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Abstract.-The purpose of this project was to assess the use of hydrologic data and flow duration analysis in the establishment of winter instream flow standards for trout streams in Wyoming. Relations between measures of flow duration during winter and trout abundance or habitat features for trout in eight study streams in southeastern Wyoming could not be identified. Statistics describing winter flow duration frequencies for 31 streams across Wyoming were highly variable among streams. Variation in winter flows was highly related to elevation and the proportion of the drainage that was irrigated, but the ability to predict flow duration values for individual streams was low. Discharge data during winter were less accurate than during other times of the year due to common and extensive periods when daily flow records were estimated. Flow duration analysis by itself does not appear to have potential to establish winter instream flow standards for Wyoming trout streams. However, such analysis can be used to assess the frequency of achieving instream flows for trout that may be defined using other techniques.

There is a lack of scientific data to establish or support winter instream flow standards for trout in streams (Hubbs and Trautman 1935; Maciolek and Needham 1952; Benson 1955; Needham and Jones 1959; Chisholm et al. 1987) due in large part to the difficulties of conducting winter field studies. This lack of information has resulted in frustration on the part of water development interests and agencies responsible for management of water resources. As a result, assessments of winter flow needs have often been based on hydrologic data and defined as a predetermined proportion of the historic mean daily flow at a particular site on a stream.

In Wyoming a criterion based on hydrologic data to determine minimum instream flow recommendations for fish during winter has been used by the Wyoming Game and Fish Department. The criterion for winter was an exceedence criteria of 50% of the average daily flow during late summer and fall (July 1 to September 30). Past recommendations by the Wyoming Game and Fish Department (WGFD) referenced to this criterion have occasionally been considered infeasible by the Wyoming Water Development Commission (WWDC) because unappropriated water from storage or direct natural flows at the level defined by the criterion cannot be achieved on an annual basis (Bruce Brinkman, WWDC, personal communication). The WWDC is required by statute to develop a hydrological analysis for each reach of stream on which the WGFD would like an instream flow right (John Barnes, Wyoming State Engineer's Office, personal communication). This criterion is no longer considered appropriate by the WGFD because it may not allow maintenance of existing fisheries in some situations (Thomas Annear, WGFD, personal communication).

Substantial variation in ice accumulation on Wyoming streams has been identified, primarily associated with variation in elevation (Chisholm et al. 1987). Streams and rivers that flow through valleys where there is a relatively low channel slope (< 1.5%) and little accumulation of snow tend to have extensive amounts of ice formation in the channel during winter. Conversely, at high elevations, stream channels tend to be narrower and there is extensive snow accumulation over the streams which tends to provide insulation. Consequently, there is often very little ice accumulation in stream channels at high elevations. As a result of the variation in ice formation on Wyoming streams associated with movement from low-elevation valleys to high-elevation mountain systems, sampling protocols or methods for defining winter instream flow needs for fisheries may exhibit varying utility among locations.

There are no widely accepted methods to define minimum instream flow needs for trout in ice- and snow-covered streams during winter, as there is during ice-free periods of the year (Annear and Conder 1984). Accumulation of ice on stream channels changes hydraulics and prevents sampling in standard ways. Therefore, methods for determination of instreams flow needs during ice-free periods are often not applicable to many streams during winter. Because ice conditions and stream channel hydraulics may vary from year to year, winter flow recommendations by the WGFD usually assume a best-case condition of minimal hydraulic change (from ice-free conditions) with the realization that in some years the recommended flow may not accurately reflect fish habitat availability because of the effects of ice accumulation (Thomas Annear, WGFD, personal communication).

Several methods have been developed to assess instream flow needs that require differing intensities of field sampling, discharge data and information on the requirements of different fish species (Bovee 1982; Annear and Conder 1984; Orth and Leonard 1990). Due to the difficulty of sampling during winter and the lack of assessment tools that consider instream habitat conditions at differing discharges and the habitat requirements of fish during winter, it is logical that instream flow criteria based on hydrologic data were applied, but such an approach may not provide sufficiently accurate biological information to maintain trout fisheries or enable reasonable water use.

There is a history of using hydrologic criteria to define minimum instream flow needs during ice-free periods. In Wyoming, Wesche (1973) recommended 25% of average daily flow during the summer (July-September) to support good trout populations. Burton and Wesche (1974) found that in six streams where this criterion for instream flow was met or exceeded 50% of the time between July and September 30, the streams had good trout fisheries (246-705 fish/acre). Comparatively, among five streams that did not meet the criterion, trout populations were absent or much lower ($\leq$ 190 fish/acre).

The most widely applied technique using hydrologic criteria is the Tennant method (Tennant 1976). Tennant recommended use of a percentage of the historic mean annual flow to estimate minimum instream flow requirements. He related minimum instream flow to the general condition of fish, wildlife, recreation and environmental resources of streams. He suggested the optimum range from October through March was 60-100% of mean daily flow. He stated that excellent condition was achieved with 30% of mean daily flow from October through March; good condition with 20% of mean daily flow; and fair or degrading condition with 10% of mean daily flow. The Tennant method has proven to be one of the least biased methods of defining minimum instream flow (Annear and Conder 1984). However, this approach is limited by its failure to incorporate site-specific biological and hydrological information and inability to quantify trade-offs (Annear and Conder 1984). In situations were only reconnaissance-grade minimum instream flow estimates are required (such as early planning stages of water projects), the Tennant method is considered a useful tool.

