Quantifying Flood Risk for Pine Flat Reservoir in the Upper Kings Canyon Watershed

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ABSTRACT

Significant increases in annual maximum precipitation intensity are projected across California. Global climate models show reductions in the Sierra Nevada's annual snowpack, and an increasing incidence of atmospheric river storms. The hydrological future painted by these projections is one where California reservoirs receive more water from huge storms earlier in the season, and less water from snowpack later on. These projected higher inflow rates are correlated with higher flood risk. The worst case scenario is "catastrophic-overtopping" where spillways cannot accommodate the reservoir's outflow, and the dam begins to spill from areas it was not designed to. In this study I analyze the hydrology of the Upper Kings Canyon watershed, to determine the likelihood of catastrophic overtopping of the Pine Flat Dam between the present day and year 2100. I aggregated historical reservoir volumes for each month of the year, to determine three probable starting reservoir levels for each month, and for each probable starting level a minimum inflow rate for a storm to cause overtopping. Working backwards I calculated precipitation volumes correlating to said overtop-causing inflow rates. Comparing existing Cal-Adapt precipitation projections against historical values with a Gumbel distribution, I determined the probabilities of precipitation exceeding the overflow causing values. Final calculations showed that overtopping is less than 0.01% likely for any given month, except for April and June conditions where reservoir capacities are 2 standard deviations above the mean, where probabilities of overflow are 99% and 86.8-96.2% respectively.

KEYWORDS

Atmospheric River, Climate Change, California Flood, Kings River, Extreme Precipitation

INTRODUCTION

Global mean surface temperature (GMST) has been rising for decades, resulting from increases in atmospheric levels of anthropogenic greenhouse gasses (GHG's), mainly CO_2 and CH_4 (Tett et al. 1999). Average global temperatures in 2005 sat 0.6° C higher than the 20th century average (WMO 2005), making 2005 the 2nd hottest year on record at the time. Now in 2023, 2005 does not even register as one of the top 10 hottest years, and 2023 is developing to be the hottest year on record globally. The most optimistic policy projections of the Intergovernmental Panel on Climate Change (IPCC), where net zero CO_2 emissions are achieved by 2050, estimate GMST to rise anywhere between 1.1-2.9° C above 1980-1999 averages by the year 2100 (IPCC 2007). Worst case scenarios estimate a rise in GMST of 2.4-6.4° C. Because predicting future climate is impossible, these IPCC climate scenarios are defined as likely outcomes given broad ranges of potential global policy choices. Climate scenarios vary between situations where world population peaks at 2050, and fossil fuels are phased out, to situations where world population grows until 2100 and fossil fuels remain in intense use. Altogether, the IPCC AR4 describes 6 realistic policy scenarios leading to 6 unique climate outcomes, all of which result in a higher future GMST compared to pre-industrial GMST. Regardless of exactly how much hotter the future of Earth will be, a warmer atmosphere is already causing the destabilization of the global hydrological cycle, leading to droughts and floods affecting regions that previously never prepared for such events (Hagemann et al. 2013).

California is a special case in the evolving global hydrological cycle, as the mean yearly precipitation for the region is projected to stay relatively constant for every emissions scenario modeled by the IPCC. So regardless of global increases in CO_2 and mean surface temperature, the mean annual precipitation across the state of California will not change. However, extreme precipitation events, meaning torrential storms and prolonged droughts will become more common (Dettinger 2011) with warming weather. So maintaining the same mean yearly precipitation, while having a higher proportion of extreme precipitation events, means both droughts and storms will become increasingly common. Both of these phenomena are detrimental to human activity, as drought just in the 2014-2015 growing season alone was responsible for 1.7 billion dollars of agricultural damages within California (Lund et al. 2018). Flooding on the other hand, has historically contributed to greater explicit financial damages- 4.8

billion dollars just for the 2023 water year (Smith 2020)-- in addition to countless intangible damages such as lost income due to road closures, reduced access to services, and mortality in the worst cases (Allaire 2018).

