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Field measures of gravel quality in the South Platte River north of Denver, Colorado: a pilot study

by

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

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FIELD MEASURES OF GRAVEL QUALITY IN THE SOUTH PLATTE RIVER NORTH OF DENVER, COLORADO: A PILOT STUDY

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Summary

This pilot study of gravel in the bed of the South Platte River north of Denver was undertaken to identify field measures of aggregate quality and sampling methods that would be useful in modeling and assessing alluvial gravel deposits in the Front Range Urban Corridor. Gravel bars in the streambed were selected for initial study because they represent a uniform depositional environment that is readily accessible for sampling. Although gravel is not mined from the bed of the South Platte, the terraces that serve as the source of gravel for the streambed are mined extensively. Two sites, one upstream near Welby (78th Avenue) and one 18 miles downstream near Ft. Lupton, were selected to study the downstream range of gravel aggregate quality in the segment of the South Platte valley that is currently being mined north of Denver. A four-level sampling design was used to allow measurement of variation over various distances within the river gravel. Particle size was determined by sieving, the lithology of pebbles was identified, and shape and rounding of pebbles was measured.

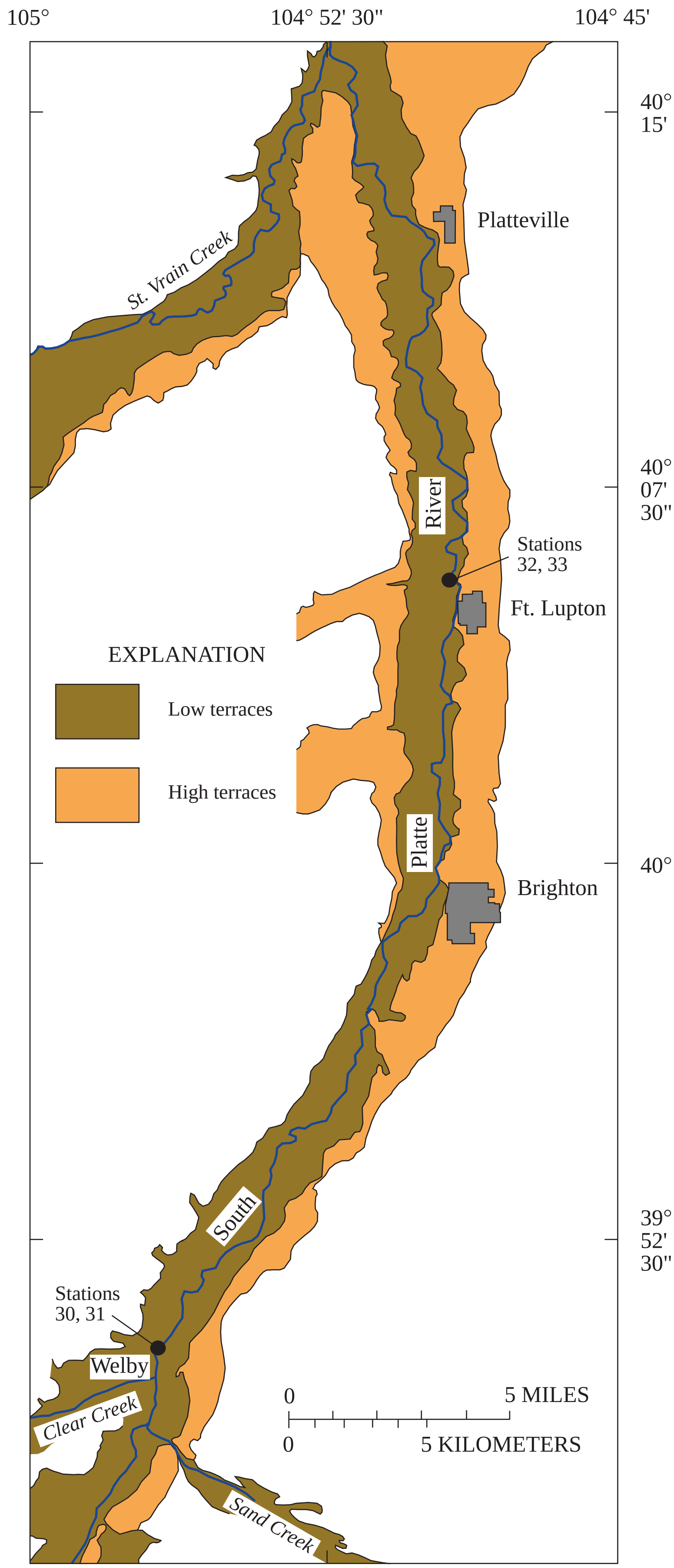
Analysis of variance revealed measures of particle size, shape, and roundness that have downstream (between-site) variation in the South Platte and could be used to map gravel quality. Among measures of particle size, the cumulative weight percent of particles >4 mm shows a higher proportion of downstream variation than any other parameter. Percent pegmatite is the only measure of pebble lithology that probably could be mapped downstream. Additional sampling, using an optimal sampling plan, would be required to confirm indications of the pilot study, that large particle size diminishes downstream, the percentage of pegmatite among pebbles increases, the proportion of spherical (equidimensional) pebbles increases, and pebble roundness decreases downstream. Many other measures have high variation between successive gravel bars (spaced about 600-900 feet apart); with proper sampling design, they could be measured and mapped at the scale of individual gravel pits but not regionally within a drainage. A few measures, including particle sorting and pebble lithology, have mostly local (between-sample) variance and cannot be mapped at any useful scale.

Purpose and limitations of study

The South Platte River valley north of Denver is the last major source of gravel aggregate remaining in the metropolitan area (Schwochow, 1980); in 1995-96 the valley north of Denver was the site of 15 active permitted mine operations for sand and gravel (Hemborg, 1996). As production moves down the valley, the quality of gravel produced from the valley will change. Downstream changes in gravel aggregate quality along the South Platte River are not only of interest to gravel producers in the area but are also relevant to urban planning. An understanding of these changes may enable better prediction of the potential downstream limit of gravel production and of post-mining land uses.

This pilot study of gravel in the bed of the South Platte River north of Denver (Figure 1) was undertaken to identify field measures of aggregate quality and sampling methods that would be useful in modeling and assessing alluvial gravel deposits of the South Platte River and other streams of the Front Range Urban Corridor. Field study methods for gravel aggregate quality are time-consuming; efficient measures of quality and optimal sampling designs were sought to facilitate rapid study. A secondary objective of the study was to gather data that could be compared with gravel aggregate quality in adjacent stream terraces and assess the utility of using stream gravel as a sampling medium for estimating quality of aggregate in terrace deposits.

Although gravel is not mined from the bed of the South Platte, the terraces that serve as the source of gravel for the stream bed are mined extensively. The gravel bars of the river offer some advantages for study, in that they represent a uniform, observable depositional environment that is readily accessible. In contrast, study of terrace deposits requires excavations, which are not everywhere present, and the deposits themselves require stratigraphic study before they



can be sampled properly. Additionally, the approach of sampling streambed gravel for assessing aggregate quality could be used where no gravel is currently mined. The principal disadvantage of sampling streambed gravel as a proxy for terrace gravel is the possibility of sampling bias. Sampling bias in streambed gravel may be caused by the confinement of sampling to layers near the surface and by the possibility that the characteristics of stream gravel have been affected by human activities and structures or by natural environmental change. If gravel in adjacent terraces was deposited long ago, under different environmental conditions of climate and stream size, then it may not share all of the quality characteristics of modern stream gravel.

The data gathered for this pilot study are limited to twelve samples taken from four gravel bars at two sites. This level of sampling was sufficient to provide useful measures of the general quality of gravel aggregate in the area studied, to identify useful measures for field studies of gravel aggregate, and to guide optimization of field sampling design. However, the small number of samples studied severely limits the precision of estimates of mean values and tests for differences among sampling sites. Also, for the small number of samples taken in the pilot study, correlations among various measures are prone to random effects; hence, no detailed analysis of correlation was undertaken.

Figure 1.—Location of study area and valley of South Platte River north of Denver, Colorado, showing sample sites and principal terrace levels (terraces modified from Colton, 1978, and Trimble and Machette, 1979).

Description of gravel bars and relationship to terrace deposits

Gravel bars in the South Platte River comprise a sample of coarse sediment in the low terraces of the South Platte valley. The river continually reworks terrace sediment as its channel migrates laterally across the valley (Figure 2). Since the end of the Pinedale ice age about 11,000 years ago (Wayne and others, 1991), the South Platte has eroded and reworked the Broadway, Louviers, and older terrace deposits. By this process of erosion and redeposition, the river has formed a suite of low terraces that are generally referred to pre-Piney Creek, Piney Creek, and post-Piney Creek levels (Scott, 1965). Also, the low terraces may themselves be reworked by the river. The depth of reworking probably varies locally, but based on bank heights and exposures in gravel pits, it appears to be in the range of 5-10 ft in the area studied.

