Fraser River: History in a Changing Landscape

27

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Abstract

The Fraser River of British Columbia is among the longest montane rivers in the world. Draining a mainly wildland catchment, its hydrology is dominated by the annual snowmelt freshet and sediment yield by material recruited along the banks of the river from Pleistocene valley fills. The upper course of the river was captured from arctic drainage in late Quaternary time. Another Quaternary legacy is one of the world's greatest salmonine fisheries. As it approaches the sea, gradient declines and the gravel load of the river is deposited, creating a wandering-braided channel zone that supports an exceptionally rich aquatic ecosystem. But it also presents a potentially escalating flood hazard to settlements along the river and to major arteries of communication. In the sand-bed deltaic reach of the river, persistent dredging for navigation has created the reverse problem of riverbed degradation and loss of sand recruitment to the delta front. Natural history and human development are intertwined in complex ways along the lower course of this river.

Keywords

Fishery • Flooding • Fluvial sedimentation • Fraser river • Quaternary history • River management

27.1 Introduction

Fraser River drains 232,000 km^2 of south-central British Columbia—the heartland of Canada's westernmost province (Fig. 27.1). About 80 % of the province's population resides in the Fraser drainage, most of it within the Lower Fraser Valley. The source of the river is traditionally placed near Mt. Robson, the highest peak in the Canadian Rocky Mountains; in fact it rises 90 km southeast in the Rocky Mountain Trench. It flows 1375 km to the sea at Vancouver, Canada's principal Pacific coast city. It is the seventy-seventh largest river in the world by discharge and the largest river draining from British Columbia into the Pacific Ocean. About 70 % of its drainage area consists of the Nechako, Fraser and Thompson Plateaus, the uplands that lie between the Rocky and Cariboo mountains to the east and the Coast Mountains to the west (Fig. 27.1). These are regions of ranching, logging and mining, activities that form the economic base of interior British Columbia life. Only two tributaries have been impounded, and the free-running river is host to the greatest remaining runs of Pacific salmon (*Oncorhyncus* spp.). The native cultures of the region have depended on the salmon for the more than 10,000 years they have been present, as do major commercial and recreational fisheries today.

In 1792, the English captain, George Vancouver, managed to miss the river while producing otherwise highly accurate charts of the Strait of Georgia and much of the British Columbia coast, but in that same year, the Spanish navigators Dionisio Galiano and Cayetano Valdés y Flores located and anchored in the North Arm on Fraser delta. The first European overland explorer, Alexander Mackenzie, travelled the tributaries of the upper river on his way to the Pacific Ocean at Bella Coola in 1793, but another North West Company fur

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Fig. 27.1 Map of Fraser River basin showing principal places mentioned in the text. Dashed arrows denote routes of prehistoric drainage. *Inset* position of Fraser River drainage basin in Canada

trader made the first descent of the forbidding canyons of the middle river: Simon Fraser—for whom the river is named—and John Stuart reached the sea in 1808. Fifty years later, after the establishment of a British colony on Vancouver Island, placer gold was discovered on a river bar near Yale, precipitating a gold rush that began fifty years of mining along the river, and the establishment of the colony of British Columbia. Ultimately, the greatest strikes were made along tributaries of the Cariboo, Cottonwood and Willow rivers, themselves left bank tributaries of Fraser River in the Cariboo Plateau (Sutherland Brown and Ash 2009). In response to the gold fever, paddlewheel river boats began to ply the lower river and the Cariboo wagon road was pushed north and eventually forced through the canyons. In the 1880s, the Canadian Pacific Railway laid track through the lower canyons, an engineering triumph of its day. This feat was largely achieved by indentured Chinese laborers whose descendants have remained a significant part of British Columbia society. Today, the river still directs the patterns of provincial commerce and lies at the center of environmental management issues in the province. It has been a dominating factor in many of the events of British Columbia's history.

27.2 The History of the River

The hydrography of the river is remarkable. North of Latitude 51 °N the tributaries, and eventually the Fraser itself, flow toward the north (Fig. 27.1). Elements of the drainage history were first interpreted in studies of the Cariboo placers (Lay 1940). The ancestral drainage is traced back more than 10 Ma to a mid-Miocene landscape of moderate relief (Mathews 1991) when a northward flowing river occupied a broad valley in the northern two-thirds of the basin. Cobble conglomerates near 51.5 °N, directly overlying mid-Miocene lavas, indicate northeasterly drainage, while palynomorphs indicate a warm climate (Mathews and Rouse 1984). That river drained to the Peace-Mackenzie system via what is today the Crooked River valley north of Prince George, where the divide remains less than 50 m high. The ancestral valley remains present in the mid-Fraser basin as a broad terrace (Figs. 27.2a, 27.3), still with its northerly gradient (made somewhat steeper by subsequent tectonic delevelling), above the incised Pleistocene valley.

The Neogene history of the interior plateau has been punctuated by episodes of volcanism that produced more or less extensive basalt flows. Dating the lavas demarcates the antiquity of intercalated fluvial, lacustrine and, latterly, glacial deposits. End-Pliocene lavas (2.8 Ma: Andrews et al. 2012) dammed the ancestral river at Dog Creek (Mathews and Rouse 1986) at the same time that the Coast Mountains to the west were being rejuvenated. At 1.0 Ma, the lava dam event was repeated. This lava overlies an early glacial till (Fig. 27.3: inset). These events impounded lakes to the south of the dam that might have spilled to the south.

The actual reason for the reversal of the northern drainage remains obscure. It could be directly due to lava blockage, or to glacial derangement of drainage. Or the rejuvenated Coast Mountains may have steepened a south flowing stream to the point that it pirated the system by aggressive headward erosion. Recently, evidence has been discovered of minerals from the northeastern Rocky and Omineca Mountains in the Nitinat sea fan, the submarine repository of the fine fraction of Fraser sediments, lying off the mouth of the Strait of Juan da Fuca (Andrews et al. 2012). The 0.76 Ma age of the fan constrains the drainage reversal to have occurred sometime between 0.76 and 1.0 Ma; the more recent date would associate drainage reversal with marine isotope stage 16 continental glaciation.

South of Dog Creek the river follows the Fraser Fault (which may have been influential in the act of piracy), dividing the Coast Mountains from the Cascade Mountains to the east, until it escapes toward the sea west of Hope, BC, at the gap between the two mountain belts. The reach along the fault zone consists of a series of deep canyons, collectively known as 'Fraser Canyon,' in which the river may have downcut at rates of up to 150–200 m Ma^{-1} (Andrews et al. 2012), thus securing the southward drainage.