O'Shea (1995) found that minimum instream flow requirements based on hydrologic records and geomorphology could be developed for streams in Minnesota. He found that minimum instream flow requirements defined as a percentage of mean annual discharge were significantly related to drainage area and soil features.

He assumed that discharge was directly proportional to drainage area, given the relatively uniform climate and geology across Minnesota (Morisawa 1962). However, in Wyoming there is substantial variation in climate and geology due to variation in elevation and processes of mountain formation (Knight 1994). Additional variability in discharge is likely to result from the extent of water development and irrigation in a watershed. As a result, it is uncertain if minimum instream flow recommendations to maintain trout fisheries based on a state-wide hydrologic criteria can be applied in Wyoming.

The purpose of this project was to assess the use of hydrologic data in the establishment of winter instream flow standards for trout streams in Wyoming. We utilized analysis of flow duration curves in our assessment. Flow duration curves identify the percent of time that specified discharges (defined as a percentage of average daily flow) are equaled or exceeded. Our objectives were to: (1) describe physical conditions and trout habitat at various locations in watersheds during winter; (2) determine the extent to which spatial and temporal variation in stream flow affects physical conditions and trout habitat in streams during fall and winter; (3) describe stream flows from fall through winter in streams with and without irrigation and water development in the watershed; and (4) determine if criteria based on flow duration curves can provide standards for minimum instream flow determinations to maintain trout fisheries during winter.

Methods

Winter habitat--Objectives 1 and 2

This portion of the study was conducted on the Laramie Range and Snowy Range of the Medicine Bow Mountains in southeastern Wyoming. Eight sites selected for study were proximal to active year-round water flow gaging stations maintained by the U.S. Geological Survey or Wyoming Water Resources Center (Table 1). The sites were selected to encompass a wide range of elevations and mean annual discharges.

The study sites were visited in the fall 1993 and one transect was identified across each of three habitat types--riffle, pool and transition zone between a riffle and pool. Sampling was conducted at each site during the fall (October-November) 1993, winter (January-February) 1994, fall 1994 and winter 1995. In the fall 1994, transects at two additional riffles, pools and transition zones were added at three sites (South Brush Creek, Nash Fork Creek at Brooklyn Lodge and Little Laramie River) to assess variation within sites.

The ends of each transect were marked with two steel pins installed at the same elevation. Measurements of physical habitat features were made at evenly spaced, fixed locations across each transect with a minimum of 10 locations across a transect. Habitat features included wetted width, water depth, water velocity near the streambed and at 0.6 of the water depth and dominant substrate type. Substrate categories were: clay (particles $\leq$ 0.0002 inches in diameter), silt (0.0002-0.0024 in), sand (0.0025-0.79 in), gravel (0.80-2.50 in), cobble (2.51-10.0 in), and boulder ($\geq$ 10.0 in). During winter, snow depth and ice thickness were measured at each point. At sites with extensive snow accumulation, a narrow trench was dug in the snow across the stream at each transect to enable measurements. At sites with ice cover, an ice auger was used to drill holes in the ice at each fixed location across each transect so measurements could be taken.

Discharge was measured at each transect for each sampling period. Discharge estimates were normalized by dividing the computed values by the mean annual discharge for the site to enable comparisons among streams. Hydrologic data for the period of record for each stream were obtained from the Wyoming Water Resources Center. Geomorphic features (elevation, drainage area and channel slope) were estimated from U.S. Geological Survey 1:24,000 scale topographic maps for each site. Estimates of standing stocks in the study streams were obtained from Wyoming Game and Fish Department records, Burton and Wesche (1974) and Lanka (1985).

To assess the quality of trout habitat during winter, criteria were established for three life stages--incubating embryos, age-0, and juvenile or adult. Suitable incubation habitat for brook trout or brown trout embryos was defined as areas of gravel substrate with particle diameters of 0.80-2.50 in and water depths of 6.0-8.0 in with mean velocities of 1.0-1.2 ft/s (Reiser and Wesche 1977; Grost 1989; Beard and Carline

1991). Habitat for age-0 trout was defined as points with water depth of 2.0-4.0 in and water velocities of $\leq$ 0.25 ft/s (LaVoie 1993; Smith and Griffith 1994). Suitable winter habitat for juvenile and adult trout was defined as having depth of $\geq$ 6.0 in and velocity $\leq$ 0.50 ft/s (Wesche 1980; Chisholm et al. 1987). A point on a transect was identified as suitable habitat if it simultaneously met all criteria for a particular life stage.

Relations among variables describing geomorphology of the watershed, winter flow duration values, winter habitat features and trout standing stocks were assessed using linear regression analysis (Zar 1984). Analysis of covariance (using elevation as the covariate) was used to assess differences between sampling years (Zar 1984). Kruskal-Wallis tests were used to evaluate differences in habitat features among sites in three elevation classes (Zar 1984).

