The physical science of fluvial geomorphology is flawed because it ignores processes that are not easily quantifiable and physically or statistically manipulable. The influence of vegetation on river behaviour and fluvial geomorphology is a set of these processes. Vegetation may exert significant control over fluvial processes and morphology through five mechanisms: flow resistance, bank strength, bar sedimentation, formation of log-jams, and concave-bank bench deposition. Examples of these mechanisms, largely drawn from the Squamish River in British Columbia, are presented, and implications for future research are briefly discussed.

The theory and empirical basis of fluvial geomorphology have seen radical developments during this century. Reflecting trends in natural science in general, there has been a pronounced shift from general qualitative description of river-related landforms to detailed quantitative analysis of fluvial processes. In particular, the science of fluid mechanics and the technique of physical modelling of fluvial processes have been fully absorbed into the methodology and methods of today's fluvial geomorphology. As a direct result, significant advances have been made in our understanding of river systems. Yet fluvial geomorphologists have become increasingly concerned with some of the related costs of embracing this physical science paradigm. For example, discussions of the nature of equilibrium, and more recently of time scales in geomorphology, have raised the serious question of whether these process studies in steady-state time have much relevance at all to understanding river geomorphology, the most significant aspects of which often are dominated by processes operating at far longer time scales.

The physical science of fluvial geomorphology is also flawed by a related but much less discussed limitation: it does not cope well with processes that are not easily quantifiable and physically or statistically manipulable. This criticism of quantitative analysis has been commonly debated in human geography, but it has never been an issue in geomorphology. Rather, problems of this type in scientific fluvial geomorphology have been resolved as they are in other disciplines: by simply excluding them from the research experience. Unfortunately, this too often carries the implicit and unjustified connotation that the 'other' processes are unimportant.

Nowhere in the methods of fluvial geomorphology is this arbitrary selection process more common or less desirable than in physical (and mathematical) modelling of fluvial proces-
ses. It is common because of the scaling difficulties presented by dynamic similarity criteria; and it is undesirable because it limits not only the quality of information we receive but also the scope of our questions. For example, much of what we understand about channel migration and point bar development has its basis in the results of flume experiments or in field studies designed to answer questions raised in the laboratory.

An important case of a phenomenon excluded by this information filter – and the subject of this paper – is the role of riparian vegetation in the fluvial process-response system. Vegetation is very difficult to quantify and exceedingly difficult to model in a flume. It is therefore excluded from these exercises with the rationalization that flume channels can mimic their real counterparts rather closely in many respects, despite the omission of vegetation from laboratory experiments. It is a basic contention of this paper, however, that the role of riparian and aquatic vegetation is considerably understated in fluvial geomorphology and that certain kinds of vegetation-related fluvial processes are virtually overlooked, or poorly understood at best.

Some of the discussion to follow is based on casual rather than controlled observations. Clearly, such impressions can support conjecture only, but they are presented here in the cause of stimulating debate. Should that, in turn, lead to carefully designed and tested hypotheses regarding the effects of vegetation on the nature of rivers, the purpose of this paper will have been well served.

SOME GENERAL OBSERVATIONS AND COMMENTARY ON THE LITERATURE

It long has been recognized that vegetation may be an important control on river form and activity, but most of the discussion is general and rather speculative. The literature is of two basic types: that dealing with the indirect relations among vegetation-water/sediment yield-river morphology, and that dealing with the direct impact of boundary vegetation on channel morphology. The former includes a substantial literature based on controlled cutting and burning of forests in experimental watersheds and will not be discussed here. This paper is concerned only with the direct influences of vegetation on fluvial processes and morphology.

The literature on the direct effects of vegetation on fluvial processes and channel morphology is limited to very few papers indeed. Of these, several are not concerned with process per se but rather involve a vegetation influence in order to explain historical channel changes. For example, Hadley and Graf speculate that channel contraction and degradation observed on Oraiil Wash in northeastern Arizona and on Green River, Colorado, respectively, relate to an associated encroachment of vegetation on the channel. The results of this type of inquiry are obviously debatable (see the challenge by Everitt) and are not very useful in the present context.