A notable legacy of the Pleistocene glaciations, during which ice repeatedly emanated from both the eastern and western mountains to coalesce near Fraser River and form the Cordilleran Ice Sheet, is the major lakes occupying montane valleys on either edge of the plateau (Fig. 27.1). The lakes were created by valley-directed ice streams that carried ice out of the mountains. Today Fraser River is deeply incised below the interior plateaus (Fig. 27.2a). The Quaternary inner valley of the river and the valleys of its major tributaries are filled with a complex sequence of Pleistocene lacustrine sediments, tills and outwash, in places capped by Holocene alluvial fans, debris flow deposits or slopewash, through which the rivers have degraded onto or near rock (Fig. 27.2b). Fraser River now flows in a trench within the Quaternary valley, itself inset into the Miocene valley, and in places between high rock walls (Fig. 27.2c). Upstream from Soda Creek (52°20′N), in contrast, and west of Hope, it flows unconfined in a broad valley with floodplain (Fig. 27.2d): in the north, Fraser River occupies its ancestral valley.

Fig. 27.2 Views of Fraser River: **a** Fraser River near 51°46′N, view northward (*upstream*) north of the confluence with Chilcotin River, prominently showing the broad Miocene valley; Iron Canyon in the *middle* ground (photograph by J. M. Ryder); **b** incised into Pleistocene sediments, north of Lillooet; **c** the White Canyon. Both views near 50° 50′N; **d** Fraser River in the gravel-bed reach of lower Fraser Valley, view looking downstream (west) east of Chilliwack, BC (photograph by A. Zimmermann)

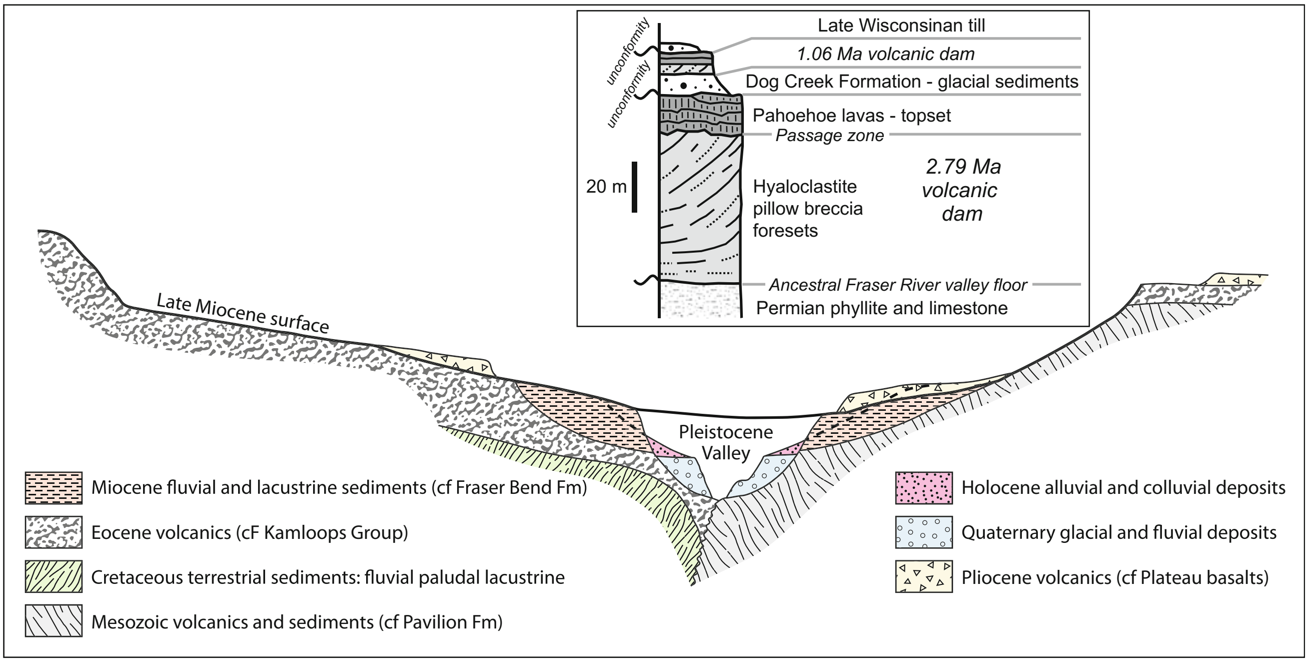

Fig. 27.3 Schematic cross section of Fraser Valley in the interior plateau country (after W.H. Mathews): *Inset* stratigraphic details at Dog Creek (after Andrews et al. 2012, their Fig. 2b)

27.3 The Contemporary River: Hydrology and Sedimentation

The plateaus lie within the rain shadow of the Coast Mountains and are subhumid. Little runoff is generated in summer, but they accumulate a substantial snow load in winter and, in the surrounding mountains, heavy accumulation occurs. Snowmelt on the plateaus (1000–1300 masl) occurs synchronously over a wide area in spring, producing the major hydrological event of the year. Nival melt dominates the flow regime to the extent that the annual hydrograph in most years resembles a single-event hydrograph (Fig. 27.4). High flow occurs throughout late May, June and early July and recedes in August and September. Water yield from the basin is relatively high, around 0.8 m depth per annum from the mountain headwaters (Table 27.1: Fraser at Hansard) and more than 1 m near the coast, declining to less than half that value in the plateaus. The mean annual flow at Mission, the farthest downstream gauge on the river, is 3410 m^3s^{-1} and the mean annual flood is 9790 m^3s^{-1} (McLean et al. 1999). The 1894 flood, in which flows are estimated to have reached 17,000 ± 1000 m m^3s^{-1} at Hope (NHC 2008), is the historic flood of record (the Hope gauge, established in 1912, contributes the longest record of flow on the river: see Fig. 27.5d). Without the large lakes in the basin, the flood regime would be more extreme. Winter flows in the lower river dip to values less than 1000 m^3s^{-1}, for an annual range of about 10×. The significance of the Thompson River, the largest tributary, is evident in that, with one-quarter of the combined drainage area at the confluence, it increases the mean flow by about 45 % and the annual flood by more than 50 %. In 1952, a diversion (for hydroelectric power generation) across the mountains from the Nechako River, a northern tributary, effectively reduced the size of the basin by 5.6 % and mean annual flows by 3 %. Since then, however, mean flows in the river have actually increased by 6 %, probably as a consequence of the secular increase in precipitation that has affected the province over the course of the twentieth century. The flood sequence, however, shows no persistent trend, though throughout the twentieth century the river experienced decades-length periods of greater floods and lesser ones under the influence of the oscillating thermal condition of the North Pacific Ocean and the weather that it creates (Mantua et al. 1997).

