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Sedimentary links and the spatial organization of Atlantic salmon (*Salmo salar*) spawning habitat in a Canadian Shield river ☆

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Abstract

The segmenting of gravel-bed rivers flowing through mountain valleys into a number of discrete 'sedimentary links', each characterized by downstream fining of alluvium, is a relatively recent concept which offers promise to model the large-scale spatial organisation of many types of aquatic habitat (reproductive, feeding, refuge, etc), strongly dependent on dominant bed sediment calibre. Although, so far, the ecological application of the concept has mainly focused on benthic invertebrates, here we illustrate its application to fish (Atlantic salmon; *Salmo salar*). Moreover, the link concept has also been primarily applied to alpine river environments where link formation is triggered by point sources (mainly tributaries) supplying coarser sediment. However, somewhat lower relief, mountain valley landscapes of North Eastern Canada are often structured into sedimentary links triggered by non-point, 'supply zones' of coarse sediments, originating in bedrock canyon reaches or valley bottom deposits of glacial drift. Here, we propose an adaptation and extension of the original, sedimentary link concept to such landscapes and test its utility along one such system, the Ste Marguerite River (SMR), a salmon river draining the Canadian Shield in the Saguenay region of Québec. We first discuss a simple field and office based method of link delineation. Then we discuss potential sources of minor, sublink scale grain size variability and their effects on how sedimentary links are defined. Lastly, we demonstrate the usefulness of the link structure to model the distribution of Atlantic salmon spawning habitat (a habitat that depends critically on bed texture). Our results indicate that a revised sedimentary link typology is needed to describe longitudinal grain size patterns where non-point, valley-segment scale sources of coarse sediment are important and that consideration of the research purpose and scale is important in defining meaningful link units. We also show that salmon spawning zones can be directly predicted from the link structure: along the SMR, spawning activity is apportioned within each of the discrete links, in those sub-zones where surface sediment size and sand content are optimal for reproduction.

Keywords: Sedimentary link; Downstream fining; Atlantic salmon; Spawning habitat; Valley landscapes; Substrate sand content

1. Introduction

A longitudinal reduction in the calibre of alluvial sediments is a common phenomenon along gravel-bed rivers, which has been of interest to fluvial geomorphologists for some time (Sternberg, 1875; Bradley et al., 1972; Knighton, 1980; Dawson, 1988; Ferguson and Wathen, 1998). The downstream decline in the mean grain size is

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typically described by a negative exponential law (Sternberg, 1875); and irregularities or scatter about this trend are often related to tributary entry points (Knighton, 1980). Rice and Church (1998) greatly improved the statistical explanatory power of downstream fining sequences by classifying their study rivers into a series of discrete 'sedimentary links', separated by nodes or recruitment points of coarser sediment. The initiation of such sedimentary links has been associated with a supply of coarse sediment from tributaries, and other point sources such as valley-side landslides (Rice and Church, 1998). Coarse material inputs to rivers have also been associated with tributary fan contacts (Bradley et al., 1972; Dawson, 1988), or glacial drift (Bradley et al., 1972).

The extant conceptual model of a series of sedimentary links is illustrated in Fig. 1 (adapted from Rice et al., 2001). A step-like pattern of grain size within a fluvial network is observed (Fig. 1): nodes with sudden increases in grain size coincide with lateral sources of coarse sediment; these are followed by a regular downstream fining of this sediment by fluvial sorting and abrasion processes (Rice, 1998; Rice and Church, 1998). The application of the link concept has been primarily focused on rivers flowing in alpine, high mountain environments, where point sources of coarse sediment (from tributaries draining steep, erosive side valleys) dominate (Knighton, 1980; Dawson, 1988; Rice and Church, 1998; Rice, 1999). Subsequently, the current conceptual model for sedimentary links (Fig. 1: note discharge increase, at head of each link) has been tailored to such landscapes.

In contrast, sedimentary links initiated by non-point sources of coarse sediment have received less attention (Bradley et al., 1972). These include: valley-segment scale sources such as long bedrock canyons, extended glaciofluvial terraces undercut by the river or large alluvial fans of paraglacial age (Church and Ryder, 1972). In non-alpine and tectonically relatively inactive mountain landscapes of NE Canada, coarse (boulder size) sediment recruitment to the river network is often unrelated to tributary entry points, but is often associated with glacial-era valley organisation. It is unclear whether a sedimentary link/model of the type illustrated in Fig. 1 is adequate to describe link types initiated by both point and valley-segment type source zones in older glaciated Shield landscapes of NE Canada.

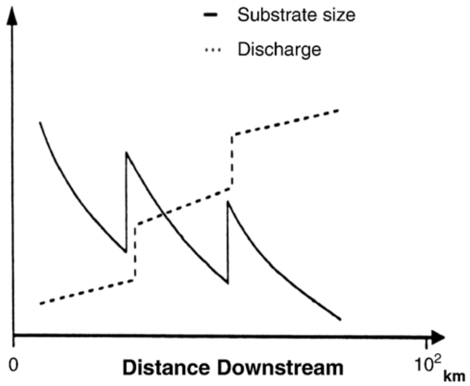

Fig. 1. The conceptual model for the sedimentary link highlighting point sources of coarse sediment at tributaries (Rice et al., 2001).

Operational considerations with regards to link delimitation in diverse landscapes also need further development. Approaches to link delimitation depend on landscape characteristics and on the nature and quality of available grain size data. In order to delimit sedimentary links, Rice and Church (1998) performed a statistical analysis of available, detailed longitudinal grain size data sets for the Pine and Sukunka Rivers in the Rocky Mountains of British Columbia, Canada. In many situations, however, such high resolution, continuous grain size data are not available along a river system. To address this Rice (1998) attempted, with some success, to identify node-producing tributaries based on tributary basin parameters obtained from air photos and topographical maps. The author pointed out, however, that this technique might not work in watersheds with different physiography and geomorphic history. Here, a practical, general method of link delineation is described based on readily available data sources and cursory field visits, which can be applied to different landscape types and link typologies.

However, a substantial challenge when delimiting links lies in distinguishing major link-scale downstream fining trends from more secondary, local or sublink scale, grain size variations. When examining a potentially significant tributary source of coarse sediment, Rice and Church (1998) considered both the sediment delivery capabilities (grain size and volume of supply) and whether or not the sediment source produced a clear grain size increase, or discontinuity, in the overall downstream fining trend (cf Fig. 1). Smaller, sublink scale variations in grain size (e.g. that occur at the local 'reach' scale and so extend only over a few consecutive riffles) can be due to minor lateral sediment inputs from landslides or tributaries (Rice and Church, 1998), or due to processes unrelated to new inputs of coarse material. The latter include local constrictions in channel width, which are associated with higher local flow stresses and reduced residence of finer fractions, or recent meander cutoffs producing complex bed 'regrading' responses, involving lowering and coarsening upstream of the cutoff (and the opposite patterns downstream; Dietrich et al., 1989; Talbot and Lapointe, 2002). Such minor, sublink scale grain size variability can occasionally create ambiguity in defining sedimentary links. To this end, we will also illustrate and discuss various cases of sublink variation in grain size in the context of sedimentary links in a glaciated Shield landscape.

