GOLD IN THE DOCUMENTS:
Estimating Placer Mining Excavation Volumes in the Fraser Basin, British Columbia, Using Historical Sources

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INTRODUCTION

Placer mining over the past two hundred years has perturbed geomorphic processes in many auriferous regions, including through much of the Fraser basin in British Columbia. Mining activity may open territory to human – and particularly colonial – settlement, spur deforestation, release mercury into the environment, divert water from small streams, and discharge waste sediment into water bodies (e.g., Rohe 1986; Dassman 1999). Historical placer mining typically used flowing water to mobilize large volumes of sediment, which was flushed through sluice boxes and usually discharged into streams, often causing downstream destabilization and aggradation (e.g., Gilbert 1917; Knighton 1989; James 2010). In places where placer mining was concentrated in high-impact, low-frequency excavations, direct inventory of individual mines through either field investigation or evaluation of company records may yield an adequate picture of the disturbance associated with mining. In other areas, such as along the Fraser River, the dominant impact is from many small mines (Nelson and Church 2012). In these places, a census inventory of mining activity is costly, but the cumulative impact of the mining may still have important consequences for geomorphic processes and river management policy. For example, placer waste sediment has likely contributed to elevated rates of sediment accumulation in the gravel bed reach of the Fraser River (Nelson and Church 2012; Ferguson et al. 2015). Previous work has painstakingly documented the contribution of mines along the main stem of the Fraser (Kennedy 2009; Nelson and Church 2012; Nelson, Kennedy, and Leinberger 2012); however, relatively little is known about sediment supply from mining activity along the river's tributaries (but see Galois 1970; and Prins 2007). The impact of this material on the channel downstream has not been modelled.

This article shows how it is possible to combine qualitative accounts of historical mining activity with limited quantitative information to estimate regional impacts of mining. Specifically, it uses the case study of placer mining history along the Fraser River and tributaries (Figure 1) to present a method to estimate the volume of sediment excavated by placer mining by combining records of the amount of gold produced by mining, qualitative descriptions of the kind of mining that was done, and practical constraints governing mining economics. It focuses on the period from the beginning of mining activity on the river in 1858 through the first decade of the twentieth century when widespread placer mining activity in the area was dwindling, though certainly not extinct. If such an approach can be validated, it may prove a useful method both for understanding the historical impacts of mining and for understanding the ongoing environmental impacts of active artisan and/or illegal placer resource extraction (e.g., Byizigiro 2016), in which cases similarly limited data may be all that is available.

Research along the Fraser River (Kennedy 2009; Nelson and Kennedy 2012) has revealed historical sources that allow estimation of the geomorphic impact of mining activity using the proxy record of gold production and historical records of mining. The Fraser River is one locality where the impact of relatively small-scale placer mining has been documented: Nelson and Kennedy (2012) mapped about 450 individual mines along the Fraser River. They used historical sources to identify likely locations of mines and defined mine boundaries through field investigation. Nelson and Church (2012) estimated the volume of each mine on the basis of a regression relation established for fully surveyed sites, using mine area as the independent variable. It is therefore possible to compare established estimates of the impact of mining with estimates derived from the proxy record developed in this article. Though the information gained from investigation of such records is bound to be approximate, it may prove adequate to estimate the order of magnitude of mining impacts (cf. James 1999).

The inevitably incomplete character of historical information presents a number of pitfalls, but many – for example, Nir (1983); Petts, Holler, and Roux (1989); James (1997); and Higgit and Lee (2001) – have found it a valuable resource. Hooke and Cain (1982), Trimble and Cooke (1991), and Trimble (2008) describe appropriate methods for using historical sources in geomorphology and outline key concerns with this approach. These concerns include location of potentially valuable historical documents, assessment of the accuracy and reliability of documents, methods for abstracting useful information from these documents, and the need to corroborate such information.

