NM WRRI Student Water Research Grant Progress Report Form

Progress Report due Feb 1, 2017
Draft Final Report due June 1, 2017
Final Report due June 30, 2017

1. Student Researcher: Michael Wine
   Faculty Advisor: Daniel Cadol

2. Project title: Spatial prediction of soil hydraulic properties accounting for variable wildfire burn severity, Valles Caldera, New Mexico

Abstract:

Projections of future water resource availability typically neglect ecological disturbance effects on regional water availability because these effects remain unknown. Here we show that considering wildfire in modeling streamflow significantly improves model skill. Mixed effects modeling attributed 2-12% of long-term annual streamflow to wildfire effects. The importance of this wildfire-linked streamflow relative to predicted climate change-induced streamflow reductions is larger than previously thought, ranging from 20%-330% of the streamflow decrease predicted to occur by 2050. The rate of post-wildfire vegetation recovery and the proportion of watershed area burned controlled the wildfire effect. Our results demonstrate that in large areas of the western USA affected by wildfire, regional predictions of future water availability are subject to greater structural uncertainty than previously thought.

3. Description of research problem and research objectives.

Since the 1950's accelerated human activities have altered key Earth cycles and systems in ways that have profound, often indirect, future effects on renewable water resources (Karl and Trenberth, 2003) and have made the assumption of hydrologic cycle stationarity untenable (Milly et al., 2008). Acknowledging that our climate is non-stationary, future water resource availability relative to the present is typically projected on the basis of future greenhouse gas emissions scenarios and their consequent impacts on precipitation and evaporative demand, as determined by hydrometeorologic models (Milly et al., 2005). Implicit in these highly impactful projections of climate change effects on water resources is an assumption that anthropogenic climate change is essentially the only component of global-scale human-induced changes relevant to future water resource availability. Indeed the accuracy of projections of future water resource availability is assumed to be high, bolstered by assessment of an ensemble of climate models (Milly et al., 2005). These projections are in turn considered and heeded by western USA water managers as they formulate long-term plans to cope with large reductions in the availability of renewable freshwater resources.

However, in addition to effecting modifications to climate forcings used in hydrologic predictions, climate change also effects ecological disturbances; these climatic controls on ecological disturbance may in turn be amplified by other components of global change (Dale et al., 2001; Scheffer et al., 2001). Widespread global change-induced ecological disturbances include woody encroachment (Van Auken, 2000), tree mortality due to pest-pathogen complexes (Kurz et al., 2008), and wildfire (Westerling et al., 2006). Assuming that these ecological disturbances can substantially influence Earth's future water balance, they represent structural uncertainties in the current approach to projecting future water resource availability. Assessing the importance of remaining structural uncertainties in future water resource availability predictions is of paramount importance given the reliance of water managers on these predictions. To date there is evidence of increased water yields due to pest-pathogen complexes (Bearup et al., 2014) and decreased water yields due to woody encroachment (Huxman et al., 2005). However, the extent of these ecological disturbances in the western USA is not yet sufficiently widespread to estimate their future effects on regional water availability from retrospective environmental data.

In contrast, evidence is mounting that increases in western USA wildfire activity since the 1980's (Westerling et al., 2006) significantly enhance regional water availability (Kinoshita and Hogue, 2015; Bart, 2016; Wine and Cadol, 2016). This increase in wildfire activity in the western USA is occurring in response to changing climatic conditions and land management paradigms (Figure 1). Climatic changes increasing the frequency of large wildfires include warmer temperatures and earlier snowmelt (Westerling et al., 2006). Land management paradigms contributing to an increase in large wildfire frequency include reduced grazing rates (with resultant increases in fine fuel loads) and an outstanding fire deficit due to fire suppression since the 1940's (Marlon et al., 2012). While enhanced infiltration-excess overland flow and associated flooding are well-known consequences of wildfires, these fires also reduce transpiration (Dore et al., 2010), increase soil water storage (Cardenas and Kanarek, 2014), and enhance groundwater recharge (Ebel, 2013) and accompanying baseflow (Kinoshita and Hogue, 2015). The objective of this study was to assess the hydrologic effects of wildfires across gauged basins of the western USA.

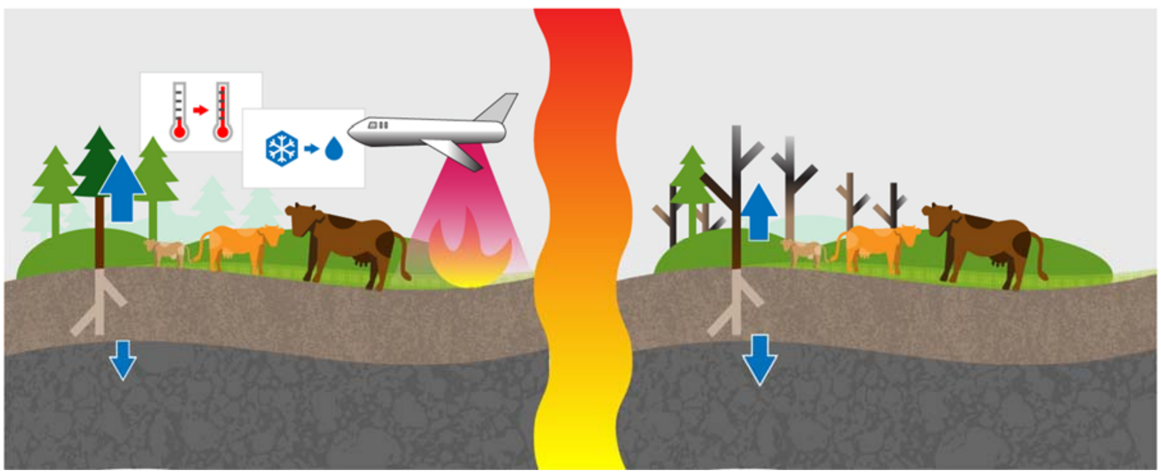

Figure 1: Rising temperatures, earlier snowmelt, and changing land management paradigms—including reduced grazing rates and a transition from suppressing to managing wildfire—have contributed to increased wildfire frequency in western North America. Following wildfire hydrologic fluxes (blue arrows) are modified to reflect reduced transpiration and enhanced groundwater recharge.