Sedimentary links highlight major longitudinal variations in river bed sediment calibre (from steep, boulder rapids to low gradient, shifting sandy meanders), that are generally associated with variations in river slope as well as flow type (depth, velocity, turbulence intensity) and lateral channel stability conditions. As such, the link structure can provide aquatic ecologists with a useful tool for explaining the distribution and abundance of running water fauna and flora, which are generally very sensitive to this suite of abiotic factors. Sedimentary links have already been shown in an ecological setting to explain the organization of macro invertebrate benthos (Rice et al., 2001). Their use in modelling fish habitat remains untested. Here we argue that sedimentary links represent key riverine landscape structures, which are extremely useful to understand the spatial organization of salmonid spawning habitat. The selection of the appropriate spatial scale to conduct research on Atlantic salmon (*Salmo salar*) freshwater ecosystem structure is a well recognized problem (Heggenes, 1996; Imhof et al., 1996; Lewis et al., 1996; Mason and Brandt, 1999). The sedimentary link concept focuses on easily identifiable, river segment scale landscape structures that address the key role played by bed grain size distributions in salmon ecology. In particular, characteristics of sedimentary links may reveal the distribution of Atlantic salmon spawning habitat, as primary controls on suitable spawning habitat are textural and involve bed material size (Kondolf and Wolman, 1993) and the percentage fines (<2 mm) within the riffle substrate (Chapman, 1988).

The primary objective of this paper is to propose an extension of the sedimentary link concept for lower relief, ‘old mountain’ landscapes and test its utility along the Ste Marguerite River (SMR), a salmon river draining the Canadian Shield in the Saguenay region of Québec, in which valley-scale deposits of coarse sediment (mostly of Pleistocene age) are important in initiating links. Secondly, a simple and practical approach to link delimitation, applicable to both point and valley-segment sources of coarse sediment, is illustrated. The effects of sublink grain size variation, from meander straightening and unusually sharp bends, are also illustrated here and discussed in the context of how to define sedimentary links. Lastly, the distribution of Atlantic salmon spawning habitat in the SMR is modelled using sedimentary link patterns in surface sediment size (D_{50}), and the percentage of fines (<2 mm) in the riffle substrate.

2. Study area

The study system is the Principal (Main) branch of the SMR, which flows into the Saguenay Fjord, in Québec, Canada (Fig. 2). The SMR consists of two main branches, the Principal and the Northeast, which drain similar sized sub-basins, totalling 2115 km^2 of drainage area. A large tributary, the Northwest, flows into the Principal branch ~ 40 km upstream of the mouth of the SMR (Fig. 2). The

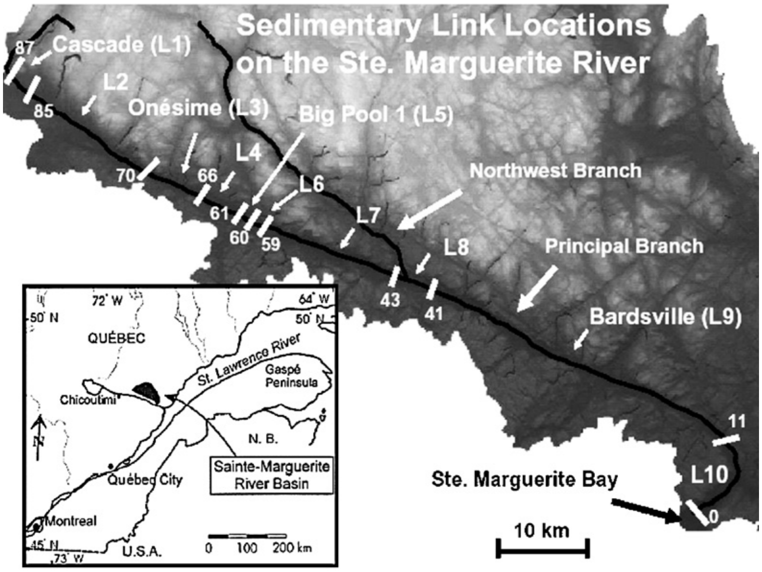

Fig. 2. The Ste Marguerite River (SMR) draining into the Saguenay fjord, located in north-eastern Québec, Canada. This figure also illustrates the location of all ten links. Tributaries are not shown, to maintain clarity. The numbers associated with the start and endpoints for each link represent the distance (km) upstream from the Baie Ste Marguerite.

mean annual peak daily discharge on the Principal branch upstream of the North–West tributary is 70 $m^3 s^{-1}$.

The SMR drainage basin is situated within the Grenville Orogenic Province of the Canadian Shield (Laurin and Sharma, 1975). This geological region consists of granitic gneiss and migmatite rocks, first formed during the Early Precambrian and later metamorphosed during the late Precambrian (Proterozoic). The Principal branch flows through a long and narrow, entrenched, U-shaped valley that, like the Saguenay Fjord it parallels, was scoured by continental glaciers during the Pleistocene epoch. Local relief along the SMR valley exceeds 400–500 m (from valley bottom to first hilltops). This valley branch contains abundant glaciofluvial deposits forming channel-side terraces; in the middle and lower reaches, these deposits overlay marine clays from a regional transgressive episode dated at the end of the last glaciation. The main contemporary sources of coarse sediment recruitment along the channel are boulder rich glaciofluvial deposits and valley-side talus deposits of Paraglacial age (the period immediately accompanying and following glacier retreat; Church and Ryder, 1972). As it flows over and through these coarse deposits and erodes their toe, the SMR channel entrains these boulders and their cobble breakdown products at very slow rates, over century time scales. This contrasts with the potentially higher input rates of coarse sediments into main-stem valleys that originate from active, point source tributary valleys in alpine environments described by Rice and Church (1998). Thus, in this proposed extension of the sedimentary link concept, new links can be initiated wherever a coarse textured valley bottom deposit markedly alters for a significant downstream distance the dominant main stem grain sizes and channel slope, whether these coarse materials have a significant throughput rate or, conversely form a nearly static armour, close to the entrainment threshold at typical, mean annual flood flows.

3. Methods

3.1. Link delineation

In order to minimize field visits, potential link locations along the SMR were first identified through the study of available air photos and a Digital Elevation Model (DEM), constructed from 10 m contour data on the 1:20 000, Quebec series topographic data base. A number of valley bottom deposits of coarse sediment with significant topographical expression were identified on the DEM (Fig. 3), which matched boulder rapid reaches of the channel visible on the 1:15 000 air photos. Prior to field visits, no attempts were made to locate individual tributaries that may initiate a sedimentary link. Field visits of reaches near potential source zones were conducted to confirm the presence of sedimentary links. In addition, a canoe survey of the Principal branch of the SMR was conducted, with the exception of boulder-rapid sections, in order to locate other sedimentary links not identified with the air photo and DEM analyses.

