



The University of Oklahoma®
Department of Geography and Environmental Sustainability

Dear Professor Yang,

We believe we have responded to all comments made by the two anonymous reviewers and carried out all proposed modifications to our manuscript. In the majority of cases, we have added or changed text and modified figures and tables based on each observation. The comments from the reviewers were, for the most part, helpful and insightful. We are thankful to the editor, Professor Dawen Yang, who carefully reviewed these comments on the submitted manuscript and suggested minor reviews before its acceptance.

The major issues of model performance scores and vegetation dynamics were fully tackled during the reviews through explanatory text and the inclusion of a new section called “*Model assumptions and study limitations*” where we inform the reader of the potential misinterpretation of the results regarding the lack of consideration of (1) vegetation phenology and dynamics and (2) soil hydraulic properties recovery, during forest thinning post-treatment conditions. We also add caveats about two other key elements that might constraint model extensibility relating (3) precipitation uncertainty propagation to the hydrologic model and (4) lack of high resolution observational data, that might hinder our model results from being fully realistic. Additionally, we have conducted the minor changes suggested by the reviewers that range from typos and sentence re-writing to figure and table changes.

In the following pages, please find a list of specific changes that address major and minor comments from the two reviewers and a copy of the manuscript with outlined changes.

Sincerely,

Hernan A. Moreno
Assistant Professor
Department of Geography and Environmental Sustainability
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Changes following the two reviewers:

For a complete understanding of these changes, we refer to the previous documents in HESSD with more in-depth discussion of proposed major and minor reviews. The following list of modification symbols refers to the subsequent PDF document copy, where TC mean text changes, SC means section order changes and FC means figure changes.

1. **TC1:** In section 3.5, text has been added regarding the complementary view of the three model evaluation scores during the calibration and validation periods. The two added sentences provide more background on the role of possible sources of uncertainty (e.g. precipitation) that propagate into the model results.
2. **TC2:** An entirely new section 4.5 titled “*Model assumptions and study limitations*” has been added, in order to inform the reader of the potential misinterpretations of the results, particularly relating the lack of consideration of vegetation phenology and soil hydraulic recovery.
3. **TC3:** In section 3.4, we have clarified that we are not considering vegetation phenology or re-growth within the modeling.
4. **TC4:** In section 3.6, describing the design of numerical experiments, we point that we are not including any dynamic evolution of vegetation in the simulations and refer to the new section 4.5 for potential consequences of not doing this.
5. **TC5:** In section 5, we added a caveat for interpretation of the conclusions in views of the lack of consideration of any vegetation physiologic dynamics.
6. **TC6:** New references have been added in the references section.
7. **TC7:** In section 3.3, the description of the distributed model, tRIBS, has been shortened.
8. **TC8:** In section 3.5, we have provided a short description of calibration parameters in Table 2 and their role in controlling different components of the water balance.
9. **SC1:** The organization of some sections has been changed. The new order of the sections is: 4. Results and Discussion, 4.1 Streamflow shifts and extreme probability, 4.2 Effects of forest thinning on mean and variability of basin-scale water balance components, 4.2.1 Inter-annual trends, 4.2.2 Seasonal shifts and emerging hydrological patterns, 4.3 Distributed hydrologic effects of forest removal, 4.4 Soil column water balance in hillslopes with contrasting solar aspect, 4.5 Model assumptions and study limitations, 5. Summary and Conclusions.
10. **FC1:** A larger map of the US has been added to Figure 2, pointing out to the location of the study basin.
11. **FC2:** A new Figure 3b has been added, showing the relative change in basal area for post-treatment conditions.
12. **TC9:** In section 2.2, a sentence has been modified regarding the representation of the thinning plans and directing the reader to an accurate source of information.

13. **TC10:** In section 3.1, a new sentence has been added describing the mean annual temperature and runoff in the region of study with the corresponding citation.
14. **TC11:** In section 3.3, “Appendix A2” has been replaced by “Appendix B”
15. **TC12:** In section 4.3, the word “temperature” has been added to the text.
16. **TC13:** Section 5 has been re-organized. Some sentences from the summary and concluding remarks have been removed. Conclusion number one corresponds now to the findings with the probabilistic streamflow analysis.
17. **TC14:** In Section 1.1, Biederman et al. 2014 has been added and the sentence re-organized to reflect this observation.
18. **TC15:** In Section 1.1, the sentence has been modified according to Dung et al. 2012. This new reference has been added as well.
19. **TC16:** In Section 2.1, Fatichi et al. 2014, has been added as a pertinent reference.
20. **TC17:** In Section 2.2, SI units have been used to describe the restoration and basal areas.
21. **TC18:** In Section 3.3, the sentence was changed according to what the reviewer suggested for melt water and routing.
22. **TC19:** In Section 3.3, we have added a clarification on the computation of surface latent heat fluxes so it is clear that these fluxes represent evaporation and transpiration in the model.
23. **TC20:** In Section 3.4, we have added the words “dynamic steady-state conditions”.
24. **TC21:** Equation 4 has been corrected by including the mean of observed data.
25. **TC22:** In Section 4.5, we have added a short discussion on the effects of scarce information for model validation and confidence.
26. **TC23:** In Section 3.6, Appendix A2 has been replaced with Appendix B.
27. **TC24:** A portion of the initial text from section 4.3 has been moved to Section 3.2. (Observed data and climate forcing) to introduce climate features of Tonto Creek. Figures have been re-organized according to the reviewer’s comments. Figure 7 is now Figure 5 and Figure 9 is now Figure 6.
28. **TC25:** We have moved a sentence from Section 4.3 on snow effects to the second conclusion in Section 5.
29. **TC26:** Figure 11 is now Figure 8 and equations 6 through 8 and explanatory sentences have been moved from Section 4.4 to Section 3.6.
30. **TC27:** We removed Tables 4 and 5 and moved some sentences to Section 3.6 to shorten

Section 4.4.

31. **TC28:** In Section 4.1, we have clarified that Q1 and Q4 correspond to low and high streamflow values, respectively.
32. **TC29:** We have replaced the word “disaster” from the last line in Section 4.1 and the Section 5 (Conclusions) and accommodated the sentences for a better meaning.
33. **TC30:** In Section 5, we have removed a long paragraph from lines 11-25, that started with “We have shown the benefits of using spatially-distributed thinning scenarios...”, as it seemed rather repetitive.

Modeling the Distributed Effects of Forest Thinning on the Long-Term Water Balance and Stream Flow Extremes for a Semi-Arid Basin in the Southwestern U.S.

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1 **Abstract.** To achieve water resources sustainability in the water-limited Southwestern US, it is crit-
2 ical to understand the potential effects of proposed forest thinning on the hydrology of semi-arid
3 basins, where disturbances to headwater catchments can cause significant changes in the local water
4 balance components and basin-wise stream flows. In Arizona, the Four Forest Restoration Initiative
5 (4FRI) is being developed with the goal of restoring 2.4 million acres of ponderosa pine along the
6 Mogollon Rim. Using the physically based, spatially distributed tRIBS model, we examine the po-
7 tential impacts of the 4FRI on the hydrology of Tonto Creek, a basin in the Verde-Tonto-Salt (VTS)
8 system, which provides much of the water supply for the Phoenix Metropolitan Area. Long-term
9 (20 year) simulations indicate that forest removal can trigger significant shifts in the spatio-temporal
10 patterns of various hydrological components, causing increases in net radiation, surface temperature,
11 wind speed, soil evaporation, groundwater recharge, and runoff, at the expense of reductions in in-
12 terception and shading, transpiration, vadose zone moisture and snow water equivalent, with south
13 facing slopes being more susceptible to enhanced atmospheric losses. The net effect will likely be
14 increases in mean and maximum stream flow, particularly during El Nino events and the winter
15 months, and chiefly for those scenarios in which soil hydraulic conductivity has been significantly
16 reduced due to thinning operations. In this particular climate, forest thinning can lead to net loss of
17 surface water storage by vegetation and snow pack, increasing the vulnerability of ecosystems and
18 populations to larger and more frequent hydrologic extreme conditions on these semi-arid systems.

19 1 Introduction and Goals

20 1.1 Introduction

21 Quantifying the hydrological effects of extensive, human-driven forest thinning is of primary im-
22 portance for sustainable water resources management in semi-arid basins, where disturbances in the
23 upland vegetation density and architecture can trigger zonal alterations to the components of the wa-
24 ter balance (Biederman et al., 2014) resulting, sometimes, in stream flow shifts along an entire basin
25 (MacDonald, 2000; Reid, 1993; Webb and Kathuria, 2012). Because precipitation is cycled through
26 forests and soil, upland modifications in vegetation cover are expected to affect the dynamics of the
27 entire basin in terms of water yield quantity and quality, and peak and low flows (Jones, 2000; Moore
28 and Wondzell, 2005; Schnorbus and Alila, 2004, 2013).

TC 14

29 In north-central Arizona, the U.S. Forest Service is leading a collaborative effort known as the *Four*
30 *Forests Restoration Initiative* (4FRI), a large-scale restoration of ponderosa pine (*Pinus ponderosa*)
31 along the Mogollon Rim, with the primary goal to mitigate fire risk through forest thinning (Hamp-
32 ton et al., 2011; Stephens et al., 2013). In addition to the Phoenix Metropolitan Area (PMA), and
33 other towns and cities in the region, a number of ecological communities depend upon the freshwa-
34 ter derived from basins whose headwaters extend along the restoration areas (Arizona Department
35 of Water Resources, 2010; Baker, 1986). Besides changes in mean water yields, projected forest
36 removal could potentially affect base flows during dry periods (Dung et al., 2012; Lin et al., 2007),
37 while increasing the risks of downstream flooding in the rapidly responsive, steep-slope mountain
38 basins (Eisenbies et al., 2007; Jones, 2000; Jones and Grant, 1996; Jones and Post, 2004). It is,
39 therefore, critical to understand the hydrologic effects of forest thinning, in conjunction with the cu-
40 mulative effects of climate change and other stressors (e.g., population increase, urbanization, etc.)
41 that can be expected to exacerbate the impacts of human interventions in current basin land cover
42 (Barnett et al., 2005; Dale et al., 2001; National Research Council, 2008).

TC 15

43 Traditionally, evidence of the connections between forest thinning and water yield responses has
44 been based on paired watershed studies. Most of these studies have identified immediate increases in
45 runoff and sediment production (Bosch and Hewlett, 1982; Brown et al., 2005; Hibbert, 1983; Horn-
46 beck et al., 1993; Sahin and Hall, 1996). However, in basins where water yield depends mainly on
47 snow accumulation and melt, researchers have reported high variability and uncertainty tied to site-
48 specific topographic, forest structure and microclimatic conditions (Cline et al., 1977; Lundquist
49 et al., 2013; Schelker et al., 2013; Stottlemeyer and Troendle, 2001; Troendle and Reuss, 1997;
50 Venkatarama, 2014; Woods et al., 2006). Multiple authors have found a direct relationship between
51 thinning, snow interception reduction and ablation increase (Link and Marks, 1999; Lundquist et al.,
52 2013; Varhola et al., 2010; Venkatarama, 2014). In Arizona, most of the data and knowledge re-
53 garding hydrologic response to treatments in piñon-juniper and ponderosa pine forests have been
54 obtained from the Beaver Creek research watershed, located within the Verde River basin (Baker,

55 1984, 1986; Brown et al., 1974). Results indicate that the thinning of ponderosa pine leads to statisti-
56 cally significant short-term increases in runoff, particularly in steep north-facing slopes. In addition,
57 the duration of snow on south-facing slopes is affected by thinning intensity, overstory removal, and
58 higher exposure to wind and solar radiation (Baker, 1986).

59 More recently, physically-based, spatially-distributed hydrological models have complemented the
60 experimental approach to provide new insights into the processes undergoing change, both prior and
61 post forest removal (Bathurst et al., 2004; Legesse et al., 2003; Li et al., 2007). Such work indicates
62 that, due to shifts in evapotranspiration and soil hydraulic properties and moisture, increases in water
63 yield can be expected after forest thinning (Hundecha and Bardossy, 2004; Li et al., 2007; Serengil
64 et al., 2007; Webb and Kathuria, 2012)

65 **1.2 Goals, organization and scope of this paper**

66 While much has been learned from the Beaver Creek experiments, greater understanding is still nec-
67 essary to provide the long-term estimates of water yield needed by water managers and land and
68 water decision makers for semi-arid basins in Arizona. In this regard, the application of highly real-
69 istic, physically-based, spatially-distributed models that appropriately simulate the detailed behavior
70 of catchment dynamics at relevant spatial and temporal scales can provide valuable insights.

71 Here we examine the potential impacts of extensive forest thinning on the hydrology of Tonto Creek,
72 selected as a prototypical semi-arid watershed suitable for the inference of long-term impacts on wa-
73 ter yield and extreme conditions on neighboring basins. Additionally, we explore the mechanisms
74 responsible for change due to forest removal from local to basin scale. Specifically, we examine the
75 following three questions related to the sustainability of water resources of this region:

76 (1) Is the 4FRI likely to produce significant alterations in stream flow and the components of the
77 water balance at the basin scale?

78 (2) If so, what are the expected magnitudes of annual and seasonal water changes?

79 (3) What are the physical mechanisms likely to be responsible for observed hydrologic shifts at the
80 element (smallest computational unit) scale and how do they alter the soil column water balance in
81 hillslopes having contrasting aspects?.

82 We address these questions using a calibrated, high resolution, catchment-scale hydrological model
83 (see section 3) as a tool to reproduce the spatio-temporal dynamics of the Tonto Creek basin, both
84 prior and post-forest treatment, under long-term (20-year) historic climate forcing. Using 20 con-
85 secutive years provides an ample range of climate variability (including El Niño-Souther Oscillation
86 (ENSO) phases), while the study of "feasible" forest thinning scenarios within a distributed model
87 provides management and policy relevance to the research questions in this study. In particular, we
88 analyze the shifts in the probability distribution functions of mean and extreme (low and peak) stream
89 flow values, and the implications for water security and flood risk of downstream communities. Fur-
90 ther, we investigate the inter-annual and seasonal mechanisms that explain effects of forest thinning

SC 1

91 on river flows, snow water equivalent, basin evaporation and transpiration, and soil water storage in
92 the vadose and saturated zones. Subsequently, a closer look to the spatially distributed hydrological
93 fields evidence their relation to the areas where restoration occurred and the physical mechanisms
94 responsible for such responses. Finally, a more detailed analysis of the changes triggered at the
95 element scale is performed at sites having contrasting (north and south) hillslope aspect.

