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Research Article

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Leveraging Precipitation Modification around Large Reservoirs in Orographic Environments for Water Resources Management

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Abstract

This research explored the possible modification of precipitation around large reservoirs in the Cascade Range and Sierra Nevada Mountains in the Western US where orographic precipitation is dominant. After investigating the hypothesis that an additional and man-made source of moisture, such as an artificial reservoir and irrigated landscapes, can modify pre-dam state of orographic process on the windward side or the convective process on leeward side of the mountain, the result is interpreted in terms of better water resources management for future reservoirs. Mann-Kendall's trend analysis and Sen's slope estimator were applied for testing the hypothesis using historical hydrometeorological observations (precipitation, relative humidity- RH, and dew point temperature-DPTP). Four blocks of reservoirs (two from Cascade Range and two from Sierra Nevada) and six individual reservoirs were considered in this analysis. Comparison of post-dam period results for the selected reservoirs showed that atmospheric moisture content on the leeward side has a higher slope of increase than windward side. On the other hand, extreme precipitation (90th percentile and above) was found to have an increasing trend for both windward and leeward side during the post-dam era. A key conclusion of this site specific research article is that there is an indication reservoirs in drier location (leeward side) seem to increase precipitation more than those on the windward side. This means we can make use of this extra quantity of flow volume in post-dam period for a sustainable water resource management. Such approach can be part of climate change mitigation and resilient approach to extreme events. As large reservoirs are big parts of socioeconomic development specially in economically emerging countries around the globe, new approach into dam design and operation is important. This means identifying any impact of reservoirs and land use land cover change then leverage this impact as an advantage rather than otherwise.

Keywords: Orography; Artificial reservoirs; Precipitation; Humidity; Sierra Nevada; Cascade Range

Introduction

There is an open argument that the potential change associated with construction of a dam (hereafter used alternatively with 'reservoir') is considered to be adverse from the perspective of climate change. Recent studies have shown the impact of these reservoirs on climate and local storm distribution [1,2] though the scale and extent of their impact is not completely understood over a variety of geophysical settings and spatial scales [3,4]. As the scientific and engineering community is gearing towards climate change mitigation, it is worth considering resilience and sustainable plan that can address both extremes of flows for reservoirs. There are around 75,000 dams in the US alone with a height greater than 2m [5]. Based on the data available from Global Reservoir and Dam database (GRanD) [6], many of these dams are concentrated on large mountain ranges. The role geographical location and topography plays on local weather formation can be leveraged in the future for changes in extreme floods. As orography is a major factor in creating climate variation on leeward and windward side of a mountainous feature [7-10], it can be hypothesized that reservoirs in the leeward side are extra moisture source which can increase the convective process hence humidity and precipitation. On the other hand the windward side has abundance of moisture which the presence of a reservoir intensifies even more.

The conventional mindset in water resources development is to capture water where it is easily available (i.e. windward side) or provide supply where regions are drier (i.e., leeward side). The Central Valley of California is a good example where inter-basin water transfer is implemented between the Sacramento and San Joaquin river basins. Such practice can be implemented in areas where there is unbalanced water distribution, such as leeward areas.

In an era of increasing climate change awareness, the relationship between topography (orographic precipitation formation) and large reservoirs has not been studied in detail. The hypothesis that leeward reservoirs increase precipitation and humidity more than those on the windward side can be tested using the Mann-Kendall [11,12] trend analysis and Sen's slope estimator [13]. The West coast of the US (Sierra Nevada and Cascade Range) is an ideal area for such consideration as precipitation in the area is highly affected by orographic and convective processes during growing season (April-September). This area has very distinct topographical features ranging from coastal plains to mountains. The orographic control is terrain driven and stronger on the windward side. The convective control, which is driven more by differential surface heating, is less sensitive to terrain and stronger on the leeward side. Folsom and Oroville Dam of California are examples of windward dams that regulate surface water flows from the Sierra Nevada Mountain (Figure 1). Owyhee, Shasta, and Weber dams in Nevada are examples on the leeward side that are used for water supply, irrigation and hydropower generation. Majority of the dams are on the western side from the Cascade Range and Sierra Nevada Mountains. There is sparse distribution on the leeward side of these mountain ranges.