The balance of the published papers deal with particular fluvial processes related to vegetation and are discussed below. The work of these authors and my own research experience suggest that vegetation may exert significant control over fluvial processes and morphology through five important mechanisms: resistance to flow, bank strength, nucleus for bar sedimentation, construction and breaching of log-jams, and concave-bank bench deposition. The first two of these mechanisms are acknowledged widely in the literature and will be given much briefer consideration than the other three.
VEGETATION AND RIVER CHANNEL DYNAMICS

VEGETATION CONTROLS ON FLUVIAL PROCESSES AND MORPHOLOGY

It is important to recognize that the processes discussed below have a scale-dependent importance. In very small rivers the effect of vegetation on channels may be overwhelming. For example, Zimmerman, Goodlett, and Comer note that vegetation effects in headwater streams in northern Vermont so dominate the channel morphology that the usual hydraulic geometry relations are largely obscured. Indeed, most headwater reaches of small mountain streams are characterized by important vegetative influences. The role of vegetation as an influence on channel form and process in larger rivers is less important, though it may still be quite significant. The present discussion centres on rivers that drain areas of the order of thousands of square kilometres and have average discharges of the order of hundreds of cubic metres per second. In particular, many examples will be drawn from the Squamish River in southwestern British Columbia. It is a proglacial gravel bed river draining 3600 km² of partially logged slopes in the Coastal Mountains near Vancouver. In the study reach, the river carries a mean annual discharge of about 250 m³/sec. Other aspects of the channel geometry and flow pattern are described elsewhere.

Resistance to Flow

It has long been recognized that channel and floodplain vegetation, as part of the boundary roughness elements, may exert a considerable influence on the resistance to flow. Indeed, the Cowan method for estimating the magnitude of Manning $n$ includes a vegetation correction factor $n_4$ in Equation 1:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5,$$

ranges of which are shown in Table 1. This empirically based procedure indicates that, with other factors constant, variation in bank vegetation in small channels can easily produce an order of magnitude variation in Manning $n$. In larger channels, bank vegetation will have a relatively smaller but nevertheless significant influence on flow resistance. For example, Richards has attributed discontinuities in some hydraulic geometry relations to stage dependent roughness effects of bank vegetation.

Other studies concerned with these direct flow resistance effects of vegetation are reviewed by Shen, although the secondary effects imposed by continuity on channel width, flow depth, and bar formation, and also on form resistance, are poorly documented.

Bank Strength

Channel form and the lateral stability of a river, depending as they do on the strength of the bank materials, may be influenced significantly by the binding properties of vegetation growing on and near the river banks.

Since vegetation binds sediment and increases its strength, and since critical tractive force theory implies that bank slope is proportional to shear strength, physical reasoning would suggest that well-vegetated banks will be associated with lower ratios of width to depth than will poorly vegetated banks. This relation between channel form and the character of riparian vegetation is commonly implicit in geomorphic writing, but it has not been the subject of any systematic study. Most of the evidence of a relation between vegetation character and channel form cited in the literature is of a historical and qualitative
### TABLE 1

