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Evaluating the Impact of Rising Temperature on Water Demand in the Klamath River Basin, a Watershed in Western United States

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Abstract
This study investigates the impact of climate change on water availability within the Klamath River Basin, a significant watershed in the western United States. Critical factors including precipitation, snowpack, and potential evapotranspiration (PET) was explored to understand how climate change dynamics may exacerbate water scarcity, and stakeholder conflicts in the region. The study uses 40 years of historical climate data of these sites (Big Red Mountain and Silver Lake), findings indicate a slight but statistically inconclusive decrease in both precipitation and snowpack, despite a significant positive correlation between temperature and PET. Observations from the study highlight the vulnerabilities of the Klamath River Basin's water resources, especially with warmer temperatures that may shift precipitation patterns from snow to increased rainfall, creating concerns for seasonal water storage and availability within the region. The impact of these shifts poses significant risks to agricultural, environmental, and cultural water needs, with implications for regional water management and climate adaptation strategies. The study emphasizes the urgent need for collaborative, data-informed approaches to equitable water allocation amidst growing climate pressures.

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Introduction

The demand for water as an essential resource cannot be over-emphasized because of the role in sustaining the existence of various expressions of life forms. Vegetation, biodiversity depend on green water for sustenance. Recreational processes, domestic and industrial usage depends on blue water for sustenance, thus there seems to be a synergistic relationship between both classifications of water based on utility. With a focus on the western United States, water has been a major resource of opportunities and challenges to the nation, and has been integral for the development of the western United states especially in agriculture thereby motivating human settlements. However there have been prevalent challenges with water availability due to various climate impacts such as droughts, water contamination. As a result, competition between water users often escalates to persistent conflicts within affected regions (Dettinger *et al*. 2015) [3]. The prevalent water crisis is a common situation to major rivers in the western United States and the Klamath river basin is not exempted from this crisis. This region has been faced with issues on water scarcity, allocation and management which has escalated to becoming local and national issues thus leading to the continuous intervention from the government. The Klamath River is divided into the Lower and Upper Basins, and is estimated to cover about 12,100 square miles. The Upper Basin has limited water resources and its water management majorly revolves around Reclamation projects dated as far back as 1900's (CRS report, 2005). The Reclamation project provides water for irrigation purposes for farmers in the Upper Basin for continued farming as well as pastoral farming for cattle rearing.

A return flow from the upper basin serves as water sources for the Lower Klamath National Wildlife Refuge which contains wetlands that serve as layovers to accommodate migratory birds identified as threatened species under the ESA (Dettinger *et al*., 2015) [3]

The Upper basin is the habitat for two endangered species of fishes - Suckers and Salmons who are of cultural and ceremonial values to the Klamath tribes (Mucioki *et al*., 2022) [9]. In the past, the Klamath river was one of the largest habitats for the Salmon species , but there has been drastic climate change with negative impacts on the quality of the river especially during drought (Dettinger *et al*. 2015) [3]. In 2001, the Bureau of Reclamation prioritized providing water to protect the endangered species of fish at the expense of providing water for farming activities due to the severe drought, thus impacting irrigation and farming activities which further aggravated the existing conflicts between the farmers and the Klamath tribes (Inside climate news, 2021; Klamath summary report, 2016) [6]. It is evident that the limited supply of water in the Klamath river basin is responsible for the conflict in that region. The decision of the federal government in May 2021 to reduce water supplies for irrigation to 180,000 acres for agricultural purposes exacerbated the existing conflict within affected stakeholders. This aggravation is justified due the inherent nature of humans to ensure they succeed in their various fields, farmers always want to be in business all year round for food availability and income generation, the Klamath tribe had a justifiable reason to protect their cultural heritage related to the endangered species influencing their decision to enforce their water rights thereby leaving the farmers with lesser rights to water as a resource in a critical drought season (Ji *et al*., 2021; Mucioki *et al*., 2022) [7, 9]. The operational priorities of the Bureau of Reclamation in the Klamath River has a top-down arrangement where ESA compliance to protect endangered species is topmost priority, provision of water to the Klamath tribes and irrigators is the next and the rest of the water is for the National Wildlife Reserve in the Lower Klamath, subject to the fulfillment of the contractual obligations of the first two sets of priorities.