Flow duration analysis--Objectives 3 and 4

The Water Resources Data System (WRDS) at the Wyoming Water Resources Center was searched to identify gaging stations with suitable hydrologic data on streams with trout fisheries. We selected stream gaging stations based on these criteria: (1) daily discharge data were available for a 10-year period beginning with Water Year 1985, (2) the streams were not downstream of a mainstem reservoir or highly regulated by small upstream reservoirs, (3) the streams were not substantially influenced by flows from springs or geothermal sources, (4) the gaging stations were on stream reaches known to support trout fisheries, and (6) the streams were in Wyoming.

Exceedence values representing the percent of time a specified discharge was equaled or exceeded were computed. Discharge values were normalized by dividing by mean annual discharge to allow comparisons among sites. Discharge data were stratified for the winter (January-March) period with exceedence values computed for that period.

For each gaging station, the elevation of the stream gage, drainage area upstream from the stream gage, the area and proportion (percent) of upstream watershed that was irrigated land, and the existing upstream water storage capacity were identified.

Multiple regression analysis was used to assess relations between normalized exceedence values and variables describing the watershed (Zar 1984). Variables were included in multiple regression models only if each independent variable significantly accounted for variation in the dependent variable.

Based on the quantities of irrigated land and relations of normalized exceedence values to elevation, the study sites were divided into three elevation classes. Analysis of variance was used to assess difference in normalized exceedence values and other variables describing the watersheds among the three elevation classes (Zar 1984). Bonferroni's pairwise comparisons of means was used to make paired comparisons between classes.

Statistical analyses

All analyses were conducted using STATISTIX 4.1 (Analytical Software 1994). Significance was determined at $\underline{P} \leq 0.05$ for all tests.

Results

Winter habitat

Wide ranges in geomorphic and discharge features occurred among the eight study sites in southeastern Wyoming. Mean annual discharge (Q_{AA}) ranged from 3.6 to 166.0 ft^3/s among the eight sites (Table 1). Measured winter flows (Q) were normalized by dividing the measured values by Q_{AA}. When Q/Q_{AA} for each winter was regressed against geomorphic features (drainage area or elevation), a significant ($\underline{P}$ = 0.0080) positive relation was observed between Q/Q_{AA} and drainage area in the winter 1994, but no other significant relations were observed. No significant relations were found between any of the geomorphic features or measures of discharge and previous estimates of standing stocks of trout in the streams.

Elevation and mean annual discharge were related ($\underline{P}$ < 0.0001, r^2 = 0.98). Consequently, elevation and mean annual discharge were considered redundant variables (Table 1). Because elevation had stronger relations to habitat features it was selected as the covariate in analysis of covariance. Elevation has a significant negative relation with mean water depth and mean ice thickness, but a significant positive relation with mean snow depth.

Significant differences in habitat features were observed between the two years of the study. Among pools, mean water depth ($\underline{P}$ < 0.0001), mean water velocity ($\underline{P}$ < 0.0001), mean ice thickness (ln transformed, $\underline{P}$ = 0.032) and mean snow depth (ln transformed, $\underline{P} = 0.0036$) differed between years with greater values in 1994-95 than in 1993-94. At riffles, significant differences in mean water depth were also observed between years ($\underline{P} < 0.0001$), but significant differences in mean ice thickness or mean snow depth were not detected. Within transition areas, mean water depth ($\underline{P} < 0.0001$) and mean water velocity ($\underline{P} < 0.0001$) were significantly greater in 1994-95 than in 1993-94, but significant differences in mean ice thickness or mean snow depth were not observed.

Habitat features appeared to be clustered with relation to elevation (Table 2). These differences indicated three elevation classes among the eight sites: low (7,387-7,787 ft), middle (8,016-9,099 ft) and high (10,325-10,516 ft). Ice thickness and snow depth differed significantly among the three classes. The low-elevation class had the greatest ice thicknesses and lowest snow depths. The high-elevation class had the greatest snow depths and no ice during winter. The middle-elevation class was highly variable in both ice and snow accumulation.

Transition areas had the highest frequency of suitable habitat for incubating embryos (13.6% of points sampled) and age-0 fish (8.0%), whereas pools had the most plentiful habitat for juvenile and adult trout (33.6%). Consequently, the influences of winter conditions on habitat availability were assessed for each life stage only in the habitat type where habitat was most plentiful.

The amount of suitable incubation habitat decreased significantly with increasing elevation (r^2 = 0.58, P = 0.0274), as did the amount of suitable age-0 habitat (r^2 = 0.69, P = 0.0105). A significant relation between the amount of juvenile and adult habitat and elevation was not observed.

Analysis of covariance was used to assess differences in the amount of habitat from fall to winter. Egg incubation habitat declined significantly (P = 0.0130) from fall to winter in 1994-95, but no significant difference was observed in 1993-94. Age-0 habitat increased from fall to winter for both 1993-94 (P = 0.0081) and 1994-95 (P = 0.0052). There was also a significant difference in the abundance of age-0 habitat between the 1993-94 and 1994-95 study years (P = 0.0003) with greater quantities the second year. No significant differences in juvenile and adult habitat were observed between fall and winter or between the two study years.

