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Conceptual model of river ice formation along sedimentary links

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This paper presents a conceptual model relating the large-scale distribution of river ice types to the longitudinal sequence of river forms and flows typically encountered along the sedimentary links of gravel bed rivers. Sedimentary links are discrete river segments each characterized by a node of coarse sediment recruitment followed by a gradual downstream fining of substrate and an associated reduction of channel slope. Because these downstream changes in substrate and slope are associated with changes in channel morphology and hydraulics, they create a longitudinal sequence of river environments moving from steep, fast flowing and turbulent boulder bed channels at the head of links to meandering, slow-flowing, low-gradient sand channels at the downstream end. We describe how these spatial variations in the geomorphology and flow characteristics of rivers should interact with river ice formation processes to produce a predictable large-scale pattern of river ice types in gravel bed rivers.

1. Introduction

For specific hydroclimatic settings, different types of river ice form according to the types of river environments. For example, border ice predominantly forms along the banks of slow flowing, low gradient river sections, while frazil ice production is enhanced by the turbulent flows of steep boulder bed rapids and coarse-grained riffles. However, despite the close association between river ice types and river environments, few attempts have been made to study how large scale variations in river geomorphology and hydraulics may determine the spatial distribution of ice types across the riverscape.

This paper presents a conceptual model relating the large-scale distribution of river ice types to the longitudinal sequence of river forms, grain size and flow characteristics encountered along the sedimentary links of gravel bed rivers. A better understanding of these large-scale distribution of ice types is needed to determine the overal stability of ice covers when winter flooding occur but also to estimate the amount of ice of different types available to procuce ice jams in a specific watershed.

2. The sedimentary link concept

It has been shown that gravel-bed rivers can often be segmented into a number of discrete sedimentary links, each characterized by a node of coarse sediment recruitment followed by a gradual downstream fining of substrate and an associated reduction of channel slope (Figure 1). Originally, the link concept was developed for high mountain river environments where the supply of coarse sediment is mainly related to tributary inputs, valley-side landslides and tributary fan contacts (Rice, 1998; Rice and Church, 1998). However, Davey and Lapointe (2007) proposed an adaptation and extension of the original concept to account for sedimentary links of lower mountain landscapes of North Eastern Canada where coarse sediment inputs are often related to supply zones (rather than points or nodes) originating in bedrock canyon reaches or valley bottom deposits of glacial drift.

Because the downstream changes in substrate and slope along sedimentary links are associated with changes in channel morphology and hydraulics, they create a longitudinal sequence of distinct river environments. In the **upstream section** of the link, where the coarse sediment is supplied to the river, the channel is steep and generally made of boulder size bed material (Figure 2). There, the flow is characterized by low relative submergence values (flow depth/ bed material size often < 1) with high velocity and turbulent rapid-like flows. Below this coarse sediment input zone, the combined actions of hydraulic sorting and abrasion processes result in a gradual downstream fining of bed material size and a concomitant reduction of channel slope. In the **middle section** of the link, bed material is in the coarse to small gravel size range, and river morphology is dominated by pool-riffle sequences and alternating gravel bars located on both sides of a sinuous thalweg. Riffles are characterized by fast and shallow water flowing over coarser bed material than in the pools where the flow is deeper and slower outside high flow periods. In the **downstream section** of the link, the continuation of the grain size fining process gives rise to a meandering, slow-flowing, low gradient sandy channel where pool-riffle sequences are less distinct or absent (Figure 2).

In the next section, we describe how these spatial variations in the geomorphology and flow characteristics of rivers should interact with river ice formation processes to produce a predictable large-scale pattern of river ice types in gravel bed rivers.

3. Expected distribution of river ice types along sedimentary links

Border ice

Border ice usually forms in the calm, slowing-flowing water found along channel banks and around protruding boulders (Prowse 1994). There, the reduced vertical mixing of the flow combined to the rapid cooling rate of the exposed bank and bed material favors the formation of surface thermal ice that then continues to grow laterally into the flow until higher flow velocities and/or flow turbulence stops its progression. Within the context of a sedimentary link, we suggest that border ice will occur predominantly in the downstream section and in the slow-flowing pools of the middle section, although some border ice will also form around the protruding boulders of the upstream section.