Projections for the future envisage significant increases—up to order 100 %—in spring runoff in the mountains as the result of accelerated melt of a heavy snowpack, itself the consequence of increased winter snowfall. On the plateaus, however, spring runoff is expected to decline by up to 25 %, the consequence of increased portions of the early and late winter precipitation falling as rain, leaving a reduced snowpack (M. Schnorbus, personal communication, October 2014; see also Shrestha et al. 2012). The net projected effect is for little change in flood frequency over the bulk of the range, but an order 10 % increase in the greatest floods, bringing 15,000 m^3s^{-1} (Hope flow) to within 100 years'

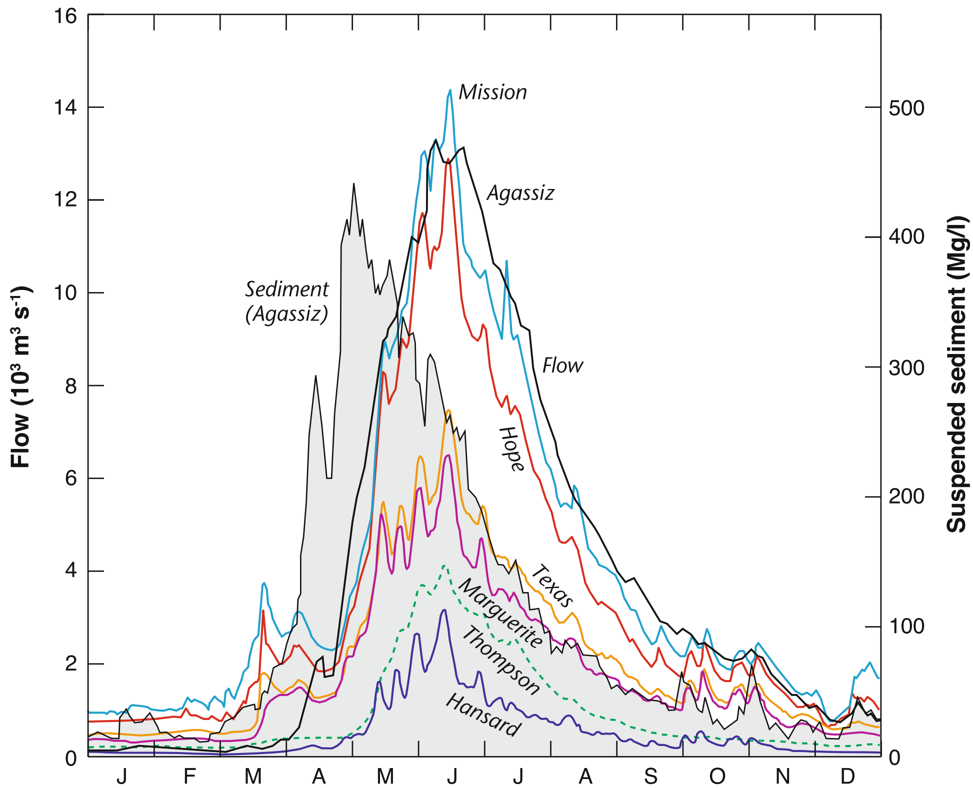

Fig. 27.4 The 1972 annual hydrograph at principal gauges along Fraser River and on Thompson River (station details in Table 27.1) and graph of suspended sediment concentration at Agassiz. Agassiz is located 130 km from the mouth of the river in the 'gravel reach' of the Lower Mainland (Fig. 27.1)

Table 27.1 Flow and suspended sediment in Fraser River

Station	WSC No.	Drainage area (km^2)	Mean annual flood (m^3s^{-1})	Mean flow (m^3s^{-1})	Water yield ($m^3km^{-2}a^{-1}$)[a]	Mean susp. sed. conc. (mg 1^{-1} = g m^{-3})	Mean sediment load (Mg a^{-1})	Sediment yield (Mg $km^{-2}a^{-1}$)
At Hansard	08KA004	18,000	1999	480	841×10^3	197	2990,000`	166
Near Marguerite	08MC018	114,000	4477	1460	404	235	10,800,000	95
Above Texas Crk.	08mF040	154,000	5030	1736	355			
Thompson R at Spences Bridge	08LF051	55,400	2740	772	439			
At Hope	08MF005	217,000	8,665[b]	2730	390	212	18,100,000	83
Mission	08MF024	228,000	9790	3410	471	159	17,200,000	75
Silverhope Crk.	08MF009	350	86[c]	14.4	1300	9.1	4120	11.8

Flow data typically cover the period 1951–present, except Hope. Sediment data may not be comparable between stations because of different periods of record and varying sampling effort. Most sediment data were collected between 1966 and 1986. WSC: Water Survey of Canada
[a]Divide by 10^6 to obtain runoff depth in meters
[b]1951–2012 only: record extends to 1912
[c]9 years only

recurrence. Conversely, winter flows are expected to increase from typically less than 1000 m^3s^{-1} (Hope) to greater than that figure.

The Pleistocene valley fills throughout the Fraser River basin and Tertiary and Cretaceous sediments along the valleysides—particularly lacustrine silts and volcanic clays—are erosion prone in the freeze-thaw environment of the regional winter. The older formations give rise to massive, slow-moving earthflows lubricated by the annual, snowmelt-driven variation in groundwater, many of which descend down the steep slopes from the plateaus to the river (Bovis 1985), while in a few places along the middle river,