**CHANNEL CONDITIONS AND ROUGHNESS COEFFICIENT DETERMINATION BY THE COWAN PROCEDURE**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Values</th>
<th>Channel conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_0$: materials involved</td>
<td>0.020</td>
<td>Smooth alluvial boundary</td>
</tr>
<tr>
<td></td>
<td>0.025</td>
<td>Rock-cut boundary</td>
</tr>
<tr>
<td></td>
<td>0.024</td>
<td>Fine gravel boundary</td>
</tr>
<tr>
<td></td>
<td>0.028</td>
<td>Coarse gravel boundary</td>
</tr>
<tr>
<td>$n_1$: degree of channel</td>
<td>0.000</td>
<td>Smooth – best attainable for given materials</td>
</tr>
<tr>
<td>cross-section irregularity</td>
<td>0.005</td>
<td>Minor – comparable with dredged channel in good condition; slightly eroded banks</td>
</tr>
<tr>
<td></td>
<td>0.010</td>
<td>Moderate – comparable with dredged channel in fair-to-poor condition; some bank slumping and general bank erosion to minor extent</td>
</tr>
<tr>
<td></td>
<td>0.020</td>
<td>Severe – extensive bank slumps and moderate bank erosion; jagged irregular rock-cut channels</td>
</tr>
<tr>
<td>$n_2$: variation in channel</td>
<td>0.000</td>
<td>Gradual – changes in size and shape gradual</td>
</tr>
<tr>
<td>cross-section shape and area</td>
<td>0.005</td>
<td>Occasional alternation – large and small sections alternate occasionally or shape changes cause occasional shifting of flow side to side</td>
</tr>
<tr>
<td></td>
<td>0.010–0.015</td>
<td>Frequent alternation – large and small sections often alternate or shape changes cause frequent shifting of flow from side to side</td>
</tr>
<tr>
<td>$n_3$: relative effect of</td>
<td>0.000</td>
<td>Negligible – Determination of $n_3$ is based on presence</td>
</tr>
<tr>
<td>obstructions</td>
<td>0.010–0.015</td>
<td>Minor – and characteristics of obstructions such as debris deposits, stumps, exposed roots, boulders, and fallen and lodged logs. Conditions considered in other steps must not be re-evaluated (double counted) in this determination. In judging the relative effect of obstructions, consider the extent to which the obstructions occupy or reduce average water area, the shape of obstructions (sharp or smooth), and the position and spacing of obstructions.</td>
</tr>
<tr>
<td></td>
<td>0.020–0.030</td>
<td>Appreciable –</td>
</tr>
<tr>
<td></td>
<td>0.020–0.060</td>
<td>Severe –</td>
</tr>
<tr>
<td>$n_4$: vegetation</td>
<td>0.005–0.010</td>
<td>Low – dense but flexible grasses where flow depth is 2–3 times the height of vegetation, or supple tree seedlings (willow, poplar) where flow depth is 3–4 times vegetation height.</td>
</tr>
<tr>
<td></td>
<td>0.010–0.025</td>
<td>Medium – turf grasses in flow 1–2 times vegetation height, stemmy grasses where flow is 2–3 times vegetation height; moderately dense brush on banks where $R_h &gt; 2$ feet.</td>
</tr>
<tr>
<td></td>
<td>0.025–0.050</td>
<td>High – turf grasses in flow of same height; foliage-free willow or poplar 8–10 years old and intergrown with brush on channel banks where $R_h &gt; 2$ feet; bushy willows 1 year old, $R_h &gt; 15$ feet.</td>
</tr>
<tr>
<td></td>
<td>0.050–0.100</td>
<td>Very high – turf grasses in flow half as deep; bushy willows (1 year old) with weeds on banks, some vegetation on bed; trees with weeds and brush in full foliage where $R_h &gt; 15$ feet.</td>
</tr>
<tr>
<td>$m_5$: degree of meandering</td>
<td>1.000</td>
<td>Minor – sinuosity index = 1.0 to 1.20</td>
</tr>
<tr>
<td></td>
<td>1.150</td>
<td>Appreciable – sinuosity index = 1.20 to 1.5</td>
</tr>
<tr>
<td></td>
<td>1.300</td>
<td>Severe – sinuosity index = 1.5</td>
</tr>
</tbody>
</table>
nature and must be interpreted cautiously. The longer-term studies (over decades, say) are difficult to interpret, because the vegetative change has accompanied other environmental changes (for example, climatic and hydrologic) and the question of causation versus association is virtually impossible to answer.\textsuperscript{15} However, the general conclusions of these particular studies accord with those of shorter-term studies (over a few years), of pronounced vegetation change and channel response.\textsuperscript{16} All indicate that encroachment of vegetation into a fluvial environment is accompanied by a decrease in the form ratio, mainly through contraction of channel width. In other words, the weight of evidence presented in these studies supports the general ideas deduced from critical tractive force theory. A study by Nevins is particularly interesting in this context, because it recounts how the Turanganui River channel in New Zealand was quickly converted from a braided to a meandering pattern following the designed planting of willow shrubs at selected bends.\textsuperscript{17} The importance of bank vegetation in reducing the tendency of some rivers to braid rather than meander was suggested earlier by other writers.\textsuperscript{18} The fact remains, however, that the argument for an active role of riparian vegetation in controlling channel form is not convincingly supported by the evidence and the question is open to debate. It might be noted that arguments have largely been centred on the cases of vegetation versus no vegetation. Specifying variations in the influence of the quantity and quality of riparian vegetation on channel morphology is beyond the state of the art at present.

