

STREAM NOTES

To Aid in Securing Favorable Conditions of Water Flows

Rocky Mountain Research Station

October 2010

Understanding Controls on Flow Resistance Along High-Gradient Mountain Streams

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Quantifying flow resistance is an essential part of understanding hydraulics of streams. The interaction between stream flow and its boundaries dissipates energy as water moves around and over objects such as boulders, wood, and bedforms. Predictions of flow resistance are used for flood estimation, habitat assessment and prediction, design of fish passageways, and stream rehabilitation projects. In low-gradient channels, resistance to flow and subsequent dissipation of energy occur when water is forced around channel bends or over bedforms such as ripples and dunes and from grain resistance. High-gradient channels dissipate energy when water flows over poorly sorted grains in the bed and banks and over bedforms such as steps and pools, creating a constant alternation between supercritical and subcritical flow and causing energy dissipation through hydraulic jumps. Mountain streams differ from low-gradient channels by having large boulders that are of the same order of magnitude as the depth of flow, low values of relative grain submergence

(R/D_{84} , where R is hydraulic radius and D_{84} is the 84th percentile particle size), armored beds, and wood that commonly spans the channel. Equations developed for predicting flow resistance in low-gradient streams have high errors (exceeding 25 percent) when applied to high-gradient mountain streams. The poor predictive ability of these equations indicate that the hydraulics of high-gradient channels are still poorly understood. Flow resistance governs the energy available for the transport of water, sediment, and other materials through the stream system. Improving our understanding of both the driving and resisting forces in mountain channels will help advance understanding of flow hydraulics, sediment transport, channel form and stability, stage-discharge relations, and aquatic habitat.

The morphology of high-gradient channels is typically characterized as step-pool, cascade, and plane-bed channels. Step-pools generally form at gradients between 0.03 to 0.10 m/m and have alternating steps and pools. Steps create flow resistance by

STREAM NOTES is produced quarterly by the Stream Systems Technology Center located at the Rocky Mountain Research Station, Fort Collins, Colorado. STREAM is a unit of the Watershed, Fish, Wildlife, Air, and Rare Plants Staff in Washington, D.C. John Potyondy, Program Manager.

The PRIMARY AIM is to exchange technical ideas and transfer technology among scientists working with wildland stream systems.

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skin friction over large particles and wood, form drag from pressure differences around the upstream and downstream sides of protruding objects, and spill resistance created from flow acceleration and deceleration over the steps. Cascades form at gradients greater than 0.06 m/m and are characterized by tumbling flow over large, randomly arranged particles that can create substantial flow resistance, dependent on stage. Plane-bed channels have a uniform topography, lack well-defined bedforms, and occur at gradients between 0.01 and 0.03 m/m.

The total value of frictional losses can be represented with the dimensionless Darcy-Weisbach friction factor (f) or by the Manning coefficient (n):

$$V = \left(\frac{8gRS_f}{f} \right)^{1/2} = \frac{1}{n} R^{2/3} S_f^{1/2}$$

where, V is mean velocity (m/s); g is gravitational acceleration (m/s^2); R is hydraulic radius (m); and S_f is friction slope (m/m). The focus of this paper is on the Darcy-Weisbach friction factor mainly because it is non-dimensional and can be physically interpretable as a drag coefficient. The following relation, $n = R^{0.167} (f/8g)^{0.5}$, can be used to convert the Darcy-Weisbach friction factor to Manning's n .

Part of the uncertainty in applying empirically-based equations to new sites is that the relative importance of different sources of resistance can vary between sites. Total resistance is typically partitioned into grain (form drag on individual particles and viscous/skin friction on their surfaces), form (dunes, bars, steps, wood), and spill (flow transitions and wave drag on elements protruding above the water surface) resistance. The contribution made by each of these sources of resistance can differ in relation to gradient, channel morphology, or other factors. Previous studies have typically focused on quantifying and/or partitioning resistance within a particular channel morphology. Therefore, our primary objective is to understand how resistance varies with gradient, channel morphology, and relative submergence of grains (R/D_{84}), steps (R/H), and the bed (R/s_{bed}) throughout a channel network to help in the development of predictive equations for high-gradient mountain channels.