In the absence of pre-existing grain size information, the criteria to determine the start of a new sedimentary link for this project was a clear and significant increase (visually noticeable in field visits) in the median size (D_{50}, representing 50% of the cumulative size distribution) of the riffle/barhead surface layer sediments. Note that along the SMR, in all cases reported here, the head of new links not only showed an increase in D_{50} but were also marked by the reappearance of boulders (particle diameters >26 cm) as the dominant local bed sediment (i.e., the D_{84}, 84th coarsest centile of grain size, was greater than 26 cm). Latulippe et al. (2001) present a quick, visual characterisation technique to assess the bed surface D_{50} and D_{84}. To be deemed significant here, the grain size anomaly or deviation from the previous upstream fining trend must also affect the entire channel width and be perceptible over at least 3–5 successive riffles or 10–20 channel widths downstream. The source of coarse sediment was investigated in the field by noting the origin of the coarse supply, be it tributary, alluvial fan, dry lateral source (valley-side landslide), or valley bottom glaciofluvial deposit, etc. For each sedimentary link, locations were determined where the river entered (box 1 on Fig. 3) and exited (box 2 on Fig. 3) each deposit zone of coarse sediment as well as locations of

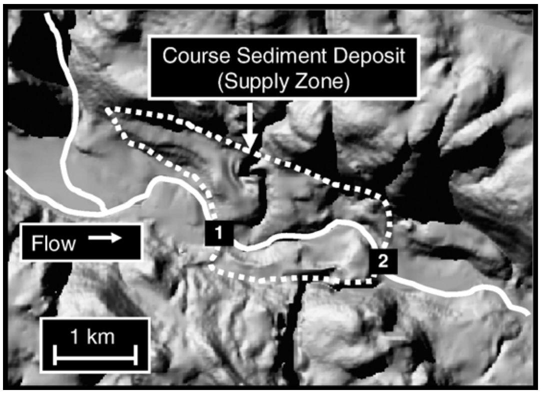

Fig. 3. An example of a large valley-segment source of coarse material detectable from a 1:20 000 DEM. Field visits were conducted to confirm where the river enters (1) and where the river exits (2) a source zone and whether a sedimentary link indeed exists at this location. The dashed line represents the spatial extent of the deposit of coarse material in the valley bottom. The dark areas are shadow zones in the oblique view of the DEM.

gravel–sand transitions and sand reaches. In total, 10 such sedimentary links were identified on the Principal Branch of the SMR (Fig. 2), and these ranged in length from under 1 km to 30 km.

3.2. Sediment sampling

Four of the ten links delimited on the Principal Branch of the SMR were selected (based on their accessibility) for detailed sediment sampling: Cascade (L1), Onésime (L3), Big Pool 1 (L5), and Bardsville (L9; Fig. 2). A 100-pebble count technique (Wolman, 1954) was used to describe the grain size distribution for the coarsest patch of bed surface sediments at the upstream end of each emergent point bar (or occasionally, channel median bar). These patches provide easily accessible samples of the coarsest mobile bed materials in a reach. This type of sediment sampling program is similar to that employed by Rice (1999) to delimit sedimentary links in the Sukunka and Pine Rivers. After sediment sampling, the median sediment size (D_{50}) or sediment size was used to characterize the surface texture of each emergent point bar. Grain size sampling commenced at the most upstream part of the link (usually a boulder rapid) and ended at the most downstream point-bar within the link, before the transition to sand occurred.

To determine the percentage of sand (<2 mm) infiltrated within the riffle substrate in cobble–gravel reaches (an indicator of salmon spawning habitat quality), a bulk sampling technique was employed. Bulk sampling analyses sub-pavement (or sub-surface) grain size distributions and involves the removal of approximately 100 kg of the riffle sediment, using shovels and buckets, to a depth of 30 cm and sieving this material into six separate size classes in the field, ranging from 16 to 128 mm. In addition, a 2 kg sample of the bulk sediments, smaller than 16 mm, is also removed and sieved in the lab into seven separate size classes, ranging from 0.064 to 8 mm. To standardise results for inter-comparisons, the final sand content is expressed as a % of the total sample truncated at 90 mm (all material finer than 90 mm). All riffles in the Cascade, Onésime, and Big Pool 1 links were bulk sampled. However, only a portion of the Bardsville link was bulk sampled because of metric boulder-sized sediments in some areas, which make the bulk sample technique impractical.

3.3. Evidence of unusual channel curvature and meander cutoffs

From the grain size long profiles of each of the four links selected for detailed study (Cascade, Onésime, Big Pool 1, and Bardsville), incidences were also noted of minor, reach or sublink scale, along-stream fluctuations in grain size and these were compared to sites with unusually tight meanders (relative radius of curvature <1), concave bank bench features (Andrle, 1994) or recent meander neck cutoffs. The Bardsville link contained such recent meander cutoffs and abrupt bends where the river hits the valley wall. Air photos (years 1968 and 1972) and field visits (summer of 2002) confirmed the exact locations of such features within each link.

3.4. Spawning survey

Current Atlantic salmon spawning sites were surveyed along the entire 80 km long Principal branch of the SMR. Two fishing guides responsible for annual spawner surveys, both with 30 years of experience on the SMR, were interviewed to provide detailed information on spawning locations over the last 5 years for the entire length of the river. In 2004, a 3-day canoe survey was also conducted with these guides to locate each spawning riffle and assess the number of spawners typically observed in each reach in mid-fall (late September to October). The locations were recorded by a hand-held GPS and mapped using air photos. Here, data regarding the mean number of spawners identified for each spawning riffle makes no distinction between male and female spawners and are representative for the last 5 years of spawning activity observed by local guides.

4. Results

4.1. Sedimentary link grain size patterns along the SMR

Downstream grain size decline is typically fitted by an exponential model (Sternberg, 1875; Rice and Church, 1998; Rice, 1999). As in Rice (1999), here grain size values (in mm) were converted into the ψ scale ($\log_2 D$, where $D$is measured in mm, equivalent to $-\varphi$), such that a linear model describes the exponential size decay downlink,

$$\Psi = \Psi_0 - \alpha_d L_f \qquad (1)$$

where ψ is the psi value of the surface D_{50} of the grain size distribution; ψ_0 is the psi value at $L=0$, the upstream end of the segment; L_f is the distance (km) along the downstream fining segment; and α_d is the decline rate in grain size units per kilometre. Fig. 4 displays the relationship between the D_{50} (in ψ units) and distance downlink for the Bardsville, Onésime, Cascade, and Big Pool 1 links, which were sampled in detail. (Although separated in the

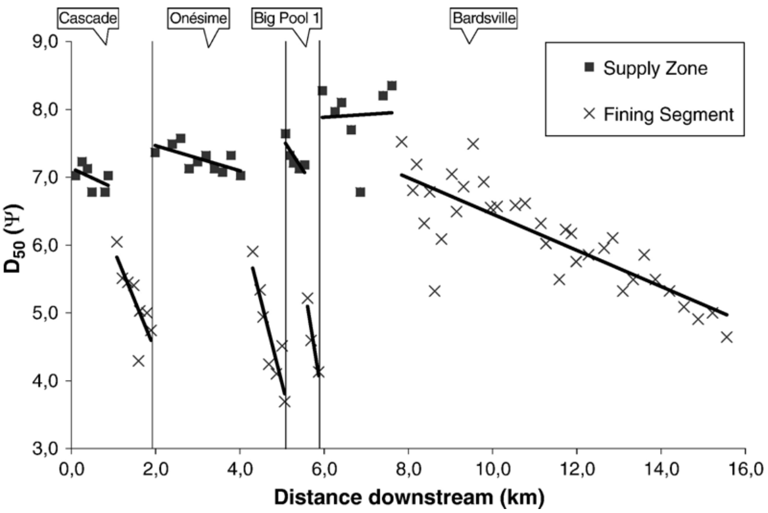

Fig. 4. Grain size (bar head D_{50}) pattern downlink along the Cascade, Onésime, Big Pool 1, and Bardsville links. Note, these 4 links are non-contiguous in the field (cf. Fig. 2). They were plotted sequentially here for simplicity.

field, the four links are plotted consecutively here for convenience.) Along each link, the segment where the river flows through and is confined within valley-scale sources of coarse sediment is labelled as the supply zone; while the downstream section of the link where grain size decline occurs is labelled the fining segment (here the valley typically widens and the channel is flanked by floodplains). Both supply zone and fining segment are modelled separately using Eq. (1). Quality of fit is summarised in Table 1.