Warm weather when combined with storms in California tends to create an atmospheric river (AR) effect, where moisture in a storm system dumps rapidly. Historically, California weather follows the Mediterranean regime with a wet winter/spring rainy season, so cold storms with light rain have been the norm. Now, warm winter storms are becoming more common, which creates flood risk due to the rapid dumping of water. Last century's 100-year storm will now become today's 20-year storm, assuming business-as-usual GHG emissions (Mallakpour et al. 2019). Additionally, these warm storms have a higher snowline which is especially problematic in the Sierra Nevada mountains of California. Areas of the Sierra below 2500 meters in elevation are most prone to this reduction in snowfall (Cayan et al.. 2008). Sierra foothills below 1000 meters in elevation will no longer receive snowfall by 2070 assuming business-as-usual GHG emissions continue globally. So watersheds below 2500 meters elevation in the Sierra foothills, are going to start receiving doubly increased runoff from warm storms contributing to torrential conditions, but also due to less precipitation falling as snow.

Both the biggest, and the lowest elevation (<2500m) watersheds in the Sierra are located on the Western side of the mountain range. These west-facing watersheds feed more than a dozen of the largest reservoirs in California, and all of the major Western Sierra reservoirs are below 1000 meters elevation. One such example is the Pine Flat Reservoir, which impounds the largest river by flow, the Kings River. The Pine Flat Reservoir is not critically important as a water resource, like similarly large waterworks, but it does serve the crucial role of controlling floods downstream in the Tulare Basin, home to over 100,000 people. Increased runoff due to more precipitation yet less snowfall, has the potential to inundate reservoirs, 82% of which are more than 63 years old (Hossain et al.. 2009), and therefore were built to withstand hydrological regimes of a bygone era. They were built to store predictable amounts of spring and summer snowmelt runoff, in addition to some early season rains in the fall and winter. If future hydrological predictions for the region are correct, then it is likely that Western Sierra reservoirs will begin receiving large chunks of their yearly inflow in just a few rainstorms.

This new hydrological regime creates a potential for catastrophic dam failure by overtopping, which could lead to devastating flooding in downstream communities. Although predicted changes to climate and hydrology are well understood on a large scale, specific watersheds have yet to be sufficiently analyzed for a probable maximum flood (PMF), which is a combination of maximum meteorological and hydrological conditions "reasonably possible" (Lave and Balvanyos 1998). Using these probable maximum flood values, the risk of catastrophic dam overtopping as well as potential damages, can be quantified under various IPCC climate scenarios.

It was important to quantify catastrophic dam overtopping risk for the Pine Flats Reservoir as it sits above the Tulare Lake Basin, home to over 100,000 people, and some of the most productive agricultural land globally. To do this, I asked the following central question for a set of environmental and meteorological conditions predicted to be likely by IPCC models and GCM analyses in the 2099 Sierra region. What quantity of rainfall runoff (PMF) in a watershed will cause an inflow at the reservoir's head greater than the dam's maximum outflow, for a long enough period of time to fill the reservoir past maximum capacity. It was important to use a set of likely future environmental conditions when asking this question, because the answer is different depending on a huge number of factors, such as snowpack level, reservoir fullness, precipitation intensity, precipitation duration, etc. In answering the main question, I used the RCP 4.5 and RCP 8.5 emissions scenarios, which predict different future hydrologic conditions depending on present day emissions quantities, and government actions globally. My second sub question was, how much outflow can the dam handle depending on its fullness? Dams usually have primary outflows, and then emergency overflows. To achieve catastrophic overtopping, both of these outflow rates must be exceeded by the inflow from the watershed. Lastly it was crucial to understand what current meteorological regimes look like for a watershed, as current rainfall data can be used as a base to estimate the probability of future maximum precipitation events.

METHODS

Study Site

The Upper Kings Canyon Watershed describes the area above Pine Flat Dam, in the western Sierra Nevada mountains of California (Figure 1). Flowing through the watershed is the mighty Kings River, which is the primary inflow for partially endorheic Tulare Lake Basin. Prior to the US colonization and settlement of California in the 1850's, Kings River flowed unrestricted into the massive Tulare Lake. After 1850, diversions of the river for agricultural purposes caused Tulare Lake to dry up completely. Now tens of thousands of Californians inhabit the area historically occupied by Tulare Lake, which currently sits as a flood plain. If Pine Flat Dam overflows, then citizens downstream in the Tulare Lake Basin could be at risk. Particularly at risk are the cities of Reedley, population 25,441, and Kingsburg, population 12,441.