Study Area and Methods

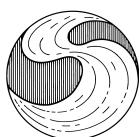
East St. Louis Creek (ESL) and Fool Creek (FC) are located at elevations of 2900-3900 m in the Fraser Experimental Forest of the Arapaho-Roosevelt National Forest in north-central Colorado. Runoff is dominated by snowmelt with small contributions by summer convective storms.

East St. Louis Creek drains approximately 8.73 km² and the Fool Creek basin drains approximately 2.89 km². Each basin is dominated by cascade and step-pool channel morphologies. Fourteen channel reaches on ESL and FC were selected in the field based on visual assessment of morphology; nine step-pool reaches and five cascade reaches (fig. 1). Upper and lower boundaries of each reach were chosen to ensure consistent morphology and gradient within the reach. Step-pool reaches in both ESL and FC include large amounts of wood, over 95 percent of which is found in the steps. Cascade reaches were selected based on visual assessment of tumbling flows over irregularly spaced particles, the lack of or limited occurrence of regularly spaced steps and pools, and having small or under-developed pools.

All fourteen reaches were surveyed at four stages using a combination of a laser theodolite and LiDAR (Light Detection and Ranging). The LiDAR was used to capture banks and channel geometry at base flow, whereas the water surface and bed data were collected with the laser theodolite at both base flow and bank filling flows. Reach-average mean velocity was measured using fluorometers and Rhodamine WT dye tracers.

Multiple regressions were used to test for significant relationships between flow resistance and potential control variables such as gradient. Discharge is used in some of the predictive models as a dimensionless flow variable, $q^* = q/(gD^3)^{0.5}$, where q^* is dimensionless discharge, q is discharge per unit width, and D is a characteristic grain size.

Models that include dimensionless discharge are only useful when the ultimate goal is to predict velocity when discharge is known. However, the goal is more often to find variables that will help in prediction of f and subsequently both discharge and velocity.



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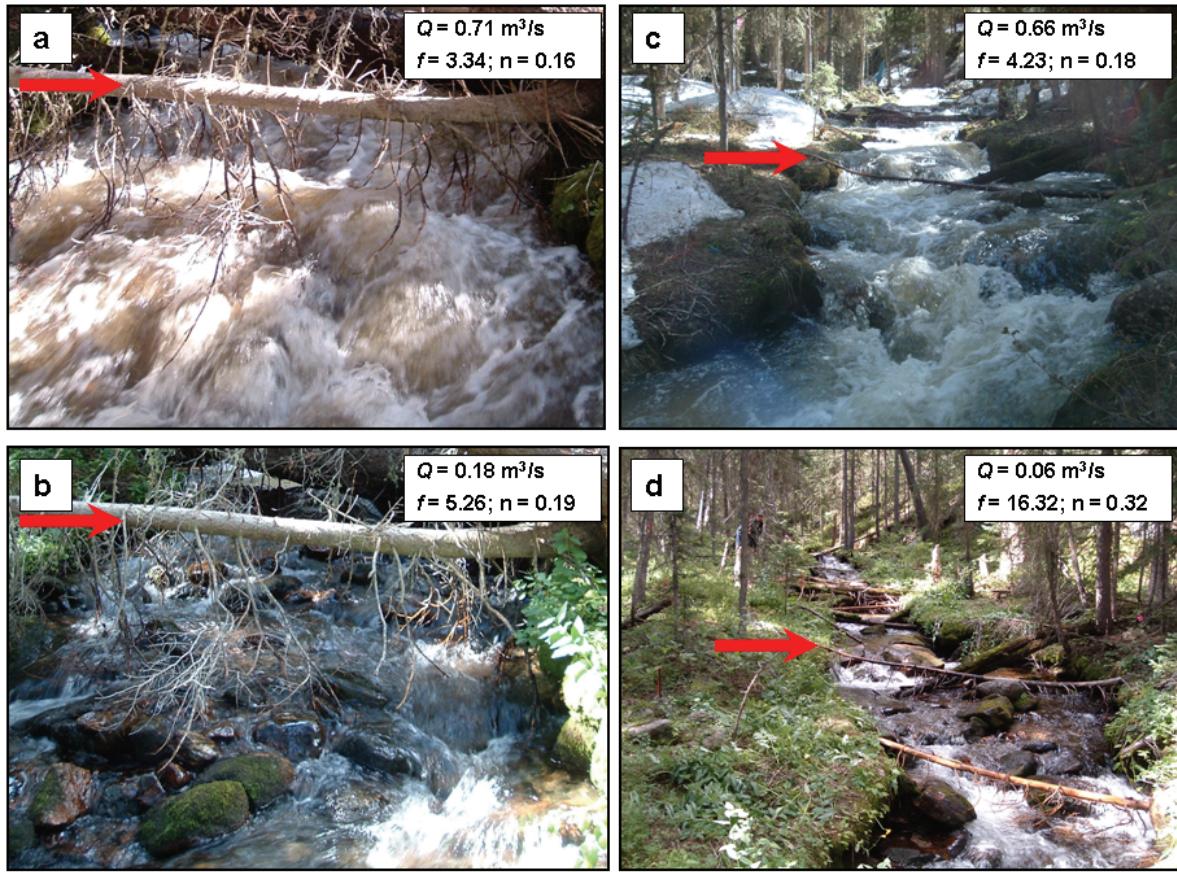


