

Morphology of Spearfish Creek, Lawrence County, South Dakota, USA

Abstract

Spearfish Creek is a 60-kilometer stream in the Black Hills of South Dakota, USA. The purpose of this study was to evaluate the bathymetry and substrate of the creek through the city of Spearfish. Four, 400-meter reaches located within the city limits of Spearfish were sampled along 51 equally-spaced transects. Bathymetric charts were produced using Ordinary Kriging interpolation of measured and synthetic cross-sections. Grain size and cementation maps were produced using the Empirical Bayesian Kriging method in ArcGIS Pro. Mean (SE) wetted width significantly decreased going downstream, from 10.0 (0.2) m at the most upstream site to 6.9 (0.1) m at the farthest downstream site. Bankfull width followed a similar pattern with minimum and maximum wetted width values of were 1.4 m and 20.5 m, respectively. Mean depth significantly increased from 21 (1) cm to 32 (0.1) cm from most upstream to the farthest downstream site. Grain size was predominantly cobble in the three upstream sites, while the most downstream site was predominantly gravel. Mean cementation rate was approximately 56% and was highest in the upstream sites. Cementation was wide-spread and was typically associated with cobble substrate. Bathymetric charts indicated that the bed form followed a typical trend, showing deeper areas in the middle of the stream and graduating to shallower on the banks. Grainsize maps followed a similar pattern to depth, graduating from larger sizes in the middle to finer grains along the bank. The results of this study provide a foundation for future monitoring efforts, geomorphic assessments, and restoration planning.

Keywords: spearfish creek, bathymetry, substrate, cementation

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Introduction

Spearfish Creek is a major stream located in the Northern Black Hills of South Dakota, USA (Figure 1). It is a tributary of the Redwater River and part of the Belle Fourche River watershed basin. The creek has headwaters approximately 10 km south of Cheyenne Crossing, South Dakota, and flows northward through Spearfish Canyon where it is diverted near Maurice, South Dakota. At Maurice, the creek enters an aqueduct where it travels 8.85 km to a hydroelectric power plant at the south edge of the city of Spearfish. Consequently, this section of the creek bed lies dry for the majority of the year. At the power plant, the water is then discharged back into the creek bed just above the Spearfish City Campground. Spearfish Creek runs 5.3 km through the city of Spearfish and then another 10.5 km north of the city before joining Redwater River.

Spearfish Creek originates from, and is partly recharged by, cold spring discharge from the Madison limestone and Minnelusa Formation aquifers^{1,2} From its headwaters, the creek flows over Precambrian basement rocks and older sedimentary units before re-entering the Madison Limestone and Minnelusa Formation near the City of Spearfish.^{2,3} Because the Madison and Minnelusa formations are composed of limestone, the creek is rich in calcium carbonate.¹⁻⁴ Calcium carbonate cementation has been documented in Spearfish Creek⁵ and deposits of calcareous tufa can be found along Spearfish Creek's tributaries, even causing waterfalls.¹

Human influences shape the hydrology and geomorphology of Spearfish Creek. The aqueduct dewatering nearly 9 km of stream bed is a clearly visible major impact.² In addition, unmonitored water discharge by D.C. Booth Historic National Fish Hatchery, storm drainages located along the creek, dense residential development, minor agriculture, and areas of recreational activity within the city may impact water quality and channel form.⁶⁻¹⁰

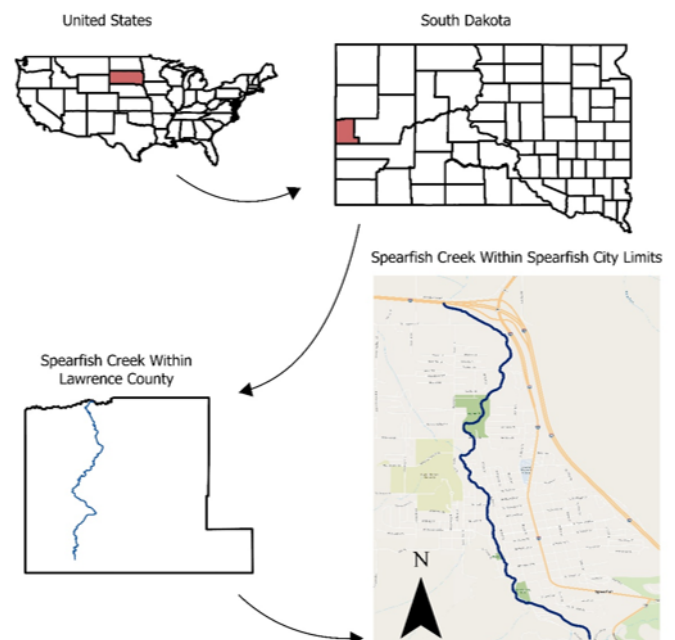


Figure 1 Location of Spearfish Creek in Lawrence County and the City of Spearfish, South Dakota, USA.