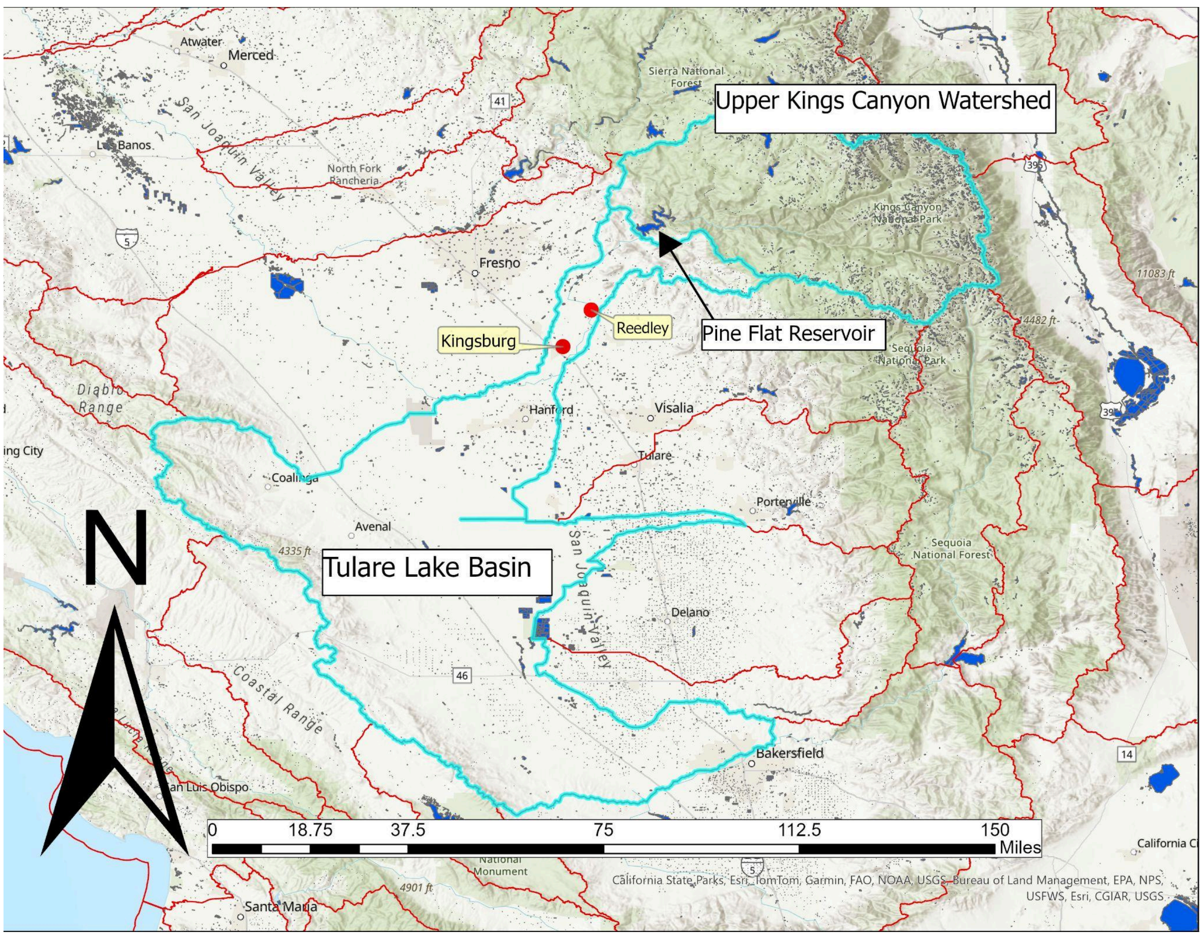

Figure 1. Kings River hydrological area. Tulare Lake occupied the majority of the western basin prior to 1850.