Gravel pits in the low terraces reveal two ages of alluvial sediment: 1) older, lower sand and gravel thought to have been deposited prior to about 11,000 years ago, and 2) younger, overlying sand and gravel formed by post-Pinedale channel migration, erosion, and redeposition of sand and gravel. Commonly, the two ages of alluvial sediment can be distinguished by discontinuities in color and grain size in the walls of gravel pits. Locally, the younger sand and gravel beds contain abundant logs. Radiocarbon dates of logs from the younger sand and gravel indicate that some of it was deposited as recently as 300 years ago or less.

Gravel bars in the river bed represent the first stage of redeposition of alluvial sediment eroded from the river banks (Figure 2). They form only during flood stage, when the river leaves its sinuous low-flow channel and flows directly across the bars. During flood stage, the river carries a coarse bedload of sand, pebbles, and cobbles, which it deposits on the bar surface as the flood ends and the water level drops. When the channel moves to another location, the gravel bars are reincorporated into the floodplain, where they appear as beds of gravel in the younger alluvium. The gravel bars themselves contain a range of particle sizes and vary locally from gravelly to sandy. After a flood, the surface of the bar may be covered with coarse gravel, but sand occupies the interstices beneath the surface. Pebbles on the bar surface lie in imbricate position and are arranged in patterns of varying particle size that reflect the direction of flow. Debris, including logs, may be left on the surface also. Foresets, exposed in the eroded flanks of the gravel bar, represent migration of the bar as it follows and backfills channel meanders. All of these features are seen in gravel beds of the terraces.

The gravel bars in the South Platte sampled for this study are lateral bars (for a discussion of bar terminology, see Church and Jones, 1982). Lateral bars are characteristically attached to alternate banks of the river at low flow. A typical lateral bar in the South Platte consists of a broad gravel surface separated from the bank by a small back-channel or chute that becomes active during flood stage. Bushes and other vegetation may grow along the bank side of the chute, and in some cases have encroached on the main part of the bar. At low flow, the river may undercut the flank and lower end of the gravel bar, but modification of the bar is minor until the next flood. Bars are also common in the middle of the channel where the South Platte assumes a braided pattern; these mid-channel bars were not sampled for this study.

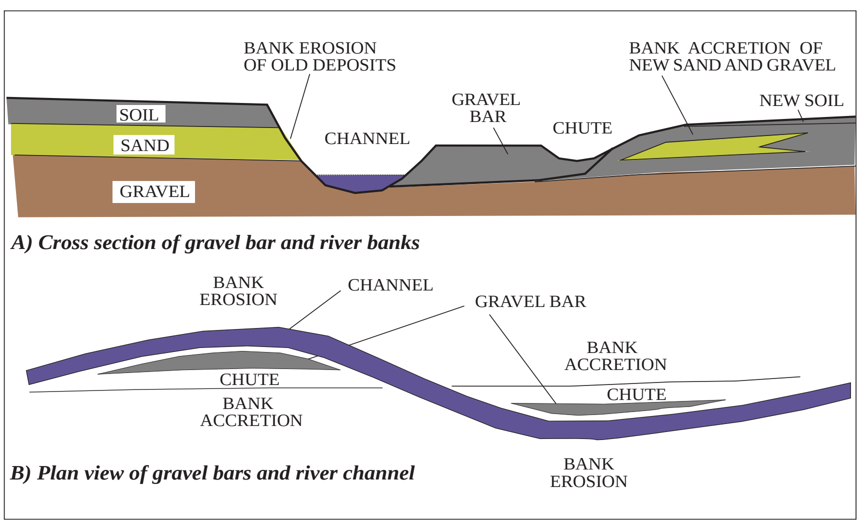
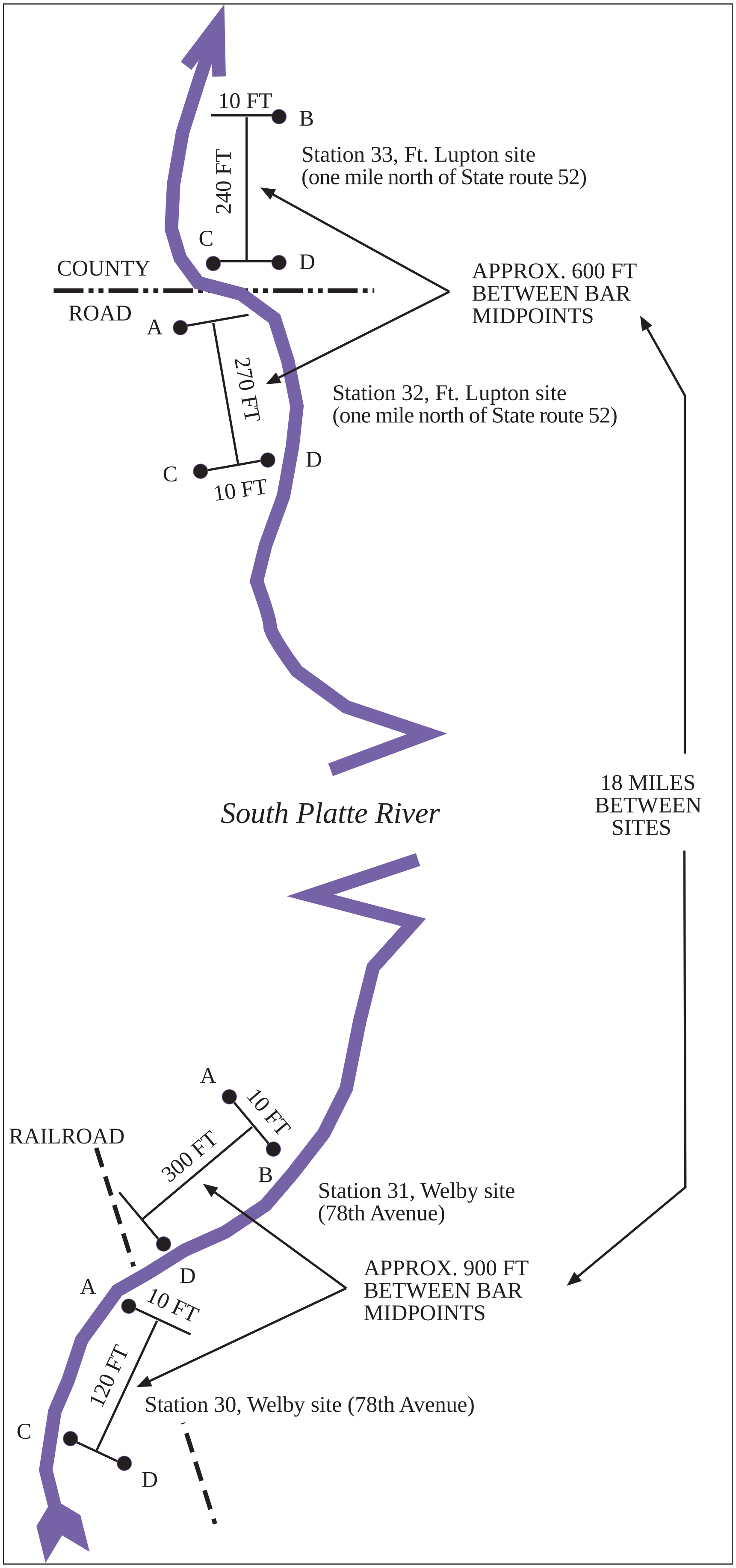


Figure 2.--Sketches illustrating gravel bars in the South Platte River. A) Cross-section of gravel bar; B) Plan view of successive gravel bars. Not to scale.



Sampling and methods

Two sites that are readily accessible by road were selected for sampling (Table 1; Figure 3). The southernmost, upstream site is near Welby (78th Avenue, City of Thornton, Commerce City 7 1/2' topographic map), where a railroad bridge crosses the South Platte River. The site is immediately downstream from the confluence of Clear Creek and the South Platte. The northernmost, downstream site is near Ft. Lupton, one mile north of State Highway 52, where a Weld County road crosses the river (Ft. Lupton 7 1/2' topographic map). The two sites are about 18 miles (mi) apart, and were chosen to encompass the present extent of gravel mining in terraces of the South Platte. No major tributary with access to a source of coarse gravel enters the South Platte between the two sampled sites.

Modifications made to the river channel and its banks are a possible source of variation in characteristics of gravel deposited by the river. Such modifications are common along the South Platte because the floodplain is farmed and mined extensively and contains numerous structures and facilities. The river below the upstream site near Welby has been straightened, and levees protect the adjacent floodplain. In addition, the river makes a sharp bend and a railroad crosses the river. The railroad bridge is wide and does not appear to be capable of obstructing high water except during rare large floods. Gravel bars immediately upstream and downstream from the bend in the

Figure 3.--Sampling design for gravel bars at two sites on the South Platte River near Welby and Ft. Lupton, Colorado.