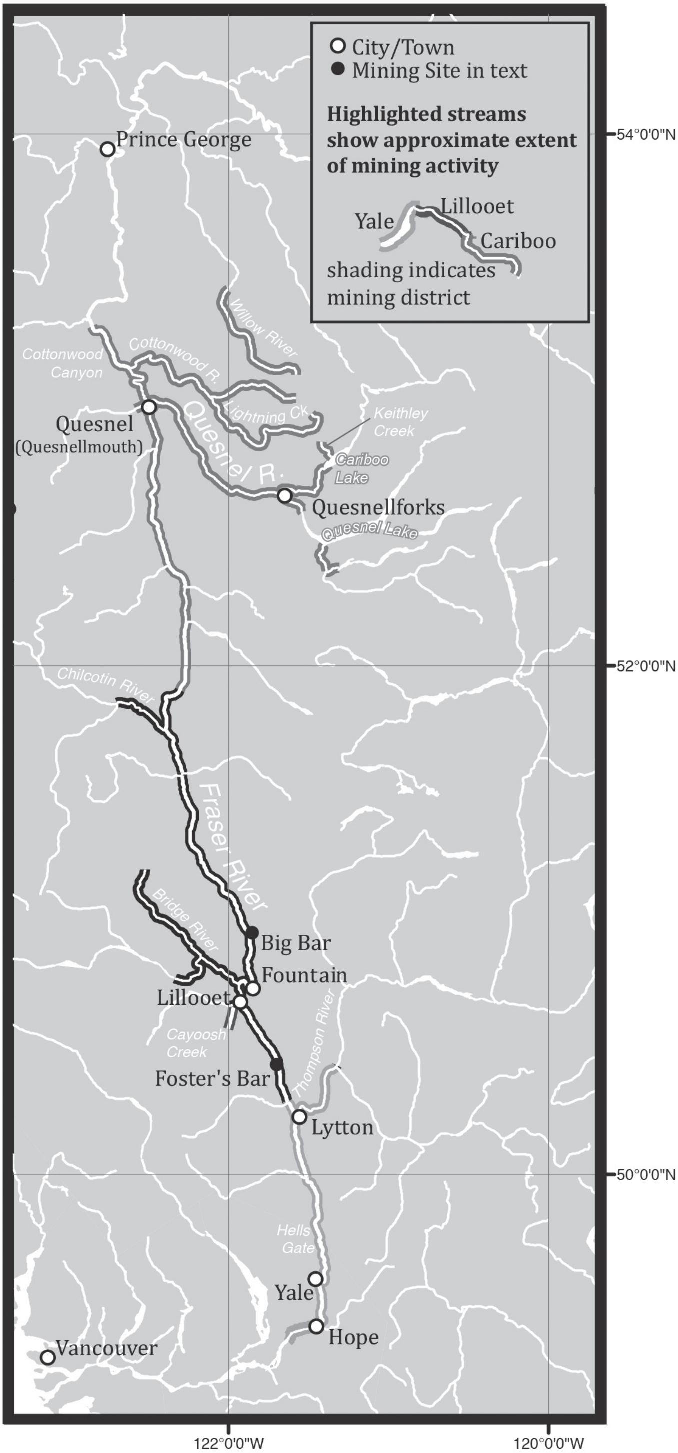

Figure 1. Key placer mining production areas along the Fraser River and tributaries.

Methods Previously Used to Estimate Placer Mining Gravel Excavation Volumes

Previous workers evaluating the geomorphic impact of placer mining have applied four principal methods to estimate the volume of gravel excavated by historical placer mining in other localities, including California and New Zealand, in situations in which mining company production records are not available to allow direct inventory of sediment excavation.

Early studies of the volume of excavated gravel in California used records of water consumption and estimates of the volume of gravel that could be moved by that volume of water (Gilbert 1917). For example, Banyaurd (1891) used water record to estimate that hydraulic mining mobilized 860 million cubic metres of sediment in the Sacramento River Basin. Incomplete water use records, uncertainty in the definition of the unit of measure – a miner's inch[1] – and variable duties complicate this approach.

The second approach used to estimate the impact of California placer mining was direct survey. Gilbert (1917), noting the uncertainty in previous estimates of placer waste sediment, directly surveyed mining excavations and estimated that 1.3 billion cubic metres of sediment were produced – 51 percent more than had been previously estimated based on water records.

The third method was also applied to a late phase of licensed hydraulic mining on tributaries of the Sacramento River between 1893 and 1953. James (1997) used records of sediment accumulation in debris dams downstream of placer mines to estimate excavation. He considered the estimate to be a minimum value because it is based on volumes trapped by debris dams that have a low reservoir trap efficiency.

Finally, Nir (1983) estimated gold yield from an average pay value for South Island, New Zealand. He used the reported production yields of six companies that, combined, produced 1,820 kilograms of gold from 358,750 tonnes of gold-bearing deposits to estimate that, on average, one tonne of deposit yielded 5.1 grams of gold. A total of 825,353 kilograms of gold was produced on the South Island between 1857 and 1960 (Salmon

[1] A miner's inch is typically defined as a flux of water, but in the context of duty (and, in other places, reservoir volume) descriptions, the value must be defined as a volume. Presumably this volume is a miner's inch day. Duties of a miner's inch reportedly range from one and a half to thirty-six cubic yards per miner's inch [day] depending on the material being excavated (Gilbert 1917). Reported values for the flux range from 1.38 to 1.78 ft^3 min-1 (Kent 1895) because a standard method of measurement was lacking. The value 1.5 ft^3 min-1 ultimately became the standard in most places (Ricketts 1943).

1973), so Nir estimates that approximately 160 million tonnes of material were moved by mining.

METHODS: QUANTIFYING MINING ACTIVITY FROM HISTORICAL SOURCES

Knowledge of Fraser River mining comes from historical documents – including both published and manuscript sources – and scholarship. These provide information on the timing, extent, intensity, and styles of placer mining along the river, a foundation for Fraser River environmental history, and a valuable source of insight into the physical remains left by the mining. Nelson and Kennedy (2012) present a summary and discussion of principal records of mining activity. These include records of the establishment, sale, and transfer of mining claims and water rights recorded in the ledgers of gold commissioners and assistant gold commissioners, and narrative and tabular reports presented in the annual reports to the minister of mines. Quantitative records in the annual reports include the amount of gold produced annually in various regions, the number and ethnicity of miners, and the number and kinds of mines operating. A set of conversion factors based on the economics and practical constraints of mining can be applied to transform historic records of mining activity into an estimate of that mining's geomorphic impact, quantified as an excavation volume.

Figure 2 shows the relationships of information often available in historical documentation to excavation volume (G in m^3 in the subsequent set of equations). These relationships may be formalized as follows: let P = the amount of gold produced (troy oz), c = the concentration of gold in the host gravel (oz m^{-3}), d = miner days worked (person day), e = miner efficiency (m^3 $day^{-1}person^{-1}$), w = miner wages (in terms of gross gold extraction) ($ $day^{-1}person^{-1}$), V = the value of gold ($ troy oz^{-1}), n_m = number of miners working (persons), and N = season length (days).

Then,

$G = P/c$ (1)

$G = d\,e$ (2)

$P = (w\,d) / V$ (3)

$c = w / (e\,V)$ (4)

$d = n_m N$ (5)

The excavation volume (G) can be calculated several ways from this set of equations depending on which input variables are known. This can be done using Equation 1 if *P* and *c* are known or using Equation 2 if *d* and *e* are known. Gold production value (*P*) is the most comprehensively known of the variables, but it can also be estimated by applying Equation 3. Gold concentration (*c*) can be calculated using Equation 4, but it is also (especially in the case of hydraulic mines) sometimes directly reported in historical sources. Miner days (*d*) is not a value ever directly reported, but the number of miners working in a given season is often reported, so miner days can be estimated using Equation 5 if the season length (*N*) is known. Miner efficiency (*e*) depends greatly on the mining technique and can be fixed for each technique based on the historical record. The value of gold (*V*), miner wages (*w*), and number of miners (n_m) can also be determined by consulting the historical record. The following paragraphs discuss values for these variables and how they were determined. Because the equations in this system are all linear, the ultimate estimate of the volume of gravel excavated by mining (*G*) responds linearly to changes in the value of any given input parameter (and is linearly affected by error in the input quantities) and is not especially sensitive to the value of any single parameter.

