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THE IMPORTANCE OF GEOMORPHOLOGY IN HYDRAULIC ENGINEERING: THE CONTRIBUTION OF ROLF KELLERHALS

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ABSTRACT

Dr. Rolf Kellerhals was an inspiration to young engineers and geomorphologists in western Canada during his career that spanned the decades of the 1970s, 1980s and 1990s. As a specialist in river engineering, he emphasized the importance of utilizing the tools of the geomorphologist to improve our understanding of river processes and our predictions on how rivers respond to engineering projects. Much of his work related to assessing the effects of hydro power projects and diversions on river stability and morphology. He demonstrated how interpretative methods could provide independent predictions from standard hydraulic engineering methods such as hydraulic modelling and how in many cases the interpretative methods were the most reliable tools that were available.

This paper reviews the contribution made by Dr. Kellerhals using case histories and examples from past projects. It also shows that his message is still very relevant today, where so much emphasis is on the use of complex morphodynamic models that often have limited validation testing over the long time scales that are required to assess project impacts.

Keywords: - (River engineering, fluvial geomorphology, sedimentation)

1. INTRODUCTION

1.1 The Role of Geomorphology in Hydraulic Engineering

In 1954 Emory Lane, a civil engineer with the US Bureau of Reclamation, explained the importance of using geomorphic concepts for predicting the response of alluvial channels to engineering works such as dams, diversions and channelization measures. Lane (1954) stated, “a knowledge of fluvial morphology will enable the hydraulic engineer to predict the changes and to reduce the detrimental effects to a minimum and take advantage of favorable effects”. Lane introduced engineers to the concept of equilibrium in natural stream systems to show how changing a parameter such as discharge (Q) or sediment load (G) would affect other channel parameters such as slope (S) or sediment grain size (D) in order to restore long-term equilibrium. This is illustrated in the simple stream balance relation below (Eq. 1):

$$[1] \quad GD \propto QS$$

For example, if a stream is flowing in a condition of equilibrium and its sediment load is decreased, equilibrium can be restored if the water discharge or slope of the channel is decreased sufficiently, or if the size of the sediment is increased (the channel becomes armoured).

1.2 Progress in Canada

During the 1960s and 1970s a number of civil engineers in western Canada embraced Lane's advice and integrated geomorphology with classical hydraulics to develop the multi-disciplinary practice of river engineering that is commonly applied today. Much of this development took place at the University of Alberta in Edmonton and various provincial agencies, where applied research was conducted under the auspices of the Research Council of Alberta. This highly creative group of engineers who advanced the subject of river engineering included Prof. Tom Blench, Charles R. Neill, Dr. Victor J. Galay, Dr. Dale Bray and Dr. Rolf Kellerhals. However, adopting this approach into general practice has been relatively slow, as evidenced by the introductory comments on assessing river processes in Kellerhals, Church and Bray, 1976:

"*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 writer's 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 made a similar plea 20 years ago and although that paper is often quoted, its message seems to have been largely ignored*."

1.3 Contribution of Rolf Kellerhals

Rolf Kellerhals' career spanned a period of over 30 years and involved both research and consulting from his office in Heriot Bay on Quadra Island, British Columbia. He received his MSc. Degree in Civil Engineering from the University of Alberta in Edmonton and a PhD in the Interdisciplinary Hydrology Program from the University of British Columbia in Vancouver. He was the editor of the first Canadian Hydraulics Conference, which was held in Edmonton in May 1973 and was a widely regarded authority in both the engineering and geoscience community. During his career, he collaborated with many experts in the field of geomorphology, including Prof. Michael Church and Mike Miles, and helped to expand the role of geoscience as a field of practice. He passed away in August, 2016.

1.4 Purpose

This paper reviews some of the key concepts that were embedded in Rolf Kellerhals' work and highlights its relevance to present engineering practice. It is important to emphasize that although he often used the tools and methods of a geomorphologist, his writing and conference presentations were often directed at the engineering community, emphasizing the importance of using geomorphic methods as an independent check or confirmation of traditional engineering methods based on hydraulics and semi-theoretical sediment transport equations. In this respect, he shared and extended the insights provided in Lane's earlier work. Therefore, it is fitting to re-emphasize his message in the setting of an engineering conference.