For the most part, supply zones fail to exhibit a significant downlink trend in D_{50} (three out of four links, see Table 1) as recruitment of coarse fractions is more or less continuous along these zones. In contrast, all links display significant reductions in the D_{50} along the fining segment (Table 1). Note that downstream fining rates (cf. Fig. 4, slopes of the linear models) are not constant across downstream fining zones; thus a longer fining zone does not necessarily imply a proportionally wider range of bed calibres along its course. Indeed, some very short links can fine from boulders to sand.

Table 1
The significance and strength of the D_{50} versus the downlink distance relations for the four, detailed study links

Link	Zone	r^2	p-value
Bardsville	Supply	0.002	0.80
	Fining	0.44	<0.05
Onésime	Supply	0.43	0.04
	Fining	0.73	<0.05
Big Pool 1	Supply	0.67	0.09
	Fining	0.90	<0.05
Cascade	Supply	0.22	0.33
	Fining	0.70	<0.05

The gradual decrease in riffle sediment calibre along the fining segments of links is accompanied by a predictable increase in sand content in the sub-pavement layer. Results from regression analysis of riffle sand content against distances along fining zones are given in Table 2. All fining zones displayed a positive relation between distance and percent sand content in the riffle substrate, however, only the trend within the Bardsville link was significant at the 5% level (Table 2).

4.2. Link delineation methods

Of the 10 sedimentary links ultimately identified along the Principal branch of the SMR, six links were correctly located based on office analyses of 1:15 000 air photos combined with 1:20 000 DEM (Table 3). Only one potential deposit of coarse material identified on air photos and the DEM failed to initiate a new sedimentary link. Boulder rich glaciofluvial deposits initiated a total of seven links along the Principal branch of the SMR. However, two coarse glaciofluvial deposits initiating links (L2 and L7) could not be identified using air photos and DEM; these deposits were only noticed after a canoe

Table 2
Significance and strength of relations between distances along fining segment and the % sand content in the riffle substrate

Link	r^2	p-value	N
Bardsville (L9)	0.68	0.003	10
Onésime (L3)	0.06	0.6	7
Big Pool 1 (L4)	0.27	0.47	4
Cascade (L1)	0.34	0.12	8

N is the number of riffle zones sampled in each fining segment.

Table 3
Lengths of source zones, fining segments and any sand reaches for all 10 SMR links

Link	Name	Total link length (km)	Source zone (km)	Fining segment (km)	Sand reach (km)	Cause of link	Located using only air photos and DEM
L1	Cascade	1.54	1.03	0.51	0	Canyon	Yes
L2	St. Germain	14.70	–	–	–	Glacio-fluvial	No
L3	Onésime	4.70	2.49	1.06	1.15	Glacio-fluvial	Yes
L4	Gross Rapide	4.38	–	–	0	Glacio-fluvial	Yes
L5	Big Pool 1	1.10	0.37	0.73	0	Glacio-fluvial	Yes
L6	Big Pool 2	0.90	0	0.49	0.41	Trib/lateral input	No
L7	Meander	16.05	–	–	3.02	Glacio-fluvial	No
L8	Northwest	4.45	0	4.45	0	Alluvial fan	No
L9	Bardsville	29.50	2.15	7.26	20.09	Glacio-fluvial	Yes
L10	Le Pont	11.40	–	–	0	Glacio-fluvial	Yes

A dash indicates that data is unavailable. Also indicated are the types of source zones and whether or not the start of each link was correctly identified through air photos and the DEM.

survey of the area. The canoe survey also revealed two other links that are not triggered by glaciofluvial deposits and which had not been identified by the map and air photo analyses; L6 (triggered by input from a small tributary) and L8 (a relict alluvial fan). In the field, the start of each sedimentary link (especially links initiated from a glaciofluvial deposit) was fairly easy to locate. Most link transitions are characterized by gravel or sand-sized material being abruptly interrupted by an outcrop of boulder-sized material on the channel bed (Fig. 5). Table 3 also gives the lengths of each supply zone, fining segment and sand reach for SMR links. Remoteness of sites prevented data acquisition regarding the lengths of these sub-zones for L2, L4, L7 and L10.

4.3. Sublink variations in grain sizes along the 29-km-long Bardsville link

Air photo analysis and subsequent field visits disclosed the existence of two unusually sharp channel bends at valley wall contacts and one relatively recent (30-year old), large meander neck cutoff along the Bardsville link.

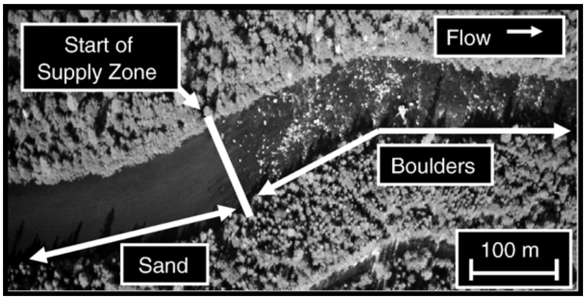

Fig. 5. In many cases such as this (L3 to L4 transition), link transitions on the SMR are marked by an abrupt and striking change from gravel–sand sized material to boulder sized material.

Fig. 6 illustrates one of the tight, channel bends at valley wall contacts (concave bank (1) on Fig. 7). In section 1 (before the river makes contact with the valley wall) the riffle sediments are characterized by large cobbles (D_{50}=73 mm). Near the sudden turn where the channel is deflected by the valley wall, the unusually tight curvature (in most cases, over short distances relative curvature values lie near 1 near the contact point) triggers a strong water surface super-elevation and flow constriction, causing outer bank flow separation and the formation of a typical ‘concave bank bench’ of fines (Andrle, 1994). This constriction effect apparently reduces the local sediment transport capacity, leading at section 2 (Fig. 6) to a sudden reduction in mean riffle bed calibre to medium gravel (D_{50}=34 mm). Approximately 250 m downstream however, the effect of the tight bend on sediment transport is lessened and large cobbles reappear on the bed starting at section 3 (D_{50}=64 mm). Note on Fig. 6 the occurrence of an isolated riffle (also in section 2) where salmon spawning has been observed in a reach otherwise devoid of such activity. A second, similar site with unusual channel curvature in the Bardsville link (concave bank 2 on Fig. 7) also occurs because of a valley wall contact, and is very similar in morphology to the one illustrated in Fig. 6. The locations of the two unusually sharp bends are plotted on the D_{50} profile in Fig. 7.

