel junction bars
- 4 4 (4) mid-channel bars
- 5 5 5 diamond bars
- (6) 6 6 diagonal bars
- 7 7 7 sand waves or large dunes

Meander dimensions:
belt width *0* mi.
wave length *0* mi.
sinuosity *1.14*

Natural obstructions:
- (0) 0 none
- 1 1 logs
- 2 2 beaver dams
- 3 3 boulders (lag material)
- 4 4 vegetation

Degree of obstruction:
- (0) 0 none
- 1 1 occ. minor
- 2 2 occ. major
- 3 3 frequent minor
- 4 4 frequent major

Comments: *complete transition from well-established islands to low gravel bars*

Lateral Channel Activity

Lateral activity:
- 0 not detectable
- 1 downstream progression
- 2 progression and cut-offs
- 3 mainly cut-offs
- 4 entrenched loop development
- (5) irregular lateral activity
- 6 avulsion

Lateral stability:
- 0 stable
- 1 slightly unstable
- (2) moderately unstable
- 3 highly unstable

Comments: ________

Channel Banks and Bed

Alluvial bank material:
- 0 0 0 no alluvial banks
- 1 1 1 clay and silt (cohesive)
- 2 2 2 silt and sand (non-cohesive)
- 3 3 3 sand and gravel (< 64 mm)
- (4) 4 4 sand to cobbles
- 5 5 5 sand overlain by silt
- 6 6 6 gravel overlain by silt
- 7 7 7 cobbles overlain by silt

Non-alluvial bank material:
- (0) 0 0 alluvial bank material
- 1 1 1 lacustrine deposits
- 2 2 2 till
- 3 3 3 easily erodible rock
- 4 4 4 moderately erodible rock
- 5 5 5 resistant rock
- 6 6 6 boulders

Percentage of left bank in alluvium *100*%
Percentage of right bank in alluvium *100*%

Bank vegetation:
- 0 none
- (1) weak
- 2 good
- 3 very strong

Predominant bed material:
- 1 sand
- 2 sand with local gravel
- 3 gravel
- (4) gravel with local sand
- 5 sand and gravel

Depth of alluvium:
- 0 no alluvium
- 1 shallow
- 2 moderate
- (3) deep

Estimated depth of alluvium *~1* ft.

Reference or comments: *bedrock banks occur beyond immediate reach*

Bed Rock Below Channel

Presence of rock outcrops in channel bed:
- (0) none
- 1 one occurrence
- 2 two occurrences
- _ ________ occurrences
- 9 several occurrences

Rock type at channel base:
- (0) 0 0 not applicable (none for great depth)
- 1 1 1 compact clay
- 2 2 2 shale
- 3 3 3 limestone
- 4 4 4 sandstone
- 5 5 5 conglomerate
- 6 6 6 granite
- 7 7 7 ________

Erodibility:
- (0) 0 0 not applicable
- 1 1 1 soft cohesive
- 2 2 2 easily erodible
- 3 3 3 moderately erodible
- 4 4 4 resistant

Comments: ________

additional information, not readily quantifiable.

The general principles on which the classification is based are as follows: (1) The length of river which can be considered a "reach" for the present codes as variable—the main criterion is homogeneity; (2) the coding proceeds from a broad view of the general setting to a progressively more detailed description of the channel banks and bed; (3) the codes incorporate standard terminology as much as possible; (4) the coded criteria are quantitatively delimited wherever possible; and (5) multiple codes are used in decreasing order of importance when one code does not adequately describe the situation.