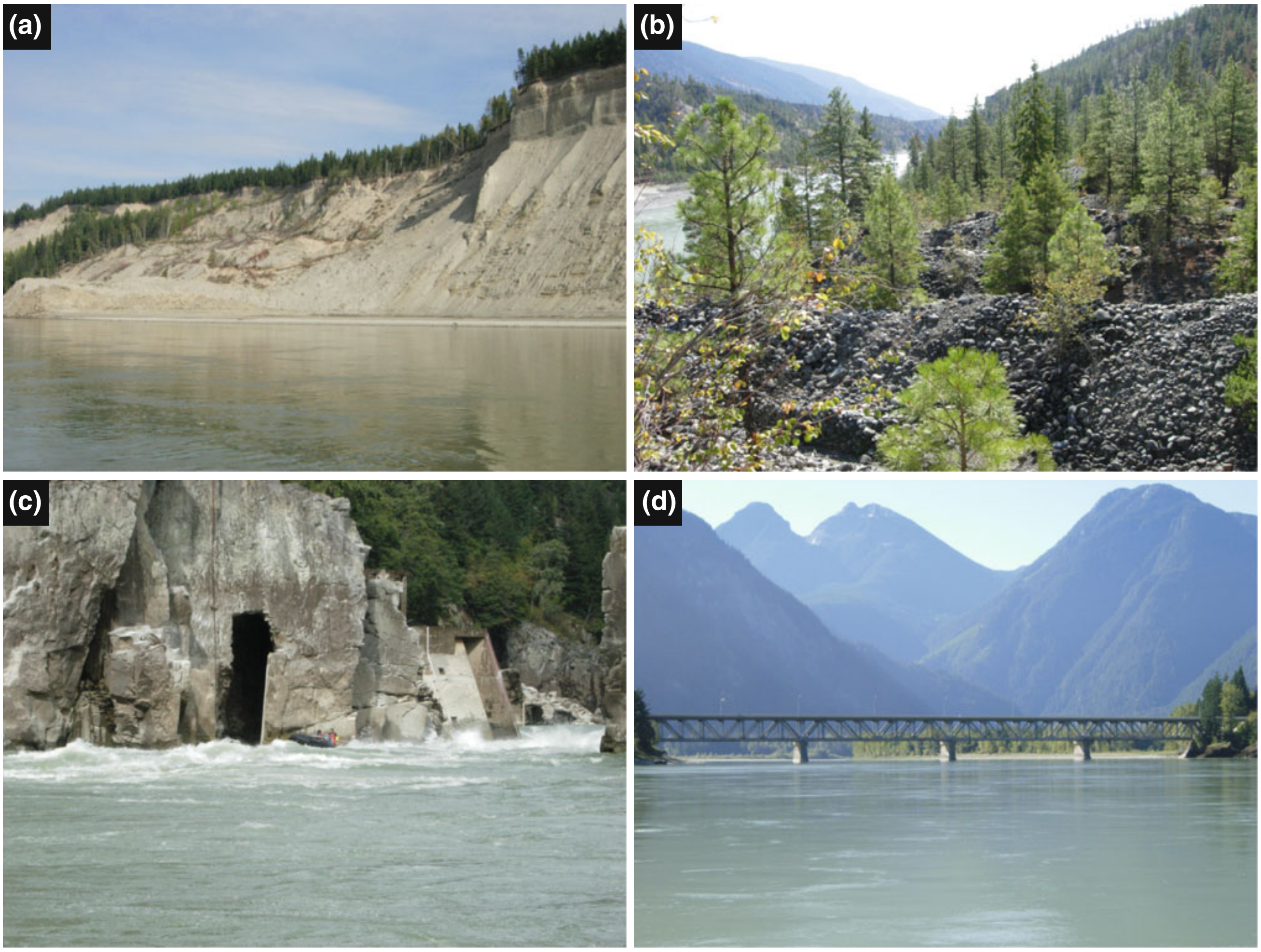

Fig. 27.5 Fraser River landscapes: **a** retrogressive landslide, left bank, about 10 km south of Quesnel, a prolific source of sediment to the river; **b** nineteenth-century placer workings at Browning's Bench, south of Lillooet, a significant transient source of sediment; **c** Hell's Gate, 30 km north of Yale, where the river is only 35 m wide but about 60 m deep at high flow, when water velocities may exceed 10 m/a; **d** view downstream to the gauge section at Hope, where the river enters its lower, fully alluvial course

massive, chronically retrogressing landslides occur in glacilacustrine silts that are common from north of Dog Creek into the Prince George area (Tipper 1971) (Fig. 27.5 a). The dominant forest and range landscape contributes relatively little sediment, so most of the sediment carried by the river originates in the riverbanks from the earthflows and from Pleistocene valley fill. Through autumn and winter, dry ravel delivers material to river level from noncohesive deposits, while frost heave prepares cohesive surfaces for subsequent erosion. With the first rise of the nival melt, this material is mobilized by the river. By the time of peak runoff, much of the available material, including sand deposited along the river edge in the preceding year, has been re-entrained. River banks under direct attack and susceptible to repeated, retrogressive failure, continue to contribute material throughout the flood, but the peak of suspended sediment concentration precedes the runoff peak by a month or more (Fig. 27.4) and the annual pattern of suspended sediment yield is markedly clockwise hysteretic.

The suspended sediment budget of the river from three stations with a history of measurements is given in Table 27.1. The load is modest in comparison with that of many major rivers of the world (see the compilation in Milliman and Meade 1983). Unit area sediment yield decreases steadily down the system, but load per kilometer along the channel actually increases. Areal sediment yield recorded at the mainstem stations is an order of magnitude higher than yields measured in a gauged montane tributary of the river (Table 27.1), consistent with the sources of sediment being along the banks of the river itself.

The river is a steep mountain river—remarkably steep for its size—averaging 0.0009 in gradient through the canyons (Fig. 27.5c) where it is able to move large cobbles and boulders. After the river enters the lower valley