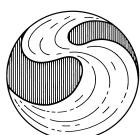
Figure 1: Photographs of a cascade reach at high flow (a) and low flow (b) and a step-pool reach at high flow (c) and low flow (d). The arrows indicate the same location on each of the corresponding photographs.

Results and Discussion

Gradient is a dominant channel characteristic that influences variations in f among all reaches (table 1). Gradient is related to all other potential control variables such as grain size, channel type, and step geometry, but these other variables were not always significantly related to total f . It is important to understand how gradient is related to f and other stream characteristics as this is a metric that can be used to predict velocity and discharge at different stages. The results in table 1 indicate that the higher the gradient then the higher the f . As gradient increases, more energy is likely dissipated from cascading flow and abrupt transitions from supercritical to subcritical flow. Gradient is a significant explanatory variable that is greatly improved when paired with dimensionless discharge or wood load (models 1, 2, 3, and 4). Discharge, as represented by dimensionless discharge, is also significant in controlling how different components of resistance interact and control the submergence of large bed elements by changing flow patterns over boulders and logs,

causing flow separation around the object, and/or skimming flows over the object. Since discharge is often an unknown, gradient is considered one of the more useful explanatory variables because it is correlated with many of the other control variables and improves each model in which it is included. Therefore, gradient influences total resistance over all channel types and components of resistance, but how each component of resistance interacts at higher gradients is dependent on the relative submergence of each roughness element.

Wood load was found to be significantly related to total f for all reaches. Wood increases resistance, particularly at higher flows, most likely because a larger number of logs are submerged at higher flows (fig. 2). Logs on the channel bed that have diameters on a scale with the water depth locally increased water depth and created a significant backwater effect, which decreases the resistance related to grains. Conversely, logs near the water surface and only in the flow during high-flow conditions may create a large increase in velocity



beneath the log and a hydraulic jump above the log, causing localized supercritical flow (fig. 2).

The majority of the wood was found in the steps, therefore the significance of wood is also related to the significance of the steps in increasing resistance. Steps composed of a combination of wood and boulders tend to have heights, widths, and lengths that are greater than steps composed of only wood or only boulders. Also, steps with wood tended to create larger backwater areas behind the steps causing smaller grain sizes to be deposited behind the steps. Wood load was found to be positively correlated with gradient. This is most likely related to an increase in step steepness as log steps increase step height, therefore creating steeper gradients. Because of cross-correlation with other variables, wood load was not found to greatly improve models that only included cascade or step-pool reaches (table 1; models 7 and 8). Although the wood load can be representative of step

geometry, the relative submergence of the steps (R/H) better represents this facet of roughness.

