# CHANNEL MORPHOLOGY CONSIDERATIONS IN EVALUATING FLOOD AND EROSION CONTROL STRUCTURES

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## Abstract

A wide range morphologies and structure types were evaluated in a detailed river engineering assessment of over 50 flood control and erosion protection structures throughout British Columbia, undertaken on behalf of the provincial government. The structures were constructed for emergency flood control over the last 60 years. Most were repaired/improved on numerous occasions, typically in response to a flood. The purpose of this paper is to review the interaction of channel morphology, flood mechanism and structures, specifically to evaluate: (1) the geomorphology of the different streams; (2) the flooding mechanisms for each of the different stream types; (3) the effectiveness of different structure types for a given channel morphology; and (4) the impacts structures can have on channel morphology. Several examples from our study are presented to show the variety of structures and river types evaluated.

## Résumé

Il y a tout un éventail de morphologies et de types de structures qui ont été évalués en détaille dans une évaluation de technologie d'ingénirie de rivières pour plus que 50 structures de protection contre l'érosion et d'inondation dans l'ensemble de la Colombie Britannique, entreprise pour le gouvernement provincial. Les structures ont été construites pour le contrôle d'inondation d'urgence pendant les 60 dernières années. Les plupart on été réparés/améliorés pendant de nombreuses occasions, typiquement en réponse à une inondation. Le but de cet article est pour faire une revue sur l'interaction de la morphologie de canaux, du mécanisme d'inondation et de structures contre les inundations.

## 1. INTRODUCTION

A detailed river engineering evaluation was undertaken for over 50 flood and erosion control structures throughout British Columbia. The purpose of the study was to evaluate structure condition and effectiveness and gather information for Emergency Response Plans. The 52 structures evaluated are located on a diverse range of rivers, ranging from small and steep alluvial fan streams to large rivers with highly developed floodplains. A description of natural processes and channel morphology was an important part of the assessment. Once the key natural processes and potential failure mechanisms (erosion, flooding, aggradation, debris jam potential, bridge/culvert constrictions) are understood, appropriate flood response and maintenance measures can be undertaken.

The large number of sites evaluated presented a good opportunity to review the different stream types commonly encountered in BC and evaluate the flooding mechanisms and the effectiveness of different types of structures for the various channel morphologies. Even modest size structures change channel morphology since they can affect bankfull/channel-forming floods that occur frequently. A companion paper (Hundal, 2003) reviews the reporting format used in our study as well as flood response strategies.

Our study evaluated several large rivers and urban sites. However, most of our sites were located on small to medium size, mountain gravel bed rivers. Development in BC often occurs on an alluvial/debris flow fan or floodplain, due to the mountainous nature of the province. Large urban development in BC is also located on flood prone land (e.g. much of the Lower Mainland is protected by the Fraser River Dikes). This type of development is typically protected by engineered 'standard dikes' that are maintained and operated by a local authority, which implements an ongoing dyke management program. However, the structures we evaluated were non-standard, typically constructed for emergency flood control, greatly varying in quality and with no local authority implementing a maintenance program.

## 2. CLASSIFICATION OF CHANNEL MORPHOLOGY

Commonly used river classification systems include Rosgen (1996) and Kellerhalls et al. (1976). Since our paper discusses a specific sub-set of rivers (i.e., small to medium, mountain gravel bed rivers), we used a simplified classification system of five stream types. In comparison Rosgen's classification system has over 40 stream types. Table 1 shows the influence of geomorphic parameters on stream type and provides an aid in applying our classification system. The classification system described below is applied on a 'reach' basis. Streams often have different classifications in adjacent reaches.

Debris Flow (DF) – A very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel. Debris flows occur in small watersheds (of the order of 10 km$^2$). Debris flows have landslide characteristics.

Alluvial Fan (AF) – A fan shaped deposit formed by debris floods/bedload deposition, either where a stream issues

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from a narrow mountain valley onto a plain or broad valley, or where a tributary stream joins a main stream.