Slightly modified versions of the two coding sheets are reproduced herein as Tables 1 and 2 with entries, by way of an example, for Red Deer River near Sundre, Alberta, Canada, the reach shown in Fig. 1. This reach, in the Rocky Mountain foothills, has a mean flow of 900 cfs (25 m^3/s), a 2-yr flood of 6,000 cfs (170 m^3/s) and a maximum observed flow of 23,000 cfs (650 m^3/s). Some of the table entries required examination of the appropriate topographic

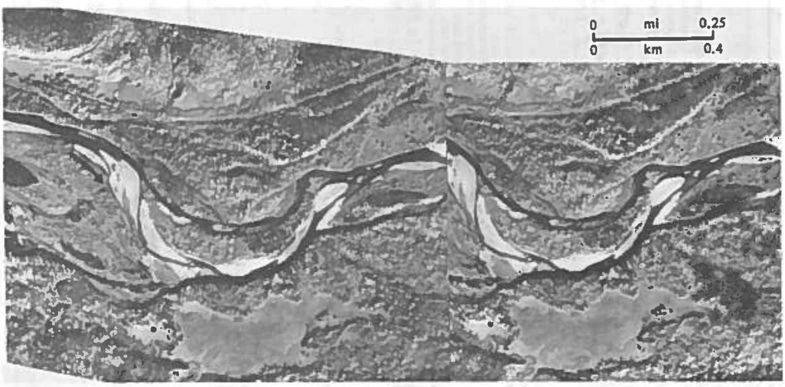

FIG. 1.—Red Deer River near Sundre, Alberta: Discharge is 630 cfs (18 m^3/s); Stereo Pair from Vertical Aerial Photographs (Province of Alberta Photographs 1388-5730-4629-107 and 108)

map and of more extensive photo coverage than is reproduced herein. The topographic map indicates a river slope of 0.0070. A close-by but morphologically different reach of the same river is described in Ref. 12.

Some of the codes are trivial and are only included to ensure that the subject is not forgotten, while others are rather site-specific for conditions in Alberta. Most users would probably need to modify the system somewhat for their specific purpose. A detailed description of the system is therefore not warranted but is available (3). The following analysis will concentrate on those aspects of the classification which cause most difficulties, or require arbitrary definitions.

Flood Plains, Terraces, and Valley Flat.—Engineers and geomorphologists tend to assign distinctly different meanings to the term "flood plain." To engineers it is that part of a valley floor subject to occasional flooding, with different agencies using various definitions for "occasional." In a recent paper the 100-yr flood is advocated (19), while in British Columbia the 200-yr flood has been adopted. To geomorphologists the flood plain is a surface developed at the present river level through erosion and sediment deposition associated with ral migration and overbank flooding. Terraces are similar surfaces developed .ome time in the past at a higher elevation.

:onsidering that an area subject to flooding at some arbitrary recurrence :rval may include several distinct fluvial features and will therefore be difficult dentify on aerial photographs, and considering further that extreme floods particularly severe ice jams can cause the flooding of areas that both engineers geomorphologists would normally call "terraces," the engineering use of ood plain" was abandoned and the term reserved for alluvial surfaces presently ıg developed by the river. The term "valley flat" was adopted for relatively surfaces on the valley floor subject to flooding and carries no genetic ılication. The distinction between genetic flood plains and low terraces can quite difficult and is often not required for engineering purposes (41).

:ivers that are both shifting laterally and degrading slowly produce gently lined slip-off slopes or stair-like sequences of terrace levels that grade gradually) a valley flat. From an engineering point of view, the difference has great ıificance as some parts of such surfaces may be beyond most flood levels l the river will have greater lateral stability than in the case of a true flood in. The valley flat must then be limited at some arbitrarily selected elevation t may be defined by a recurrence interval if sufficient data are available.

'erraces are generally covered by a capping of deposits similar to flood-plain ›osits, possibly modified by various terrestrial processes (wind action, soil mation). The underlying material may be anything from alluvium (thus, alluvial ·ace) to till or bedrock. Distinguishing between these is often important, :e a bedrock terrace will offer more resistance to erosion than one composed overburden. Sometimes this can be achieved either through knowledge of recent geologic history of a region or through careful examination of cut-banks ere the terrace is under attack by the river.

