Hydrological and Ecological Sensitivities to Climate Variability for Four Western U.S. Mountain Ecosystems.

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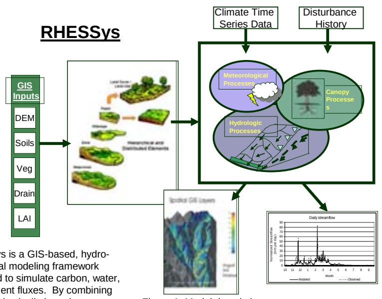
ABSTRACT

National Parks in Western U.S. mountain ecosystems are rapidly changing as a result of the direct and indirect effects of climate change. With warming temperatures, these systems are experiencing earlier melt and reductions in snow accumulation. The impact of these changes on other hydrologic patterns, such as summer streamflow, and ecosystem structure and function may be significant, but is likely to vary across the Western U.S. We used RHESSys, a spatially distributed, dynamic process model of water, carbon, and nitrogen fluxes, to examine the interplay between ecological and hydrological sensitivities to climate in four National Parks across the Western U.S., including watersheds in the North Cascades, WA (Stehekin watershed), Glacier, MT (McDonald watershed), Rocky Mountain, CO (Snake watershed), and Yosemite, CA (Upper Merced watershed) National Parks. We explored climate-driven patterns in net primary production, evapotranspiration, and streamflow. Analyses show while some systems are more hydrologically sensitive to climate variations, others are more ecologically sensitive. The greatest reduction of summer streamflow in response to warming currently occurs in the Upper Merced watershed, whereas the greatest sensitivities of vegetation responses in evapotranspiration and net primary productivity occur in the North Cascades National Park. The Snake and McDonald rivers were not as sensitive to climate changes compared to the other sites.

RHESSys



RHESSys is a GIS-based, hydro-ecological modeling framework designed to simulate carbon, water, and nutrient fluxes. By combining a set of physically-based process models and a methodology for partitioning and parameterizing the landscape, RHESSys is capable of modeling the spatial distribution and spatio-temporal interactions between different processes at the watershed scale.

Figure 1: Model description

RHESSys represents the temporal and spatial variability of ecosystem processes at a daily time step over multiple years by applying a set of physically based process models over spatially variable terrain.

http://fiesta.bren.ucsb.edu/~rhessys/index.html
Tague, C.L. and L.E. Band. 2004

VALIDATION

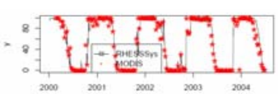


Figure 2: Upper Merced simulated snow versus MODIS data

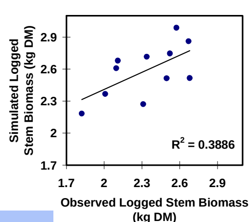


Figure 3: McDonald CLIMET data set compared to RHESSys output, methodology by White, 1988.

Table 1: Comparison of observed and simulated mean annual streamflow measurements for four sites, and Nash-Sutcliffe (NS) and NS for log transformed streamflow for 10 year calibration runs, conducted for each site.

	McDonald	Snake	Stehekin	Upper Merced
Mean annual streamflow, WY 1956-2003				
Observed (mm)	886	378	1547	699
Simulated (mm)	851	447	1774	634
Error %	4.0	-18.4	18.1	9.3
10 yr calibration runs (1970-1979, 1980-1989, 1980-1989, 1980-1989, respectively)				
NS	0.53	0.43	0.57	0.71
Logged NS	0.71	0.65	-0.19	0.72
Error in Mean Annual Str. (%)	-13.7	-4.4	-13.9	12.0

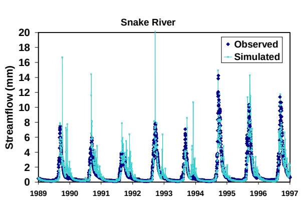


Figure 4: Simulate versus observe streamflow from the Snake watershed.