Spearfish Creek is economically, recreationally, and ecologically important to the local area.^{2,11-14} The creek is a premiere trout fishing stream, with a large population of self-sustaining brown trout (*Salmo trutta*) dominating in the lower reaches, including in the city of Spearfish.^{5,15-18} It is one of very few streams in the Black Hills with a naturally-reproducing rainbow trout (*Oncorhynchus mykiss*) population located above the aqueduct.^{15,19} Self-sustaining brook trout

(*Salvelinus fontinalis*) predominate in the upper reaches of Spearfish Creek. The Spearfish Creek watershed is also home to a number of other relatively unique or sensitive plant and animal species.^{21–24}

Despite the importance of Spearfish Creek there is limited data on the geomorphology and bathymetry of the stream, particularly within the city limits of Spearfish. This information is essential to identifying critical management areas, as well as assessing those factors influencing the physical characteristics of the creek. Thus, the objective of this study was to collect baseline data, including depth, thalweg, width, grain size classifications, and cementation, from Spearfish Creek in the city of Spearfish, South Dakota, USA.

Methods

Study area

The study area consisted of four reaches, from upstream to downstream, of Spearfish Creek located within the city limits of Spearfish, South Dakota, USA (Figure 2). The reach locations were roughly equidistant and were chosen to include specific points of interest, particularly where discharge was entering the creek or areas adjacent to public parks.

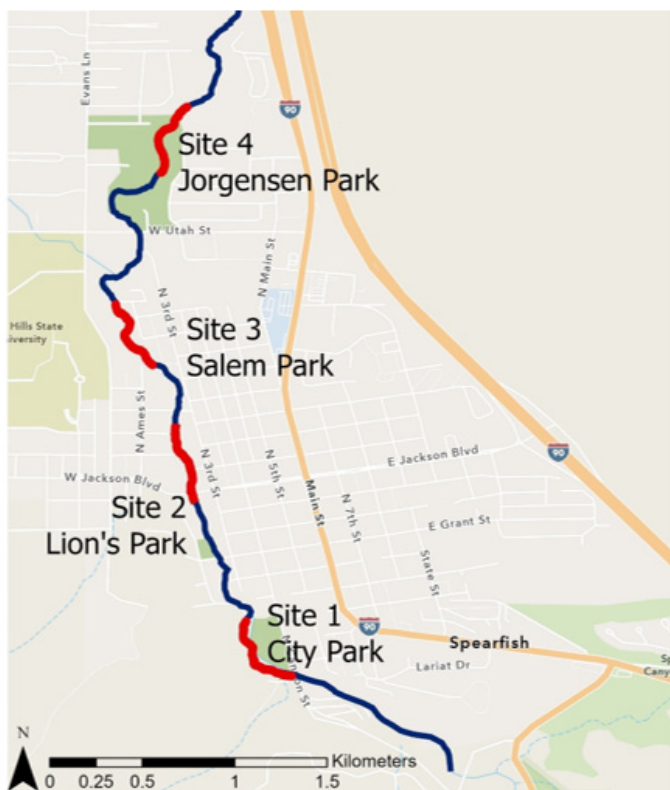


Figure 2 Site locations in Spearfish Creek within Spearfish city limits, South Dakota, USA.

Site 1 was the southernmost and furthest upstream site. It began at the intersection of the creek and South Canyon Street (44.48145° N, 103.85999° W) and ended with a low-head dam (44.48409° N, 103.8622° W) at the north end of Spearfish City Park. Spearfish City Park runs the length of this reach along on the right bank. The D. C. Booth Historic National Fish Hatchery is located to the south of the creek and discharges into two locations within this reach. Site 1 also included two locations where the creek divided into two channels around small islands (Figure 3).



Figure 3 Image of Site 1 (City Park) on Spearfish Creek in the city of Spearfish, South Dakota, USA with points of interest noted.

Site 2 began just south (upstream) of the intersection of Spearfish creek and Jackson Boulevard (44.49006° N, 103.86476° W). The reach contained all of Lions Park, ending just after the north end of the park (44.49349° N, 103.86565° W). A recreational path ran along the right bank, nearly through the entire reach. Site 2 contained multiple storm drain discharge points (Figure 4). The banks of the creek in this site were predominantly man-made.

Site 3 began at a pedestrian bridge on the north side of Salem Park (44.49658° N, 103.86675° W). It contained all of Salem Park and ended near Kampus Court (44.49951° N, 103.86854° W). Salem Park is on the right bank on the upstream part of the site. On the other side (left bank) of the creek is a gravel parking lot where erosion created a ditch leading directly to the stream. Dower's Hole, a man-made pool with depths greater than 3 meters, is located towards the south end of this reach. The pool is a popular area for recreation and minor creek bank degradation is visible (Figure 5).

Site 4 was the northernmost and furthest downstream site. It began within Jorgensen Park near a small pedestrian bridge (44.50592° N, 103.86633° W) and extended north of the park to 44.5091° N, 103.86505° W. The upstream half of the reach lay within park boundaries, while the downstream half was influenced by adjacent residential development (Figure 6). A recreational path ran along the left bank of the creek for nearly the entire reach. Table 1 shows the sampling days, along with discharge and gauge height data for the days the sites were sampled from the USGS gage located in Spearfish City Park (United States Geological Survey).²⁵



Figure 4 Image of Site 2 (Lions Park) on Spearfish Creek in the city of Spearfish, South Dakota, USA with points of interest noted.