Frazil ice

In contrats, frazil ice occurs in the most turbulent sections of a river. Frazil ice is composed of fine ice crystals that form in the turbulent supercooled water of riffles, rapids and falls. In such areas, supercooling is attained because of the absence of a static ice cover, which enhances heat loss from the river to the cold atmosphere (Michel 1971, Beltaos et al. 1993). This formative process suggest that production of frazil ice should predominantly be concentrated in the rapid-like flows of the upper section and in the steeper riffles of the middle section of a sedimentary link.

Once the initially small frazil ice crystals are produced, they tend to agglomerate and form flocs that are transported near the water surface or underside the ice cover because of their buoyancy (Shen and Wang 1995). As they drift at the water surface, frazil flocs often freeze together to form pans which can in turn freeze together to form larger rafts. When the surface concentration of drifting pans and rafts is large, ice bridging is likely to occur at flow constrictions caused by natural variations of channel width, border ice growth (Beltaos, 1995), tight meander bends and bridge piers. As bridging occurs, the drifting frazil ice pans and rafts come to a hault where they may freeze together to form a juxtaposed ice cover or a frazil ice jam. Three factors suggest that these processes are more likely to occur in the downstream section of a link. First, the flow conditions are favorable to the lateral growth of border ice that may narrow the active river width. Second, the meandering form of the channel creates constrictions favoring ice accumulations. Third, the reduction of channel slope decreases the capacity to evacuate the incoming ice discharge. To a lesser extent, the same dynamics should also occur in the slow-flowing pools of the middle section of a link where border ice forms.

When entering an ice-covered reach, frazil ice crystals are swept under the leading edge of the stable ice cover and then rise its underside where they are transported downstream in the form of a cover-load transport analogous to the bed-load transport of sediments (Shen and Wang, 1995).

Frazil ice crystals are then transported downstream until they reach an area where water velocity is sufficiently low to allow deposition. Frazil ice deposits are therefore found along irregularities of the bed, banks, and ice cover base (Calkins et al. 1982; Lawson et al. 1986) and beneath the ice cover of slow-flowing pools where they may form hanging dams occupying a very large percentage of the pool volume (Michel and Drouin, 1981**;** Ashton, 1986; Allard et al. 2009). Frazil ice hanging dams should therefore be concentrated in the downstream section and in the slow-flowing pools of the middle section of sedimentary links. Smaller volumes of frazil ice deposits may also be formed along the banks and bed irregularities of the middle and downstreams sections.

Anchor ice

Anchor ice generally forms by the accretion of frazil ice crystals on the streambed (Beltaos et al. 1993; Kerr et al. 2002; Doering et al. 2001; Stickler and Alfredsen 2005) of shallow, fast flowing and turbulent river sections with large bed particles (Yamazaki et al. 1996; Terada et al. 1998). Thick anchor ice deposits on riffles create dams that often block drifting frazil ice pans and rafts, thereby forming a stationary ice front leading to the formation of a solid ice cover in the pool located imediately upstream form the anchor ice dam. Because anchor formation is favored by fast and shallow flow conditions (Bisaillon and Bergeron, 2009), it should be most frequently found in the rapid-like upper section of a link and in the riffle reaches of the middle section.

4. Concluding comments

The conceptual model presented in this paper suggests that the observed spatial variations in the geomorphology and flow characteristics of sedimentary links should interact with river ice formation processes to produce a predictable large-scale pattern of river ice types in gravel bed rivers.