Flow duration analysis

A total of 31 gaging stations that met our criteria were identified from across Wyoming (Table 3). Statistics describing flow frequencies during winter were highly variable among the 31 sites. For example, the normalized mean winter discharge ranged from 0.08 to 0.63 (8-63% of mean annual discharge). The sites of the gaging stations ranged in elevation from 3,620 to 9,050 ft above sea level, had drainage areas of 9.2 to 4,175 mi^2, and had 0.0 to 20.9% of the land irrigated (Table 4).

Regression analysis was applied to determine if watershed features could account for variation in exceedence values computed from normalized flow data. Relations were observed for normalized discharge values that were equalled or exceeded 50% (Q_{50}) of the time during winter (January-March), fall (October-December), and the entire water year. Only those relations that were statistically significant are reported (Table 5).

During the winter, elevation of the gaging station, drainage area upstream from the gaging station, and the percent of the drainage area that was irrigated land were each significantly correlated with winter Q_{50} (Table 5). However, the coefficients of determination (r^2) were low and the standard error of the estimates were high, indicating poor predictive capabilities.

Two multiple-regression equations accounted for a higher amount of variation in winter Q_{50} with two significant dependent variables (Table 5). The highest amount of variation (R^2 = 0.55) was accounted for from knowledge of elevation and the percent of irrigated land. A lesser amount of variation (R^2 = 0.48) was accounted for using elevation and the area of irrigated land as independent variables.

Winter Q_{50} values for individual streams were highly correlated with fall Q_{50} and yearly Q_{50} values for the same streams (Table 5). Consequently, when Q_{50} values for the fall and entire water year were subjected to regression analysis, results were similar to the winter. The Q_{50} values were related to elevation, the percent of irrigated land, and the area of irrigated land (Table 5). No significant relations were observed between Q_{50} values and average daily flows.

The greatest variation in Q_{50} was observed at mid-elevation sites between 5,000 and 7,200 ft (Figure 1). Variation in Q_{50} on each side of the regression line between 5,000 and 7,200 ft substantially reduced the predictive capability of the model.

Given the insight provided by the regression analysis and plots of relations between flow duration values and watershed features, we divided the data set into three elevation classes: low (< 5,000 ft), middle (5,000-7,200 ft) and high (> 7,200 ft). Significant differences in Q_{50} and drainage area were found among the three classes. Additionally, no drainages in the high-elevation class had irrigated land within them.

Flow duration frequencies among the three elevation classes were developed for the winter period (Table 6). The normalized mean daily flow equaled or exceeded 50% of the time during the winter was 0.16 among the high-elevation streams (n = 9), 0.26 among the middle-elevation streams (n = 15), and 0.44 among the low-elevation streams (n = 7). We found the high-elevation sites to have substantially lower flow regimes during the winter period than the lower-elevation classes. Between the low- and middle-elevation classes, middle-elevation sites had lower flow regimes than low-elevation sites with the exception of extreme values at both ends of the flow duration spectrum (10 and 90% of time).

Discussion

Winter habitat

The most limited physical habitat for trout in unregulated montane streams or in drainages with irrigated lands seems to occur in late winter due to declining flows from fall through winter. Substantial changes in stream habitat for some life stages of trout occurred from fall to winter in montane streams in southeastern Wyoming. Declining discharges from fall to winter were expected and observed. Measured discharges during fall were 11-47% (1993 mean = 27%, 1994 mean = 17%) of average annual discharge (Q_{AA}) and during winter were 7-35% (1994 mean = 18%, 1995 mean = 14%) of Q_{AA}. Declining water velocities and depths from fall to winter were related to declining discharges which reduce the amount of incubation habitat for brook trout and brown trout embryos in redds and the quantity of pool habitat important to juvenile and adult trout (Chisholm et al. 1987). By late winter, flow input from groundwater and lakes is mostly depleted and physical habitat is generally at its lowest point of the year.

Variation in habitat features was observed between the two study years and was associated with variation in discharge. Variation in the availability of suitable habitat for incubating embryos and age-0 fish in transition areas between riffles and pools was observed between fall and winter, as well as between years. These changes were primarily a factor of variation in flow, not the accumulation of ice in transition areas. More precipitation fell in summer 1993 (32.3 in) near the Brooklyn Lodge site) than in summer 1994 (27.8 in), but precipitation in the fall (3.4 in 1993, 3.8 in 1994) was similar. However, precipitation was higher during winter 1994 (15.2 in) than during winter 1995 (10.0 in). Lower discharges were observed during the 1993-94 than during the 1994-95 sampling period. It appears that precipitation during the preceding summer influences winter discharge in unregulated, montane streams and subsequently affects the extent and quality of habitat for trout during winter.

Elevation has a significant influence on winter habitat features in montane streams of southeastern Wyoming. This observation is in concurrence with Chisholm et al. (1987) and Berg (1994) who found elevation to be the major variable affecting winter habitat conditions in streams.

High-elevation sites (> 9,100 ft) experienced snow bridging that remained throughout the winter over the entire channel. These sites were not affected by ice during the winter and remained essentially free flowing throughout the winter. Consequently, methods that assume ice-free conditions when modeling habitat suitability under differing flow regimes, such as the Physical Habitat Simulation model (Milhous et al. 1984), could be used to assess minimum instream flow needs during most winters in high-elevation sites. Additionally, while flows gradually declined through the winter, overall flows were more stable during winter at high-elevation sites compared to middle-and low-elevation sites.