Table 1.--Location and lengths of gravel bars sampled in the South Platte River north of Denver, Colorado. Locations are for bar midpoints, determined from 1:24,000 USGS topographic maps of the Commerce City (Welby site), and Ft. Lupton (Ft. Lupton site) 7 1/2' quadrangles. FT, feet.

SITE	GRAVEL BAR (STATION)	LATITUDE	LONGITUDE	BAR LENGTH (FT)
Welby	30	39° 50' 16" N.	104° 56' 54" W.	150
-do-	31	39° 50' 23" N.	104° 56' 46" W.	375
Ft. Lupton	32	40° 5' 37" N.	104° 49' 14" W.	340
-do-	33	40° 5' 43" N.	104° 49' 18" W.	300

river at the railroad crossing were selected for sampling. The river at the downstream site appears to be less modified than at the upstream locality; it has not been straightened, but it has two channels south (upstream) of the county road crossing. During low flow the river follows a meander; however, during high flow the river uses a cutoff about 1/4 mi west of the meander. High flow through the cutoff is responsible for deposition of the gravel bars found within it and immediately downstream. The bridge at the site is wide and does not appear to present a major obstruction to flow except during rare large floods. A low levee west of the river is about 100 ft or more from the channel. The first gravel bars above and below the bridge were selected for sampling. Vegetation was minimal on all of the bars sampled.

A four-level (also called "hierarchical" or "nested") sampling design was used to allow measurement of variation over various distances within the river gravel (Figure 3). Multilevel sampling designs like the one used here are discussed in detail by Miesch (1976). From highest to lowest, the four levels are defined by distance between sites, between gravel bars, between ends of gravel bars, and between samples (Figure 3). At each site, two gravel bars, located in sequence and on opposite sides of the river, were selected as primary sampling stations and assigned unique station numbers. The distance between the midpoints of the gravel bars sampled was about 900 feet (ft) at the Welby site and about 600 ft at the Ft. Lupton site. Inspection of other bars at the sampled sites showed that the distances between bars ranges from about 600 to 1,000 ft at each site. For each gravel bar (stations 30-33), both upstream and downstream ends of the bar were sampled. The distance between upstream and downstream samples on each bar was set at 80 percent of the length of the bar, which yielded distances of 120, 300, 270, and 240 ft. At each end of the gravel bar, two samples were located ten feet apart, yielding a total of four sample locations (A, B, C, and D) from each bar. To reduce the workload of sample processing, one of the four sample locations from each bar was eliminated by flipping a coin twice. The total number of samples collected and processed was twelve.

Gravel samples weighing 30-50 pounds (lbs) were dug from a 2 X 2 foot area in the top 10 inches (in) of the bar. Samples ranged in weight from about 30 to 50 lbs; average sample weight was about 40 lbs. Each sample was processed in the field by dry sieving and the weight of each fraction recorded with a hand scale. Sieve mesh sizes used are given in Table 2. The 0.75-2.00 inch pebble fraction was reserved for lithologic identification, shape, and roundness determinations. The first 50 pebbles (selected blind from a bag) from the reserved size fraction were classified by lithology and roundness and measured with a ruler to determine the long (A), intermediate (B), and short (C) dimensions. Assignment of pebbles to lithologic categories was simplified and systematized to assure consistency (Table 3).

Table 2.—Sieve sizes used for particle-size analysis of gravel.

SIEVE MESH OR SIZE	METRIC SIZE
2 inches	50.8 mm
3/4 inch	18.85 mm
No. 5	4 mm
No. 12	1.65 mm
No. 35	0.5 mm
No. 60	0.25 mm

Table 3.—Criteria used for assigning pebbles to lithologic categories.

LITHOLOGIC CATEGORY	COMPOSITION	TEXTURE OR FABRIC	GRAIN SIZE
Granite	Quartz + feldspar +/- mica and amphibole	No fabric	< 10 mm
Pegmatite	Quartz + feldspar	No fabric	> 10 mm
Quartz	Quartz	No fabric	> 10 mm
Gneiss	Quartz + feldspar +mica or amphibole	Foliated +/- layered	< 10 mm > 1 mm
Schist	Quartz + feldspar + mica or amphibole	Foliated +/- layered	< 1 mm
Amphibolite	Mainly amphibole	Foliated	> 1 mm
Diabase	Pyroxene or amphibole + feldspar	Subophitic texture	> 1 mm
Mafic porphyry	Phenocrysts: feldspar + Fe-Mg minerals Matrix: dark-colored	Porphyritic texture	Phenocrysts > 0.5 mm
Intermediate porphyry	Phenocrysts: feldspar + Fe-Mg minerals Matrix: light-colored	Porphyritic texture	Phenocrysts > 0.5 mm
Felsic porphyry	Phenocrysts: feldspar +/- quartz Matrix: light-colored	Porphyritic texture	Phenocrysts > 0.5 mm
Sandstone	Quartz > feldspar	Rounded grains	< 2 mm
Quartzite	Quartz grains and cement	Metamorphic fabric	< 2 mm

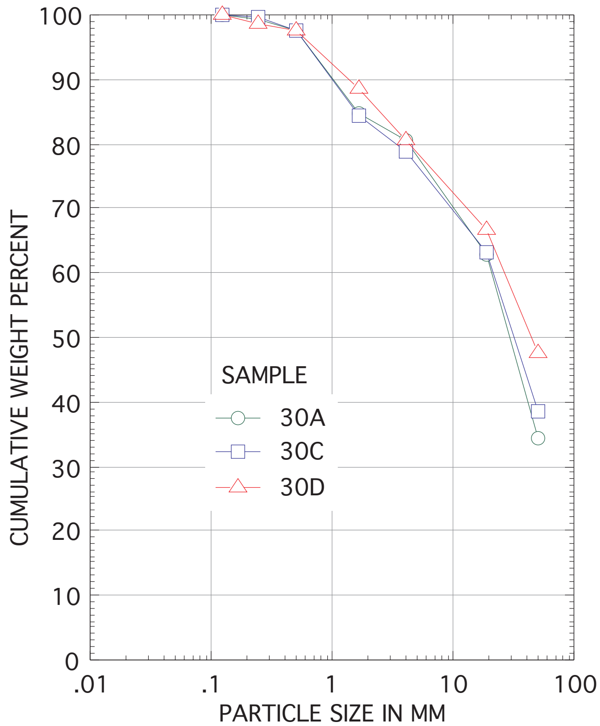
Thus lithology, shape, and roundness were determined for a total of 600 pebbles, distributed 300/site, 150/gravel bar, and 50/sample. Study methods, statistical analysis, and interpretation of particle size, shape, and roundness are described by Pettijohn (1975), and additional details on methods of measuring and statistical analysis of particle size are provided by Krumbein and Pettijohn (1938).

Results

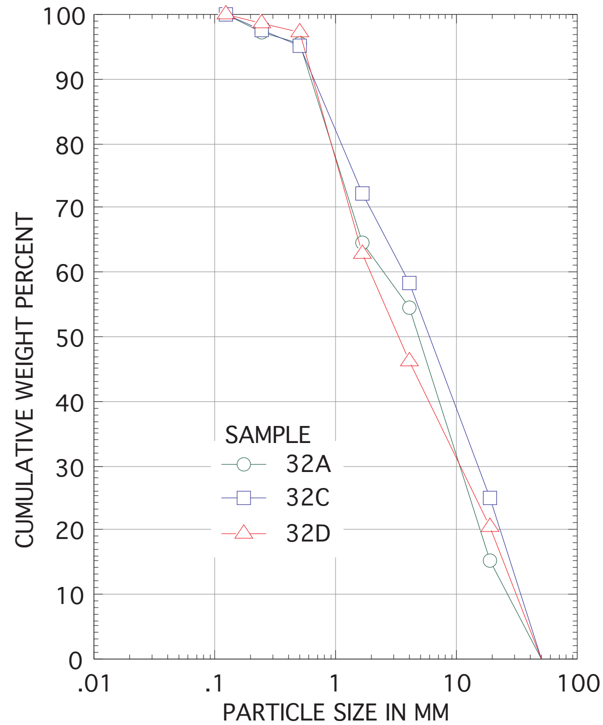
Sampling of the gravel bars at the Welby and Ft. Lupton sites shows that the channel of the South Platte is depositing gravel of good quality throughout the 18 miles between sites. Although sampling was not sufficient to distinguish differences between the mean values at each site with a high level of statistical significance, some major differences are evident from examining the data. The coarseness of gravel diminishes greatly in this distance. The major variation in pebble lithology is a relative increase in abundance of pegmatite, accompanied by minor decreases in other rock types, most notably in mafic rocks. Spherical pebbles are more abundant downstream. In contrast to results of studies of gravels in other regions, roundness decreases downstream. Confirmation of downstream changes in gravel characteristics identified here would require adjustments in the sampling design in order to discriminate between site means. This topic is discussed under "Analysis of variance."