The role of vegetation in influencing the rate of lateral migration of channels may be more straightforward. Recent studies of western Canadian rivers by Hickin and Nanson have shown that river banks that are particularly well bound by roots can offer far greater resistance to lateral erosion than simple unvegetated banks of alluvium exposed to the same erosive forces.\textsuperscript{19} We found that, if discharge, water-surface slope, bend curvature, size of bank materials, and bank heights are constant, a river migrating through cleared or cultivated floodplain may erode at almost twice the rate of one reworking a naturally forested floodplain. Cottonwoods and spruce grow densely on the floodplain lands of northern British Columbia, and their roots easily penetrate to the level of the river bed. They therefore provide a strong woody mesh to reinforce the alluvial banks (see Figure 1).

Smith has provided the only systematic study of root strengthening of river alluvium.\textsuperscript{20} He performed some simple field experiments to demonstrate that the erodibility of alluvium in the banks of the Kicking Horse River in British Columbia varies inversely and exponentially with its root density. His results clearly indicate that bank erodibility there is extremely sensitive to root density and probably explains why that particular river, with its organic-rich bank sediments, is so remarkably stable; lateral shifting appears to have been minimal over time spans of hundreds of years. It is likely that this vegetative effect is particularly important on very low-slope channels that are only barely competent to erode the unvegetated alluvium.\textsuperscript{21}

There is little doubt that the commonly experienced difficulty of producing laboratory counterparts of the stable, single-thread sand-bed channel occurs in part because the vegetation essential to natural bank stability is not incorporated in flume models.

\textit{Nucleus for Bar Sedimentation}

A common sight in gravel and sand-bed rivers is the association of stranded and partly buried trees and logs on mid-channel bars. Logs commonly occur at the head of the bar with a trail of sand and gravel deposited in the wake zone (see Figure 2). Although this
association might suggest a vegetation-related origin for these bars, there is no clear supporting evidence. In most cases of mid-channel bar development on the Squamish River, the bar has formed by local channel splitting (flow divergence), and the resulting shoal and bar subsequently trap vegetative debris; the vegetation has accumulated in mid-channel because of the presence of a bar, not vice versa. The evidence for this assertion is that bars usually form in the absence of vegetation, and when vegetative debris is present it usually occurs on well-developed bars, not on those in an incipient stage of formation. Nevertheless, it also is quite apparent that vegetation rafted on to mid-channel bars can enhance their rate of development by trapping still further quantities of debris or sediment. The Squamish River is typical of sand and gravel bed rivers in this respect. The mid-channel bars with the greatest relief are those with vegetation incorporated in the sediments at the head of the bar.

