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The geometric, sedimentologic and hydrologic attributes of spring-dominated channels in volcanic areas

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Abstract

In volcanic areas of Idaho, Oregon and Montana, a number of perennial streams emerge from single springs or zones of springs. Surface drainage areas to these springs can be very small, often much smaller than the recharge area of the springs. Channels downstream of springs are often straight, or if sinuous, without regularity to the pattern. Bars are absent or poorly defined, but islands or downed timber are common in the channel. Channel width-to-depth ratios are large relative to those of runoff-dominated channels. Downstream hydraulic geometry exponents are similar, but the exponents for width and velocity are greater in spring-dominated channels. Manning roughness values are relatively large. The bedsurface in gravel-bed spring-dominated streams is armored. Computations indicate that bed material is probably capable of moving at bankfull stage.

The hydrograph of spring-dominated streams is damped as compared to runoff-dominated streams locally and elsewhere. Peak flows occur months after precipitation or snowmelt. Mean annual flow for spring-dominated streams averages 72% of the flood with a recurrence interval of 2 years; the mean annual flow for runoff-dominated channels averages 18% locally and 25% elsewhere. The 50-year flood averages 1.6 times the 2-year flood on the annual series while the corresponding value for runoff-dominated channels in the region is 2.5. The damped hydrograph of spring-dominated streams suggests that they are somewhat different from runoff-dominated channels in the relationship between water and sediment. In spring-dominated channels, 34% of sediment is transported by flows above the 2-year flood—less than is observed typically in runoff-dominated channels. The effective discharge is similar in magnitude to the 2-year flood. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Spring-dominated channel; Runoff-dominated stream; Hydrograph

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1. Introduction

Spring-dominated or spring-fed channels are those that receive the bulk of flow from discrete groundwater discharge (springs) (Whiting and Stamm, 1994, 1995; Stamm and Whiting, 1994). In contrast, runoff-dominated streams receive the bulk of flow from distributed sources in the watershed. Whiting and Stamm (1995) described qualitatively the geomorphology of a limited number of spring-dominated perennial channels in areas of volcanic rock in Idaho and Oregon. Spring-dominated channels are wide, bars are developed poorly, and logs and aquatic vegetation may clog the channel. The often organic-rich floodplain soils of spring-dominated channels

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are very moist. Streambeds lack a cover of fines indicating that sediment transport occurs frequently enough to flush fine sediment although the surface drainage area to the channels is very small.

The streamflow in spring-dominated channels is relatively constant but because of channel geometry and hydrology has flow probability characteristics different than runoff-dominated channels. In the one spring-dominated channel investigated by Whiting and Stamm (1995), baseflow was 65% of the bankfull discharge, whereas the respective value for runoff-dominated channels is 10%. Flows exceeded bankfull 20% of the time whereas the typical value for runoff-dominated channels is 2–4%. Peak flows occurred in late summer or fall whereas peak flows in runoff-dominated channel in the study areas occur with the spring snowmelt. This was attributed to tortuous subsurface flowpaths to the springs. Bankfull flows occurred with a recurrence interval of about 1.7 years at Browns Creek, which is roughly

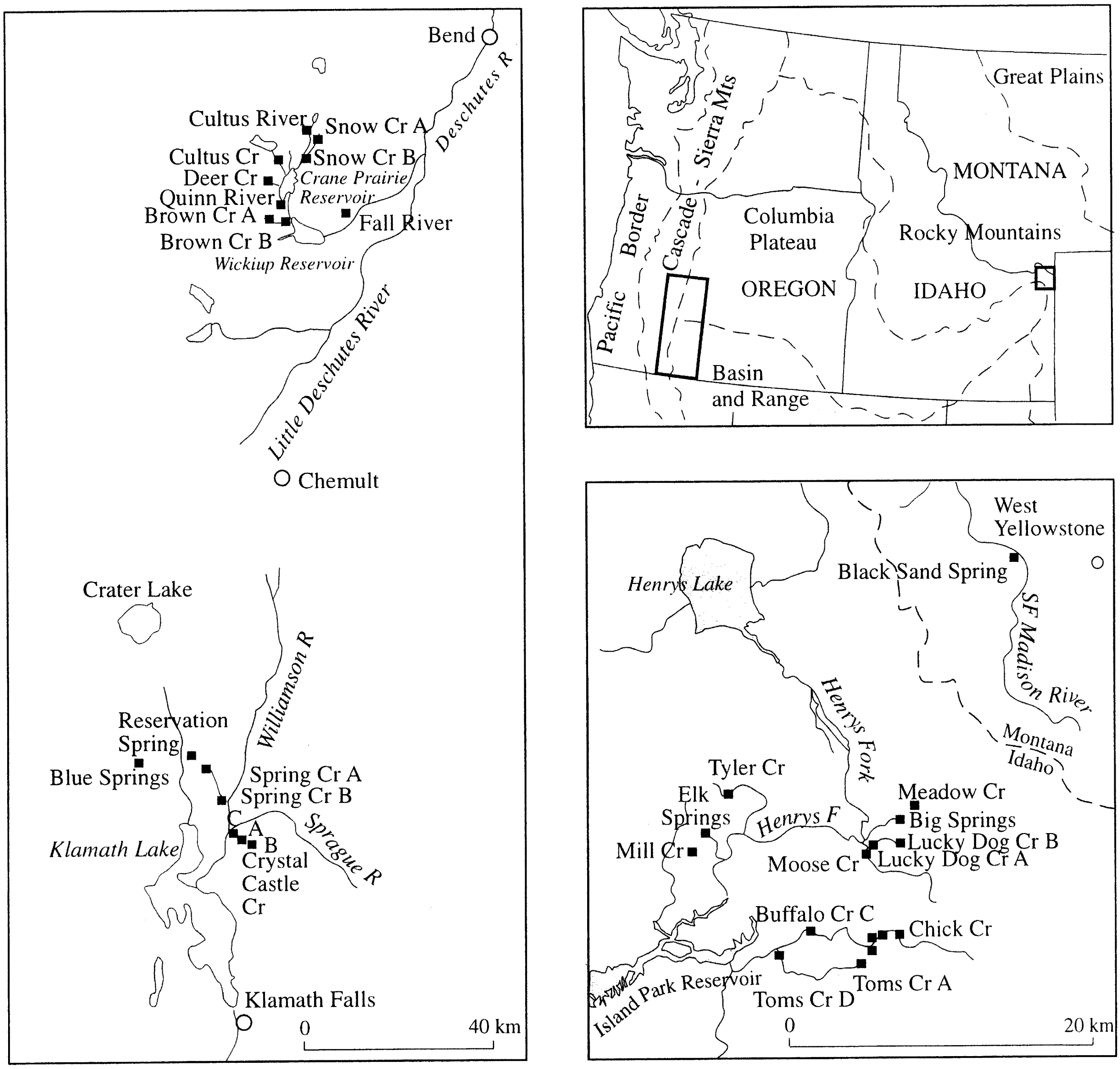

Fig. 1. Location map of spring-dominated streams.