The 4000 km^2 Upper Kings Canyon Watershed (UKCW) starts at an elevation of 300 m at the Pine Flat Reservoir, going all the way up to 4343 m at the eastern boundary of North Palisade peak. So for any given storm-system, precipitation falling on the low-elevation, western edge of the watershed may be water while in the high-elevation, eastern edge precipitation may be snow. To more accurately describe precipitation patterns in this large watershed, I subdivided it into 8 basins (Figure 2). Each sub-basin was the minimum unit for which I would calculate historical precipitation with corresponding runoffs, and model future precipitation with corresponding runoffs. I used the 3 publicly accessible USGS gage stations in the UKCW to correlate historical precipitation values with flow data. Stream gage 11218400 (Figure 2 marked in red) measured outflows from sub-basins 2 & 3, just below where Dinkey Creek and the North Fork Kings River converge. I will refer to this as gage 23. Gage 11213500 (Figure 2 yellow) measures outflows from sub-basins 4-8, right above where the Kings River merges with North Fork Kings River. I will refer to this as gage 48. The final stream gage, 1121500 (Figure 2 pink), is located at the base of the Pine Flat dam which measures outflows of the whole watershed. I will refer to this as the dam gage. Ideally I would have stream gages at the outflow for each of the 8 sub-basins, but most rivers in California do not have stream gages.