4. Description of methodology employed.

Methods and study area

We developed a single framework to directly interrogate the importance of wildfires as a structural uncertainty affecting the accuracy of future water resource availability projections at the scale of the western USA. This framework integrates geospatial climate (Daly et al., 1994), wildfire (Eidenshink et al., 2007), streamflow, and moderate spatial resolution remotely sensed post-wildfire vegetation recovery (Masek et al., 2006) datasets from 39 watersheds across seven ecoregion divisions in the western USA (Figure 2). We modeled the rate of exponential post-wildfire recovery of plant mesophyll tissue by ecoregion (Table 1). We then used these ecoregion-specific vegetation recovery curves in a linear mixed-effects (LME) modeling framework to estimate the proportion of streamflow attributed to wildfires in all long-term gauged basins across the western USA, after controlling for climatic effects.

Experimental design

We first selected all USGS reference watersheds 20% or more of which were burned within a five-year period in the western USA, according to the Monitoring Trends in Burn Severity dataset (Eidenshink et al., 2007). We then estimated annual precipitation within each watershed at a water year time scale from PRISM (Daly et al., 1994). (For most analyses we used a Contiguous USA Albers Equal Area Conic projection, except where distance preservation was required in which case we projected to Contiguous USA Albers Equidistant. All geospatial analyses were performed using ArcGIS 10.5; where automation was required the arcpy site package was used.)

We also assessed post-wildfire vegetation recovery, allowing this recovery to vary by ecoregion division (Bailey, 1995). Where possible we used existing post-wildfire vegetation recovery curves, including in the Mediterranean Division (Hope et al., 2007) and the Mediterranean Regime Mountains (McMichael et al., 2004), or existing post-wildfire vegetation recovery datasets (Wine and Cadol, 2016). Where these were unavailable we extracted peak annual time series of NDVI (normalized difference vegetation index) from remotely sensed Landsat-derived Level I at surface reflectance imagery (Masek et al., 2006). NDVI is an effective means of assessing plant vigor in that this band ratio's value attains a maximum value when chlorophyll absorption of red light peaks and healthy mesophyll tissue reflection of infrared light decreases (Campbell and Wynne, 2011). Typically, we considered recovery within all non-intersecting wildfire perimeters in Landsat scenes intersecting the 39 study watersheds. However, in the Marine Regime Mountains due to a high frequency of cloud-covered conditions, we considered post-wildfire recovery only within those wildfire perimeters that intersected study watersheds. We constructed post-wildfire recovery datasets by assuming that recovery is a monotonic process and that the rate of recovery is non-increasing. In fact, variability may occur in vegetation index data due to climatic conditions—especially wet years that enhance plant growth or dry years that inhibit growth—thereby masking the overall recovery trend. Furthermore, the peak vegetation index is affected by when satellite imagery is available. This availability in turn is influenced by the number of satellites that are in orbit and fully functional as well as by cloud cover. Where peak vegetation values did not follow our assumptions of monotonic non-increasing recovery rate, we filled these values by bilinear interpolation from the two (temporally) nearest values. In years where vegetation index data suggested a hiatus from recovery had occurred we filled We fit all remotely sensed recovery datasets with a Gauss-Newton algorithm (R Core Team, 2017) to the simplified asymptotic function:

$$1 - e^{-\frac{t}{l}}, \tag{1}$$

where t is the number of full years that have elapsed since the fire and *l* is the characteristic recovery time scale parameter. Finally, we calculated a wildfire impact index (WII) of year i in ecoregion j as:

$$WII_{ij} = \sum_{t=1984}^{t=i-1} \mathrm{BA_t} \cdot \mathrm{e}^{-\frac{i-1-t}{l_j}}, \quad (2)$$

where BA_t is the proportion of the watershed burned during year t.

Statistical analysis

To test the hypothesis that wildfires significantly increase streamflow across the western USA, we created a series of increasingly complex mixed effects models (Pinheiro et al., 2017) whose terms were specified a priori. To check that the model met relevant statistical assumptions we made a series of plots to check the residuals for normality, trends relative to fitted values, and trends relative to model terms after applying square root transformations to the precipitation and streamflow terms. The model that minimizes the Akaike Information Criterion (AIC) is assumed to be optimal.

Table 1: Ecoregion divisions included in study. l is the characteristic recovery time scale parameter; larger values suggest slower post-wildfire vegetation recovery.