Table 1
Basin and channel attributes

Stream	Quadrangle (7.5 min)	Location	Basin area (km^2)	Elevation (m)	Channel slope	Q (m^3/s)	Width (m)	Depth (m)	Velocity (m/s)
Spring-dominated									
Big Springs	Big Springs, ID	center of NW1/4 Sec. 33 T14N R44E	0.15	1947	0.00098	6.19	68.4	0.34	0.129
Black Sands Creek	Madison Arm, MT	SW1/4 NE1/4 Sec. 31 T13S R5E	0.082	2015	0.00092	0.70	25.3	0.25	0.098
Blue Springs	Mares Egg Spring, OR	SE1/4 NE1/4 Sec. 23 T33S R6E	0.48	1274	0.00599	0.089	3.75	0.32	0.074
Browns Creek A	Davis Mt., OR	NE1/4 SW1/4 Sec. 30 T21S R8E	0.65	1341	0.00883	0.336	10.1	0.27	0.139
Browns Creek B	Davis Mt., OR	SE1/4 NW1/4 Sec. 29 T21S R8E	55.9	1323	0.00774	1.671	10.5	0.36	0.541
Buffalo River A	Island Park, ID	SW1/4 SW1/4 Sec. 21 T13N R44E	0.80	1928	0.00296	0.21	14.3	0.29	0.040
Buffalo River B	Island Park, ID	SW1/4 SW1/4 Sec. 21 T13N R44E	24.1	1928	0.00299	0.78	6.84	0.31	0.243
Buffalo River C	Island Park, ID	SE1/4 NW1/4 Sec. 24 T13N R43E	42.7	1916	0.00126	4.81	34.3	0.45	0.255
Buffalo River D	Island Park, ID	SW1/4 SW1/4 Sec. 21 T13N R44E	25.0	1928	0.00284	1.28	24.3	0.29	0.139
Chick Creek	Island Park, ID	SE1/4 NE1/4 Sec. 21 T13N R44E	22.9	1935	0.00319	1.08	4.41	0.55	0.487
Crystal Castle Cr A	Chiloquin, OR	SW1/4 SW1/4 Sec. 7 T35S R8E	9.10	1387	0.01420	0.0061	0.94	0.074	0.020
Crystal Castle Cr B	Chiloquin, OR	SE1/4 SE1/4 Sec. 2 T35S R7E	14.3	1289	0.03020	0.0050	1.56	0.14	0.015
Cultus River	Crane Prairie Res., OR	NE1/4 NW1/4 Sec. 20 T20S R8E	0.11	1387	0.00212	0.065	7.45	0.22	0.024
Elk Springs Creek	Island Park Dam, ID	NW1/4 NW1/4 Sec. 5 T13N R43E	0.28	1975	0.04900	0.024	1.00	0.13	0.206
Lucky Dog Cr A	Island Park, ID	SW1/4 NW1/4 Sec. 3 T13N R44E	0.15	1951	0.00021	0.92	14.7	0.37	0.112
Lucky Dog Cr B	Island Park, ID	NE1/4 NE1/4 Sec. 5 T13N R44E	5.75	1947	0.00174	1.35	6.32	0.51	0.453
Meadow Creek	Big Springs, ID	NE1/4 SE1/4 Sec. 16 T14N R44E	0.19	1957	0.00206	0.44	9.32	0.32	0.167
Mill Creek	Island Park Dam, ID	NW1/4 SE1/4 Sec. 6 T13N R43E	1.88	1961	0.01090	0.19	3.90	0.32	0.152
Reservation Spring	Fort Klamath, OR	NW1/4 NE1/4 Sec. 23 T33S R7E	0.12	1274	0.00258	1.73	22.0	0.37	0.225
Snow Creek A	Elk Lake, OR	SW corner of Sec. 34 T19S R8E	0.33	1402	0.00920	0.768	10.8	0.36	0.116
Snow Creek B	Crane Prairie Res., OR	NE 1/4 NE 1/4 T20S R8E	3.58	1387	0.01010	0.82	11.2	0.43	0.144
Spring Creek A	Fort Klamath, OR	SW 1/4 NE 1/4 Sec. 33 T33S R7E	72.8	1283	0.00013	1.99	45.4	0.61	0.071
Spring Creek B	Fort Klamath, OR	NW1/4 NE1/4 Sec. 9 T34S R7E	33.8	1283	0.00011	7.71	48.0	1.05	0.166
Toms Creek A	Island Park, ID	SW1/4 SW1/4 Sec. 29 T13N R44E	0.94	1920	0.00595	0.0872	5.69	0.18	0.057
Toms Creek D	Island Park, ID	NE1/4 NE1/4 Sec. 27 T13N R43E	14.4	1914	0.00026	1.18	9.15	0.76	0.179
Tyler Creek	Sawtell Peak, ID	NE1/4 SW1/4 Sec. 28 T14N R43E	3.15	1999	0.00811	0.20	1.83	0.27	0.201
Run-off dominated									
Crystal Castle Cr C	Chiloquin, OR	SW1/4 SW1/4 Sec. 7 T35S R8E	8.95	1393	0.00106	0.006	0.60	0.059	0.041
Deer Creek	Crane Prairie Res., OR	SE1/4 SE1/4 Sec. 26 T20S R7E	53.1	1396	0.0308	0.110	3.26	0.17	0.075
Moose Creek	Island Park, ID	SW1/4 NE1/4 Sec. 5 T13N R44E	39.7	1948	0.00103	0.64	3.01	0.54	0.382

equivalent to values for snowmelt- and runoff-dominated channels.

Manga (1996, 1997, 1999) investigated the hydrology of several of these spring-dominated systems in Oregon described by Whiting and Stamm (1995). The springs were modeled as fed by an unconfined aquifer recharged by annual snowmelt. Manga (1999) showed that the annual hydrograph peak in late summer and fall was tied to the snowmelt in the same year although the discharged water was several years to decades old. Manga (1997) reported that most of the precipitation could be accounted for by evapotranspiration and a delayed spring-dominated hydrograph, which indicated a very small portion of the annual precipitation ran quickly off the landscape.

In this study, we aim to describe more quantitatively than in Whiting and Stamm (1995) the geomorphology and hydrology of a larger set of spring-dominated streams in volcanic settings. Specifically, we investigated the geomorphic setting, planform, and topography of the spring-dominated channels; the size and nature of the bed and bank material; and the frequency and duration of flows. The geomorphic and hydrologic attributes of the spring-dominated channels were compared with those of runoff-dominated channels. Finally, we examined whether the distinctive hydrology of spring-dominated streams was reflected in the fluvial geomorphology of these streams.

2. Field area

Many spring-dominated channels are found in eastern Idaho, southwestern Montana, and southcentral Oregon (Fig. 1). During the summer of 1996, 26 reaches along 16 streams were studied to characterize the geometry, hydrology, and sediments of such systems (Table 1). Three local streams with characteristics of runoff-dominated systems were studied to provide a contrast to the spring-dominated systems. Several of the streams were described briefly in an earlier report based upon a reconnaissance of 10 spring-dominated streams (Whiting and Stamm, 1995).

The channels studied in eastern Idaho and southwestern Montana are located in the easternmost part of the Columbia Plateau (Snake River Plain) and neighboring Middle Rocky Mountains physiographic provinces (Fenneman, 1931). Elevations of study reaches range from about 1915 to 2015 m but surrounding uplands reach 3200 m. Annual precipitation is 750–1000 mm except up to 1500 mm at higher elevations (University of Idaho, 1995). Most of the precipitation falls as snow (US Geological Survey, 1994a). The area is underlain by Quaternary rhyolite and basalt (Christiansen and Blank, 1972).

The spring-dominated streams investigated in southwest Oregon are located along the border of the Cascade-Sierra Mountains and Basin and Range physiographic provinces (Fenneman, 1931). The spring-dominated channels are found at elevations from 1270 to 1400 m. This region is largely in the rain shadow of the Cascades to the west. Mean annual precipitation, dominated by snow, decreases from over 2000 mm to the west to about 500 mm in the eastern part of the study area (US Geological Survey, 1994b). The area is underlain by Quaternary basalt and basaltic andesite.

3. Methods

Various measurements were made to characterize the geomorphology, hydrology, and sediment at sites. Potential sites to investigate were identified from previous work on spring-fed streams in the study areas (Whiting and Stamm, 1995) and by examination of topographic maps in the regions.

Channel planform, as observed in the field and from topographic maps, was classified following Kellerhals et al. (1976). Stream width was measured with a cloth tape at about 15 transects spaced about a channel width apart along the channel. At these transects, depth of water was measured using a stadia rod at approximately one-quarter, one-half, and three-quarters the channel width. The elevation of the water surface along one bank and the elevation of the nearby bankfull surface at each transect was surveyed. One detailed cross-section was surveyed of the channel and valley bottom with at least 20 points at regular intervals in the channel and at additional points on the floodplain and low terraces. The cross-section was measured between bends, if they existed, in a reach with good definition of the floodplain along both banks and in reaches free of obstacles. At the cross-section, discharge was measured using standard methods (US Geological Survey, 1977). A Pygmy or Price current meter attached to a topset wading rod was positioned at 0.6 of the depth from the surface; the point velocity was taken as the mean velocity of the column of water. Twenty verticals were measured typically for 60 s. Local velocity and depth were integrated across the channel to give the flow discharge—the mid-section method used by the US Geological Survey and shown by Hipolito and Loureiro (1988) to give the most precise measurement of total discharge through. Precision in measurement of depth is about 1 cm, width about 1%, elevation of the water surface about 0.2 cm, bankfull surface elevation several cm, channel bed elevations 0.1 cm, velocity several percent, and discharge 5%.