Small to Medium Size Gravel Bed River/Straight or Braided (GBR/SB) – Low sinuosity stream that often has flood channels draining through its floodplain. Small GBR/SB streams are sensitive to watershed disturbance that introduces sediment into the system, as well as riparian vegetation removal and the presence of Large Woody Debris (LWD). Once disturbed, these streams are prone to braiding, aggradation, bank erosion and lateral movement. Medium size GBR/SB streams are less sensitive to riparian vegetation removal but are sensitive to the blockage of flood channels that are important for conveying floodwaters for bankfull type events.

Medium Size Gravel Bed River Meandering (GBR/M) – Repeatable meander pattern, typically sinusoidal, regular and unconfined, however meanders can be irregular and moderately confined. Overbank flow occurs on the inside of meanders and can result in downstream meander progression and cutoffs.

Large river's (L) - Characterized by long duration flood waves (in the order of several days) and flood stages greater than a few metres above top of bank. Standard dikes typically protect floodplain development. Large rivers are not discussed herein since they have specific morphologic and flood response issues that are beyond the scope of this paper.

Tidal (T) – Secondary descriptor used if a stream has a tidal component (e.g. GBR/SB-T).

Table1. Influence of Geomorphic Parameters on Stream Type

| **Debris Flow** | **Alluvial Fan** | **GBR/SB** | **GBR/M** |
|---|---|---|---|
| -- | ← Bankfull Discharge | → | ++ |
| ++ | ← Slope | → | -- |
| ++ | ← Substrate Grain Size | → | -- |
| Transport Limited (Overloaded) | ← Sediment Transport | → | Supply Limited (High Transport Capacity) |
| -- | ← Sinuosity | → | ++ |
| ++ | ← Influence of Debris Jams | → | -- |

Notes:

1. Increasing value of parameter is indicated by ++. Decreasing value of parameter is indicated by -- (e.g., a GBR/M stream would have a greater bankfull discharge than Debris Flow (DF) stream).
2. Entrenchment and confinement are not defined in the above table since most of the sites evaluated are located on flood prone land where the degree of entrenchment and confinement is low.
3. Riparian vegetation is very important for the morphology of small GBR/SB streams. It is less important for larger streams (i.e. GBR/M) and smaller streams (i.e. DF and AF).
4. LWD is an important morphologic parameter for all the above stream types.

The overall breakdown by different stream types is shown in Table 2. 'Alluvial Fan' and 'Gravel Bed River/ Straight or Braided' together account for two-thirds of the total number of sites. Based on the authors' experience, the above ratio is a fair representation of the large proportion of flooding/erosion problems that are generally encountered at these stream types in BC, given the exclusion of large rivers for this discussion.

Table 2. Number of Different Stream Types

| Stream Type | Number | Examples |
|---|---|---|
| Debris Flow | 2 | Russell Ck., Belgo Tribs. |
| Alluvial Fan | 18 | Mission Ck., Norrish Ck., |
| Gravel Bed River/ Straight or Braided | 16 | Elk R., Similkameen R., Bella Coola R. |
| Gravel Bed River/ Meandering | 10 | Naver Ck., Eagle R. |
| Large | 6 | Fraser R., N. Thompson R., Skeena R. |
| Total | 52 (Seven of these sites had a tidal component.) | |

## 3. FLOODING MECHANISMS FOR DIFFERENT STREAM TYPES

Table 3 summarizes the common flooding mechanisms for the different stream types. The examples for each stream, presented later in the paper, contain a more detailed discussion of the flooding mechanisms.