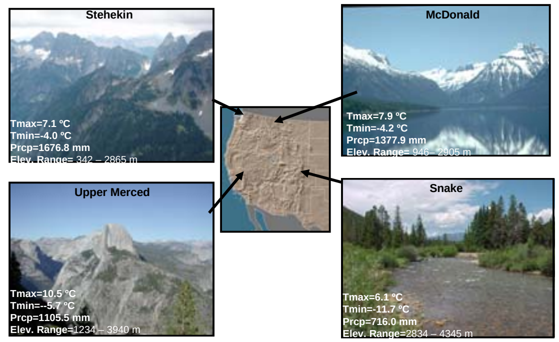


Figure 5: Location, elevation, and basin averaged climate data from 1954-2003 for 4 WMI sites

QUESTIONS ADDRESSED

Assumption: Model-based analysis of ecosystem responses to historic climate variability can offer insight into the sensitivity and vulnerability of snow dominated mountain systems to future climate change.

1) How do four snow dominated western mountain watersheds, the McDonald , Stehekin, Snake, and Upper Merced differ in terms of historic climate (minimum and maximum temperatures and precipitation), ecological (net primary production), and hydrological (evapotranspiration and streamflow) fluxes?

2) How do the sensitivities of hydrological and ecological fluxes to inter-annual climate variation differ across these four watersheds?

RESULTS

Evapotranspiration – Average by Day of Year

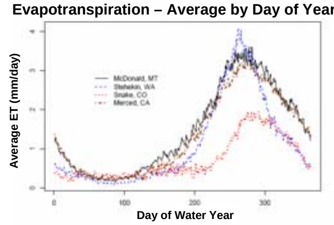


Figure 6. Mean watershed evapotranspiration by day of year (average over a 47 year simulation period from water year 1956-2003). Stehekin had highest peak in ET, but dropped off more rapidly, most likely due to water stress. The shorter growing season in the Snake leads to a smaller and delayed peak in ET.

Streamflow – Average by Day of Year

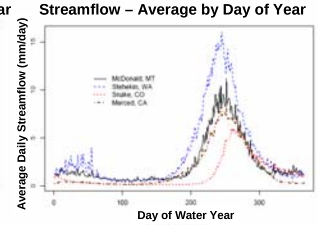


Figure 7. Mean watershed streamflow by day of year (average over a 47 year simulation period from water year 1956-2003). The timing and magnitude of peak streamflow varies substantially across sites. Sites with the highest peaks (Stehekin) also have the earliest timing of peak streamflow - reflecting gradients in both precipitation and temperature across these western mountain ecosystems Colder temperatures and higher elevations leads to later streamflow in the Snake.

Sensitivities to Climate

	Merced			McDonald			Stehekin			Snake		
	GS Mean Temp (ºC)	Annual Precip (mm)	Peak Snowdepth (mm	GS Mean Temp (ºC)	Annual Precip (mm)	Peak Snowdepth (mm	GS Mean Temp (ºC)	Annual Precip (mm)	Peak Snowdepth (mm	GS Mean Temp (ºC)	Annual Precip (mm)	Peak Snowdepth (mm
Spring Discharge	**↑**	**↓**	↓	↑	↓	↓	↑	↓	↓	↑	↓	↓
Summer Discharge	**↓**	**↑**	↑	↓	↑	↑	↓	↑	↑	↓	↑	↑
Transpiration	↑	0	0	0	0	0	↓	**↑**	↑	↑	0	0
Evapotranspiration	0	↑	↑	0	↑	↑	**↓**	**↑**	↑	0	0	0
NPP	0	↑	↑	0	↑	0	**↓**	**↑**	**↑**	**↑**	0	↓
Min 7-Day Avg Strm	↓	↑	↑	0	↑	**↑**	0	↑	0	0	0	0

Table 2. Four site comparison of 3 climate indices with 6 hydro-ecological variables. Upward arrow represents positive relationship, downward represents negative. Width of arrow represents relationship with the steepest slope on the regression line.

Streamflow Sensitivity to Temperature

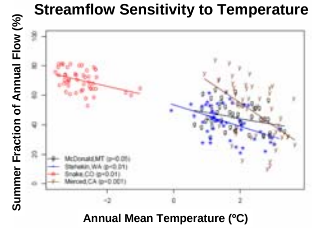


Figure 8. Fraction of Summer runoff versus annual mean temperature (ºC) from water years 1956 to 2003. Although runoff decreases significantly in response to temperature at all sites, the Upper Merced had the largest decrease.