96 **2 Background**

97 **2.1 Effects of forest thinning on hydrology**

98 Forest disturbance and management activities have been shown to influence nearly all components
99 of the water budget from the plot to the entire basin scale (Ice and Stednick, 2004; Waring and
100 Schlesinger, 1985). Figure 1 illustrates the components of the water balance in a typical forested
101 hillslope in the semi-arid southwestern US (with snow presence during the winter months). Liquid
102 and solid precipitation (P) are the principal control on spatial distribution, timing and magnitude of
103 runoff, evapotranspiration, snow accumulation, soil water fluxes and storage. Forest reduction will
104 impact mostly surface water storage and flow, and sub-surface flow within the vadose zone. Removal
105 of trees reduces leaf area and, thus, plant interception (Int) allowing more net precipitation (P_{net}) to
106 reach the ground surface (National Research Council, 2008; Verry et al., 1983). During the winter,
107 reductions in Int lead to increases in snow pack depth and cover (Woods et al., 2006). Increases in
108 P_{net} result in increases in soil moisture, plant water availability and rapid runoff production, particu-
109 larly during intense rainfall events (Helvey and Patric, 1965). In contrast, reduced biomass consumes
110 less water volume through plant transpiration (T) but enhances evaporation from the soil, melted wa-
111 ter and/or sublimation from frozen surfaces (E_{soil}, S_{snow}) due to reduced shading of clear-sky short
112 wave solar radiation and sheltering for turbulent moment transfer by wind gusts (Biederman et al.,
113 2012; Gustafson et al., 2010; Harpold et al., 2012a, b; Musselman et al., 2008; Veatch et al., 2009).
114 Thus, water yield increases are expected earlier in the year due to a premature snow melt season
115 caused by increased wind and short wave radiation exposure in this semi-arid, high elevation forest
116 (Helvey, 1980; Hornbeck and Smith, 1997; Jones and Post, 2004; Link and Marks, 1999; Mahmood
117 and Vivoni, 2013; Megahan, 1983).

118 It has also been shown that silvicultural manipulations in forests, via prescribed fires, have produced
119 changes in the hydraulic properties of the underlying soil that can persist for several years depending
120 on the fire intensity and soil composition (Benavides-Solorio and MacDonald, 2005; DeBano, 2000;
121 Moody et al., 2005; Neary et al., 1999; Robichaud, 2000; Shakesby and Doerr, 2006; Lear and
122 Danielovich, 1988; Woods et al., 2007). Previous studies report reductions of between 10 to 40%
123 in soil hydraulic conductivity during post-fire conditions (Leighton-Boyce et al., 2007; Robichaud,
124 2000; Shakesby and Doerr, 2006). Additionally, effects of forest operations for mechanical thin-
125 ning, such as logging and carrying of heavy material on roads, trails, and hillslope contours, favor

126 the occurrence of faster and larger volumes of overland flow due to soil compaction (Bowling and
127 Lettenmaier, 2001; Cline et al., 2010; Cuo et al., 2006; Fatichi et al., 2014; Harr et al., 1975; Jones
128 and Grant, 1996; Marche and Lettenmaier, 2001; Wemple and Jones, 2003). Field studies conducted
129 during pre- and post-treatment conditions reveal reductions of up to 67% in soil hydraulic conduc-
130 tivity for randomly distributed locations within an area mechanically restored with heavy equipment
131 (Grace et al., 2006; Grace III et al., 2007). The duration of this disturbance to soil conditions has
132 received very little attention in the literature; however, a few authors consider it to be highly variable
133 (from months to years) and dependent on both climate conditions and whether recurrent operations
134 are maintained (Cline et al., 2010; Robichaud, 2000). The overall effects of human-driven forest
135 modifications include induced changes in the basin hydrology through direct forest effects and soil
136 collateral effects, which then determine the total hydrological response during storm and inter-storm
137 periods.

TC 16

138 **2.2 The Four Forest Restoration Initiative (4FRI) as an agent of hydrologic change for the** 139 **Verde-Tonto-Salt system**

140 The 4FRI, led by the U.S. Forest Service, is targeting the restoration of up to 9712 km² of contiguous
141 ponderosa pine of the Kaibab, Coconino, Apache-Sitgreaves, and Tonto National Forests across the
142 Mogollon Rim in Arizona. The primary goal of 4FRI is to improve forest resilience and function
143 by reducing forest cover, through the use of prescribed burns and mechanical thinning to histori-
144 cal conditions similar to that of the early 20th century (Hampton et al., 2011; Schoennagel et al.,
145 2004). The projected treatment areas overlap with the headwaters of important water supply basins
146 including the Little Colorado, an important tributary of the Colorado River, and the Verde-Tonto-Salt
147 system whose surface waters serve important cities and villages in north-central Arizona, including
148 the PMA (see Fig. 2).

TC 17

149 Agency representatives and stakeholder groups recently agreed on future reductions in the current
150 basal area conditions of the ponderosa pine from an average of 2755 m²/km² to 1332 m²/km², by
151 focusing in the removal of small-diameter trees (Hampton et al., 2011; Sisk et al., 2006) to reduce the
152 threat of intense fire events to human communities, wildlife habitat and key ecosystem components
153 (Allen et al., 2002; Chambers and Germaine, 2003). Figure 3 (a and b) illustrates the current "pre-
154 treatment" and projected "post-treatment change" basal area of ponderosa pine for Tonto Creek. The
155 "post-treatment" scenario was obtained from the Four Forest Restoration Initiative implementation
156 plan (<http://www.fs.usda.gov/4fri>). The reader is referred to (Hampton et al., 2011) for more details
157 on the density criteria and projections. Restoration of sensitive areas is discouraged, including those
158 with steep slopes or sensitive soils, in proximity to streams, having wildlife regulations, and areas
159 of recent tree harvesting. However, the vast majority of the ponderosa pine covered area, classified
160 as Community Protection Management Areas (CMPA), aquatic and municipal watersheds, Mexican
161 Spotted Owl (MSO) restricted and wildlife habitat, have been declared suitable for restoration.

TC 17

TC 9

162 3 Study Region, Data and Methods

163 3.1 Study region and watershed characteristics

164 The Verde-Tonto-Salt (VTS) system is located in the central Arizona highlands, characterized by
165 rugged mountains with steep slopes separated by narrow valleys. The headwater catchments of the
166 VTS system lie on the Mogollon Rim, a large escarpment that holds a wide diversity of vegeta-
167 tion types and ecosystems (Arizona Department of Water Resources, 2010). Because of the high
168 elevations and associated higher amounts of rainfall and snowfall, the Mogollon Rim area contains
169 the state's most important water-producing watersheds and the greatest concentration of perennial
170 streams, which, in turn, support riparian habitat (Arizona Department of Water Resources, 2010).
171 Precipitation is bimodal at a mean annual value of 481 mm/y, with the largest amounts during the
172 winter months due to frontal storm systems and a secondary rainy period during summer, coincident
173 with the highest evapotranspiration rates, via monsoon-driven precipitation (Arizona Department of
174 Water Resources, 2010). The mean annual temperature and runoff in the region have been estimated
175 as 17.9 °C and 79.8 mm/y (Arizona Department of Water Resources, 2010). The VTS system pro-
176 vides groundwater to small communities and individual farmers, mostly based on the Tonto and
177 Verde Rivers, and, along with the water allocation from the Lower Colorado River through the CAP
178 canal, groundwater and treated effluent, supplies water for the two million inhabitants of the PMA
179 in the Salt River Valley Water Users Association. We use the Tonto Creek basin as a case study to
180 explore the potential impacts of the 4FRI during 20-year long simulations by imposing historic cli-
181 mate forcing. Although Tonto has the smallest catchment area in the VTS system, the areal fraction
182 covered by ponderosa pine is one of the largest, and so it provides a good indication of the processes
183 triggered by forest removal across the whole VTS system. Table 1 summarizes the major character-
184 istics of this basin. Slopes vary around a mean of 28% with a standard deviation of (21%) induced by
185 drastic changes in elevation over short distances. The contrasting relief and the steep slopes lead to
186 rapid runoff responses and short concentration (or response) times. Figure 4 shows the spatial distri-
187 bution of elevation, hydrography, vegetation, soils and depth to bedrock for the study basin. Overall,
188 the area is characterized by a dominance of sandy loam soils, forest vegetation and deep impervious
189 rock. The projected restoration area lies between the lines of 1800 m to 2400 m elevation.

TC 10

190 3.2 Observed hydrologic data and climate forcing

191 We compiled regional weather and rain gauge, snow, and stream flow station data at a daily time
192 scale from the NOAA, National Climatic Data Center (<http://www.ncdc.noaa.gov/cdoweb/search>),
193 Natural Resources Conservation Service (<http://www.wcc.nrcs.usda.gov/snow/>), and USGS National
194 Water Information System (<http://waterdata.usgs.gov/nwis>), respectively (see Fig. 2). This set of sta-
195 tions was selected because of the continuous data availability from 01/01/1990 to 12/30/2010, the
196 prevalence of stations within the VTS basin and few information gaps (<0.5% gaps). For regional cli-

197 mate forcing, we used the NASA Land Data Assimilation Systems data set (NLDAS;(Mitchell et al.,
198 2004)), which includes net radiation, atmospheric pressure, air temperature, wind speed, precipita-
199 tion and vapor pressure (<http://ldas.gsfc.nasa.gov/nldas/>). NLDAS is released on a $1/8^{th}$ -degree grid
200 over central North America on an hourly basis, constituting a superb climate forcing for continuous,
201 distributed modeling purposes. For precipitation, NLDAS constructs its forcing dataset from CPC
202 PRISM-adjusted $1/8^{th}$ -degree daily gauge analyses, temporally disaggregated using Stage II radar
203 fields (Mitchell et al., 2004). Since the quality of distributed hydrologic simulations highly depends
204 on the accuracy of Quantitative Precipitation Estimates (Carpenter and Georgakakos, 2004; Collier,
205 2007; Moreno et al., 2013, 2014), we first evaluated and bias corrected NLDAS rainfall forcing to
206 minimize model error propagation from the precipitation input (see Appendix A1). Using NLDAS,
207 it can be seen that Tonto Creek presents a bimodal precipitation distribution with above-average val-
208 ues during DJFM and JAS and a unimodal temperature pattern whose peak occurs during JJAS (Fig.
209 5). Further, a map with the spatial distribution of mean annual precipitation and surface air temper-
210 ature is presented in Figure 6. Comparing with Fig. 3 it can be determined that projected areas for
211 forest thinning coincide with the higher annual basin precipitation ($P > 500 \text{ mm/y}$) and lower mean
212 temperatures ($Temp < 16 \text{ }^\circ\text{C}$, see Fig. 6a,b).

TC 24

TC 24

213 3.3 Distributed hydrologic model

214 The *Triangulated Irregular Network (TIN)-based Real-time Integrated Basin Simulator* (tRIBS)
215 (Ivanov et al., 2004a; Vivoni et al., 2007b) is a continuous, physically-based simulator of water-
216 shed dynamics. The model uses spatially-varying topographic, soil and vegetation characteristics
217 and time-evolving distributed climate forcing to represent the processes governing movements of
218 surface and subsurface water in a basin. tRIBS uses a TIN scheme to reduce computational workload
219 and accurately represent topography, water flow paths and river networks (Vivoni et al., 2004). This
220 TIN geometry determines a network of sloped Voronoi polygons that communicate through their
221 edges by mass continuity and flux equations. Underground dynamics are constrained by spatially-
222 varying depth to bedrock, which acts as an impermeable surface that determines the lower aquifer
223 boundary. tRIBS can be run on a multi-processor computer by taking advantage of parallelization via
224 domain decomposition (Vivoni et al., 2011). tRIBS computes short and longwave radiation fluxes
225 using geographic location, time of the year, cloudiness, aspect, emissivity, slope and albedo at each
226 computational element. Incoming solar radiation is reduced by vegetative shading according to Beer-
227 Lambert law (Brantley and Young, 2007; Marshall and Waring, 1986) (see Appendix B). Effects of
228 distant landscape on the amount of incoming radiation are accounted through radiation scattering
229 and sheltering functions that are controlled by land-view factors and hillslope albedo (Rinehart et al.,
230 2008). Surface latent (i.e. evaporation and transpiration), sensible and ground heat fluxes are com-
231 puted using meteorological conditions and soil moisture (Ivanov et al., 2004b). Snow processes are
232 accounted for through a single-layer snow module with a coupled energy and mass balance approach

TC 7

TC 11

TC 19

233 that accounts for direct and diffuse solar (shortwave) and long wave radiation, snow interception and
234 unloading, sublimation of intercepted and on-the-ground snow, accumulation and ablation of snow,
235 and infiltration of melt water (Mahmood and Vivoni, 2013; Rinehart et al., 2008). Vegetation inter-
236 cepts snow falling in solid form, based on its leaf area index, and unloads snow in relation to air
237 temperature. Remaining on-the-ground and canopy snow can be sublimated depending on absorbed
238 shortwave and longwave radiation and aerodynamic conditions (Liston and Elder, 2006; Pomeroy
239 et al., 1998; Wigmosta, 1994). Melt water can either infiltrate or run off and eventually is routed
240 down-slope to the channel as surface or subsurface runoff. Rainfall interception follows the canopy
241 water balance scheme (Rutter et al., 1971, 1975) including throughflow, drainage, storage and evap-
242 oration, values that are determined by plant architecture properties and vegetation fraction. Evap-
243 otranspiration processes account for (1) evaporation from wet canopy (E_{int}), (2) evaporation from
244 bare soil (E_{soil}), and plant transpiration (T). Total evapotranspiration (ET) is estimated using the
245 Penman-Monteith equation that depends on the surface energy balance and aerodynamic conditions
246 for surface and plants. The below-canopy distribution of the vertical wind speed follows a decay-
247 exponential function depending on the biometric features of the forest determined by projected LAI
248 and vegetation height (see Appendix B) (Sypka and Starzak, 2013; Yi, 2008). Evapotranspiration
249 partitioning depends on the ability of E_{soil} and T to extract soil water from the surface and root
250 zones and is determined by constant model stress factors (Ivanov et al., 2004a; Mendez-Barroso
251 et al., 2013). A kinematic approximation for unsaturated flow is used to compute infiltration and
252 propagate soil moisture fronts in an anisotropic soil column according to an exponentially decaying
253 hydraulic conductivity condition (Cabral et al., 1992; Garrote and Bras, 1995; Ivanov et al., 2004a).
254 The coupled framework of the unsaturated and saturated processes results in a set of runoff mecha-
255 nisms, namely: infiltration-excess runoff (Horton, 1933), saturation excess runoff (Dunne and Black,
256 1970), groundwater exfiltration (Hursh and Brater, 1941), and perched return flow (Weyman, 1970).
257 Routing of surface flow is achieved via hydrologic overland flow and hydraulic channel routing that
258 uses a kinematic wave approximation (Vivoni et al., 2007a).