:are must be exercised in using the terms "rock" and "bedrock" in order avoid misleading connotations of solidly lithified erosion-resistant material. ologically, any body of sediment that has not been modified by weathering ›y organic soild formation since its deposition constitutes a "rock formation;" term "bedrock" is reserved for lithified material, but this still allows a le range of erosion resistance. On the Great Plains, bedrock frequently includes ely-indurated mudstones or shales that turn quickly to clays on exposure, poorly cemented sandstones that easily disintegrate.

'ig. 1 shows a situation with a discontinuous genetic flood plain and several ı terrace levels. Collectively they make up a continuous valley flat. There ılso a prominent high alluvial terrace, dissected by a tributary. All these tures are underlain by late Quaternary alluvium.

:elation between River Channel and Its Valley.—The interaction between a er channel and its valley is of significance for many engineering projects l yet there is no widely accepted approach to dealing with this topic.

Not all river reaches are associated with valleys: Those on aggradational tures such as fans, deltas, and broad alluvial plains are essentially independent any valley. If there is a valley, it may or may not be stream-cut and if s stream-cut, this may have been done by a much larger river than the nderfit" stream presently occupying it. Actively slumping valley walls may an important constraint, often recognizable by irregular river width wherever river flows along a valley wall.

Two aspects of the river-valley interaction must be examined in most situations: (1) Relation of the channel to the valley flat; and (2) the relation of the channel to the valley walls. Proposed classification for the first item is as follows:

1. Aggrading: Deltaic reaches and braided reaches filling the entire valley floor. Channel avulsions, which can present a serious threat to many engineering structures, are associated with most aggrading situations.
2. Not obviously degrading or aggrading: River reach associated with a low valley flat that appears to be a genetic flood plain. According to Wolman and Leopold (41) slow aggradation or degradation are not incompatible with the presence of a genetic flood plain.
3. Partly entrenched: Short segments of the reach are entrenched in alluvial or in nonalluvial materials.
4. Entrenched: River reaches with no associated valley flat.

Entrenched channels are frequently degrading but it is dangerous to assume that this is necessarily the case. Deep entrenchment followed by a period of aggradation leads to situations in which the channel still appears entrenched.

A classification of the second item, the relation between channel and valley wall, is as follows: (1) Occasionally confined—the river is occasionally deflected by the valley wall or by a resistant terrace; (2) frequently confined—as in No. 1 but more frequent; (3) confined—the river is regularly deflected by the valley walls or by terraces; and (4) entrenched—by definition, any entrenched channel is also continuously confined. The channel of Fig. 1 is best classified as "not obviously aggrading or degrading," although "partly entrenched" could also be justified by the discontinuous nature of the genetic flood plain. The channel is "frequently confined" by high alluvial terraces and "occasionally confined" by the valley wall (beyond the stereo coverage).

Channel Description.—The widely used classification of plan form as meandering straight, or braided (for example, Ref. 17) is unsatisfactory for several reasons, the main one being that the terms are not mutually exclusive. Single thread channels can meander in various distinctly different modes. Multiple or split channels present even greater difficulties since a range from infrequent channel islands, through frequent islands to multiple channels and, finally, truly braided channels occurs. Some split channels meander distinctly and, to complicate the issue further, there is also a complete sequence from usually flooded channel bars, with surface levels well below the valley flat, through islands at the valley flat level to islands at high terrace levels. Plan form is therefore stage dependent.

The proposed solution is to describe channel features under three main headings: (1) Channel pattern; (2) islands; and (3) channel bars and major bed forms. The channel should be primarily described near mean flow, with notes added if the pattern changes distinctly at higher or lower stages. Flows near the mean have a relatively high probability of occurring and being photographed: Descriptions derived from photographs of extreme conditions should be so notated.

Channel Pattern.—The channel pattern classification is shown in Fig. 2 and consists of the following terms:

1. Straight: Very little curvature within reach; occurs mainly in braided channels, delta distributaries, and structurally controlled channels.

2. Sinuous: Slight curvature with a belt width of less than approximately two channel widths.

3. Irregular: No repeatable pattern; structurally controlled angular patterns would be classified "irregular" with appropriate comment. Many braided and split channels fall into this category.

