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Fuel-Reduction Treatments in Riparian Areas

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Fuel reduction treatments are being conducted throughout watersheds of the western USA to reduce hazardous fuels in efforts to decrease the risk of high-severity fire. The number of fuel reduction projects that include near-stream environments is increasing, bringing new challenges to riparian management. Riparian areas are protected by administrative regulations, some of which are largely custodial and restrict active management. However, riparian areas have also been affected by fire suppression, land use, and human disturbance. Manipulative treatments of vegetation and other fuels may be needed along certain stream segments (Figure 1) to maintain riparian biodiversity and restore valued functions.

A recently published General Technical Report (GTR; Dwire et al. 2016) synthesizes current knowledge on the effects of wildfire and fuels treatments in riparian areas of the interior western USA (Figure 2). The goals of the report are to serve as a framework for planning and implementing fuels

Figure 1: Fuels treatment in a riparian zone.

StreamNotes is an aquatic and riparian systems publication with the objective of facilitating knowledge transfer from research & development and field-based success stories to on-the-ground application, through technical articles, case studies, and news articles. Stream related topics include hydrology, fluvial geomorphology, aquatic biology, riparian plant ecology, and climate change.

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reduction treatments that include stream-riparian corridors, and to assist with NEPA requirements for assessment of potential project impacts. The report includes: (1) a literature review of fire effects on riparian and aquatic characteristics and functions, provided as background for considering the need and potential impacts of fuel treatments; (2) a review of the potential effects of prescribed fire and mechanical treatments on riparian and aquatic resources and biota; (3) results of an online survey of resource managers, summarizing information about proposed and completed fuel reduction projects in riparian areas and wetlands in the interior west; (4) suggestions for pre-and-post project-level monitoring for riparian fuels projects, and (5) a presentation of case studies, describing riparian fuel treatments with different objectives and methods.

On National Forest System lands, protection of riparian areas is governed by special rules, stated as Standards and Guidelines in the Forest Plan for each National Forest, and best management practices (BMPs). To establish more consistency and direction across different regions, the USDA Forest Service published the first volume of National Core BMPs to improve agency performance and accountability in managing water quality consistent with the Clean Water Act (USDA Forest Service 2012). Included are a set of BMPs that address Wildland Fire Management Activities (Table 1). These BMPs outline general guidance for common wildland fire management operations, including use of prescribed fire, managing wildfire using a range of strategies (from monitoring to control and suppression) and rehabilitating fire and fire suppression damage to watersheds. The development of site-specific BMP prescriptions based on site conditions and local and regional requirements is still required to achieve compliance with established state, tribal, and national water quality objectives. However, the overall guidance has incorporated ecological knowledge regarding the role of fire and acknowledges the importance of addressing fire and fuel treatments in riparian areas – this is a step forward in watershed management.

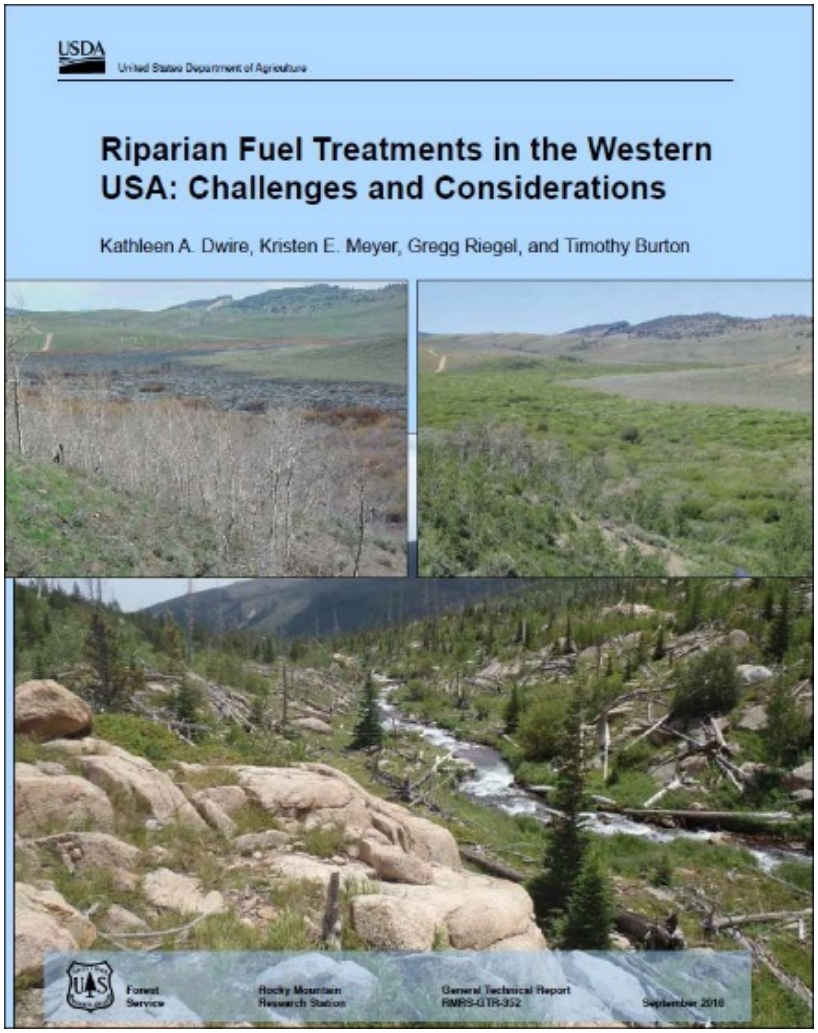

Figure 2: Rocky Mountain Research Station General Technical Note for riparian fuel treatments.