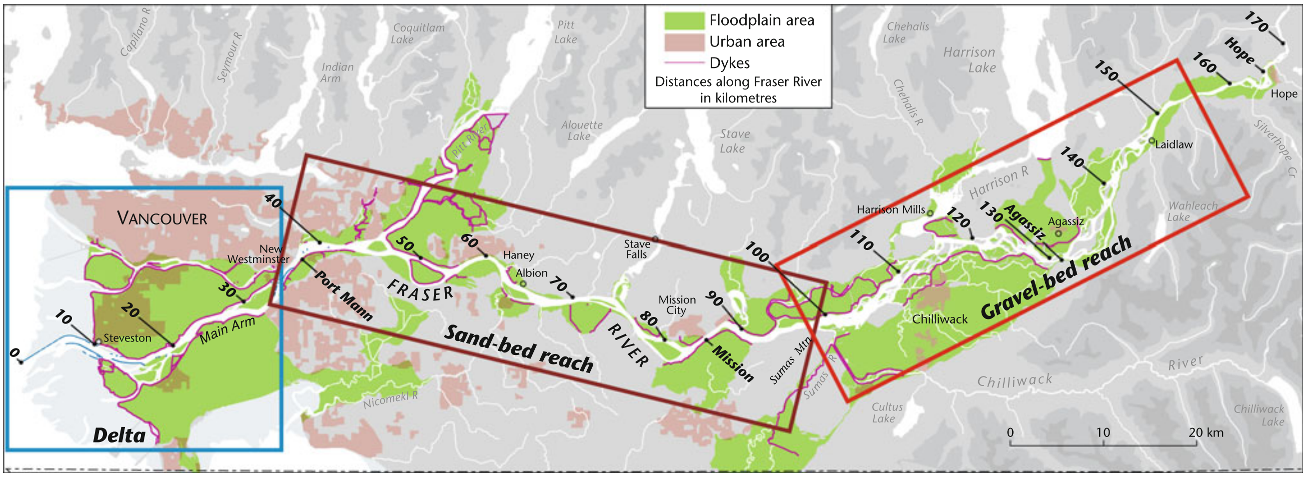

Fig. 27.6 Map of Lower Fraser River, showing the gravel- and sand-bed reaches, and the delta

Table 27.2 Sediment budget of the Lower Fraser River (mean annual load, 10^3 Mg a^{-1})

Station	WSC	Suspended load				Bedload			Total
	Station	Clay	Silt	Sand	Total	Sand	Gravel	Total	Load
Agassiz (gravel bed)	08MF035	2750	8590	5190	16,530	49	227	276	16,806
Mission (sand bed)	08MH024	2690	8280	6080	17,050	154	–	154	17,204
Sand Heads[a]	*Estimated*	*2700*	*8200*	*3000*	*13,900*	*1300*	–	*1300*	*15,200*

[a]Sand Heads is the mouth of the river. Measurements at Agassiz and Mission were conducted between 1966 and 1986

(Figs. 27.5d and 27.6), the gradient declines as it approaches the sea. The cobble–gravel portion of the sediment load is deposited in a 48-km reach between Laidlaw and Sumas Mountain on what amounts to an extended, low-angle, alluvial fan, confined between mountains to the north and south (Rice et al. 2009; Church and Rice 2009; Ham and Church 2012). At Sumas Mountain, 100 km from the sea, the river undergoes an abrupt gravel–sand transition (Venditti and Church 2014). Once unconfined, the river in the gravel-bed reach exhibits a wandering, low-order braid morphology with islands (Fig. 27.2d). After the transition to sand, it flows in a single-thread channel to the head of its delta near Port Mann, 35 km from the sea. The sediment budget for the gravel and sand-bed reaches was established by McLean et al. (1999) on the basis of a sampling program conducted by the Water Survey of Canada over a period of 20 years and is shown in Table 27.2. Clay and silt loads are today essentially unchanged all the way to the sea (to within measurement error), though in former times substantial silt was lost to the floodplain and delta surface. However, there appears to be an increment of sand in the lower river, while the gravel load is lost in the gravel-bed reach. While McLean et al. estimated the gravel budget to be about 227,000 Mg a^{-1}, further investigation has led to a higher consensus figure of about 400,000 Mg a^{-1} as the gravel influx (Ferguson and Church 2009).

The sand budget of the lower river is thought before the mid-twentieth century to have been in approximate equilibrium, with the 6 million Mg passing Mission mostly reaching the delta front, about half as washload (grain size finer than 0.18 mm) and half as bed material load. Extensive dredging in the latter half of the twentieth century to improve deep-draft navigation below Port Mann (Fig. 27.6) has removed an average of 3 million Mg from the river bed each year. This has prompted upstream-progressing bed degradation (McLean et al. 2006), mobilizing about 1 million Mg a^{-1}, so that about 1 million Mg a^{-1} of bed material now arrives to nourish the delta front, a reduction of 67 %. It should be emphasized that these figures are all inferential and hence may be subject to significant error.

The delta itself provides a long-term perspective on the sediment budget of the river. At the close of the last glacial period c. 13,000 cal. years ago, the sea flooded into the Lower Mainland space now occupied by the lower river and its floodplain. The river rapidly filled this shallow marine embayment with sediment and about 10,000 radiocarbon years ago—that is 11,000 actual years—began to deposit the modern delta from New Westminster seaward (Clague et al. 1983). Today the delta occupies about 1000 km^2 and has an average sediment thickness of about 120 m (Mathews and Shepard 1962), so that the volume of deltaic sediments is approximately 1.2×10^{11} m^3. Given 11 ka of sedimentation, the mean annual sediment influx has been about 10 million m^3 or 16 million Mg (with bulk density 1.6 Mg m^{-3}). This is comparable with the (pre-dredging) sediment yield of the river (18.2 million Mg a^{-1}), but most of the clay-sized sediment and part of the silt will have escaped the identified delta body. The implication is that past (particularly, one supposes early post-glacial) sediment yield was greater than that of today, but not dramatically so. One concludes that the size of the system effectively buffers the mainstem from perturbations in sediment yield that may afflict smaller tributaries as the consequence of fire, insect pests in the forest, a major landslide, Neoglacial sediment production in the mountain rims or, latterly, human land use. The persistence of the principal sediment sources along the banks of the river itself also contributes to the apparent long-term consistency of sediment yield (Church and Slaymaker 1989). To be sure, there must have been some major spikes in sediment yield along the river; the Fraser mainstem itself has been blocked by landslides at least twice (Ryder et al. 1990). There is evidence, however, that the river is able to transport considerably more than its historical load of sediment (see below).

27.4 Contemporary Problems of River Management

27.4.1 Floods and the Fishery

The river today remains one of the world's great producers of salmonine fish (Northcote and Larkin 1989) because of its mountain headwaters, which produce fast, clean water from annual snowmelt, because of the major lakes in the system that provide spawning and rearing habitat for some species, because of the gravel substrates that the fish use for spawning, produced by erosion of the valley fills throughout the basin, and because of moderate turbidity that protects the fish from predators. The bounty is, then, a product of Quaternary history and the geomorphology of the river. The fish themselves have evolved into their modern form and families with the growth of the mountains and the river over millions of years (Montgomery 2000) and so are peculiarly adapted to the environment of the river. The Pink salmon (*O. gorbuscha*) run in the gravel reach of the Fraser River may exceed 10 million fish in some years. (Pinks return to spawn in the Fraser River only in odd-numbered years.) The large side channels of the gravel reach are important Chum salmon (*O. keta*) spawning habitats, while Sockeye (*O. nerka*) spawn in the many lakes and their outlet channels. The gravel reach habitats also contribute to large-value fisheries outside this area: the large bars in the gravel reach of the Fraser River may be the most productive of all instream rearing habitats within the watershed for Chinook salmon (*O. tshawytscha*). The river also harbors populations of the iconic Northern White Sturgeon (*Acipenser transmontanus*) with further populations upstream. Altogether there are 42 native species of fish in the river, 31 of which are found in the lower river.