2 APPLYING FLUVIAL GEOMORPHOLOGY TO HYDRAULIC ENGINEERTING PROBLEMS

2.1 Need for Improved Understanding of River Behaviour

The 1960s and 1970s were a time of unprecedented natural resource development in western Canada, including hydroelectric development as well as expansion of roads, rail lines and pipelines routes that crossed some of the most challenging rivers in North America. The available hydraulic engineering methods for predicting river processes such as scour and erosion and for assessing the channel response to large engineering projects such as dams and water diversions were very limited. Part of the problem is that alluvial river processes are complex and it is difficult to formulate realistic models that can accurately represent physical processes such as turbulence, sediment transport and erosion, given the variability and range of sediments that compose the bed and banks of most streams. Furthermore, most of the practical experience and empirically-based engineering methods (such as Regime Theory) had been developed on sand bed rivers (Lacey, 1929) from parts of the world having a very different physiography and geological setting than the recently glaciated, steep, mountainous gravel bed rivers of western Canada. Consequently, there was a recognized need to improve predictive methods for design and project assessment.

This paper reviews four areas of research where significant contributions were made by Rolf Kellerhals:

1. Critical importance of collecting field data and long term observations to support predictions of future river response. More generally, he emphasized throughout his career the importance of long-term observations and data collection as a critical component for making sound water resource management decisions.
2. Systematic description of the hydraulic and geomorphic characteristics of gravel bed rivers, including development of equations for predicting stable channel dimensions.
3. Development of methods for classifying rivers and identifying the factors that govern their morphology and channel stability.
4. Assessment of the downstream effects of large engineering projects such as dams and water diversions on channel morphology. Dr. Kellerhals emphasized that environmental impacts from projects could not be properly evaluated unless the physical changes to the habitat were accurately estimated.

2.2 Hydraulic and Geomorphic Characteristics of Gravel Bed Rivers

So-called "Regime Theory" equations were developed in the 1920s to predict stable channel dimensions on sand bed canals transporting low sediment loads in the Indian sub-continent (Lacey, 1929). Other semi-theoretical investigations had been carried out in hydraulic laboratories. However, most of this work was restricted to sand bed channels and was of limited use when applied to most mountainous environments in western Canada. In fact, in the early 1960's very little systematic investigations of river hydraulics and channel processes on the steep, laterally unstable, gravel bed rivers of western Canada. Systematic observations and characterization of gravel bed rivers and river processes was pioneered by the combined efforts of several researchers and provincial agencies in Alberta starting in the 1960s and 1970s.

Kellerhals (1969) analyzed the hydraulics of coarse gravel bed channels in natural channels that were near the threshold of sediment transport. These so-called "threshold" channels had adopted to past flow conditions by adjusting their dimensions and slope until the bed load transport rate in the channel was negligible. Subsequently, Kellerhals, Neill and Bray (1972) characterized the hydraulic and geomorphic characteristics of alluvial mobile bed channels at 110 reaches in Alberta. These field studies encompassed the entire province and represented a major undertaking that to the author's knowledge has not been replicated. The information was subsequently used to develop empirical equations to predict stable channel dimensions of gravel bed rivers (Bray, 1973). The primary data has continued to be valuable for developing more general, semi-theoretical stable channel equations (Parker, 1978). Kellerhals and Church (1989) combined the Alberta river reach data with data from sand bed rivers and canals and as well as from large rivers from Asia and South America to illustrate the consistency of these channel scaling relations. Figure 1 is a version of this relation, as presented in Church (2015). The plots show that channels can be thought of as dynamic models of each other. However, the width to depth ratio of alluvial channels increases with increasing channel forming discharge, so that the scaling is distorted (the channels are not geometrically similar).