4. Irregular meanders: A repeated pattern is vaguely present in the channel

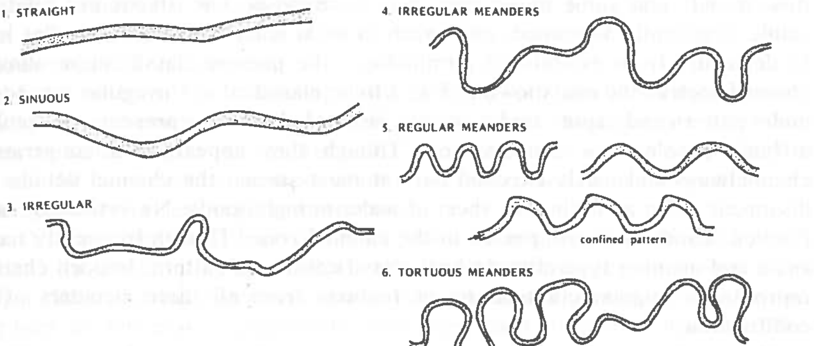

FIG. 2.—Codification of River Channel Patterns

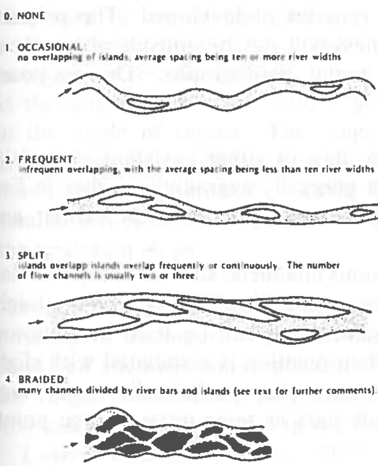

FIG. 3.—Codification of Islands

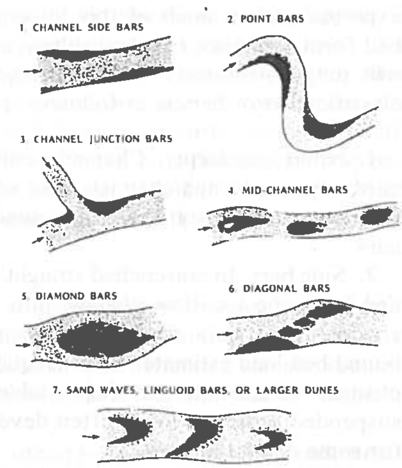

FIG. 4.—Codification of River Channel Bars

plan; free meanders of sand-bed channels with high bed load, and many entrenched meanders are irregular.

5. Regular meanders: Characterized by a clearly repeated pattern. The angle between the channel and the general valley trend is less than 90°; confined meanders are often exceedingly regular. Freely meandering gravel-bed channels on a relatively steep slope may also be regular.

6. Tortuous meanders: A more or less repeated pattern characterized by angles greater than 90° between the channel axis and the valley trend; this pattern is frequently associated with free meanders of sand-bed streams in flood plains dominated by vertical accretion. Many underfit streams belong in this group. Steep streams entrenched in very soft bedrock can also adopt a tortuous pattern.

Islands.—The island classification is shown in Fig. 3. At the long-term mean flow islands and some major bars may be exposed but islands are relatively stable, frequently vegetated, and reach to or at least close to valley flat level. In departure from established terminology, the present classification allows a channel such as the one shown in Fig. 1 to be classified as "irregular meanders" under pattern and "split" under islands. Braided channels represent a particularly difficult problem for classification. Though they appear as a congeries of channelways and partly exposed bars at most stages, the channel details may disappear under a continuous sheet of water in high floods. Nevertheless, rarely flooded islands may also persist in the channel zone. Though frequently named as an end-member type in traditional classifications of pattern, braided channels represent a singular combination of features from all three elements of our codification.