From that model, it is proposed that the freeze-up dynamics of the upstream section of a sedimentary link will be dominated by the production of frazil ice and the growth of anchor ice at the bed surface. In the middle section of a link, river ice formation will be mainly controlled by the flows an forms typical of pool-riffle sequences. Deep, slow flowing pools will lead to border ice growth and formation of a static ice cover, while steep, fast flowing shallow riffles will favor the production of frazil and anchor ice. When anchor ice deposits become thick enough, they will stop the drift of frazil ice floes and pans and lead to the formation a juxtaposed ice cover on the upstream pool. In situations of large frazil ice production, frazil ice hanging dams are also likely to form in the deep pools of the middle section of a link. The freeze-up of the downstream section of a sedimentary link will be associated with the evolution of border ice. If no very cold spells occur at the onset of freeze-up, border ice growing from both banks will eventually merge to create a complete static ice cover. However, if a cold spell occurs and frazil ice is abundantly produced, the narrowing effect of border ice on active channel width will trigger the formation of an ice bridge and of a juxtaposed ice cover. Here again, under cover ice forms (e.g. hanging dams) are likely to occur if the production of frazil ice is sufficient in the upstream section of the sedimentary link.

Future work on this topic should include a field validation of the conceptual model through systematic observations and quantification of ice production, formation and characteristics along sedimentary links. Special attention should be paid to study the effect of the timing of hydroclimatic events on the resulting spatial distribution of river ice types along sedimentary links. Such a study should help determine the extent to which the production of frazil ice from the upstream and middle sections contribute to the ice cover formation of the downstream section.

After thorough field validation in different gravel-bed rivers is conducted, the proposed model describing the large-scale distribution of ice types along sedimentary links will be useful for estimating types and volume of ice available during winter and spring floods and to predict the potential location of ice jams.

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6. References

Allard, G., Buffin-Bélanger, T. and Bergeron, N.E., 2009. Frazil ice as a geomorphic agent. Proceedings of the 15th CRIPE Workshop on River ice, St. John’s, Newfoundland and Labrador, June 15 - 17, 2009.

Ashton, G.D., 1986. Rivers and Lake Ice Engineering, Water Resources Publications, Littleton, Colorado, USA, 485 p.

Beltaos, S. (1995). River Ice Jams. Highlands Ranch, Colorado, Water Resources Publications, LLC, 372 pages.

Beltaos, S., Calkins, D.J., Gatto, L.W., Prowse, T.D., Reedyk, S., Scrimgeour, G.J., and Wilkins, S.P., 1993. Chapter 2: Physical effects of river ice. In Environmental impacts of river ice (Prowse, T. and Gridley, N., eds). Saskatoon, Canada: National Hydrology Research Institute. 3-74.

Bisaillon, J-F. and Bergeron, N.E., 2009. Modeling anchor ice presence-absence in gravel bed rivers. Cold Regions Science and Technology **55**, 195-201.

Doering, J.C., Bekeris, L.E., Morris, M.P., Dow, K.E. and Girling, W.C., 2001. Laboratory study of anchor ice growth. Journal of Cold Regions Engineering **15**: 60-66.

Calkins, D.J, Deck, D.S. and Martinson, C.R.**,** 1982. Resistance coefficients from velocity profiles in ice-covered shallow streams, Canadian Journal of Civil Engineering 9: 236-247.

Davey, C. and Lapointe, M., 2007. Sedimentary links and the spatial organization of Atlantic salmon (Salmo salar) spawning habitat in a Canadian Shield river. Geomorphology **83**: 82-96.

Kerr, D.J., Shen, H.T., and Daly, S.F., 2002. Evolution and hydraulic of anchor ice on gravel bed. Cold Regions Science and Technology 35, 101-114.

Lawson, D.E., Chacho, D.F. and Brockett, B.E., 1986. Sub-ice channels and longitudinal frazil bars, ice-covered Tanana river, Alaska. In Proceedings of the XX IAHR Symposium.

Michel, B., 1971. Winter regime of rivers and lakes. Cold Regions Science and Engineering Monograph III-B1a, Cold Regions Research and Engineering Laboratory, U.S. Army, Hanover, New Hampshire, U.S.A., 131 p.