Studies on Folsom and Owyhee reservoirs have shown that the artificial reservoir considered on the leeward side of Cascade Range (i.e., Owhyee reservoir) has influenced extreme precipitation and flood more than Folsom reservoir, which is on the windward side of

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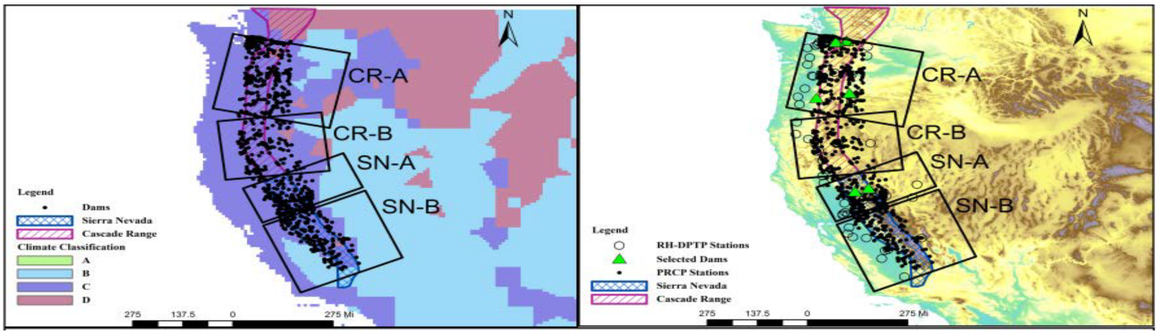

Figure 1: Dams near Sierra Nevada and Cascade Range.

Sierra Nevada [1,2]. Other studies [14-16] have shown the impact of LULC changes and other anthropogenic activities on hydrological and meteorological processes. Anthropogenic activities (e.g. LULC change and artificial reservoirs) make the land-atmosphere interaction even more complex by impacting meteorological and hydrological variables. Artificial reservoirs increase the evaporation from open surface and evapotranspiration from irrigated lands. At the same time land use land cover changes that are associated with these artificial reservoirs can affect the humidity, latent heat, albedo and other parameters which are important in the process of precipitation formation. Apparent increase in precipitation demonstrated in present studies can be part of a new planning and water resources management practice. The effect of geographical location and topography on local weather formation is well explored by [7,8,17,18]. However, no specific study has been done to investigate how artificial reservoirs interact with a topographic feature. This study is different from previous studies in such a way that a new dimension, geographical location of a reservoir, is investigated towards dam design and operation. The impact of anthropogenic activities is implicitly studied while topographical impact is explicitly explored.

As the potential interaction between large reservoirs and precipitation in orographic environments keeps improving owing to further studies, we can improve water resources management in a changing climate and increasing pressures from urbanization and population growth. Understanding the anticipated meteorological and hydrological impacts that dam construction have on the windward and leeward sides of a mountain can help the engineering community better plan and operate reservoirs.

Data and Methodology

Four blocks of reservoirs were selected over the Cascade Range (CR) and Sierra Nevada (SN) Mountains (two from CR and two from SN; Figure 1). The block represented a 'cluster' of GRanD dams within a selected mountain range. The basis for the selection of these blocks is the Köppen climate classification and annual average precipitation. Since the data used for analysis is ground and point-based data, selecting a single station meant that it can potentially represent different neighboring reservoirs rather than a unique one in the area. Therefore, it was more reasonable to select 'blocks' of reservoirs on the basis of other criteria like climate classification rather than analyze an individual reservoir or individual point ground station. Our approach also helped in handling the difference in construction year of individual reservoirs. According to the National Inventory of Dams (http://geo.usace.army.mil/nid/) most of the dams in the US were constructed after 1950. Therefore, it is logical to compare trends of average quantiles starting from 1950 for both windward and leeward sides. In addition to the block of reservoirs, individual reservoir pairs were selected on both sides of the mountain to support the final result. From Cascade Range, Howard A. Hanson and Keechelus dams and Green Peter and Pelton dams were chosen as pairs. In Sierra Nevada, Little Grass and Grizzly Valley dam were selected. The pairs are shown as a windward-leeward pattern in Figure 1.

