Extremes of Opportunity? A generalized approach to identify intersections between changing hydrology and water management.

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Abstract

For water managers, changing hydrology can underscore existing vulnerabilities as well as offer new opportunities. The purpose of this paper is to put forth a generalized approach to identify potential intersections between changing hydrology and water management. The generalized approach includes 4 steps: (i) Articulate management vulnerabilities and opportunities, (ii) Quantify current water contributions from sources that may provide the hydrologic opportunity, (iii) Identify key climatic and atmospheric drivers of the hydrologic opportunity, and (iv) Explore the opportunity-management nexus. The framework is demonstrated using a case study example of the Middle Rio Grande Basin of New Mexico and its downstream delivery point, Elephant Butte Reservoir. In Step 1, we articulate how New Mexico's water supplies are vulnerable to decreasing snowpack, but also that the summer monsoon season could offer a potential, currently under-developed, water supply opportunity. In Step 2 we examine historical Elephant Butte Reservoir inflows and find that although monsoon season volumes vary from year-to-year, they are an important contribution to annual water supply. Further, we find that the upper percentile inflows contribute a disproportionately larger fraction of the monsoon volume relative to their frequency of occurrence. Step 3 examines possible climate and atmospheric drivers for different characteristics of monsoon season interannual variability, finding that most monsoon inflow characteristics show a strong association with average precipitation over the contributing watershed and atmospheric precipitable water. In Step 4 we suggest how this information could be integrated into existing planning and operations for the Rio Grande Basin.

1. Introduction

In many river basins in the Western United States, snowmelt provides the primary contribution to water supply (Serreze 1999); hence, most reservoirs are designed to capture snowmelt runoff. However, increasing temperatures (Hayhoe et al. 2018) and decreasing snowpack (Mote et al. 2005, 2018) have already been observed across the Western United States (US), and general circulation models predict that these trends will continue into the future (Collins et al., 2013). Taken together, these changes suggest increasing threats to water storage and availability in these reservoirs (Barnett et al. 2005). It is generally thought that increasing greenhouse gases will lead to an intensification of the hydrologic cycle, with an increase in heavy precipitation, potentially increasing local runoff (Seneviratne et al. 2012). In addition to posing flooding threats, these potentially increasing extreme precipitation events present opportunities to mitigate the impacts of decreasing snowmelt runoff volumes on water supply. However, the relevance of changing hydrology, including extremes, will depend on the particular water management context. As such, the purpose of this paper is to put forth a generalized approach to identify potential intersections between changing hydrology and water management.

The generalized approach includes 4 steps: (i) Articulate management vulnerabilities and opportunities, (ii) Quantify current water contributions from sources that may provide hydrologic opportunities, (iii) Identify key climatic and atmospheric drivers of the hydrologic opportunity, and (iv) Explore the opportunity-management nexus. In this paper, we first present the generalized framework (Section 2), which is demonstrated using a case study example of a reservoir in the Rio Grande Basin, New Mexico. This is followed by discussion and conclusions (Section 3).

2. Framework to Identify Intersections

2.1 Step 1. Articulate management vulnerabilities and opportunities

The relevance of changing hydrology is dependent on the particular water management context. Articulating local management vulnerabilities and potential opportunities is a critical first step towards adaptation planning. In this step, we provide background information on climate and water resources for New Mexico basins that include projects managed by the US Bureau of Reclamation.

2.1.1. Background: Similar to many water systems in the Western US, one key vulnerability for New Mexico is decreasing snowpack. Snowpack provides the main water source for most of the New Mexico river basins that begin in Colorado, (including the Rio Grande, San Juan, and Chama Rivers) and northern New Mexico (such as the Pecos River) (Gutzler 2013). As such, most of the reservoirs in these river systems are designed to capture snowmelt runoff, with storage located in the headwaters of the basins where temperatures and evaporation rates are lower (Gutzler 2013). Recent work by Chavarria and Gutzler (2018) has shown decreasing snowpack and increasing temperatures in the upper Rio Grande, resulting in slight decreases in snowmelt runoff. Further, they found that small precipitation increases have offset the impact of decreasing snowpack (Chavarria and Gutzler 2018). However, there is growing evidence that runoff efficiencies in the basin are becoming more sensitive to temperature (Lehner et al. 2017).