Interpretation of cumulative frequency plots shows that maximum particle size may exceed 100 mm sieve diameter at the Welby site (stations 30 and 31, Figure 4A,B) but probably does not exceed 50 mm at the Ft. Lupton site (stations 32 and 33, Figure 4C,D), a decrease of 50 percent (pct) or more in 18 mi. Cumulative weight percents for individual sieve sizes, such as P>1.65 mm and P>4 mm, decrease by 16 and 32 pct, respectively. Percentile (except P_{10}) and quartile measures of particle size, derived from cumulative frequency curves (Figure 4), show downstream decreases of 75-83 pct (Table 4). Particle size of the two gravel bars at the Welby site differs considerably, and size on the lower bar (station 31) exhibits more variability than on the upper bar (station 30). Particle size is relatively uniform within gravel bars at the Ft. Lupton site. Sorting is variable with no discernible pattern, skewness of particle size distributions is positive and tends to increase downstream, and kurtosis is slightly positive and remarkably uniform (Table 4).

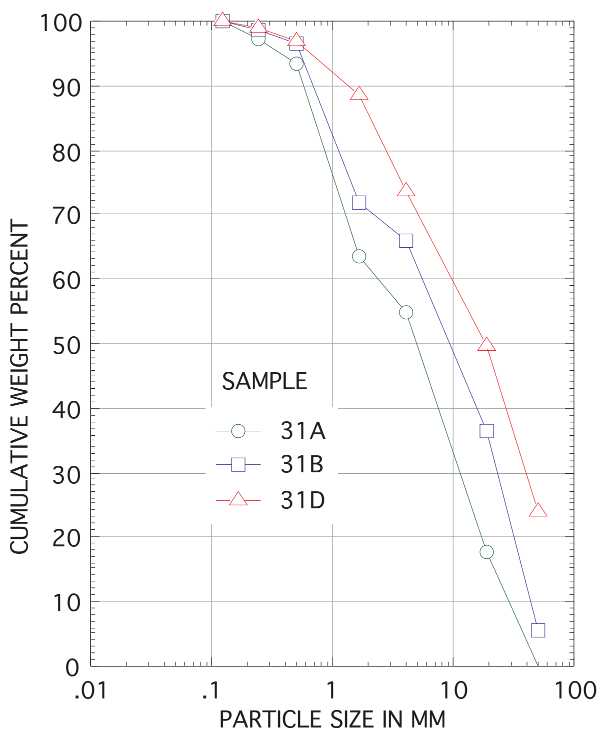
Pebble lithology is dominated by rocks derived from the Precambrian granite-gneiss terrane



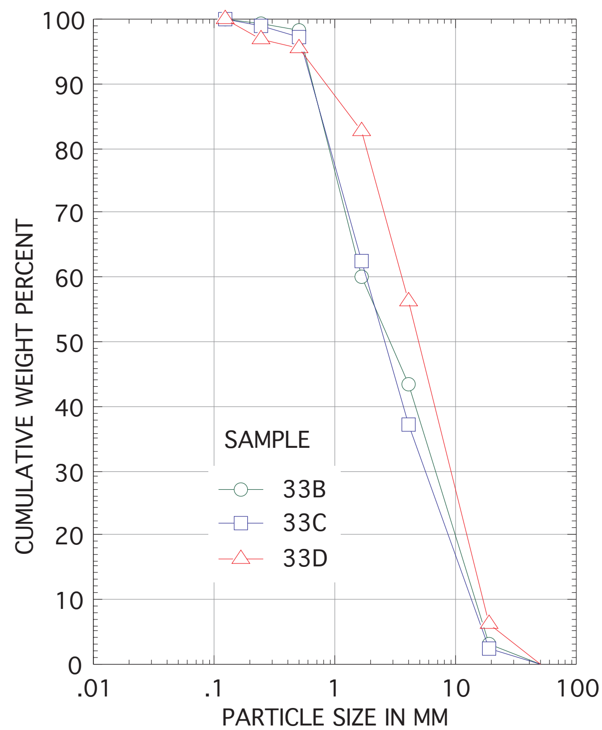
A: Station 30, Welby site



C: Station 32, Ft. Lupton site



B: Station 31, Welby site



D: Station 33, Ft. Lupton site

Figure 4.—Cumulative frequency distributions showing particle size for gravel bars at A) station 30, Welby, B) station 31, Welby, C) station 32, Ft. Lupton, and D) station 33, Ft. Lupton, Colorado.

Table 4.—Particle-size parameters for gravel bars of the South Platte River at sites near Welby and Ft. Lupton, Colorado. P>, cumulative weight percent for stated particle size; P_{10}, 10th percentile; P_{50}, 50th percentile; P_{90}, 90th percentile; Q_1, 1st quartile (= 25th percentile); Q_3, third quartile (= 75th percentile). Sorting (geometric quartile deviation) = $\sqrt{(Q_3 / Q_1)}$; skewness (geometric quartile skewness) = $\sqrt{((Q_1Q_3) / (P_{50})^2)}$; kurtosis (Kelley's quartile kurtosis) = $(Q_3 - Q_1) / (2(P_{90} - P_{10}))$. MM, millimeters; PCT, percent.

SAMPLE NUMBER	P> 1.65 MM (PCT)	P> 4 MM (PCT)	P_{10} (MM)	P_{50} (MM)	P_{90} (MM)	Q_1 (MM)	Q_3 (MM)	SORTING	SKEWNESS	KURTOSIS
Welby site										
30A	84.0	80.7	1	30	100	6	70	3.42	0.68	0.32
30C	84.5	78.8	1	30	200	6	90	3.87	0.77	0.21
30D	88.4	80.5	1	50	400	7	200	5.35	0.75	0.24
Station 30 Mean	85.7	80.0	1	37	233	6	120	4.21	0.73	0.26
31A	63.6	54.8	0.6	5	30	1	10	3.16	0.63	0.15
31B	72.0	66.0	0.7	9	40	1	30	5.48	0.61	0.37
31D	88.6	73.7	1	20	90	3	40	3.65	0.55	0.21
Station 31 Mean	74.7	64.8	0.8	8	53	2	27	4.10	0.60	0.24
Welby Mean	80.2	72.4	0.9	23	143	4	73	4.15	0.67	0.25
Ft. Lupton site										
32A	64.5	54.4	0.6	5	30	1	10	3.16	0.63	0.15
32C	72.1	58.2	0.7	6	40	1	20	4.47	0.75	0.24
32D	62.8	46.2	0.6	3	30	1	20	4.47	1.49	0.32
Station 32 Mean	66.5	52.9	0.6	5	33	1	17	4.03	0.96	0.24
33B	60.1	43.3	0.6	3	20	1	8	2.83	0.94	0.18
33C	62.5	37.0	0.6	3	10	1	7	2.65	0.88	0.32
33D	82.7	56.4	0.8	5	20	2	10	2.24	0.89	0.21
Station 33 Mean	68.4	45.6	0.7	4	17	1	8	2.57	0.90	0.24
Ft. Lupton Mean	67.5	49.3	0.7	4	25	1	13	3.30	0.93	0.24
Net downstream change between sites (in percent)										
Change	-16	-32	-22	-83	-83	-75	-82	-20	+39	-4