259 3.4 Computational domain, model parameters and initialization

260 We obtained a 30-m Digital Elevation Model (DEM) from the National Elevation Dataset (Gesch
261 et al., 2002) for the central Arizona region. A grid sensitivity analysis was performed, leading to
262 a convenient mesh simplification through selection of a coarser grid resolution that guaranteed: (1)
263 preservation of the spatial distributions of elevation, slope, curvature and hillslope aspect, and (2)
264 scheduling of a multiple-year parallelized model calibration procedure in a feasible period of time.
265 A TIN geometry was then constructed following a modified VIP (Very Important Point) method
266 that minimized the number of computational nodes and the Kullback-Leibler divergence between
267 topographic density functions. This resulted in an optimum horizontal point density of $d=0.86$ and
268 $n_t=1970$ ($d=n_t/n_g$, where n_t is the number of TIN nodes and n_g is the number of DEM cells) with an

269 equivalent cell size of $r_e=964$ m. The final TIN represents the basin topography with high accuracy
270 and preserves the finest level structures of stream network, river flood plains and watershed divide
271 through a double buffer node strategy.

272 tRIBS requires specification of the spatially varying parameters associated with individual soil and
273 vegetation classes, and of those that describe the properties of the hillslope and channel network
274 routing, and the underground aquifer (Ivanov et al., 2004b; Moreno et al., 2012). Soil and vegeta-
275 tion parameters are assigned to the different classes represented in Fig. 4. Soil texture maps were
276 derived from the State Soil Geographic (STATSGO) Data Base at 1:250,000 scale providing full
277 regional coverage. Similarly, vegetation type and fraction maps were obtained from the USGS Na-
278 tional Land cover Dataset (Homer et al., 2004) at 30m resolution for the year 2006. Distributed land
279 cover properties were determined by vegetation parameters extracted from ancillary 2006 Landfire
280 products (<http://www.landfire.gov/>) and mathematical expressions, from the literature, depending on
281 the "pre-treatment" and "post-treatment" forest basal area maps (see Fig. 3). Associated parameters
282 include vegetation fraction, Leaf Area Index (LAI), vegetation throughfall and canopy storage (see
283 Appendix B). We consider only two vegetation fraction cases ("pre-treatment" and "post-treatment")
284 ignoring any intermediate vegetation phenology, re-growth or recurrent thinning operations (see Sec-
285 tion 4.5). A spatially distributed bedrock depth map, at 1500m spatial resolution, was obtained from
286 the Northern Arizona Regional Groundwater-Flow Model (Pool et al., 2011) and used to set a lower
287 impermeable aquifer boundary. Finally, a geomorphic relation between channel width (w in m) and
288 contributing area (A in km^2) was derived from 21 field measurements taken during a field campaign
289 along the basin main channel, resulting in the expression $w=9.303A^{0.243}$ with $R^2=0.76$.

TC 3

290 tRIBS also requires a spatially-distributed initial condition, provided by the depth to groundwater
291 surface, to set soil moisture profiles following a hydrostatic equilibrium assumption. A 1500m spa-
292 tial resolution hydraulic head map, issued for spring 1990, from the Northern Arizona Regional
293 Groundwater-Flow Model (Pool et al., 2011) was adopted as the distributed initial condition. The
294 depth to groundwater then had a mean value of 248 m with a standard deviation of 183 m. The model
295 was spun-up for one year (January to December, 1990) when dynamic steady-state conditions were
296 reached in stream flow, groundwater and vadose zone moisture profiles.

TC 20

297 3.5 Calibration and evaluation strategy

298 Our results are supported by calibration and evaluation tests with continually available hydrological
299 information on the ground. First, a one-at-a-time (OAT) sensitivity analysis facilitated determination
300 of the relative importance of model parameters as evaluated by performance criteria (Gupta et al.,
301 2009; Gupta and Kling, 2011), revealing that watershed responses are mainly controlled by the set
302 of soil and vegetation parameters shown in Table 2. For the case of soil parameters, those properties
303 are the saturated hydraulic conductivity (K_s) and its decay exponent with depth (f), the air entry
304 bubbling pressure (ψ_b) and the pore size distribution index (λ_0). These parameters control the infil-

TC 8

305 tration, percolation, throughflow and runoff production rates, water retention and vadose zone wet
306 front evolution. Complementary, for the vegetation classes, three parameters were found to domi-
307 nate the runoff production through controls on interception, soil moisture, evapotranspiration and
308 snow melt rates. Those parameters are albedo (a), vegetation height (H_v) and optical transmission
309 coefficient (K_t). Parameters, other than those listed in Table 2, were assigned reference values from
310 the literature within feasible ranges of variation (Ivanov et al., 2004a, b; Moreno et al., 2012; Rutter
311 et al., 1971). Subsequently, daily time series of stream flow (Q) and snow water equivalent (SW)
312 were used as targets for model calibration, during the ten year period $N=[01/01/1991,12/31/2000]$,
313 selected to include important drivers of seasonal and inter-annual climate variability including win-
314 ter frontal, monsoonal systems, Pacific Decadal Oscillation (PDO) and ENSO events (Dominguez
315 et al., 2010). For calibration, we implemented a model pre-emption framework (Razavi et al., 2010)
316 to improve computational efficiency by terminating model runs in poorly performing parts of the
317 parameter space. The Shuffled Complex Evolution (SCE) algorithm (Duan et al., 1993) was used to
318 find optimum values within feasible ranges of variation that minimize the normalized residuals of
319 simulated and observed time series of Q and SW , as dictated by the normalized objective function
320 $M(t)$ evaluated at each pre-emption time (t), according to the following expression:

$$321 \quad M(t) = w_1 F_Q(t) + w_2 F_{SWE}(t); \quad 0 \leq t \leq N \quad (1)$$

322 With:

$$323 \quad F_x(t) = \frac{SSE_x(t)}{N\sigma_{ox}^2}; \quad x = Q \quad \text{or} \quad x = SWE \quad (2)$$

$$324 \quad SSE_x(t) = \frac{1}{N} \sum_{j=1}^t (x_j^{sim} - x_j^{obs})^2 \quad (3)$$

$$325 \quad \sigma_{ox}^2 = \frac{1}{N} \sum_{j=1}^n (x_j^{obs} - \bar{x}^{obs})^2 \quad (4) \quad \text{TC 1}$$

$$326 \quad w_1 = w_2 = 0.5 \quad (5)$$

327 where w_1 and w_2 are optimization weights, σ_{ox} is the standard deviation of observed values and
328 x_j^{obs} , x_j^{sim} are the observed and simulated values during simultaneous time steps j .

329 Calibrated values, illustrated by Table 2, were then used to evaluate model robustness during the
330 period 01/01/2001 to 12/31/2010. Figure 7 shows the daily observed and simulated time series of
331 Q and SW for the calibration and evaluation periods with complementary information about model
332 skill at the daily time scale, in terms of the Mean Squared Error (MSE), Nash-Sutcliffe Efficiency
333 (NSE) and Pearson correlation coefficient ρ_{so} . Together, these scores provide a complementary view

334 of the model simulations in terms of the mean, variability and overall correlation. Figure 7 and skill
335 scores suggest that despite certain discrepancies in the simulation of long recessions, and certain
336 peak stream flows and snow water equivalent maximums, the model is able to reproduce the distinct

337 hydrologic patterns that determine the presence of on-the-ground snow and mean and variability of
338 stream discharge. As indicated before, the overall quality of hydrologic simulations is largely tied to
339 the quality of hourly precipitation inputs whose uncertainties propagate basin-wise (Bardossy and
340 Das, 2008; Borga et al., 2006; Michaud and Sorooshian, 1994). Model robustness is indicated by the
341 evaluation scores, which summarize predictive capability during the entire 20-year period.

TC 1

342 3.6 Design of numerical experiments

343 Our goal is to understand the individual and collateral effects of forest thinning and related soil
344 disturbances due to forest removal operations on the total hydrologic response, using historic cli-
345 mate forcing. Modeling experiments were therefore conducted during the period 01/01/1991 to
346 12/31/2010 with adoption of a base case scenario determined by 2006 soil and vegetation cover
347 maps (Fig. 4). Forest thinning induces model changes in vegetation fraction, Leaf Area Index (LAI),
348 vegetation throughfall and canopy storage (see Appendix B). In all cases we assume that litter is
349 also removed from the thinned areas and vegetation condition does not dynamically evolve dur-
350 ing "post-treatment" conditions (see Section 4.5). Soil changes are fundamentally represented by
351 modifications in the saturated hydraulic conductivity, which are triggered by compaction and water-
352 repellency processes after mechanical thinning and prescribed burning. Given the high uncertainty
353 in such values, as reported in the literature, we assume three additional cases of "post-treatment"
354 steady reductions in original soil hydraulic conductivity (imperviousness; from Table 2) between 10
355 and 40% (10, 20, 40%) of the current values and only in the areas covered by ponderosa pine. Table
356 3 summarizes the simulation of scenarios and the corresponding adopted naming convention (Case).
357 While representing post-fire conditions as constant over time might be considered unrealistic, the
358 results are indicative of the immediate sensitivity of basin response to a drastic (as planned) land
359 cover change. Spatially distributed water footprints due to forest thinning can be understood through
360 an element-scale view of the long-term shifts on water fluxes and stocks. This analysis is performed
361 through the selection of multiple domain elements located within forest treated areas of different
362 thinning intensity values; elements with contrasting solar aspect are paired according to similar el-
363 evation, slope, air temperature, wind speed, net radiation, evapotranspiration and soil moisture to
364 compare their hydrologic evolution from pre- to post-treatment conditions. A total of eight element
365 pairs were found to fulfill these requirements. For each element, the components of the water balance
366 can be estimated as in the soil column schematic in Fig. 8, where surface and subsurface reservoirs
367 and input/output fluxes have been included in annual ($\Delta t=1$ year) mass continuity equations (Equa-
368 tions 6 through 8). The different pre- and post-forest-thinning components of the water balance in
369 the soil column are appraised to only evaluate the effect of thinning in contrasting hillslope aspects.

TC 23

TC 4

TC 26

$$370 \quad Input - Output = \frac{\Delta(Storage)}{\Delta t} \quad (6)$$

$$371 \quad P + (R_{in} - R_{out}) + (\theta_{in} - \theta_{out}) + (GW_{in} - GW_{out}) - S_{snow} - S_{int} - E_{soil} - E_{int} - T =$$

$$372 \quad \frac{\Delta(SW)}{\Delta t} + \frac{\Delta(Int)}{\Delta t} + \frac{\Delta(\theta)}{\Delta t} + \frac{\Delta(GW)}{\Delta t} \quad (7)$$

$$373 \quad P + R + \theta f + GW f - S_{snow} - S_{int} - E_{soil} - E_{int} - T = \frac{\Delta(SW)}{\Delta t} + \frac{\Delta(Int)}{\Delta t} + \frac{\Delta(\theta)}{\Delta t} +$$

$$374 \quad \frac{\Delta(GW)}{\Delta t} \quad (8)$$

375 4 Results and Discussion

SC 1

376 4.1 Stream flow shifts and extreme event probability

377 Forest removal affects the distribution and magnitude of stream flows in a different manner depend-
 378 ing on the seasonal magnitude of runoff generation, the shifts in *INT*, *SW*, θ and *GW* and the soil
 379 hydraulic conditions imposed by thinning operations. Field observations have shown an immediate
 380 decrease in soil hydraulic conductivity, but recovering to historic soil conditions with time, after
 381 forest treatment. This section addresses the concerns for increased flood risks during heavy rain-
 382 storms and sustained river water supply for urban populations and ecological processes during low
 383 discharge conditions, as a result of a vegetation-reduced system.

384 According to the annual patterns of precipitation, temperature (Fig. 5) and stream flow (Fig. 11a),
 385 there are three differentiable conditions in Tonto Creek characterized by the (1) wetter, higher flows
 386 during winter (e.g. January) season and (2) the summer monsoon (e.g. August), and (3) drier, low
 387 flow circumstance during the pre-monsoon period (e.g. June). Hourly time series from the refer-
 388 ence and simulated cases are classified by hydrologic period (winter, pre-monsoon, monsoon, and
 389 all months included) to understand the probability distribution shifts that forest thinning produces
 390 on quartiles, Q_1 through Q_4 (where Q_1 and Q_4 correspond to low and high flows respectively) and
 391 low order statistical moments (μ , σ) of long-term (20-y) simulations (Fig. 9). Results are expressed
 392 in terms of ratios relative to distributional values obtained by the reference case for each type of
 393 hydrologic condition.

TC 28

394 Model results indicate that Q_1 , μ , σ and Q_4 are larger across cases, confirming not only the higher
 395 runoff efficiency but also the increased flood risk for riverine communities during the winter season
 396 under post-treatment conditions. In contrast, during the monsoon season, differences in the soil hy-
 397 draulic conductivity play a major role in the distribution of stream flow values. For instance, V and
 398 VS10 produce net reductions in μ , σ and Q_4 ; increases in the same statistics are observed for the
 399 most impervious cases (VS20, VS40). In the long term, if hydraulic conductivities return to normal,
 400 it might mean reductions in the mean and extreme runoff production during monsoon showers. On
 401 the other hand, during pre-monsoon conditions, forest thinning seems to be increasing the lowest

402 stream flows, but has a mixed effect on μ , σ , Q_3 and Q_4 . In these cases, the less impermeable scenar-
 403 ios achieve reductions in distribution values, indicating drier hydrologic conditions, while the most
 404 permeable scenarios (VS20, VS40) evidence increases in the same distributional parameters.
 405 Results for all months together suggest net increases in Q_1 , μ , σ and Q_4 , indicating a net distri-
 406 butional shift to the right, relative to the reference case. These changes in distributional values of
 407 stream flow triggered by land cover changes may support the need for decision making oriented to-
 408 wards water preservation during dry conditions and mitigation or adaptation of the negative effects
 409 of floods on urban settings and ecological communities.