Rivers that originate further south in the state get a smaller proportion of their flow from snowpack, and warm season precipitation increases in importance. Warm-season precipitation has historically provided a secondary water source in the Western US (Serreze et al., 1999). If the total volume of this secondary supply were to increase in response to increasing ocean and air temperatures, warm-season precipitation could provide a potential water-supply opportunity for New Mexico, which might make up, at least in part, for decreasing supplies from snowmelt runoff. In summer, the central and southern parts of the state are influenced by the North American Monsoon (Gutzler 2013; Adams and Comrie 1997), which result in significant contributions to annual precipitation (Douglas et al. 1993). Tropical cyclones also contribute during this time, though much less (<10%) during the main monsoon period (June 15-Sept 30), and more (up to 80%) in the relatively dry month of October (Wood and Ritchie 2013). For New Mexico, most extreme precipitation occurs in summer, followed by fall (Kunkel et al. 1999), and most flooding has been observed in summer (Villarini, 2016). Pournasiri Poshtiri et al (2018) examined recent trends in warm season precipitation characteristics, including extremes, and found that negative trends dominate warm season, June, and August, while positive trends dominate July and for some September precipitation characteristics. However, the majority of locations in New Mexico do not exhibit significant trends. The increasing trends for the July indicators show the most potential for water supply, with the location of these significantly positive trends mainly concentrated in the southeastern and eastern part of New Mexico. They also found that trends are more detectable in the frequency of extreme precipitation rather than the magnitude, similar to the findings of Mallakpour & Villarini (2017). As such, for times and locations showing increasing trends, their results suggest that water managers looking to exploit changes in precipitation might not need to plan for larger events, but rather for more frequent events.

The coarse resolution of general circulation models, which are typically used as a basis for projections of future climate and hydrology, limit the ability of these models to resolve monsoonal patterns. Therefore, there is currently low confidence in our ability to project changes in monsoonal patterns as the climate warms (Seneviratene et al. 2012). For parts of the US Southwest, projections for winter and spring seasons at the end of the century (2070-2099) show decreasing precipitation, though changes for this region in all seasons are small and relatively insignificant (Hayhoe et al. 2018). However, some past research (e.g., Asmerom et al., 2013) has suggested a correlation between ocean temperature and monsoon intensity. Seneviratne et al. (2012) recommend that any examination of monsoonal changes should consider large-scale circulation and dynamics, rather than solely examining precipitation. Examining current and future weather patterns, Prein 2018 finds a robust signal for an increase in the frequency of monsoonal circulations in New Mexico, particularly monsoonal patterns that contribute to the majority of monsoon season precipitation, as well as heavy precipitation events.

If Prein's conclusions are correct, there may be opportunities to exploit changes in warm season precipitation for water management (Gutzler, 2013, Llewellyn & Vaddey, 2013), warranting further investigation.

2.2. Step 2. Quantify current water contributions from sources that may provide hydrologic opportunities.

Quantifying the current contribution of water sources that might provide future water supply opportunities provides a critical baseline to which future climate or infrastructure scenarios can be compared. As articulated in Step 1, given decreasing snowpack, a potential opportunity for New Mexico could be moisture from the monsoon season. In this section we provide an example of quantifying current monsoon season contributions to annual water supply.

As a case study, we examine the Middle Rio Grande Basin of New Mexico and its downstream delivery point, Elephant Butte Reservoir, located in the south-central New Mexico (see Figure 1). This reservoir provides significant water storage (up to approximately 2 million acre feet) for both snowmelt runoff and summer precipitation events. The analyses in Step 2 rely on the following dataset and definitions:

- Elephant Butte Reservoir inflows: Data are available from 2000-2017, and are calculated as the sum of the Rio Grande Low Flow Conveyance Channel at San Marcial and the Rio Grande Floodway at San Marcial (URGWOM Technical Team, 2005).

- Monsoon season volume: We define the monsoon season volume as the sum of Elephant Butte Reservoir inflows from July 1 through September 30 (Jul-Sep). Initial analyses also included June 15-June 30, a time period that is often considered to be part of the monsoon season, but here it was found that that these inflows were still influenced by snowmelt.
- Annual volume: We define the annual volume to be the sum of Elephant Butte Reservoir inflows during the calendar year (Jan-Dec).
- Percentile-based indices: The definition of an extreme inflow at a particular location is site-specific; hence, percentile-based indices can be calculated from the historical Elephant Butte Reservoir inflows. We examine several percentiles: P99 is the 99th percentile flow, i.e., the value at which only 1% of daily inflows are higher. Similarly, we examine P95 (the 95th percentile, where only 5% of the daily inflows are higher), P90 (the 90th percentile), P75 (the 75th percentile), and P50 (the 50th percentile, or median daily flow).

In this step, we look at the interannual variability of monsoon season volumes and their contribution to annual inflows to Elephant Butte Reservoir (2.2.1), as well as the relationship between monsoon season volumes and upper percentile thresholds/extremes (2.2.2) and frequency and magnitude characteristics (2.2.3).