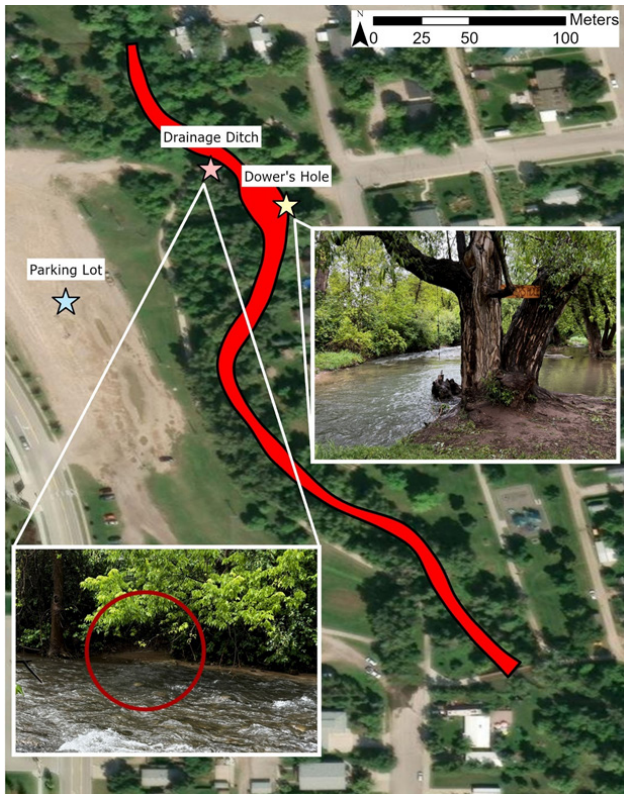


Figure 5 Image of Site 3 (Salem Park) on Spearfish Creek in the city of Spearfish, South Dakota, USA with points of interest noted.

Table 1 Date sample, discharge (m³/s), and gauge height (m) for four sampling sites in Spearfish Creek within the city limits of Spearfish, South Dakota. Discharge and gauge height were collected from the USGS gage located in Spearfish City Park (United States Geological Survey, 2025)

| | Site 1 | Site 2 | Site 3 | Site 4 |
|-------------------------------|--------|--------|---------|--------|
| Date Sampled | 13-Mar | 11-Mar | 6-Apr | 26-Mar |
| Discharge (m ³ /s) | 1.4158 | 1.3875 | 1.49513 | 1.5432 |
| Gauge Height (m) | 1.52 | 1.52 | 1.53 | 1.52 |



Figure 6 Image of Site 3 (Jorgenson Park) on Spearfish Creek in the city of Spearfish, South Dakota, USA with points of interest noted.

Transect and sub-transect location

Each site was measured and sampled with 11 transects, as per standard methods.^{26,27} Transects were equally spaced at 40 m apart and were labeled A through K starting downstream. Artificial transect placement occurred at 0.2 times the channel width to allow for accurate bathymetric interpolation.²⁸ Supplemental sub-transect placement occurred every 8 m between transects. Sub-transects were labeled A-1, A-2, A-3, A-4, and so forth respectively (Figure 7). Where the creek split into two channels, corresponding transect and sub-transect placement occurred.

Data collection

Stream width was measured using a tape with 0 placed on the left bank at the water's edge. Eleven transect data points were equally-spaced across the stream, with one point at either bank and nine equally-spaced points within the water. Henceforth the left bank will be referred to as 0% across the transect and the right referred to as 100%. Six sub-transect points of collection were also equally-spaced with one point at either bank and four equally-placed within the water.

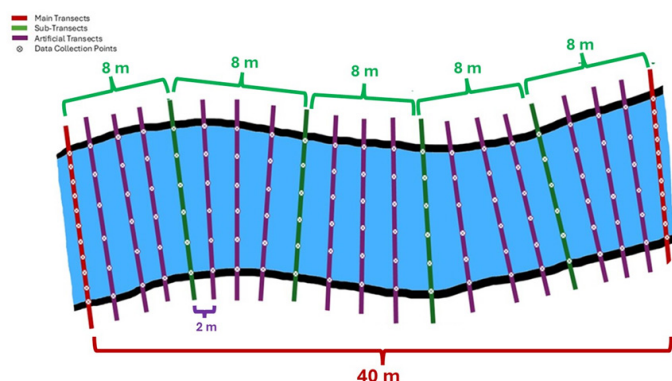


Figure 7 Equally-spaced model of main transects (across 40 m), sub-transects (8 m apart), and artificial (2 m apart) transects with data collection points along each transect (not to scale).

Depth

Depth was recorded at each transect and sub-transect point to the nearest cm. Thalweg location and depth were collected at every transect and sub-transect. Thalweg depth was determined by locating and recording the greatest depth along the transect or sub-transect to the nearest cm.

Grain size

Grain size was recorded at each transect and sub-transect point. It was estimated visually and tactilely, as per Lazorchek et al.²⁶ and EPA.²⁷ Grain size was determined using the EPA NRSA Wadable Field Manual (2023), with modification to account for cementation of bed material (Table 2). Grain size values were recorded as fines = 1, sand = 2, gravel = 3, cobble = 4, and boulder = 5.