This observation suggests that, although vegetation may have no significant influence on the location of mid-channel bars, it may be important to their growth and development of relief. The development of relief, in turn, is essential to creating an environment favourable to the establishment of riparian vegetation. It follows that vegetation is likely to be essential for the development and continued stability of the vegetated islands of anastomosed rivers.

Vegetation may also constitute an essential element in the formation of scrolls or ridge and swale topography of point bars. Nanson has described point-bar formation on the Beatton River in northeastern British Columbia. The process, thought to be common to all rivers in the region, involves the accumulation of a slightly convex upward gravel basement on top of which is deposited finer material, eventually to form the ridge of the scroll bar.
pattern. This process is repeated for each scroll bar as the channel migrates laterally across its floodplain.

Even at the earliest stage of development the gravel base for the developing ridge supports riparian vegetation. Willow and alder are early colonizers, and as the bar develops, grasses, cottonwood, and eventually spruce become established in sequence (see Figure 3). Some young bar surfaces also support older trees that clearly do not form part of the age gradient of the normal riparian succession. These older trees may have been transplanted from elsewhere on the floodplain. On the Squamish River, and on others in the region, it is common to see floating rafts of forest litter and mosses and young tree seedlings that have been torn from the outer banks of river bends upstream. These rafts often become grounded on the point bar and provide an ideal nursery for tree growth. They vary in size from a few square centimetres up to large slabs of several square metres in area. They also act as local anchor points for stringers of coarse sediment deposited in their wake zone.

In addition to living vegetation, logs and trees also are left stranded on the point bars by the receding annual flood. Trees, with their root bowls partly buried and their trunks aligned downstream and parallel to the line of the river, are a ubiquitous feature of point bars in British Columbia and Alberta.

The rate of sedimentation on these emerging scroll bars exceeds 10 cm/year and almost certainly is caused by the filtering and sheltering action of vegetation. Again, the location of the scroll bar may be related to bend geometry and to secondary bend-flow effects, but the development of relief is dependent on the enhanced sedimentation rates over the vegetation-roughened scroll bar surface. These observations accord with those of many other observers of this type of river sedimentation.

Recently, Nanson has introduced the notion that the scroll bars on BC and Albertan river floodplains have a vegetative origin. His extensive survey of many of these rivers in 1980 convinced him that, almost without exception, scroll bars develop there around grounded trees and logs. Indeed, it may well be that scroll bars owe both their location and their relief form to a vegetative control. Obviously, it is a notion that is testable, but an answer must await further fieldwork. Interesting support for Nanson’s position comes from laboratory flume studies, since it has not yet been possible to generate Beatton River-type point
FIGURE 3. Scroll bars initially form on point bars of the Beatton River as low aprons of gravel supporting pioneer plant colonies of willow and alder (A). Scroll bars grow by accumulations around grounded logs and trees left on the gravel apron by falling discharge (B). Over time (about 30–40 years), sand and silt accumulate and are stabilized by cottonwood seedlings to form a typical scroll bar (C).
bars. The missing vegetation element is a possible explanation; certainly, it deserves greater attention than it has received to date.

**Construction and Breaching of Log-jams**

The point was made earlier that, because river island formation is dependent on vegetation-sediment interaction, anastomosed river systems are not suited to analysis by physical modelling in a flume. But there is a further reason to strengthen this contention: channel avulsions, so much a part of anastomosing channel dynamics, may be substantially controlled by vegetation through the construction and breaching of log-jams.