410 4.2 Effects of forest thinning on mean and variability of basin-scale water balance compo- 411 nents

412 Hydrologic effects of headwater forest thinning are reflected through both local changes in the mean
 413 and variability of water fluxes and stocks and basin-scale shifts in discharge yield. The following
 414 analysis supports this statement by quantifying the magnitude and direction of the water changes
 415 that are statistically significant at the basin scale. First, an inter-annual examination is conducted to
 416 understand shifts in key water variables and their patterns, both in the long-term and during warm
 417 and cold phases of ENSO. Like the entire Southwestern U.S., the Tonto Creek basin experiences in-
 418 creases in total annual precipitation (P) during El Niño (by 20%) and reductions during La Niña (by
 419 11%), with both phases presenting slight reductions in mean air temperatures ($Temp$), as estimated
 420 from NLDAS corrected 20 year records (Fig. 10 a and b). Since water balance is affected by ENSO,
 421 alterations in the basin's response to forest thinning are also expected. In addition to inter-annual
 422 variations, seasonal shifts are expected as modifications in the below-canopy energy balance, wind
 423 speed and net precipitation impose differential effects according to each month's climate regime. Re-
 424 sults are presented in terms of each simulated case relative to the corresponding reference scenario,
 425 and for each ENSO phase type, as 20-year mean and standard deviation ratios and monthly absolute
 426 differences.

427 4.2.1 Inter-annual trends

428 In the long-term, forest thinning leads to changes in water distribution that are exacerbated during an
 429 ENSO event. Results suggest increased annual average stream flows (Q) of up to 7%, but reductions
 430 of snow water equivalent (SW) of 16% and snow covered area (SA) of about 5% (Figure 10c),
 431 while only slight reductions (less than 2%) in vadose zone soil moisture and evapotranspiration (θ
 432 and ET) are observed. Similarly, 10 cm and root zone soil moisture (θ_{10} and θ_{root}) and depth to
 433 groundwater (DG) do not show significant changes, relative to the reference case. Comparatively,
 434 thinning simulation cases differentially impact the mean Q , with VS40 being the most efficient in
 435 increasing runoff through a decrease in soil infiltration capacity. In addition, temporal hydrologic
 436 variability appears to be dampened by forest thinning, with the exception of stream flow, as illustrated

437 by the lower time series standard deviations of Fig. 10d. Interestingly, ENSO appears to modulate
438 these shifts by exacerbating or moderating forest thinning impacts. For instance, El Niño enhances
439 direct surface responses in Q and θ_{10} and compensates for the losses in SW and SA . In contrast, La
440 Niña dramatically reduces Q , SW and SA (See Fig. 10c). In terms of time series variability, ENSO
441 appears to intensify reductions in inter-annual variability due to forest thinning across the tested
442 variables, with the exception of ET during La Niña and SA during EL Niño, as illustrated by Fig.
443 10d. A seasonal analysis (next subsection) facilitates identification of the emerging monthly patterns
444 responsible for these inter-annual trends.

445 4.2.2 Seasonal shifts and emerging hydrological patterns

446 At the monthly scale, forest thinning increases stream flows and groundwater recharge, at the ex-
447 pense of reduced interception and snow pack, and a pattern emerges of a less regulated runoff system
448 that exacerbates both higher-and lower-levels of river flow. At Tonto Creek, the high precipitation
449 and low air temperatures during winter months drive the unimodal annual cycle of Q and SA with
450 maximum values in January of each year (Figs. 11 a,f). Cumulative effects of this wetter period
451 are also observed through delayed responses of θ , DG and SW , with maximum peaks appearing in
452 March (Figs. 11b,c,e). Comparatively, the second rainfall peak only produces Q values below the
453 annual mean, as most water leaves the basin through higher ET rates, a typical behavior of water-
454 limited basins (Figs. 11a,d). For the most part, forest thinning tends to increase Q , in particular for
455 those months with already high runoff production and for those cases with the most impervious soils
456 (i.e., DJF and VS40; see Fig. 11g). Nonetheless, during the monsoon season (JAS), changes in Q are
457 less clear across thinning cases with the less impervious scenarios (V, VS10), instead showing net
458 reductions in Q , even when ET values have been simultaneously reduced (Fig 11g,j). The emerging
459 shift in patterns of SW and SA reveal reductions that are more marked during their peak values (i.e.
460 during MA; Figs. 11k,l).

461 Aside from SW , vadose zone water availability (θ) does not show significant changes during the year
462 due to thinning (Fig. 11h). In contrast, the depth to groundwater decreases almost uniformly year
463 round, with the least impervious scenario having the largest aquifer recharge values (Fig. 11i). On
464 balance, reductions in snow water equivalent and, less likely, in evapotranspiration linked to vege-
465 tation removal, compensate for the increased (especially winter) runoff and groundwater recharge,
466 resulting in an emerging pattern shifting from surface snow to groundwater storage, an issue in
467 semi-arid basins whose deep aquifers may remain disconnected from the channel base flows for
468 many months of the year. A detailed spatial analysis (next sub-section) provides information about
469 important local water trends for mountain ecosystems settled directly on thinned areas of the forest.

470 4.3 Distributed hydrologic effects of forest removal

471 As forest reduction will only occur in the headwaters of Tonto Creek basin (see Fig. 3), direct hydrologic effects are likely to be particularly marked in such areas, which are subject to higher annual
472 basin precipitation and lower mean temperatures. Figure 12 presents the spatial hydrologic patterns for the reference case (first column) and projected changes for three representative cases (V, VS10,
473 VS40; columns 2 through 4) relative to the reference. Results shown in Fig. 12 indicate that averaging over time, spatial differences due to changes in soil hydraulic conductivity (i.e. V vs. VS10 or
474 VS40) are not salient among cases but rather that any level of forest removal imposes major changes
475 in local water.
476

477 Runoff and Soil Moisture: In terms of runoff (R_{ref}), current rates attain the highest values in shrub-
478 land and low basal area ponderosa pine cover, as most of the water in forested areas is intercepted or
479 bound up by snow pack for slower release to the channel network in the spring. Consistently across
480 scales, thinning promotes increases in local runoff production, of up to 40% in heavily thinned areas
481 and for the most impervious case (VS40). On the other hand, storage of water in the vadose zone
482 (θ_{ref}) is characterized by higher values in proximity to the channel network and riparian areas, particularly in high elevation areas, dominated by forest cover and higher rainfall values. Forest removal
483 induces mixed shifts in θ , but a dominant reduction trend is observed in heavily thinned areas, with
484 VS40 producing the largest reduction rates (of up to 15%) in θ .
485

486 Evapotranspiration: Coupled to soil moisture, atmospheric losses through evapotranspiration are evidently larger along the river network and riparian areas where ET consumes available surface and
487 subsurface water through rates that equal annual precipitation ($ET \sim P \sim 700$ mm/y) in some riparian
488 corridors. Except in heavily thinned transects with slightly higher temperature ($Temp$), where increases of up to 30 mm/y in ET are seen, the vast majority of the thinned area indicates decreases in
489 ET , of up to 40 mm/y, presumably associated to reductions in transpiration rates (T). As impervious
490 cases (i.e., VS40) produce increases in surface runoff production to river network, both θ and ET
491 decrease more drastically.
492

493 Snow: In terms of snow processes, current conditions allow the formation, accumulation and melt of
494 on-the-ground snow differentially across the Mogollon Rim during the winter and spring months. In
495 the case of the Tonto Creek basin, exceptional wet, cold winter seasons result in a local maximum
496 of 1000 mm snow water equivalent ($SW_{max,ref}$), with snow pack persisting (NDS_{ref}) for up to 170
497 consecutive days. Forest thinning consistently reduces NDS for as long as 60 days and SW_{max} by as
498 much as 350 mm, in the most intensively thinned areas by an increased forcing of shortwave energy
499 on thinned patches.
500

501 In summary, model simulations reveal that vegetation removal is the most important factor determining distributed changes in fluxes and storages of water, more so than hydraulic changes in soil.
502 The Tonto Creek basin presents spatially-distinct responses to forest thinning characterized by punctuated increases in runoff and generalized decreases in soil moisture, evapotranspiration and snow
503
504
505
506

TC 12

507 persistence and volume, compared to historically simulated levels. In the next sub-section, the phys-
508 ical mechanisms inducing change at the element level are explored in higher detail, through soil
509 column analysis of multiple computational elements with contrasting annual radiation differences.

510 **4.4 Soil column water balance in hillslopes with contrasting solar aspect**

511 This section is aimed to identify the effect of forest thinning in contrasting solar aspects. Figure 13
512 (a and b), summarizes two examples of the typical shifts in the soil column water balance terms as a
513 proportion of the reference case. Although only two element pairs (7N, 6S and 6N, 7S) are shown,
514 the balance of evidence indicates that forest thinning induces local increases in below-canopy P_{net}
515 ($P-Int$), NR , T_s and WS , which trigger increases in R (exacerbated by soil imperviousness), S_{snow} ,
516 and E_{soil} , at the expense of reductions in GWf , Int , E_{int} , T and SW . While, in general, the soil
517 columns experience comparatively slight reductions in ET , one of the most evident shifts involves
518 a compensatory partitioning with reductions in E_{int} and T and increases in E_{soil} in both hillslope
519 aspects. The degree of thinning ($\Delta VF\%$) appears to elicit a direct and proportional influence on the
520 relative change of NR , T_s , Int , S_{snow} , E_{soil} , E_{int} , T , and SW across the eight pixel pairs.

521 A more detailed scrutiny of these trends during a typical water year is illustrated by Fig. 14 for an
522 element-pair (7N-6S), and considers the most important fluxes and reservoirs ranging from atmo-
523 spheric ($ET+S$), surface (R , SW), and subsurface (θ , GW) components. Table 4 shows mean total
524 annual changes across the eight element pairs (N, S) for all tested cases. Figure 14 and Table 4 in-
525 dicate that larger reductions in the total atmospheric losses ($ET + S$) can be achieved in the North
526 facing slopes, particularly for the most impervious cases (e.g., VS20, VS40) and more marked dur-
527 ing the first ET peak in March. Additionally, larger gains in runoff are achieved from the north facing
528 slopes especially during the winter peak and more significantly for the most impervious cases. (i.e.
529 VS20, VS40).

530 Regarding water reservoirs, reductions in snow water due to forest thinning are far larger for south
531 facing slopes where four elements (1S, 5S, 3S, 7S) evidence total depletion of snow-pack between
532 15 and 25 days earlier than during reference conditions. The trade-offs between less snow and faster
533 melt mechanisms are clear through the increase of element runoff and a greater recharge (GW) of the
534 aquifer, whose groundwater table levels appear deep and sometimes disconnected from the surface
535 channel network . The interplay of θ and GW is clear when comprehensible increases in saturated
536 thickness lead to corresponding reductions in vadose zone water storage in the bedrock-limited soil
537 column element.

538 **4.5 Model assumptions and study limitations**

539 This section explains a set of important model assumptions and limitations that help with the inter-
540 pretation of the results, estimation of the scope and identification of potential lines for future work
541 from this study. The following items are presented without an order of importance as the amount of

542 uncertainty introduced by each of them was not quantified in a systematic fashion. (1) The model
543 does not consider dynamic changes in vegetation physiology, re-growth and/or mortality rates. This
544 assumption ignores the actual (probable) response of vegetation to "post-treatment" conditions, if
545 thinning operations are discontinued. This would include, but is not limited to, progressive increases
546 in basal area (and thus sapwood area), concomitant linear increase in projected leaf area index for
547 conifers (McDowell et al. 2008) and the accompanying physiological, radiative and hydraulic re-
548 sponses of the over-story and understory vegetation (dePury and Farquhar, 1997; Ivanov et al., 2008;
549 Sampson et al., 2006) being ignored. Notwithstanding, typical growth rates (woody increment) at this
550 geographic region are of about 2% per year, depending on the species (Worley, 1965) and so, likely
551 canopy processes would be slow to respond during the modeling period considered in this study. A
552 misrepresentation of the vegetation evolution during "post-treatment" time would, most likely, re-
553 sult in underestimation of interception capacity and on-the-ground snow duration but overestimation
554 of runoff rates. (2) The model does not consider gradual recovery in soil saturated hydraulic con-
555 ductivity during the "post-treatment" condition that would, most likely, result in reduction of runoff
556 volumes but increases in vadose zone soil moisture. (3) The uncertainty propagation from the NL-
557 DAS precipitation product to the hydrologic simulations and the lack of "groundtruth" hydrologic
558 information (i.e. rain gauges, nested stream flow gauges, snow, evapotranspiration and soil moisture
559 stations) hinders the entire validation process and simulation skill and constrains the comparison to
560 only a few measuring stations of stream flow and snow. This fact seriously constrains extrapolation
561 of results to other variables that were not verified during this modeling effort. Nonetheless, results
562 can be fully understood relative to a base case scenario that was aimed to reproduce hydrologic con-
563 ditions as real as possible. Finally, (4) the model did not analyze the effects of forest thinning in
564 sediment and pollutants load to streams and reservoirs. Further studies should investigate the com-
565 bined effects of deforestation and their subsequent shifts in water residence times from surface to
566 groundwater reservoirs.

TC 2

TC 22

567 5 Summary and Conclusions

568 This study investigated the long-term effects of simulated forest thinning for both element and basin
569 scale hydrologic balance and extreme discharges in a semi-arid basin of the southwestern U.S. We
570 used the *4FRI* forest restoration project as the context for these silvicultural operations applied to
571 the headwaters of Tonto Creek along the Mogollon Rim, the most water productive region in Ari-
572 zona. Long-term hydrologic simulations in this basin are challenging due to topographic complexity
573 as well as the lack of ubiquitous hydrologic measurements on the terrain. In appraising the spatio-
574 temporal water footprints of forest removal, we investigated the changes induced in the probability
575 distribution functions that involve mean and extreme discharge events in long-term and during three
576 distinct seasonal hydrologic conditions. The mechanisms that support this shift behavior are explored

TC 13

577 through an analysis of the inter-annual and seasonal effects on the mean and variability of hydrolo-
578 logic variables and the water-related outcomes induced by the occurrence of ENSO phases. Finally,
579 an emphasis was placed on identifying the mechanism through which water transitions occur due
580 to changes in the solar radiation, surface temperature, wind speed and water balance at the element
581 scale in contrasting slope aspects. Our results are summarized below.

582 (1) Forest thinning leads to a less regulated hydrologic system for mean and extreme events. A prob- **TC 13**
583 abilistic analysis of the magnitude of recurrence of mean and extreme event conditions indicates
584 a net increase in the annual stream flow distributions, particularly dominated by larger, consistent
585 increases in mean and maximum events during the winter months. This shift can increase the risk of
586 negative flood related effects directly downstream of the treated areas. For the less impervious sce-
587 narios (V, VS10), consistent increases in runoff are not observed for the mean and higher quartiles
588 during the dry and low flows of the pre-monsoon and monsoon seasons, leading to an even drier
589 hydrologic condition. Consistently across seasons, impervious soils contribute to increased stream
590 flow values.