Table 3. Flooding Mechanism By Stream Type

| Stream Type | Flooding Mechanism |
|---|---|
| Debris Flow (DF) | Channel aggradation leading to avulsion. |
| Alluvial Fan (AF) | Channel aggradation leading to avulsion, overbank flow, flow in distributary channels, LWD jams. |
| Gravel Bed River/ Straight or Braided (GBR/SB) | Flood channels draining through floodplain, overbank flooding of low-lying land. Bank erosion /lateral movement due to aggradation/ LWD jams/ice jams. |
| Gravel Bed River/ Meandering (GBR/M) | Flooding of inside of meander bends, downstream meander progression. |

## 4. STRUCTURE TYPE AND EFFECTIVENESS

Table 4 lists the applicability and effectiveness of structures for the various stream types. The terminology used in Table 4 is well understood, with the possible exception of the following: (1) 'Top of Bank Riprap Windrow' refers to rockfill that is typically 0.6 m to 1.8 m higher than top of bank; and (2) 'Gravel Plug of Overbank Flood Channel' refers to a small berm located on a floodplain that blocks overbank flow entering a flood channel.

Table 4. Structure Type Effectiveness and Applicability By Stream Type

| **Structure Type/Flood Relief Measure** | **DF** | **AF** | **GBR/ SB** | **GBR/ M** |
|---|---|---|---|---|
| Top of Bank Dike | M | M | L | L |
| Setback Dike | H | M | H | H |
| Bank Protection | M | H | H | H |
| Spurs/ River Training Struc. | L | L | H | M |
| Top of Bank Riprap Windrow | M | M | M | M |
| Gravel Plug of Overbank Flood Channel | H | H | M | L |
| Channel Excavation | H | H | M | L |
| Flood Relief Channel | L | M | M | M |
| LWD Removal/management | H | H | M | L |

i. Effectiveness and Applicability of works is defined as: H = High; M = Moderate; and L = Low.

## 5. DEBRIS FLOW EXAMPLE – RUSSELL CREEK

Russell Creek is a good example of problems associated with development on the alluvial fan of small debris flow streams that are common in the Kootenays and the coastal regions of B.C. Natural stream channel instability is exacerbated by road, railway and pipeline crossings that constrict the stream and restrict sediment conveyance. The site is located 18 km east of Creston.

### 5.1 Channel Description and Flood Mechanism

Russell Creek is a steep (8% to 10%) alluvial fan stream subject to debris flows. The drainage area is relatively small (23 km$^2$) and the watershed responds quickly to rainstorms. The flooding mechanisms are: (1) Overbank flow and potential channel avulsion at the fan apex; and (2) flooding and avulsion at the four road and railway crossings located in the mid to lower portions of the fan, which constrict the channel and restrict sediment conveyance. The stream channel is heavily aggraded resulting in a streambed elevation higher than the fan surface (the streambed is actually at a higher elevation than the top of the setback dike, in some sections). There is a significant amount of instream large woody debris in the upper third of the fan. Although no significant changes in channel location have occurred within the last fifty years, road crossings now exacerbate natural depositional processes since they impede sediment conveyance.

### 5.2 Structure Effectiveness and Impact on Channel Morphology

The Russell Creek structure consists of a dike located on the edge of the upper third of the fan, and is setback up to 150 m from the channel. The 180 m long dike protects several residences and other infrastructure from flooding by directing the overbank flow back in to the main channel. The setback dike only protects against overbank flow occurring at the top portion of the fan, it does not protect against flooding and erosion that could occur at other locations, especially at the numerous crossings, located on the lower portion of the fan.

The existing structure was constructed in 1999 and structure is in good condition and will function well for directing overbank flow back towards the main channel. Some repair and additional improvement to the structure may be required if an avulsion occurs and the channel were to relocate adjacent to the structure. However, flooding and erosion could also occur at any of the four bridge/culvert crossings. The crossings are usually cleared out after a flood - no regular dredging is undertaken.

Structure impacts on channel morphology at 'Debris Flow' sites include:

(A) Top of bank dike/riprap windrow at the fan apex that prevents overbank flow and channel avulsion. This may increase downstream sediment conveyance and result in aggradation further downstream.