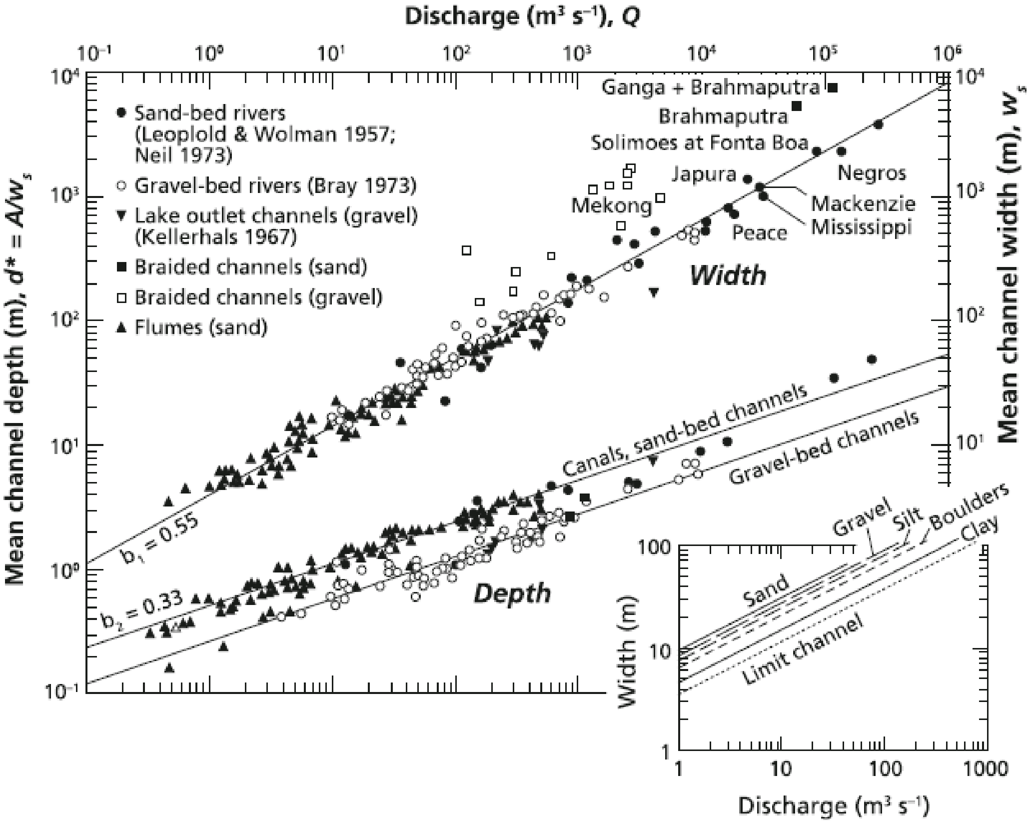

Figure 1: Scaling relationships for river channel geometry (reproduced from Church, 2015).

2.3 River Classification and Interpretation of River Processes

Geologists have developed a wide range of systems and methods for classifying and characterizing rivers. However, Kellerhals, Church and Bray (1976) were more concerned with using river classification as a diagnostic tool to understand the key factors that governed the river's morphology in order to make engineering predictions about its stability and future pattern of channel changes. Kellerhals, Church and Bray (1976) commented that the characteristics of a river channel will change wherever a change occurs in any of the conditions that govern fluvial morphology. Reasonably detailed knowledge of these conditions is therefore an essential prerequisite to the proper planning of any engineering interference with a river. The main factors that govern the morphological characteristics of a river were considered to be:

- The supply of sediment and water;
- The nature of the materials that the river flows through, and
- The geological setting and geological history of the region.

The role of glacial history in affecting river processes was generally not appreciated by engineers. Kellerhals, Church and Bray (1976) pointed out that the end of the last major glaciation (about 10,000 years 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 re-depositing 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.

The classification system was intended as a practical tool for engineers in the field and used readily available information such as historical air photos and maps. The basis for the method and type of information that was collected are generally consistent with the systematic evaluation of river regime described in Neill and Galay (1967). Figure 2 illustrates the approach for classifying channel plan form features.

The end point for the classification assessment was not to just describe the river morphology but to make quantitative predictions about future river behavior. In particular, it was emphasized that geomorphic-based methods should, whenever possible, be used to provide independent checks on traditional engineering calculations. The following examples were cited:

- Sediment transport computations can sometimes be checked against growth rates of alluvial fans and deltas or against point bar progression rates.
- Maximum flood levels can be checked with evidence of silt deposition, ice scour trim lines, or evidence contained in vegetation.
- Local scour at natural constrictions or spurs is still one of the most reliable indicators of potential scour at bridge abutments or pipeline crossings.