591 (2) Headwater forest thinning can lead to hydrologic shifts in the areas directly affected by this
592 procedure that are reflected by anomalies in the average basin-scale integrated values. Observable
593 basin-scale changes occur through increases in runoff (7%) and decreases in snow-water (-16%) and
594 snow-covered areas (-5%). This result is consistent with recent observations in high elevation forests **TC 25**
595 (Metcalfé and Buttle, 1998; Musselman et al. 2008; Lindquist et al 2013; Venkatamaran 2013).
596 Increases in soil impermeability due to removal operations exacerbate alterations, particularly in
597 runoff volume. Climatic stressors like ENSO affect the magnitude of such re-distributions, princi-
598 pally through modifications in precipitation availability. For instance, El Niño appears to exacerbate
599 runoff production while La Niña reduces snow presence due to a rainfall suppression effect.

600 (3) At the monthly scale, forest thinning results in stream flow augmentation, particularly during the
601 winter precipitation peak but less clearly for the monsoon season, when the most permeable sce-
602 narios instead decrease runoff yields, on average. Conversely, consistent reductions in the depth to
603 groundwater (maximum in January), evapotranspiration (maximum in July) and snow water (maxi-
604 mum in April), are observed across simulated scenarios, thus lowering the historic maximum values
605 occurring in corresponding months.

606 (4) The Tonto Creek basin presents spatially-distinct responses to forest thinning characterized by
607 local increases in runoff and generalized decreases in interception, soil moisture, evapotranspira-
608 tion and snow persistence and volume, when compared to the current reference case. In terms of
609 runoff, local increases in runoff production in heavily thinned areas and for the most impervious
610 case (VS40) are observed. In contrast, mixed shifts in θ , but with a dominant reduction trend, are
611 observed in heavily thinned areas, with VS40 producing the largest reduction rates. Regarding *ET*,
612 except for a few increasing trends in heavily thinned transects with slightly higher surface tem-
613 perature (*Temp*), the vast majority of the thinned area indicates decreases on *ET* associated with

614 reductions in transpiration rates (T). Because impervious cases (i.e., VS40) impose increases in sur-
615 face runoff production to the river network, both θ and ET decrease more drastically in this case.
616 Forest thinning consistently reduces snow persistence and peak values in intensively thinned areas.
617 (5) Multiple element soil column analysis indicates that gains in runoff and aquifer recharge are
618 due to net reductions in interception, snow water equivalent and, less likely through reductions in
619 evapotranspiration. Removal of forest canopy shading creates a nearly balanced mechanism where
620 decreases in transpiration are compensated by increases in soil evaporation rates. The annual net
621 radiation imbalance between north and south facing slopes in this north-litudinal basin results in
622 increased vulnerability of south facing areas to less snow accumulation and faster melt periods by
623 increases in surface temperature, sublimation and evaporation rates.

624 Despite this modeling study does not consider vegetation dynamics (e.g. re-growth) and soil
625 hydraulic properties recovery during the long term simulations, the use of highly credible (Hamp-
626 ton et al., 2011) forest thinning projections and three additional simulation scenarios considering **TC 5**
627 increases in soil imperviousness provide one set of reasonable, spatially distributed cases to iden-
628 tify potential effects on the mean and extreme hydrologic conditions in this semi-arid region. This
629 situation could, specially, apply if authorities decide to maintain forest thinning operations in the
630 long term. The results of this study are based on the use of a distributed hydrologic model that was
631 calibrated and verified during 20 consecutive years at daily scale, using 12.5-km, 1-hour resolution
632 climate forcing from the NASA Land Cover Data Assimilation System (NLDAS;(Mitchell et al.,
633 2004)) with precipitation fields locally adjusted through rain gauge data. The tuning and evaluation
634 procedures both provided appropriate skill scores for stream flows and snow water equivalent, de-
635 spite some discrepancies introduced by model forcing, initial conditions and structural errors. While
636 calibration and validation coefficients are not optimal, model performance offers the possibility of
637 quantifying changes introduced by forest thinning, independent of the model structural and para-
638 metric uncertainty, as results are primarily presented relative to model simulations made with 2006
639 vegetation conditions, which we adopted as current reference case.

640 **Appendix A: A1 Precipitation Bias Correction**

641 While a global bias correction procedure (Steiner et al., 1999) provided poor rainfall adjustments, a
642 modified local correction strategy (Seo and Breidenbach, 2002) produced much better hourly rainfall
643 estimates due to the high spatial variability of this phenomenon. This approach uses the three closest
644 daily ground rain gauges to correct hourly volumes of the NLDAS gridded precipitation product (R)
645 pixels following a weighting strategy according to the following expressions:

$$646 \quad r_c = r_o \sum_{i=1}^3 w_i \beta_i + \sum_{i=1}^3 w_i \delta_i \quad (\text{A1})$$

647 Where

$$648 \quad \beta_i = \begin{cases} 1 & \text{if } g_i/r_i > \beta_t \\ g_i/r_i & \text{if } g_i/r_i < \beta_t \end{cases} \quad (\text{A2})$$

$$649 \quad \delta_i = \begin{cases} (g_i - r_i)/24 & \text{if } g_i/r_i > \beta_t \\ 0 & \text{if } g_i/r_i < \beta_t \end{cases} \quad (\text{A3})$$

650 r_c : bias-corrected R (mm).

651 r_o : raw R at the pixel centered at μ_o (mm).

652 w_i : weight given to the R-gauge pair at the i^{th} vertex in the triangle of R-gauge pairs that encloses
653 μ_o .

654 β_i : multiplicative sample bias from the i^{th} R-gauge pair.

655 δ_i : additive sample bias from the i^{th} R-gauge pair.

656 g_i : gauge rainfall measurement (mm) at the i^{th} vertex in the enclosing triangle.

657 r_i : collocating R rainfall estimate (mm) at the i^{th} vertex in the enclosing triangle.

658 β_t : adaptable parameter that denotes the threshold for the multiplicative or additive bias.

659

660 The neighboring R-gauge pairs are identified by triangulation, which connects all available R-
661 gauge pairs into a mesh of triangles. The weights, w_i , $i=1,2,3$, sum to unity and are inversely pro-
662 portional to the distance to the neighboring R-gauge pairs in the enclosing triangle. An iterative
663 procedure was conducted to select the best $\beta_t=1$ that minimized the MSE between observed and
664 corrected rainfall at rain gauge locations. Figure A.1 illustrates the spatial distribution of precipi-
665 tation for the VTS system, averaged during 21 years (1990 to 2010) as measured by (a) Thiessen
666 polygons derived from 30 daily rain gauges, (b) raw NLDAS and (c) bias-corrected NLDAS estima-
667 tions. Figure A.2 shows an example scatterplot comparing daily rain gauge values (x-axis) with raw
668 and corrected NLDAS (y-axis) for one of the thirty stations within the study region.

669 **Appendix B: B1 Model Vegetation Relations**

670 A set of empirical relations are used to relate remote sensing and field information to vegetation
671 parameters and processes in our hydrologic model. Such processes account for vegetated fraction
672 (VF), Leaf Area Index (LAI), throughfall (p) and canopy storage (S) and below canopy light (Q/Q_0)
673 and wind speed attenuation (U_h), in ponderosa pine forests.

674 90-m resolution vegetation fraction maps were derived for pre- and post- treatment basal area con-
675 ditions only (i.e. ignoring plant evolution or phenology) from historical measurements in northern

676 Arizona across seven different ponderosa pine forest densities, as reported by the small-diameter
 677 wood supply report (Hampton et al., 2011) following the expression:

$$678 \quad VF = \frac{BA + 2.794}{2.898}; \quad R^2 = 0.99 \quad (B1)$$

679 Where VF is the vegetation fraction (%) and BA is the measured basal area (ft²/Ac). LAI maps for
 680 ponderosa pine were derived following an empirical relation with basal area from field measurements
 681 in ten study sites with different pine densities (Armstrong, 2012) through a relation that minimized
 682 residuals between observed and predicted LAI:

$$683 \quad LAI = \begin{cases} 0 & \text{if } BA = 0 \\ Abs(-0.00003738369BA^2 + 0.01683112155BA - 0.03539819521) & \text{if } BA > 0 \end{cases} \quad (B2)$$

684 LAI values were verified on typical ranges for ponderosa pine forests under different vegetation
 685 fraction conditions. Vegetation fraction and LAI values for non-ponderosa covered areas were ex-
 686 tracted from the 2006 Landfire products (<http://landfire.gov/>) and derived from existing literature
 687 (Mendez-Barroso et al., 2013; Mitchell et al., 2004), respectively. Free throughfall coefficient (*p*),
 688 which accounts for the fraction of rainfall not captured by plants, and canopy capacity (*S*), were
 689 derived from the expressions B3 and B4 (Carlyle-Moses and Price, 2007; Mendez-Barroso et al.,
 690 2013; Pitman, 1989):

$$691 \quad p = \exp(-1.5LAI) \quad (B3)$$

$$692 \quad S = 0.5LAI \quad (B4)$$

693 The Beer-Lambert law was adopted to account for the reduction in radiative transmittance due to
 694 dense canopies (Brantley and Young, 2007; Marshall and Waring, 1986) following:

$$695 \quad \frac{Q}{Q_0} = \exp((K_t - 1)LAI) \quad (B5)$$

696 Where K_t is the optical transmission coefficient. Finally, below canopy momentum transfer by
 697 wind speed was corrected by forest density as surface rugosity factor following (Sypka and Starzak,
 698 2013; Yi, 2008):

$$699 \quad U(h) = U_H \exp\left\{-\frac{1}{2}LAI\left(1 - \frac{h}{H_c}\right)\right\} \quad (B6)$$

700 Where $U(h)$ is the wind speed at the height h within the canopy, in m/s, U_H is the wind speed at
701 the top of the canopy, in m/s, and H_c is the top of the canopy, in m.

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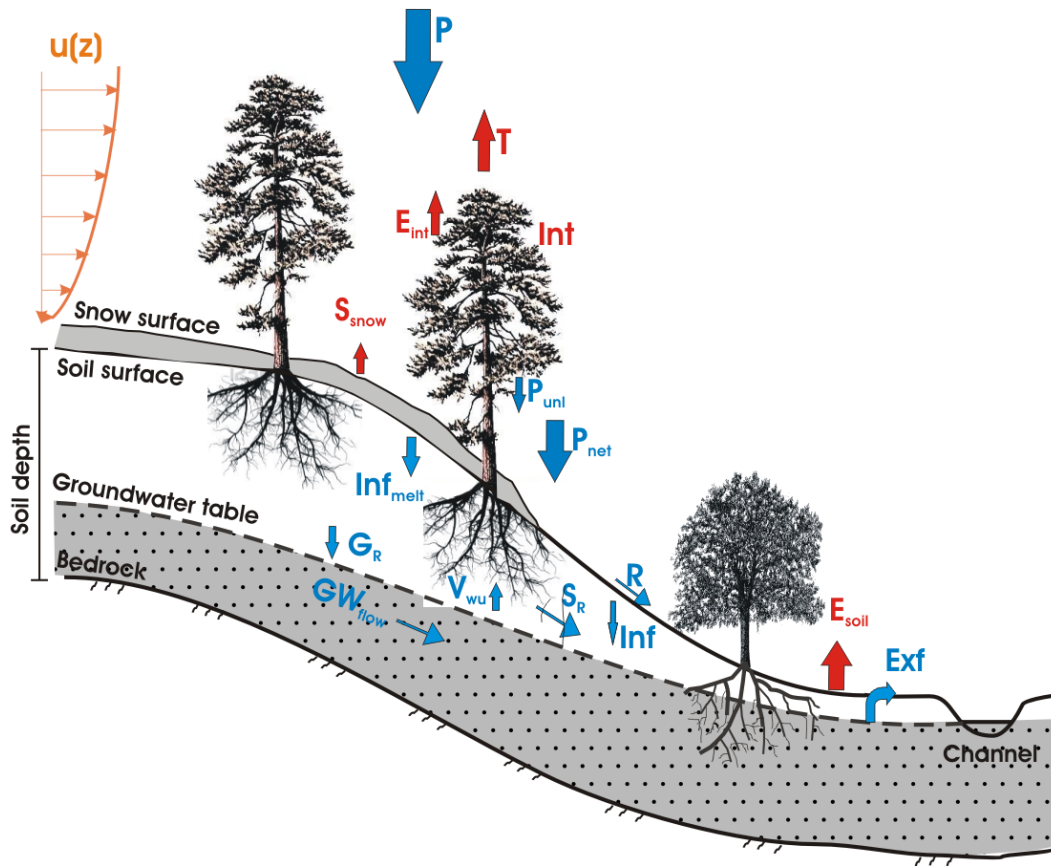


Figure 1. Elements of the water balance in a forested hillslope: A fraction of the gross precipitation or snow (P) is intercepted by vegetation (Int) and the remaining volume reaches the ground as net precipitation or snow (P_{net}). Intercepted water (Int) is either unloaded from leaves and branches (P_{unl}) or temporarily stored for evaporation (E_{int}) back to the atmosphere. If snow occurs, P_{net} builds up snow pack. When thermodynamic conditions allow, retained water in the snow can sublimate (S_{snow}), or after melting, it can infiltrate (Inf_{melt}), runoff (R) or be transpired by plants (T), evaporated from soil (E_{soil}), serve as groundwater recharge (G_R) or remain as soil moisture in the vadose zone. Analogously, if only liquid precipitation occurs, P_{net} redistributes according to the processes mentioned above, except for the snow related mechanisms. Runoff (R) can be produced through infiltration excess, saturation excess, perched return flow and/or groundwater contribution (Exf). Subsurface flow can occur through lateral vadose zone flow (S_R) and/or groundwater flow (GW_{flow}). An aerodynamic component has been added to this plot to mark the importance of the surface roughness by trees on evaporation and sublimation water fluxes.