(B) Setback dikes in the middle portion of the fan that direct overbank flow towards the channel. These structures can be effective and do not have a detrimental impact on channel morphology

(C) Crossings that restrict sediment conveyance increase channel aggradation and increase the risk of channel avulsion locally. These impacts alter the natural process channel aggradation, avulsion and relocation.

Figure 1. View downstream showing Russell Creek aggradation at road crossing.

## 6. ALLUVIAL FAN EXAMPLE - MISSION CREEK DIKES

Mission Creek's alluvial fan is subject to debris floods, aggradation and potential channel avulsion during spring freshet floods and occasional winter ice jam floods. These natural processes continually stress the dike system, which maintains a single channel across the fan and provides flood and erosion protection for extensive property and infrastructure in Kelowna. Figure 2 is a 1963 aerial photo, when there was less development and the features discussed below were more visible.

### 6.1 Channel Description and Flood Mechanism

Following the 1948 flood, Mission Creek was channelized through its fan, causing it to degrade in the upper reach and aggrade in the lower reach. Subsequent bank top and setback diking has been undertaken to maintain the creek in its channel. The fan area is 12 $km^2$ and the channel slope is 0.5%. The total dike length is 10 km. Gravel accumulation has been dealt with through periodic gravel removal operations. The erosion threat and level of erosion protection varies greatly. The crest level is generally at the 1:200 year flood construction level, although gravel build up in the channel can reduce the level of protection provided.

### 6.2 Structure Effectiveness and Impact on Channel Morphology

There are numerous site specific and general potential failure mechanisms including: Piping along irrigation / drainage culverts or tree roots, backflooding at ungated culverts, and piping or slope failures at locations with a high hydraulic gradient (at irrigation ditches, etc.), loss of riprap/erosion of the dike (particularly due to log jams or gravel aggradation redirecting flow), overtopping due to bed aggradation or ice jams reducing channel capacity, and ice/log jam occurring at bridges.

Failure of the dike would flood the farms, houses and extensive infrastructure located in Kelowna on the fluvial fan. Overbank flooding would be relatively shallow, but very powerful. Overbank flow is unlikely to re-enter the channel, and would seek another path to Okanagan Lake. Failure would result in a significant risk to life if it were sudden and came without warning.

The following structure impacts on the channel morphology are noted on Figure 2.

(A) Blockage of distributary channels results in loss of conveyance capacity and loss of fish habitat.

(B) Confinement due to bank protection works and stream crossings results in increased aggradation in depositional areas, requiring ongoing dredging.

(C) Dikes prevent overbank flow locally and increase sediment conveyance and may result in an aggradation problem further downstream. This can also extend the mouth further into the lake, thereby increasing channel length, decreasing slope and exacerbating aggradation problems.

Mitigative/restoration measures to deal with the above impacts, include:

1. Flood relief channels or reactivation of distributary channels. This may increase hydraulic conveyance and restore fish habitat, but may reduce sediment conveyance and be opposed by development pressures.
2. In urban settings, overland flow decoupled from the main channel may find flow paths along streets. Appropriate design of streets and adjacent buildings, to convey overland flow, may reduce flood damage. However, this is much more difficult to implement when significant development has already taken place.