Gravels deposited in the lower river sustain the system of bars and multiple channels (Fig. 27.2d) that create the rich range of aquatic habitats. But it is supposed that the deposited gravels systematically raise the bed of the river, thence the water surface. Sedimentation in the gravel-bed reach in the latter half of the twentieth century suggests that this does in fact occur (Fig. 27.7). To the population of the

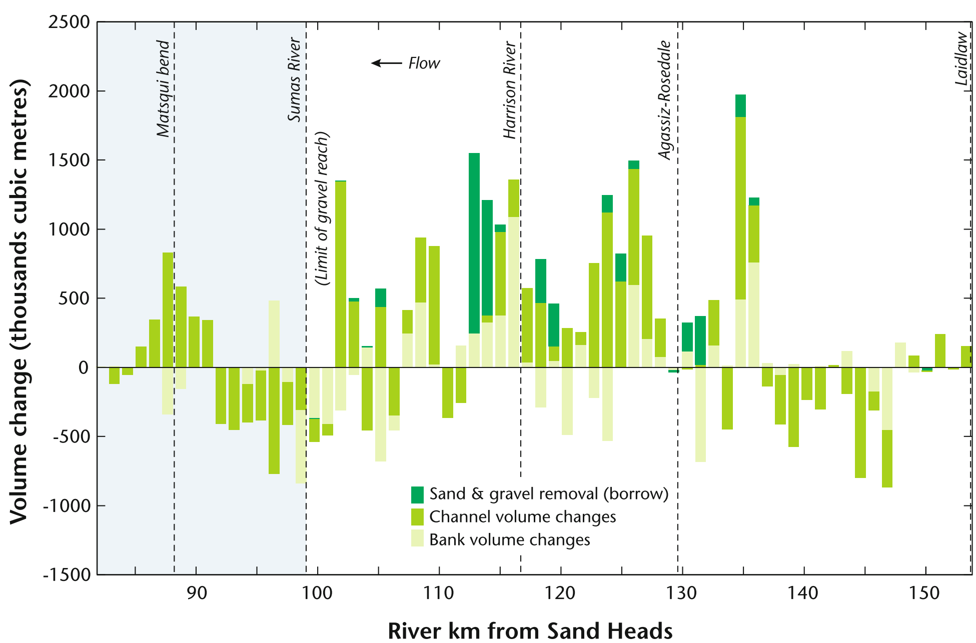

Fig. 27.7 Bed material sediment budget of the gravel-bed reach of lower Fraser River, 1952–1999

rapidly urbanizing lower valley, this gives the appearance of a steadily escalating risk of flooding.

There is a history of disruptive floods in the lower valley (Watt 2006). The great flood of 1894 inundated most of the valley floor and prompted the commencement of a century of dyke building and dyke improvements. Yet in 1948, the dykes failed in several places and flooding occurred again. In 1972 (Fig. 27.4) and in recent years, there have been concerns for dyke security during high spring runoff. How to manage this perceived hazard in the long term—in particular, whether to remove gravel from the river—raising the possibility of severe damage to the fish habitat—is the subject of an important public debate. Both elements of the problem are predicated on hydrological and geomorphological conditions that must be well understood in order to find a resolution. In particular, the problem requires that the pattern of sedimentation in the gravel-bed reach be well understood and it requires the projection of trends in flow and in gravel recruitment in the long term.

27.4.2 Floods and the Community

The river provides other values to society than the fishery. First, it is a central element in the culture of First Nations resident along the river, all of whom sustain a traditional focus on the fishery. For many residents of Fraser Valley, the river is an important site for recreational boating, picnicking and nature study. Most important, perhaps, the river and its remaining riparian zone are the most significant elements of the landscape to provide relief from the increasingly pervasive urbanism of the lower Fraser Valley. With the population of the region projected to grow by more than 40 % in the next 25 years from 2.7 million (2011 census) to a projected 3.9 million (www.bcstats.gov.bc.ca/data/pop/pop/popproj.asp), the river will more and more become the central element in the maintenance of a 'liveable environment.' These reasons, as well as concern for the fishery, argue for the maintenance of the river in its natural state, with as little human interference as possible. The contemporary lower river is, then, caught in a classic problem posed by the opposition of social development and environmental stewardship. Again, it is vital to understand patterns of sedimentation and sound projections for future flows.

On the best currently available analysis, the distribution of spring flood flows in the future—discussed above—is not expected to change significantly, but it is expected that floods with recurrence interval in the order of a century may increase in magnitude, though not beyond the estimated 1894 flow of 17,000 m^3s^{-1}, the reference flow for design of the dykes. But an additional factor enters consideration of flood defenses, that is, the residual risk to communities, infrastructure and lives posed by a flood that exceeds the designed level of protection or breaches a dyke (Jakob and Church 2011). Near the mouth of the river the city of Richmond, with an increasing population currently of 175,000, is built on an island of Fraser delta, as is Vancouver's airport. Considering also the towns in the lower valley, it is clear that the investment, level of economic activity and concern for lives justify a level of protection against floods that extends well beyond the provincially mandated level of 200 years or even the current flood of record. This might lead to further upgrading of river dykes and confinement of the river. An alternative more in keeping with the river environment would be to set dykes back in order to increase conveyance in an adequate channel zone, but that would expose floodplain properties to inundation.

It is commonly imagined that gravel moves carpet like along the bed of the stream and, when deposited, raises the streambed more or less uniformly. That is not true. Gravel moves in short hops, from a point of erosion in the river bank or bed, to a point of deposition in the next encountered bar (Pyrce and Ashmore 2003). Bar growth obstructs the channel and forces it to move laterally, prompting new erosion and onward movement of the sediment load. While the aggradation during the latter half of the twentieth century was, on average, 8.6 cm (but reduced to 2.1 cm net by gravel mining), gravel accumulations actually occur locally where aggressive bar building occurs and may amount to 1 or 2 m of change in mean bed elevation. This has two important consequences. First, the threat posed by high water levels is, in the short term, a local one, not a general one. Extra high water occurs in the backwater upstream of an expanding bar, the zone of backwater influence being in the order of a kilometer. In some places, the construction of dykes and their attendant protection has aggravated problems by constricting the channel zone of the river; about 70 % of the outer channel banks in the gravel reach are now hardened by riprap placement, even where the dykes are set back from the river. Second, bars steer the river—they determine the channel alignment. The flow resistance generated by channel bends is a much more important mediator of water level along the channel than is any individual bar. So it appears that gravel removal, if it should occur at all, should be locally focused to defuse locally generated instances of high water.