FC 1



Elevation (m)

3837

137

Basin boundaries

Major streams

Restoration area

Snow stations

Stream gauges

Weather stations

VERDE-TONTO-SALT

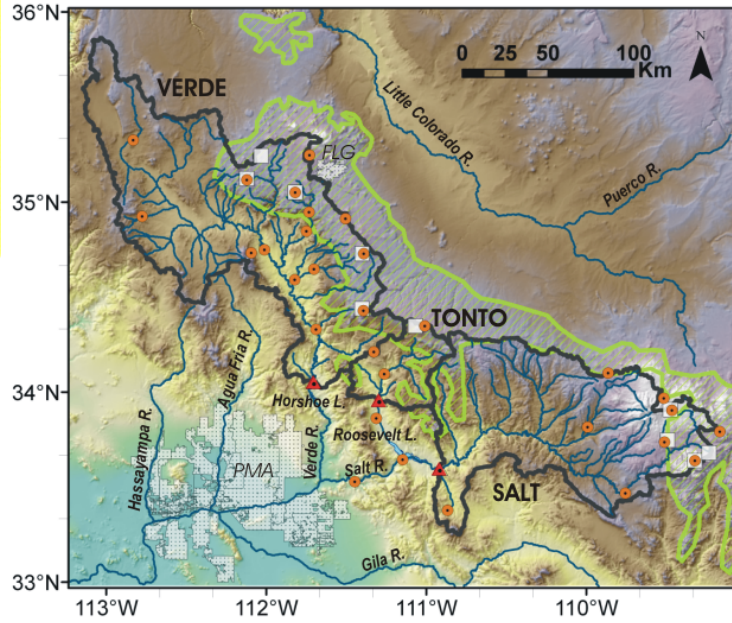
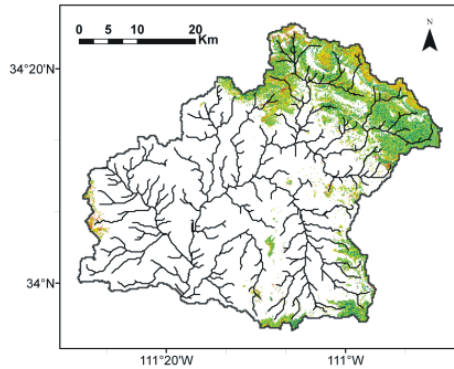
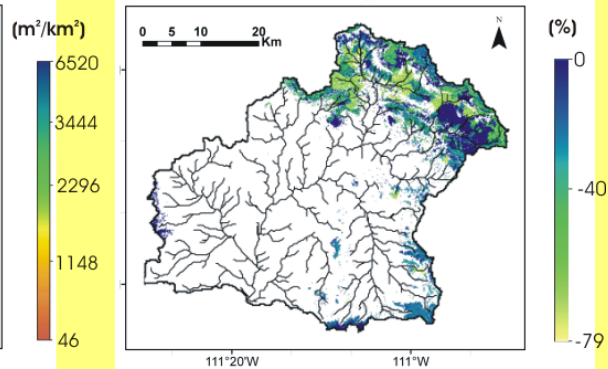


Figure 2. Map detailing the projected 4FRI restoration area and the Verde, Tonto and Salt (VTS) watershed divides. Detailed river networks, major cities and lakes, and the three basin outlets that define the VTS system are shown on a 30m USGS digital elevation model.

(a) Pre-treatment Basal Area



(b) Post-treatment Change in Basal Area



FC 2

Figure 3. Spatial distribution of ponderosa pine consensus restoration for: (a) pre-treatment basal area conditions, and (b) change in basal area due to forest treatment. Data provided by the Laboratory of Landscape Ecology and Conservation Biology of the Northern Arizona University (NAU)

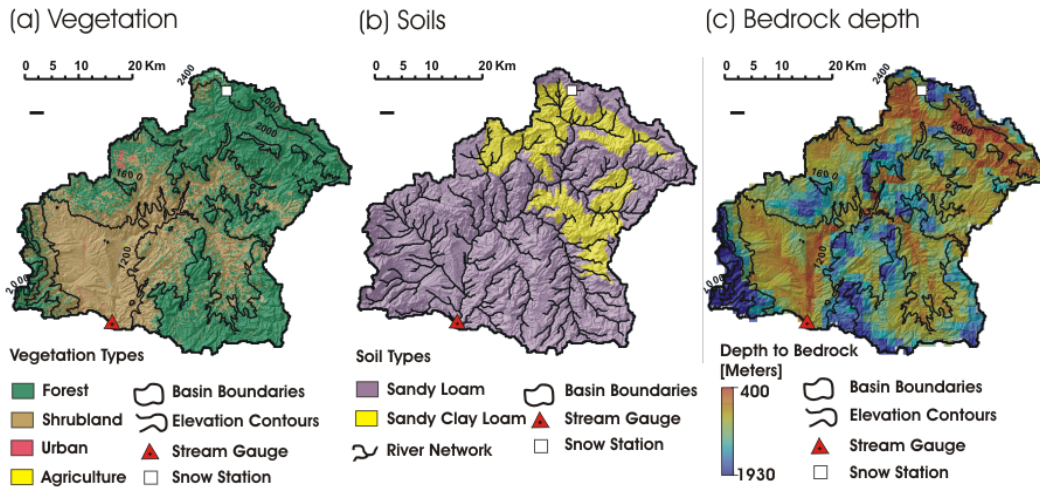


Figure 4. Spatial distribution of (a) vegetation types from USGS National Land cover Dataset (Homer et al., 2004) at 30m resolution for year 2006, (b) soil types from the State Soil Geographic (STATSGO) at 1:250,000 scale, and (c) depth to bedrock at 1500m spatial resolution as obtained from the Northern Arizona Regional Groundwater-Flow Model (Pool et al., 2011) clipped for Tonto Creek basin. Elevation contours, hydrography and location of snow (Snowtel-Promontory) and stream flow (USGS-Tonto Creek Abv. Gun Creek) stations are also shown.

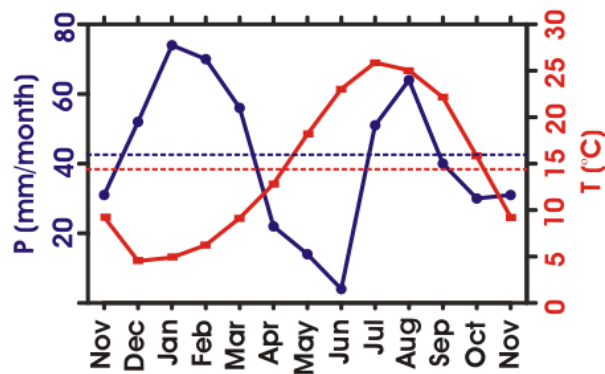


Figure 5. Mean monthly values of precipitation (blue) and air temperature (red) from 1990-2010 NLDAS time series within the Tonto Creek watershed divide. Dashed lines represent mean annual value for each variable. A water year starting in November will be used henceforth to better visualize the changes in maximum and minimum values due to forest thinning along the year.

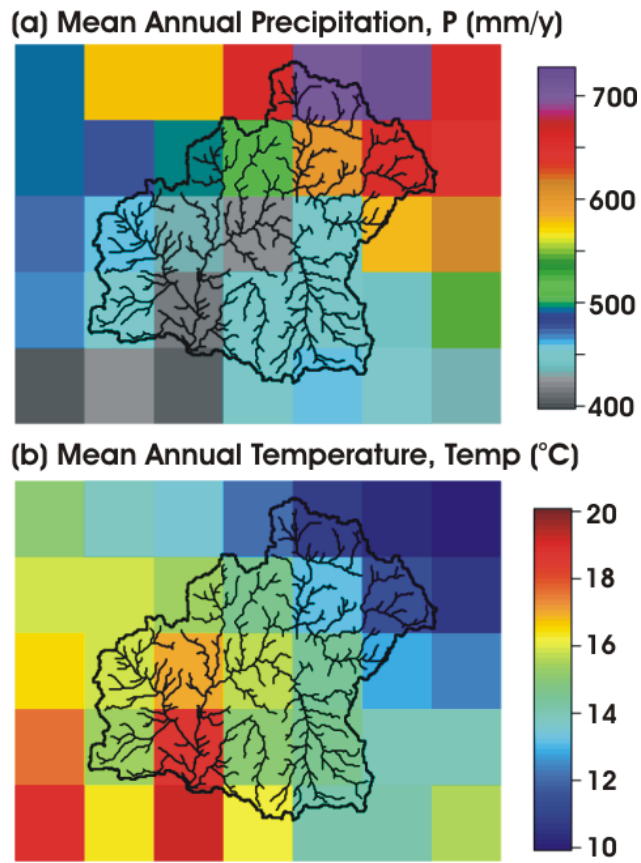


Figure 6. Mean multi-annual distribution of (a) precipitation and (b) air temperature values from 1990-2010 NLDAS time series for the Tonto Creek basin.

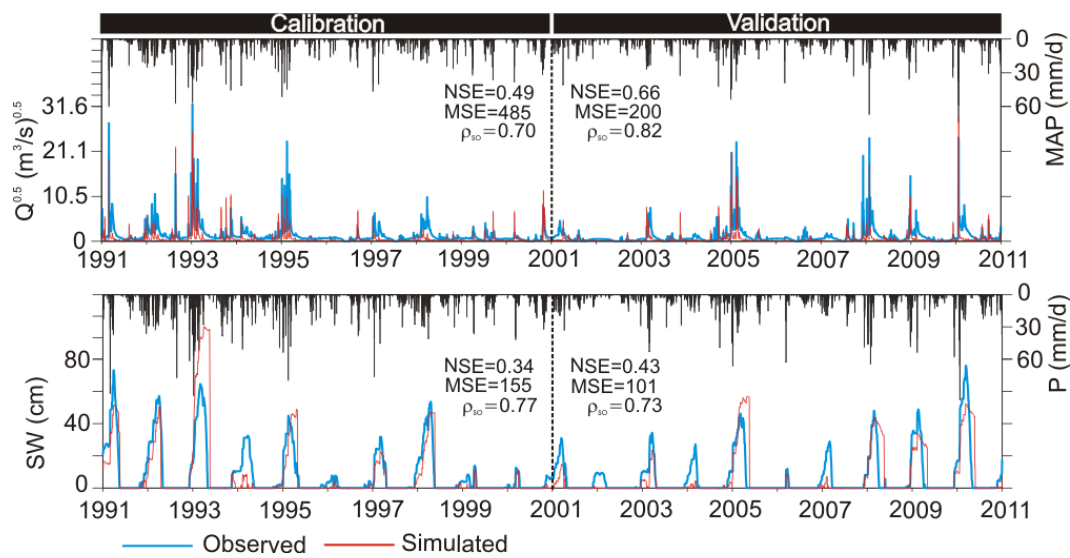


Figure 7. Observed (blue lines) and simulated (red lines) hydrograph and snow water equivalent time series resulting from model calibration (1991-2000) and validation (2001-2010) at the basin outlet and collocated snow station model voronoi element (shown in Figure 4), along with NSE, MSE, and ρ_{so} skill scores. To improve the visualization of low stream flow values, the time series of discharges have been elevated to a 0.5 exponent. Mean areal MAP and pixel precipitation (P) are derived from the corrected NLDAS product.

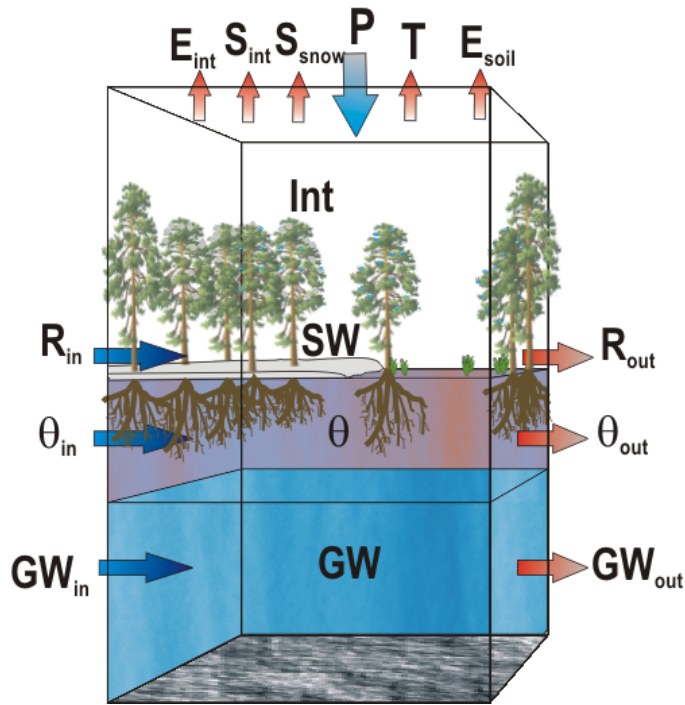


Figure 8. Soil column water balance storages and fluxes of a typical hillslope computational element. The computational element's Voronoi geometry has been represented by a rectangular shape in the interest of simplification. Water is mostly stored through vegetation interception (Int), snow accumulation (SW), vadose zone soil moisture (θ) and groundwater in the saturated zone (GW). Surface and subsurface water (in and out) fluxes include above canopy gross precipitation (P), vegetation transpiration (T), evaporation from intercepted water (E_{int}), evaporation from soil (E_{soil}), sublimation from intercepted (S_{int}) and on-the-ground snow (S_{snow}), net surface ($R=R_{in}-R_{out}$) and subsurface runoff ($\theta_f = \theta_{in} - \theta_{out}$) and net ground water flow ($GW_f=GW_{in}-GW_{out}$). The column is constrained by an impervious bedrock layer whose depth varies from element to element.