Michel, B. and Drouin, M., 1981 Courbes de remous sous les couverts de glace de la Grande Rivière. Canadian Journal of Civil Engineering 8: 351-363.

Prowse, T.D. (1994) Environmental significance of ice to streamflow in cold regions. Freshwater Biology 32**:** 241-259.

Rice, S., (1998). Which tributaries disrupt downstream fining along gravel-bed river? Geomorphology 22: 39-56.

Rice, S., Church M. (1998). Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary link. Earth Surface Processes and Landforms 23: 345-363.

Shen, H.T. and Wang, D.S, 1995. Under cover transport and accumulation of frazil granules, Journal of Hydraulic Engineering 121: 184-195.

Stickler, M. and Alfredsen, K., 2005. Factors controlling anchor ice formation in two Norwegian Rivers. Proceedings of the 13th CRIPE Workshop on River ice, Hanover, NH, September 15-16.

Terada, K., Hirayama, K. and Sasamoto, M. 1981. Field measurement of anchor and frazil ice. Proceedings of 14th IAHR Symposium on Ice, 697-702.

Yamazaki, M., Hirayama, K., Sakai, S., Sasmoto, M., Kiyohara, M., and Takiguichi, H., 1996. Formation of frazil and anchor ice. In Proceedings of the IAHR Ice Symposium, 488-496.

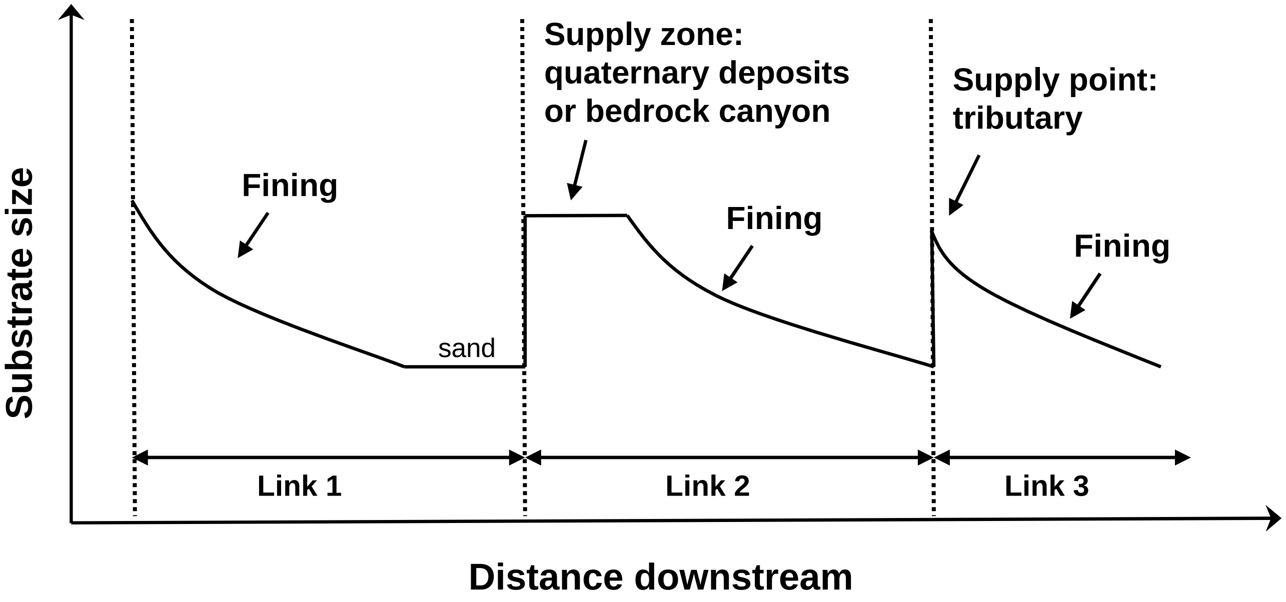

Figure 1. Schematic representation of grain size fining sequences along sedimentary links.