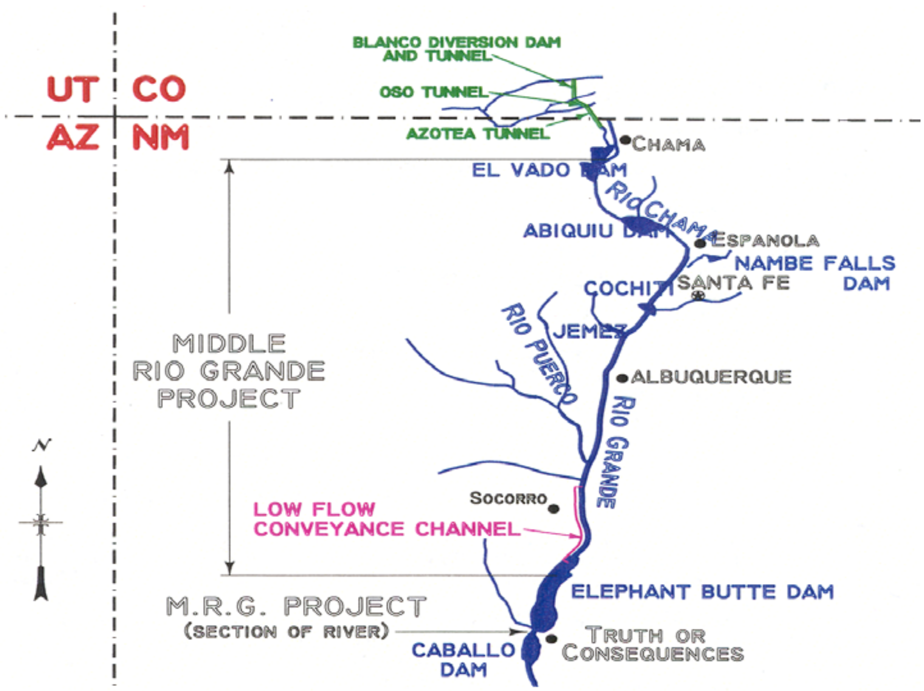

Figure 1. Map of Middle Rio Grande Basin of New Mexico and its downstream delivery point, Elephant Butte Reservoir, New Mexico.

2.2.1. Monsoon season volumes vary from year-to-year, but they are an important contribution to annual water supply: The interannual variability of Elephant Butte Reservoir inflows and storage volumes play a role in the operations and management decisions in the basin. Figure 2a (left) shows the annual monsoon season volumes for the 2000-to-2017 period analyzed; the average volume is about 68,383 acre-feet (af), the minimum was 16,432 af in 2003 and the maximum was 254,214 af in 2006. It is also useful to look at the contribution of the monsoon volume to annual volume, as in some years, even relatively low volumes may provide critical contributions. Figure 2b (right) shows that on average, monsoon volumes provide 14.4% of the annual supply, with a minimum of 4.00% in 2017 and a maximum of 43.6% in 2006. There is no statistically significant trend to the contribution, though it is hard to tell with the short sample size (18 years).