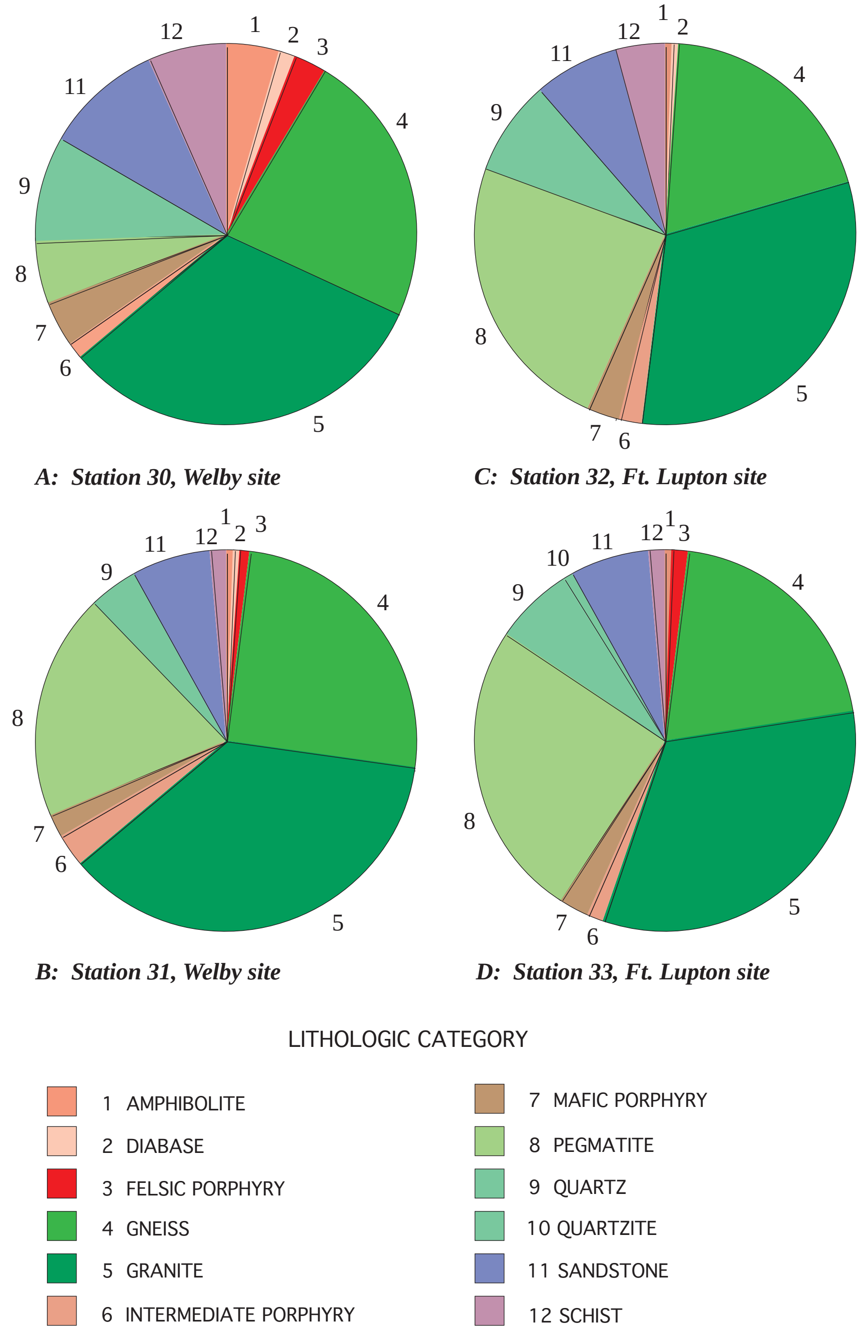


Figure 5.—Pie diagrams showing pebble lithology (0.75-2 inch sieve fraction) for gravel bars at A) station 30, Welby, B) station 31, Welby, C) station 32, Ft. Lupton, and D) station 33, Ft. Lupton, Colorado. Each pie combines counts of 50 pebbles each for 3 samples (total of 150 pebbles).

of the Front Range (Figure 5). Granite, pegmatite, vein quartz, and gneiss are the principal rocks identified from the Front Range terrane. Much of the granite is coarse, making the distinction between granite and pegmatite in the gravel somewhat arbitrary. Schist and mafic rocks (mainly diabase and amphibolite) are common minor constituents. Volcanic porphyry, including intermediate to silicic types from both the Front Range and the plains, commonly comprises about 6 percent (more at the Welby site) of the pebbles; some of the volcanic rocks may be deleterious to aggregate quality (Langer and Knepper, 1995). Two types of sandstone, derived from the Lower Cretaceous Dakota Sandstone and the Pennsylvanian and Permian Fountain Formation along the range front, are common also (Table 5); they are not considered deleterious constituents. Pebbles of Dakota Sandstone are fairly common and always appear to be well-indurated and hard. Quartzite (of Precambrian? origin) and petrified wood (probably derived locally from the Late Cretaceous and Paleocene Denver Formation) are rare constituents of the gravel. Petrified wood was not encountered in the samples but was observed on the gravel bars. Overall, pebble lithology of the gravel bars compares closely with that recorded for gravel in terraces nearby (Colton and Fitch, 1974). Downstream changes in pebble lithology are limited principally to a major increase in pct pegmatite, a small increase in pct quartz, and small decreases in pct schist, mafic rocks, and volcanic porphyry (Table 5). Although minor in absolute values, pct mafic rocks declines by 73 pct of original abundance in 18 mi; the observed decrease probably reflects weak resistance to abrasion during stream transport. Although pegmatite appears to become an important constituent in the pebble size fraction downstream, the overall content of pegmatite in the gravel would be expected to decrease as particle size decreases and pebbles of coarse-grained rocks are reduced to individual mineral grains.

Pebble shape is dominated by disc shapes (oblate spheroids)

Table 5.--Lithology of pebbles in gravel bars of the South Platte River at sites near Welby and Ft. Lupton, Colorado. Lithologic identification determined for 50 pebbles per sample, 18.85-50.8 mm (0.75-2.00 in) size fraction. PCT, percent.

SAMPLE NUMBER	PCT GRANITE	PCT PEGMATITE	PCT QUARTZ	PCT GNEISS	PCT SCHIST	PCT MAFIC ROCKS	PCT PORPHYRY	PCT SANDSTONE	PCT QUARTZITE
Welby site									
30A	28	2	10	28	6	2	12	12	0
30C	26	4	10	26	10	12	6	6	0
30D	42	10	6	16	4	4	6	12	0
Station 30 Mean	32	5.3	8.7	23.3	7	6	8	10	0
31A	30	20	4	32	0	0	10	4	0
31B	40	22	6	24	0	0	0	8	0
31D	40	16	2	20	4	4	6	8	0
Station 31 Mean	36.7	19.3	4	25.3	1.3	1.3	5.3	6.7	0
Welby Mean	34.3	12.3	6.3	24.3	4	3.7	6.7	8.3	0
Ft. Lupton site									
32A	34	24	6	24	4	0	4	4	0
32C	36	22	8	12	4	2	6	10	0
32D	24	26	10	22	4	2	4	8	0
Station 32 Mean	31.3	24	8	19.3	4	1.3	4.7	7.3	0
33B	30	32	8	22	0	0	4	4	0
33C	26	22	6	24	2	2	6	12	0
33D	42	22	6	16	2	0	6	4	2
Station 33 Mean	32.7	25.3	6.7	20.7	1.3	0.7	5.3	6.7	0.7
Ft. Lupton Mean	32	24.7	7.3	20	2.7	1	5	7	.3
Net downstream change between sites (in percent)									
Change	-7	+100	+16	-18	-32	-73	-25	-16	--

and, except for station 30 at the Welby site, by spherical particles (Figure 6). Shapes were classified according to the method of Zingg (Pettijohn, 1975, p. 54) and the sphericity (tendency toward equidimensional shape) was calculated according to the method of Krumbein (1941). The percentage of spherical pebbles is much greater at the downstream site, but the difference between gravel bars at Welby is also striking (Table 6). Rod- and blade-shapes are also common (Table 6), but axial ratios below 0.5 are rare for individual pebbles (Figure 6), so that even these shapes should not yield weak particles. In general, differences among sites and stations for calculated values of