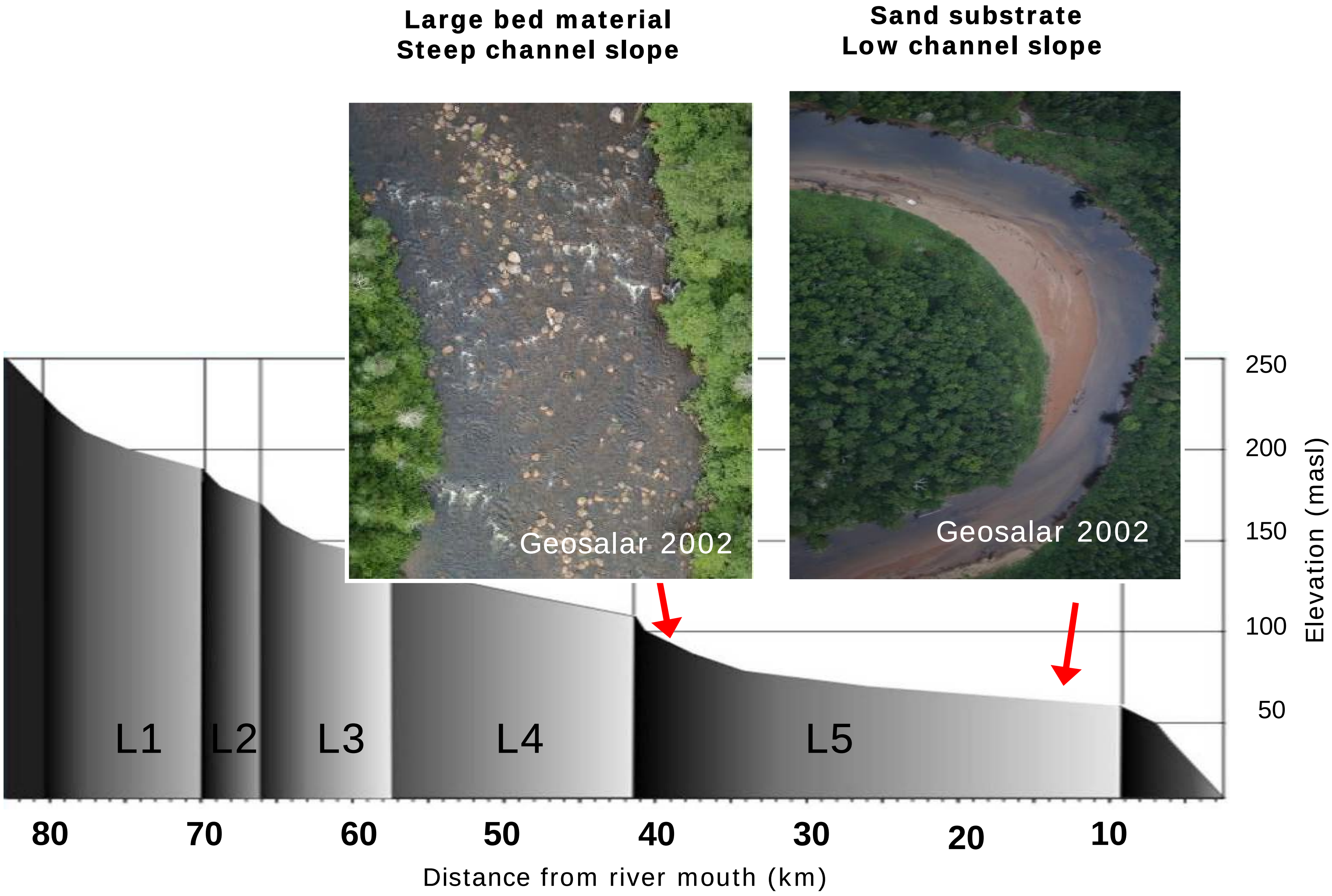

Figure 2. Example of sedimentary links on the Sainte-Marguerite River, Québecm Canada.