Data on precipitation was taken from the Global Historical Climatology Network Data (GHCND) that is archived by NOAA's National Climatic Data Center (NCDC). The number of stations used for averaging over a selected block ranged from a minimum of 3 to a maximum of 30 precipitation measuring stations. Relative Humidity (RH) and average Dew Point Temperature data (DPTP) were available from NCDC through the International Research Institute for climate and society (IRI) of Colombia University. While RH provides information on the moisture saturation level, dew point temperature show the absolute measure of moisture availability in the atmosphere that may be potentially originating from the artificial reservoirs. These point data are supplemented by satellite data, PERSIANN-CCS (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System, [19]) with high spatial resolution of 0.04 degrees (~ 4 km). The analysis period was the growing season (April-September) to account for the convective processes on either side of the mountains. A 30 year moving window was used to derive the precipitation quantiles associated exceedance probabilities such as 10% (P90), 5% (P95), and 1% (P99) for the growing season period. This is consistent with the recommendation by the World Meteorological Organization (WMO) to study climate change using 30 or more years' of data. A rainfall threshold of 1 mm/day was used to define a day with rain. Data was analyzed for both pre and post-dam periods to identify any potential shift in the precipitation patterns after dam construction on the windward and leeward side of the mountain.

Results and Discussion

The Mann-Kendall trend test (at 95% significance level) for temperature, dew point temperature, and relative humidity show trends on both windward and leeward sides as presented in Figure 2. Most of the trends were observed on the windward side for Dew Point Temperature (DPTP), Temperature (TP), and minimum Relative Humidity (RH); while on the leeward side the more trends are observed for maximum relative humidity. It can also be seen that most of the trends are in upward direction (increasing trend) for all the meteorological parameters considered. The trend and Sen's slope of the two sets (CR-A Windward/Leeward; CR-B Windward/Leeward; SN-A Windward/Leeward; SN-B Windward/Leeward) of percentiles were analyzed for each block of reservoirs and individual pairs as

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shown in Figure 3. Higher percentiles (>P90) are the subsequent focus for detection of changes in precipitation patterns since less impact is observed on the mean (P50) than the extremes.

Since the percentiles were computed over a 30 years moving window, comparison of Sen's slope estimate provided an insight on the temporal rate of change in extreme precipitation occurrence. The slope estimates for the percentile time series for the block of reservoirs selected revealed non-conclusive over a large spatial domain, but indicative trend on the increase in precipitation observed on either side of the mountains considered. However, for two blocks considered (CR-B and SN-A) the argument that artificial reservoir can marginally impact extreme precipitation more on leeward side seemed to be supported. Since the period pertained to the growing season is considered, the contribution of local convective systems is inherently more for precipitation than