Ecoregion division	l	Abbreviation
Temperate Steppe Regime Mountains	12.2	TStRM
Tropical/Subtropical Regime Mountains	4.2	TSuRM
Tropical/Subtropical Steppe Division	2.7	TSSD
Temperate Desert Division	10.8	TDD
Mediterranean Regime Mountains	3.9	MeRM
Mediterranean Division	2.5	MD
Marine Regime Mountains	9.5	MaRM

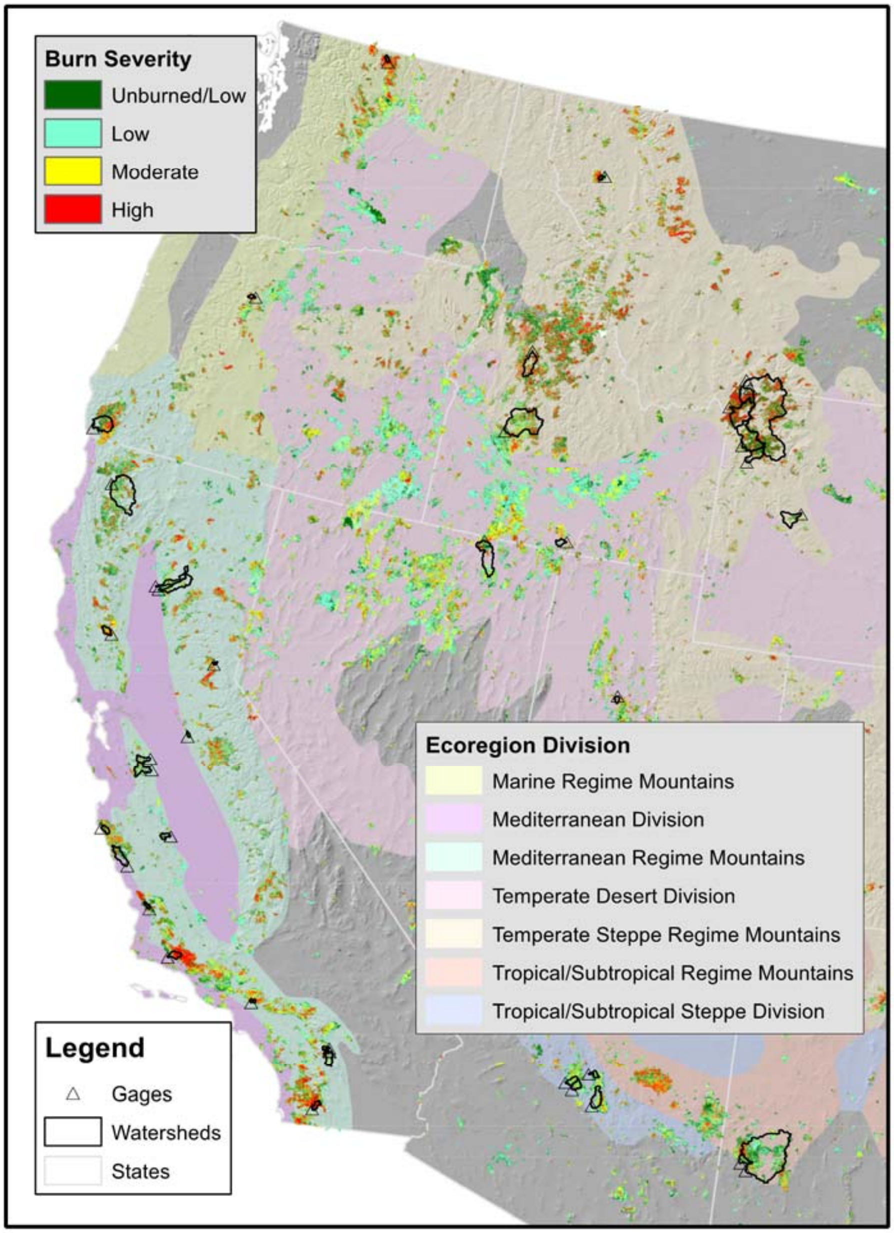

Figure 2: Map of 39 continuously gaged watersheds located in seven western USA ecoregion divisions. Burn severity is derived from the moderate resolution Monitoring Trends in Burn Severity (Eidenshink et al., 2007) dataset (1984-2014). Fires of moderate to high severity replace existing forest stands with pioneer species.

5. Description of results; include findings, conclusions, and recommendations for further research.

The 39 watersheds in this study comprise all USGS reference watersheds 20% or more of which burned within any consecutive five-year period from 1986-2015. These watersheds range in size from small catchments to the large 6,784 km^2 Yellowstone River watershed, thereby making the analysis directly relevant to regional water availability. Over the course of the three-decade span of this study 320 wildfires burned forested areas within these watersheds. Analysis of over 10,000 Landsat images reveals highly variable post-wildfire recovery of plant mesophyll tissue—an indicator of transpiration—among different ecoregion divisions (Figure 3). Post-wildfire vegetation recovery varies as a function of pre-fire ecology, post-fire climatic conditions, burn severity and characteristics, and post-fire management treatment.