Riparian Management in Western Firescapes

Wildland fire has played a vital role in shaping ecological heterogeneity across landscapes of the western USA — landscapes dissected by a complex network of drainages and stream-riparian ecosystems, which have also been influenced by fire as a recurring natural disturbance (Luce et al. 2012). With increased recognition that fire was historically common in many riparian areas, resource managers are increasingly including riparian areas in fuels projects as part of watershed improvement projects (Dwire et al. 2016). Effective riparian management preserves the dynamic connections of riparian areas to surrounding uplands, as well as to stream channels. Understanding the effects of wildfire and fuel reduction requires integration of information about the spatial extent of past

Table 1: Best management practices for wildland fire management activities (from USDA Forest Service 2012).

National Core Best Management Practice (BMP)	Objective
Wildland Fire Management Planning	Use the fire management planning process to develop measures to avoid, minimize, or mitigate adverse effects to soil, water quality, and riparian resources during wildland fire management activities.
Use of Prescribed Fire	Avoid, minimize, or mitigate adverse effects of prescribed fire and associated activities on soil, water quality, and riparian resources that may results from excessive soil disturbance as well as inputs of ash, sediment, nutrients, and debris.
Wildland Fire Control and Suppression	Avoid or minimize effects to soil, water quality, and riparian resources during fire control and suppression efforts.
Wildland Fire Suppression Damage Rehabilitation	Rehabilitate watershed features and functions damaged by wildland fire control and suppression-related activities to avoid, minimize, or mitigate long-term adverse effects to soil, water quality, and riparian resources.

management and other human disturbance and temporal aspects of natural disturbance regimes, including fire return intervals and frequency of landslides (Elliott et al., 2010; Luce et al. 2012). In the western USA, "we live in a fire environment and need to plan accordingly" (quote from Penny Morgan in Luce et al. 2010). Our recent GTR reiterates these connections and provides a synthesis of current knowledge of fire effects on riparian and aquatic characteristics and functions.

Fuels in Riparian Areas

As in surrounding uplands, fire suppression has contributed to the accumulation of fuels in riparian areas, particularly in forest types with low-to-mid-severity fire regimes. Yet, for most riparian plant communities, few data are available on fuel loads, fuel characteristics, or fuel distribution (but see Van de Water and North 2011, Dwire et al. 2015). Riparian areas are frequently the most productive areas in a given region and contain structurally and floristically diverse vegetation. In many areas, riparian vegetation may differ from adjacent uplands in overstory species composition; have higher stem densities and basal area; have greater dominance of shrubs and deciduous hardwoods; and have higher herbaceous cover.

The limited research on the influence of riparian vegetation and fuels on fire properties has mostly been conducted in conifer-dominated areas of the Pacific Northwest. Much less is known about riparian areas in the western USA where plant communities are dominated by deciduous trees and shrubs, including alders (*Alnus spp.*), willows (*Salix spp.*), quaking aspen (*Populus tremuloides*), and cottonwoods (*Populus spp.*). These riparian plant community types differ considerably in fuel characteristics (chemistry, fuel composition, and moisture content) from conifer, shrub, or grassland-dominated uplands. Montane meadows border numerous stream segments in mountains of the western USA, including ranges throughout the Great Basin. These grass- and sedge-dominated meadows often produce high loads of fine fuels that can burn late in the fire season.

Differences in riparian and upland vegetation result in differences in fuel profiles and total fuel loadings. Streamside areas frequently have more complex vertical layers within the canopy and subcanopy, i.e. well-developed ladder fuels, more fine fuels, and greater fuel moisture than surrounding uplands. These components are strongly predictive of riparian fire severity (Halofsky and Hibbs 2008).

Despite these notable differences, many forested riparian areas in the western USA are occupied by the same overstory species as surrounding uplands. Even in these riparian stands, stem densities, standing biomass, and shrub and herbaceous understory diversity are usually greater than upslope stands. In a study of subalpine forests of northern Colorado and southern Wyoming, the overstory species composition and basal area were found to be similar in riparian and upland plots, but understory stem densities and shrub diversity were generally higher in riparian plots (Figure 3; Dwire et al. 2015). Where vegetation and fuel profiles are similar across upland and riparian stands, they are likely to burn with similar frequency and intensity.

We strongly encourage the assessment of fuels in riparian areas and wetlands before and after treatments. More information is needed on the diverse range of riparian fuel profiles and their responses to different treatments, and resource managers are urged to collect quantitative data on riparian fuels whenever possible and — at a minimum — to photograph before-and-after-treatment conditions.