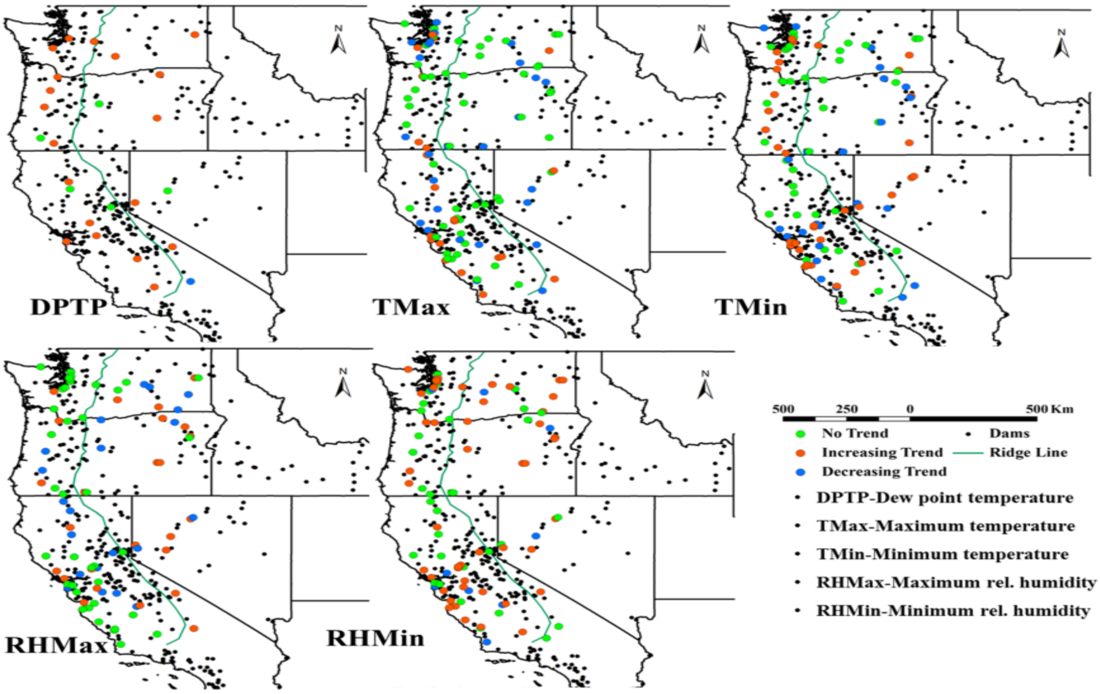
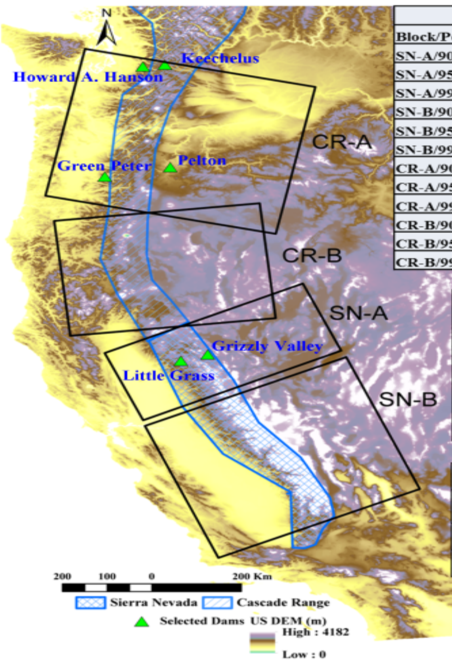


Figure 2: Meteorological trend along the western US.



Precipitation

	Windward		Leeward	
Block/Percentile	Significance	Slope estimate	Significance	Slope estimate
SN-A/90	***	-0.11	+	-0.02
SN-A/95	***	-0.11	+	0.05
SN-A/99	NS	-0.07	**	0.10
SN-B/90	NS	0.01	**	-0.06
SN-B/95	**	0.07	**	-0.07
SN-B/99	***	0.17	**	-0.27
CR-A/90	***	0.06	**	0.02
CR-A/95	***	0.10	**	0.02
CR-A/99	***	0.17	NS	0.01
CR-B/90	NS	-0.04	NS	0.01
CR-B/95	NS	-0.09	NS	0.01
CR-B/99	NS	-0.17	NS	0.02

Rel. Humidity

	Windward		Leeward		Remark
Block	Significance	Slope estimate	Significance	Slope estimate	
SN-A	NS	-0.07	NS	-0.64	RH Max
SN-B	NS	0.25	***	1.43	
CR-A	+	0.16	NS	0.27	
SN-A	+	0.95	NS	0.23	RH Min
SN-B	*	0.33	NS	-0.66	
CR-A	NS	0.14	NS	0.07	

Dew Point Temp.

	Windward		Leeward	
Block	Significance	Slope estimate	Significance	Slope estimate
SN-B	*	0.13	+	0.23
CR-A	**	0.25	**	0.27

NS: Not significant
+: 90%
*: 95%
**: 99%
***: 99.90%

Figure 3: Post dam trends and their significance for selected blocks.