Table 2 Grain size classification with description and diameter (mm)

| Classification | Assigned Value | Description | Diameter (mm) |
|----------------|----------------|---|---------------|
| Fines | 1 | Silt, clay, and muck | <0.06 |
| Sand | 2 | Gritty, up to ladybug sized | 0.06 - 2 |
| Gravel | 3 | Ladybug to tennis ball sized | Feb-64 |
| Cobble | 4 | Tennis ball to basketball sized | 65 - 250 |
| Boulder | 5 | Basketball to car sized | 250 - 4000 |
| Cemented | | Any size consolidated material (not shiftable by kicking) | - |

Wetted width and bankfull width

Wetted width and bankfull width were recorded at every transect and sub-transect to the nearest 0.1 m. Wetted width was defined as the width of the channel as delineated by the presence of water.²⁶ Bankfull, or the “active” channel was defined as the stream width filled by moderate-sized flood events.²⁶

Bathymetric charts and maps

Bathymetric charts were produced in ArcGIS Pro 3.4.0. Artificial transects and points were generated every 2 m where main or sub-

transects did not occur (Figure 9). Artificial transect lengths, wetted width, and bankfull width were calculated by a weighted average formula using the closest transect lengths of wetted width and bankfull width. Artificial point depths were calculated using a weighted average formula of the closest transect depths. The Ordinary Kriging interpolation method²⁹ was used for bathymetric charts, and the Empirical Bayesian Kriging interpolation method³⁰ with curvilinear coordinates was used for grain size and cementation maps.

Statistical analysis

Data were analyzed using the SPSS statistical program (24.0, IBM, Armonk, New York, USA). One-way Analysis of Variance (ANOVA) was performed and if significant differences occurred, Tukey’s post-hoc means testing procedure was conducted. Significance was pre-determined at $p < 0.05$.

Results

Comparison between reaches

Mean wetted width significantly decreased going downstream, from 10.0 (0.2) m at site 1 to 6.9 (0.1) at site 4 (Table 3). Bankfull width followed a similar pattern, significantly decreasing from 12.2 (0.2) m at site 1 to 7.1 (0.1) m at site 4. Both the minimum and maximum wetted width values were observed in site 1, at 1.4 m (divided channel) and 20.5 m, respectively. In contrast, the minimum bankfull width of 3.9 m was recorded at the furthest downstream location, site 4, whereas the maximum bankfull width was 24.0 m at site 1, the furthest upstream location. Mean depth significantly increased from 21 (1) cm at site 1 to 32 (0.1) cm at site 4. Grain size was 3.4 to 3.6 in the three upstream sites (1, 2, and 3), which was significantly greater than the 3.0 mean grain size observed at site 4. A similar pattern was observed with mean cementation, which ranged from 1.5 to 1.8 in the three upper sites which were significantly greater than the 1.3 value obtained for site 4. Site 2 had the highest cementation at 1.8.

Comparison between transects within reaches

There was considerable variation in all variables among the transects at each site (Table 4). At site 1, wetted width varied from 5.0 m to 18.7 m among the transects and the values for bankfull width were very similar. Depth varied from 3 cm to 50 cm and grain size ranged from 2.6 to 3.8 among the transects. Cementation went from completely uncemented (1.0) to nearly-completely cemented (1.9) in the site 1 transects. While there was substantial variation in wetted width, bankfull width and depth among the transects within the lower three sites (2, 3, and 4), it was less than that observed in site 1. Grain size among the transects ranged the most in site 4, from 1.6 to 4.0. Cementation among the transects in site 2 was the most consistent, ranging from 1.6 to 2.0.

Comparison between data point location across transects

Water depth was significantly deeper at transect sampling points 40% to 60% for sites 1, 2, and 3 compared to those sampling points closer to each bank (Table 5). The water depth profile was different at site 4, where there were no significant differences across the transects. Depth only varied by 2 cm from 20% to 80%. Like the other reaches, the lowest depths in site 4 were found along the banks at 0% and 100%.

Table 3 Mean (SE) wetted width, bankfull width, depth, grain size, and cementation at each of four sites in Spearfish Creek within the city limits of Spearfish, South Dakota, USA. Minimum and maximum values for wetted width and bankfull width are also included, along with maximum depth readings. Grain size values were recorded as fines = 1, sand = 2, gravel = 3, cobble = 4, and boulder = 5. Cementation values were denoted as uncemented = 1, cemented = 2. Means followed by different letters are significantly different (N = 11; p < 0.05)

| Site (Park) | Wetted Width (m) | | | Bankfull Width (m) | | | Depth (cm) | | Grain Size | Cementation |
|---------------|------------------|-----|------|--------------------|-----|------|------------|-----|--------------|-------------|
| | Mean (SE) | Min | Max | Mean (SE) | Min | Max | Mean (SE) | Max | Mean (SE) | Mean (SE) |
| 1 (City) | 10.0 (0.2) z | 1.4 | 20.5 | 12.2 (0.2) z | 6.7 | 24 | 21 (1) x | 111 | 3.4 (0.1) y | 1.5 (0.1) y |
| 2 (Lions) | 7.5 (0.1) y | 4.4 | 12.2 | 8.0 (0.1) y | 4.4 | 15.1 | 29 (1) y | 94 | 3.6 (0.1) z | 1.8 (0.1) z |
| 3 (Salem) | 7.1 (0.1) yx | 3.7 | 16.1 | 7.4 (0.1) x | 4.3 | 16.1 | 28 (1) y | 300 | 3.5 (0.1) zy | 1.5 (0.5) y |
| 4 (Jorgenson) | 6.9 (0.1) x | 3.9 | 12.4 | 7.1 (0.1) x | 3.9 | 12.8 | 32 (1) z | 130 | 3.0 (0.1) x | 1.3 (0.5) x |