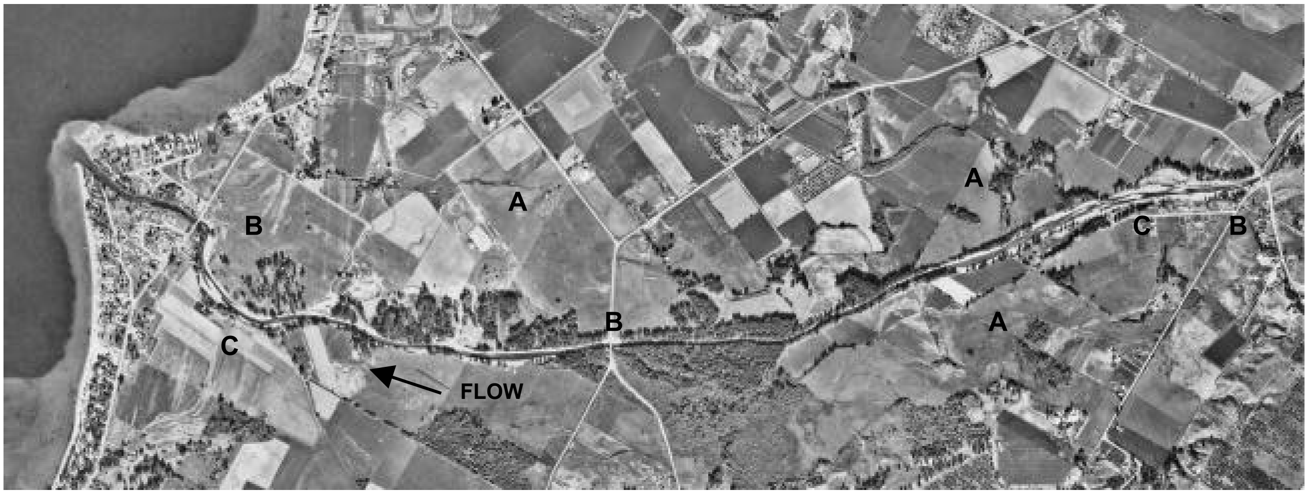

Figure 2: Aerial Photo of Mission Creek at Kelowna

## 7. GRAVEL BED RIVER/STRAIGHT BRAIDED EXAMPLE – ELK RIVER AT HOSMER

The Elk River at Hosmer provides a good example of a larger GBR/SB stream since in adjacent reaches its morphology displays both a single sinuous nature as well as a braided morphology.

### 7.1 Channel Description and Flood Mechanism

The Elk River has a wide, braided unconfined channel, with a wide floodplain dissected by numerous flood channels. The stream has numerous depositional features such as point and mid-channel bars. Historically, the channel location was mobile and depended greatly on the development of depositional features. Dike and erosion protection works have confined the channel and restricted floodplain conveyance. Bridge constrictions can result in channel instability due to the change in upstream deposition patterns and the blocking of overbank flow by highway embankments.

The largest impact on the stream channel morphology is due to floodplain development, which results in: (1) the removal of riparian vegetation; (2) channel confinement due to bank protection; and (3) dike works that block off floodplain inundation and flood-channel flow.

### 7.2 Structure Effectiveness and Impact on Channel Morphology

The Elk River at Hosmer (15 km upstream of Fernie) is indicative of the flooding and erosion problems encountered on these streams. The following features are noted on the airphoto below:

(A) Overbank flow occurs along low depressions that dissect the floodplain. A gravel plug structure is located at entrance of an overflow flood channel located on the Elk River floodplain. The structure was constructed in 1997 in response to the large 1995 flood. The plug blocks a flood channel that drains toward several residences located 200 m south of the structure, behind a local road.

(B) The Hosmer highway bridge blocks overbank flow. Gravel mining, which is no longer operating used to remove river gravel from bars.

(C) Well-defined flood channels originate approximately 3 km upstream, and drain through the middle of Hosmer.

(D) A right bank dike setback approximately 500 m from the bank of the Elk River. The dike blocks floodplain flow draining down-valley towards several farmhouse buildings and a trailer park.

Small size GBR/SB are particularly sensitive to watershed disturbance that introduces sediment into the system, as well as riparian vegetation removal. Once disturbed, these streams are increasingly prone to braiding, aggradation, bank erosion and lateral movement. LWD plays a significant role in the channel morphology of these streams. On disturbed streams a continual cycle of erosion and channel widening resulting in loss of vegetation, which jams and results in further erosion. Bridge crossings (especially with centre piers) are subject to debris jams, often resulting in flooding and erosion of adjacent properties. Select removal or anchoring of debris and trees that are severely undermined may be effective measures to prevent channel instability.