It was emphasized that if geomorphological evidence disagrees with computed values, most prudent engineers will give it precedence.

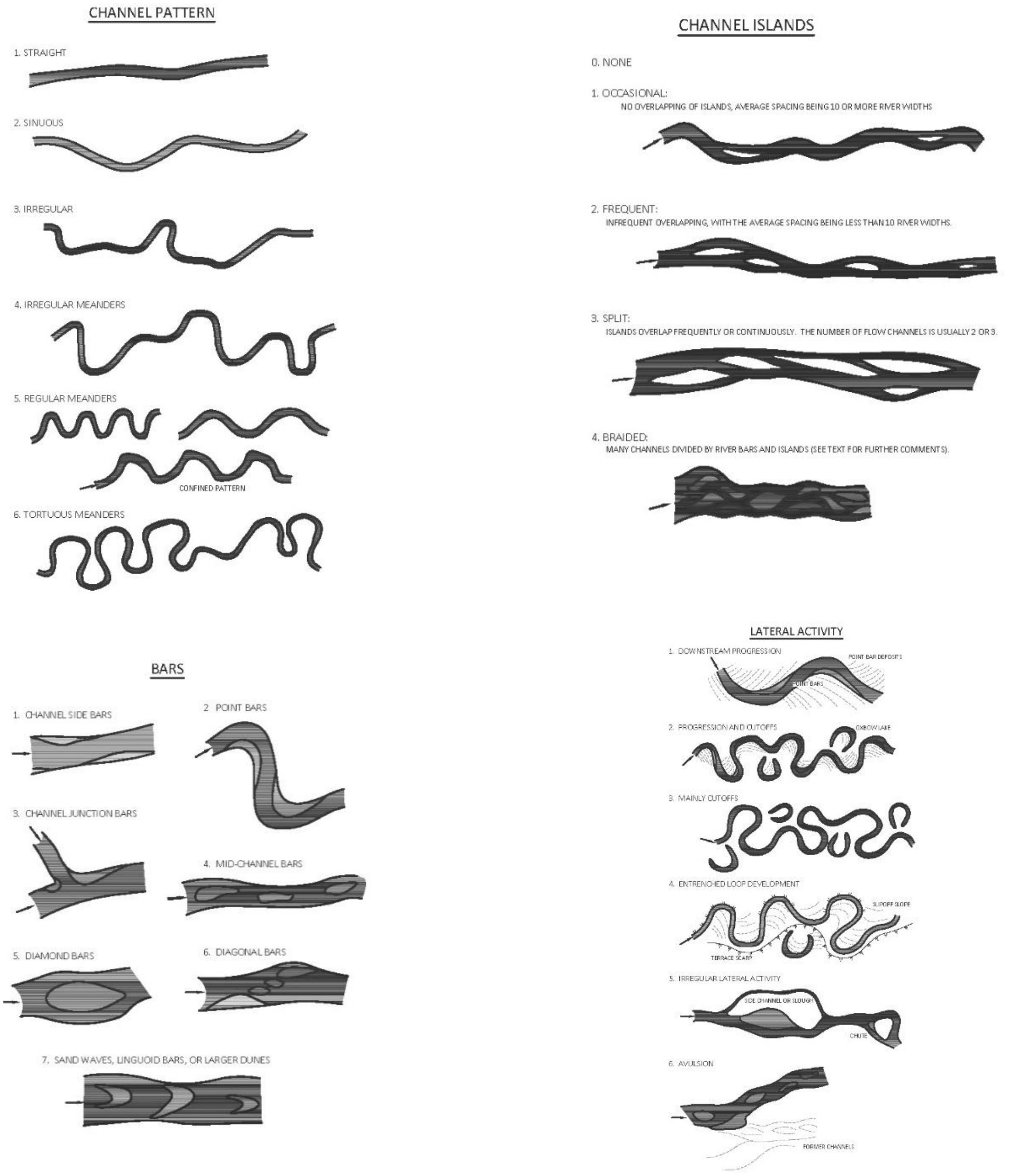

Figure 2: Classification of plan form features of river channels (from Kellerhals, Church and Bray, 1976).