Grain size on the bed surface was estimated following the method of Wolman (1954). Along three or more transects of the channel, a total of 50 or more grains were selected blindly, the intermediate (*b*-axis) measured, and the length recorded. Grains were replaced on the bed. In addition, surface and subsurface particle size was determined. Twenty-five surface grains were measured in an approximately 1 m^2 area, the surface grains were removed to a depth about one median particle diameter, and then 25 subsurface grains were measured. These measurements were made in submerged areas away from obstructions to the flow where the bed was gravel and the cross-section relatively uniform. Precision in measurement of particle size using this approach is probably about 10%.

Bank material was collected at two or three locations on the floodplain—at least one near the channel and one at the outer edge of the floodplain. Cores extended to the approximate level of the channel bottom. Segments of the cores were collected separately and described, and the material returned to the lab for analysis. Samples were air-dried for weeks, then sub-samples oven-dried at 80°C for several hours. Dried samples were weighed and then placed in a muffle furnace at 440°C. After combustion of the organic component, samples were cooled in a desiccator and re-weighed. The percentage of organic material in samples is the mass lost divided by the dried weight of the sample multiplied by 100. The characterization of organic content follows accepted methods (ASTM, 1995).

Basin area was estimated from topographic maps (USGS 7.5 min quadrangles) using a planimeter.

4. Results

4.1. Physiography of spring-dominated basins

The spring-dominated streams that were studied range in basin area from 0.082 to 72.8 km^2 (Table 1). Twelve of the 26 reaches have basin areas less than 1 km^2. Recharge area is certainly larger than surface drainage area in most of these basins (Whiting and Stamm, 1995). Topographic maps indicate the streams are perennial below the springs but ephemeral channels exist above the springs at some sites. Stream length above the study sites ranges from several kilometers to just a few meters as determined by observation in the field and by reference to topographic maps. Elevations at the sites range from 1274 to 2015 m (Table 1).

Many streams emerge from springs that are at the base of adjacent highlands—i.e., Black Sands Springs (Fig. 2a) and Reservation Spring (Fig. 2b). The locations of these springs are probably controlled by permeability contrasts between rock units and along faults. Benjamin (2000) notes that Big Springs, Lucky Dog, and Moose Creek have their source at springs near the contact of the overlying more permeable Buffalo Lake rhyolite flow and the Lava Creek Tuff. Nearby Buffalo River, Chick Creek and Toms Creek springs are found in the Lava Creek Tuff, but Benjamin (2000) supposes a similar mechanism controls their location. The springs in central Oregon (Cultus River and Browns Creek) are found near the surface contact of permeable basalts above and less permeable sediments below (Manga, 1998). Many of the springs in southern Oregon are located along the trace of northwest to north trending normal faults associated with Basin and Range extension. Fig. 2b shows springs emerging at the base of a steep, fault-controlled slope at Reservation Spring. The stream below Reservation Spring lies in a narrow box-canyon that suggests that spring-sapping (e.g., Laity and Malin, 1985; Schumm et al., 1995) has played a role in the evolution of topography.

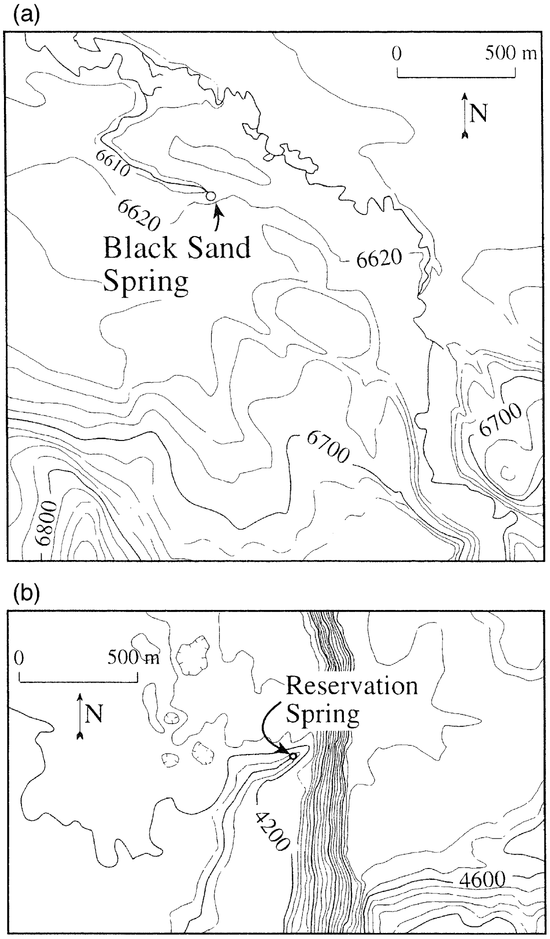

Fig. 2. (a) The topography surrounding Black Sands Springs, MT. (b) Topography surrounding Reservation Springs, OR.

Springs discharging to the channels appear to be exsurgent—i.e., due to the concentration of diffuse flow at the springhead rather than resurgent—the re-emergence of a former surface stream.

4.2. Channel topography and flow patterns

The planform of spring-dominated channels is best described as irregular (Kellerhals et al., 1976). The channels are not straight, but no regularity occurs in the occasional bend. On a few systems like Black Sands Spring, the stream is relatively straight near the source and becomes more sinuous downstream (Fig. 2a). It is not uncommon to observe small islands, many of which are little more than tufts of grass (Fig. 3). Many of the islands may have become established on woody debris that collected in the channel.

Channel bars, if any, are developed poorly. This was shown by mapping and by sets of longitudinal measurements of water depth at quarter-width intervals across the channel. The amount of timber in the channel ranges up to five pieces capable of spanning the channel width per channel width. The 'jack straw' position of timber in many of the streams—haphazard orientation of timber in the channels—suggests that streamflow has been insufficiently strong to remove or reorient this material for many years. Other evidence for the persistence of the woody debris includes the following (M. Manga, personal communication, 2000): nurse trees growing on the downed trees, air photos from the 1950s which show downed trees identifiable today, and calculation of the drag necessary to move the debris (Manga and Kirchner, 2000).

Flow pattern in these channels is often controlled by the presence of the logs in the channel or islands. Flow snakes around these obstacles such that multiple corridors of higher velocity occur often. The flow measurements at cross-sections do not illustrate the phenomenon because cross-sections were selected for quality of measurements and simplicity of flow. At some sites (e.g., Buffalo River A), thick mats of water cress (*Rorippa nasturium-aquaticum*) can fill the channel especially later in the season (Fig. 4). These mats sometimes cause flow to be concentrated in very narrow longitudinal slots between mats. The organic mats also appear to be sufficiently thick late in the growing season to raise the water level as they raise resistance to flow.

Spring-dominated channels usually have a well-defined floodplain along at least one bank (Fig. 5). Few scroll bars or old channelways are apparent in the field to indicate significant lateral migration although the presence of the floodplain in many systems could be evidence for migration over longer time frames. In some settings (Tyler Creek and Browns Creek), a terrace or terraces are found along the stream. At sites in Oregon, some cores near the channel contain Mazama ash indicating persistence of some parts of the floodplain for 7 ka.

Channel width at bankfull stage in spring-dominated systems ranges from 0.97 m at Elk Springs

Fig. 3. Small islands often dot the course of spring-dominated channels; many of these may have been established as tufts of grass on woody debris.

Fig. 4. Thick mats of vegetation (*R. nasturium-aquaticum*) grow in some channels—Buffalo River, ID.