In employing these relations, the assumption is made that a relatively small proportion of recovered gold came from anomalously rich locations. Also, it is assumed that the full value of gold produced was converted into miners' wages. This second assumption is reasonable for the early period of mining because most of the work was done by miners working individually or in small partnerships. During the later period of mining activity larger, more capital-intensive, companies played a bigger role in the total mining activity and the proportion of total yield converted into profits is uncertain.

Gold Production (P)

The record of gold production provides the most temporally comprehensive and spatially well-resolved quantitative summary of gold mining activity in the Fraser basin. Estimates of total province-wide gold production were made from 1858 to 1873 and are shown in a table appended to the annual report to the minister of mines (ARMM) for 1875. It is possible to use qualitative knowledge of the relative intensity of activity in different localities of mining for the period from 1858 to 1860 to distribute the total product by region. For the period after 1860, mining activity across the province was too complex for such a distribution to be

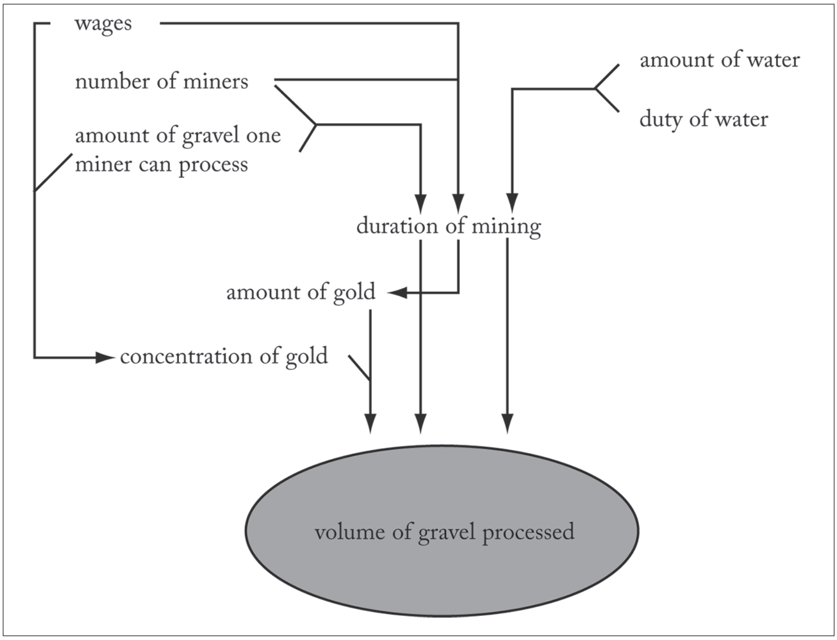

Figure 2. Interrelation of proxies for placer mining gravel excavation volumes and practical and economic constraints.

reasonable. In 1874, explicit regional reporting of annual gold production values begins in the annual reports. This record is fairly continuous. The boundaries and resolution of the reporting districts changed somewhat, and periods of one or two years are occasionally omitted for a particular area (e.g., British Columbia Department of Mines 1899). In some cases, in order to produce as comprehensive and spatially well resolved a record as possible, values are estimated for particular localities and years. Where production values bracketing missing years were available, the value for that period was estimated as the average of the surrounding years unless there was an indication of a major stepwise change in activity in the region, such as a major known discovery or exodus of miners, in which case the value for the most similar adjacent year was used. In some cases production values were not resolved by locality, but the numbers of miners and/or claims operating in the different localities were reported. In these cases, Equation 3 was employed to apportion the regional value to the number of miners or claims. Sometimes this apportionment was further nuanced if the average wages were known specifically for each region. Tables 1a and 1b show the reported gold production values and interpolated estimates.

TABLE 1

Annual gold production (in dollars of gold) for various regions along and tributary to the Fraser River

Table 1a. Reported and estimated gold production (in $) for the province of British Columbia and several regions along and tributary to the Fraser River. Except where otherwise noted, these values are as reported by regional gold commissioners in the ARMM.

Year	Province wide	Yale Division, Fraser River	Lillooet District (exluding Cayoosh Creek)	Quesnel/ Keithley District & Northern Fraser in Cariboo Division	Swift and Cotton-wood rivers
1858	520,353	520,353			
1859	1,615,070	538,744*	876,325‡	200,000	
1860	2,228,543	557,135**	676,325‡	995,082	
1874	1,844,618		55,000	38,084	12,000
1875		10,000‡	40,000‡	40,716	
1876	2,474,904	9,114	25,000	95,905	30,000†
1877	1,786,648	12,000	32,455*	12,833	48,300†
1878	1,275,204	14,000	32,455*	50,910	22,630
1879	1,290,058	14,000	39,910	162,700	
1880	1,013,827	10,800	81,800	95,300	
1881	1,046,737	8,400*	40,717	207,500	
1882	954,085	6,000	64,200	100,860	11,650
1883	794,252	5,000	68,000	92,740	4,860
1884	736,165	15,000	107,934	101,200	4,860
1885	713,738	29,000	94,700	71,000	11,400
1886	903,651	25,000	120,000	72,800	7,000
1887	693,709	20,000	73,750	79,520	5,700
1888	616,731	14,500*	37,660	80,127	6,520
1889	588,923	14,500*	26,239	57,500	8,200
1890	494,435	9,000	41,455	54,150	8,300
1891	429,811	6,400*	52,506	41,300	6,750
1892	399,526	6,400*	39,763	44,500	4,500
1893	379,535	3,800	51,376	37,050	4,500
1894	405,516	3,800‡	30,267	46,700	2,000
1895	481,683	48,400	40,663	86,910	36,000
1896	544,026	65,108	33,665	197,050	
1897	513,520	58,680	37,480	200,000	
1898	643,346	60,840	42,614	214,860	
1899	1,344,900	74,720	42,700	193,300	
1900	1,278,724	57,542	36,905	510,000	
1901	970,100	45,440	26,080	240,000	
1902	1,073,140	47,000	27,440	160,000	
1903	1,060,420	50,400	25,820	132,000	
1904	1,115,300	31,200	34,500	150,000	
1905	969,300	4,600	30,000	96,000	
1906	948,400	5,000	16,800	39,600	
1907	828,000	3,000	12,000	44,000	
1908	647,000	3,000	13,200	30,000	
1909	477,000	2,000	10,000	12,000	

Table 1b. Reported and estimated gold production (in $) for regions in the Cariboo. Sources are the same as for Table 1a.