Although these regressions are meant for explanatory purposes and not for prediction, fig. 3 helps to demonstrate which variables may be useful for developing new predictive equations in these higher-gradient streams. Inclusion of a flow variable (q^*), gradient, and channel type increases the ability to explain the variability at sites FC1 and FC2, but do not explain the variability as well at sites ESL2 and FC3. In model 1, gradient is a proxy for both grain size and step steepness, which combines with dimensionless discharge and channel type to better explain the variability in these two reaches. Wood load is a dominating factor at sites ESL2 and FC3, which means that it is more difficult for model 1 to account for the higher values of total resistance in these reaches when only a grain submergence variable (q^*) is used.

Table 1. Linear regressions of $(8/f)^{0.5}$ and f versus independent variables and categorical variables.
Independent Variables^a

Dependent Variable ^b	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7 Cascade ^c	Model 8 Step-pool ^d
$(8/f)^{0.5}$	Intercept			0.29*	0.88*		0.89*	0.32*
f	Intercept	84.95*	242.64*			5.97*		6.20*
S_0^e (gradient)		1.32*	0.79*	-0.54*			-0.50*	0.57*
R/D_{84}					0.39*		0.78*	
R/H^f								-1.75*
R/s_{bed}^g							0.72*	
q^h (dimensionless discharge)		-0.65*	-0.75*			-0.66*		
wood load			0.13*					
Step-Pool ⁱ		1.62*	1.09					
Cascade		1.00*	1.00					
F-statistic	33.57	21.84	11.88	11.32	51.89	96.38	13.62	36.37
p-value ^j	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
R ²	0.66	0.65	0.18	0.18	0.49	0.65	0.62	0.69
Adj. R ²	0.64	0.62	0.17	0.16	0.49	0.64	0.57	0.68

^a Variables with * indicate that value is significant at the $\alpha = 0.05$ level.

^b Variables in bold were transformed using the natural log.

^c Regression includes only cascade reaches

^d Regression includes only step-pool reaches

^e Numbers shown are exponents of independent variables, if it is a categorical variable and that category is true than the number should be multiplied with the intercept.

^f The relative submergence of a step (where H is the step height)

^g R/s_{bed} is the relative submergence of the standard deviation of bed elevation. The s_{bed} value was found using the residuals of a regression of the thalweg longitudinal profile.

^h Part of Channel Type categorical variable that includes two levels; step-pool and cascade channel types.

ⁱ Where 0.001 is indicated, the value is actually < 0.001.