Table 4 Wetted width, bankfull width, and mean (SE) depth, grain size, and cementation at each of 11 transects at four sites in Spearfish Creek within the city limits of Spearfish, South Dakota, USA. Transects A to K refer to furthest upstream to furthest downstream transect. Minimum and maximum values for wetted width and bankfull width are also included, along with maximum depth readings. Grain size values were recorded as fines = 1, sand = 2, gravel = 3, cobble = 4, and boulder = 5. Cementation values were denoted as uncemented = 1, cemented = 2

| Site (Park) | Transect | Wetted Width (m) | Bankfull Width (m) | Depth (cm) | Grain Size | Cementation |
|---------------|----------|------------------|--------------------|------------|------------|-------------|
| 1 (City) | A | 7.4 | 5 | 21 (5) | 3.8 (0.6) | 1.2 (0.1) |
| | B | 5 | 11.6 | 28 (2) | 3.2 (0.1) | 1.1 (0.1) |
| | C | 11.1 | 18.8 | 21 (3) | 3.3 (0.3) | 1.6 (0.2) |
| | D | 10 | 10 | 33 (8) | 3.6 (0.4) | 1.4 (0.2) |
| | E | 6.3 | 7.3 | 30 (7) | 3.8 (0.3) | 1.3 (0.1) |
| | F | 8.5 | 18 | 13 (2) | 2.9 (0.4) | 1.3 (0.1) |
| | G | 10.5 | 16 | 50 (13) | 2.6 (0.5) | 1.0 (0.0) |
| | H | 18.7 | 18.7 | 15 (3) | 3.3 (0.3) | 1.6 (0.2) |
| | I | 9 | 9 | 3 (1) | 3.4 (0.2) | 1.6 (0.2) |
| | J | 8 | 8 | 29 (6) | 3.8 (0.6) | 1.9 (0.1) |
| | K | 9 | 11 | 20 (4) | 3.7 (0.6) | 1.9 (0.1) |
| 2 (Lions) | A | 10 | 10.9 | 20 (4) | 3.3 (0.4) | 1.7 (0.1) |
| | B | 8 | 8.7 | 30 (4) | 3.9 (0.1) | 1.9 (0.1) |
| | C | 6.7 | 6.9 | 24 (5) | 3.7 (0.3) | 1.6 (0.2) |
| | D | 9 | 9.2 | 34 (8) | 3.0 (0.4) | 1.6 (0.2) |
| | E | 5.9 | 6.6 | 26 (5) | 4.0 (0.0) | 2.0 (0.0) |
| | F | 6.9 | 7.1 | 27 (5) | 3.4 (0.4) | 1.8 (0.1) |
| | G | 4.4 | 4.4 | 36 (6) | 4.0 (0.0) | 1.9 (0.1) |
| | H | 8.4 | 8.8 | 25 (4) | 3.9 (0.1) | 1.9 (0.1) |
| | I | 7.3 | 7.6 | 25 (4) | 3.9 (0.1) | 1.9 (0.1) |
| | J | 7.8 | 7.8 | 32 (3) | 3.4 (0.5) | 1.6 (0.2) |
| | K | 6.1 | 6.1 | 62 (8) | 2.4 (0.4) | 1.7 (0.1) |
| 3 (Salem) | A | 4.3 | 4.7 | 41 (7) | 4.0 (0.0) | 1.4 (0.2) |
| | B | 7.5 | 7.5 | 23 (4) | 3.4 (0.3) | 1.3 (0.1) |
| | C | 6.5 | 6.5 | 45 (10) | 3.6 (0.4) | 1.1 (0.1) |
| | D | 8.6 | 8.7 | 31 (6) | 3.7 (0.2) | 1.4 (0.2) |
| | E | 7.2 | 7.5 | 18 (5) | 3.7 (0.1) | 1.4 (0.2) |
| | F | 5.7 | 6 | 41 (7) | 3.7 (0.2) | 1.6 (0.2) |
| | G | 8.4 | 8.4 | 21 (4) | 2.9 (0.3) | 1.2 (0.1) |
| | H | 4.9 | 4.9 | 35 (7) | 3.6 (0.2) | 1.6 (0.2) |
| | I | 6.3 | 6.4 | 33 (7) | 3.6 (0.2) | 1.9 (0.1) |
| | J | 5.7 | 5.7 | 40 (4) | 3.3 (0.3) | 1.8 (0.1) |
| | K | 8.9 | 9.8 | 22 (4) | 3.6 (0.2) | 1.9 (0.1) |
| 4 (Jorgenson) | A | 12.4 | 12.8 | 31 (5) | 3.0 (0.4) | 1.4 (0.2) |
| | B | 8.2 | 8.3 | 39 (8) | 1.6 (0.3) | 1.6 (0.2) |
| | C | 7.2 | 7.5 | 42 (7) | 2.7 (0.3) | 1.4 (0.2) |
| | D | 8.6 | 8.8 | 45 (12) | 2.9 (0.1) | 1.1 (0.1) |
| | E | 7 | 7 | 22 (5) | 2.3 (0.3) | 1.4 (0.2) |
| | F | 9.3 | 9.5 | 15 (4) | 2.7 (0.3) | 1.0 (0.0) |
| | G | 7.7 | 7.7 | 41 (6) | 3.0 (0.4) | 1.4 (0.2) |
| | H | 5.5 | 5.5 | 41 (5) | 2.6 (0.2) | 1.2 (0.1) |
| | I | 4.7 | 4.7 | 31 (4) | 4.0 (0.0) | 1.2 (0.1) |
| | J | 4 | 4.1 | 51 (10) | 3.2 (0.4) | 1.3 (0.1) |
| | K | 5.4 | 6 | 33 (4) | 4.0 (0.0) | 1.3 (0.1) |