*	not reported, estimated as average of bracketing years
**	estimated by number of miners and wages assuming a 3-month mining season
†	estimate based on sum then apportioned by number of people working or by number of claims operating
‡	based on qualitative descriptions of amount of activity in various regions

Quesnellmouth general	Fraser below Quesnel	Fraser above Quesnel	all Quesnel/ Keithley Division	Lower Quesnel	Upper Quesnel	North Fork Quesnel	South Fork Quesnel
			200,000‡				
			995,081‡				
		4,630**	33,480**				
			40,716*				
			47,952†		4,930†	19,719†	13,446†
			12,833†				
15,000			35,910†				
62,700			100,000				
	8,391	19,616		32,693	11,000	8,200	10,400
82,300	7,945*	74,354‡	125,200				
	7,500	51,660		8,600	6,000	19,100	8,000
	5,000	49,640		5,400	8,400	16,000	8,300
	6,500	54,600		5,400	8,000	15,000	9,000
	7,000	37,500		5,000	8,000	9,000	4,500
	10,700	32,000		3,500	6,000	8,600	12,000
	16,120	38,500		4,900	5,000	5,000	10,000
	17,000	39,125		5,402	6,000	2,600	10,000
	17,000	17,300		5,200	5,000	3,000	10,000
	17,500	12,600		5,500	3,750	3,000	11,200
	12,000	7,500		5,000	4,000	2,500	10,000
	10,000	2,500		7,000	5,500	8,500	9,500
	7,500	6,800		4,000	6,500	3,750	8,500
	7,000	16,000		6,000	4,000	3,500	9,000
	6,000	3,250		7,360	3,000	3,000	63,500
			197,050				
			200,000				
			214,860				
			193,300				
			510,000				
			240,000				
			160,000				
			132,000				
			150,000				
			96,000				
			39,600				
			44,000				
			30,000				
			12,000				

The gap in the gold production record for the period from 1861 to 1873 occurs because no records were located describing gold production specifically in the Fraser basin during those years. Records are available for the whole of British Columbia, but by this time other areas were producing gold and the record is not subdivided into individual mining regions. Furthermore, historical records of placer mining activity do not clearly indicate the kinds of mining that were occurring along the Fraser River during this period, and so it is not possible to produce estimates of the amount of gravel moved in the study area. Haggen (1924) gives summary gold production values for the whole mining history up to the publication year in different parts of the Cariboo (see Table 2).

Wages (w)

Mining-contemporary reports use the term "wages" to describe miner productivity in terms of gross gold extraction as dollars per person per day. Reports of miners' wages over the period of interest indicate that they commonly produced gold value from three to fifty dollars per miner day, as detailed below. Wages for employees of larger capitalized companies are not used to solve Equation 3, but they can provide some insight into the typical return to individuals mining independently. In California prior to the Fraser rush, miners initially made around sixteen dollars per miner day. As the mining industry there matured in the late 1850s and early 1860s, it was organized into companies employing wage labourers at three dollars per miner day (Jung 1999) with unknown additional profit.

Early reports from British Columbia describing mining prospects along the Fraser (Matthias quoted in Howay 1914, 19) suggest that miners were making from three to twelve dollars per day. Exceptionally high-grade locations would pay on the order of twenty-five to fifty dollars per miner day (e.g., British Columbia Department of Mines 1880, 425; Howay 1914, 73). The wage distribution was probably positively skewed so that the majority of miners earned on the lower side of the spectrum. It appears reasonable to assume an average wage of ten dollars per day. Although there is a wide range of plausible values for this term, it is important to remember that a change in the value used for wages results in a directly proportional change in the estimate of excavated gravel.

Value of Gold (V)

Wages and gold production volumes are typically reported in dollars. These can be converted to ounces of gold on the basis of the value paid to miners for the gold they collected. The value of gold in the study

TABLE 2
Summary gold production and estimates of excavation technologies used for parts of the Cariboo reported in Haggen (1924)

Location	Estimated gold production (dollars)	% hydraulic	% sluice	% rocker box
Fraser River at Quesnel	1,000,000	50	20	30
Fraser River, sundry bars in Cariboo	1,000,000	20	20	60
Sundry claims, N. Fork Quesnel	1,000,000	60	20	20
Spanish Creek	500,000	100	0	0
Golden River Quesnel	222,648	0	0	100
South Fork - sundry claims	1,000,000	60	20	20
Roses Gulch	80,000	100	0	0
Chinese farm	70,000	100	0	0
Chinese pit, Bullion	900,000	100	0	0
Consolidated Cariboo (Bullion)	1,214,128	100	0	0
Quesnel River Campan Creek	1,250,000	100	0	0
Quesnel River, sundry claims	3,000,000	60	20	20
Lightning Creek	8,000,000	50	30	20
Tributaries of Willow River	8,000,000	50	30	20
Regional summary values				
Quesnel River and tributaries	9,236,776	76	11	13
Fraser River in Cariboo	2,000,000	35	20	45

area was variable depending, presumably, on its purity. Reported values range from $10 to $18 an ounce, with values of $15 to $16.50 representing the vast majority of the gold recovered in the areas of interest (see, for example, the tables "Province of British Columbia Mining Statistics" that are appended to the ARMM during the 1880s). This article retains the usage of mining-contemporary dollar values to report the amount of gold recovered.

Miner Efficiency (e)

Miner efficiency is here defined as the volume of gravel that one miner can process in a typical ten-hour working day. The different techniques used to move sediment and recover gold resulted in a wide range of miner efficiencies. Here we consider five mining techniques employed along the Fraser River: gold pan, rocker box, sluice, ground sluice, and hydraulic (for descriptions of the techniques, see Lindström et al. 2000; and Kennedy 2009). There were a handful of ill-fated and short-lived attempts at dredging on both the Fraser River (Kennedy 2009) and the Quesnel River (Nelson et al. 2012), but these did not contribute a substantial proportion of the total placer gold production.