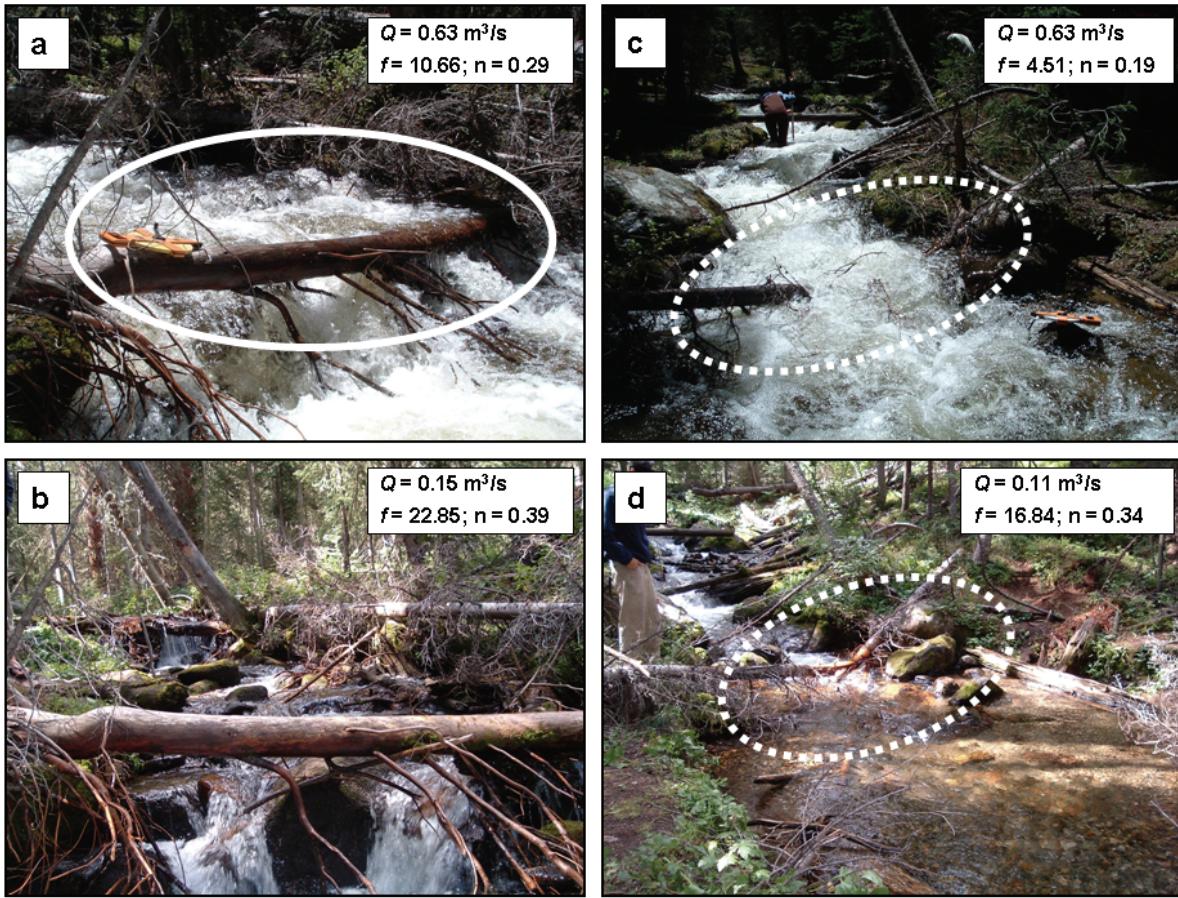


Figure 2: Examples of individual pieces of wood in the study reaches. Note that these pieces are only in contact with the water during high flow. a) Site ESL5 at high flow. Note that the log spans the channel and creates a slight backwater along the left bank. b) Site ESL5 at low flow. Note that flow goes completely underneath the wood. c) Site ESL2 at high flow. Note the flow cascading over the broken log. d) Site ESL2 at low flow. Note that flow goes completely underneath the wood.

Summary

The regression results presented here are not meant to be used as predictive equations, but to guide in the development of predictive equations for mountain streams. The results indicate that gradient is a significant control variable that is useful when combined with a variable that represents the flow depth in relation to the dominant roughness element for that channel type. Discharge is significant in controlling how different components of resistance interact and control the submergence of large bed elements by changing flow patterns over boulders and logs. When discharge is known, a variable such as dimensionless discharge is a significant explanatory variable for both step-pool and cascade reaches, particularly when combined with gradient. Because step-pool reaches are influenced mainly by step geometry and cascade reaches by grain

size, two separate models are shown for these channel types (models 7 and 8) when discharge is unknown. Gradient combined with relative submergence of a characteristic grain size (R/D_{84}) is the best model for a cascade reach and gradient combined with relative submergence of the step (R/H) is the best model for a step-pool reach. When different channel types are not defined, then the best explanatory variable was the relative submergence of the standard deviation of bed elevation (model 6). Reaches with high wood load should be considered carefully and may have higher values of total resistance than are predicted by standard equations using only grain size or step height. Further work should be done to consider if separate resistance equations could be applied to step-pool and cascade channels determined from remote data.