Channel Bars.—Channel bars and major bed forms are shown in Fig. 4. They probably contain more information on channel processes and bed load sediment transport in particular than any other river features, but due to the unfortunate preoccupation of river-related research with two-dimensional flume experimentation much of this information remains undeveloped. The primary bed form sequence (ripples, dunes, antidunes) will not be considered as these will only fortuitously be identifiable on aerial photographs. The proposed classification of bars is as follows:

1. None (apparent): Channels eroded in clay or other resistant materials, narrowly constricted channels, and very flat generally aggrading reaches in fine alluvial materials (typically fine sand bed, clay banks), may not exhibit any bars.
2. Side bars: In entrenched straight or sinuous channels, side bars may develop and force the low-flow channel into a more meandering path. In very straight channels they may migrate and their migration rate can be used for a lower bound bed load estimate. More frequently their position is associated with slight channel bends and therefore stable. Channels that periodically carry high suspended sediment loads often develop side bars as temporary storage points for some of that material.
3. Point bars: These features form on the inside of well-developed bends. Dunes on the point bar are indicated by ragged edges of the water surface and are normally associated with relatively coarse sand beds. In gravel beds, point bars are often extensions of diagonal bars (mentioned subsequently).
4. Channel junction bars: Where a tributary joins a larger river, a bar frequently occurs immediately downstream, or on both sides of the tributary mouth. This represents a storage point for sediment delivered by the tributary that is not immediately moved on.
5. Midchannel bars: One type of midchannel bar typically found in the larger gravel-bed channels has been described by Galay and Neill (8). It has a

crescent-shaped plan form similar to barchan dunes, with grain-size decreasing along the bar. In the lee of the bar, between the horns, suspended load material tends to accumulate. The bar position remains stable over decades with bed load transport taking place across the bar. In cross section, the bars are often very regular inverted parabolas. The top of the bar surface corresponds closely to the top of gravel deposits under adjoining flood plains, with the flood-plain level being some 3 ft–10 ft higher due to suspended load deposits of fine sand and silt. Deposition of suspended load in the lee of log jams, that tend to form on midchannel bars, sometimes converts them into islands. Fig. 1 shows various stages of this process.

6. Diamond bars: Also called linguoid bars or "spool" bars by sedimentologists, they are an extreme development of midchannel bars characteristic of braided rivers in sand or gravel (see Ref. 14). The surfaces usually become flat on top and the constricted channelways between them often form erosional chutes, which produces a very regular appearance.

7. Diagonal bars: This type of bar occurs only in gravel-bed channels, being particularly common in the smaller ones. At lower flows the bar is associated with a riffle and the river may cut several shallow channels across the bar. The bars do not move significantly over time spans of several decades. Most of the exposed bars in Fig. 1 are diagonal bars.

8. Sand waves, linguoid bars, or large dunes: This type of bar is common in relatively active sand-bed channels. In early development they form relatively featureless shoals in many comparatively wide channels. When fully developed, they may be crescent-shaped with horns pointing upstream or may appear as a sand sheet, shoaling to a front that runs diagonally across the river. The most characteristic feature, which distinguishes them from midchannel bars, is the dune-like profile, with a gentle upstream side and a downstream side at the angle of repose. The length of such bars is of order channel width, and the height is normally more than 50% of mean bankfull depth. The bars move and are therefore suitable for lower-bound bed load estimates. Much smaller dunes of the type observed frequently in flume studies may occur on the upstream slope.

From the type of bars and the presence or absence of bed forms, it is normally possible to distinguish between sand and gravel-bed channels. In the case of sand-bed channels, more accurate bed material size estimates are not required for rough calculations. In gravel-bed channels, bed material size is important and can only be estimated in the field.