Effects of Fuel Management Activities on Riparian and Aquatic Resources

Despite the ongoing research focus on the effects of fuel treatments, results from studies specifically conducted in riparian areas are limited. Riparian vegetation contributes to the maintenance of aquatic habitat for native fishes and

other aquatic biota through: (1) provision of shade for thermal modification of stream temperature; (2) allochthonous organic matter inputs to aquatic food webs; (3) inputs of large wood for instream habitat complexity; and, (4) provision of streamside habitat and stabilization of streambanks. Each of these functions could be altered at the reach scale with changes in riparian vegetation, including short-and-long-term responses to fire and fuel treatments (Luce et al. 2012). In our GTR, we summarized numerous studies from the literature that investigated the effects of wildfire, prescribed fire, and mechanical thinning or forest harvest on these four valued riparian functions, as well as features of riparian-stream ecosystems.

The immediate goal of most fuel reduction treatments is to change vegetative structure and reduce fuel continuity to reduce crown fire behavior and potential wildfire size. From our literature review, we learned that the effects of prescribed burning on both upland and riparian species composition appear to be either negligible or similar to effects of low-severity wildfire, and generally neutral or beneficial. The effects of mechanical treatments on riparian species composition are more complex, however, and could result in longer-term changes, depending on magnitude of environmental impacts, such as soil compaction.

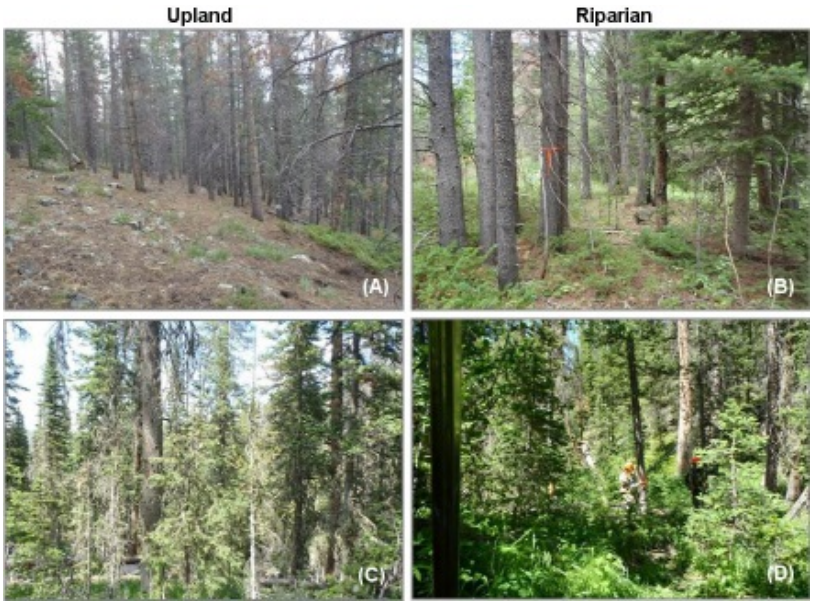

Figure 3: Variable stand conditions were sampled in both upland and riparian plots: (A) upper left Bennett Creek, Roosevelt National Forest, CO, upland; (B) upper right, Bennett Creek, Roosevelt National Forest, CO, riparian; (C) lower left, Cortez Creek, Medicine Bow National Forest, WY, upland; (D) lower right, Cortez Creek, Medicine Bow National Forest, WY, riparian.

Management Implications

- Riparian areas are spatially diverse; the spatial arrangement of different riparian plant communities and attributes within a watershed can influence both the response to fuels treatments and the effectiveness of fuels reduction.
- Current knowledge on the effects of mechanical fuel treatments on streams, riparian areas, and aquatic and near-stream habitat and biota is limited. Proceed cautiously, particularly in watersheds where species of concern are present.
- Determination of desired riparian conditions remains challenging. In-depth discussions among interdisciplinary teams are critical for consideration of potential outcomes and developing consensus on desired targets for maintaining specific habitat elements and natural processes.
- Control of invasive species remains a challenge during and following fuel reduction treatments. The occurrence of non-native invasive plant species is not uncommon in many treatment areas. For some projects, control of invasive species can be an explicit project objective.
- Uncertainty regarding future changes in climate, streamflow, and fire frequency and severity increases the complexity of treatment design. Stream-riparian corridors are dynamic, and planning for project outcomes need to allow for changes, ranging from natural successional processes to multi-scale responses to episodic disturbances like flooding or high severity wildfire.
- Promote landscape resilience through improved integration of fuels projects with other restoration activities, fire management and post-fire stabilization, and climate change adaptation.