Table 5 Mean (SE) depth, grain size, and cementation within transect locations at four sites in Spearfish Creek within the city limits of Spearfish, South Dakota, USA. Mean wetted and bankfull width for each site is also provided. Within transect locations begin at 0% (left bank) and end at 100% (right bank). Grain size values were recorded as fines = 1, sand = 2, gravel = 3, cobble = 4, and boulder = 5. Cementation values were denoted as uncemented = 1, cemented = 2. Means followed by different letters within a site are significantly different (N = 51; $p < 0.05$)

| Site (Park) | Wetted width (m) | Bankfull Width (m) | Location | Depth (cm) | Grain Size | Cementation |
|---------------|------------------|--------------------|----------|------------|--------------|--------------|
| 1 (City) | 10.1 | 12.2 | 0 | 4 (1) w | 3.3 (0.1) z | 1.6 (0.1) xy |
| | | | 20 | 26 (2) y | 3.6 (0.1) z | 1.8 (0.1) z |
| | | | 40 | 34 (3) z | 3.6 (0.1) z | 1.7 (0.1) yz |
| | | | 60 | 30 (2) yz | 3.6 (0.1) z | 1.5 (0.1) x |
| | | | 80 | 20 (2) x | 3.5 (0.1) z | 1.4 (0.1) wx |
| | | | 100 | 3 (1) w | 2.9 (0.2) y | 1.3 (0.1) w |
| 2 (Lions) | 7.5 | 8.1 | 0 | 7 (2) x | 3.1 (0.2) x | 1.6 (0.1) x |
| | | | 20 | 36 (2) yz | 3.6 (0.1) y | 1.8 (0.1) yz |
| | | | 40 | 41 (2) z | 4.0 (0.1) z | 1.9 (0.1) z |
| | | | 60 | 40 (2) z | 4.0 (0.1) z | 1.8 (0.1) yz |
| | | | 80 | 34 (2) y | 3.7 (0.1) yz | 1.7 (0.1) xy |
| | | | 100 | 5 (1) x | 3.4 (0.1) xy | 1.6 (0.1) xy |
| 3 (Salem) | 7.2 | 7.5 | 0 | 4 (1) w | 2.8 (0.2) x | 1.5 (0.1) |
| | | | 20 | 37 (3) y | 3.6 (0.1) y | 1.6 (0.1) |
| | | | 40 | 49 (6) z | 4.0 (0.1) z | 1.4 (0.1) |
| | | | 60 | 40 (2) y | 3.8 (0.1) yz | 1.4 (0.1) |
| | | | 80 | 28 (2) x | 3.7 (0.1) yz | 1.5 (0.1) |
| | | | 100 | 5 (2) w | 3.1 (0.2) x | 1.5 (0.1) |
| 4 (Jorgenson) | 6.8 | 7.1 | 0 | 11 (3) y | 2.2 (0.2) y | 1.3 (0.1) |
| | | | 20 | 41 (3) z | 3.4 (0.1) z | 1.2 (0.1) |
| | | | 40 | 41 (3) z | 3.4 (0.1) z | 1.2 (0.1) |
| | | | 60 | 41 (3) z | 3.2 (0.1) z | 1.1 (0.1) |
| | | | 80 | 39 (3) z | 3.2 (0.9) z | 1.3 (0.1) |
| | | | 100 | 12 (3) y | 2.3 (0.2) y | 1.6 (0.1) |

Grain size along the transects was different for each of the sites. At site 1, the grain size of 2.9 at the right bank (100%) was significantly different from the rest of the points, which ranged from 3.3 to 3.6. At site 2, the grain size of 4.0 at 40% and 60% was significantly different from the grain size of 3.4 to 3.6 at 20%, 80%, and 100%, which in turn were significantly different from the grain size of 3.1 at 0%. At site 3, grain size from 20% to 80% were significantly larger than those at either bank. While grain size was smaller at site 4, it followed a pattern similar to that observed at site 3 with 0% and 100% significantly smaller than 20% to 80%.

Significant differences along the transects in cementation were only observed at sites 1 and 2. At site 1, the 1.8 cementation value at 20% was significantly greater than the 1.3 cementation value at 100%. Cementation ranged from 1.4 to 1.7 at the other sampling points. At site 2, cementation at 1.6 was significantly lower at 0% and 100% compared to the 1.9 cementation at 40%. Cementation values at the other sampling points were very similar. There were no significant cementation differences along the transects at sites 3 and 4. All of the values at site 3 ranged from 1.4 to 1.6, while at site 4 the range was 1.1 to 1.6.