A 35-year old neck cutoff of a large meander located along the Bardsville link is shown in Fig. 8. Air photo analysis revealed that this meander was part of the active channel prior to 1969. By 1972 the large meander had been abandoned (partly through human disturbance to the floodplain forest in the neck zone). The typical pattern of gravel bed channel re-adjustment to meander straightening caused by normal reach scale re-profiling (Dietrich et al., 1989; Talbot and Lapointe, 2002) was observed here which introduces a local perturbation to the

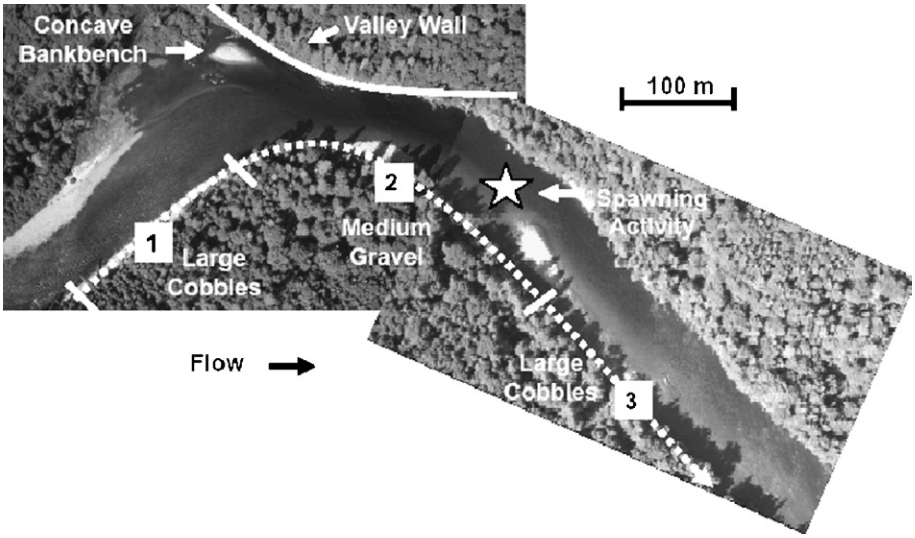

Fig. 6. A depositional, concave bank bench where the river contacts the valley wall is illustrated here (cf. concave bank formation 1, on Fig. 7). Sections 1–3 are based on the dominant sediment present within the channel. The star indicates a riffle site where some spawning activity has been reported.

downstream fining trend: i.e. bed level degradation (lowering) upstream of the cutoff associated with coarsening of the bed surface and bed level aggradation (rise) with accumulation of finer cobble–gravels downstream of the cutoff. The zones where the bed material coarsened (upstream) and became finer (downstream) are identified in Fig. 8. The location of the cutoff is shown on the grain size profile (Fig. 7): the five riffles upstream of the cutoff plot consistently above (coarser than) the overall downstream fining trend line while, downstream of the cutoff, a negative anomaly in the riffle D_{50} is observed. Note that removal of riffle D_{50} data affected by all the identified, sublink scale effects discussed here (the cutoff and two abrupt bends at valley walls; solid circle in Fig. 7) improves the r^2 from 0.68 to 0.85. Essentially, within the Bardsville link, the sublink 'noise effect' is

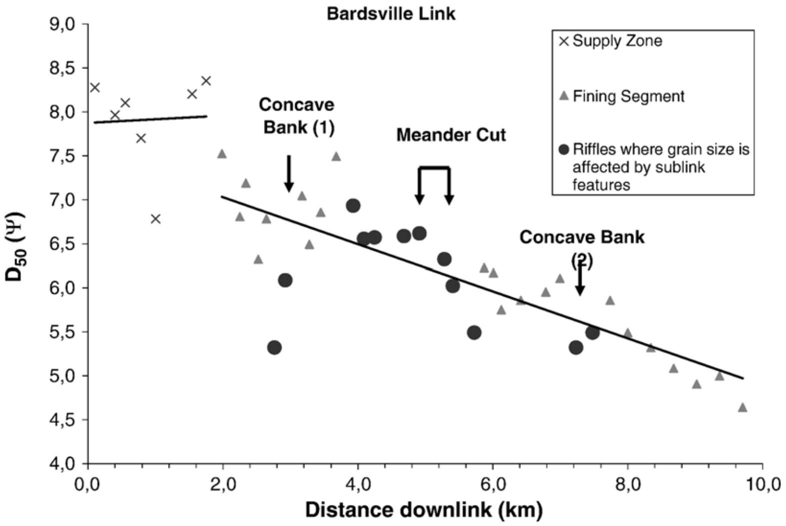

Fig. 7. The D_{50} longitudinal profile of the Bardsville Link along with the locations of two depositional, concave bank benches and one meander cutoff, discussed in the text. Circle markers indicate where the D_{50} of the riffle has likely been affected by fluvial processes associated with abrupt bends and recent meander cutoffs.

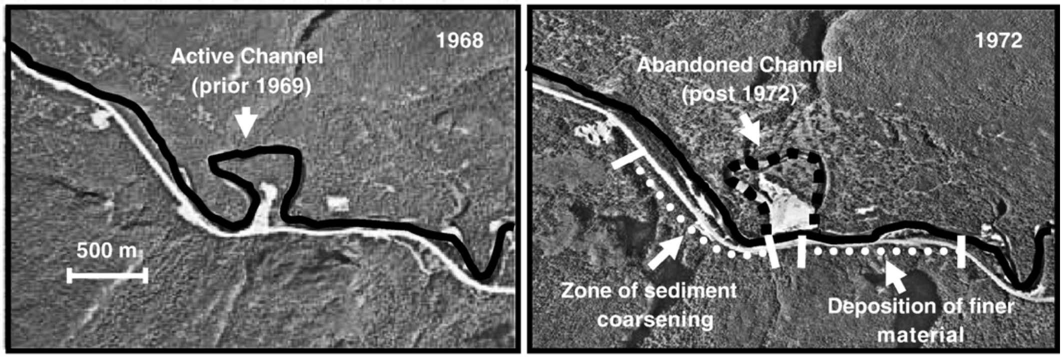

Fig. 8. Prior to 1969, this large meander was an active part of the river channel but by. 1972, it was cutoff. Also shown are reaches where the cutoff triggered sediment coarsening upstream and sediments fining, downstream, as discussed in text. Refer to Fig. 7 for the location of this meander cutoff along the Bardsville link.

considerable, on top of the otherwise strong downlink trend signal.

4.4. *Substrate characteristics and spawning site distribution within links*

To interpret link-scale trends in the distribution of spawning activity, the substrate characteristics of spawning sites (D_{50} of spawning sediment and percent sand <2 mm in riffle substrate) were assessed. In total, 29 spawning riffles were identified along the whole principal branch of the SMR based on interviews and site visits with local fishery guides. The majority of these spawning riffles (19) were located in areas where riffle substrate information was available. Table 4 displays basic statistics on the size of bed surface layer sediments and the percent sand content (<2 mm) of the riffle subsurface layer substrate where spawning activity was reported to take place. The mean (standard deviation) is 51 mm (11 mm) for pavement D_{50} and 13% (4%) for percent sand in the sub-pavement layer.