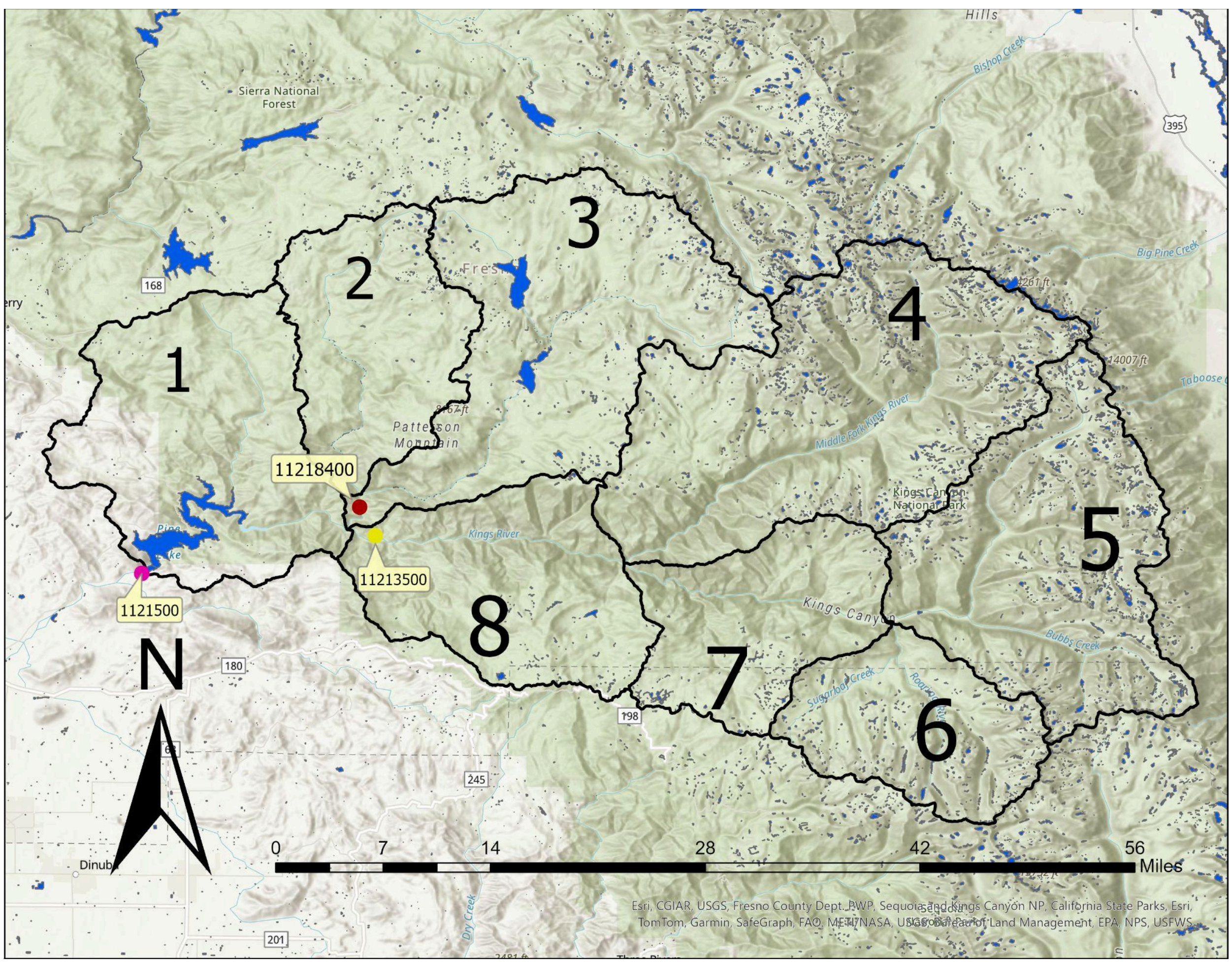

Figure 2. Three USGS gage stations, and HU10 subdivisions of the Upper King River Watershed. Gage stations are labeled with Hydrologic Unit Code. Sub-basins are: 1) Pine Flat Reservoir-Kings River Watershed HU1803001008 2) Dinkey Creek Watershed HU1803001005 3) North Fork Kings River Watershed HU1803001006 4) Middle Fork Kings River Watershed HU1803001003 5) Upper South Fork Kings River Watershed HU1803001002 6) Roaring River Watershed HU1803001001 7) Lower South Fork Kings River Watershed HU1803001004 8) Mill Flat Creek-Kings River Watershed HU1803001007

Data Collection

For this study I compiled data from a number of online sources- primarily from National Water Information System (USGS 2024), Watershed Boundary Dataset (USGS 2024) and Cal-Adapt (Cal-Adapt 2022), the California Data Exchange Center (DWR 2024), and the National Weather Service (NWS 2024).

To define the area of the Upper Kings Canyon Watershed, I downloaded the USGS's Watershed Boundary Dataset (WBD) (USGS 2024), which is a mapping dataset containing every watershed in the continental United States. USGS assigns watersheds a hydrologic unit (HU) with length as short as 2 digits for the largest national watersheds, all the way to 16 digits for the smallest local watersheds (Figure 3). The UKCW is a medium level boundary represented by an 8 digit hydrologic unit code, HUC8. Each of the sub-basins represented (Figure 2) are at the HUC10 level of detail. They require more digits as the area they represent is more specific. Plugging the WBD shapefile into arcGIS, I accessed the attribute table for HUC8 and HUC10.

Figure 3. USGS Hydrologic unit watershed numbering system (USGS 2024).

To locate gage stations I used the National Weather Service's national observations webpage to locate active streamflow gages in the Upper Kings Canyon Watershed. After locating the 3 relevant stream gages, I found their hydrologic unit code (HUC), which I then searched into the USGS National Water Information System (NWIS). The NWIS provided time series data for each gage location in terms of average cfs for each month of the year.

The oldest data comes from gage 48, which measured flow rate in cfs from Oct 1926-Aug 1982. Second oldest is the data from the dam gage, measuring flow rate from Jan 1954- Sep 1990. Flow data from the gage 23 below Dinkey creek was recorded from 1961-2013, but their time series was not available, so I just used the average calculated by USGS.

To determine future precipitation, I used Cal-Adapts climate snapshot feature. The climate snapshot provides projections for future 1-year-storms by HU10 watershed area, which is the level of detail for the 8 sub-basins within the Upper Kings Canyon Watershed. Future projected values were divided into RCP 4.5 and RCP 8.5 categories representing different emissions scenarios, and further into scenarios for 2035-2064, and for 2070-2099. So each sub-basin had 4 future projected annual mean 1 day max precip values (1-year-storm). The climate snapshot also had total yearly precipitation level projections for each of the 8 HU10 watersheds, which I compared to historical yearly precipitation measurements. All of the future projected annual precipitation values were within 3% of historical average annual precipitation values, so that led me to believe that current mean precipitation rates will persist until 2099.

To determine the overall volume of water flowing through the watershed, I used the California Department of Water Resources' "historical data selector" tool which allowed me to search for overall "full natural flow" for the Upper Kings Canyon Watershed. Although USGS gage data provided average flow rate by month, it did not always provide cumulative yearly flow data. CDWR's full natural flow represents the total volume of water passing through the watershed measured in acre feet, which is useful for calculating approximate evapotranspiration rates across the watershed. I also used the historical data selector to obtain prior monthly reservoir levels. The reservoir level dataset lacked adequate size, measuring monthly dam level only from 2015-2023, but it was the only data I could find publicly accessible.

To obtain structural information about Pine Flat Dam's maximum outflow capability, I read an investigative report conducted jointly by the CDWR and Bureau of Reclamation (USBR 2003), which cited a 1989 army corps document, stating a maximum outflow rate of 17,100 cfs (Corps 1989a). I could not find the 1989 army corps environmental assessment from which this maximum outflow value was obtained.