Acknowledgements

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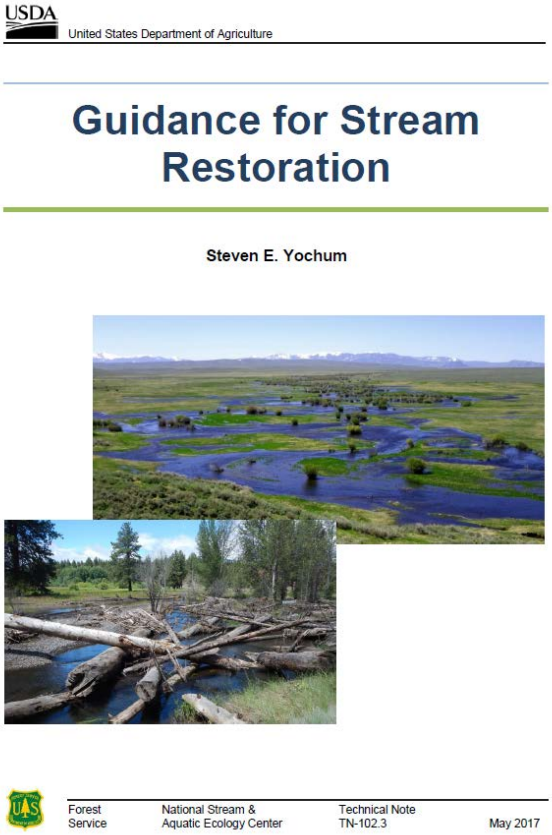
Notices and Technical Tips

- **Direct technical assistance from applied scientists at the National Stream and Aquatic Ecology Center** is available to help Forest Service field practitioners with managing and restoring streams and riparian corridors. The technical expertise of the Center includes hydrology, fluvial geomorphology, riparian plant ecology, aquatic ecology, climatology, and engineering. If you would like to discuss a specific stream-related resource problem and arrange a field visit, please contact a scientist at the Center or David Levinson, the NSAEC program manager.
- **Long term changes to water quality** has been documented in a new USGS interactive map product. "This mapper provides results from the largest-ever assessment of water-quality changes in the Nation's streams and rivers. More than 185 million water-quality records from over 600 Federal, State, Tribal, and local organizations were screened as part of this assessment. The mapper shows stream trends in water chemistry (nutrients, pesticides, sediment, carbon, and salinity) and aquatic ecology (fish, invertebrates, and algae) for four time periods: 1972-2012, 1982-2012, 1992-2012, and 2002-2012." The mapper is available here.
- Scientific America recently published an article on **carbon sequestration in wet meadows.** "An unusual research project is determining whether restoring California's meadows can reduce atmospheric carbon dioxide."

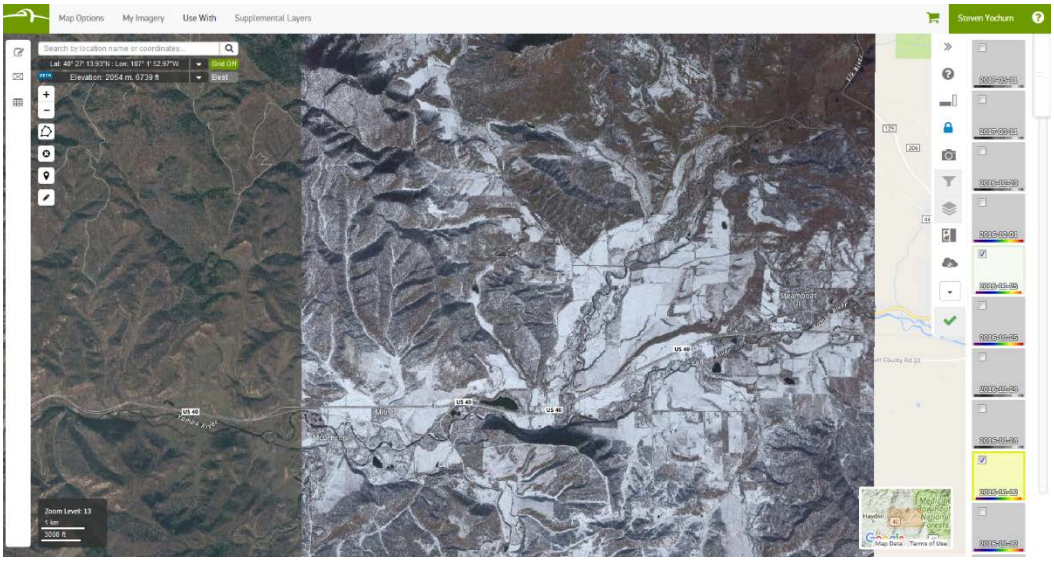
Notices and Technical Tips

- The annual update to the National Stream and Aquatic Ecology Center's technical note ***Guidance for Stream Restoration*** has been published on the Center's website (TN-102.3). The most substantial changes in this year's revision include the addition of more fundamental principles to the Preliminary Field Assessment chapter, the introduction of a restoration spectrum to the form versus process-approaches discussion, and many new links to new (or newly found) technical guidance and tools. Below is the publication's abstract:

  A great deal of effort has been devoted to developing guidance for stream restoration. The available resources are diverse, reflecting the wide ranging approaches used and expertise required to develop effective stream restoration projects. To help practitioners sort through this extensive information, this technical note has been developed to provide a guide to the available guidance. The document structure is primarily a series of short literature reviews followed by a hyperlinked reference list for the reader to find more information on each topic. The primary topics incorporated into this guidance include general methods, an overview of stream processes and restoration, case studies, data compilation, preliminary assessments, and field data collection. Analysis methods and tools, and planning and design guidance for specific restoration features, are also provided. This technical note is a bibliographic repository of information available to assist professionals with the process of planning, analyzing, and designing stream restoration projects.