NPP Sensitivity to Temperature

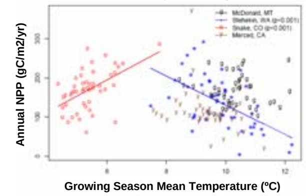


Figure 9. Annual NPP versus growing season mean temperature (ºC) from water years 1956 to 2003. Snake is a high cold environment, thus NPP increased with temperature. The significant decline of NPP with increase temperature in Stehekin resulted from decreases in water availability at higher temperatures, possibly due to earlier snowmelt and increased evaporation. NPP in McDonald and Merced was insensitive to temperature.

NPP Sensitivity to Precipitation

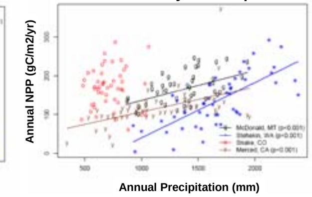


Figure 10. Annual NPP versus annual precipitation (mm) from water years 1956-2003. Stehekin NPP showed the strongest response to changes in precipitation. Snake was insensitive to precipitation at the watershed scale.

Evapotranspiration and Transpiration Sensitivity to Temperature

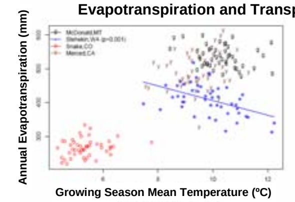


Figure 11. Annual ET versus growing season mean temperature (ºC) from water years 1956-2003. Stehekin's significant decrease in evapotranspiration with increasing temperatures demonstrates a strong biological response to climate variability. ET was not limited by temperature at other sites.

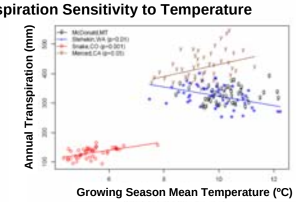


Figure 12.Annual transpiration versus growing season mean temperature (ºC) from water years 1956-2003. Transpiration increases with increasing growing season temperature at Snake and Upper Merced, but decreases at Stehekin. Snake's short growing season is lengthened by warmer temperatures. Transpiration was not responsive to temperature at McDonald, possibly due to sufficient water availability.

Evapotranspiration Sensitivity to Precipitation

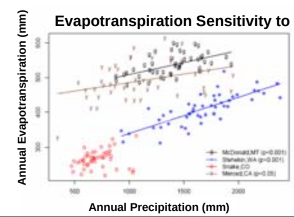


Figure 13. Annual ET versus annual precipitation (mm) from water years 1956-2003. While McDonald, Upper Merced, and Stehekin all significantly increase with increased precipitation, Stehekin shows the largest increase in ET per unit precipitation. Snake shows no significant response.

CONCLUSIONS

Many western US mountains share common eco-hydrological characteristics, yet their responses to climate vary widely. Shared characteristics include:

- Majority of precipitation is received in winter months,
- Stream hydrographs are snowmelt-driven, and
- Vegetation productivity is highly responsive to climatic controls

(Barnett et al. 2005, Beninston 2006, Prentice et al. 1992, Stephenson 1990).

Altitude, latitude, continental location, and topographic relief interact with climate to create textured landscapes that affect individual mountain range ecological responses to climate (Beninston 2003, Christensen et al. *In Press*). To understand how western mountain ecosystems vary in their sensitiveness to climate, it is important to examine site-specific responses. This work reports on the inter-annual heterogeneity of hydro-ecological responses to climate at 4 watersheds across the western US.

We found:

- streamflow was most sensitive to climate in the Upper Merced, implying hydrological sensitivities,
- Stehekin to be an ecologically sensitive watershed, where NPP, ET, and Trans were more sensitive to historic inter-annual variation in temperature and precipitation than other sites, and
- sites differed in terms of relative sensitivity of ecosystem fluxes (NPP and ET) to variation in temperature versus precipitation. Snake was highly sensitivity to temperature while McDonald, Upper Merced and Stehekin responded more strongly to precipitation variation.

Exploring these differences will help in our understanding of various climate change effects in mountain ecoregions, and also for adaptive management purposes. Future work on this project will use this research as a baseline to estimate how vulnerable these mountain ecosystems are to climate change.

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