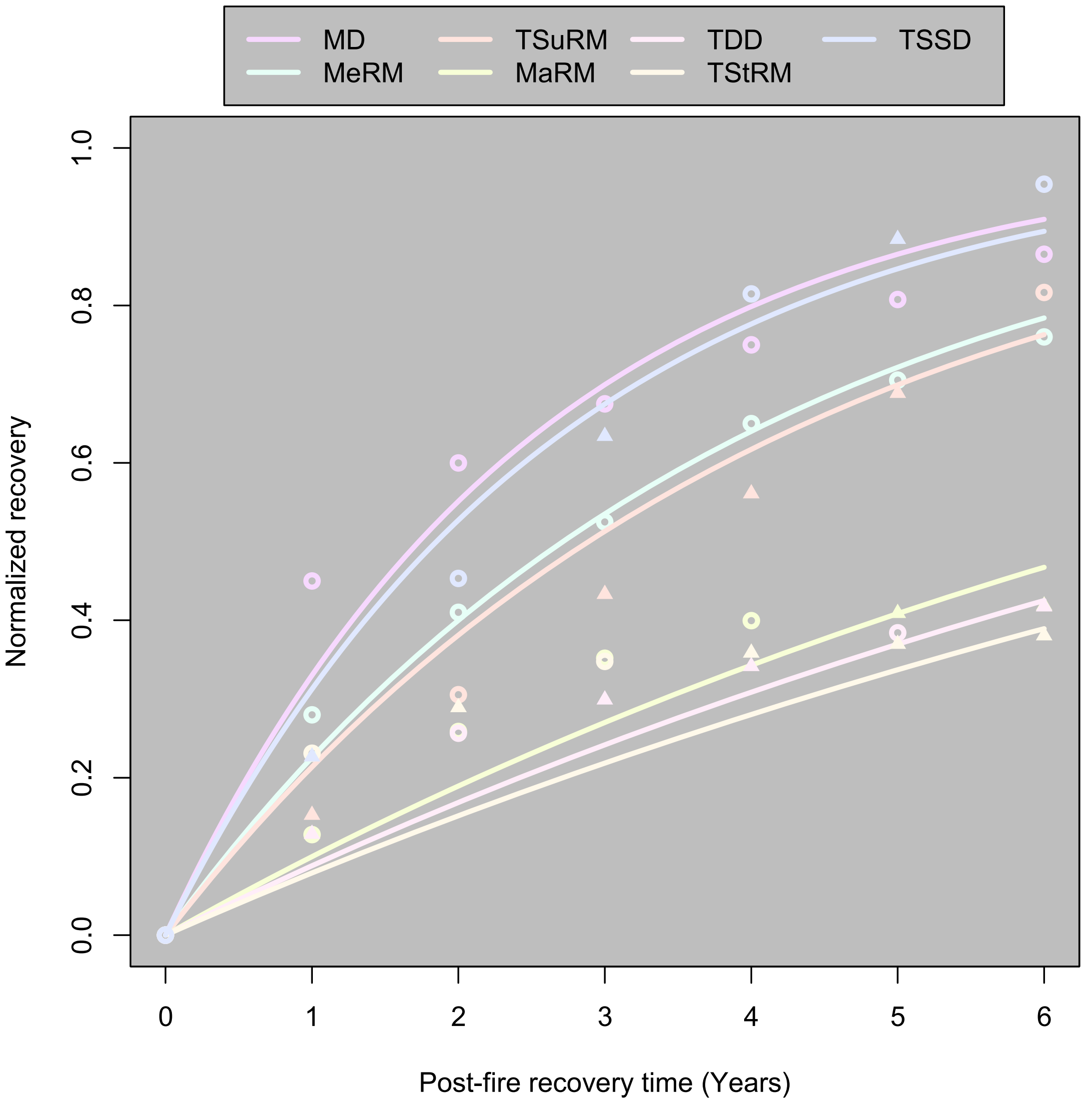

Figure 3: Normalized post-wildfire vegetation recovery by ecoregion division. Curves are assumed to follow the simplified asymptotic function form $1 - e^{-\frac{t}{i}}$. Circles and triangles indicate measured and estimated values, respectively.

To test the hypothesis that western USA wildfires significantly increase water availability across this region, we use this spatiotemporal variability in post-wildfire vegetation recovery as a quantitative predictor of streamflow. Our results show that wildfires significantly improve prediction of streamflow across the western USA ($p < 0.001$), after controlling for precipitation and watershed characteristics (Figure 4, Table 2). The proportion of streamflow attributed to reduced evapotranspiration following wildfires varies substantially by ecoregion division (Figure 5) due to spatial variation in wildfire frequency and post-wildfire recovery rate and ranges from 2-12%. The largest wildfire contribution to streamflow occurred in the Tropical/Subtropical regime mountains ecoregion division, where lightning strikes are unusually frequent (Wine and Cadol, 2016). As a point of comparison climate change-based ensemble hydrologic predictions suggest a 1-18% reduction in streamflow in western North America by 2050 (Milly et al., 2005). This magnitude of wildfire contribution to streamflow—typically neglected in solely climate-based predictions of future water availability—if considered would increase the structural uncertainty of predicted streamflow to 20-330% (Figure 6) of the magnitude of the value predicted by conventional climatically based approaches (Milly et al., 2005). Hence, our results demonstrate that predicting future streamflow on the basis of climatic change alone rather than on the basis of global change—the integral of climatic and ecological changes—results in overly uncertain predictions of future water availability.

Table 2: Streamflow models of increasing complexity, where y_{ij} is streamflow from the ith year of the jth watershed, as a function of precipitation (x_0), random intercepts by watershed (u_{0_j}), random slopes by watershed (u_{1_j}), ecoregion division ($\alpha_{k(j)}$), and wildfire impact index (x_1).