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synoptic (large scale weather) processes in the region that occur mostly during winter. The blocks of reservoirs that show relative increase in extreme precipitation on the leeward side are interesting in a way that they have similar elevation and located in mid-latitudes as compared to the other block with high/low latitudes where the leeward side observed no apparent increase in extreme precipitation.

As it can be seen on Figure 3, there is an increase in relative humidity (both maximum and minimum) except in some area of the Sierra Nevada. It is also evident that there is relatively steeper change in minimum relative humidity than the maximum RH. An increase in dew point temperature was observed on both windward and leeward sides. However, there was a relatively higher increase slope on the leeward side. The increasing trend in dew point temperature and relative humidity can be related to the presence of artificial reservoirs in the region that could be supplying extra moisture for the local and regional land-atmosphere interaction process. The spatial distribution of satellite-based PERSIANN-CCS precipitation data shown in Figure 4 shows the yearly average value for the month of July in each year. Local features are represented well as the specific period is characterized by lesser impact from large scale fronts both from the Pacific and Rocky mountains. The figure shows that more precipitation is generally observed on the leeward side than the windward side for the area considered in this study during the growing season. This is a good indication of the involvement of reservoirs in the convective system.

The percentiles for individual pairs of reservoirs are shown in Tables 1 and 2 for selected dams on windward and leeward side. There was a marginal increase in precipitation percentile for some of the dams selected. Slope comparisons of percentiles for pairs of reservoirs show that there is a relatively higher slope in the post-dam periods for the leeward dams than the windward dams. Pertaining to the significance of the trend statistics, potentially presence of a reservoir on the leeward side has increased the RH and DPT. Leeward side of a mountain in orographic environments is significantly drier than the windward side. Thus the 'background' (pre-dam) level of humidity is sufficiently low in magnitude and variability on the leeward side for the additional moisture contribution by dams (lake and land use land cover change) to be detected clearly from observations. It should be noted though that the deciphering of the stand-alone effect of the reservoir seems

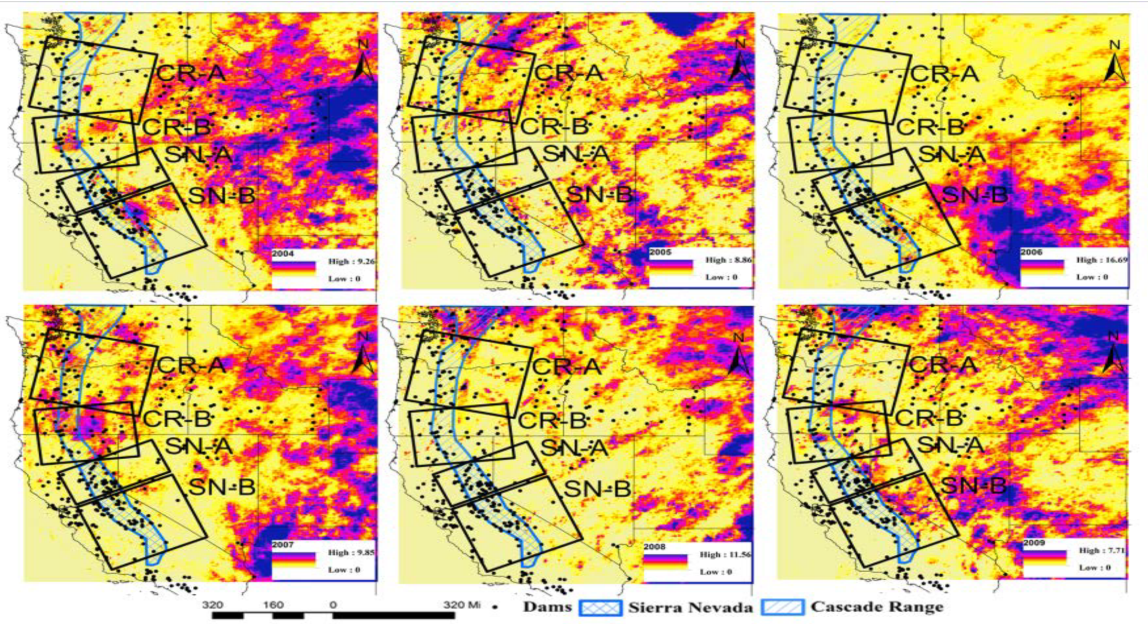

Figure 4: Monthly average precipitation (mm/day) product from PERSIANN-CCS for the month of July (2004-2009).