Kellerhals and Church (1990) described a more specific case of classification applied to assessing hazards on alluvial fans, including high gradient fans subject to debris flows and debris floods.

2.4 Assessing Downstream Effects of Dams and River Diversions

Lane's application of dynamic equilibrium (Eq. 1) provides a tool to predict the expected change to a river's longitudinal profile in response to flow regulation or reduction in sediment supply downstream of a dam. However, it does not describe how the plan form of a river will respond. Mollard (1973) presented a conceptual model which related channel plan form to factors such as sediment supply and river discharge. Kellerhals and Church (1989) adapted this model and illustrated how it could be used for predicting channel plan form response to engineering works (Figure 3).

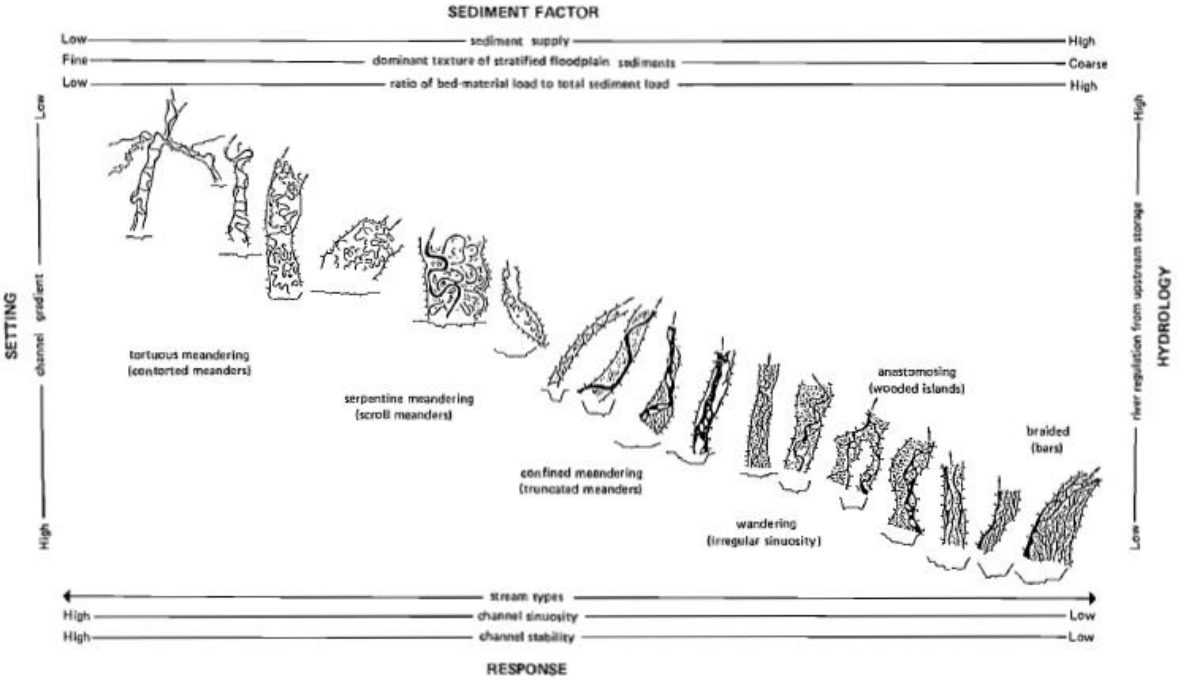

Figure 3: Conceptual model of the relation between channel plan forms types (Kellerhals and Church, 1989)

Figure 2 and Figure 3 provide simple tools for assessing the impact of engineering projects such as dams or river diversions on downstream river morphology. Kellerhals and Miles (1996) concluded that although there was a pressing need for predictive models, these simple relations remained the state of the art for assessing the relation between channel morphology and the imposed driving factors of discharge and sediment supply. The main reason for this unsatisfactory situation was attributed to our poor understanding of sediment transport processes in a three dimensional environment. This was because the engineering community has been absorbed with two-dimensional sediment transport in laboratory flumes and in some artificially trained and straightened European rivers. When the results of this work are misapplied to the more normal three-dimensional river situations (where channel width and alignment are free to adjust), they often lead to wrong answers. In some cases, even the predicted direction of change has been wrong (Kellerhals and Miles, 1996).