The least efficient extraction method, the gold pan, was primarily used for exploration and not production. A miner working a gold pan can process approximately 0.5 yards of material in a day (British Columbia Department of Mines 1946). The rocker box is the least efficient technique that was consistently used for production. A miner operating a rocker box could process three yards of material a day. Mines worked by rocker box often have a characteristic pit-and-mound topography suggesting that material was not displaced a large distance.

Sluices, in contrast, may displace large volumes of gravel. In a sluice, a slurry of water and sediment is fed into a long inclined box, the bottom of which is fitted with riffles that sort the sediment by density and retain gold. Tailings are discharged from the tail of the box either onto a slope with a large void space or into a stream that would wash them away. The size and capacity of a sluice depends on the scale of the operation, character of gold, and amount of water available (British Columbia Department of Mines 1946). Kennedy (2009) reports that two people can process twenty to thirty yards of gravel a day with a normal sluice of the mining era, so the efficiency of one miner can be estimated as 12.5 yards per day.

It is probably not realistic to assign a "miner efficiency" to ground sluicing and hydraulic operations because these, much more than sluices, are dependent on the operating conditions of the mine, including the amount and head of available water, the grain size distribution of mined sediment, the slope of the ground surrounding the placer deposit, and the degree of consolidation of mined sediment. Fortunately, direct values of typical gold concentrations in worked hydraulic mines are reported by Haggen (1924), so it is not necessary to evaluate miner efficiency for these locations.

Gold Concentration (c)

Table 3 summarizes the values presented in the preceding paragraphs and shows resulting estimates of typical gold concentrations derived by applying Equation 4 for sluice and rocker box operations. Under the conditions shown in Table 3, rocker boxes pay a range of values from \$1 to \$16 yd^{-3}, but typically \$3.3 yd^{-3}. The lowest pay from a sluice (maximum gravel processed and minimum wages) is 20¢ yd^{-3}, while the highest pay for a sluice (minimum gravel processed and maximum wages) is \$5 yd^{-3}. Under normal conditions, a sluice operation would pay 80¢ yd^{-3}.

TABLE 3
Practical constraints on mining and typical gold concentrations for mines utilizing various gold extraction techniques

	Rocker box	Sluice	Hydraulic
wages (w)	\$3 (minimum)-\$10 (good)-\$50 (exceptional)		
miner efficiency (e)	0.4 m^3	7.6-11.5 m^3	highly dependent on conditions
value of gold (V)	\$10-\$18 per ounce (\$15 typical)		
gold concentration (c in oz/m^3)	0.5-1.8-8.8	0.02-0.07-0.35	0.002-0.005-0.05

Typical gold concentrations for hydraulic operations are reported directly by Haggen (1924). He reports that the cost of hydraulic mining in the Cariboo in the early twentieth century ranged from 2¢ to 65¢ yd^{-3} and that most gravels mined by hydraulic methods in the Cariboo paid approximately 10¢ yd^{-3}. Ground sluicing is not included in the table because no specific mention of the gold concentrations found at ground sluice sites has been located. Presumably, ground sluice sites would have paid values somewhere between hydraulic and sluice sites. These values, of course, can be converted to dollars per cubic metre or ounces per cubic metre by applying conversions of 1.31 yd^{-3} per cubic metre and the typical value (V) of \$15 oz^{-1} for BC gold in the nineteenth century.

Careful historical reading to understand the methods of production is critical for reasonable application of this method because the estimated concentration of gold is highly sensitive to the technology used to extract it. Variable unit costs control the economic viability of mining; that is, as the value of deposits diminishes, so the unit cost of moving gravel must also diminish. There is a three-and-a-half order of magnitude difference between the minimum paying gold concentration for hydraulic mining

(3¢ yd^{-3}) and the maximum concentration for high-paying rocker box work ($100 yd^{-3}).

Miner Days (d)

Miner days may be calculated using Equation 5 if the number of miners working and the length of the mining season are known. The number of miners working in a given area is occasionally directly reported in the annual reports and other historical sources. The number of miner days worked per individual miner depends on the length of the mining season, which, in turn, depends on local conditions, including the length of the frost-free season, the stage of the river, and the period of snowmelt and high tributary stream discharge when water was available to work mines. It is probably reasonable to assume a mining season of approximately three months between spring freshet and exhaustion of the useable (tributary) water resource along most of the length of the Fraser River. Some miners moved seasonally between sluicing on river terraces during the high-flow melt season and rocker box work on river bars once the water level fell, which would extend the mining season for those individuals by a couple of months.

Mining Methods

Although not an explicit variable in Equations 1-5, mining methods control miner efficiency, which is a variable necessary to predict the volume of gravel excavated by mining. Because miner efficiency spans three orders of magnitude, the ultimate prediction of the volume of excavated material is most sensitive to the determination of mining methods. Table 4 shows estimates of the percentage of gold extracted by each of the principal techniques in regions along the Fraser and Quesnel rivers (Figure 1) for the period 1858 through the first decade of the twentieth century. These estimates are best judgments based on a qualitative reading of various manuscript and published historical sources, including ledgers kept by the government agents and gold commissioners recording establishment and transfer of mining claims and water rights (British Columbia Archives, government records from agents at Yale, Lytton, Lillooet, and Cariboo),[2] historical narratives (Bancroft et al. 1887; Dawson 1889; Howay 1914, 1926; Haggen 1924; Ormsby 1971), and the annual reports to the minister of mines (British Columbia Department of

[2] BCA, GR 252 boxes 12-14, Govt. Agent Yale; BCA, GR 1054 box 1, fol. 1, Lytton Gold Commissioner; BCA, GR 224 box 21 and 22, Govt. Agent Lillooet; and BCA, GR 216 vols. 30-33 and 76, Govt. Agent Cariboo.

Mines 1874 to 1910). Nelson (2011) presents a detailed historical narrative tracing activity in the post-gold rush mining period from 1860 into the first decade of the twentieth century – which provides the basis for the quantitative interpretation shown in Table 4 – based on these sources.