Figure 4 shows two commonly occurring circumstances in which floodplain vegetation and log-jams play an important part in influencing channel pattern. The first is the case of the chute cut-off, a common feature on meandering rivers with scroll bar floodplains. High-amplitude bends on this type of river are particularly vulnerable to chute cut-off, because the older swales provide direct access across the neck of the bend during floods. Further, vegetation on these older floodplain sites is often decadent; it has little understorey and exhibits rapid natural thinning by dying and wind throw. In other words, the forest vegetation offers little resistance to flood flows that scour the rear of the floodplain in the bend, ultimately leading to a chute cut-off. This sequence of events may be prevented, however, if the developing chute is blocked by a log-jam. This circumstance appears to be quite common in rivers that meander actively within the confines of a relatively narrow valley. Active migration ensures an abundance of floodplain trees in the channel, and the narrow valley restricts the path of floodwaters. Manifestly underfit rivers in former glacial floodways, such as the Fort Nelson, Muskwa, and Prophet rivers in northeastern British Columbia, provide good examples of this type of channel confinement. During floods, floating vegetation is carried on to the rear of the floodplain where it becomes snagged in the floodplain forest. The accumulating logs, in turn, filter out other vegetative debris being carried by the river, until the jam is substantial enough to deny the river access to the floodplain. In this manner, a potential chute cut-off can be averted. Figure 4B shows such a log-jam on a bend of the Muskwa River near Fort Nelson. In this case the log-jam has advanced a maximum distance of about 200 m into the floodplain as a massive lobe of logs, trees, and fine sediment. It protects about 200 m of channel bank and is over 3 m thick at the channel banks. Until the log-jam is dismantled, it is most unlikely that channel avulsion can occur here through chute cut-off development.

Even after a chute develops, the process can be reversed by the formation of log-jams. Figures 4C and D illustrate a second circumstance in which log-jams can alter channel patterns. Here, a log-jam growing at the head of an island favours one channel over another and eventually closes it, thus eliminating the original channel bifurcation. But in this circumstance it appears that the log-jam may be a necessary but not always sufficient cause for channel closure. The log-jam provides a stable framework for a dam, but finer debris must also be present if the interstitial areas are to be filled. For example, on the Squamish River it is not uncommon for a log-jam to occupy one of the arms of a bifurcation completely, while at the same time allowing continued flow through the log framework. These jams also may produce locally accelerated near-bed flow that will cause scouring, leaving the log-jam as a sort of natural bridge but an ineffective diverter of flow.

The closure of main channels by log-jams is probably not a frequent event, but the survival of the smaller channels in these anastomosing river systems may be much depen-
FIGURE 4. (A) A chute cut-off on the Beatton River. (B) A log-jam on the Muskwa River. (C and D) Secondary channels have been sealed off by log-jams on this reach of the Squamish River.
dent on the occurrence of log-jams. Certainly, on the Squamish River, most of the major changes in channel pattern recorded by sequential aerial photographs over the last several decades involve channel abandonment and flow diversion associated with the formation or destruction of log-jams.

For example, Figure 5 depicts three sequential views of a reach of the Squamish River between 1960 and 1980, showing a history of channel avulsion associated with the formation and breaching of log-jams. Between 1960 and 1978 numerous small secondary channels supplying flow to the western side of the valley in the reach between site 1 and site 3 were sealed off. Vegetation encroached onto many of the previously active gravel bars, and the overall effect was to concentrate fluvial activity on the eastern side of the valley. There is little direct evidence that this shift in channel alignment was caused by log-jams, but the concentrations of buried logs in the newly formed westerly floodplain deposits in this reach make it a likely explanation.

The easterly shift in channel alignment by 1978 caused new secondary channel development in the downstream reach between sites 2 and 5. Extensive areas of former floodplain

Figure 5. Sequential aerial photographs of the Squamish River showing channel changes associated with clearing of floodplain vegetation and the construction of log-jams (A: 1960; B: 1978; C: 1980) (BC Government aerial photographs).
Figure 6. (A) Typical planform of a confined river meander. Downstream migration of the channel has left a depositional vacancy and slough at bends (a) and (b), while sedimentation of fines and vegetation has produced concave-bank benches at bends (c) and (d). (B) An oblique view of a concave-bank bench in the reach depicted in Figure 6. (C) Concave-bank bench sediments here include an important vegetative component. (D) Aerial photograph of concave-bank benches on the confined meanders of the Fort Nelson River (BC Government aerial photograph BC5180-239).
Vegetation and River Channel Dynamics