Model #	Model form	AIC
1	$y_{ij} = \beta_o + \beta_1 \cdot x_{0_{ij}} + u_{0_j} + e_{ij}$	5,588
2	$y_{ij} = \beta_o + \beta_1 \cdot x_{0_{ij}} + u_{0_j} + u_{1_j} \cdot x_{0_{ij}} + e_{ij}$	5,314
3	$y_{ij} = \beta_o + \beta_1 \cdot x_{0_{ij}} + \alpha_{k(j)} + u_{0_j} + u_{1_j} \cdot x_{0_{ij}} + e_{ij}$	5,272
4	$y_{ij} = \beta_o + \beta_1 \cdot x_{0_{ij}} + \beta_2 \cdot x_{1_{ij}} + \alpha_{k(j)} + u_{0_j} + u_{1_j} \cdot x_{0_{ij}} + e_{ij}$	5,186

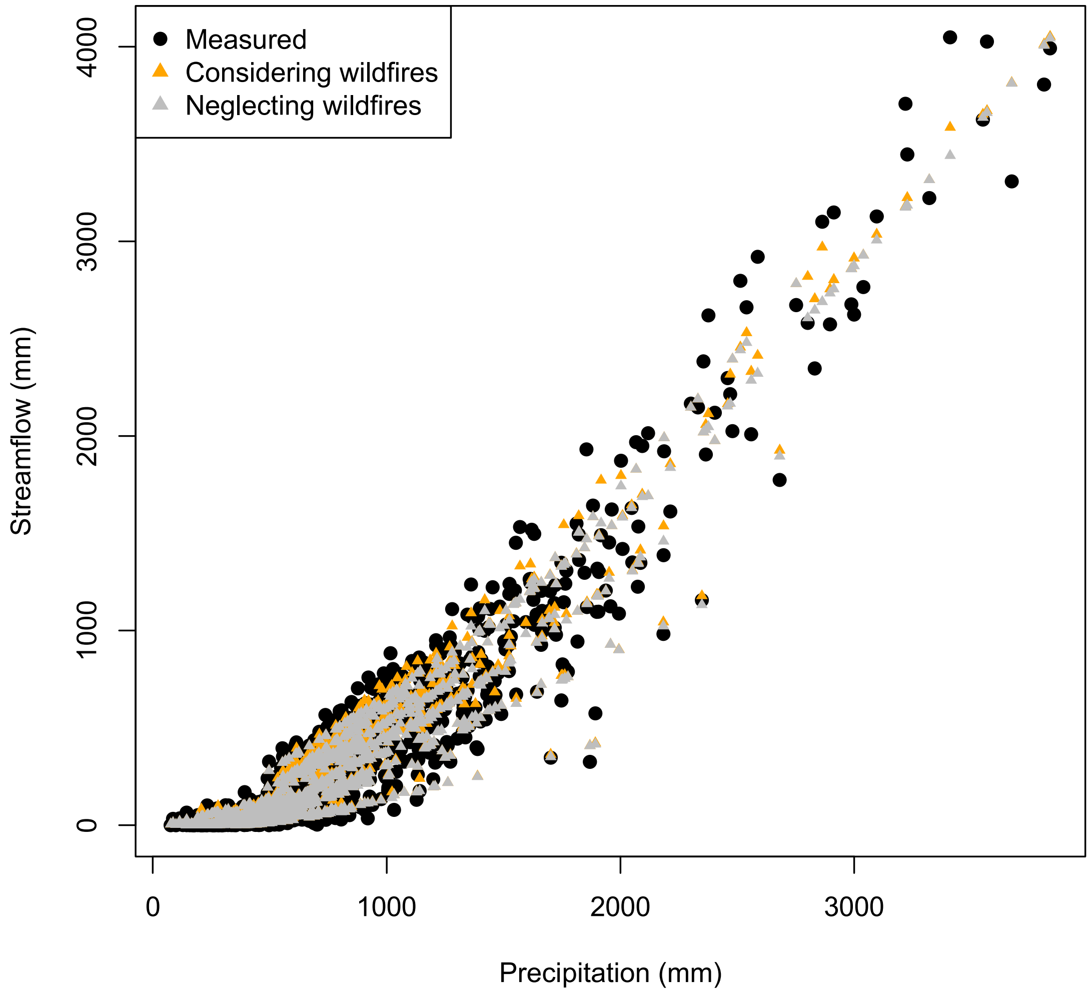

Figure 4: Response of annual measured streamflow from 39 USGS gauges (1986-2015) to precipitation as modeled by PRISM (Precipitation-elevation Regressions on Independent Slopes Model)(Daly et al., 1994). In years affected by recent wildfires the difference between the orange and gray triangle indicates the fitted effect on streamflow attributed to wildfire influence.