Middle-elevation sites (8,016-8,098 ft) had both snow and ice on the surface of the water, as well as areas of open water associated with riffles and rapidly flowing areas, during the winter. Habitat features at sites in this elevation class were highly variable during and between winters. Clearly, these sites did not exhibit stable conditions. We hypothesized that the open water areas lead to frequent occurrences of frazil ice and anchor ice in the channel. As a result of the spatial and temporal variability in habitat during the winter, middle-elevation sites are likely to have frequent winter habitat conditions that limit trout survival. Unnatural reductions in flows during winter would likely extenuate the conditions experienced by trout.

Sites in the low-elevation class (< 7,787 ft) where found to have the thickest ice cover, with little snow cover. Cold weather in the late fall quickly induced surface ice to form and it remained throughout the winter. Surface ice continued to grow throughout the winter, particularly along the stream margins, and excluded potential habitat for age-0 trout (LaVoie 1993), as well as juvenile and adult fish. These sites also experienced substantial variation in habitat features during and between winters which changed hydraulic conditions and habitat features in the streams. It is possible that hydraulic effects of ice could be modeled to predict habitat features important to trout in low-elevation streams.

As a result of variation in physical habitat associated with declining stream flows from fall through winter, differences in precipitation and discharge among years that affect habitat, and influences of elevation, which is probably a surrogate for features describing climate, the potential for development of a state-wide winter instream flow standard based on hydrologic data does not appear feasible.

Flow duration analysis

Flow duration analysis provided a wide range of values describing winter flow regimes among the 31 streams studied. Analysis of the data on watershed features identified significant influences of elevation, drainage area, and the proportion of the drainage area that was irrigated on statistics describing flow duration. However, the analysis was unable to account for sufficient variation in flow duration statistics to enable strong prediction.

One reason for the lack of relations may be that substantial portions of the data from winter periods are frequently extrapolated leading to inaccurate descriptive statistics computed from these data. Flow records for almost all streams included in our data set indicated that daily flow records during winter were commonly estimated for periods of a few days to several weeks. For example, among the 31 study streams during the winter (January-March) of 1994, only two streams had no extrapolated daily data and four had extrapolated data for the entire 90-day period. The average was 52 days of extrapolated data among the 31 study streams during the winter of 1994. This is likely due to periodic effects of ice on recording devices. Similar periods of estimated flow data were rare during other periods of the year.

Flow duration values from the eight streams in southeastern Wyoming studied during the winters of 1994 and 1995 showed few relations between geomorphic features and measures of flow frequencies. No relations were found between standing stocks of trout in the streams and measures of flow frequency, but it is likely that a wide array of habitat features in addition to flow frequencies are influencing standing stocks in the eight study streams. All of the study streams were unregulated montane streams with little or no irrigated land upstream from the gaging stations, so the influences of water storage, water diversion, and irrigation had no effect on the hydrologic or biological dynamics of these streams.

We observed substantial variability in winter flow regimes, but we were unable to account substantially for the variation using watershed features. Additionally, we were unable to identify any significant relationships between statistics describing winter flow frequencies and fish abundance or other factors related to habitat quality for fish in the eight study streams in southeastern Wyoming. This finding illustrates the high level of complexity of factors affecting trout populations, as well as the potential high risk of error when applying a simple hydrologic standard to identify a meaningful instream flow for trout.

Potential application of winter flow frequencies

Despite the inability of flow duration analysis to define winter instream flow needs for trout in Wyoming, flow duration analysis may be useful in the process of determining and negotiating winter instream flows for individual reaches of streams. When a minimum instream flow value or series of values are defined through habitat assessment techniques in the future, flow duration analysis may assist in determining the frequency of achieving particular values. The information on winter flow availability for three elevation zones in Wyoming (Table 6) can be used in this manner.

Conclusions

Conclusions regarding the use of flow duration data to develop instream flow standards for trout during winter are:

(1) Relations between measures of winter flow duration and trout abundance or habitat features for trout in eight study streams in southeastern Wyoming could not be identified, probably because a wide array of factors other than winter flows affect trout populations in unregulated, montane streams.

(2) Statistics describing winter flow duration frequencies are highly variable among streams and the variation cannot be sufficiently accounted for from watershed features to

enable precise estimates for specific locations in watersheds.

(3) Discharge data during winter are less accurate than during other times of the year due to common and extensive periods when daily flow records are estimated; consequently, flow duration curves for winter cannot be expected to be accurate.

(4) Flow duration analysis does not appear to have potential to establish winter instream flow standards for Wyoming trout streams in and of itself; however, it can be used to assess the frequency of achieving instream flows for trout that may be defined using other techniques.

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TABLE 1. Location (Range, Township, Section), elevation, and discharge (ft^3/s) for the eight study streams in southeastern Wyoming (Q_{AA} = average annual discharge, Q_{50} = annual median discharge, Q_m = average measured discharge during 1993-1995 study).