Table 4
Statistics for the bed surface sediment size and sand content of the riffle substrate at observed Atlantic salmon spawning sites on SMR

Statistics	D_{50} of spawning gravel (mm)	% Sand (<2 mm) in spawning riffles	Spawning location in fining segment of links (fractionalized distance)
Minimum	33	4	0
Maximum	73	19	1
Range	40	15	1
Median	52	14	0.70
Mean	51	13	0.58
Standard deviation	11	4	0.35

Also given are the statistics on the relative location of observed spawning sites along fining segments (fractional distances along fining segment excluding sand reaches).

Within each of the 10 surveyed links, the centroid or center of gravity of observed spawning activity (its average, along stream location, weighted by reported number of spawners) occurred at a point along each downstream fining zone where median size of the surface pavement was in the suitable D_{50} range of 40–60 mm. Table 4 also lists statistics on relative location of spawning riffles along six links (L1, L3, L5, L6, L8, and L9), expressed in fractional link distances (with 0 the head and 1 the tail of the downstream fining zone, excluding sand dominated reaches). No spawning was reported within any supply zone of a sedimentary link for the SMR. The results from Table 4 suggest that spawning can occur at any relative distance within the fining segment, as long as this site provides substrate within the suitable range of calibre. However, in SMR links that initiate at coarse boulder rapids, spawning tends to occur towards the middle to downstream end of the cobble–gravel fining segment in a sedimentary link (median fractional distance = 0.7).

Fig. 9 illustrates the detailed distribution of reported spawning riffles (circles) along the Bardsville link. The D_{50} riffle values along the fining segment are plotted against the fractional link distance. The location of both unusual channel curvatures (valley wall contacts) and the recent meander cutoff are again shown. The circle markers represent a riffle where spawning has taken place in the last 5 years. The black rectangle crossing Fig. 9 indicates the upper and lower limit for spawning sediment median size (D_{50}) observed along the whole SMR (Table 4). The observed percentage of sand (<2 mm) within the riffle substrate along the Bardsville link is also plotted in Fig. 9, with a regression fit describing the increasing trend in sand content towards the observed sand transition observed near km 25 ($r^2 = 0.68$, $p < 0.05$; see Table 2).

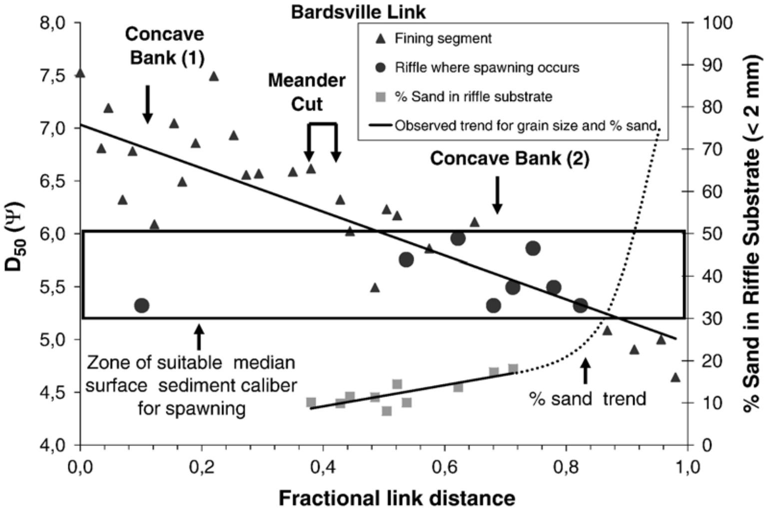

Fig. 9. The D_{50} profile of the Bardsville Link plotted against fractional distance down the fining zone (where 1 = head of sand reach). The circle markers indicate a riffle where spawning by Atlantic salmon actively is documented. The black rectangle delimits the range of median surface sediment size where salmon spawning has occurred along the entire Ste Marguerite River. The observed and predicted trend (dashed line) of the percentage of sand within the riffle subsurface substrate is also shown.

Because of high flow conditions, the downstream four riffles of the Bardsville link, just above the gravel–sand transition, could not be bulk sampled. However, a dashed line is used in Fig. 9 to illustrate the most probable continuation of that trend to reach 100% sand at the known transition point.

The main cluster of spawning riffles within the fining segment of the Bardsville link occurs at fractional distances of 0.54 to 0.82, where the downstream fining trend produces appropriately sized cobble gravel substrate, that is low in sand content. Note however, the occurrence of one isolated spawning riffle at the upstream end of the fining segment (at a fractional distance of 0.1). The location of this isolated spawning riffle coincides with the valley wall contact (1) described above. Another isolated spawning riffle occurs well downstream within the sand reach of the Bardsville link (not shown on Fig. 9). A field visit revealed that this spawning riffle corresponds to a small island of cobble gravel-sized sediments within the sand reach. The source of this isolated cobble gravel patch is a small tributary. This textural anomaly failed to affect the whole channel width over three to five successive riffles and thus was classified as sublink scale. Interestingly, this local increase of sediment size within the long sand reach was enough to attract a few spawners. A similar phenomenon was also observed in the St Germain link (L2, Table 1), where three isolated riffles of gravel–cobble sized sediments were observed within the sand reach. These were associated with a minor valley wall contact and also attracted some spawning activity.

5. Discussion

5.1. Adaptation of the sedimentary link concept to the SMR

It is important to note, first, that the sedimentary link concept is not equally relevant for all river environments: it has its greatest utility along mid-order rivers flowing within mountain or plateau valleys, where a frequent alternation can occur between, on the one hand, coarse supply zones from laterally constraining valley walls (or steep, valley-side-tributaries) and, on the other hand, downstream fining zones along floodplain reaches occupying wider valley sections. The link concept is of poor relevance in small, low order 'erosive', headwater streams (where floodplain reaches are less frequent) or along major, lowland rivers (where inputs of coarse sediments are rare).

The breakdown of gravel-bed river courses in mountainous landscapes into natural landscape units called 'sedimentary links', is a relatively new technique that has had limited application. Thus far, the link concept (Fig. 1) has been primarily focused on alpine environments where links are structured around discrete tributaries or point sources of coarse sediment (Dawson, 1988; Ferguson and Wathen, 1998; Rice and Church, 1998). The primary objective of this paper is to propose an extension of the sedimentary link model beyond alpine environments to a Canadian Shield river, where coarse sediments supplied from non-point, bedrock sections or valley bottom glaciofluvial sources may dominate link initiation.

In an analogous fashion to alpine sedimentary links portrayed in Fig. 1, SMR links display a clear downstream fining trend in D_{50}(Fig. 4). However, SMR links also show a relatively 'flat' D_{50} segment upstream at the supply zone of the link, within which grain sizes can increase or decrease downstream. These flat segments immediately precede the fining segments. Along the study river, these non-point supply zones generally correspond to segments where the river flows through valley bottom glaciofluvial terrace deposits of coarse sediment. Thus, the model of sedimentary links can be modified to reflect two distinct source zone types (Fig. 10).

Point sources, as defined here, correspond to coarse sediment recruitment into the Principal channel at a precise point (an individual major landslide site, or tributary confluence), such that the Principal channel immediately sorts and/or transports this newly injected material downlink. On the other hand, non-point or valley-segment sources of coarse material are associated with spatially extensive valley bottom or valley-side deposits (extending over a zone of generally >10 channel widths in length). Because of the non-alluvial nature and complex geometry of these deposits, the D_{50} within these source zones will not necessarily show downstream fining and may vary in a complex way. The source zones are then followed by a downstream fining segment, common to both link typologies.