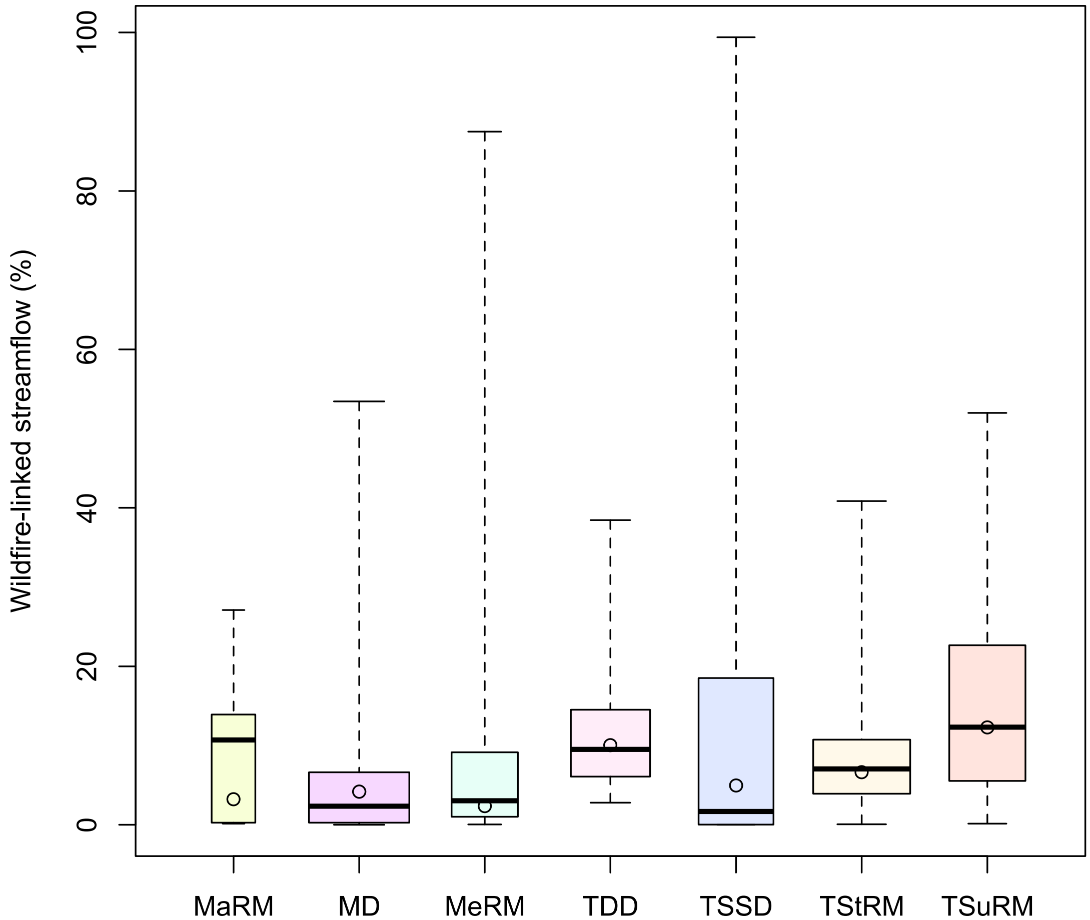

Figure 5: Contribution of wildfires to streamflow by ecoregion. Boxplot represent the distribution of wild-fire linked streamflow during years affected by wildfire whereas circles represent the contribution of wildfire to streamflow integrating over all years, including those not affected by wildfire. The width of boxplots is proportional to the fraction of wildfire-affected years.

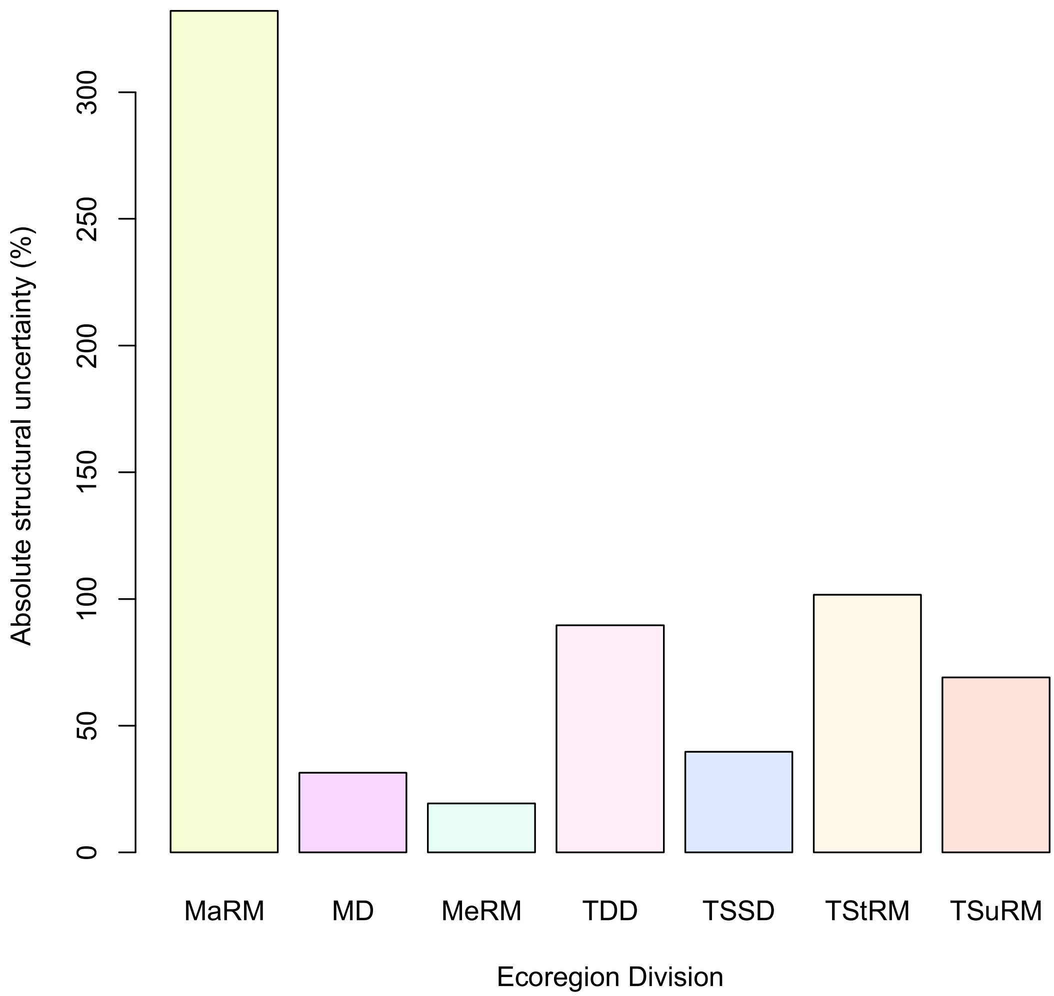

Figure 6: Absolute structural uncertainty due to wildfire hydrologic impacts is calculated by ecoregion division as the 30-year mean wildfire contribution to streamflow as a proportion of the streamflow decrease predicted by conventional climatically based methods (Milly et al., 2005) to occur by 2050.