Maps

A bathymetric chart, grain size map, and cementation map for site 1 are shown in Figure 8. The deepest points at this site were located in two pools on the southern end of the reach. The bed form followed a typical trend, with deeper areas in the middle of the stream and graduating to shallower on the banks. This reach also contained two areas where the channel was divided into two. Generally, the grain

size map follows a similar pattern to the depth, graduating for larger sizes in the deeper middle to finer grains along the shallower banks. However, in some areas an inverse of this pattern was observed, with finer grains in the middle and larger sizes along the banks. The cementation map illustrates the positive relationship between cementation and the occurrence of cobble-sized substrate, along with no obvious relationship with depth.



Figure 8 Site 1 bathymetric (left), grain size (center), and cementation (right) maps. Bathymetric chart represents stream depth in cm with contours at an interval of 30 cm.

Similar to site 1, the bathymetric chart for site 2 shows the channel bed is lowest in the middle and graduates upwards to the banks (Figure 9). The grain size map illustrates how this site was dominated by cobble, with only pockets of smaller (gravel-silt) or larger (boulder) grain size within channel bed. The cementation map shows again the positive relationship between cobble-size grains and cementation. Cementation is wide-spread in this cobble-dominated site, with only pockets of uncemented substrate. The bathymetric chart for site 3 indicates a relatively gradual gradient, similar to sites 1 and 2 (Figure

10). Unique to this site is one point 3 m deep in the middle of a stream bend. Cobble dominates in this site and is again associated with high cementation. The bathymetric chart for site 4 shows a depth gradient in the same pattern as the three upstream sites (Figure 11). The grain size patterns are similar to sites 1 and 3, with larger grain size found in the lower areas of the bed channel. However, unlike the other sites, this site is dominated by gravel. There is little cementation, and the cementation that does occur is associated with cobble-sized substrate.



Figure 9 Site 2 bathymetric (left), grain size (center), and cementation (right) maps. Bathymetric chart represents stream depth in cm with contours at an interval of 30 cm.



Figure 10 Site 3 bathymetric, grain size, and cementation maps. Bathymetric chart shows values in cm with contours at an interval of 30 cm.

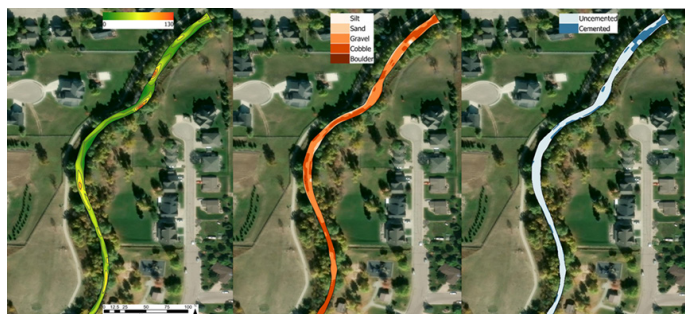


Figure 11 Site 4 bathymetric, grain size, and cementation maps. Bathymetric chart shows values in cm with contours at an interval of 30 cm.

Discussion

To our knowledge, this study is the first to document and characterize substrate and fluvial geomorphology data for Spearfish

Creek through the city of Spearfish. Across the four sites, the stream shows a systematic downstream change in channel morphology, with increasing depth and decreasing width as suggested by Malik and Islam.³¹ In addition, this reach of Spearfish Creek within the city of Spearfish has considerable spatial variation in grain size composition and cementation.

Channelization & urbanization

Spearfish Creek has been altered from its natural state by diversion of the entire flow (with exception of high flow events) into an aqueduct upstream of city limits, resulting in a water loss zone downstream of the aqueduct.^{2,32} The diverted water is re-introduced from a hydropower electrical generating power plant a few hundred kilometers above site 1. While there is minimal bedrock water loss from Spearfish creek as it passes through Spearfish,³² the alteration of natural flow dynamics likely has geomorphic consequences in the sites sampled in this study.^{33–35}

The discharge from the D. C. Booth Historic National Fish Hatchery may explain the increased creek width at site 1.^{9,10} Wastewater discharge is known to alter stream morphology.^{36,37} In addition, site 1 is bordered by Spearfish City Park and Spearfish Creek is heavily used for recreation. In particular, children playing directly in the creek, including moving rocks, are also likely impacting stream width and morphology.³⁸ The reduction in width and increase in depth moving downstream in Spearfish Creek in Spearfish follows the pattern frequently observed with urbanization.^{39–41}

Karstic influence & underlying geology

Rock formations in the Black Hills of South Dakota, which includes the city of Spearfish, commonly display karst features.^{4,42,43} Composed of dissolvable limestone, the Minnelusa and Madison formations are approximately 40 m underneath Spearfish Creek in the sites used in this study and are known for karstic sinkholes and springs locally.^{2,4,44} While reaches of Spearfish Creek lose and gain water because of the underlying karst,^{2,4,5,44} there is minimal influence from these aquifers on Spearfish Creek as it passes through Spearfish.³² Younger, confining, fine-grained sedimentary layers, overlying the Minnelusa and Madison formations impede water penetration.⁴ Thus, while Spearfish Creek over its entire length is influenced by karst formations, the creek bed in Spearfish is not directly karstic. Karst systems often exhibit complex hydrology, making channel morphology difficult to interpret without detailed hydraulic data,^{44,45} but karst is assumed to have limited impact on the hydrology of the creek through the city.