The revised conceptual model is summarised in Fig. 11. The revised model thus includes three components for each sedimentary link: a supply point or zone, a fining segment, and (in some cases) a sand reach. The sand reaches are not included here within the fining segment, *sensu stricto,*because the D_{50} in sand reaches can remain nearly constant over long distances. In addition, the length or presence of the sand reach can vary from link to link. In fact, Rice (1999) did not observe any sand reaches within the links located along the Sukunka and Pine Rivers. The existence of a sand reach at the lower end of a fining zone can be obviated by the occurrence of a new, coarse supply point, occurring before a sand reach could occur due to downstream fining. Conversely, aggradation (bed rise) at the head of an active coarse supply zone can, in some settings, sufficiently decrease channel gradients upstream, to trigger sand reaches at the toe of even relatively short fining zones lying immediately upstream of the aggrading zone.

Rice's (1999) hypothesis to identify node points marking the start of new sedimentary links, asserting that tributary sediment load regime (size and quantity) can be predicted based on tributary basin characteristics, does not apply to the source zones of glacial or paraglacial age along the study river. The valley-segment sources of coarse sediment initiating the majority of links on the

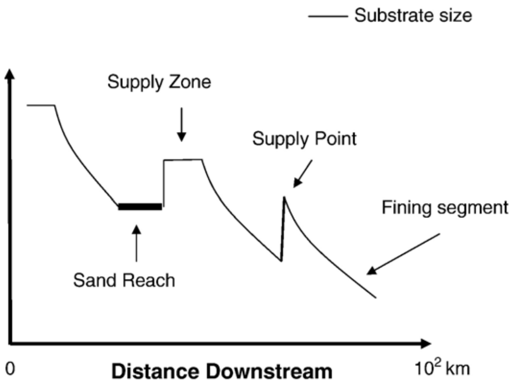

Fig. 11. Revised conceptual model of the sedimentary link incorporating two source types: local supply points and valley-segment supply zones.

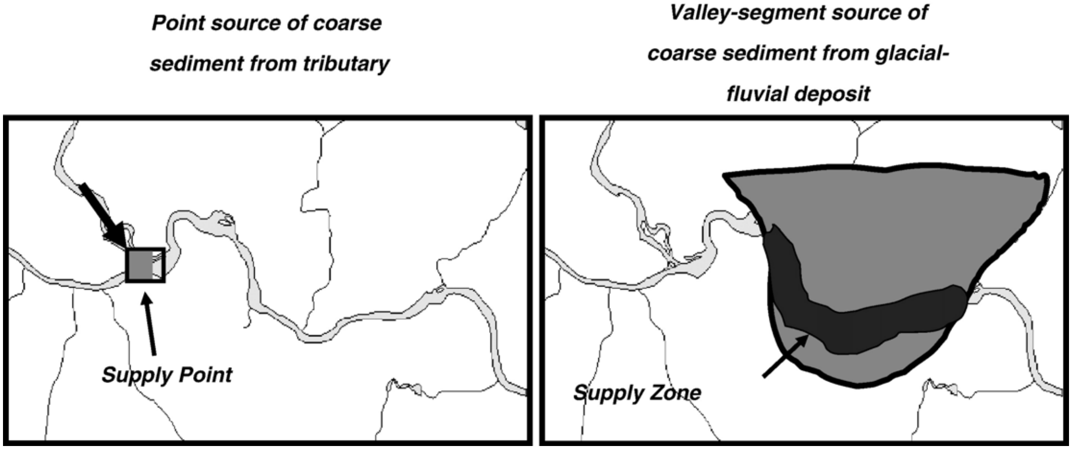

Fig. 10. Two different source types, point and valley-segment sources, in the formation of sedimentary links.

SMR are not hydrologically determined but correspond to ancient deposits from glacial era processes.

The relative length of supply and fining zones within any link can thus vary widely, depending on the landscape setting. Although the SMR system studied did not feature bedrock canyon segments, such canyons can also act as regional, coarse supply zones. Such bedrock canyon segments may also be notable for the heterogeneity of channel bed character over short distances: with boulder rich and bedrock-rich reaches, interspersed with occasional cobble–gravel or sand bars, in the lee of bedrock headlands. In some landscape settings, such long canyon zones can even constitute, in aggregate, a large proportion of the total river course. For such reasons, it may arguably be more convenient to classify such long, heterogeneous source canyons as distinct, extra-link river segments and choose to include only the downstream ends of these long, source zones and the subsequent fining segments (and sand reaches) within sedimentary links, proper. It is also possible that such complex, canyon segments include fine-scale patches of salmonid spawning substrate, at locations that cannot be easily detected without field visits or the use of high resolution aerial videography.

Finally, it is important to note that, with regards to underlying fluvial geomorphic processes, the proposed extension involves somewhat of a qualitative shift in focus from the original link concept of Rice and Church (1988). In their original model, total sediment transport rates as well as sediment calibre were ‘reset’ (usually both increased) at each tributary node point, where both additional alluvium and water were injected into the mainstem river. Although the authors accepted the existence of ‘dry sources’ of sediment (with no associated point source of discharge), the resetting of water and/or sediment flux boundary conditions at identified nodes was seen as central to the link concept breakdown. In contrast, along the SMR landscape, contemporary coarse sediment input rates from source zones appear to be small. Along the SMR, the importance of the source zones lies less in the changes in contemporary sediment transport rates along these sectors (which remain unquantified) than in the major changes in channel characteristics (bed texture and channel slope) caused by the rivers passage through these zones and with the fining products that have extended downstream from these zones over millennia.

5.2. Sedimentary link delineation in rivers

The delineation of sedimentary links using pre-existing systematic grain size information along rivers is a fairly straightforward process (Rice and Church, 1998). Without the luxury of such detailed grain size information, however, the utility of the sedimentary link concept for use in geomorphic and ecological applications requires a methodology that is simple to employ in any watershed, with either point or zone sources of sediment (Fig. 10).

The use of air photos and, where available, a detailed DEM worked well along the SMR to identify valley bottom areas with topographic expression (Fig. 3 for example), suggestive of potential boulder supply zones and the absence of a floodplain (Table 3). However, the construction of a high resolution DEM can be time consuming and impractical in certain watersheds. In addition, the resolution of a particular DEM may be insufficient in revealing the texture of smaller, yet significant, glaciofluvial valley deposits that initiate sedimentary links (L2 and L7 on the SMR for example).

In general, the first line of attack to identify major links should be through stereo-paired air photo interpretation of valley bottom deposits, distinguishing areas with floodplains from those featuring terraces, or conspicuous coarse valley-side colluvium. This information should be combined with the identification of boulder rapids on air photos and with major changes in channel slope observed from long profile data extracted from topographic maps. In addition, reviewing available surficial geology maps and consulting with a quaternary geologist could also provide valuable information regarding the texture of possible link-forming valley deposits. Following this office analysis, a field component is useful to ultimately confirm the presence of a sedimentary link, as the start and endpoints of most links are most easily identifiable once in the field (Fig. 5).