Stream	Location	Elevation (ft)	Q_{AA}	Q_{50}	Q_m
Laramie River	R77W, T14N, S36	7,387	166.0	57.8	43.7
Little Laramie River	R77W, T15N, S4	7,606	103.0	31.8	16.6
Rock Creek	R79W, T19N, S25	7,787	84.0	16.0	12.5
North Brush Creek	R81W, T16N, S8	8,016	62.0	25.9	10.1
South Brush Creek	R81W, T16N, S20	8,098	32.0	9.0	5.8
Nash Fork at Snowy Range Ski Area	R79W, T16N, S20	9,099	14.0	6.0	2.1
Nash Fork at Brooklyn Lodge	R79W, T16N, S14	10,325	4.9	2.5	0.9
Telephone Creek	R79W, T16N, S15	10,516	3.6	1.1	0.3

TABLE 2. Mean measurements of selected physical habitat features for the eight study streams in southeastern Wyoming.

Stream	Mean water depth (in)	Mean water velocity (ft/s)	Mean ice thickness (in)	Mean snow depth (in)
Laramie River	7.6	0.74	3.1	0.4
Little Laramie River	5.9	0.64	5.2	<0.1
Rock Creek	5.3	0.45	2.2	0.9
North Brush Creek	5.3	0.58	0.8	8.7
South Brush Creek	5.3	0.48	1.5	8.0
Nash Fork at Snowy Range Ski Area	3.2	0.31	1.3	8.5
Nash Fork at Brooklyn Lodge	2.2	0.23	1.2	12.8
Telephone Creek	3.7	0.18	0.0	39.7

TABLE 3. Normalized winter (January through March) flow duration statistics for 31 gaging stations from across Wyoming that met our criteria for flow duration analysis.

Gaging station	Station number	Normalized discharge Q_{90}	Q_{50}	Q_{10}
Low-elevation sites (< 5,000 ft)				
Goose Creek near Acme	6305700	0.35	0.55	0.81
Tongue River near Dayton	6298000	0.28	0.33	0.38
Little Big Horn River at state line	6289000	0.39	0.45	0.55
Piney Creek at Kearney	6323000	0.27	0.41	0.64
Little Wind River near Riverton	6235500	0.30	0.44	0.66
Little Wind River above Arapahoe	6231000	0.30	0.46	0.63
Popo Agie River near Arapahoe	6233900	0.30	0.41	0.63

TABLE 3. Continued.

Gaging station	Station number	Normalized discharge Q_{90}	Q_{50}	Q_{10}
Middle-elevation sites (5,000 - 7,200 ft)				
Wind River near Crowheart	6225500	0.20	0.28	0.34
Bull Lake Creek above Bull Lake	6224000	0.06	0.08	0.11
South Fork Shoshone River near Valley	6280300	0.17	0.21	0.27
North Platte River above Seminoe Reservoir near Sinclair	6630000	0.27	0.40	0.85
Medicine Bow River above Seminoe Reservoir near Hanna	6635000	0.14	0.31	0.52
East Fork Wind River near Dubois	6220500	0.16	0.23	0.33
South Fork Little Wind River above Washakie Reservoir near Ft. Washakie	6228350	0.11	0.14	0.18
Green River near LaBarge	9209400	0.26	0.36	0.65

TABLE 3. Continued.

Gaging station	Station number	Normalized discharge Q_{90}	Q_{50}	Q_{10}
Little Medicine Bow river at Boles Spring near Medicine Bow	6634620	0.03	0.06	0.18
Box Elder Creek at Boxelder	6647500	0.04	0.08	0.33
Cache Creek near Jackson	13018300	0.21	0.30	0.44
Little Snake River near Slater, CO	9253000	0.13	0.17	0.37
Fontenelle Creek near Herschler Ranch near Fontenelle	9210500	0.30	0.42	0.79
Encampment River near Encampment	6625000	0.28	0.35	0.45
Laramie River near Bosler	6661585	0.20	0.43	1.11
High-elevation sites (> 7,200 ft)				
Middle fork Powder River near Barnum	6309200	0.18	0.22	0.30
Pine Creek above Fremont Lake	9196500	0.07	0.09	0.14
Hams Fork below Pole Creek	9223000	0.12	0.20	0.36

TABLE 3. Continued.

Gaging station	Station number	Normalized discharge Q_{90}	Q_{50}	Q_{10}
Rock Creek above King Canyon Canal near Arlington	6632400	0.10	0.13	0.17
North Brush Creek near Saratoga	6622700	0.20	0.23	0.27
North Fork Powder River near Hazelton	6311000	0.11	0.15	0.19
Encampment River above Hog Park	6623800	0.17	0.20	0.27
Rock Creek above Rock Creek Reservoir	6637750	0.10	0.18	0.23
Shell Creek above Shell Creek Reservoir	6278300	0.05	0.08	0.10

TABLE 4. Elevation (ft), drainage area (mi^2), area of irrigated land (mi^2), percent of irrigated land, and average annual daily flow (ADF, ft^3/s) for each of the 31 sites that met our criteria for flow duration analysis.