Cementation

Cementation rates of approximately 55% occurred in the sites of Spearfish Creek described in this study. Stream substrate cementation is influenced by many factors, including pH, temperature, pressure, water velocity, and water volume.⁴⁶ While frequently the result of carbonate minerals,^{47–50} biological activity⁵¹ and other suspended cementing agents⁵² may cause cementation. Calcium carbonate is a common cementing agent in streams, and its precipitation is the primary source of cementation in Spearfish Creek.^{47–50} Spearfish Creek is supersaturated with calcium carbonate because of its origination and groundwater inputs from limestone aquifers.^{1,5} Stetler and Sieverding⁵ documented cementation in Spearfish Creek upstream from where it is diverted into the aqueduct, well upstream from any of the sites of this study. They noted that cementation within the channel was spatially variable, fluctuated between precipitation and dissolution, and was likely controlled by water temperature, groundwater upwelling, and algal growth and decay.⁵ Grain size can also influence cementation.^{53,54}

This was observed in the present study, where cementation was mostly associated with cobble-sized grains and was much less abundant on gravel-sized grains.

Carbonate cementation can affect many aspects of stream morphology and ecology.^{55–59} Of particular concern with Spearfish Creek is the potential effect of cementation on sport fish populations, such as brown trout and rainbow trout. Similar to cementation, Bolliet et al.⁶⁰ observed that stream substrate embeddedness could impact the growth of juvenile brown trout. Cementation may impact trout spawning.⁶⁰ Stetler and Sieverding⁵ suggested that the timing of cementation and dissolution in Spearfish Creek above the aqueduct diversion was at least partially responsible for successful rainbow trout reproduction and hindered brown trout spawning efforts. While the relationship between fish reproductive success and carbonate cementation in streams is not well documented, the prevalence of cementation might make redd construction more difficult. However, trout redds are extremely numerous throughout Spearfish Creek and its tributaries.^{16–19,62,63} This suggests that cementation does not occur at rates that inhibit redd construction or that the carbonate dissolution because of water temperatures or algal action⁵ allows cementation to decrease to a level suitable for trout spawning. In addition, brown trout reproductive success in Spearfish Creek is extremely successful.^{14,64}

Grain size

The decrease in grain size from predominantly cobble at site 1 to predominantly gravel at site 4 follows the typical pattern of downstream fining.^{65–67} The changes observed in this study in stream bed grain size may affect the flow resistance in the channel, stability of the bed, and quantity of aquatic habitat.^{68,69} Grain size and grain distribution can also influence other channel characteristics, including bedload transport.⁷⁰ Because of the importance of Spearfish Creek as a recreational trout fishery,^{15,64} the potential impacts of grain size on fish populations is also worthy of discussion. Grain size is one factor that controls habitat availability for fish.^{68,69} In addition to influence food availability, cover, and rearing habitat,⁷⁰ grain size is also critical for successful reproduction.^{71–73} The gravel to cobble substrate observed in this study is ideal for spawning trout that prefer coarse substrate for redd excavation.^{69,74} That the grain size in Spearfish Creek is suitable spawning habitat is supported by the abundance of redds observed in prior years by Martling et al.¹⁶ near site 1 and Robidoux et al.¹⁷ near site 4.

Limitations

This study was limited in scope and duration. The results of this study may not be representative of the entire creek because only four, 400-m reaches within the limits of the city of Spearfish were examined. However, the United States Environmental Protection Agency National Rivers and Streams Assessment Program²⁷ uses one reach per stream to produce reports on the conditions of water resources of that stream. Data for this study were collected in only one spring season. Consequently, these results may not be indicative of different years, seasons, or conditions due to changes in sediment transport or flow rate.⁶⁸ Substrate size classifications, depth, wetted width, and bankfull width measurements may be impacted by the inexperience of the observer and alternation of observers between sites.^{68,75} While visual and tactile estimates may be less accurate than specific measurements, numerous studies validate their use.^{26,27,68}

Bathymetric charts produced in this study using field data and extrapolated in ArcGIS Pro, may be less accurate than modern sonar

methods.⁷⁶ Bathymetry of large waterbodies is typically measured by shipboard and echo sounding,^{77–79} and remote sensing methods with an accuracy limit minimum of 12 m.⁷⁷ However, manual depth measurements may be sufficient for bathymetric charts,^{80,81} particularly if Geographical Information Systems (GIS) technology is also used^{78,79} as occurred in this study.

Summary

This initial study documenting bed topography of four reaches of Spearfish Creek within Spearfish can serve as a baseline for future studies within the same sites or in Spearfish Creek as a whole. The results of this study can be used to characterize morphologic patterns,^{68,80,82} calculate sediment transport and budgets,^{80,82} monitor sedimentation and erosion, and make management decisions on the aquatic habitat.^{78,79,83} Further monitoring of the stream can provide insights into the evolution and health of Spearfish Creek.

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Conflicts of interest

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