Flood channels and depressions that drain the floodplains of medium size GBR/SB play a key flood conveyance role for this type of stream especially for bankfull/channel-forming events that occur relatively frequently. These 'frequent' flooding mechanisms can be different than the floodplain inundation occurring during extreme (e.g. 1:100 year or greater events). Flood protection works that block these flood channels result in a change in channel morphology. The stream becomes single channel, narrower and deeper.

A riprap windrow located on the top of bank (locally tall riprap) has proven effective at several sites on the Bella Coola River and Cheakamus River at preventing overbank flow and debris deposition on the floodplain. The 'flashy' nature of flooding at these sites means that flood levels above the top of bank occur for several hours and a conventional dike cross section is not required. The dikes may be outflanked, but the resulting inundation is less of a problem than that normally accompanying high debris load.

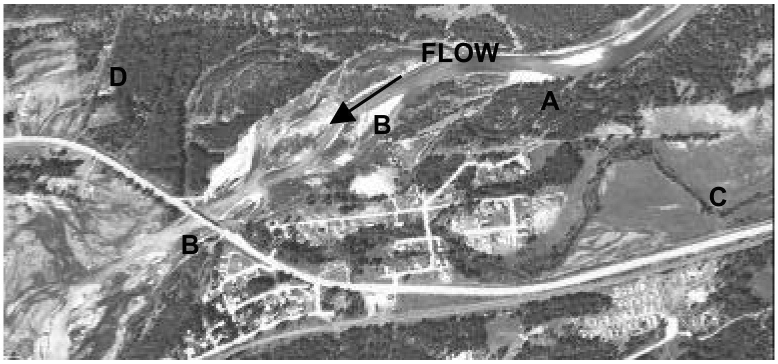

Figure 3: 1994 Aerial Photo of Elk River at Hosmer

## 8. GRAVEL BED RIVER/MEANDERING EXAMPLE – NAVER CREEK AT HIXON

### 8.1 Channel Description and Flood Mechanism

Naver Creek is a relatively large gravel bed river with well-developed, fairly regular sinusoidal meanders within a wide floodplain. It conveys large quantities of woody debris and sediment. The main channel instability mechanism is downstream meander progression, leading to meander enlargement and cutoffs. The wide and flat floodplain is subject to frequent overbank flow, especially the floodplain area on the inside of the meander bends. Instream, the channel has large point bars on the inside of the meander bends that contribute to the severe attack occurring on the outside of the meander bends.

Naver Creek at Hixon (65 km south of Prince George) is indicative of the flooding and erosion problems encountered on these streams. As shown on the airphoto below, significant channel movement occurred at 'A1' and 'A2', where the meanders have migrated 100 m. The meanders at 'A2' and 'B' have cutoff and resulted in a channel shift of 100 m.

### 8.2 Structure Effectiveness and Impact on Channel Morphology

Initially, river training works were built at 'A1' to direct the channel back to its old course, after downstream meander progression had occurred. The original works failed and the present works, consisting of riprap bank protection and a top of bank berm, were built at the existing stream bank location to prevent further erosion and overbank flooding. The berm is open-ended, hence, it is intended to reduce flooding and the amount of debris deposited on the floodplain. It is not intended to block all overland flow.

The stream conveys a considerable amount of woody debris during floods. Part of the reason for building the berm was to prevent debris from piling up on the floodplain where the community center sports fields are located. Debris jams likely were a significant factor in the previous channel instability at this location. There was a large flood in 1993 that caused considerable damage within the watershed including damage to roads, private property and erosion protection works. Flood damage was due in part to large amount of bedload and debris within the channel.