While the results of this retrospective study have important implications for predictions of future water resource availability, the results presented here may differ from future contributions of ecological disturbances to water resource availability. There is widespread agreement that wildfires will increase in certain regions of the western USA on the basis of diverse lines of reasoning including paleofire data (Marlon et al., 2012), climatic trends that influence conditions conducive to wildfire (Jolly et al., 2015), and integrated modeling of key controls on wildfire—climate, vegetation biomass, and ignition sources (Krawchuk et al., 2009). Similarly, while pest-pathogen-complex-induced tree mortality currently elicits limited watershed-scale hydrologic impact (Penn et al., 2016; Slinski et al., 2016), anticipated future increases in the conditions conducive to die-off (Breshears et al., 2009) could make this disturbance relevant to regional hydrology in the future. Conversely 'unparalleled' woody encroachment—estimated as high as 300 million ha in North America—would have an opposing influence on water yields relative to wildfire and die-off (Van Auken, 2009). Consideration of ensembles of possible future disturbance scenarios and their hydrologic consequences in addition to changing climate is needed to transition from climate change- to global change-based hydrologic predictions, with the aim of reducing structural uncertainties inherent in model predictions. Inclusion of ecological disturbances may require modeling not just ecological dynamics, but also the economics and public policy that influence Anthropocene ecological disturbances.

In addition to likely future increases in ecological disturbance frequency, the death of climatic stationarity (Milly et al., 2008) also implies the death of the theory of ecological succession. Ecological succession is defined as 'the process by which a plant or animal community successively gives way to another until a stable climax is reached (Stevenson and Lindberg, 2010)'. In the presence of a now non-stationary climate this theory of post-disturbance succession is moot. As a consequence, the simplified model of vegetation recovery fit in this study (Figure 3) may tend to underestimate disturbance impacts by incorrectly assuming that plant communities will revert to the pre-fire climax community. Climax species in water-limited regions are well adapted to maximize extraction of water from the subsurface (Seyfried et al., 2005) consistent with the vegetal equilibrium or ecological optimality hypothesis (Eagleson, 1978; Eagleson, 1982; Eagleson and Tellers, 1982; Milly and Eagleson, 1987; Milly, 1994; Milly and Dunne, 1994; Kochendorfer and Ramirez, 2010; O'Grady et al., 2011), despite critiques of this hypothesis (Kerkhoff et al., 2004). Following a disturbance under post-successional conditions, we speculate the series of plant communities that colonizes a site is likely to be less well adapted to the site due to the non-stationary climatic conditions, thereby potentially enhancing groundwater recharge (Figure 7). If true, the models in this study would underestimate the contribution of ecological disturbances to streamflow.

Figure 7: A June 2016 photo of the summer 2013 Thompson Ridge fire burn scar in Valles Caldera, New Mexico. Following wildfire formerly forested areas may convert to montane meadows. Herbaceous plants found in a montane meadow are have lower leaf area index relative to broad-leaf or needle-leaf trees (Myneni et al., 2002), which is directly related to transpiration.

The results of this study suggest a need to revisit the role of land cover change and ecological disturbances in influencing streamflow. Ecological disturbances resulting in land-cover change are conventionally hypothesized to exert negligible influence on the water balance at increasingly large spatial scale (Blöschl et al., 2007). However, this study, which includes five large watersheds that are each over 1,000 km^2 in area demonstrates that the unprecedented scale of Anthropocene ecological disturbances has made these disturbances substantial and significant predictors of present and future regional water yields in ecoregions across western North America (Figure 8). This study and past work (Wine and Cadol, 2016) demonstrate that at small spatial scales wildfire contribution to streamflow is intermittent, whereas at larger spatial scales this patchwork of wildfire histories integrates to sustained increases in streamflow due to wildfire effects.