The results presented in this paper are a subset of



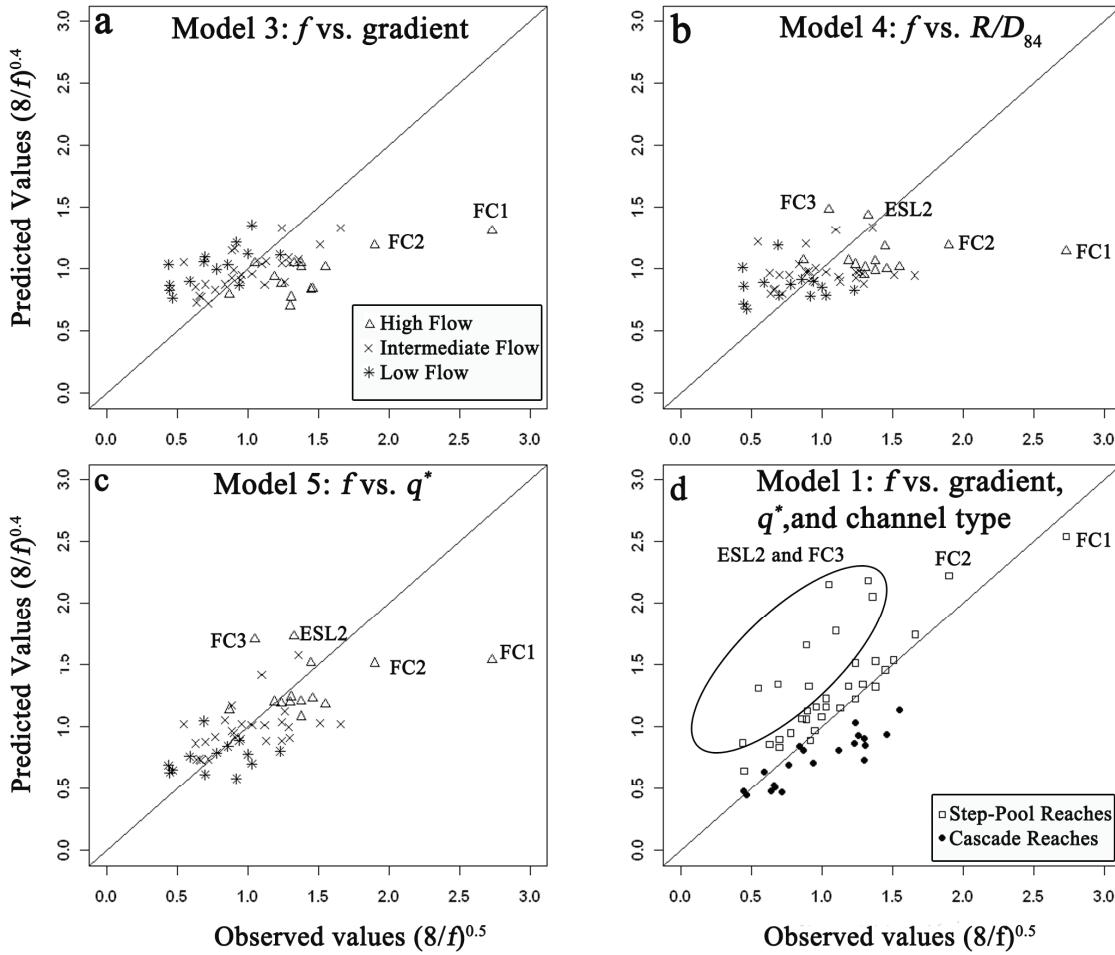


Figure 3. Predicted versus observed $(8/f)^{0.5}$ for model 3 (a), model 4 (b), and model 5 (c). The data points are separated by low, intermediate, or high flows to show how f tends to be under-predicted at high flows and over-predicted at low flows for model 3 and model 4, but not for model 5. The combined model of gradient, dimensionless discharge, and channel type is shown in model 1 (d). The regression models can be found in table 1.

the results found for a larger project assessing flow hydraulics and flow resistance in high-gradient channels and are considered the most pertinent for management purposes. This paper was adapted from the following articles:

- David, G.C.L.; Wohl, E.; Yochum, S.E.; Bledsoe, B.P. 2010. Controls on spatial variations in flow resistance along steep mountain streams. *Water Resources Research*. 46: W03513, doi:10.1029/2009WR008134.
- David, G.C.L.; Wohl, E.; Yochum, S.E.; Bledsoe, B.P. 2010. Controls on at-a-station hydraulic geometry in steep headwater streams, Colorado, USA, *Earth Surface Processes and Landforms*, doi: 10.1002/esp.2023.

Please refer to those articles for a more in-depth discussion and complete list of references on this topic.