TABLE 4

Estimates of the percent of gold produced by each principal mining technique by decade and mining district

	Fraser River in Yale District			Fraser River in Lillooet District			Fraser River near Quesnel			Quesnel River and tributaries			Quesnel District (fraser, quesnel and tributaries)		
	RB	Sl	H	RB	Sl	H	RB	Sl	H	RB	Sl	H	RB	Sl	H
1858-59	50	50	0	60	40	0	70	30	0		—		70	30	0
1860s	40	55	5	40	55	5	50	50	0	40	40	20	45	40	15
1870s	40	55	5	40	55	5	50	50	0	40	40	20	45	40	15
1880s	15	25	60	25	35	40	20	20	60	30	30	40	25	30	45
1890s	5	5	90	15	25	60	10	10	80	5	5	90	10	5	85
1900s	50	50	0	35	55	10	10	10	80	5	5	90	10	5	85

During the initial gold rush at Yale, most mining was done by sluice and rocker box. Large-scale gold extraction was limited in the Yale area from the early 1860s until the late 1880s and early 1890s, when hydraulic operations dominated production (British Columbia Department of Mines 1885, 1891, 1893). By the late 1890s hydraulic mining was "at a standstill" and never recovered (British Columbia Department of Mines 1898, 1108). The earliest mining in Lillooet District was dominated by rocker box work, but significant sluices were established by 1859. Significant production from both rocker boxes and sluices continued in the Lillooet District through the mining era, but hydraulic operations dominated production in the 1880s and 1890s (British Columbia Department of Mines 1889, 1890, 1893). Mining along the Fraser River near Quesnel exclusively targeted the bed and floodplain of the river until 1880, when important discoveries of gold were made in higher terraces (British Columbia Department of Mines 1880, 429). Initially, these bench claims were worked with rocker boxes (British Columbia Department of Mines 1881, 394), but eventually they were worked more intensively by hydraulic methods (e.g., British Columbia Department of Mines 1891, 563) and some dredging activity. Hydraulic mining in the area continued into the beginning of the first decade of the twentieth century. Although some smaller-scale mining along the Quesnel River and its sediment tributaries was undertaken from 1859 through the 1870s, most of the important mining in this area occurred by hydraulic methods from the 1880s into the early twentieth century.

RESULTS AND DISCUSSION

Estimating Gravel Excavation along the Fraser River

Combining estimates of gold production values (Table 1 and Table 2) and the average pay values for each mining technique (Table 3) in Equation 1, and proportion of gold extracted by different mining techniques (Table 2 and Table 4), allows estimation of the total volume of gravel excavated in each area (Figure 1) through time, as shown in Figure 3. Based on these values, over the period from 1859 to 1909 but excluding the years from 1860 to 1874, mining excavated an estimated 6.8 million cubic metres of gravel along the Fraser and Thompson rivers in the Yale District, 10.8 million cubic metres of gravel in the Lillooet District, and 36.7 million cubic metres of gravel in the Cariboo along the Fraser and Quesnel Rivers, of which at least 3.5 million cubic metres came from directly along the Fraser during a period of more detailed reporting from 1881 to 1890. Haggen (1924) provides a detailed summary of historic mining activity in the Cariboo mining district, including information that can be used to estimate gold production in that area. He reported summary gold production values for the Fraser River that are more specific than are the summary figures available in the tables of the annual reports and that also include specific production from individual mines, which allowed mining methods to be determined. He estimated total gold production along the Fraser River of $1 million at Quesnel and an additional $1 million from bars further afield along the river. I estimate that 35 percent of gold production in this part of the Fraser River was from hydraulic, 20 percent from sluice, and 45 percent from rocker box mining methods. This leads to an estimate of 9.5 million cubic metres of gravel excavated from along the Fraser River in the Cariboo.

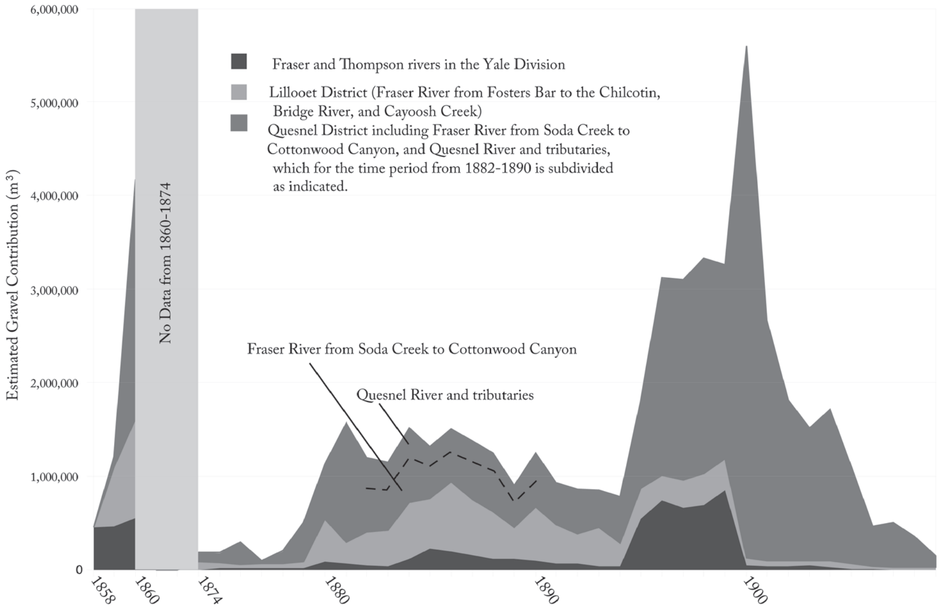

Figure 3. Estimated total amount of gravel processed through time by placer mining along the Fraser River and tributaries.

Evaluating the Method by Comparing Historically Based Estimates with Physically Observed Excavation

Nelson and Church (2012) estimated that 58 million cubic metres of sediment were excavated along the Fraser River between Hope and Cottonwood Canyon, with an absolute lower bound estimate of 47 million cubic metres and upper bound estimate of 62 million cubic metres, which is uncertain because unmapped mines probably exist. These estimates can be apportioned by the geographic unit of mining districts to facilitate comparison with estimates based on the historical record. Along the Fraser River, the best estimate mapped mine excavation volumes sum to an estimated 14 million cubic metres of sediment in the Cariboo District, with 8.2 million cubic metres in the Quesnellemouth Division and 5.6 million cubic metres in the Quesnelleforks Division; 21 million cubic metres in the Lillooet District, with 6.6 million cubic metres from above Big Bar and 9.1 million cubic metres between the Bridge River confluence at Lillooet and Big Bar, and 5.7 million cubic metres between the Bridge River confluence and the boundary of the Lillooet and Yale districts at Fosters Bar; and 23 million cubic metres in the Yale District, with 16.5 million cubic metres from above Hells Gate and 6.3 million cubic metres below Hells Gate.