However, it is safe to deduce that the water shortage will worsen due to climate change and its negative impact on the environment. With this current decline in water supply, there is a need to evaluate climate change impacts on the availability of water as a resource in the nearest future, to equip the stakeholders with relevant information on mitigation, adaptation measures (Adger *et al*., 2005) [10] and as a presentation of facts on the need for enhanced collaboration to solve the one problem about water scarcity. There is a need to amicably address existing climate influenced problems such as drought, increased temperature in the river, water quality, endangered species of fish amongst other complex problems while focusing on efficient planning and implementation of strategies to prepare for anticipated changes (Dettinger *et al*., 2015) [3]. Therefore, with increased temperature, precipitation as snow in the winter season will decrease and this will also lead to a decline in the amount of stream flow in the summer months.

The aim of this study is to evaluate existing relevant historical climate data associated with the Klamath river watershed to explore the impact of climate change on trends in water resources by evaluating two critical components; firstly by evaluating the trend in annual precipitation and snow pack in the Klamath region, and secondly, by estimating the relationship between daily air temperature and potential evapotranspiration (PET). The outcome of this study will provide insights to evaluating water availability in the nearest future and plan for water conservation strategies to ensure continuity of water as a resource in the Klamath region.

Methods

Trend analysis of Precipitation and Snowpack

The data source for the assessment of precipitation and snowpack was from the United States Geological Service (NRCS, 2023) [14] for the Big Red Mountain Snow Telemetry (SNOTEL) site 341, in the upper Klamath Basin. The Big Red Mountain is situated in Oregon and it is estimated at 6050 feet above sea level. The dataset comprises the records of "water year" and snow water equivalent (SWE) for the years spanning from 1980 to 2020. "Water Year" is defined as the total water accumulated over a period of twelve months starting from October 1st and ending September 30th. The year given in the analysis is the year the "water year" ended. SWE refers to the depth of the snowpack during spring on April 1st of each year measured in inches. This extended period was chosen to ascertain a comprehensive evaluation of long-term water resource trends in the upper Klamath Basin. The data was reviewed to check for missing values before uploading to Google sheets for analysis. To visually represent annual precipitation, the Water Year was plotted on the x-axis, and the respective precipitation accumulation at the start of the water year was plotted on the y-axis. Similarly, to visually represent the time series of SWE, year is plotted on the x-axis and SWE on the Y axis. Bar graphs were used for both variables for data visualization. Time series was plotted to identify the linear equation to determine the slope and intercept of the trend in the data. The time series will provide information to our research question to ascertain if annual precipitation and snow water equivalent changes with time due to climate change in the Klamath region.

Estimation of Potential Evapotranspiration

The data used for the estimation of daily evapotranspiration comes from a particular site at the north end of the Upper Klamath Basin called Silver Lake. University of Oregon has a website that manages solar radiation and temperature data for certain sites in Oregon, Silver Lake inclusive (UO, 2022). Data for six months starting from May 2021 to October 2021 was collected because summer 2021 was very hot in the region and therefore this time period contains a wide range of temperatures for the purpose of understanding the impact of temperature on evapotranspiration. The solar radiation data was provided as the daily total energy with units in kilowatt hours per meter squared, and the temperature data was given as a daily mean in units of degrees celsius. PET was estimated using the Priestley-Taylor equation as formulated in Rao *et al*. (2011) [11]. Certain modifications were made to the equation for the purpose of this study. Ponderosa Pine is a dominant forest species in the Klamath Mountains (Fry and Stephens, 2006) [5], hence, must be considered when evaluating PET in this region. The correction factor denoted as α used in this study is 0.87 to reflect the species associated with Klamath Basin which is Ponderosa Pine (water limited, daytime), the value was taken from Table 3 in Rao *et al*. (2011) [11] paper. In addition, the elevation level value was adjusted to reflect the true elevation at Silver Lake which is 1,324 meters above sea level. All other values in the equation remained intact. The Priestley-Taylor equation is presented below:

$$\lambda PET = \alpha \frac{\Delta}{\Delta + \gamma} R_n \quad (1)$$

$$\lambda = 2.501 - 0.002361\,T \quad (2)$$

$$\Delta = 0.200\,(0.00738\,T + 0.8072)7 - 0.000116 \quad (3)$$

$$\gamma = \frac{c_p\,p}{0.622\lambda} \quad (4)$$

Where
PET = potential evapotranspiration (mm)
λ = latent heat of vaporization $(MJ\ kg^{-1})$
T = daily mean air temperature (C) α = correction factor = 0.87
Δ = slope of the saturation vapor pressure versus temperature curve $(kPa\ C^{-1})$
γ = psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance (kPa^{-1})
cp = specific heat of moist air at constant pressure $(1.013\ kJ^{-1}\ C^{-1})$
p = atmospheric pressure (k Pa) EL = elevation (m)
Rn = net radiation $(MJ\ m^{-2}\ d^{-1})$

For the purpose of this study, total solar total radiation was converted to net radiation using the equation below. This equation was also adapted from Rao *et al*. (2011) [11].

$$R_n = 0.84 R_s \times 4.1868 \times 10^{-2} \quad (5)$$

where
R_n = daily total net radiation $(MJ\ m^{-2}\ d^{-1})$
R_s = daily total solar radiation (in Langleys; $1\ Ly = 41{,}840\ Jm^{-2}$)

The six months data equivalent to a total of 181 data points of solar radiation and temperature was uploaded to Google Sheets software for analysis. The temperature data column was sorted from the lowest to highest and plotted on a scatter plot with temperature on the x-axis and PET on the y-axis to illustrate the relationship between PET and temperature. The equation of the line as y= mx+b was calculated, with the units of the slope being the millimeter increment in evapotranspiration per day per degree C change in temperature.

Results

Trends in Water Year Precipitation

The trend analysis of precipitation in the Big Red Mountain is presented in Figures 1 below. From the study, the time series shows no significant change was identified for annual precipitation accumulation in the water year even with increasing temperature in the region.
The equation of the trend line suggests that, on average, precipitation decreases at a rate of 0.193 inches per water year as shown in Fig 1. The confidence interval for the slope was (-0.6023, 0.2153), which suggests that the trend may not be statistically significant because the interval includes zero. The trend analysis indicates a decrease in precipitation at Big Red Mountain, although the statistical significance is inconclusive.
However, it is not surprising that there is no significant change in precipitation despite the temperature rise in this region over this 40 year period. Projections explain that precipitation will grow wetter in the north and dry in the south (Dettinger *et al*. 2015) [3]. Consequently, the Klamath basin is located between the north and south region, the strategic location is a factor for the almost no change in precipitation.

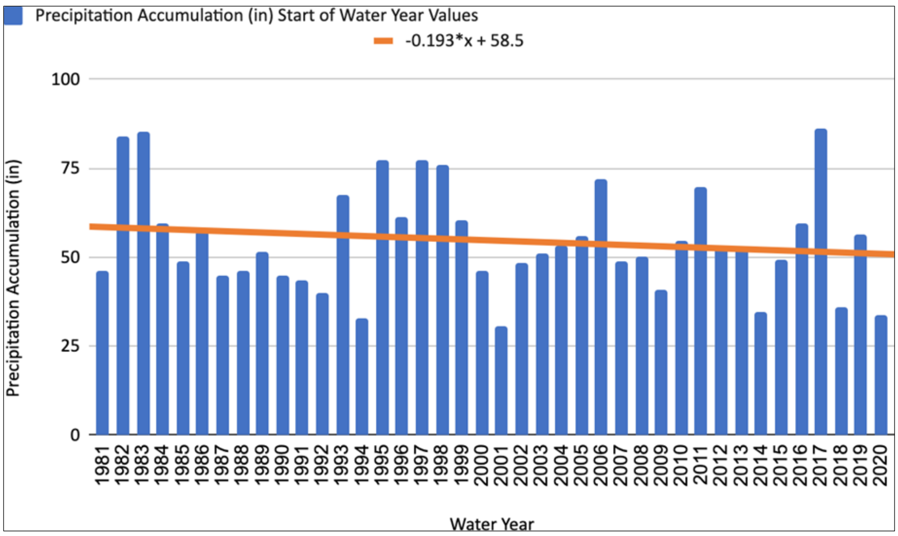

Fig 1: Trend analysis of precipitation accumulation in (inches), calculated with water year. Data from 1980 to 2020 from a site in the Upper Klamath River Basin called "Big Red Mountain'. Source: NRCS (2023) [14].