Gaging station	Elevation	Drainage area	Irrigated area	Percent irrigated	ADF
Low-elevation sites (< 5,000 ft)					
Goose Creek near Acme	3,620	411	0	0	139.0
Tongue River near Dayton	4,060	204	0	0	150.0
Little Big Horn River at state line	4,350	193	0.3	0.1	126.0
Piney Creek at Kearney	4,655	118	0.2	0.2	67.6
Little Wind River near Riverton	4,902	1,904	98.3	5.2	563.5
Little Wind River above Arapahoe	4,990	660	40.6	6.2	159.2
Popo Agie River near Arapahoe	4,996	796	57.7	7.2	283.5

TABLE 4. Continued.

Gaging station	Elevation	Drainage area	Irrigated area	Percent irrigated	ADF
Middle-elevation sites (5,000-7,200 ft)					
Wind River near Crowheart	5,635	1,891	39.1	2.1	1,027.0
Bull Lake Creek above Bull Lake	5,874	187	0	0	255.0
South Fork Shoshone River near Valley	6,200	297	0.7	0.2	353.0
North Platte River above Seminoe Reservoir near Sinclair	6,401	4,175	335.9	8.1	970.4
Medicine Bow River above Seminoe Reservoir near Hanna	6,415	2,338	67.2	2.9	142.1
East Fork Wind River near Dubois	6,440	427	3.1	0.7	207.0
South Fork Little Wind River above Washakie Reservoir near Ft. Washakie	6,440	90	0	0	116.0
Green River near LaBarge	6,520	3,910	309.4	7.9	1,356.0
Little Medicine Bow River at Boles Spring near Medicine Bow	6,570	969	8.1	0.8	35.2

TABLE 4. Continued.

Gaging station	Elevation	Drainage area	Irrigated area	Percent irrigated	ADF
Box Elder Creek at Boxelder	6,710	63	0	0.1	24.7
Cache Creek near Jackson	6,750	11	0	0	10.6
Little Snake River near Slater, CO	6,831	285	3.1	1.1	184.0
Fontenelle Creek near Herschler Ranch near Fontenelle	6,950	152	1.2	0.8	59.3
Encampment River near Encampment	6,970	265	13.8	5.2	205.6
Laramie River near Bosler	7,030	1,790	81.9	4.6	126.0
High-elevation sites (> 7,200 ft)					
Middle Fork Powder River near Barnum	7,220	45	0	0	23.0
Pine Creek above Fremont Lake	7,450	76	0	0	156.4
Hams Fork below Pole Creek	7,455	128	0	0	78.5
Rock Creek above King Canyon Canal near Arlington	7,790	63	0	0	69.8
North Brush Creek near Saratoga	8,020	37	0	0	41.6

TABLE 4. Continued.

Gaging station	Elevation	Drainage area	Irrigated area	Percent irrigated	ADF
North Fork Powder River near Hazelton	8,180	25	0	0	13.9
Encampment River above Hog Park	8,270	73	0	0	93.1
Rock Creek above Rock Creek Reservoir	8,330	9	0	0	7.1
Shell Creek above Shell Creek Reservoir	9,050	23	0	0	30.1

TABLE 5. Statistically significant ($P \leq 0.05$) regression equations accounting for variation in 50% exceedence values for 31 streams in Wyoming during winter (January-March), fall (October-December), and the entire water year. Independent variables are elevation (ELEV, ft), drainage area (AREA, mi^2), area of irrigated land (IRRI, mi^2), and percent of the drainage that is irrigated (%IRRI).

Equation	Adjusted r^2 or R^2	P	Standard error
Winter Q_{50}			
= 0.707 - 0.0000675 ELEV	0.41	<0.0001	0.106
= 0.236 + 0.0000473 AREA	0.11	0.0371	0.130
= 0.222 + 0.0276 %IRRI	0.26	0.0019	0.119
= 0.672 - 0.0000647 ELEV + 0.000501 IRRI	0.48	<0.0001	0.100
= 0.608 - 0.0000577 ELEV + 0.0208 %IRRI	0.55	<0.0001	0.093
= - 0.022 + 0.886 FALL Q^{50}	0.85	<0.0001	0.054
= - 0.065 + 0.870 YEARLY Q^{50}	0.77	<0.0001	0.067
Fall Q_{50}			
= 0.828 - 0.0000771 ELEV	0.49	<0.0001	0.103

TABLE 5. Continued.

Equation	Adjusted r^2 or R^2	P	Standard error
= 0.288 + 0.0239 %IRRI	0.17	0.0120	0.131
= 0.805 - 0.0000752 ELEV + 0.000329 IRRI	0.51	<0.0001	0.101
= 0.753 - 0.0000696 ELEV + 0.01577 %IRRI	0.56	<0.0001	0.096
= - 0.047 + 0.9771 YEARLY Q_{50}	0.89	<0.0001	0.047
Yearly Q_{50}			
= 0.858 - 0.0000731 ELEV	0.47	<0.0001	0.102
= 0.344 + 0.0234 %IRRI	0.17	0.0114	0.127
= 0.351 - 0.0000480 AREA	0.11	0.0362	0.132
= 0.824 - 0.0000703 ELEV + 0.000484 IRRI	0.54	<0.0001	0.095
= 0.783 - 0.0000657 ELEV + 0.0157 %IRRI	0.54	<0.0001	0.095

TABLE 6. Mean normalized winter flow values and ranges (in parentheses) for various flow duration classes for the three Wyoming elevation zones.