Sediments were remobilized, and vegetation was replaced by active gravel bar surfaces. By 1980, however, the effects of channel realignment on this reach were clearly being reversed. In this case, the river was denied further access to the secondary anabranches because log-jams sealed their entrances. Ground surveys in 1983 confirmed that two major log-jams at site 2 (also shown in Figure 4c), and a third at site 4, have caused channel abandonment by the river at these locations. Here, there is no gravel bar development and the channel diversion is being accomplished entirely by the log-jams.

Elsewhere in the Squamish valley there are sites where it is altogether unclear whether log-jams have preceded or followed channel abandonment. They are associated with accumulations of gravel, thus presenting the same problem of distinguishing between causation and association noted in the discussion of mid-channel bar development.

Concave-Bank Bench Deposition

Another feature that may, in certain circumstances, owe its origin and character to the presence of vegetation is the concave-bank bench. It forms on the outer bank of a river bend that has overtightened by impinging on a resistant obstacle, such as a valley wall. As the bend migrates down valley, it leaves behind a depositional ‘vacancy’ to which the bed material has no access because of the nature of bend flow (see Figure 6). This ‘vacancy’ is enclosed by a separation zone that receives only fine sand and silt carried in suspension by eddies imported from the main flow. This type of sedimentation was first documented by Carey for the Mississippi River, but it has been examined more recently by various researchers. Because the concave bank is a relatively inefficient depositional environment for the coarser bed material, complete floodplain formation in this zone is dependent on the abundant supply of fines or of vegetation. If both are deficient, the vacancy left by migration remains as a gutter (see Figure 6a), analogous to the commonly produced dead slough zone in flume models in coarse non-cohesive sediment. If the supply of fine sand and silt is deficient, this gutter may still infill if there is abundant vegetation being carried by the river. Floating trees, logs, and leaf litter are carried into the separation zone, adding to the bulk of depositional material and increasing the efficiency of the zone as a sediment trap (see Figures 6b and c). Carey and Page and Nanson, from their studies of the Lower Mississippi River and the Murrumbidgee River, respectively, report that the organic content of the concave-bank benches is very high. Both also report considerable quantities of marsh gasses released by shallow drilling.

These concave-bank bench deposits commonly occur on most single thread rivers, where local variations in migration rates cause channel bend distortions. In such cases they occur as localized features. Where bend distortion is systematic, as in some manifestly underfit streams, these organic-rich concave-bank benches may represent up to one-third of the entire floodplain sequence (see Figure 6d).

Implications for Future Research

Because we know so little about the ways in which vegetation influences river behaviour and fluvial geomorphology, any discussion of these matters is inevitably speculative, raising many more questions than it provides answers. In my judgment, however, there is sufficient circumstantial evidence to suggest that some of these questions deserve the serious attention of physical geographers. For example, there is a clear need for geographic studies designed...
to isolate the influence of quantity and, particularly, quality of vegetation on channel morphology and on lateral migration rates. This need possibly calls for a global approach, similar to that used by Park in his analysis of hydraulic geometry regionalization. Such an approach might also shed light on the role of vegetation in the development of scroll bar floodplains. If sedimentation around grounded trees and logs is an essential ingredient in this process, it could be expected that this type of floodplain would be quite uncommon in areas naturally devoid of forest, and more recently absent in areas such as the United Kingdom, where the forest cover has been largely removed.

There also is a clear need for systematic sedimentologic studies of contemporary point bars and floodplains, specifically designed to evaluate the importance of vegetation in the initial stages of sedimentation. The hypothesis that sedimentation rates on vegetated bars are greater than those on unvegetated surfaces clearly is testable by field survey.