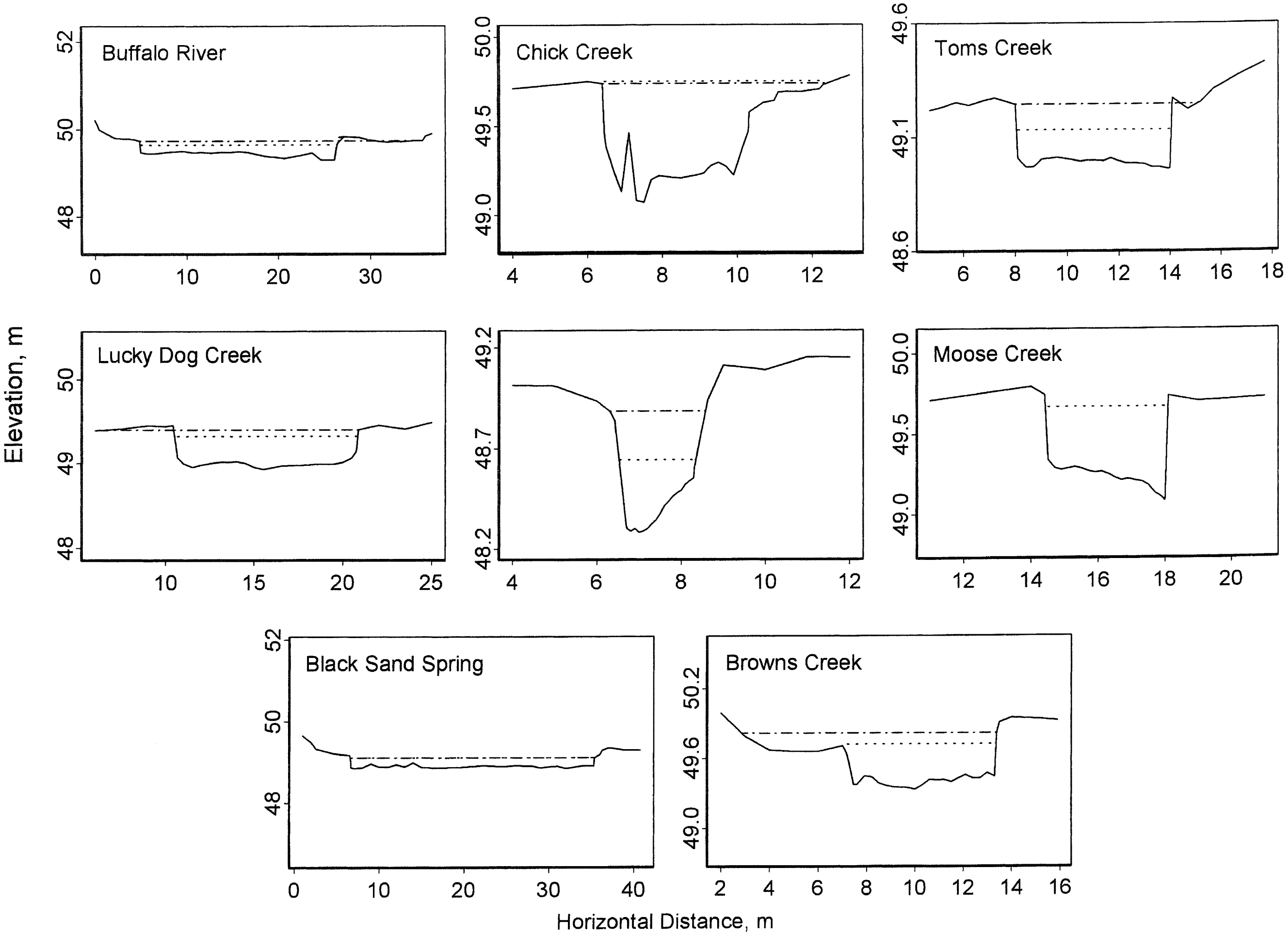

Fig. 5. There is usually a well-defined floodplain along at least one bank. The bankfull flow level is shown (-·-·-) as is the water level at the measured stage (· · · · ·).

to 68.4 m at Big Springs. Channel width is variable along the channel. Channel depth at bankfull ranged from 0.12 m at Elk Springs to 0.97 m at Spring Creek (Table 2). Bankfull width-to-depth ratio at sites ranges from 4 at Tyler Creek to 98 at Big Springs. The mean value is 34, and the standard deviation (σ) is 27. The width-to-depth ratio of spring-dominated streams appears to be greater than that of runoff-dominated streams. The mean value for 39 runoff-dominated channels in the Salmon River Basin in Idaho is 19 ($\sigma = 9$) (data from Emmett, 1975). The difference in width-to-depth ratios is statistically significant (t-ratio $= -3.22$, $n_1 = 39$, $n_2 = 26$, $s_d = 4.71$).

The slope of the water surface at the spring-dominated sites ranges from 0.00011 at Spring Creek to 0.049 at Elk Springs Creek (Table 1). The median value for the spring-dominated sites is 0.0030.

4.3. Flow discharge, flow resistance, and estimated bankfull discharge

The measured flow discharge at sites ranged from 0.0050 to 6.19 m^3/s. Using the measured geometry

Table 2
Bankfull geometry and estimated discharge

Stream	Bankfull width (m)	Bankfull depth (m)	Manning n	Bankfull discharge (m^3/s)	Shields number
Spring-dominated					
Big Springs	68.4	0.70	0.0569	20.5	0.138
Black Sands Creek	25.4	0.28	0.1072	0.848	0.039
Blue Springs	3.75	0.32	0.4399	0.089	0.232
Browns Creek A	10.1	0.24	0.3080	0.277	0.143
Browns Creek B	10.3	0.30	0.0964	1.22	0.061
Buffalo Creek A	14.7	0.36	0.4588	0.308	0.108
Buffalo Creek B	8.03	0.40	0.0643	1.39	0.072
Buffalo Creek C	34.3	0.55	0.0658	6.69	0.084
Buffalo Creek D	24.8	0.37	0.1266	1.95	0.127
Chick Creek	4.03	0.55	0.0734	0.974	–[a]
Crystal Castle Cr A	1.28	0.24	0.2213	0.0517	–[a]
Crystal Castle Cr B	1.57	0.22	na[b]		0.212
Cultus River	8.37	0.33	0.4077	0.142	–[a]
Elk Springs Creek	0.97	0.12	0.2642	0.0205	0.356
Lucky Dog Cr A	16.4	0.50	0.0427	1.68	–[a]
Lucky Dog Cr B	7.09	0.42	0.0576	1.12	0.049
Meadow Creek	9.39	0.28	0.1378	0.356	0.350
Mill Creek	3.90	0.32	0.2904	0.190	0.303
Reservation Spring	22.0	0.35	0.1206	1.58	0.036
Snow Creek A	10.9	0.61	0.2356	1.82	0.283
Snow Creek B	11.2	0.51	0.3203	1.08	3.122
Spring Creek A	45.8	0.61	0.1135	2.01	–[a]
Spring Creek B	48.0	0.97	0.0688	6.77	0.013
Toms Creek A	6.07	0.25	0.2776	0.159	0.200
Toms Creek D	9.42	0.70	0.0712	1.07	–[a]
Tyler Creek	1.91	0.52	0.0783	0.553	0.365
Runoff-dominated					
Crystal Castle Cr C	0.96	0.16	0.0248	0.0491	–[a]
Deer Creek	3.94	0.37	0.2543	0.463	0.085
Moose Creek	3.16	0.53	0.0441	0.658	0.055

[a] Grain size was characterized as < 1 mm.
[b] Unreasonable roughness number.

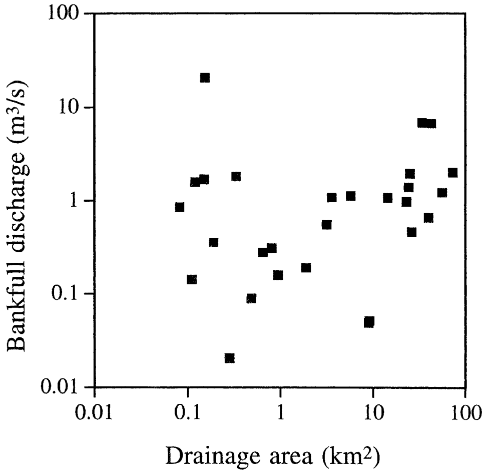

Fig. 6. Bankfull discharge is uncorrelated to drainage area at spring-dominated sites.

and measured flow discharge (Table 1), the roughness was estimated using the Manning equation:

$$n = \frac{S^{0.5}R^{0.66}}{\bar{U}} \tag{1}$$

where n is the roughness value, S is slope, R is the hydraulic radius, and $\bar{U}$ is the channel-wide average velocity. Hydraulic radius is the cross-sectional area divided by the wetted perimeter of the cross-section. Manning's n in spring-dominated channels was quite variable and ranged from 0.043 to 0.46 (Table 2). The mean value was 0.180 ($\sigma = 0.131$). The roughness of spring-dominated channels is greater than that of other channels in the region. The average Manning n value for the runoff-dominated streams in the Salmon River basin was 0.046 ($\sigma = 0.017$) (data from Emmett, 1975). The difference in roughness is statistically significant (t-test ratio $= -6.35$, $n_1 = 39$, $n_2 = 25$, $s_d = 0.0211$).

Manning's n was higher where more vegetation, islands, or downed timber were found in the channel. For instance, the n-value at Buffalo River A, which is clogged with water cress (*R. nasturium-aquaticum*), was 0.46. In systems with at least two study sites along the stream, roughness and the amount of organic debris in the channel were directly related in five of six cases. If the amount of debris increased downstream, roughness increased; or if the amount of debris decreased downstream, roughness decreased.