Percent of time discharge is exceeded	Elevation range (ft)		
	3,600-5,000 (n=7)	5,001-7,200 (n=15)	7,201-9,050 (n=9)
90	0.31 (0.27-0.35)	0.17 (0.12-0.22)	0.12 (0.09-0.16)
80	0.36 (0.32-0.40)	0.19 (0.14-0.25)	0.14 (0.10-0.18)
70	0.39 (0.34-0.43)	0.21 (0.16-0.27)	0.15 (0.11-0.19)
60	0.41 (0.36-0.47)	0.23 (0.17-0.30)	0.16 (0.12-0.20)
50	0.44 (0.37-0.50)	0.26 (0.19-0.33)	0.16 (0.12-0.21)
40	0.46 (0.39-0.53)	0.29 (0.21-0.36)	0.17 (0.13-0.22)
30	0.49 (0.41-0.57)	0.33 (0.24-0.42)	0.18 (0.14-0.23)
20	0.54 (0.44-0.63)	0.44 (0.30-0.58)	0.20 (0.15-0.25)
10	0.61 (0.49-0.73)	0.64 (0.36-0.91)	0.23 (0.16-0.29)

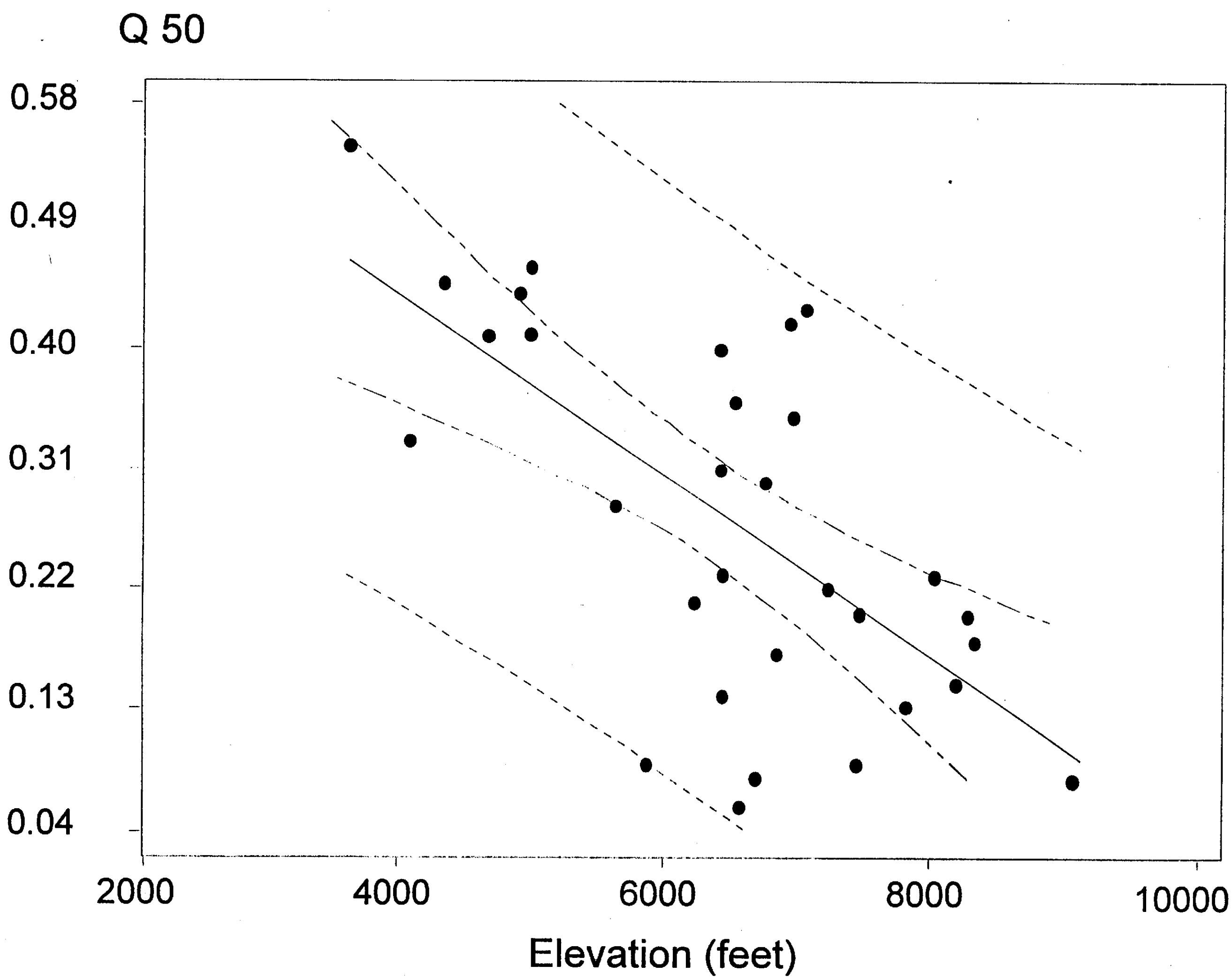

FIGURE 1. Linear regression line, 95% confidence interval, and 95% prediction interval describing the relation between elevation and normalized median discharges at 31 gaging stations across Wyoming.