The role of log-jams as an influence on changes in channel pattern is another topic on which systematic field surveys could easily shed light. Perhaps the most fruitful initial step would be to identify forested river valleys for which high-resolution and frequently obtained aerial photography is available, in order to monitor channel changes in relation to log-jam formation.

Finally, experimentalists should be encouraged to model some of these processes. Although there remains an obvious scaling problem with laboratory studies of vegetation-flow interaction, there does seem to be some scope for flume work of this nature, particularly with respect to flow resistance and to bar sedimentation.

In each of these possible directions for future research there is the potential for both scientific and engineering returns. An understanding of the role of natural vegetation in fluvial geomorphology could well provide a design basis for using vegetation in a range of engineering purposes, such as stabilizing bank materials and channel planform, controlling sedimentation rates, and manipulating the rate of energy dissipation in open channel flows.

ACKNOWLEDGMENTS

The ideas of this paper have developed over a number of years, and those of merit undoubtedly owe much to discussion with numerous colleagues and former and present graduate students. Most of the observations were made during my fieldwork for projects funded by the Natural Science and Engineering Research Council of Canada.

NOTES AND REFERENCES


3 The term steady-state time is used here in the sense of some arbitrarily very short time scale, as proposed by Schumm and Lichty, op. cit.


5 Dynamic similarity requires that significant force ratios and dimensionless morphology of the model and reality are identical. But rarely can all the important scaling criteria be met simultaneously; compromises are
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necessary, because certain forces such as gravity and electrochemical forces cannot be manipulated. For example, if the ratio of water depth to boundary grain diameter (relative roughness) in a sand-bed alluvial channel were to be sustained in the typically small flows of laboratory channels, the boundary material would have to be so small that the sediment would be far too cohesive. Electrochemical and surface tension forces influencing grain attraction would become disproportionately large with respect to other forces in the flow system. This particular problem probably is the reason that true meandering, as opposed to pseudomeandering, is exceedingly difficult to reproduce in a laboratory flume. See E.J. Hickin, ‘Pseudomeanders and point dunes – a flume study,’ American Journal of Science, Vol. 272 (1972), pp. 762–99.

For example, see the discussion in A. Holmes, Principles of Physical Geology (London: Thomas Nelson, 1965), pp. 392–3.

See a recent review of some of this material in E.J. Hickin, River Channel Dynamics: Retrospect and Prospect (Burnaby: Simon Fraser University, Department of Geography Discussion Paper Series, No. 11, 1981), or a somewhat abbreviated version in E.J. Hickin ‘River channel changes: retrospect and prospect,’ Special Publications of the International Association of Sedimentologists, Vol. 6 (1983), pp. 61–83.


For example, in a recent report (G.C. Nanson and R.W. Young, ‘Downstream reduction of rural channel size with contrasting urban effects in small coastal streams of southeastern Australia,’ Journal of Hydrology, Vol. 52 (1981), pp. 239–55), it was noted that rivers emerging from the highlands on to a low-slope coastal plain of New South Wales displayed channel contraction and a reversed downstream hydraulic geometry. This, it was argued, was in part a response of low-competency streams to bank stabilization caused by the pasture grasses grown in this dairying and cattle raising area.


This process of vegetation rafting was also observed in the adjacent Lillooet River, as noted in I.M. Teversham and O. Slaymaker, ‘Vegetation composition in relation to flood frequency in Lillooet River valley, British Columbia,’ Catena, Vol. 3 (1976), pp. 191–201.


27 Refraction of dune crests around laboratory river bends can produce a type of scroll bar similar to those described for the sand-bed Wabash River (see R.G. Jackson, 'Velocity-texture-bedform patterns of meander bends in the lower Wabash River of Illinois and Indiana,' Geological Society of America Bulletin, Vol. 86 (1975), pp. 1511–22). However, these features are formed quite differently from those on the gravel-bed rivers of British Columbia and Alberta.

28 Nanson and Beach, op. cit.


33 Page and Nanson (1982), op. cit.