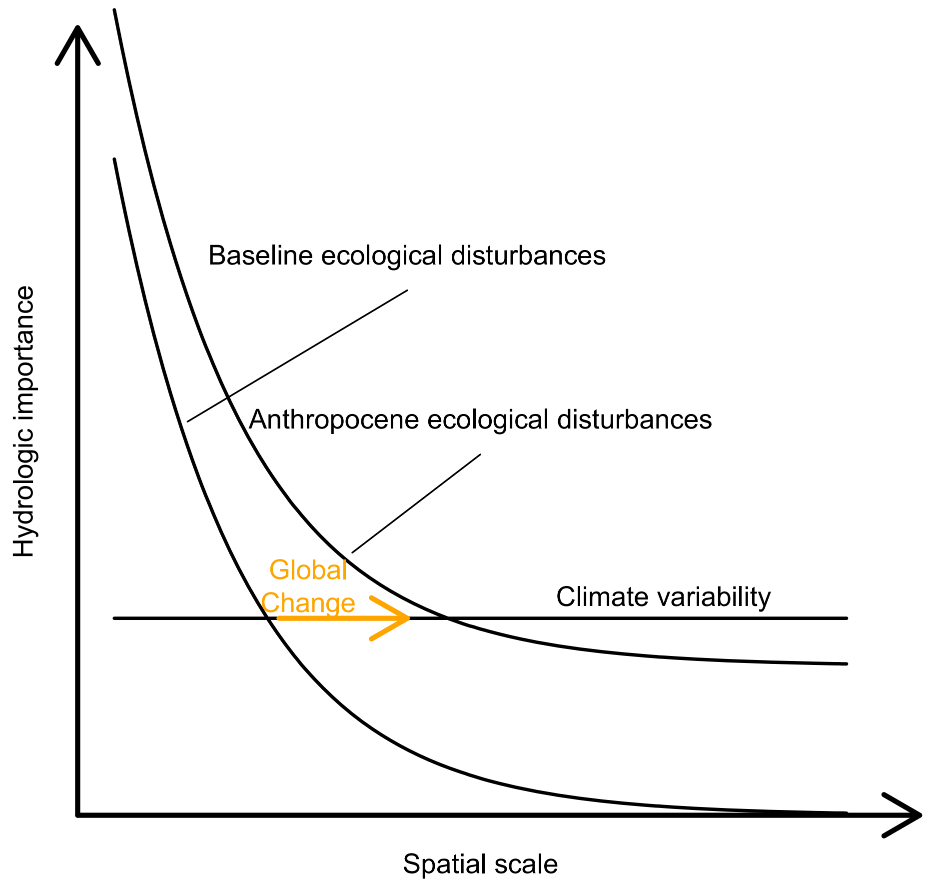

Figure 8: As a consequence of global change the importance of ecological disturbances in altering streamflow may increase and become relevant at larger spatial scales relative to pre-Anthropocene conditions.

6. Provide a paragraph on who will benefit from your research results. Include any water agency that could use your results.
   Renewable water resources are a critical factor limiting New Mexico’s economy. With climate change projected to reduce future water availability in New Mexico, improved models of the water cycle are needed for water resource planning. New Mexico’s fire regimes vary greatly across the state and are understood to affect water supplies at a regional scale. Our results demonstrate that in forested ecoregions of New Mexico wildfires are a critical streamflow generation mechanism that must be accounted for in models of climate change hydrologic impacts. This research is relevant to water agencies concerned with water supply and changes thereto as a consequence of climate change. Such agencies may include the New

Mexico Water Resources Research Institute, US Forest Service, Bureau of Land Management, New Mexico Office of the State Engineer, New Mexico Environment Department, US Geological Survey including the New Mexico Water Science Center, New Mexico Bureau of Geology & Mineral Resources, the UNM Water Resources Program, USDA Natural Resources Conservation Service, New Mexico Water Resources Association, Nature Conservancy, and the New Mexico legislature House Agriculture and Water Resources standing committee.

7. Describe how you have spent your grant funds. Also provide your budget balance and how you will use any remaining funds. If you anticipate any funds remaining after June 1, 2017, please contact Carolina Mijares immediately. (575-646-7991; mijares@nmsu.edu)

Funds ($2,300) were spent on a computer, processing wildfire soil samples to determine organic carbon and texture, and to employ an undergraduate research assistant. Remaining funds ($3,700) were spent on graduate student hourly salary between May 12th and June 30th.

8. List presentations you have made related to the project.
    - Hydrologic effects of large southwestern USA wildfires significantly increase regional water supply: Fact or fiction? Wine, ML and Cadol D. GSA Annual Meeting in Denver, Colorado, USA - September 2016.
    - Fire frequency and regional water yield in the southwestern USA. Wine, ML and Cadol D. 61st Annual New Mexico Water Conference at Western New Mexico University, Silver City, NM, USA, October 2016.
    - Ecological disturbances and the water balance: Critical considerations or trivial blips? Wine, ML. Hydrology Seminar, Socorro, New Mexico, USA – April 2017.

9. List publications or reports, if any, that you are preparing. Remember to acknowledge the NM WRRI funding in any presentation or report that you prepare.
    - In ecoregions across western USA streamflow increases during post-wildfire vegetation recovery. Wine ML, Cadol D, Makhnin O. Currently under evaluation at Science Advances. NMWRRI funding is acknowledged in this publication.
    - Non-linear long-term western USA watershed hydrologic response to wildfire and climatic dynamics. Wine ML, Cadol D, Makhnin O. In preparation; NMWRRI funding will be acknowledged.

10. List any other students or faculty members who have assisted you with your project.

Katherine Heuser assisted in processing wildfire affected soils.
Oleg Makhnin assisted with linear and non-linear mixed effects modeling of post-wildfire hydrologic effects.

11. Provide special recognition awards or notable achievements as a result of the research including any publicity such as newspaper articles, or similar.

12. Provide information on degree completion and future career plans. Funding for student grants comes from the New Mexico Legislature and legislators are interested in whether recipients of these grants go on to complete academic degrees and work in a water-related field in New Mexico or elsewhere.

Michael will defend his dissertation July 2017 and anticipates degree receipt August 2017. He has been awarded a Fulbright post-doctoral scholarship studying hydrologic effects of climate change in the Jordan River headwaters.

You are encouraged to include graphics and/or photos in your draft and final report.

Final reports will be posted on the NM WRRI website.