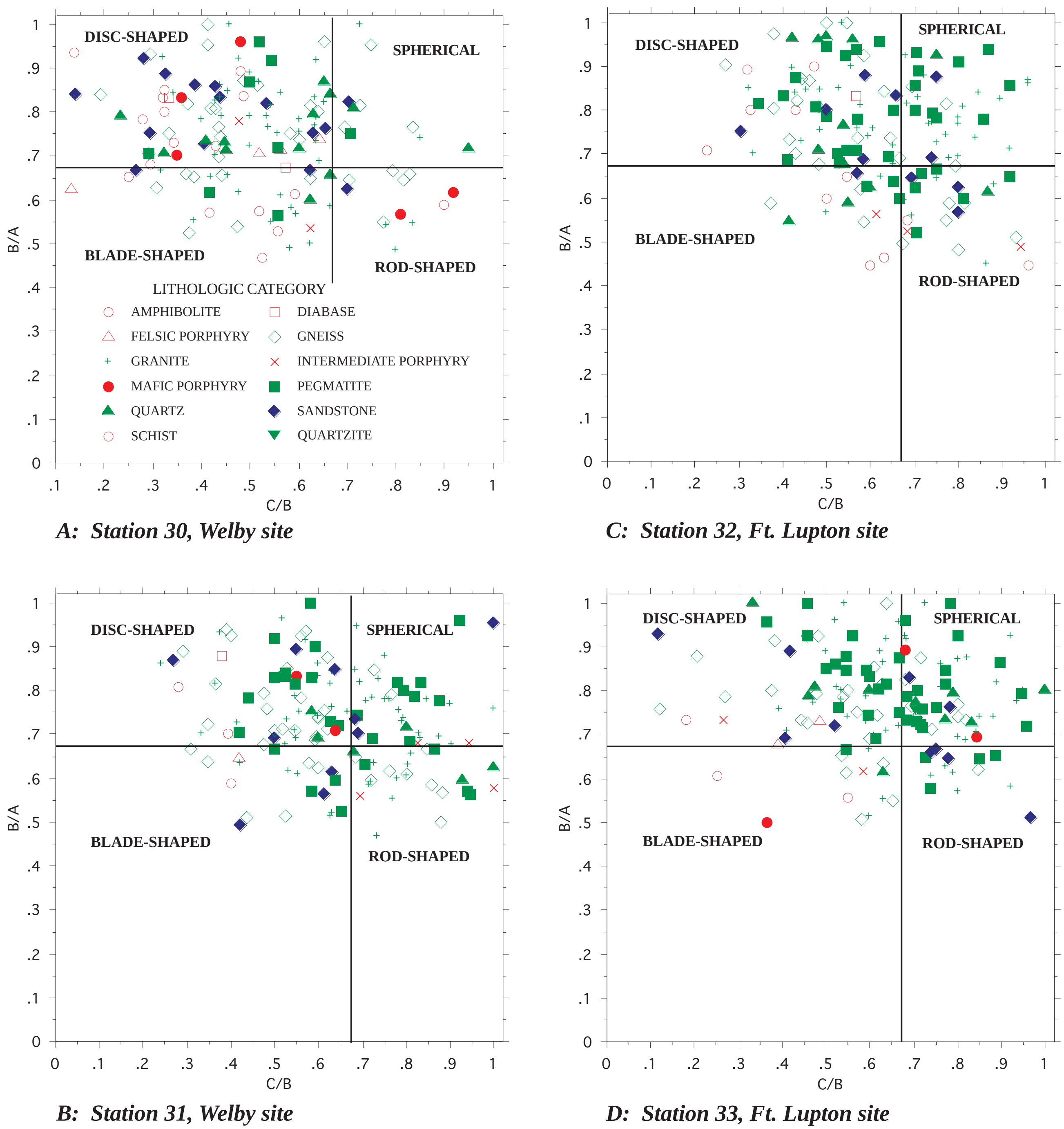


Figure 6.—Zingg diagrams showing pebble shape (0.75-2 inch sieve fraction) for gravel bars at A) station 30, Welby, B) station 31, Welby, C) station 32, Ft. Lupton, and D) station 33, Ft. Lupton, Colorado. Each diagram combines measurements of 50 pebbles each for 3 samples (total of 150 pebbles).

Table 6.—Mean shape of pebbles in gravel bars of the South Platte River at sites near Welby and Ft. Lupton, Colorado. Mean shape calculated from measured lengths of long (A), intermediate (B), and short (C) pebble axes (Pettijohn, 1975, p. 54), 50 pebbles per sample, 18.85-50.8 mm (0.75-2.00 in) size fraction. B/A is inversely proportional to flatness; C/B is inversely proportional to elongation. Sphericity (Ψ) = $\sqrt[3]{(BC/A^2)}$ measures degree of equidimensional shape; when A=B=C, Ψ = 1. Shape classified as spherical, disc-, rod-, and blade-shaped by criteria of Zingg (Pettijohn, 1975, fig. 3-18). PCT, percent.

SAMPLE NUMBER	MEAN B/A	MEAN C/B	MEAN Ψ	PCT SPHERICAL	PCT DISC-SHAPED	PCT ROD-SHAPED	PCT BLADE-SHAPED
Welby site							
30A	0.760	0.507	0.654	8	70	4	18
30C	0.729	0.540	0.648	8	54	14	24
30D	0.742	0.500	0.644	4	66	6	24
Station 30 Mean	0.743	0.516	0.649	7	63	8	22
31A	0.748	0.649	0.709	30	52	12	6
31B	0.715	0.652	0.686	24	40	22	14
31D	0.724	0.605	0.672	18	44	18	20
Station 31 Mean	0.729	0.635	0.689	24	45	17	14
Welby Mean	0.736	0.576	0.669	15	54	13	18
Ft. Lupton site							
32A	0.716	0.671	0.694	28	36	26	10
32C	0.783	0.598	0.709	26	60	8	6
32D	0.739	0.598	0.681	16	48	18	18
Station 32 Mean	0.746	0.622	0.694	23	48	17	12
33B	0.756	0.664	0.721	32	44	12	12
33C	0.765	0.592	0.689	36	46	8	10
33D	0.790	0.642	0.730	38	46	8	8
Station 33 Mean	0.770	0.633	0.713	35	45	10	10
Ft. Lupton Mean	0.758	0.627	0.704	29	47	13	11
Net downstream change between sites (in percent)							
Change	+3	+9	+5	+93	-13	0	-39

flatness (B/A), elongation (C/B), and sphericity (Ψ) appear small (Table 6), and frequency distributions of sphericity values for individual pebbles from each gravel bar show almost complete overlap (Figure 7). However, as will be discussed under analysis of variance, the modest downstream increase in mean sphericity is sufficiently consistent that, with additional sampling, a distinction might be possible. No relation between pebble shape and lithology is apparent. Gneiss, granite and pegmatite all appear to plot in the same shape field on the Zingg diagrams (Figure 6).

Pebble roundness is the only quality characteristic selected for this study that depends on subjective estimates. The 50 pebbles selected for lithologic identification and shape measurement were classified using the visual comparison chart of Pettijohn (1975, p. Fig. 3-24). Rounded and well-rounded pebbles dominate at the Welby site, but subrounded and subangular pebbles are abundant at the Ft. Lupton site (Figure 8). Average roundness also decreases slightly downstream, but the reliability of this calculated parameter is in doubt because average roundness varies greatly among stations (Table 7). The downstream decrease in well-rounded pebbles and corresponding increase in subrounded and subangular pebbles observed in the South Platte is unusual in that roundness generally increases downstream and correlates positively with sphericity (Plumley, 1948). The difference between rounding in pebbles of the South Platte and streams studied elsewhere may stem from differences in pebble lithology, such as the abundance of pegmatite, which tends to break into smaller pebbles along inter-granular surfaces and feldspar cleavages. The inference may be drawn (for further testing) that pebble roundness decreases with particle size downstream in the South Platte because the larger, rounded pebbles of pegmatite are subjected to breakage during transport in the stream.

In summary, the desirable feature of large particle size appears to vary inversely with the desirable qualities of abundant

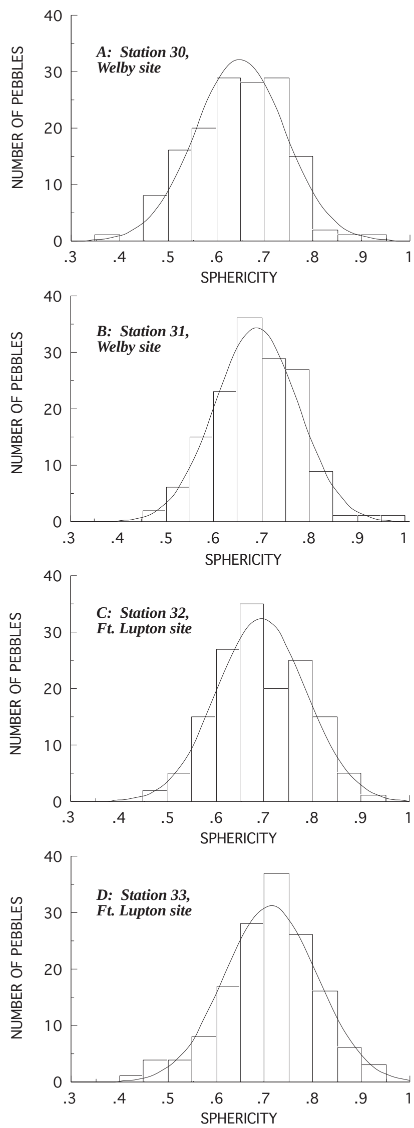


Figure 7.—Histograms showing pebble sphericity (Ψ) for gravel bars at A) station 30, Welby, B) station 31, Welby, C) station 32, Ft. Lupton, and D) station 33, Ft. Lupton, Colorado. Each histogram combines calculations on measurements of 50 pebbles each for 3 samples (total of 150 pebbles).