Inter-basin diversions provide an example of an engineering project that can induce significant impacts to both the diverted stream and the receiving channel. Large-scale water diversions where a relatively large flow is diverted across a divide and allowed to flow into a dry valley or into a relatively small stream, where it is left to develop a new larger channel, have been relatively rare. However, a number of projects were carried out in Canada during the early part of the 20th century. Following the Kemano project in 1954, where water from the Nechako River was diverted into the Lower Kemano River, there was a renewed interest in water diversions. For example, in the 1970s plans were made to divert a portion of the McGregor River (a tributary of the Fraser River) into the Parsnip River (a tributary of the Peace River) in order to increase power production from WAC Bennett Dam. As part of the assessment process, Kellerhals et al. (1979) developed case histories from 19 projects in Canada in order to characterize the type and magnitude of long term impacts that occurred. These “morphological lessons” provided a basis for understanding the variability of effects and for assessing future project effects. Based on these studies, diversions were classified into three categories:

1. Bedrock-controlled diversion routes;
2. Steep diversions through unconsolidated materials;
3. Alluvial diversions, where the diversion flows are not significantly greater than the naturally occurring peak flows in the receiving channel.

Suggested methods for predicting project effects were described for each type of diversion.

A case history approach was also used by Church (1995) to document the long term effects of WAC Bennett Dam on the Peace River. The regulation of the Peace River in 1969 reduced the flood flows downstream of the dam by a factor of two to three times. This resulted in vegetation encroachment and suspended sediment deposition over parts of the formerly active channel zone, resulting in the formation of a new lower floodplain. As a consequence, many side channels are filling in and disappearing. At an intermediate time scale, the river is unable to move the sediment inflows from its major tributaries and this is gradually leading to a more irregular, stepped longitudinal profile, due to local aggradation near the tributary confluences. These observations are very different from the general experience on sand bed rivers, where channel degradation below dams is the norm.

Following earlier work by Schumm (1977), Kellerhals and Church (1989) compiled a list of the directions of change for a range of typical engineering projects, based on the case histories and experience on gravel bed rivers in western Canada. These projects illustrate imposed changes to discharge, bed material load and wash load, and the resulting response in terms of changes to width, depth, slope, sediment size, meander wave length and sinuosity.

Table 1 summarizes the expected channel response for the different types of projects. It was indicated that in most cases neither the rate nor the magnitude of the change is quantifiable on a general basis. Because of the imperfect knowledge of river behaviour and the complexity of imposed and response conditions, the overall assessment of morphological changes due to engineering works is in general a qualitative exercise. Because of this, case histories are of critical importance for improving our predictive ability.

Kellerhals and Church (1989) emphasized that river managers need to recognize the importance of documenting and publishing complete case histories of changes in large rivers and should attempt to encourage this activity wherever possible. This includes incorporating long term monitoring as part of approvals for major projects. Also, it is important to recognize the full complexity of the ecosystem that rivers represent, including its geophysical basis, and it is necessary to cooperate to ensure that the best experience is brought to bear on each aspect of the analysis of river systems.

Table 1: Direction of morphological change and relation to driving variables observed at selected case studies (reproduced from Kellerhals et al., 1979)

	Imposed changes			*Direction of resulting change*							
River reach	Q	q_{bm}	q_w	w	d	S	D_{50}	F	λ	P	M
Nechako River, below Cheslatta confl.	-		+	-	-	n.c.	-	+	n.c.	n.c.	+
Cheslatta River											
upper reach	**+**	-	-	**+**	**+**	+	**+**	+	+	-	-
lower reach	**+**	-	+	**+**	**+**	-	+	+	+	-	-
Kemano River											
initial 20 years	+	-	-	+	+	+	n.c.	+	?	-	-
final, upper reach	+	-	-	±?	+	-?	+?	-	?	-	-
final, lower reach	+	+	-	+	+	n.c.	n.c.?	+	+	-	n.c.?
Peace River											
below dam	-	-	-	-	-	n.c.	n.c.	+	n.c.	n.c.	±?
above Pine R. confl.	-	-	-	-	-	-	-	-?	n.c.	n.c.	-
below Pine R. confl.	-	+	+	-	-	+	-	+	n.c.	n.c.	-

Notes: ? Indicates that the direction of change is either not known or not well documented. Heavy symbols, e.g. **+** indicate a drastic change.