Bankfull discharge was estimated from the surveyed geometry at bankfull assuming roughness and slope were the same at bankfull as at the measured stage. The measured discharge on the day of survey (Table 1) ranged from 11% to 137% of bankfull discharge (Table 2) at spring-dominated sites. The mean value was 82%. Unlike what is observed in runoff-dominated channels (e.g., Emmett, 1975; Whiting et al., 1999), bankfull discharge is uncorrelated to surface drainage area (Fig. 6). This result can be explained by the poor correspondence between surface drainage area and the subsurface drainage in these systems.

4.4. Downstream changes in geometry

Changes in channel geometry with downstream changes in discharge can be described in the following manner (Leopold and Maddock, 1953):

$$w = aQ^b$$
$$d = cQ^f$$
$$U = kQ^m \tag{2}$$

where w is width; d is depth; U is average velocity; a, c, and k are coefficients; and b, f, and m are exponents. Hydraulic geometry relationships for the 26 spring-dominated sites were evaluated with the assumption that channels could be treated as the headwater extent of a spring-dominated network. The geometry was examined for the common discharge of bankfull. Fig. 7 presents the hydraulic

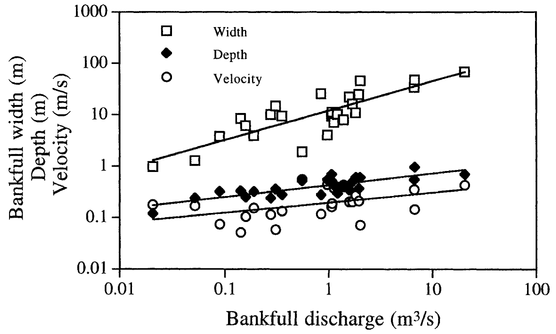

Fig. 7. Hydraulic geometry of spring-dominated channels.

geometry for spring-dominated channels. The value of each exponent for these spring-dominated systems is:

$$b = 0.57 \qquad r^2 = 0.69$$

$$f = 0.23 \qquad r^2 = 0.66$$

$$m = 0.20 \qquad r^2 = 0.20 \tag{3}$$

These exponents are somewhat similar to those reported for other channels (Leopold and Maddock, 1953; Rhoades, 1987): typically $b \sim 0.5$, $f \sim 0.4$, and $m \sim 0.1$.

Channel width increases in the downstream direction more rapidly in spring-dominated streams as compared to runoff-dominated streams, whereas channel depth increases more slowly in spring-dominated streams. Velocity increases more rapidly in spring-dominated channels as compared to runoff-dominated channels.

4.5. Streambed material

Bed material in the spring-dominated channels ranges from boulders to silt. The median size of surface particles (D_{50}) at spring-dominated sites varies from sand to gravel: a range from ~ 1 to 23 mm (Table 3). Approximately one-quarter of the

Table 3
Channel particle size

Site	Pebble count		Surface		Subsurface		D_s/D_{ss}
	D_{50} (mm)	D_{84} (mm)	$D_{50\ s}$ (mm)	$D_{84\ s}$ (mm)	$D_{50\ ss}$ (mm)	$D_{84\ ss}$ (mm)	$D_{50\ s}/D_{50\ ss^1}$
Spring-dominated							
Big Springs	3	12	5	9	2	2	2.5
Black Sands Creek	4	9	3	8	≤ 1	4	2.0[a]
Blue Springs	≤ 1	2	5	8	2	5	2.5
Browns Creek A	9	32	21	29	4	13	5.3
Browns Creek B	23	38	26	36	7	25	3.7
Buffalo River A	6	13	8	15	0	8	1.9[a]
Buffalo River B	10	22	13	20	6	11	2.2
Buffalo River C	5	9	7	8	5	6	1.4
Buffalo River D	5	12	7	12	3	5	2.3
Chick Creek							
Crystal Castle Cr A	≤ 1	2	≤ 1	3	≤ 1	3	1.0[a]
Crystal Castle Cr B	19	93	29	59	11	18	2.6
Cultus River	≤ 1	2	≤ 1	2	≤ 1	≤ 1	
Elk Springs Creek	10	44	25	56	10	16	2.5
Lucky Dog Cr A	≤ 1	≤ 1	≤ 1	≤ 1	≤ 1	≤ 1	
Lucky Dog Cr B	9	22	14	19	5	9	2.8
Meadow Creek	1	6	5	7	≤ 1	4	1.8[a]
Mill Creek	7	16	7	14	7	11	1.0
Reservation Spring	15	74	40	90	3	28	13.3
Snow Creek A	12	270	6	15	3	10	2.0
Snow Creek B	1	15	15	21	9	18	1.7
Spring Creek A							
Spring Creek B	5						
Toms Creek A	4.5	11	6	11	≤ 1	6.2	1.8[a]
Toms Creek D							
Tyler Creek	7	25	16	28	11	21	1.5
Runoff-dominated							
Crystal Castle Cr C	≤ 1	3	≤ 1	2	≤ 1	2	1.0[a]
Deer Creek	81	241	63	148	11	37	5.7
Moose Creek	6	9	6	11	3	6	2.0

[a] $D_{84\ s}/D_{84\ ss}$ presented since D_{50} not characterized precisely for particle sizes < 1 mm.

sites had a sand bed. The streambed material is often bimodal with a sand mode and a gravel mode. Occasionally, large rocks are found near the head of the channels. Particles are composed of various lithologies but the majority is volcanic.

4.6. Surface armor

The streambed at spring-dominated sites is armored where the channel is composed of gravel. The ratio of the median diameter of surface and subsurface particles (Table 3) varies from 13.3 to 1.0 at sites. The mean value was 3.1 ($\sigma = 3.0$). An armor has been interpreted by Dietrich et al. (1989) to be the product of a channel with the ability to transport more material than is supplied to it: the bed is essentially winnowed of the most easily moved small grains. Supply limitation in these spring-dominated channels may result from the lack of an extensive channel network conveying sediment to the channel and only minor lateral migration of the channel. The degree of armoring is somewhat less than is observed in many gravel bed channels in these regions —a ratio of surface to subsurface grain diameter of 3.0–4.0 (Whiting et al., 1999).

4.7. Bank material

The nature of the bank material was examined with cores from the floodplain near the channel and near the outer edge of the floodplain. At about half the sites, an additional core was collected at an intermediate position on the floodplain. Bank material, typically silt and sand, was rich in organic material. The upper part of each core was almost uniformly more organic than the entire core (30% vs. 15%). The range in organic content was from 92% at Browns Creek near the channel to 1% at Buffalo River away from the channel (Table 4). Those portions of cores with organic contents above 40% were often composed of sphagnum moss (genus *sphagnum*). In these areas, the banks were spongy when walked upon. The organic content of floodplain cores taken near the channel was slightly higher than that of cores taken at the outer edge of the floodplain: 16.5% near the channel to 6.0% at the outer edge of the floodplain ($\sigma = 19.0$ and $\sigma = 3.3$, respectively). The difference is statistically significant at the 0.05 level. A few of the cores contained fine gravel like those found on the streambed.

The organic component of the floodplain soils associated with spring-dominated channels is higher than is typically observed on floodplains from similar climates (B. Beschta, personal communication).

4.8. Mobility of the streambed

Particles on the bed of the spring-fed streams are moved regularly by the flow. During the visit to Chick Creek, sand and gravel was moving across the point bar at a stage slightly above bankfull. During reconnaissance of Wood River in September 1993, vesicular particles 1 cm in size were observed in motion. In general, the grains on the beds of the spring-dominated streams are loosely packed and are sometimes set in motion by the disturbance of the bed and flow fields while wading. The thalweg is, in general, free of a coating of fine sediment. There is only limited algal growth on particles or staining of particles that otherwise might indicate long periods when surface grains are immobile.