Trends in Snow Water Equivalent

The trend analysis of SWE in the Big Red Mountain is presented in Figure 2 below. From the results, it is surprising that there is no significant decrease in snowpack over the 40 year period in response to climate change. Generally, we expect a decrease in snowpack in April due to increased temperatures which would have reduced precipitation falling as snow in the winter seasons.

The equation of the trend line suggests that, on average, precipitation decreases at a rate of 0.2 inches per year as shown in Fig 2. The confidence interval for the slope was (-0.514, 0.077), which suggests that the trend may not be statistically significant because the interval includes zero. The trend analysis indicates a decrease in SWE per water year at Big Red Mountain, although the statistical significance is inconclusive.

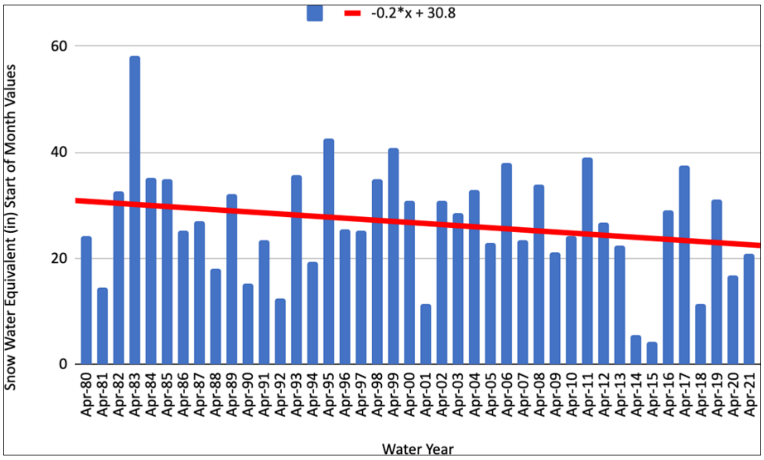

Fig 2: Trend analysis of SWE in (inches), calculated with water year. Data from 1980 to 2020 from a site in the Upper Klamath River Basin called "Big Red Mountain'. Source: NRCS (2023) [14].

Temperature and Potential Evapotranspiration

In study of the PET at Silver Lake, the aim is to find the increase in PET for every increase in mean daily temperature due to climate change impact. As shown in Fig 3, a positive slope coefficient of 0.179 indicates that for each unit increase in mean daily temperature at Silver Lake, PET tends to increase by approximately 0.179 millimeters.

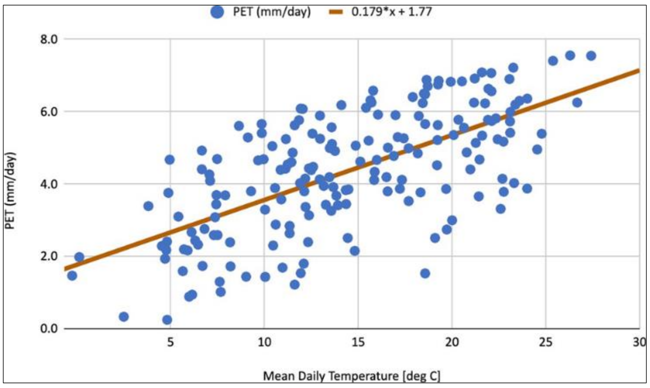

Fig 3: PET in mm/day calculated with the mean daily temperature in degree celsius, calculated using Priestley-Taylor equation. Data between May 2021 - Oct 2021 from "Silver Lake", a site in the Upper Klamath River Basin. Source: UO (2022).