Table 5 shows estimates of gravel volumes affected by mining from both the observed physical record and estimates from the gold production value proxy. The two methods yield estimates that are comparable to within a factor of three: in all cases the observed volume of sediment affected by mining is greater than the estimate based on the gold production proxy. This comparison indicates that estimates of the total sediment affected by mining made by the gold production proxy method are reasonable but consistently negatively biased. This is not unexpected because the time series sums are based on limited periods of time and necessarily do not include all activity that occurred on the river.

TABLE 5

Comparison of gravel excavation volumes (m³) estimated from historical sources with physical observation of excavations and estimation of gravel extraction volumes for areas tributary to the Fraser River where physical observations have not been made

	Estimated total sediment contribution based on Gold Production values from:		Physically observed along the Fraser
	Annual reports (1858-1860 and 1874-1909)	Haggen's (1924) estimate	
Yale Division	6,800,000	NA	22,900,000
Lillooet District	10,800,000	NA	21,400,000
Fraser in Cariboo	3,500,000*	9,500,000	13,800,000
Quesnel River and tributaries	33,200,000**	89,400,000	NA
Lightning Creek‡	NA	54,000,000	NA
Cottonwood River	700,000***	NA	NA
Willow River	NA	54,000,000	NA

* For the very restricted time period 1882-1890 when records at this resolution are available

** Estimated by subtracting the value known to have come from the Fraser from the value estimated for the whole of the Quesnelleforks/Keithley divisions and Quesnellmouth Division

*** for the years 1872-1878 and 1882-1895

‡ a tributary of Cottonwood River

Lillooet Division includes Bridge River and Cayoosh Creek

Yale Division includes Thompson River

The degree of congruence between historically based estimates of gravel excavation and observed excavations varies somewhat along the Fraser mining corridor. Nelson and Kennedy (2012), in comparing legal records of mining to physical evidence, observe inconsistency in the ratio of historical evidence to physical evidence. They find that this ratio is low in the grasslands north of Fountain and high between Yale and Lytton. They argue that the temporally discontinuous nature of the historical record, geographic and cultural barriers to colonial officials' collection of placer mining data, and the way physical evidence of mining is easier to locate in sparsely vegetated terrain than in heavily forested terrain may all contribute to the explanation of these discrepancies.

The geographic discrepancies in the data presented in this article show the worst match between the physical evidence and gravel extraction volumes estimated on the basis of the annual reports along the Fraser in the Cariboo District and in the Yale District. A discrepancy is expected in the Cariboo District, where the annual reports tabulate the gold production from along the Fraser River for only fifteen years of a forty-year period of significant mining. This locality was the one place where it was possible to compare physical evidence of placer mining with the proxy record based on Haggen's (1924) gold production values, which would have accounted for nearly the whole duration of placer mining activity (also shown in Table 5); in this case, the proxy-based estimation was within 30 percent of the physically observed value. The remaining locality with a major discrepancy is the Yale District, where the present historical data show much lower estimates of gravel extraction than has been mapped (Nelson and Kennedy 2012). One reason for the contrast between Nelson and Kennedy's (2012) data and the present data may be the very high proportion of very small-scale (often rocker box-based) mining activity in this region, which would leave abundant claim records but limited landscape evidence. The problem still remains of accounting for the very large excavations observed in the physical landscape. It is likely that significant mining occurred in this area in the period from 1860 to 1874 when no data were collected, which would explain some of the presently observed discrepancy in gravel excavation volume estimates.

In addition to geographic variability in the degree of congruence between the physically observed placer-mining excavation volumes and historical estimates of those volumes, there is a major discrepancy in the estimation of the proportion of gravel produced from hydraulic mines. The volume of sediment attributed to hydraulic mining based on estimation from gold production values along the Fraser in both the Lillooet

District and Yale Division accounts for a much greater proportion (78 and 74 percent, respectively) of the total sediment than that observed in the preserved physical record (25 and 17 percent, respectively). Along the whole Fraser mining corridor, 59 percent of sediment generated by placer mining came from sites that were classified as having a "sluice" morphology. Either increasing the gold concentration for hydraulic mines, decreasing the gold concentration for sluice mines, or shifting the estimates of which mining techniques were used could result in a match between the proportion of gravel estimated to have been excavated by each method based on the historical record and the proportion of gravel observed to have come from mines with each distinctive morphology. Only decreasing the estimate of gold concentration in sluice mines would seem appropriate because the other two approaches to calibration would result in a decrease in the total gravel excavation estimated from the historical record and an increase in the overall incongruence between estimated and observed excavation volumes. It is possible that some sites with apparent sluice morphology were worked by ground sluice or hydraulic mechanisms and were able to be profitably worked at gold concentration values much lower than was estimated for such sites in Table 3.

Applying the Method to Estimate Placer Excavation throughout the Fraser Basin

Given the general congruence of the estimated and observed gravel excavation where comparisons could be made, it seems reasonable to apply the method to estimate placer gold excavations throughout the Fraser basin. Too few data are available to both calibrate and validate the model used to estimate gold extraction volumes from the historical record. It is therefore applied directly to the available data from elsewhere in the Fraser basin with the understanding that it produces order-of-magnitude estimates useful for gaining a general picture of the geomorphic impact of placer mining. Historical reading similar to that presented above along the Fraser River and interpretation of information presented by Haggen (1924) are used to create estimates. Table 5 and Figure 4 show these data and estimates.