The ability of streamflow to move sediment is described by the dimensionless Shields Stress (τ^*):

$$\tau^* = \frac{\rho g H S}{(\rho_s - \rho) g D_{50}} \tag{4}$$

where ρ is the density of the water, ρ_s is the density of the sediment, g is the gravitational acceleration, H is the water depth, S is the channel gradient, and D_{50} is the median particle diameter. The density of the sediment was assumed to be 2.65 g cm^{-3}, although pumiceous material will have a lower density. The Shields number at bankfull stage ranges from about 0.013 to 0.365 at the sites (Table 2). The mean value is 0.167 ($\sigma = 0.118$). The critical Shields number for initiation of motion is typically thought to be 0.03 to 0.06 (Vanoni, 1964). A variety of features exert a drag on the flow reducing the amount of the total boundary shear stress that is applied to the bed and capable of moving sediment. In these channels, planform irregularities, variation in depth, islands and downed timber (cf. Manga and Kirchner, 2000) are likely to be the major sources of resistance. The Shields number as given above almost certainly overestimates the stress applied to the bed

Table 4
Organic component of floodplain soils

Stream	% Organic, uppermost sample			% Organic average, soil column		
	1	2	3	1	2	3
Spring-dominated						
Big Springs	70.7	41.3		22.1	6.2	
Black Sands Creek	39.2	41.9		13.6	14.1	
Blue Springs	33.9	20.0	39.1	12.8	17.0	
Browns Creek A	91.4	78.9	25.8	91.8	69.9	14.0
Browns Creek B	5.7	2.7	3.9	5.7	3.3	3.2
Buffalo River A	7.8	62.0	12.9	17.1		5.1
Buffalo River B	13.0	11.9	22.8	7.6	6.6	9.5
Buffalo River C	54.1	53.0	2.5	14.8	25.9	1.2
Buffalo River D	31.4	13.7		4.1	3.5	
Chick Creek	14.4	9.3	0.2	6.9	9.3	3.3
Crystal Castle Spring A	7.5	10.3		6.9	8.9	
Crystal Castle Spring B	11.6	11.7	6.3	9.3	5.8	4.6
Cultus River	46.0	47.2		14.2	12.0	
Elk Springs Creek	2.5	4.0		2.5	2.5	
Lucky Dog Creek A	26.8	28.3		16.9	7.2	
Lucky Dog Creek B	37.5	22.6		20.6	14.9	
Meadow Creek	46.2	27.2	39.3	7.6	9.5	5.9
Mill Creek	8.5	4.6		na	2.1	
Reservation Spring	7.4	7.5	7.4	7.4	8.3	6.0
Snow Creek A	58.0	10.0	12.7	17.8	8.1	6.2
Snow Creek B	61.8	19.2	7.0	19.7	16.7	7.1
Spring Creek A	21.5	7.8	8.3	16.8	6.8	5.7
Spring Creek B	5.6	6.5		3.8	4.7	
Toms Creek A	50.8	3.9		50.8	2.1	
Toms Creek D	6.0	9.8		5.2	9.8	
Tyler Creek	3.8	3.5		na	3.5	
Runoff-dominated						
Crystal Castle Spring C	6.3	6.5		5.0	5.0	
Deer Creek	13.4	43.5	3.7	13.4	43.5	3.7
Moose Creek	10.3	39.1		10.3	9.9	

(as indicated by the large Manning n values). Because the resistance has not been explicitly considered in Eq. (1), how much it overestimates the shear stress is unknown. We interpret the relatively large Shields numbers at sites to indicate that bed particles are likely to be mobile, which is consistent with visual observations of the state of the streambed.

5. Hydrology of spring-fed streams

Whiting and Stamm (1995) showed that spring-dominated channels experience a relatively narrow range of flows. Such a steady discharge without sharp peaks in the hydrograph is typical of diffuse flow—groundwater flow through low-conductivity rock and unmodified fractures. The hydrology of additional spring-dominated streams are examined and compared to the hydrology of runoff-dominated local counterparts. The spring-dominated streams are Cultus River, Quinn River, Browns Creek, and Fall River whereas the runoff-dominated channels are Cultus Creek and Deer Creek. These six streams are all in Oregon, were investigated by Manga (1996), and have been gaged by the US Geological Survey (1994b).

Hydrographs for the streams for water years 1976–1985 are presented in Fig. 8. Hydrographs are

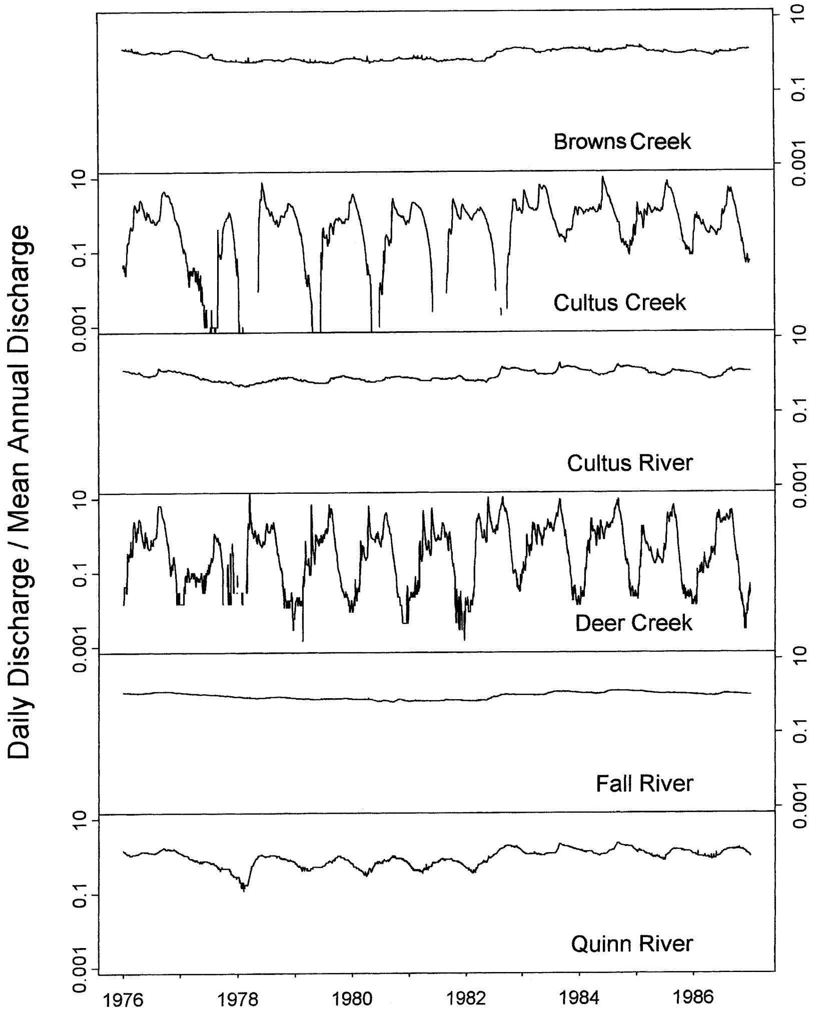

Fig. 8. Hydrographs of spring-dominated channels are damped compared to runoff-dominated channels.

normalized by the mean annual flow for the period of record (Table 5). Seasonal variation in discharge of the four spring-dominated channels is damped compared to runoff-dominated channels. The nearly steady discharge is most striking for Fall River and Browns Creek. The seasonal variation in flow is slightly greater for Cultus River and Quinn River but remains at least two orders of magnitude less than the variation of the two runoff-dominated streams, Cultus Creek and Deer Creek. This reduced range of discharge in spring-dominated channels can be seen also in Fig. 9, which plots flow exceedence probability against daily discharge scaled by mean annual flow.

Mean annual flow in the four spring-dominated channels averages 72% (range: 64–78%) of the flood with a 2-year recurrence interval (Table 5). Mean annual flow in the two runoff-dominated channels averages 18% (range: 15–21%) of the flood with a 2-year recurrence interval (Table 5). The 2-year flood on the annual series is commonly similar to the bankfull discharge (Dunne and Leopold, 1978). For Browns Creek, Forest Service hydrologists measured the bankfull discharge at 1.36 m^3/s, which corre-

Table 5
Hydrology of select sites in Oregon

Stream	USGS station number	Period of record	Mean annual flow (m^3/s)	2-year flood (m^3/s)	50-year flood (m^3/s)	Effective discharge (m^3/s)	RI of effective discharge (year)
Spring-dominated							
Cultus River[a]	14050500	1923–1925, 1938–1991	1.76	2.49	4.52	2.55	2.2
Quinn River	14052500	1938–1991	0.68	1.06	1.67	1.23	3.5
Browns Creek	14054500	1923–1925, 1939–1986, 1988–1991	1.08	1.46	2.67	1.51	2.3
Fall River	14057500	1938–1986, 1988–1991	4.15	5.31	7.38	4.92	1.5
Runoff-dominated							
Cultus Creek	14051000	1924, 1938–1985, 1987–1991	0.62	3.02	8.46	3.42	2.4
Deer Creek	14052000	1938–1986, 1988–1991	0.21	1.44	3.27	1.26	1.6

[a] The gage on Cultus River is downstream from the study site. The channel is substantially larger at the gage.