- **High-resolution satellite aerial imagery** from DigitalGlobe has been made available to employees of federal agencies through a program with the National Geospatial-Intelligence Agency. This imagery is oftentimes available at 46 cm resolution and is collected multiple times each year across North America and beyond. For more information on this program, click here. To register or login, click here.



Understanding Environmental Flows in Desert Rivers of the U.S. and Mexico through the Desert Flows Database

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Efforts to define water needs for riparian and aquatic ecosystems in arid and semi-arid systems are critical because riparian areas are essential for the survival of desert life, with stream corridors providing a large proportion of ecosystem services in these landscapes (Poff, Koestner, Neary, & Henderson, 2011; Millennium Ecosystem Assessment, 2005). To create a one-stop-shop for published ecological water needs information and illuminate critical knowledge gaps in the desert watersheds of the U.S. and Mexico, the University of Arizona's Water Resources Research Center and the Northern Arizona University School of Earth Sciences and Environmental Sustainability created the Desert Flows Database. Funded by the Desert Landscape Conservation Cooperative, the database is a geospatial tool that synthesizes environmental flow needs and ecosystem responses to changes in flows from 408 articles or reports related to ecological water requirements. The database includes studies from 105 streams and 312 species or genera from across the 839,000 square mile study area. (Figure 4)

The database design was based on information needs identified through a survey taken by 47 water and land managers at the federal, state, and local levels that work in the desert watersheds of the U.S. and Mexico. The database contains a concise summary of each study, the methods used to determine environmental flow needs or responses in each study, an assessment of method quality, risks to or stressors upon the studied species or ecosystem, dependencies or relationships between vegetation and terrestrial or aquatic species, and environmental flow need or flow response data. Environmental flow needs and flow response data are standardized using meta-categories for describing ecological impacts of flow and hydrologic elements. The ecology and hydrology are then linked using words such as "depends upon" or "enhanced by" to describe the relationship between them. The meta-categories for ecologic impacts include: abundance, age structure, survivorship, and reproduction. Hydrologic meta-categories are the natural flow regime elements identified in Poff et al., 1997: magnitude, timing, duration, frequency, and rate of change.

Perhaps the most important aspect of assembling these data into one repository is the ability to identify

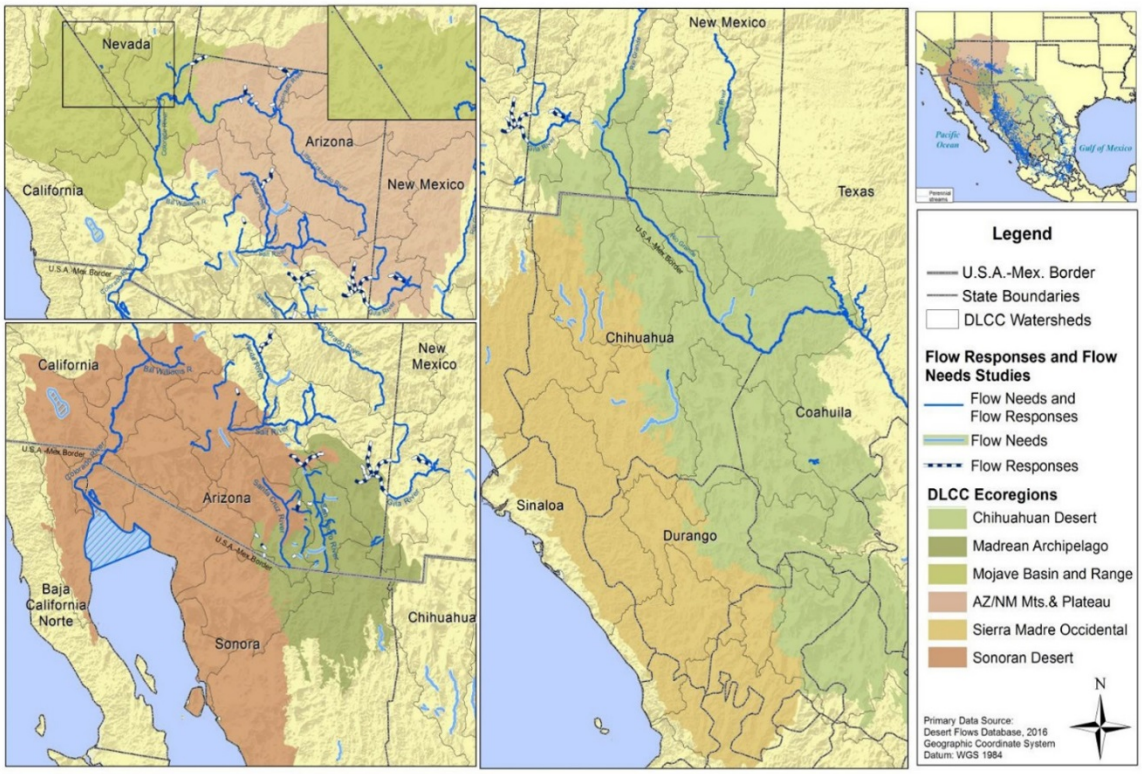

Figure 4: Desert Flows Database study area and extent of data available on environmental flow needs and/or environmental flow responses.