Data analysis

Using the data provided from CDWR's historical data search, I statistically analyzed prior reservoir volumes for the Pine Flat Dam, determining a mean dam volume for each month of the year in Microsoft Excel. Additionally, I calculated standard deviations of the monthly dam volume data, which allowed me to produce hypothetical volumes for 1 and 2 standard deviations above mean monthly dam level. I used these hypothetical mean, +1 standard deviation, and +2 standard deviation reservoir volumes as the base cases for which I then calculated necessary inflow rates for overtopping. One of the +2 standard deviation reservoir volumes ended up exceeding the reservoir capacity, so I just considered the reservoir to be at full capacity as a starting point for that month. The runoff season in the Upper Kings Canyon Watershed is considered to be February through July, so for these months I calculated overtop-causing inflow rates.

Once I had the range of possible monthly reservoir capacities, calculating the rate of inflow necessary to overtop the dam was relatively straightforward. I just subtracted the 17,100 cfs (0.393 AF/s) maximum outflow value from the inflow X, and determined what rate of inflow would cause overflow within 2 days, as peak flows relating to rain-on-snow events last less than 2 days 95% of the time (Sikorska et al.. 2018).

To determine average flow data both for the Upper Kings Canyon Watershed, and for individual sub-basins, I analyzed and modified existing streamflow data in Excel. USGS streamflow data is almost always recorded in terms of cubic feet per second (cfs) over a given interval of 15 minutes, 1 day, 1 month, etc. In order to determine a "catastrophic overtop" causing precipitation value, I reformatted average flow data in cfs as acre-feet (AF) per month, and AF/year. Because I knew the average annual flow in AF/year over the UKCW, and the average annual precipitation in feet, I then calculated a runoff coefficient for the overall watershed using the rational method (equation 1). I also determined average annual flow and precipitation values for the area above gage 23 (sub-basins 2 & 3 combined), as well as for the area above gage 48 (sub-basins 4-8 combined), which enabled me to calculate 2 runoff coefficients for the catchments above each gage. Subtracting the average annual flow and precipitation values of sub-basins 2-8 from the overall UKCW flow and precipitation data yielded me average annual flow and precipitation average values from sub-basin 1, which I could calculate yet another runoff coefficient for. So even though there are only 2 gages upstream from Pine Flat Reservoir, I subdivided the UKCW into 3 separate runoff areas to form a more accurate sense of how precipitation over the entire watershed correlates to inflow to the reservoir.

Rational method

The rational method is a simple equation for modeling watersheds of a known area to correlate precipitation with runoff at an outflow point, according to the runoff coefficient C. C simply represents the percentage of total rainfall volume across the watershed that ends up at the outflow point as runoff (D'Odorico 2024).

Q(volume of flow/time) = C * Area * P (height of precipitation)

Equation 1. Rational method relating precipitation over a basin to flow.

Not having a stream gage for sub-basin 1, I subtracted basin 2-8's mean flows from the larger UKCW mean flow, to determine on average how much water enters the Pine Flat Reservoir from SB1, which I then used to calculate sub-basin 1's runoff coefficient. From this calculation I then had 3 separate runoff areas within the UKCW(sub-basin 1, sub-basin 2 & 3, and sub-basins 4-8) which could be modeled independently. Then independently modeled outflows from the 3 runoff areas are combined to find the estimated precipitation rate.

Gumbel distribution

The Gumbel Distribution is useful in statistically describing probability of exceedance for extreme rainfall events. After having calculated the set of precipitation rates necessary to cause overtopping for each of the 3 subdivisions of the UCRW, for each dam-level, I then used the Gumbel Distribution (Equation 2) to determine likelihood of each precipitation value, using the 4 Cal-Adapt projected annual 1 day maximum rainfall averages to determine 4 return periods (NIST 2012).

$$\text{Prob}[X' \geq X^*] = 1/T_r = 1 - \exp[-\exp(-(X^* - \beta)/a)]$$

$$a = \text{sqrt}[6]/\pi * (\text{standard deviation of sample } X').\ \beta = X' - 0.5772a$$

$$X^* = \beta - a * \ln[-\ln(1 - 1/T_r)]$$

Equation 2. Gumbel distribution to determine probability of exceedance.