Where Q is channel-forming discharge, q_{bm} is bed material load, q_w is wash load, w is channel width, d is mean depth, S is slope, D_{50} is median sediment size, F is width/depth ratio, λ is meander wave length, P is sinuosity, and M is percent silt/clay in the bank materials. n.c. means "no change".

2.5 Re-assessing Assumptions About Sediment Yield in Western Canada

River engineering requires reliable long term field observations, including hydrological data. In the 1960s, Water Survey of Canada expanded the traditional hydrometric program to include measurements of suspended sediment load on many rivers. Church, Kellerhals and Day (1989) utilized this data to develop regional estimates of sediment yield in British Columbia. They found the pattern of sediment yield in British Columbia was very different from the commonly held view. Previously, most estimates of sediment yield were derived from measurements on low-lying agricultural lands and the sediment yield (defined as the sediment load per square kilometre) was found to decrease as the drainage area increased. However, the mountainous, glaciated valleys of British Columbia generally contain terraces of fluvial and glacial-fluvial outwash that often confine the rivers. These readily erodible deposits tend to cause the sediment yield to increase in the downstream direction, opposite to the accepted belief. This analysis fundamentally changed our understanding of sediment production and sediment supply in our watersheds. Without long term records at multiple stations along a river network, this type of understanding cannot be developed.

It is ironic that the sediment program in Canada was terminated in the 1990s as part of a cost saving policy. Today, many studies related to sedimentation in reservoirs or sedimentation processes are based on data that was collected over 30 years ago. It is often assumed by engineers that more sophisticated models can replace basic data and the need to make systematic observations. However, there is no evidence that this assumption is valid.

3. RELEVANCE OF KELLERHAL'S WORK TO THE PRESENT

Fluvial geomorphology has become a widely accepted practice in western Canada as a discipline and geoscientists often play a critical role in river engineering projects and in environmental impact assessments. It is also relatively common for civil engineers to take courses in fluvial geomorphology in university. As a result, river engineering often involves a multi-disciplinary team approach. The theme of much of the writing by Kellerhals and Church (1989) has, to some extent, been understood and accepted to a degree.

Progress has been made on many fronts in understanding sediment transport mechanics and morphodynamic modelling has also become a powerful tool for assessing project effects. However, the models are still limited by the physical understanding of three dimensional sediment transport processes and by the lack of long term data for properly validating their predictions (Cunge, 2013). This limitation is seldom addressed in most investigations.

There have been significant advances in field measurement and data collection that expand the tools for geomorphic assessments. These include:

- Multi-beam bathymetric surveys, which provide extremely high resolution, continuous coverage of the river bed allowing three dimensional representation of dunes and bar features.
- Acoustic Doppler Current Profiler (ADCP) systems, which allow continuous measurement of discharge. The back-scatter from the acoustic signal can be used to estimate suspended sediment concentrations in the water column, allowing for continuous monitoring of sediment transport.
- Acoustic detection of bed load movement, providing a means for determining initiation of bed load transport.
- LiDAR surveys, which provide a convenient, relatively low cost method for high resolution mapping of floodplains, bars and islands. GIS mapping software provides powerful tools for comparing changes over time to assess trends and to compute volumes of erosion and deposition.
- Drones, which provide a low cost means for surveying and monitoring channel changes over time.

These advances provide geomorphologists with a range of tools for expanding Kellerhals' interpretative methods into more quantitative fields of analysis.

4. CONCLUSIONS

Few engineers in consulting practice have been able to make fundamental advances in their discipline. Kellerhals' contribution included improving our understanding of gravel bed rivers and the role that geomorphology and geological history play in governing present river behaviour. He also taught engineers how interpretative methods could be used to improve our predictions about river behaviour and river response to engineering works. In this manner, he gave engineers a new way to view a river, not just as a conduit for carrying water, but as a dynamic, self-formed channel, often still responding to geological and climatic events that occurred thousands of years ago.

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