where the gaps exist and uncertainty remains. For example, although 105 streams have been studied for some aspect of environmental flows, less than half (45%) have been studied more than once over the past four and a half decades. Only eight rivers (Rio Grande, Colorado River, San Pedro River, Bill Williams River, Verde River, Santa Cruz River, and Pecos River) have ten or more studies that directly address environmental flows. Similarly, while the database contains information on 312 species or genera, only one-third have been studied more than once and only 15 genera (or 5%) have been studied five or more times. The most commonly studied taxa were Cottonwood (*Populus*, 66 studies), Tamarisk (*Tamarix*, 40), Willow (*Salix*, 31), Mesquite (*Prosopis*, 24), and Chub (*Gila*, 16). Summary information for evapotranspiration and groundwater for the most commonly studied vegetation is provided in Table 2. In addition to capturing species and their water requirements, this effort also catalogued the methods used to determine environmental flows and assessed the quality of evidence used. Methods ranged from qualitative descriptions of the distribution of flora and fauna associated with water sources to quantitative methods such as habitat simulation and biological event models. The majority of studies (67%) were qualitative. With regards to the quality of evidence, the most common type of data collected were from a comparison of differences between sites for a desired species or community (61%).

Effective management of riparian and aquatic ecosystems requires knowing not only where studies exist and what has been studied, but also what external stresses could impact proposed management actions. Of the studies that noted stresses, the most common were

Table 2: Summary data for evapotranspiration and groundwater levels for mature vegetation in the study area (reproduced from Mott Lacroix et al. 2017).

***Genus* Common Name**	**Relationship**	**Magnitude**		**Citation(s)**
Evapotranspiration				
Populus Cottonwood	uses	0.41-3.3	m/yr	ADWR, 2005; Cleverly et al., 2006a; Cleverly et al , 2006b; Glenn & Nagler, 2005; ; Shafroth et al., 2005; Springer, Wright, Shafroth, Stromberg, & Patten, 1999
		1.52-2.53	MCM/ km^2	Pima County, 2009a; Pima County, 2000
Tamarix Tamarisk		0.41-3.4	m/yr	ADWR, 2005; Cleverly et al., 2006b; SS Papdopulos and Associates Inc. & New Mexico Interstate Stream Commission, 2006; Shafroth et al., 2005; Nagler, Glenn, & Hinojosa-Huerta, 2009
Prosopis Mesquite		0.6-4.64	m/yr	ADWR, 2005; Baker et al., 1999
		0.49-0.91	MCM/ km^2	Beauchamp & Stromberg, 2007
Groundwater				
Populus Cottonwood	assoc. with	1.0-3.5	m/bls	Cleverly et al., 2006b; Leenhouts, Stromberg, & Scott, 2006; Merritt & Bateman, 2012; Snyder & Williams, 2000; Stromberg, Tiller, & Richter, 1996; Stromberg, Lite, Dixon, & Tiller, 2009; Stromberg, 1998
	depends upon	1.0-5.0	m/bls	Follstad Shah & Dahm, 2008; Hardy & Davis, 2013; Pima County, 2009b; Taylor & McDaniel, 1998
	enhanced by	<1.4 -4.0	m/bls	Busch & Smith, 1995; Harding & McCord, 2005; Horton, Kolb, & Hart, 2001; Lite & Stromberg, 2005
	harmed by	>1.5->3	m/bls	Horton, Kolb, & Hart, 2001; Shafroth, Stromberg, & Patten, 2000; Sprenger, Smith, & Taylor, 2002; Stromberg, 2008; Turner & Haney, 2008
Salix Willow	assoc. with	0.09 - 4.26	m/bls	Leenhouts et. al 2006; Merritt & Bateman, 2012; National Park Service, 2008; ; Snyder & Williams, 2000; Stromberg et al., 1996; Stromberg et al., 2009; Taylor & McDaniel, 1998
	enhanced by	0.0-4.0	m/bls	Busch & Smith, 1995; Horton et al., 2001; Turner & Haney, 2008
	harmed by	>2.5->3.0	m/bls	Horton et al., 2001; Leenhouts et. al 2006
Populus/Salix Cottonwood / Willow Forest	assoc. with	1.52±0.65 - <3.0	m/bls	Stromberg, Lite, & Beauchamp, 2003; Stromberg et al., 1996; Cooper & Soles, 2014
	depends upon	<3	m/bls	Stromberg, et al., 2009
Prosopis Mesquite	assoc. with	0.9 -8	m/bls	Springer et al., 1999; Stromberg et al., 1996; Stromberg et al., 2009; Snyder & Williams, 2000
	depends upon	<1.2 - 8	m/bls	Pima County, 2009a; Taylor & McDaniel, 1998; Stromberg, Wilkins, & Tress, 1993
	enhanced by	<5.0	m/bls	Baird, MacNish, & Guertin, 2000
	harmed by	14.0-18.0	m/bls	Leake, Pool, & Leenhouts, 2008; Baird, MacNish, & Guertin, 2000
Tamarix	assoc. with	0.4-4.0	m/bls	Stromberg et al., 1996; Merritt & Bateman, 2012; Stromberg et al., 2009
	enhanced by	3.5-4.0	m/bls	Horton et al., 2001
	harmed by	>2.5-3	m/bls	Horton et al., 2001