5.3. Sublink scale grain size variability and the definition of sedimentary links

The grain size discontinuity or step, is a fundamental feature of a sedimentary link (Figs. 1 and 11). Yet minor amplitude and small spatial scale fluctuations in grain size (both positive and negative) may also occur. These can be from minor landslide or tributary inputs (Rice and Church, 1998), meander cutoffs (Dietrich et al., 1989) or zones with unusual channel curvature (Andrle, 1994). However, to implement the link approach, an operational distinction must be made between grain size discontinuities initiating a new link, and sublink grain size variability.

In agreement with Rice and Church (1998), designation of a sedimentary link requires a grain size discontinuity with an associated sediment source located outside of the study channel proper. Although meander cutoffs and unusual channel curvature can produce local grain size fluctuations (Fig. 8), these mechanisms do not supply coarse sediment to the main channel, but rather, alter the proximal sediment transport capabilities of the channel. Here such features are considered to cause sublink scale variability in grain size, superimposed on the main link-scale downstream fining trends.

To some degree, however, deciding whether or not a new lateral input of coarse sediments is of sufficient textural contrast and triggers the minimum length of fining zone deemed necessary for a new link remains subjective. Careful consideration of the study object (be it benthic ecology, gravel transport dynamics, Atlantic salmon habitat, etc.) and the spatial scale of a particular project should determine the suitable link length (number of riffles) and the magnitude of the grain size step that initiates a new link. This study argues that while small-scale lateral inputs or channel features affecting the size of the D_{50} for only one or two successive riffles can have ecological significance, from a geomorphic standpoint, these reach-scale features are often superimposed upon much larger and more permanent sedimentary links defined at the valley-segment scale.

5.4. Link-scale trends in the location of spawning habitat

The availability of spawning habitat for many salmonids including Atlantic salmon primarily depends on the size of the bed surface sediments (Kondolf and Wolman, 1993), whereas the quality of the spawning habitat depends mainly upon the percent fines in the sub-pavement layer substrate (Chapman, 1988; Moir et al., 2002). In order to assess an individual river's salmonid production, 'keystone habitats' (areas of habitat that have a strong influence on the population abundance), need to be identified (Dodson et al., 1998). Our data suggests that the delineation of rivers into sedimentary links, a process-based and easily identifiable unit of landscape, may provide a highly useful conceptual approach to model the distribution of salmonid spawning reaches in rivers.

A link-scale pattern in the distribution of salmon spawning activity is evident in Fig. 9 for the Bardsville link. Here, the majority of spawning sites are located just downstream from the centre of the boulder to sand fining segment, in the reach with the optimal cobble sizes for salmon spawning. This pattern was broadly confirmed in all SMR links: in each link, the centre of gravity of observed spawning activity was located in those parts of downstream fining reaches with similar, optimal cobble sizes. However, the location of this substrate along a fining zone varies depending on the local texture at link head and the downstream fining rate. Along the SMR, for all links combined, the median location for spawning is at a fractional distance of 0.70 (Table 4) along the length of fining segments (reflecting the boulder dominance observed at the head of the SMR fining zones).

However, spawning activity also occurred over the entire range (0 to 1) of locations within the fining segment (Table 4). In some cases, fining segments can begin (or end), within the suitable range of cobble sized spawning substrate; thus the potential for spawning activity can occur along the entire fining segment. Furthermore, small-scale (sublink) variations within the overall link-scale fining trend can in some cases (as per Fig. 9) provide a few isolated riffles with suitable-sized sediments within a reach otherwise too coarse for spawning. Some minor spawning activity was also reported to occur on isolated gravel–cobble riffles within the sand reaches of the St Germain and Bardsville links.

Thus, the sedimentary link model clarifies the distribution of salmon spawning habitat because the model focuses on the general D_{50} fining trends of the surface sediments associated with links (Fig. 4). Information on these trends can help predict the general location, within each fining segment, of the size range of sediments usable by spawners. The cluster of spawning activity seen within the fining segment of sedimentary links provides optimal survival conditions for the eggs in these locations. Firstly, the majority of spawning activity takes place at these locations, but most importantly, the moderate fines content at these locations (Chapman, 1988) likely provide a better quality of spawning habitat than elsewhere within a link.

Even though the threshold values for optimal salmonid spawning substrate calibre may vary with the target salmonid species considered and even with local fish population characteristics (as well as with the type of sediment sample analysed, i.e. bed surface versus subsurface sample), the SMR evidence suggests that the watershed scale distribution of the relevant optimal substrate condition can be predicted from knowledge of the overall link structure. Although the optimal surface layer median calibre for salmon redds in the SMR is in the range 50 mm range, the calibre of D_{50} for predictably finer textured, subsurface samples of spawning gravels found within the SMR are in the range 18 to 35 mm. These values are similar to those found by Moir et al. (2002), who reported that D_{50} for spawning gravel of Atlantic salmon in the River Dee in Scotland tended to range from 10 to 38 mm with a mean value of 23 mm. Furthermore the percentage of riffle subsurface substrate fines (<2 mm) was quite similar for both the SMR (4 to 19% with a mean value of 13.5%) and the River Dee in Scotland (4 to 25% with a mean value of 10%).

In using the link concept to spatially organize Atlantic salmon spawning habitat within a river environment, it is important to consider as well the proximity of other life-stage specific salmon habitat requirements. Larger parr (salmon juveniles) prefer boulder rich habitat, both for feeding and, in cold climates, for overwinter refuge in sediment interstices (Cunjak, 1988; Coulombe-Pontbriand and Lapointe, 2004). Thus, it is possible that one particular sedimentary link along a river network contains the ideal spawning habitat for the local salmonid population (preferred surface D_{50} and riffle sand content), yet this same link (and others nearby) may lack proper habitat for larger parr (i.e.: boulders), resulting in an area with higher eventual juvenile mortality and lower overall salmonid production. Thus, when using the sedimentary link concept to classify the ecological significance of certain areas along a river network from a fisheries management perspective, it is important to consider a sequence of sedimentary links that contain, (over distances compatible with juvenile seasonal migrations), all required life-stage habitat characteristics.

6. Conclusion

Results presented here support an extension of the sedimentary link model to adequately describe the large scale longitudinal grain size patterns within the SMR. The revised conceptual model of sedimentary links contains three components that may vary in length: coarse sediment supply points or supply zones, fining segments, and in some cases, sand reaches that extend fining zones downstream to ‘base levels’ formed by coarse boulder sections with quasi-fixed bed elevation or, more conventionally, large water bodies.

Results showed that the majority of Atlantic salmon spawning on the SMR takes place in valley sectors predictable from the link-scale, grain size fining trends. We hypothesize that the reason for this clustering of spawning at this location was due, in part, to the downstream fining process, that would naturally congregate the range of suitable size spawning sediments in close proximity to each other. In addition, we believe that this clustering of spawning activity occurs where the percent fines of riffle sediments were at preferred levels for optimal survival conditions of the eggs.

In conclusion, by segmenting a gravel-bed river into identifiable and discreet units of mountain valley landscape, the sedimentary link concept allows geomorphologists to model and better understand the physical processes of river dynamics (grain size sorting, sediment movement, and transport, etc.). From an ecosystem perspective, the sedimentary link model provides a useful framework allowing fish managers and river ecologists to segment a mountain river into its dominant large-scale units of riverscape and thus appropriately stratify their research, conservation, and rehabilitation efforts.

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