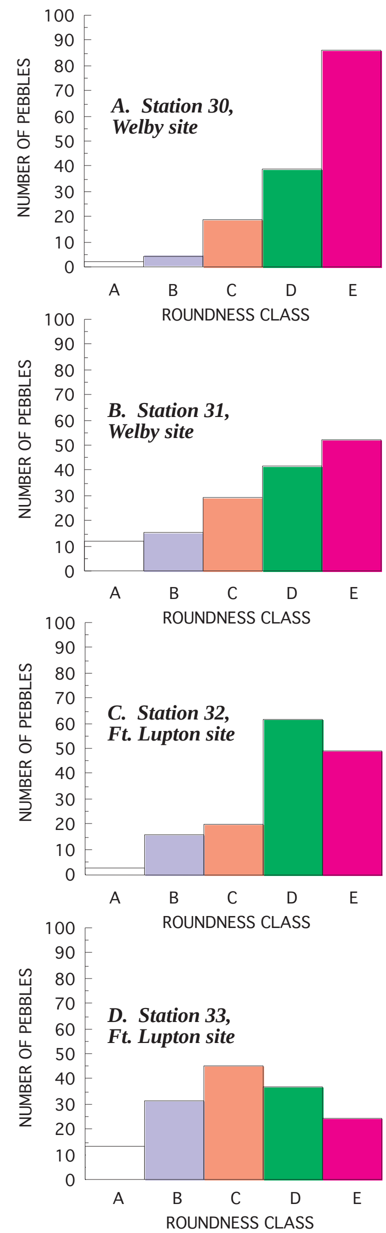


Figure 8.—Histograms showing distribution of pebble roundness for gravel bars at A) station 30, Welby, B) station 31, Welby, C) station 32, Ft. Lupton, and D) station 33, Ft. Lupton, Colorado. Each histogram combines roundness of 50 pebbles each for 3 samples (total of 150 pebbles).

Table 7.--Roundness of pebbles in gravel bars of the South Platte River at sites near Welby and Ft. Lupton, Colorado. Estimated by visual comparison with roundness classes (Pettijohn, 1975, fig. 3-24), 50 pebbles per sample, 18.85-50.8 mm (0.75-2.00 in) size fraction. Mean roundness = class abundance X mid-point values of Pettijohn (1975, table 3-9). Classes defined as follows: A, angular; B, subangular; C, subrounded; D, rounded; E, well rounded. PCT, percent.

SAMPLE NUMBER	MEAN ROUNDNESS	PCT A	PCT B	PCT C	PCT D	PCT E
Welby site						
30A	0.70	0	0	0	32	68
30C	0.57	2	6	26	18	48
30D	0.63	2	2	12	28	56
Station 30 Mean	0.63	1.3	2.7	12.7	26	57.3
31A	0.48	8	10	22	32	28
31B	0.47	8	14	20	30	28
31D	0.57	8	6	16	22	48
Station 31 Mean	0.51	8	10	19.3	28	34.7
Welby Mean	0.57	4.7	6.3	16	27	46
Ft. Lupton site						
32A	0.51	2	12	14	46	26
32C	0.58	2	10	10	32	46
32D	0.51	2	10	16	46	26
Station 32 Mean	0.53	2	10.7	13.3	41.3	32.7
33B	0.39	12	18	28	30	12
33C	0.41	4	18	38	22	18
33D	0.39	10	26	24	22	18
Station 33 Mean	0.40	8.7	20.7	30	24.7	16
Ft. Lupton Mean	0.47	5.3	15.7	21.7	33	24.3
Net downstream change between sites (in percent)						
Change	-18	+13	+149	+36	+22	-47

spherical shapes and angular surfaces (poorly-rounded particles). The gravel deposits of the South Platte can be expected to occupy a continuum between 1) coarse, disc-shaped, rounded gravel upstream and 2) fine, spherical, angular gravel downstream. A downstream increase in the proportion of pegmatite pebbles may affect gravel quality adversely.

Analysis of variance

The following discussion and application of analysis of variance is based on a detailed discussion of multi-level sampling designs and analysis of variance by Miesch (1976).

The model of variation (Miesch, 1976) for a measurement in the four-level sampling plan used in this study is given by:

$$X_{ijkm} = \mu + \alpha_i + \beta_{ij} + \gamma_{jk} + \delta_{ijkm}$$

where X_{ijkm} is a single measurement on the mth sample for the kth bar-end on the jth gravel bar at the ith site. Site i = 1 or 2 (Welby or Ft. Lupton), bar j = 1 or 2 (upstream or downstream), bar end k = 1 or 2 (upstream or downstream), and sample m = 1 or 2. Each measurement is considered as the sum of the grand mean (μ) of all sample values and the deviations introduced by each site (α_i), gravel bar (β_{ij}), bar end (γ_{jk}), and sample (δ_{ijkm}). Only single measurements were made because measurement error was deemed insignificant for dimensions and shapes of gravel particles.

The model defined by the sampling design was used to estimate the amount of variation (variance) associated with each level and thereby guide designs for future studies. If α_i, β_{ij}, γ_{jk}, and δ_{ijkm} are random variables with mean zero and variances of s_α^2, s_β^2, s_γ^2, and s_δ^2, and the variances are additive, then:

$$S_T^2 = s_\alpha^2 + s_\beta^2 + s_\gamma^2 + s_\delta^2$$

where S_T^2 is the estimate of total variance and s_α^2 is an estimate of variance between sites, s_β^2 is an estimate of variance between gravel bars, s_γ^2 is an estimate of variance between ends of bars, and s_{δ}^2 is an estimate of variance between samples. Estimates for variance components at the four levels in the sampling plan were calculated for a selection of measures and calculated parameters for particle size and pebble characteristics in the gravel bars (Tables 8-11). In the present pilot study, based on only 12 samples, total variance (S_T^2) is overestimated by the method (of Anderson and Bancroft, 1952, p. 325-330) for calculation of variance components in unbalanced sampling designs. In the tables, the total variance shown was calculated by the standard formula for variance. The variance components were then calculated by the method of Anderson and Bancroft (1952) and the components expressed in terms of percent of total variance.

One general conclusion drawn from inspection of variance components is that separate sampling of upstream and downstream ends of gravel bars is unnecessary. Variance components for the bar-end level of sampling are nil for many measures, including particle size (Tables 8-11). Separate sampling of bar-ends was included in the design because downstream decrease in particle size was seen on some surfaces of gravel bars in the South Platte. Also, downstream decreases in particle size have been described from individual channel bars of braided streams (Bluck, 1982). For the lateral bars of the South Platte, downstream variation of particle size is evidently local and limited to visually obvious coarse particles.

The analysis shows that, for measures of particle size, P>4 mm shows a higher proportion of regional variation (between sites) than any other measure or calculated parameter (Table 8). In fact, for P>4 mm, the sampling design was sufficient to distinguish site means at the 0.11 level of significance (in other words, there is only an 11 pct probability that the means are the same). Other measures (P>1.65) and derived parameters (P_{10} and P_{50}) also show strong regional variation. All of these could be used to study regional variations in particle size, but the value P>4 mm may be the most powerful measure, and it has the additional advantage of being directly acquired during sieving by

Table 8.—Four-level analysis of variance of particle-size parameters for gravel bars of the South Platte River at sites near Welby and Ft. Lupton, Colorado. P>, cumulative weight percent for stated particle size; P_{10}, 10th percentile; P_{50}, 50th percentile; P_{90}, 90th percentile; Q_1, 1st quartile; Q_3, third quartile. Asterisks (*) indicate significant differences among mean values (≤0.05 probability that means are equal). Site variance ratio = between-site variance/total within-site variance. Bar variance ratio = between-bar variance/total within-bar variance. MM, millimeters.

PARTICLE SIZE PARAMETER	VARIANCE	SAMPLING LEVEL				VARIANCE RATIO	
		BETWEEN SITES	BETWEEN GRAVEL BARS	BETWEEN BAR ENDS	BETWEEN SAMPLES	SITES	GRAVEL BARS
		Percent of total variance					
P>1.65 MM	124	41	0	13	46	0.69	0
P>4 MM	226	62	17	0	21	1.63	0.81
P_{10}	0.033	46	12	25	17	0.85	0.29
P_{50}	231	37	46*	0	17	0.59	2.71
P_{90}	12,700	19	37	11	33	0.23	0.84
Q_1	5.54	18	73*	5	4	0.22	8.11
Q_3	3,150	18	45	0	37	0.22	1.22
Sorting	1.07	7	25	0	68	0.08	0.37
Skewness	0.063	32	0	0	68	0.47	0
Kurtosis	0.005	1	0	0	99	0.01	0

Table 9.--Four-level analysis of variance of pebble lithology in gravel bars of the South Platte River at sites near Welby and Ft. Lupton, Colorado. Lithology represented by percentage rock type for the18.85-50.8 mm (0.75-2.00 in) size fraction. Asterisks (*) indicate significant differences among mean values (≤0.05 probability that means are equal). PCT, percent.