Lateral Channel Activity.—This code attempts to describe the predominant type of lateral channel activity in the reach. Care must be exercised in distinguishing between presently active processes and those active at an earlier stage, but whose traces may be well preserved on the valley flat. Features that assist in the evaluation of this code are meander scrolls (scroll bars, point bar deposits), meander scars, linear vegetation patterns, cutoffs and oxbows, and former channel or channel bar patterns on the present flood plain. The code is shown in Fig. 5 and consists of the following terms:

1. Not detectable: No signs of lateral movement (deeply entrenched channels, generally).

2. Downstream progression: The whole meander pattern moves downstream without forming cutoffs; frequently associated with confined regular meanders but also possible in steep gravel-bed channels.
3. Progression and cutoffs: Common on well-developed flood plains of meandering rivers.

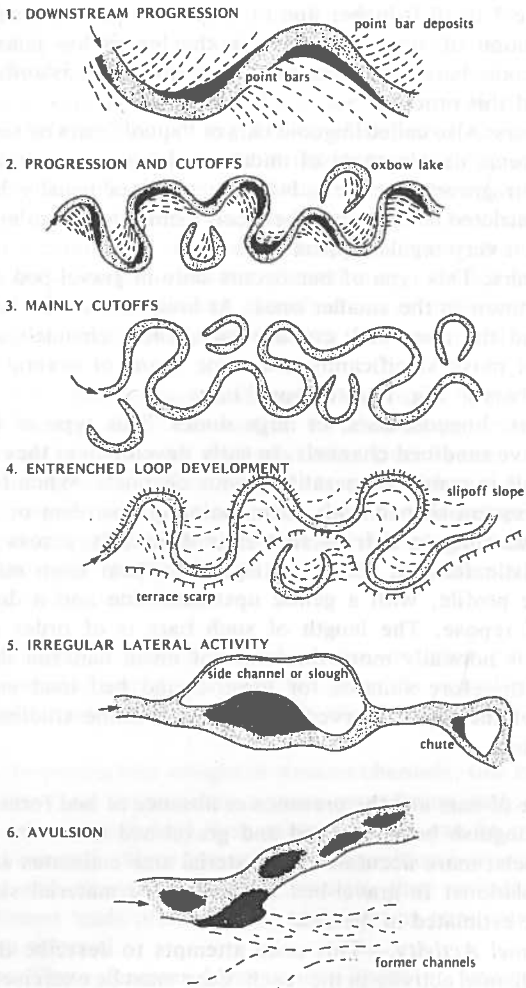

FIG. 5.—Lateral Activity of River Channels

4. Mainly cutoffs: Typical for low-gradient streams with a flood plain consisting mainly of vertical accretion deposits.
5. Entrenched loop development: Rivers working downwards and sideways into relatively easily erodible materials.
6. Irregular lateral activity: No clear pattern is detectable. Active gravel-bed

channels frequently fall into this group. The occurrence of side channels, chutes, and sloughs, indicating shifts in the main channel position, is typical. The river shown in Fig. 1 falls into this category.

7. Avulsions: Aggrading streams may break out of levees or former channel zones completely and adopt an entirely new course. In deltaic marshes, breached levees and crevasse splays indicate partial or total redirection of flow.

Conclusions

Consistent river channel classification, with emphasis on those aspects of river behavior that are most important in practical river engineering problems, is a prerequisite to the study of river processes, but existing classifications are procrustean beds for the wide variety of river forms that commonly occur in nature. A classification system is developed that makes allowance for the gradual transitions between classical channel types, whilst relying extensively on existing terminology. The details of any practical classification system should depend on both the objective of the job and on local river types.

Any analysis of river behavior or publication of river data should be qualified as to river type. The paper has emphasized classification from aerial photographs and has concentrated on those aspects that are judged most difficult to deal with and most important. The classification scheme remains useful in combined office and field investigations, whether the field phase represents one-trip reconnaissance or the beginning of systematic observations. Classification is particularly appropriate in the early stages of large-scale regional projects, such as route selection for highways or pipelines, when field records will not be available for many rivers. An application of the classification methods examined herein in the context of field reconnaissance for northern pipeline routes is provided by Lewis and McDonald (18). In all events, field investigation remains essential for the advanced stages of any project.

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