sponds to a 1.7-year recurrence interval flood. In his survey of runoff-dominated channels in the Salmon River drainage in Idaho, Emmett (1975) found that mean annual flow averaged about 25% of bankfull discharge increasing from 20% in smaller basins to 27% in larger basins. Dunne and Leopold (1978)

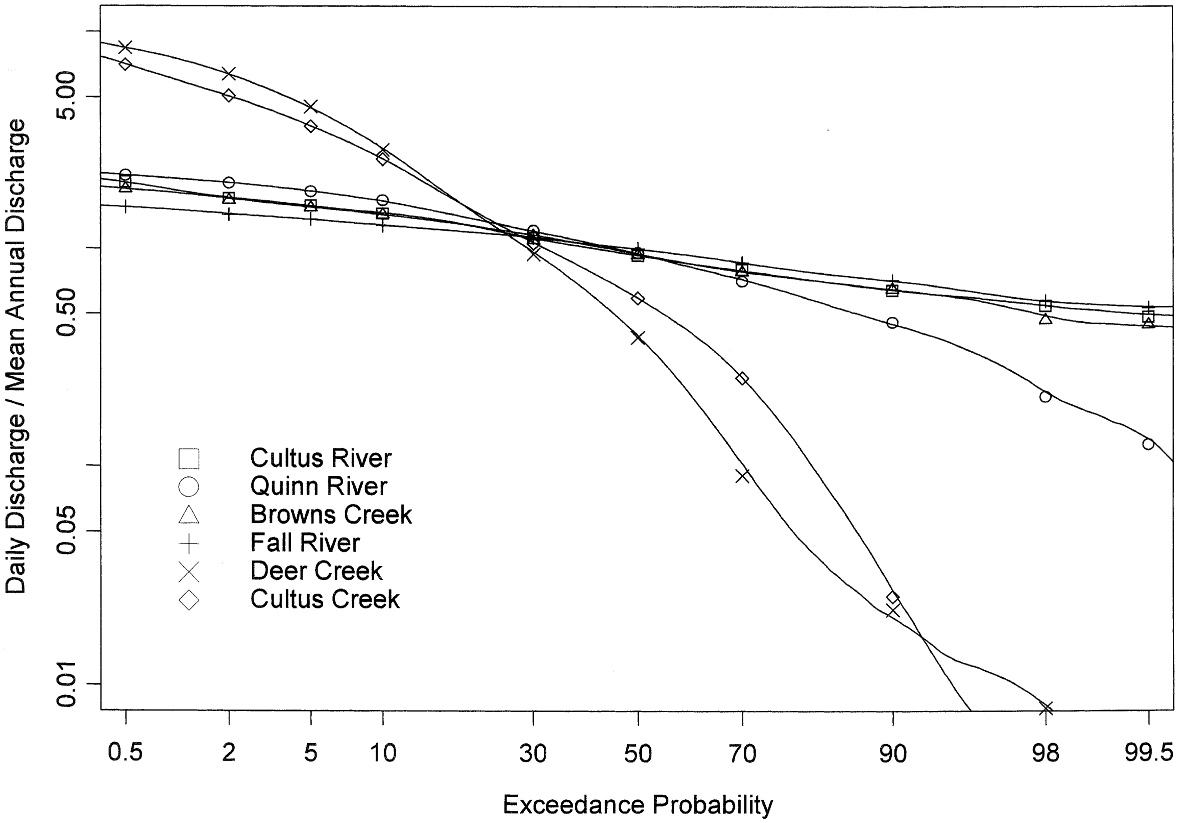

Fig. 9. Flow duration curves as scaled by mean annual discharge for spring- and runoff-dominated channels. The spring-dominated channels display substantially less variation in discharge.

found mean annual flow to be 14% of bankfull discharge in eight Wyoming streams that could be characterized as runoff-dominated. The 50-year flood averages 1.6 times the 2-year flood for spring-dominated channels, whereas the corresponding value for runoff-dominated channels in the region is 2.5.

Discharge exceeds bankfull 13% of the time (range: 10–16%) in the spring-dominated channels, whereas discharge exceeds bankfull about 2% of the time in the two runoff-dominated channels. Typical exceedence probabilities for runoff-dominated channels in the region are several percent of the time. Leopold (1994) cites examples from Idaho and Colorado where flow exceeds bankfull discharge 1 to 4.6% of the time.

6. Transport regime of channels

Whereas we did not collect bedload measurements and are not aware of any data sets in spring-dominated channels having more than a few bedload measurements, we can explore the influence of the duration of flow on the transport regime of spring-dominated systems nonetheless. The bedload yield over a period of time can be calculated from the product of the amount of sediment moved per day by a given discharge and the number of days of the given discharge integrated over the range of discharges. The relationship between bedload (G_b) and flow discharge (Q) is often described by a sediment rating curve:

$$G_b = jQ^{\beta}. \tag{5}$$

A typical value of the exponent (β) in a bedload rating curve is 2 to 3 (Leopold, 1994; Whiting et al., 1999).

The proportion of sediment moved by various percentiles of the flow is an important attribute of the transport regime of the streams. This is calculated for six streams in Oregon (four spring-dominated streams: Cultus River, Quinn River, Browns Creek, and Fall River; and two runoff-dominated streams: Cultus Creek and Deer Creek) using measured discharge at the USGS gages and assuming an exponent of 2.5 in Eq. (5). Because the aim is not to calculate the absolute amount of sediment transported by these flows, only the relative amount of sediment transported, the coefficient, j, in Eq. (5) is set to 1.

The single discharge that over time transports the most sediment is the effective discharge (Wolman and Miller, 1960; Andrews, 1980). For both the spring-dominated and runoff-dominated channels, the effective discharge is a relatively moderate event. For spring-dominated channels, the effective discharge is 103% of the flood on the annual series with a 2-year recurrence interval (Table 5). For the two runoff-dominated channels, the effective discharge is 100% of the flood with a 2-year recurrence interval. The range for the spring-dominated channels is 93–116%, and the range for the runoff-dominated channels is 87–113%. As mentioned earlier, bankfull flow discharge is often similar to the flood with a recurrence interval of 2 years. Therefore, the effective discharge in these spring-dominated systems is similar to bankfull discharge. The relative magnitude of effective discharge is similar to that in runoff-dominated channels in the same region and similar to runoff-dominated channels elsewhere (Andrews, 1980; Whiting et al., 1999).

Another way to examine the transport regime of channels is to examine the cumulative percent of sediment transported by cumulative percentages of the water. Fig. 10 shows the percent of water used to transport varying percentages of the bedload in the four spring-dominated streams and two runoff-dominated streams. In the two runoff-dominated channels, almost one-half the water (48%) transports the first 10% of the sediment. This value is similar to that reported for a variety of streams in central and northern Idaho (Whiting et al., 1999). In spring-dominated channels, 21% of the water transports the first 10% of the bedload. In spring-dominated channels, an average of 25% of the model-estimated bedload is transported by discharges below mean annual discharge (range = 17–29%), whereas in the two runoff-dominated channels, the value is 2%. In spring-dominated channels, 34% of the load is transported by discharges above the 2-year flood. In the two runoff-dominated channels, 49% of the load is transported by flows above the 2-year flood. The highest flows in runoff-dominated channels move a larger proportion of the sediment than the highest flows in spring-dominated channels despite the many

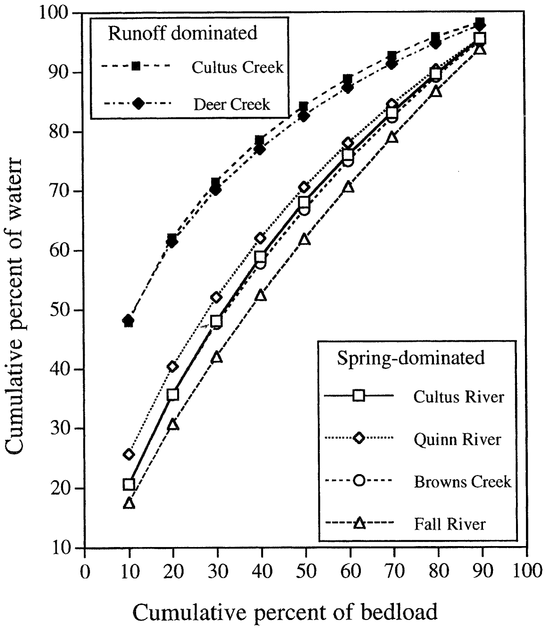

Fig. 10. Percent of water used to transport various percentages of the bedload. Spring-dominated channels transport proportionately less sediment at the highest flows.

more days of flows above the 2-year flood in the spring-dominated channels.