Discussion and conclusion

The Upper Basin is classified as an arid region with precipitation about 70% lesser than the lower basin. In the study, as expressed in Fig 1 and 2. The trend analysis of precipitation and snowpack in the Upper Klamath is not statistically significant, indicating that the observed trend could have been as a result of other factors associated with the Klamath region.

According to (USGS, 2013), 54% of the total annual precipitation in the Klamath Basin falls as snow during the winter season usually between November and February while 15% falls during summer months. The remaining 31% of the precipitation falls as rain during the transition months of October and March through May (USGS, 2013). It is however important to note that historical precipitation in the basin has consistently fluctuated from year to year with a gradual increase in this century, showing that the balance of rainfall and snowfall in the upper Klamath is expected to shift toward more rain in the future, which could have implications for water storage and availability in the basin (Dettinger *et al.* 2015; Klamath Summary report, 2016). Based on the projections that precipitation will grow wetter in the north and dry in the south (Dettinger *et al.* 2015) [3], it is not surprising that there is no significant decrease in precipitation despite the increase in temperature in this region. Consequently, the Klamath basin is located between the north and south region, the strategic location is a factor responsible for precipitation.

Snowpack in the Klamath basin is critical due to limited storage capacity of the existing reservoirs which do not have the capacity to store the snowpack volume if it were to come as rain (Klamath Summary report, 2016). This indicates a potential risk in the Klamath with the increased precipitation through rainfall instead of snowpack. From our analysis, it is surprising that there is no significant change in the amount of SWE over time in the region. Prior to this study, we hypothesized a significant decrease in SWE due to climate change impact, specifically in April due to increased temperatures which would have reduced the amount of snowpack in the winter seasons (Mucioki *et al*., 2022) [9]. In the near future, we anticipate a significant decrease in SWE in this region with rising temperatures although we are yet to observe the decrease in SWE as at the time of this study. A decrease is unavoidable in the near future given that temperature rises in this region.

In Fig 3, the positive correlation between PET and mean daily temperature clearly indicates that, PET tends to increase by approximately 0.179 millimeters for each degree C rise in temperature. Clearly, the extreme temperature in June 2021 indicates extreme temperatures are expected to further exacerbate the impacts of climate change on the water balance in the Klamath basin (Ji *et al*., 2021) [7]. The PET increases with each temperature rise means increased evapotranspiration. Report from the Reclamation project estimates that temperature in Klamath River is projected to increase by 5 degrees C in 2070 (Klamath Summary report, 2016). Relating this with the calculated slope from our analysis, we can estimate that average PET is projected to rise by 0.895 degrees C mm/day . This will lead to an unusual change in the timing, storage and availability of water, leading to significant impacts on every sector that depends on the limited water resources in the basin for sustenance especially for fish, wildlife, and the farmers in the upper basin who rely on water for irrigation activities (Dettinger *et al*., 2015; Ji *et al*., 2021) [3, 7]. As a result, a positive reinforcement of the increase in the demand for water for irrigation with temperature rise in the Upper Klamath leading to increase social, economic and environmental impacts, the scarcity will exacerbate the existing conflicts between the stakeholders which could transmute into forms of environmental injustice if the situation is not managed effectively.

Water resource allocation in the Klamath Basin is important to the diverse indigenous groups essential for their daily activities in the region, as well as the sustainability of existing ecosystems associated with the Klamath basin. Being an arid region, competition for the limited water supply is intense, and the knowledge of water losses to evapotranspiration (ET) is key information for deciding optimal water-use strategies (USGS, 2013). The impact of climate change on the water balance in the Upper Klamath basin is complicated which requires meticulous planning and effective implementation of both adaptation and mitigation strategies in response to climate change (Adger *et al*., 2005; Chaffin *et al*., 2016). Although several policy solutions such as the water-buyback program have been implemented as an economic tool for agricultural and ecological preservation in the basin (Elbakidze *et al*., 2017). It is very important to note that the existing competition for water resources between the stakeholders requires efficient coordination for equitable distribution of the scarce resources. In addition, inclusive collaboration between the stakeholders network is critical at this time to pool efforts together in order to combat the challenge faced in the Klamath region.

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