PEBBLE LITHOLOGY	VARIANCE	SAMPLING LEVEL				VARIANCE RATIO	
		BETWEEN SITES	BETWEEN GRAVEL BARS	BETWEEN BAR ENDS	BETWEEN SAMPLES	SITES	GRAVEL BARS
		Percent of total variance					
PCT GRANITE	44.7	0	7	0	93	0	0.08
PCT PEGMATITE	80.1	46	36	12	6	0.85	2.00
PCT QUARTZ	6.2	0	52	12	36	0	1.08
PCT GNEISS	30.9	17	0	0	83	0.20	0
PCT SCHIST	8.2	0	63*	0	37	0	1.70
PCT MAFIC ROCKS	11.5	6	19	6	69	0.06	0.26
PCT PORPHYRY	9.1	3	1	0	96	0.03	0.01
PCT SANDSTONE	10.8	0	3	0	97	0	0.03

simply adding the weights of gravel on the sieves of 4 mm and larger mesh openings. Fortunately, P>4 mm has been widely reported in previous studies of gravel in the Front Range Urban Corridor (e.g., Colton and Fitch, 1974; Trimble and Fitch, 1974a,b), making it a good choice for regional study. Comparable power for regional studies would be expected using P>3/16 inch (4.76 mm), a sieve size commonly used by the gravel industry. In contrast, calculated parameters such as sorting and kurtosis show little regional (between-site) variation and a high degree of local (between-sample) variation, making them unsuitable for regional comparison.

The major component of variance between gravel bars indicates that future sampling for regional studies should be adjusted to reduce the effect of this source of variation. Adjustment is determined by calculating the ratio of between-site variance to within-site variance (Table 8). From the variance ratio for P>4 mm at sites (v = 1.63, Table 8), the number of random samples required within a site ($n_r = 5$) is determined by consulting the graph given by Miesch (1976, fig. 2A). Sampling among levels can be guided by calculating the following (Miesch, 1976):

$$E_r = (s_\beta^2 + s_\gamma^2 + s_\delta^2)/n_r = 17.18$$

for $n_r = 5$ where E_r is the maximum acceptable error variance; and:

$$E_s = s_\beta^2/n_\beta + s_\gamma^2/n_\beta n_\gamma + s_\delta^2/n_\beta n_\gamma n_\delta$$

where n_β, n_γ, and n_δ are the number of gravel bars, bar ends, and samples, respectively, within a site. According to Miesch (1976, p. A9), samples must be sufficient in number and distributed so that E_s does not exceed E_r. If $n_\beta = 5$, $n_\gamma = 1$, and $n_\delta = 1$, then $E_s = 17.18$. Thus, only 10 samples are necessary to discriminate P>4 mm between two sites 18 mi apart if a single random sample is selected from each of five bars at each site. This is so because the major sources of within-site variance (among bars and among samples) can both be minimized by increasing the number of bars sampled from two to five. In contrast, sampling for the pilot study was not adequate to discriminate P>4 mm between sites 18 mi apart because $n_\beta = 2$ and $n_\gamma + n_\delta = 3$, yielding $E_s = 27$. If the sites were closer together (and thus less distinct), more gravel bars might have to be sampled.

Variance ratios were also calculated for discriminating between gravel bars, for possible guidance in designing studies scaled to individual gravel pits. Suppose that gravel beds were deposited by bars spaced 600-900 ft apart, as is the case for the bars sampled in the river, and the measure of particle size P>4 mm

Table 10.--Four-level analysis of variance of pebble shape parameters in gravel bars of the South Platte River at sites near Welby and Ft. Lupton, Colorado. Shape is represented by the mean values of B/A and C/B, where A is the pebble long axis, B is the intermediate axis, and C is the short axis, by mean sphericity (Ψ), and by the percentage of spherical, disc-, rod-, and blade shaped pebbles for 50 pebbles in the18.85-50.8 mm (0.75-2.00 in) size fraction. Asterisks (*) indicate significant differences among mean values (≤0.05 probability that means are equal). Site variance ratio = between-site variance/total within-site variance. Bar variance ratio = between-bar variance/total within-bar variance. PCT, percent.

PEBBLE SHAPE	VARIANCE	SAMPLING LEVEL				VARIANCE RATIO	
		BETWEEN SITES	BETWEEN GRAVEL BARS	BETWEEN BAR ENDS	BETWEEN SAMPLES	SITES	GRAVEL BARS
		Percent of total variance					
MEAN B/A	0.00060	20	4	5	71	0.25	0.05
MEAN C/B	0.00348	0	69*	19	12	0	2.23
MEAN SPHERICITY (Ψ)	0.00079	31	38*	0	31	0.45	1.22
PCT SPHERICAL	131	25	60*	3	12	0.33	4.00
PCT DISC-SHAPED	107	0	46	11	43	0	0.85
PCT ROD-SHAPED	46.2	0	41	5	54	O	0.69
PCT BLADE-SHAPED	42.5	28	21	0	51	0.39	0.41

was to be mapped at that scale in a bed of gravel in the pit. The number of samples required within 600-900 foot segments of the same gravel bed would be $n_r = 6$ if v = 0.81. Of course, a final sampling design for a specific gravel pit should be designed from a pilot study of the pit and the design should be tailored to produce the level of detail required by the operators.

The method of sampling design and optimization described for P>4 mm can be applied to other measures of gravel quality. Among the best candidates for study of regional variation of gravel quality in the South Platte valley are pct pegmatite (Table 9), mean sphericity (Table 10), and pct well-rounded pebbles (Table 11). For the variance ratios of these measures, 6-8 gravel bars should be sampled at each site to distinguish sites 18 mi apart. In contrast, many measures have high variation among gravel bars (spaced 600-900 ft apart); with proper sampling design, they could be mapped with confidence at the scale of individual gravel pits. A few measures, including kurtosis, pct granite, pct gneiss, pct porphyry, and pct sandstone, have mostly between-sample variance and cannot be mapped at any useful scale. Sampling in young terrace gravels could be guided by the same criteria.

Suggestions for future work

Based on results of the pilot study, the following suggestions apply for sampling gravel quality:

1) Concentrate on characteristics that are easy to measure and show variation appropriate to the scale of study. For studies of downstream variation of gravel in a single drainage such as the South Platte, particle size measures such as P>4 mm are best.

2) The number of sieves (and time spent sieving) can be reduced by using only coarse meshes; a series of sieves having mesh openings of 1 1/2, 3/4, 3/8, and 3/16 inches, commonly employed in the gravel industry, is better suited to gathering the required data on particle size than a more wide-ranging series extending to fine sand, commonly employed in sedimentologic studies and used for the pilot study. Depending upon the distribution of particle size, a wide range of sieve sizes might be required to determine sorting, skewness, and kurtosis, but these parameters are not generally mappable because they show high variation among closely spaced samples.

3) Sampling of 6-8 successive gravel bars or, in terrace gravels,

Table 11.--Four-level analysis of variance of pebble roundness in gravel bars of the South Platte River at sites near Welby and Ft. Lupton, Colorado. Roundness is represented by average roundness (calculated from class mid-point values of Pettijohn, 1975, table 3-9) and by the percentage of pebbles in classes A (angular), B (subangular), C (subrounded), D (rounded), and E (well rounded) for the18.85-50.8 mm (0.75-2.00 in) size fraction. Asterisks (*) indicate significant differences among mean values (≤0.05 probability that means are equal). PCT, percent.

PEBBLE ROUNDNESS	VARIANCE	SAMPLING LEVEL				VARIANCE RATIO	
		BETWEEN SITES	BETWEEN GRAVEL BARS	BETWEEN BAR ENDS	BETWEEN SAMPLES	SITES	GRAVEL BARS
		Percent of total variance					
MEAN ROUNDNESS	0.00943	10	65*	15	10	0.11	2.60
PCT A	15.6	0	81*	1	18	0	4.26
PCT B	53.5	34	49*	0	17	0.52	2.88
PCT C	96.3	0	48	7	45	0	0.92
PCT D	78.5	0	55	6	38	0	1.25
PCT E	305	34	37	14	15	0.52	1.28

of 6-8 successive locations spaced the same distance as gravel bars in the modern stream, are probably required to yield sufficiently precise estimates for regional study of gravel in a single drainage like the South Platte. If the gravel deposits in terraces were deposited recently, under the same conditions of climate and streamflow as the present, sample spacing in terrace gravels might be guided by a survey of gravel bar spacing in the streambed.

4) Sampling at a few sites should be sufficient to characterize pebble shape and lithology in a drainage. Studies of pebble shape and lithology are time-consuming, and shape and lithology show only minor downstream variation. However, pebble lithology is important for predicting quality of gravel aggregate in drainages having different sources; such predictions could probably be made with modest sampling across a number of drainages.

5) The relationship of rounding to gravel aggregate quality needs investigation. Rounding is easy to determine by visual estimation and shows promise of downstream change.

6) Studies using different types of samples and sampling patterns, as discussed by Otto (1938) and Griffiths and Ondrick (1968), should be tried to assure that estimates of gravel quality are unbiased and to identify ways to minimize between-sample variance.

7) Further studies should be directed toward gravel deposits in terraces of the South Platte, to test the application of suggestions made here. Such studies are underway.

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