27.4.3 Anticipating History

An important question is whether—should gravel be removed from the river—it will be replaced. If not, the

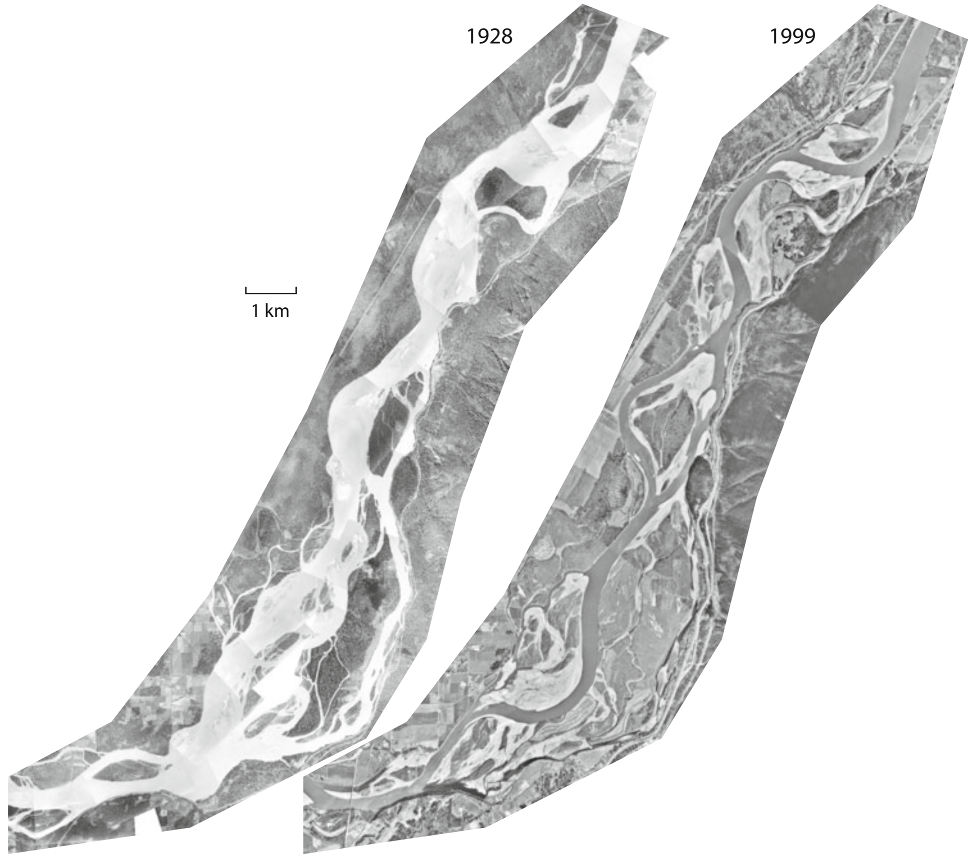

Fig. 27.8 Proximal part of the gravel-bed reach of Lower Fraser River, 1928 (*left*) and 1999. Simplification of the channel is evident between the two dates, corresponding with the degradational trend of sedimentation during the period (see Fig. 27.7: 135–148 km)

channel will be simplified by repeated removals; secondary channels and islands will disappear, and the important diversity of habitat types that supports the rich fishery will be impoverished. Indeed, the morphology of the upper part of the gravel reach has become considerably simplified over the past century, suggesting a reduction in bed material transport through the reach. That reach has slightly degraded during this period (Fig. 27.8). These observations suggest, in turn, that the yield of bed material from the upper basin has declined during the twentieth century. The nineteenth-century activities of Europeans who came into the region provide a plausible reason why this may be so. The first major intersection between European settlement and the river was the gold rush. After the first rush of 1858 to Yale, miners extensively worked both the active river bars and the terraces along the river (Fig. 27.5b) as far upstream as the Cottonwood River, a reach of some 500 km length. From the terraces, an estimated 58 million m^3 of tailings—of which about 65 % (or about 70 million Mg) consisted of cobbles, gravel and coarse sand—were dumped into the river (Nelson and Church 2012) with the peak influx occurring after 1880 when the new railway permitted the import and operation of heavy hydraulic mining equipment. Mining on the active bars loosened the bed and increased the mobilization of instream deposits. Construction of the railway and, in the early twentieth century, a second railway, dumped further, unmeasured amounts of sediment into the river. The result was an estimated order of magnitude increase in the bed material load of the middle river. A numerical model of the transfer downstream of the mining waste (Ferguson et al. 2015) shows that the bulk of the mining debris had been flushed into the terminal gravel wedge below Agassiz by 1910 and that, after 1920, slight degradation of the reach immediately upstream indeed had begun to occur (Figs. 27.7 and 27.8).

The speed with which the mining waste was evacuated from the source reaches to the terminal gravel wedge is startling. Three circumstances combined to effect it: First, the river is steep and powerful throughout the canyon reaches through which the material was transported; second, the waste material was substantially finer than the streambed sediments along the upstream and canyon reaches; hence, the river was competent to transport it all; and third, the influx of a substantial surcharge of relatively fine sediment had the effect of fining the bed surface, which then increased the bedload transport capacity of the river (Ferguson et al. 2015). There is no such large-scale disturbance along the middle or upper river today, and the prospect for land use change is such that none is likely to recur; hence, we may reasonably expect bed material recruitment in future to be similar to or smaller than that of the present day and the rate of gravel accumulation in the lower river to decline.

27.4.4 The Delta

Human activity has generated the converse problem in the delta of Fraser River where the channel naturally shoals as it approaches the sea and sand is deposited to the channel bed: The natural depth over riffles was as little as 6 m, compared with a mean depth of about 12 m in the sand-bed reach. Dredging to accommodate deep-draft marine navigation, discussed above, has prompted upstream-progressing degradation that, it is calculated, will reach upstream past Mission and re-equilibrate the reach only after about a century, supposing that no further changes occur.