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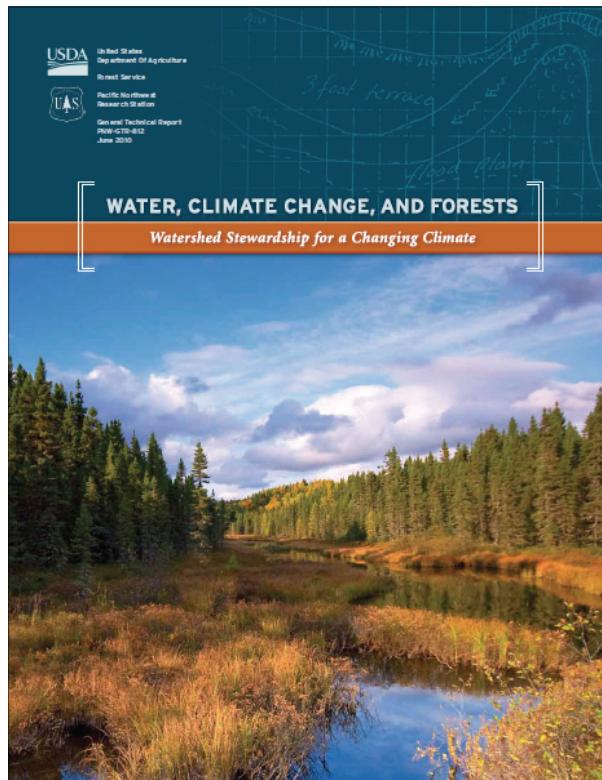


Water, Climate Change, and Forests: Watershed Stewardship for a Changing Climate

The U.S. Forest Service, Pacific Northwest Research Station recently published the report, *Water, Climate Change, and Forests: Watershed Stewardship for a Changing Climate*, that discusses the role of forested watersheds in the stewardship of water resources and watershed services in a changing climate. The report describes climate change adaptation opportunities for those involved in forest management, specifically in the context of water and aquatic ecosystems. Climate change adaptation actions focused on maintaining or improving the condition of watersheds will result in healthy, resilient watersheds that are more likely to continue supplying desired water resources and watershed services.

The “Background Section” of the report describes how forested watersheds provide invaluable watershed services with respect to the supply of water for domestic use, agriculture irrigation, hydropower consumption, and aquatic and riparian ecosystems along stream corridors. The “Background Section” of the report also summarizes the current understanding of 1) 20th century climate change in the United States, 2) future climate change projections of temperatures, precipitation, and hydrology in different parts of the United States, 3) how altered hydrologic and disturbance regimes from climate change will affect forests and watershed services, and 4) how the direct, indirect, and cumulative effects of climate change will complicate the management of water and aquatic resources on national forests.

The “Thinking Forward” section of the report outlines a watershed stewardship framework for responding to the potential effects of climate change on water resources and watershed services. Effective watershed stewardship requires 1) critical thinking about the resource values at stake, 2) collaboration with all stakeholders to develop common watershed management goals, and 3) the action or implementation of watershed stewardship practices to protect, maintain, and/or restore watershed processes so that crucial and highly valued water resources and watershed services continue to be provided into the future.



Cover page of the publication, *Water, Climate Change, and Forests: Watershed Stewardship for a Changing Climate*.

Hardcopies of *Water, Climate Change, and Forests: Watershed Stewardship for a Changing Climate* can be obtained by placing an order to Publications Distribution, Pacific Northwest Research Station by telephone (503-808-2138), facsimile (503-808-2130), or e-mail (pnw_pnwpubs@fs.fed.us). An electronic copy of PNW-GTR-812 can also be downloaded at <http://www.fs.fed.us/pnw/publications/gtrs.shtml>.

The citation for this publication is: Furniss, M.J.; Staab, B.P.; Hazelhurst, S.; Clifton, C.F.; Roby, K.B.; Ilhadrt, B.L.; Larry, E.B.; Todd, A.H.; Reid, L.M.; Hines, S.J.; Bennett, K.A.; Luce, C.H.; Edwards, P.J. 2010. Water, climate change, and forests: watershed stewardship for a changing climate. Gen. Tech. Rep. PNW-GTR-812. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 75 p.



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