7. Comparison of spring-dominated and runoff-dominated channels

There are major differences between the hydrology of spring-dominated and runoff-dominated streams, and these differences were expected to produce a difference in the sediment transport regimes. Can the muted hydrograph of the spring-dominated channels explain some of the differences in morphology and hydraulics of the spring-dominated channels?

Important differences in the morphology and hydraulics of spring-dominated streams identified earlier include the following: a larger width-to-depth ratio, a large amount of in-channel downed timber, relatively large roughness and Shields numbers, the lack of channel bars, perhaps less armoring, and a relatively high organic component in floodplain soils.

The relatively large width-to-depth ratio of the spring-dominated flows may be attributable to the reduced range of flows, particularly the uncommonness of large flows capable of either removing debris from the channel or re-orienting debris to a position where it exerts less resistance to the flow. If not moved or re-oriented, flow is forced around downed timber and small islands (often developed on organic debris). The increased roughness (Manning's *n*) of the obstructions necessitates a larger cross-sectional area to convey flow. While greater depths or a wider channel would increase conveyance, the additional form drag induced by large changes in depth may leave little shear stress available for sediment transport. Note that the spring-dominated channels typically lack bars. Other workers who have examined the effect of flow variability on width-to-depth ratio have not agreed. Osterkamp and Hedman (1982) found the width-to-depth ratio to increase with flow variability. Pizzuto (1986) found the width-to-depth ratio to decrease with flow variability.

The degree of armoring observed in these streams was smaller than that observed in runoff-dominated channels, but only modestly smaller. Dietrich et al. (1989) predicted that the surface would coarsen (armoring increase) as the supply diminished and as the shear stress relative to that required for movement increased. In spring-dominated streams, the supply of sediment from the small surface drainage should be small (supply from the spring itself is unknown) and the shear stress in excess of critical boundary shear stress is small. Consequently, supply and shear stress may be compensatory in these streams such that the degree of armoring is not very different from that seen in runoff-dominated channels.

The steady flows may promote luxuriant growth of vegetation near the banks, giving rise to the very organic rich floodplain soils of spring-dominated systems, especially near the channel. The persistence of saturated conditions on the floodplain may enhance preservation of organic material. Dissolved nutrients associated with the springs may be of importance but were not investigated in this study.

8. Conclusions

The results presented herein extend the insight provided by Whiting and Stamm (1995) in their initial description of spring-dominated streams. This study more specifically addresses the channel geometry, the nature of bed and bank material, the hydraulics, sediment transport, and hydrology of spring-dominated channels. Spring-dominated channels are relatively wider than corresponding runoff-dominated channels. Stream banks are typically rich in organic material—over 50% at some sites. The resistance to flow, as characterized by the Manning coefficient, is typically large in spring-dominated channels. Part of the greater resistance may be associated with the large amount of organic debris in the channel. The streambed is armored in spring-dominated channels consistent with sediment supply limitations. Very modest variation in the spring-dominated hydrographs occurs. Effective discharge is approximately equal in magnitude to the flood with a recurrence interval of 2 years. Bedload transport occurs over a range of discharges, and proportionally more sediment is moved by common flows than extremely large flows as compared to runoff-dominated channels.

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References

Andrews, E.D., 1980. Effective and bankfull discharges in the Yampa basin, Colorado and Wyoming. J. Hydrol. 46, 311–330.

ASTM (American Society for Testing and Materials), 1995. Standard test methods for moisture, ash, and organic matter in peat and other organic soils. Annual Book of Standards 1995, pp. 275–277.

Benjamin, L., 2000. Groundwater hydrology of the Henrys Fork springs. Intermt. J. Sci., in press.

Christiansen, R.L., Blank, H.R., 1972. Volcanic stratigraphy of the Quaternary Rhyolite Plateau in Yellowstone National Park. U. S. Geol. Surv. Prof. Pap. 729-A, 18 pp.

Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., 1989. Sediment supply and the development of the coarse surface layer in gravel-bed rivers. Nature 340, 215–217.

Dunne, T., Leopold, L.B., 1978. Water in Environmental Planning. Freeman, New York, 818 pp.

Emmett, W., 1975. The channels and waters of the Upper Salmon River area, Idaho. U. S. Geol. Surv. Prof. Pap. 870-A, 116 pp.

Fenneman, N.M., 1931. Physiography of Western United States, First Edition, Fifth Impression. McGraw-Hill, New York, 534 pp., plus map.

Hipolito, J.N., Loureiro, J.M., 1988. Analysis of some velocity–area methods for calculating open-channel flow. Hydrol. Sci. J. 33, 311–320.

Kellerhals, R., Church, M., Bray, D.I., 1976. Classification and analysis of river processes. ASCE Hydraul. J. 102, 813–829.

Laity, J.E., Malin, M.C., 1985. Sapping processes and the development of theater-headed valley networks in the Colorado Plateau. Geol Soc. Am. Bull. 96, 203–217.

Leopold, L.B., 1994. A View of the River. Harvard Univ. Press, Cambridge, MA, 298 pp.

Leopold, L.B., Maddock, T., 1953. Hydraulic geometry of stream channels and some physiographic implication. U. S. Geol. Surv. Prof. Pap. 252, 57 pp.

Manga, M., 1996. Hydrology of spring-dominated streams in the Oregon Cascades. Water Resour. Res. 32, 2435–2439.

Manga, M., 1997. A model for discharge in spring-dominated streams and implications for the transmissivity and recharge of Quaternary volcanics in the Oregon Cascades. Water Resour. Res. 33, 1813–1822.

Manga, M., 1998. Advective heat transport by low-temperature discharge in the Oregon Cascades. Geology 26, 799–802.

Manga, M., 1999. On the timescales characterizing groundwater discharge at springs. J. Hydrol. 219, 56–69.

Manga, M., Kirchner, J.W., 2000. Stress partitioning in streams by large woody debris. Water Resour. Res. 36, 2373–2380.

Osterkamp, W.R., Hedman, E.R., 1982. Perennial streamflow characteristics related to channel geometry and sediment in Missouri. U. S. Geol. Surv. Prof. Pap. 1242, 37 pp.

Pizzuto, J.E., 1986. Flow variability and the bankfull depth of sand-bed streams of the American Midwest. Earth Surf. Processes Landforms 11, 441–450.

Rhoades, D.D., 1987. The $b-f-m$ diagram for downstream hydraulic geometry. Geografisker Ann. 69, 147–161.

Schumm, S.A., Boyd, K.F., Wolff, C.G., Spitz, W.J., 1995. A ground-water sapping landscape in the Florida Panhandle. Geomorphology 12, 281–297.

Stamm, J.F., Whiting, P.J., 1994. The hydrology and form of spring-dominated streams. Stream Notes, a quarterly newsletter of the Stream Systems Technology Center, Ft. Collins, CO, April 1994, pp. 1–5.

University of Idaho, 1995. Mean annual precipitation, 1961–1990, Idaho (map).

US Geological Survey, 1977. National Handbook of Recommended Methods for Water Data Acquisition. US Government Printing Office, Washington, DC.

US Geological Survey, 1994a. Water Resources Data Idaho Water Year 1994. US Department Interior, 429 pp.

US Geological Survey, 1994b. Water Resources Data Oregon Water Year 1994. US Department Interior, 546 pp.

Vanoni, V.A., 1964. Measurement of critical shear stress for entraining fine sediments in a boundary layer. Report KH-R-7, California Institute of Technology, W.M. Keck Lab. of Hydraulics and Wat. Resour., Pasadena, CA.

Whiting, P.J., Stamm, J.F., 1994. Channel form and process in spring-dominated channels. Report to the Stream Systems Technology Center, US Forest Service, US Department of Agriculture, Fort Collins, CO, 66 pp.

Whiting, P.J., Stamm, J.F., 1995. The hydrology and form of spring-dominated channels. Geomorphology 12, 233–240.

Whiting, P.J., Stamm, J.F., Moog, D.B., Orndorff, R.L., 1999. Sediment transporting flows in headwater streams. Geol. Soc. Am. Bull. 111, 450–466.

Wolman, M.G., 1954. Method of sampling coarse river bed material. Trans. Am. Geophys. Union 35, 951–956.

Wolman, M.G., Miller, J., 1960. Magnitude and frequency of forces in geomorphic processes. J. Geol. 69, 54–74.