RESULTS

For a 2 day period, if the Pine Flat Dam releases the maximum rate of 0.393 acre feet of water per second, that correlates to 67910.4 acre feet of water released over a 2 day period. This means that for a starting condition where the dam is already full, a dam-overtopping precipitation event would need to create an inflow into the reservoir of at least 67910 acre feet over 2 days. Subtracting each potential starting value (Table 1) from 1067910, because the reservoir is 1,000,000 acre-feet in volume, left me with the necessary volume of inflow to overtop the dam (Table 2).

Table 1. Probable reservoir starting capacities based on historical values. Values are in Acre feet.

Reservoir volume scenario(AF)		February	March	April	May	June	July
Mean Reservoir Level		43458.22	126315	187619.6	256096.3	388586.8	350928
1 Standard Deviation Above Mean Reservoir Level		168608.9	469849.2	691757.7	523412.7	657491.6	509516.8
2 Standard Deviations Above Mean Reservoir Level		293759.6	813383.3	1000000	790729.2	926396.5	668105.5

Table 2. Necessary volumes of inflow to cause dam overtopping. Values are in Acre feet.

Necessary Inflow Volumes(AF)		February	March	April	May	June	July
Mean Reservoir Level		1024452	941595	880290.4	811813.7	679323.2	716982
1 Standard Deviation Above Mean Reservoir Level		899301.1	598060.8	376152.3	544497.3	410418.4	558393.2
2 Standard Deviations Above Mean Reservoir Level		774150.4	254526.7	67910	277180.8	141513.5	399804.5

For each of the inflow volumes, I applied the rational method, separating values for the 3 runoff areas, and recombining to yield the overtop-causing precipitation values for the Upper Kings Canyon Watershed (Table 3).

Table 3. Necessary precipitation volumes across watershed to cause overtopping. Values are in Acre feet.

Necessary Precipitation Volumes(AF)		February	March	April	May	June	July
Mean Reservoir Level		1875015	1723365	1611162	1485831	1243339	1312265
1 Standard Deviation Above Mean Reservoir Level		1645956	1094608	688457.1	996572.4	751172.9	1022006
2 Standard Deviations Above Mean Reservoir Level		1416898	465850.4	124293.1	507313.4	259006.7	731746.7

I combined Cal-Adapt data from each of the HU10 sub-basins to determine the future 1 day average annual maximum rainfall quantity for the 3 runoff areas, and for the entire UKCW (Table 4). Using the projected mean annual 1-day-maximum projected rainfall volumes as a baseline, I could then calculate the return time of the minimum-overtop-causing precipitation volumes (Table 3), and with that the probability of such storms occurring for both climate scenarios.

Table 4. Mean annual 1-day-maximum projected rainfall volumes. Values on the right most column represent the sum of precipitation across the entire UKCW. Values in the bottom 3 columns represent the sum of projected annual maximum precipitation for each sub-basin.

Scenarios	Sub-basins								P Vol AF
	1	2	3	4	5	6	7	8	
end R4.5 1dm vol AF	25306.79	22244.75	51189.45	69785.48	46900.81	18970.11	23338.16	24570.62	282306.2
end R8.5 1dm vol AF	26431.78	23621.8	53794.37	72720.78	49174.64	19947.19	24430.87	25728.17	295849.6
end R4.5 1dm vol AF	25306.79		73434.19					183565.2	282306.2
end R8.5 1dm vol AF	26431.78		77416.17					192001.6	295849.6
	1		2					3	
	Runoff Areas								

After using the mean values (Table 4), and extreme values (Table 3), in the Gumble distribution, I was finally able to calculate the probability of dams overtopping for the RCP 4.5 and RCP 8.5 climate scenarios (Tables 5 & 6). For both climate scenarios the mean, and 1 standard deviation above mean reservoir starting volumes, have chances of catastrophic overtopping at essentially 0. For the 2 standard deviations above mean reservoir starting volume, it is 99% likely that overtopping would occur as a result of any rainfall in the watershed for the month of April. Overtopping probability in the month of June is higher in the RCP 8.5 climate scenario.

Table 5. Probability of dam overtopping for each reservoir starting level by month under RCP 4.5 climate.