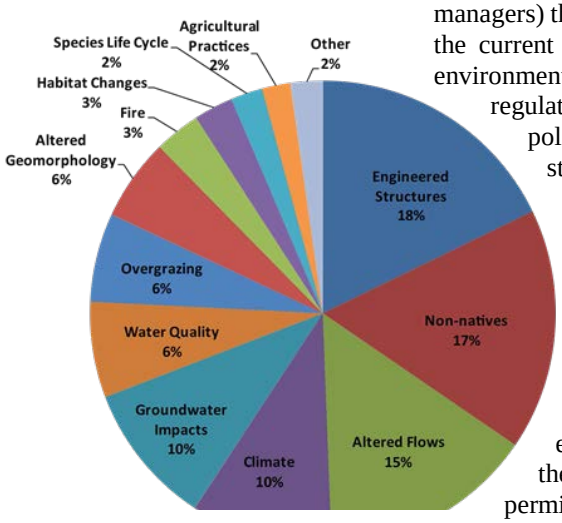

Figure 5: Stressors on riparian and aquatic ecosystems in the study area.

engineered structures (18% of studies), non-native species (17%), and altered flows (15%) (Figure 5). While climate was indicated as a stressor in 10% of the studies, climate change impacts were infrequently examined. Interestingly, the most frequently noted stressors were similar across the study area.

Going forward, there are three important considerations for the use of the Desert Flows Database. The first is the maintenance of the tool itself. The database is current as of July 2015, however, for it to remain a useful tool it must be periodically updated by the Desert Landscape Conservation Cooperative or a partner. Second, while generalized findings, particularly those for well-studied genera like cottonwoods or tamarisk, may be transferrable to less-understood systems it would be problematic to take any information within the database and directly apply it to other systems. To account for the complexity of river systems, setting any targets for flows or groundwater levels using database information should be part of an adaptive management framework where conditions are monitored and standards are re-evaluated based on empirical data. Finally, a need (identified via our initial survey of managers) that is not addressed with the current database is connecting environmental flows data with regulatory frameworks and policy standards for the study area. Understanding the regulatory framework is key since even the most complete understanding of the science will not result in management that provides environmental flows if the laws or policies do not permit or encourage it. To learn more about the project, including a step by step webinar and written guide, visit the Desert Flows Database website. The journal article (Mott Lacroix et al., 2017) on the gap analysis portion of this work is also available online.

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Management Implications

- The Desert Flows Database is a repository for environmental flow related studies that can be queried by water and land managers to determine existing information in their region, on species of concern, or by study element. For example, a search can be performed on all studies that discuss climate-change impacts or identified engineered structures as a risk to the species or ecosystem.
- Data on water needs of vegetation such as cottonwood, willow, and mesquite are relatively plentiful. However, there are only a handful of studies of macroinvertebrate or mammal water needs.
- Given the paucity of studies on most species, we must consider whether or not we can manage the entire system using existing data on riparian vegetation and fish species. Moving forward, there should be a focus on working with the people who manage riparian and aquatic systems to determine if data on a handful of species are sufficient, or if a broader array of species need to be examined.

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Flow Resistance Coefficient Selection in Natural Channels: A Spreadsheet Tool

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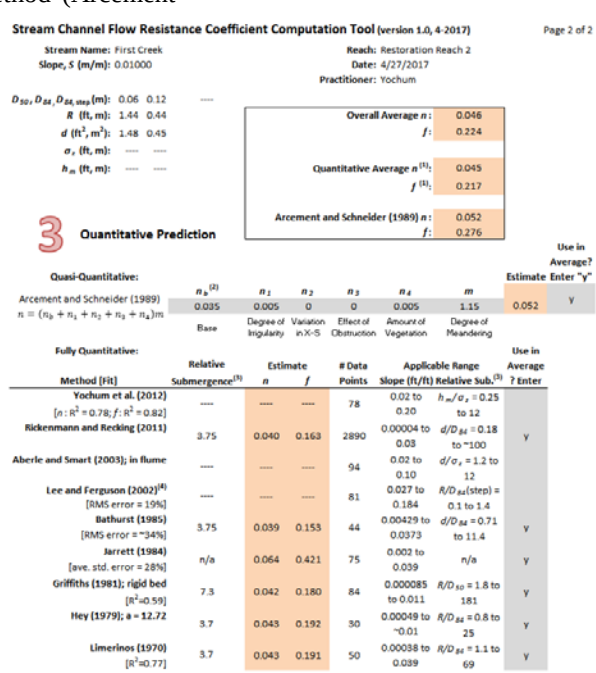
National Stream and Aquatic Ecology Center

A spreadsheet tool has been developed by the U.S. Forest Service National Stream and Aquatic Ecology Center to assist practitioners with selecting flow resistance coefficients for stream channels. Such coefficients are needed to quantify roughness for hydraulic modeling, stream assessments, stream restoration design, geomorphic analyses, and ecological studies. This Excel spreadsheet is available for download from the National Stream and Aquatic Ecology Center's tools webpage. A technical summary report has also been written in support of the tool (Yochum 2017); it is available here.