Flooding of inside of meander bends and downstream meander progression are important flood mechanisms for 'Gravel Bed River/ Meandering'. Robust erosion protection works are required to resist the severe and prolonged attack occurring at these sites. Works on GBR/M streams should be designed to accommodate the above noted flood and erosion mechanism, and if possible contain the following features:

1. Works should allow for overbank flow on the inside of the meander bends in order to reduce main channel flow, velocities and water levels.
2. Floodplain vegetation on the inside of the meanders should be preserved since it plays a significant role in maintaining floodplain stability.
3. If possible, allow debris deposition to occur on the floodplain, rather than building berms that restrict overbank flow.
4. Erosion protection designed to reduce the risk of meander cutoff, should be well keyed-in at the toe, adequately sized, and incorporate frictional elements (bioengineering LWD, vegetation) to reduce near-bank velocities.

Figure 4: 1958 Aerial Photo of Naver Creek at Hixon

## 9. CONCLUSIONS

The following channel morphology classification system was presented for small to medium size gravel bed rivers: (1) Debris Flows; (2) Alluvial Fan; (3) Gravel Bed River/Straight (low sinuosity) or Braided; (4) Gravel Bed River/Meandering. Classification of the over 50 sites evaluated provided the basis to review the interaction of channel morphology, flooding mechanism and structure (type and effectiveness). Our review indicates:

1. Maintaining the flood mechanism for bankfull/channel-forming events, that occur relatively frequently, is important for maintaining a stable channel morphology. These ‘frequent’ flooding mechanisms can be different than the floodplain inundation occurring during extreme (e.g. 1:100 year or greater events), which are frequently used as the basis for design of river engineering works.

2. ‘Alluvial Fan’ and ‘Gravel Bed River/ Straight or Braided’ together account for two-thirds of the total number of sites. Based on the authors’ experience, the above ratio is a fair representation and indicates the large proportion of flooding/erosion problems that are generally encountered at these stream types in B.C. (excluding large rivers).

3. ‘Debris Flow’ streams are naturally prone to aggradation and avulsion. However, this process is greatly exacerbated by stream crossings that restrict sediment conveyance.

4. Flood protection works confine ‘Alluvial Fan’ streams and block off distributary channels. Dredging, raising dikes and repair of bank protection works are required to deal with the increased water level and bank erosion, which occurs at these sites. These works may increase sediment conveyance locally and result in chronic aggradation problems downstream.

5. Small size ‘Gravel Bed Rivers/Straight or Braided’ are particularly sensitive to watershed disturbance that introduces sediment into the system, as well as riparian vegetation removal. Once disturbed, these streams are prone to braiding, aggradation, bank erosion and lateral movement.

6. Flood channels and depressions that drain the floodplains of medium size ‘Gravel Bed Rivers/Straight or Braided’ play a key flood conveyance role for this type of stream. Flood protection works that block these flood channels result in a change in channel morphology. The stream becomes single channel, narrower and deeper.

7. Flooding of inside of meander bends and downstream meander progression are important flood mechanisms for ‘Gravel Bed River/ Meandering’. Robust erosion protection works are required to resist the severe attack occurring at these sites. If possible works should allow for overbank flow on the inside of the meander bends, thereby reducing main channel flow, velocities and water levels.

Consideration of morphology and the review of streams on a reach and watershed basis (as opposed to a site by site review) is crucial to making sound river and floodplain management decisions.

## 10. REFERENCES

Hundal, L.S., Costerton, R.W., 2003, Evaluation of Flood and Erosion Control Structures in British Columbia. *Proceedings of Canadian Water Resources Association Conference, Vancouver.*

Kellerhals, R., Church, M., Bray, D.I., July 1976. Classification and Analysis of River Processes. *ASCE Journal of Hydraulic Engineerin*g.

Rosgen, D., *Applied River Morphology*. 1996. Printed Media Companies, Minneapolis, Minnesota.