Precipitation					
Windward			Leeward		
Dam/Percentile	Significance[1]	Slope estimate	Dam/Percentile	Significance[1]	Slope estimate
Howard A. Hanson/90	***	0.05	Keechelus/90	NS	0.00
Howard A. Hanson/95	***	0.02	Keechelus/95	**	0.05
Howard A. Hanson/99	**	-0.13	Keechelus/99	**	-0.09
Green Peter/90	**	-0.03	Pelton/90	**	0.01
Green Peter/95	NS	0.00	Pelton/95	**	0.00
Green Peter/99	NS	-0.02	Pelton/99	**	0.06
Little Grass/90	NS	0.03	Grizzly Valley/90	***	0.04
Little Grass/95	**	0.28	Grizzly Valley/95	***	0.22
Little Grass/99	**	0.07	Grizzly Valley/99	NS	-0.06

[1]NS=Not Significant, *=95%, **=99%, ***=99.90%.

Table 1: Precipitation trend analysis and slope estimate (and their significance level) for stations near selected dams.

Relative Humidity						
Windward			Leeward			
Dam	**Significance[1]**	**Slope estimate**	**Dam**	**Significance[1]**	**Slope estimate**	**Remark**
Howard A. Hanson	*	0.47	Keechelus	NS	0.17	RH Max
Green Peter	NS	-0.05	Pelton	NS	-0.74	
Little Grass	NS	0.02	Grizzly Valley	NS	0.20	
Howard A. Hanson	+	0.36	Keechelus	**	1.24	RH Min
Green Peter	NS	0.22	Pelton	NS	-0.32	
Little Grass	NS	0.96	Grizzly Valley	+	0.37	
Dew Point Temperature (DPTP)						
Windward			**Leeward**			
Dam	**Significance**	**Slope estimate**	**Dam**	**Significance**	**Slope estimate**	
Howard A. Hanson	*	0.22	Keechelus	NS	0.17	
Green Peter	*	0.18	Pelton	NS	-0.04	
Little Grass	NS	-0.13	Grizzly Valley	NS	0.11	

[1]NS=Not Significant, +=90%, *=95%, **=99%.

Table 2: Trend analysis and slope estimate (with significance level) of relative humidity and dew point temperature for stations near selected dams.

fundamentally impossible using station data alone. An increase in the dew point temperature was observed for dams on both sides of the mountain range. However, as the precipitation process on the leeward side is mostly due to a result of the convective process (as opposed to orographic on the windward side), the results presented for the dew point temperature show that the presence of reservoirs on the leeward side seem to alter the moisture availability more than on the windward side.

Conclusion

The two studies that focused on Folsom dam (windward side) and Owhyee dam (leeward side) found an increase of 4% and 8% in the 72 hour probable maximum precipitation (PMP), respectively. The conclusion of this study based on preliminary understanding of topographic influence on reservoirs' impact on local climate is that we can have a better management of flood flows during extreme storm events if we can quantify the increase. Any flood event has its own adverse effect on downstream areas, and the operation of reservoirs during such events is crucial. However, instead of releasing flood flows it may be argued that we can store and use the extra flood volume for future use in the relatively drier area, leeward side. Large reservoirs on drier locations that are being built and under design can benefit from the idea that future increase in extreme events can be alleviated if proactive solutions are presented in the design and operation phases. As the topographic formation dictates weather formation and climate classification on a larger scale, it will be important to analyze the role of specific reservoirs and their impact by implementing physically-based atmospheric models. These models can be setup on multiple reservoirs or individual pair of reservoirs (as was the case in this study) to study the anticipated impacts from these mountain ranges.

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