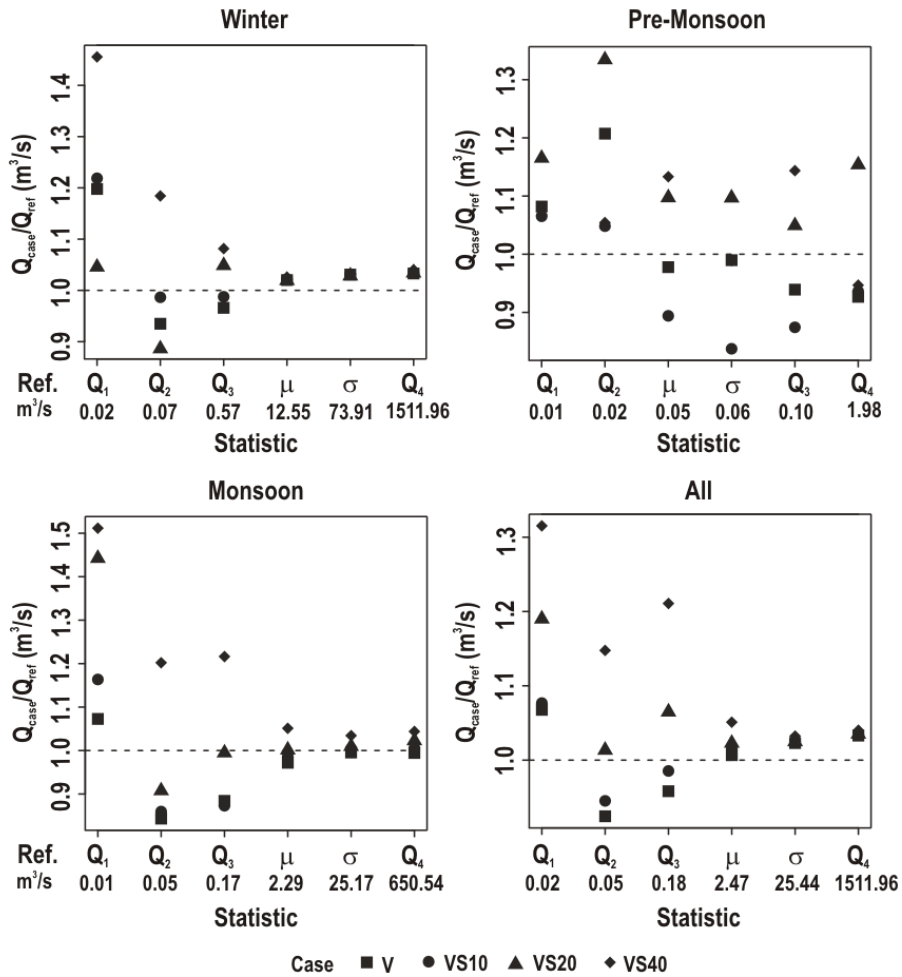


Figure 9. Long term ratios (Q_{case}/Q_{ref}) between stream flow probability distribution properties for the forest thinning scenarios and the reference case, computed from hourly simulated time series for typical winter (January), pre-monsoon (June) and monsoon (August) months and all months. Statistical properties include first, second, third and fourth quartiles (Q_1 , Q_2 , Q_3 , and Q_4), mean (μ) and standard deviation (σ). In all plots, the dashed line represents the reference case.

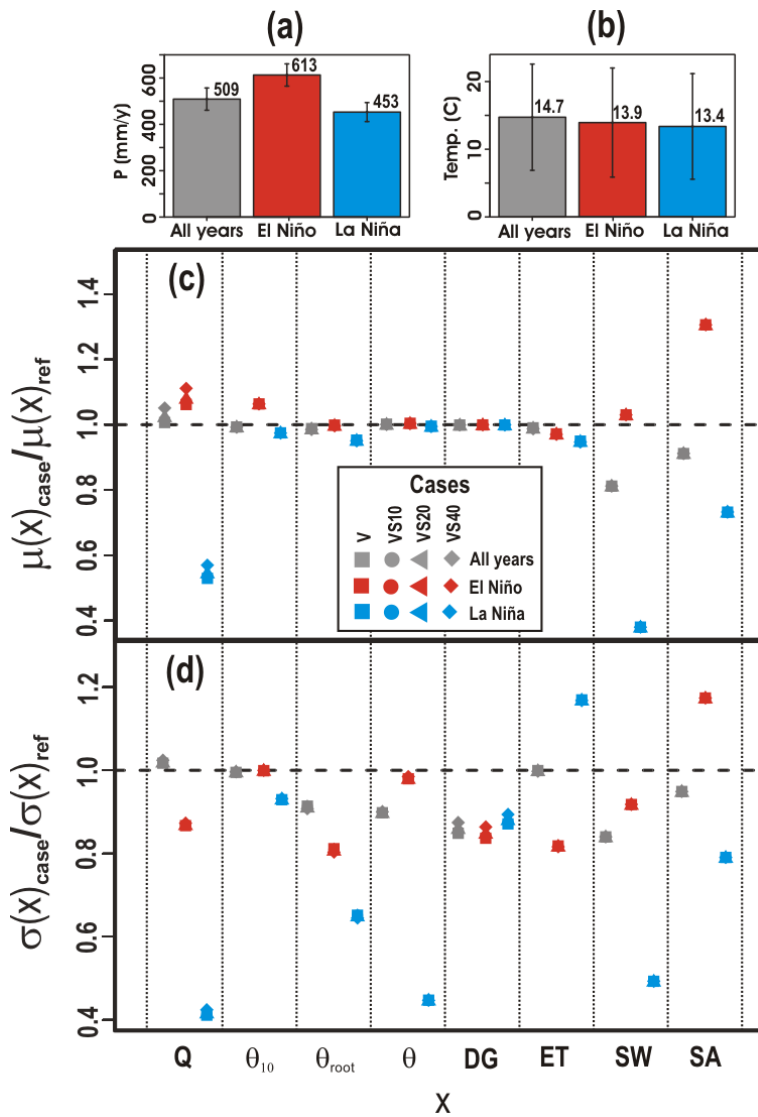


Figure 10. Mean multi-annual (a) precipitation and (b) air temperature values at Tonto Creek during the 1990-2010 period (grey), El Niño (red) and La Niña (blue) years. Standard deviation bars have been added to each variable. ENSO phases follow the anomalies in the Oceanic Niño Index from the NOAA National Prediction Center at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html. (c) Mean $\mu(X)_{case}/\mu(X)_{ref}$ and (d) standard deviation $\sigma(X)_{case}/\sigma(X)_{ref}$ ratios between forest thinning simulated scenarios (V, VS10, VS20, VS40) and reference case (represented by the dashed black lines) for all (grey), El Niño (red) and La Niña (blue) years for eight basin scale hydrologic variables (X on the x-axis) that include: outlet stream flow (Q), 10cm depth, root and vadose zone soil moisture (θ_{10} , θ_{root} , θ), depth to groundwater table (DG), evapotranspiration (ET), snow water equivalent (SW) and snow covered area (SA) mean basin values.

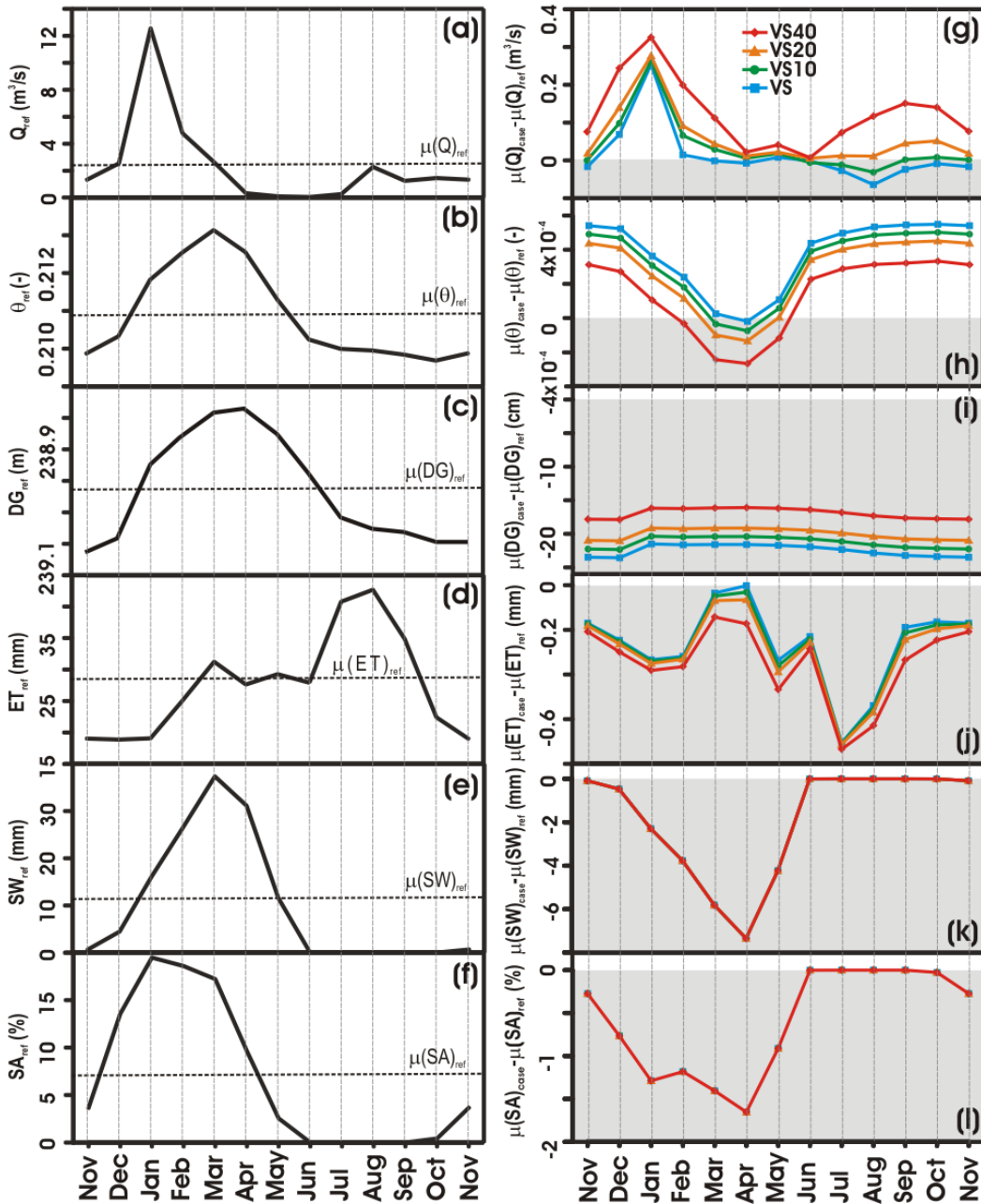


Figure 11. Mean monthly values of: (a) outlet stream flow (Q_{ref}), (b) vadose zone soil moisture (θ_{ref}), (c) depth to ground water (DG_{ref}), (d) evapotranspiration (ET_{ref}), (e) snow water equivalent (SW_{ref}), and (f) snow covered area (SA_{ref}), for the reference case as computed from 20-year (1991-2010) model simulations and integrated over the entire basin area; mean annual values are represented by dashed lines in each plot. Mean monthly differences $\mu(X)_{case}/\mu(X)_{ref}$ between thinning simulated (V in blue, VS10 in green, VS20 in orange and VS40 in red) and reference case (zero value) are illustrated for: (g) outlet stream flow $\mu(Q)_{case}/\mu(Q)_{ref}$, (h) vadose zone soil moisture $\mu(\theta)_{case}/\mu(\theta)_{ref}$, (i) depth to ground water $\mu(DG)_{case}/\mu(DG)_{ref}$, (j) evapotranspiration $\mu(ET)_{case}/\mu(ET)_{ref}$, (k) snow water equivalent $\mu(SW)_{case}/\mu(SW)_{ref}$, and (l) snow covered area $\mu(SA)_{case}/\mu(SA)_{ref}$

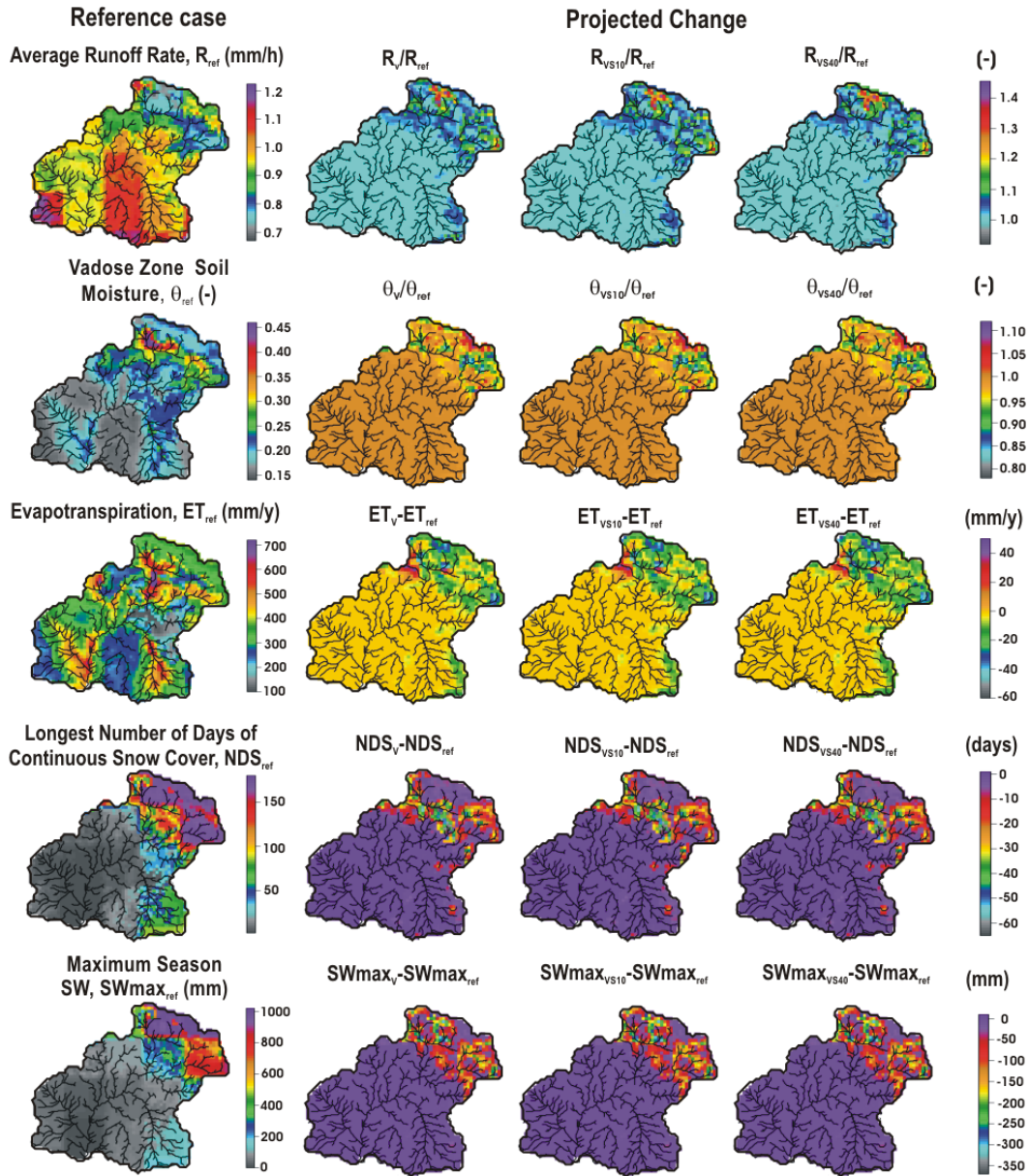


Figure 12. Simulated mean (first column) and projected changes (columns 2 through 4) in the mean multi-annual distribution of runoff (R_{ref}), vadose zone soil moisture (θ_{ref}), evapotranspiration (ET_{ref}), longest number of days with snow cover (NDS_{ref}) and maximum season snow water equivalent ($SWmax_{ref}$) due to forest thinning. Projected changes for the V, VS10 and VS40 cases are presented in terms of ratios or absolute differences, using the same color scale.