Two estimates of gravel excavation are shown for the Quesnel River, one based on records of gold production tabulated in the annual reports (shown in Table 1) and the other from gold production values presented by Haggen (1924). The tabulation from the annual reports indicates that approximately 33 million cubic metres of sediment were excavated

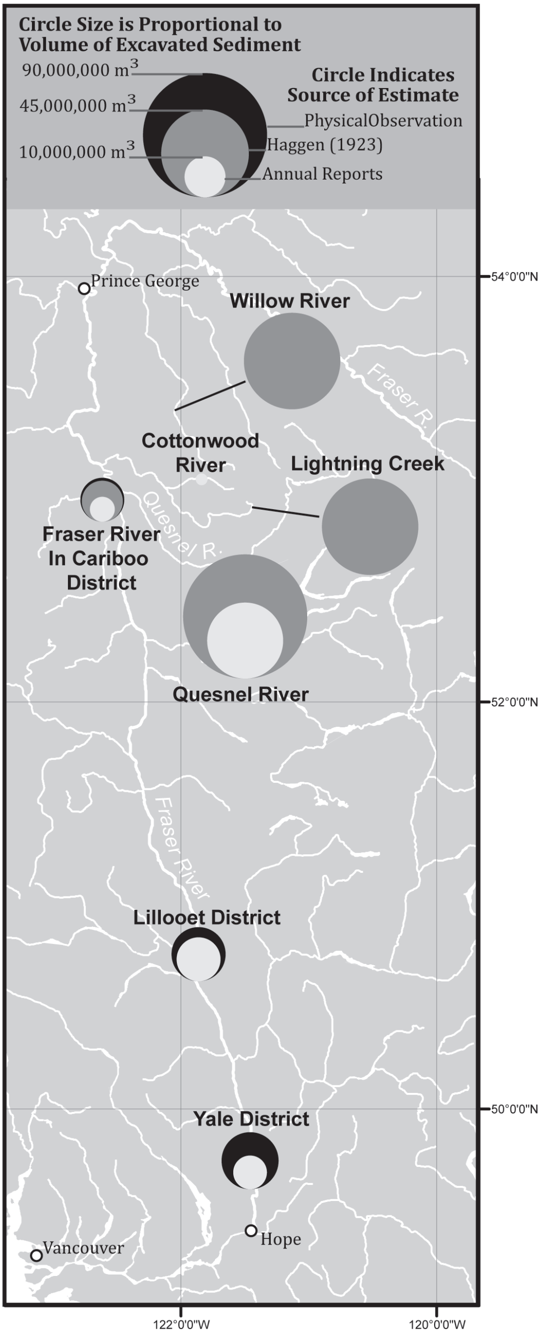

Figure 4. Proportional symbol map of measured and estimated gravel production volumes.

along the Quesnel River before 1910, while estimates based on Haggen's production values indicate that 89.5 million cubic metres of sediment were excavated in the Quesnel basin below Quesnel and Cariboo lakes.

The annual reports-based figures for the Quesnel River are lower than those calculated based on Haggen (1924), partly because some mining did continue past 1909 but principally because a much larger proportion of the gold product in Haggen's tabulation was explicitly known to have come from hydraulic mining. It is unclear whether the gold production values from the annual reports or from Haggen (1924) better represent the actual production. The annual reports better meet the tests of propinquity and contemporaneity, but Haggen (1924) presents more complete data with higher specificity. Because of the large impact on the calculations of mining technique, the specificity possible with Haggen's tabulation probably outweighs the twenty-plus-year gap between the bulk of mining activity and publication.

Less than 1 million cubic metres may have come directly from the Cottonwood and Swift rivers, but very large amounts of sediment may have been affected by mining on smaller streams higher in the Cariboo that are sediment tributaries to the Fraser. Along Lightning Creek, a tributary of the Cottonwood River and one of the most important foci of the Cariboo gold rush, 54 million cubic metres are estimated to have been mobilized; while an additional 54 million cubic metres are estimated to have been affected along the Willow River and tributaries that eventually discharge into the Fraser above Prince George. The estimates for the Cottonwood and Willow river basins are based on a very preliminary estimation of the mining techniques employed in those places and are therefore provisional.

CONCLUSION

This article presents a method for using the commonly available record of gold production to estimate the volume of sediment excavated by placer mining. It shows that the method produces reasonable order-of-magnitude (but negatively biased estimates in one locality) by comparing the volume of estimated excavation with excavation volumes established by an independent method based on observation of the physical landscape. The negative bias can partially be explained by incompleteness in the historical record of gold extraction. The bias may also indicate that either the volume of gold extracted by hydraulic mining was underestimated, which is unlikely given what is known from the physical landscape, or that the estimated gold concentration for sluice mining used in this article is low. The second explanation is consistent with landscape evidence showing that approximately 59 percent of sediment excavated by placer mining along the Fraser River was excavated by mines at which sluices were operating (Nelson and Church 2012).

This article also presents an example application of a method for estimating the amount of gravel excavated in parts of the Fraser basin where no field investigation has been undertaken. This is an area where the geomorphic impact of placer mining is of ongoing concern because sediment mobilized by mining may be influencing ongoing geomorphic processes in the Fraser River, as shown by Nelson and Church (2012) and Ferguson et al. (2015), who have related placer mining along the main stem Fraser River to modern processes in the gravel bed reach between Hope and Mission. The gold production proxy record indicates that the geomorphic disturbance from mining along Fraser River tributary streams dwarfed the impact of mining along the main stem by a factor of more than three. The impact of this waste on these tributary streams must be pronounced and may have reached downstream to their confluence with the Fraser, providing another significant anthropogenic sediment source to that river. Considering the established importance of the activity along the main stem, additional field or modelling-based geomorphic study of the impact of this sediment on the tributary streams and degree of connection to the Fraser River may be important for underpinning estimates of expected long-term gravel delivery to the aggrading gravel bed reach between Hope and Mission.

The values for miners' wages, efficiency, and gold concentrations presented in this article are specific to the Fraser basin. Because they are based on unique, region-specific economic and practical constraints on mining activity, they should not be applied to other areas without reason to suspect similar conditions. Fortunately, the data used to estimate typical gold concentrations are widespread in historical records. It may therefore be feasible to use relatively comprehensive records of gold production to estimate the geomorphic impact of placer mining in many regions.

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