At the same time, the removal of sand from the navigation channel has reduced sand delivery to the tide flats and delta front—prospectively by as much as two-thirds (see Sect. 27.3)—so that the capacity of the delta to raise its front surface level in pace with the rate of twenty-first-century sea level rise is substantially reduced. Future wave attack on the sea dykes may be correspondingly more severe than it otherwise might be.

27.5 Final Thoughts

Most of Canada remains largely empty of people, and the natural processes that shape the landscape continue as they always have. The 12,000 years of aboriginal occupation made very limited changes in this condition. Yet everywhere people with advanced engineering capabilities have settled, the landscape at local to regional scales has been subjected to a set of changes more rapid and powerful than those produced by the normal water- and gravity-driven processes of Earth's surface environment. Thus are effected significant changes in erosion, sediment transfer and sedimentation and, ultimately, in the entire landscape. Fraser River is no exception. In only 100 years, Fraser River has been subjected to an epicycle of sedimentation deriving from nineteenth-century gold mining and railway building, the effect of which today fuels concerns for river stability and protection from flooding hazards along the lower river. Engineering measures that might be taken to secure the lower valley from floods pose a risk to the viability of the exceptionally rich aquatic ecosystem of the river. Farther downstream, in the Fraser delta, dredging over half a century to secure deep-draft navigation has set in train a different set of river responses entailing degradation throughout the sand-bed reach. The contemporary evolution of the lower river—that part of the river where human settlement and activity are overwhelmingly focused—is driven by human activity, not by the natural forces of Nature. But still the canyons of the middle river remain remote, inaccessible and wild.

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References

Andrews GDM, Russell JK, Brown SR, Enkin RJ (2012) Pleistocene reversal of the Fraser River, British Columbia. Geology 40:111–114
Bovis MJ (1985) Earthflows in the Interior Plateau, southwest British Columbia. Can Geotech J 22:313–334
Church M, Rice SP (2009) Form and growth of bars in a wandering gravel-bed river. Earth Surf Proc Land 34:1422–1432
Church M, Slaymaker O (1989) Holocene disequilibrium of sediment yield in glaciated British Columbia. Nature 337:452–454
Clague JJ, Luternauer JL, Hebda RJ (1983) Sedimentary environments and postglacial history of the Fraser River delta and lower Fraser Valley, British Columbia. Can J Earth Sci 20:1314–1320
Ferguson RI, Church M (2009) A critical perspective on 1D modeling of river processes: gravel load and aggradation in lower Fraser River. Water Resour Res 45(15):W11424. doi:10.1029/2009WR007740
Ferguson RI, Church M, Rennie CD, Venditti JG (2015) Reconstructing a sediment pulse: modeling the effect of placer mining on Fraser River, Canada. J Geophys Res 120:1436–1454
Ham DG, Church M (2012) Morphodynamics of an extended bar complex, Fraser River, British Columbia. Earth Surf Proc Land 37:1074–1089
Jakob M, Church M (2011) The trouble with floods. Can Water Resour J 36:287–292
Lay D (1940) Fraser River Tertiary drainage history in relation to placer gold deposits. BC Dept Mines, Victoria. Bulletin 3:30
Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. B Meteorol Soc 78:1069–1079
Mathews WH (1991) Physiographic evolution of the Canadian Cordillera. In: Gabrielse H, Yorath CJ (eds) Geology of the Cordilleran Orogen in Canada. Geol Surv Can, Geology of Canada, vol 4, p 403–418
Mathews WH, Rouse GE (1984) The Gang Ranch—Big Bar area, south-central British Columbia: stratigraphy, geochronology and palynology of the Tertiary beds and their relationship to the Fraser Fault. Can J Earth Sci 21:1132–1144
Mathews WH, Rouse GE (1986) An early Pleistocene proglacial succession in south-central British Columbia. Can J Earth Sci 23:1796–1803
Mathews WH, Shepard FP (1962) Sedimentation of the Fraser River delta, British Columbia. Am Assoc Petrol Geol Bull 46:1416–1438
McLean DG, Church M, Tassone B (1999) Sediment transport along lower Fraser River. 1. Measurements and hydraulic computations. Water Resour Res 35:2533–2548
McLean DG, Mannerström M, Lyle T (2006) Impacts of human interventions on the lower Fraser River. Can Water Resour Assoc, BC Div, Ann Conf, Vancouver, Oct 24–25
Milliman JD, Meade RH (1983) World-wide delivery of sediment to the oceans. J Geol 91:1–21
Montgomery DR (2000) Coevolution of the Pacific salmon and Pacific Rim topography. Geology 28:1107–1110

Nelson AD, Church M (2012) Placer mining along Fraser River, British Columbia: the geomorphic impact. Geol Soc Am Bull 124:1212–1228

NHC (Northwest Hydraulics Consultants) (2008) Comprehensive review of Fraser River at Hope, Flood hydrology and flows—scoping study, Report for BC Min Env

Northcote TG, Larkin PA (1989) The Fraser River: a major salmonine production system. In: Dodge DP (ed) Proc Int Large River Symp (LARS). Can Dept Fisheries Oceans, Ottawa. Can Special Pub Fisheries Ocean Sci 106, pp 172–204

Pyrce RS, Ashmore PE (2003) The relation between particle path length distributions and channel morphology in gravel-bed streams: a synthesis. Geomorphology 56:167–187

Rice SP, Church M, Wooldridge CL, Hickin EJ (2009) Morphology and evolution of bars in a wandering gravel-bed river: lower Fraser River, British Columbia, Canada. Sedimentology 55: 709–736

Ryder JM, Bovis MJ, Church M (1990) Rock avalanches at Texas Creek, British Columbia. Can J Earth Sci 27:1316–1329

Shrestha RR, Schnorbus MA, Werner AT, Berland AJ (2012) Modelling spatial and temporal variability of hydrologic impacts of climate change in the Fraser River basin, British Columbia, Canada. Hydrol Process 26:1840–1860

Sutherland Brown A, Ash CH (2009) Great Mining Camps of Canada 3. The History and of the Cariboo Goldfield, Barkerville and Wells. BC. Geosci Can 36:1–31

Tipper HW (1971) Glacial geomorphology and Pleistocene history of central British Columbia. Geol Surv Can Bull 196:89 pp + folded maps

Venditti JG, Church M (2014) Morphology and controls on the position of a gravel-sand transition: Fraser River, British Columbia. J Geophys Res 119:1959–1976

Watt KJ (2006) High water: living with the Fraser floods. Dairy Industry Hist Soc BC, Abbotsford, BC