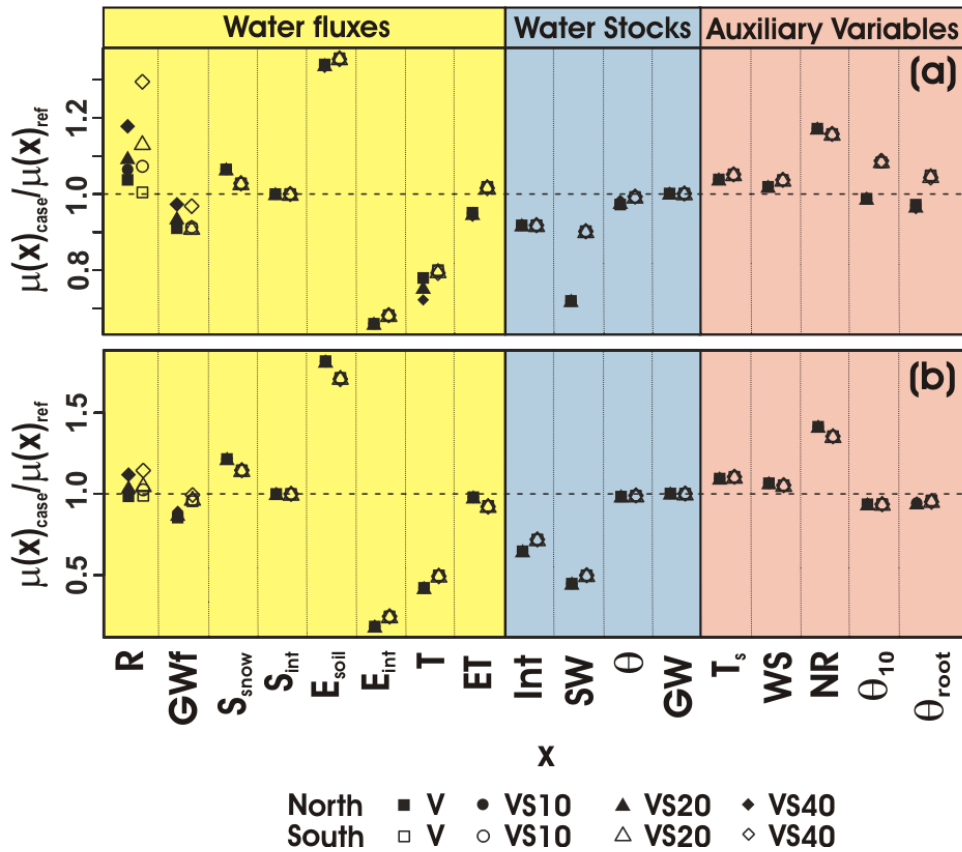


Figure 13. Long term element scale shifts in mean water fluxes and stocks relative to the reference case during 20-year model simulations. Results are presented for (a) 7N-6S, and (b) 6N-7S, as representative element pairs with different thinning degrees and contrasting hillslope aspects. Tested cases (V, VS10, VS20, VS40) are differentiated by the geometric symbols aligned vertically for each variable with North represented by solid and South represented by hollow symbols. Water fluxes include runoff (R), groundwater flow (GWf), sublimation from on-the-ground snow (S_{snow}) and intercepted (S_{int}) snow, evaporation from soil (E_{soil}) and intercepted water (E_{int}), vegetation transpiration (T) and total evapotranspiration (ET). Water stocks include vegetation interception (Int), on-the-ground snow water (SW), vadose zone soil moisture (θ) and groundwater storage (GW). Auxiliary variables, including 2m surface temperature (T_s), wind speed (WS), net radiation (NR) and soil moisture at 10cm and root zone depths (θ_{10} and θ_{root}), have been added to the plot to aid interpreting budget shifts.

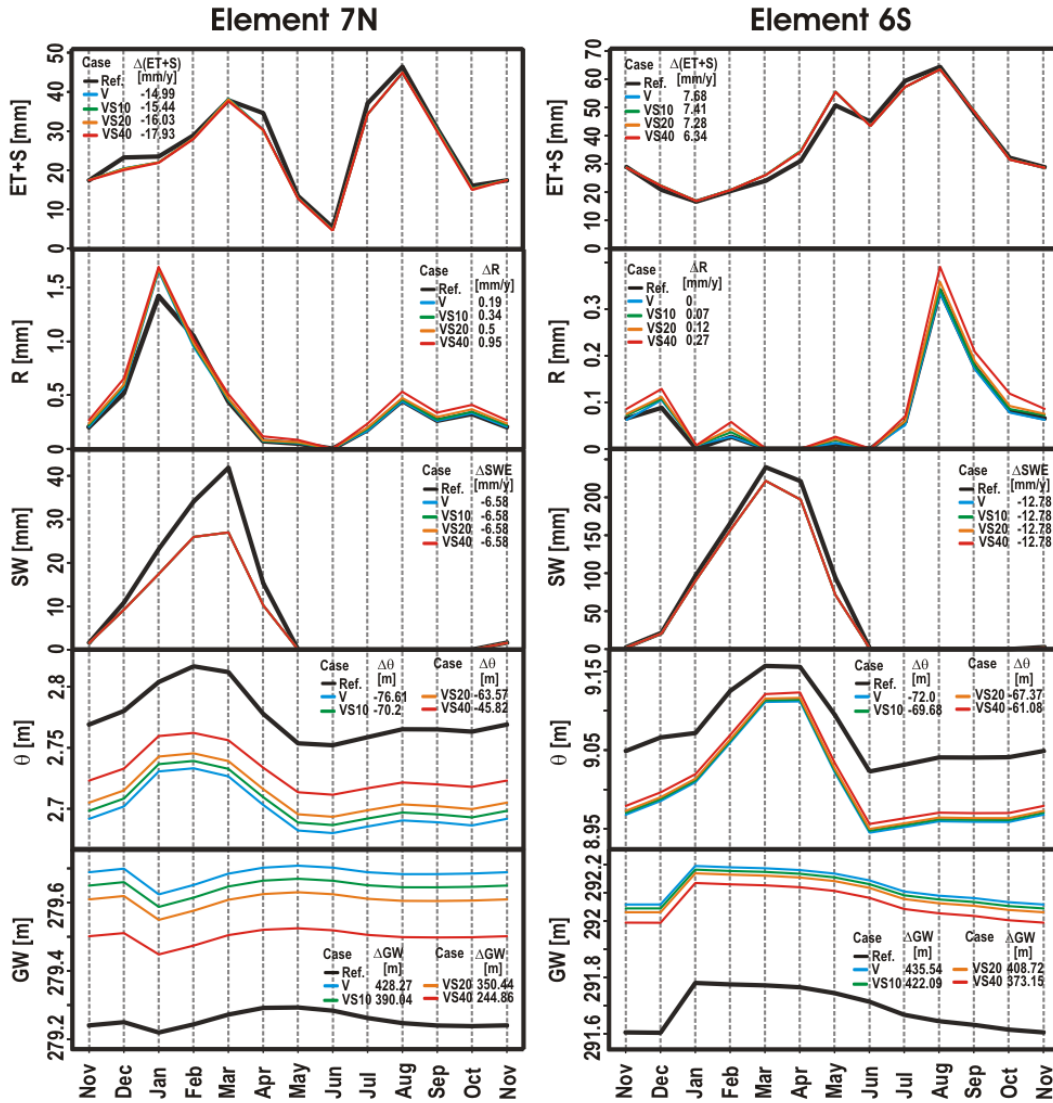


Figure 14. Mean annual cycles of simulated reference (black) and tested (colored) cases for an element pair (7N, 6S) as obtained from 20-year model results. Variables include atmospheric losses (ET+S) for all evaporation, transpiration and sublimation rates, net runoff production (R), snow water equivalent (SW), vadose zone soil moisture (θ), and groundwater storage (GW). V, VS10, VS20 and VS40 are represented by blue, green, orange and red colors, respectively. Mean annual changes (Δx) have been added to each variable to compare mean monthly changes relative to each reference case.

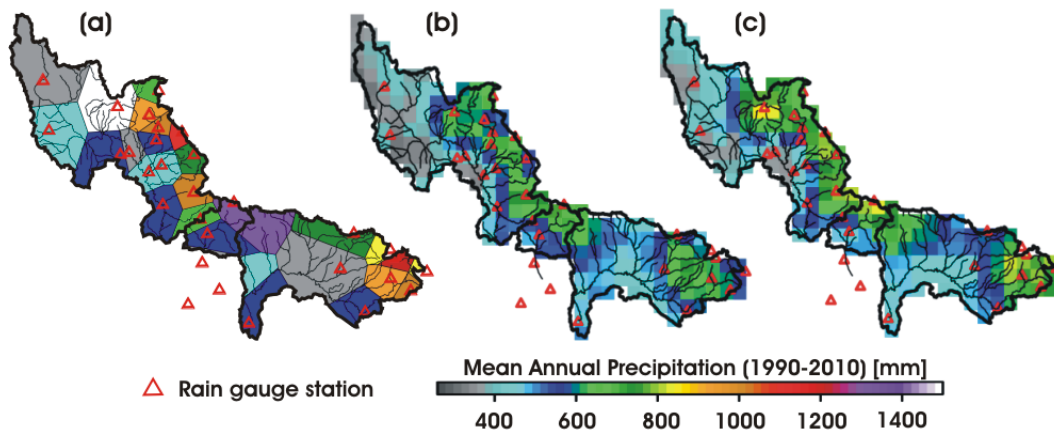


Figure A.1. Spatial distribution of long-term (1990-2010) annual rainfall as measured by (a) Thiessen polygons from 30 daily rain gauge stations, (b) raw NLDAS, and (c) locally bias corrected NLDAS estimations.

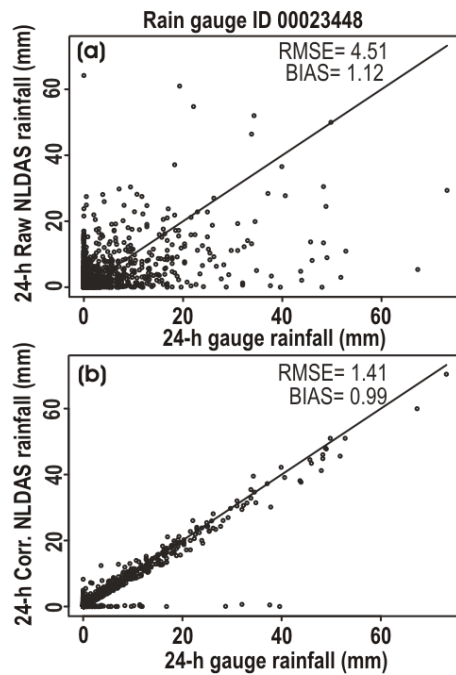


Figure A.2. Scatterplot of daily rainfall depths between (a) the raw NLDAS product and gauge rainfall and (b) the bias corrected NLDAS product and the gauge rainfall for an example rainfall station (ID 00023448) and collocated NLDAS pixel.

Table 1. Topographic, soil, vegetation and bedrock characteristics of the Tonto Creek basin.

Property	Value	Property	Value
Outlet Coordinates	111.3035 W, 33.9890 N	Std. slope [%]	20.95
Total Area [km ²]	1902.43	Major soil class 1 (% area)	Sandy loam (79.21)
Length of main channel [km]	60.91	Major soil class 2 (% area)	Sabdy clay loam (20.77)
Slope of main channel [m/km]	21.77	Major soil class 3 (% area)	Sand (0.02)
Mean elevation [m]	1552.25	Major vegetation class 1 (% area)	Forest (69.03)
Minimum/maximum elevations [m]	766/2430	Major vegetation class 2	Shrubland (26.41)
Std. elevation [m]	323.19	Major vegetation class 3	Grassland (4.08)
Mean slope [%]	27.57	Kirpich's Concentration time [h]	6.84

Table 2. Model calibrated parameters for the period 01/01/1991 to 12/31/2010 at the Tonto Creek basin. Parameters for soil are: saturated hydraulic conductivity (K_s) and its decay exponent with depth (f), pore-size distribution index (λ_0), air entry bubbling pressure (ψ_b); and for vegetation, albedo (a), vegetation height (H_v) and optical transmission coefficient (K_t).

Soil Type	K_s (mm/h)	λ_0 (-)	ψ_b (mm)	f (mm ⁻¹)
Sandy Loam	4.2881	0.3716	-133.2360	0.0291
Sandy Clay Loam	0.7376	1.5058	-740.8015	0.0366
Vegetation type	a (-)	H_v (m)	K_t (-)	
Forest	0.1805	32.0355	0.6417	

Table 3. Description of reference case (Ref) and hydrologic simulation (V, VS10, VS20, VS40) scenarios in terms of modifications in forest and soil properties.

Case	Forest Cover	Soil
Ref	2006 basal area	Calibrated K_s
V	Post-treatment basal area	Calibrated K_s
VS10	Post-treatment basal area	10% reduction in K_s across soil types in ponderosa pine areas
VS20	Post-treatment basal area	20% reduction in K_s across soil types in ponderosa pine areas
VS30	Post-treatment basal area	30% reduction in K_s across soil types in ponderosa pine areas

Table 4. Mean annual differences between forest thinning scenarios (V,VS10,VS20,VS40) and reference case for atmospheric losses (ET+S), runoff (R), snow water equivalent (SW), vadose zone moisture (θ) and ground-water storage (GW) across eight element pairs with contrasting (north, south) hillslope aspects.

$\mu(\Delta x)$	North Aspect				South Aspect			
	V	VS10	VS20	VS40	V	VS10	VS20	VS40
$\mu(\Delta(ET + S))$ [mm/y]	-16.25	-17.13	-18.18	-21.09	-11.35	-12.08	-12.74	-14.09
$\mu(\Delta R)$ [mm/y]	0.31	0.42	0.56	0.91	0.2	0.29	0.32	0.49
$\mu(\Delta SW)$ [mm/y]	-81.48	-81.48	-81.48	-81.48	-197.54	-197.54	-197.54	-197.54
$\mu(\Delta \theta)$ [mm/y]	-62.44	-58.60	-54.11	-43.39	-81.23	-79.41	-82.94	-78.10
$\mu(\Delta GW)$ [mm/y]	316.77	294.75	269.10	208.06	419.40	407.02	423.46	398.58