Roughness in channels and floodplains is a fundamental characteristic of stream corridors. Roughness induces the flow resistance to dissipate energy. Flow resistance in stream channels is generally due to (1) viscous and pressure drag on grains of the bed surface (grain roughness); (2) pressure drag on bed and bank undulations (form roughness), and (3) pressure and viscous drag on sediment in transport above the bed surface. Additionally, spill resistance associated with hydraulic jumps and wave drag on elements protruding above the water surface can be the dominant flow resistance mechanism in high-gradient channels. Hence, resistance is due to roughness induced by bed and bank grain material, bedforms (such as dunes and step pools), streambank and cross section variability, sinuosity, vegetation, large instream wood, and other obstructions (Figure 6).

Figure 6: Milk Creek on the White River National Forest (7/1/2015). Flow resistance is due to roughness from bed material (gravel dominated), streambank variability and vegetation, riffle-pool bedforms, large instream wood, and sinuosity.

Flow resistance is most frequently quantified by practitioners using the Manning's *n* coefficient. This tool provides sources for providing initial *n* estimates through tables and photographic guidance, uses inputted hydraulic and bed material characteristics to automatically compute quantitative estimates for *n* using 9 different methods (where applicable and sufficient data are available), and streamlines the use of a qualitative method (Arcement and Schneider 1989) that incorporates a wide range in flow resistance sources for computing a reach-average *n*. Using the user-chosen results, averages are computed for practitioners to select final flow resistance estimates. With the observations and measurements of stream reach conditions, this tool simplifies the estimation of flow resistance coefficients.



Stream Channel Flow Resistance Coefficient Computation Tool (version 1.0, 4-2017) Page 2 of 2

Stream Name: First Creek
Slope, S (m/m): 0.01000
Reach: Restoration Reach 2
Date: 4/27/2017
Practitioner: Yochum

$D_{50}, D_{84}, D_{84,step}$ (m):	0.06	0.12	----
R (ft, m):	1.44	0.44	
d (ft^3, m^3):	1.48	0.45	
σ_s (ft, m):	----	----	
h_m (ft, m):	----	----	

Overall Average n:	0.046
f:	0.224
Quantitative Average n [1]:	0.045
f [1]:	0.217
Arcement and Schneider (1989) n:	0.052
f:	0.276

3 Quantitative Prediction

Quasi-Quantitative:

Arcement and Schneider (1989)
$n = (n_b + n_1 + n_2 + n_3 + n_4)m$

n_b [2]	n_1	n_2	n_3	n_4	m	Estimate	Use in Average? Enter "y"
0.035	0.005	0	0	0.005	1.15	0.052	y
Base	Degree of Irregularity	Variation in X-S	Effect of Obstruction	Amount of Vegetation	Degree of Meandering		

Fully Quantitative:

Method [Fit]	Relative Submergence [3]	Estimate n	Estimate f	# Data Points	Applicable Range Slope (ft/ft)	Applicable Range Relative Sub. [3]	Use in Average ? Enter
Yochum et al. (2012) [n: R^2 = 0.78; f: R^2 = 0.82]	----	----	----	78	0.02 to 0.20	h_m/σ_s = 0.25 to 12	
Rickenmann and Recking (2011)	3.75	0.040	0.163	2890	0.00004 to 0.03	d/D_{84} = 0.18 to ~100	y
Aberle and Smart (2003); in flume	----	----	----	94	0.02 to 0.10	d/σ_s = 1.2 to 12	
Lee and Ferguson (2002) [4] [RMS error = 19%]	----	----	----	81	0.027 to 0.184	R/D_{84}(step) = 0.1 to 1.4	
Bathurst (1985) [RMS error = ~34%]	3.75	0.039	0.153	44	0.00429 to 0.0373	d/D_{84} = 0.71 to 11.4	y
Jarrett (1984) [ave. std. error = 28%]	n/a	0.064	0.421	75	0.002 to 0.039	n/a	y
Griffiths (1981); rigid bed [R^2=0.59]	7.3	0.042	0.180	84	0.000085 to 0.011	R/D_{50} = 1.8 to 181	y
Hey (1979); a = 12.72	3.7	0.043	0.192	30	0.00049 to ~0.01	R/D_{84} = 0.8 to 25	y
Limerinos (1970) [R^2=0.77]	3.7	0.043	0.191	50	0.00038 to 0.039	R/D_{84} = 1.1 to 69	y

References

Arcement, G.J., Schneider, V.R. 1989. Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains, U. S. Geological Survey.

Yochum, S.E. 2017. Flow Resistance Coefficient Selection in Natural Channels: A Spreadsheet Tool. U.S. Forest Service, National Stream and Aquatic Ecology Center, Technical Summary TS-103.1, May 2017.