Probability of Overtopping RCP 4.5		February	March	April	May	June	July
Mean Reservoir Level		<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%
1 Standard Deviation Above Mean Reservoir Level		<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%
2 Standard Deviations Above Mean Reservoir Level		<0.01%	<0.01%	>99.9%	<0.01%	>86.83%	<0.01%

Table 5. Probability of dam overtopping for each reservoir starting level by month under RCP 8.5 climate.

Probability of Overtopping RCP 8.5		February	March	April	May	June	July
Mean Reservoir Level		<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%
1 Standard Deviation Above Mean Reservoir Level		<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%
2 Standard Deviations Above Mean Reservoir Level		<0.01%	<0.01%	>99.9%	<0.01%	>96.24%	<0.01%

DISCUSSION

The range of probabilities of catastrophic dam-overtopping for the Upper Kings Canyon Watershed is very slim. For a majority of reservoir volume starting scenarios, the probability of overtopping is below 0.01%, corresponding to a return period of greater than 1 in 1000 years. Only for the starting situation where the reservoir is already 2 standard deviations more full than the mean is there any real chance of overtopping, in the months of April and June.

Probabilities for overtopping

The near 100% probability of overtopping for a 1-year-storm filling an already full reservoir is something that intuitively makes sense. The one interesting piece of data resulting from my calculations is that for the month of June, starting at a reservoir capacity 2 standard deviations above the mean, the RCP 8.5 climate scenario has a significantly larger change of overtopping the dam. This corresponds with the scientific literature, which indicates that a warmer climate, resulting from increased GHG presence, would create a more optimal condition for atmospheric river storms (Ralph et al. 2006).

Flood risk in California

Other studies on the same topic show greatly increased flood risk for certain dams in California's Sierra Nevada region, where at least 8 dams have higher risk of catastrophic flooding than the Lake Oroville Dam which famously breached in 2017 (Mallakpour et al.. 2019). It is possible that the Pine Crest Dam is an exception to the trend of increased risk of Dam overflow in the Sierra region. I however am more doubtful of my abilities to accurately calculate catchment level flows at the 4000km^2 scale. Proper management of reservoir volumes is essential to the continued function of any dam. For Pine Flat Dam, as long as the reservoir stays below 900,000 AF of stored water, the probability of overtopping is low <5%. More likely flood scenarios are the result of mechanical failures of the dam's components rather than from overtopping (USBR 2003).

Limitations

There were a number of improvements I could have made to improve the accuracy of the results of my study, had I been physically present in the Upper Kings Canyon Watershed to collect data. One of the biggest limitations to my study is that I did not distinguish between water flows from snowpack, rainwater, and groundwater. I chose to lump them all together, as I lacked snowpack data, and groundwater hydrology. Because snowmelt, rainfall runoff, and groundwater all originally come from rain, I don't think my estimates in the study are so far off. Distinguishing the rates of flow for each of these categories would certainly give a more holistic hydrological profile of the watershed. The indirect relationship between precipitation and runoff is always complicated by soil moisture and snow levels, where the largest storms often have the least runoff (Ohara et al. 2011). Modern hydrological methods require isotope analysis, where different sources of streamflow (precipitation runoff, snowmelt, groundwater) all contribute different proportions of isotopes (D'Odorico 2024).

Additionally, lack of streamflow gages, and evapotranspiration sensors, and knowledge of the local topographies within the huge watershed certainly led me to overestimating runoff values from precipitation. Even though calculating the difference between rainfall volume averages and streamflow volume average gives a ballpark idea of how much water is evapotranspiration, a portion of the difference between rainfall and streamflow is accounted for by groundwater.

Future direction and management implications

Climate change, and how it affects the hydrological regime of the Upper Kings canyon watershed is still not well studied. Even though the results of my study are optimistic for the future health of Pine Flat Reservoir, and the tens of thousands of people living below it, proactive monitoring of changes to precipitation patterns can only be a good thing. Other watersheds in the same region are assumed to not be as safe to the effects of a changing climate as has been studied thoroughly. The Army Corps of Engineers is actively monitoring all hydrological infrastructure throughout the state, and does react well to immediate changes in weather, dropping reservoir levels in preparation for storms and expected snowmelt. At least for the immediate future, it seems that the Kings River watershed is safe from flooding, but researchers more qualified than myself should revisit this topic to see if they come to a different conclusion.

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