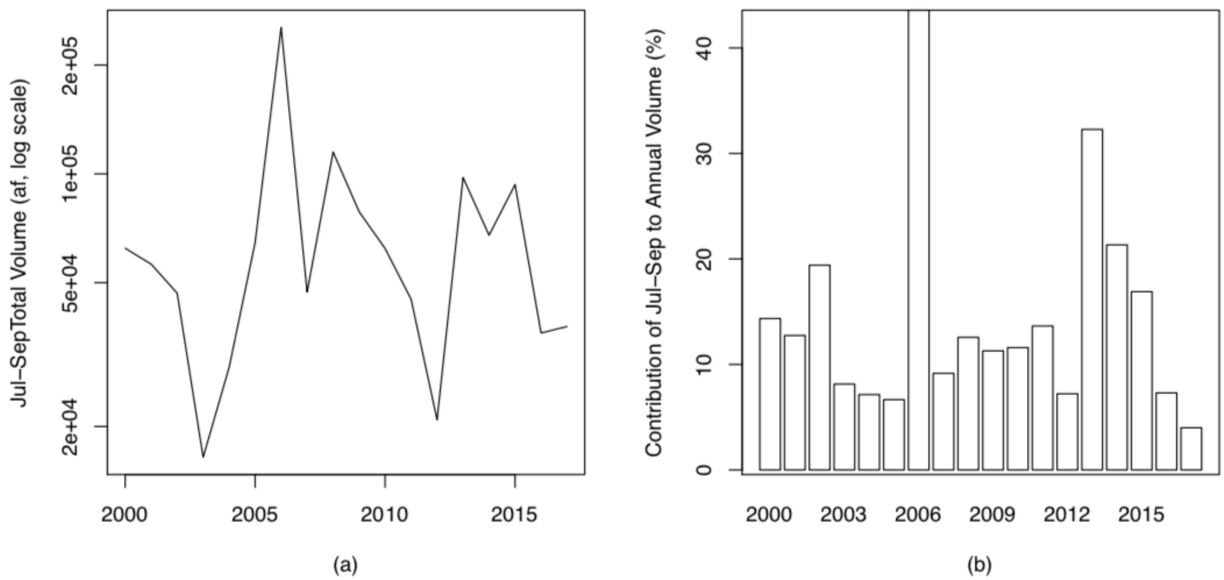

Figure 2. Monsoon (Jul-Sep) total volume in Elephant Butte Reservoir (a) and proportion of annual volume (Jan-Dec) coming from that year's monsoon (Jul-Sep) volume (b).

2.2.2. Inflows from upper percentiles contribute a disproportionately higher proportion of the monsoon volume relative to their occurrence: The percentile indices for the Elephant Butte daily inflows from the monsoon season (i.e., n = 1656 daily inflows) can be seen from the flow duration curve (Figure 3). Figure 3 shows that the upper half of daily inflows span an order of magnitude in volume: the 50th percentile (P50) is 452 acre feet and the 99th percentile (P99) is 5660 acre feet. The maximum daily flow in the analyzed period of record is 11,910 acre feet (in 2006; not shown in Figure 3). We also see that the 75th percentile (P75) for the inflows marks an inflection point: here, the absolute value of the slope starts to increase towards the higher percentiles (moving to the left in Figure 3), indicating a rapid shift towards higher daily inflows. Using these percentiles, we can look at the contribution of daily inflows above each percentile in each monsoon season (Figure 4). In Figure 4, the boxplots are comprised of the annual contributions from each percentile, hence the sample size, N, number of years, decreases; this is as expected, since the exceedance of the higher percentile indices does not occur in every year. As indicated by the median (horizontal line in box plots), the summed volumes from daily flows from the upper half of the distribution (>P50) contribute to 78% of the monsoon reservoir volume. Summed volumes from the top quarter (>P75) of daily inflows contributed 47% of monsoon reservoir volumes; top decile (>P90) of daily inflows contributed 28% of monsoon reservoir volumes. However, there is quite a bit of variability in the contribution from year-to-year for these percentiles (P50-P90). As we move into the higher, more extreme quantiles, these also play a role, but in fewer years. i.e., daily inflows above P99 are contributing disproportionately given their low occurrence, but only in the two years that they occur: this 1% occurrence accounts for 41% in 2006 and 23% in 2013 (resulting in a 32% median). The previously mentioned maximum daily inflow on record (e.g., 11,910 af), which occurred in August of 2006, contributed 5% of that year's monsoon reservoir volume.

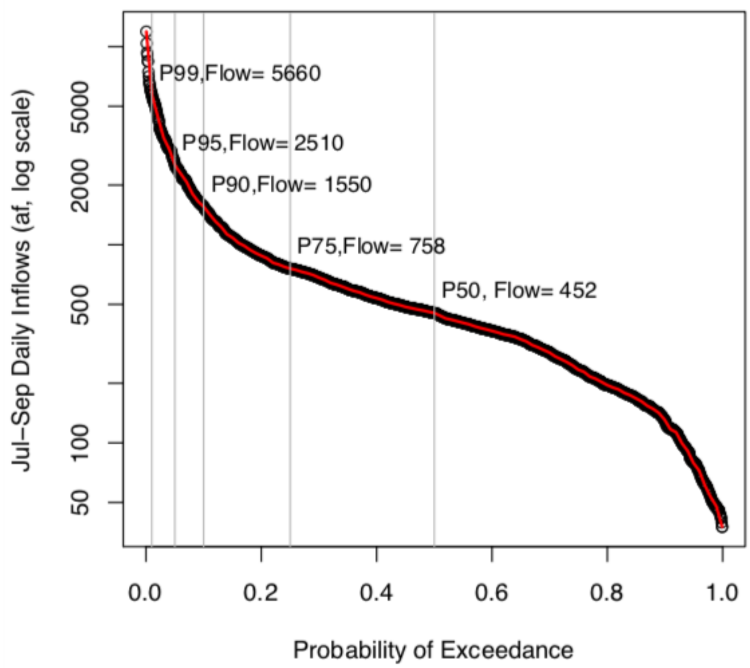

Figure 3. Flow duration curve of monsoon (Jul-Sep) daily inflows in acre feet (af; n=1656 days), with daily values of select percentile-based flow indices (P50, P75, P90, P95, P99), and smoothed spline (red line).

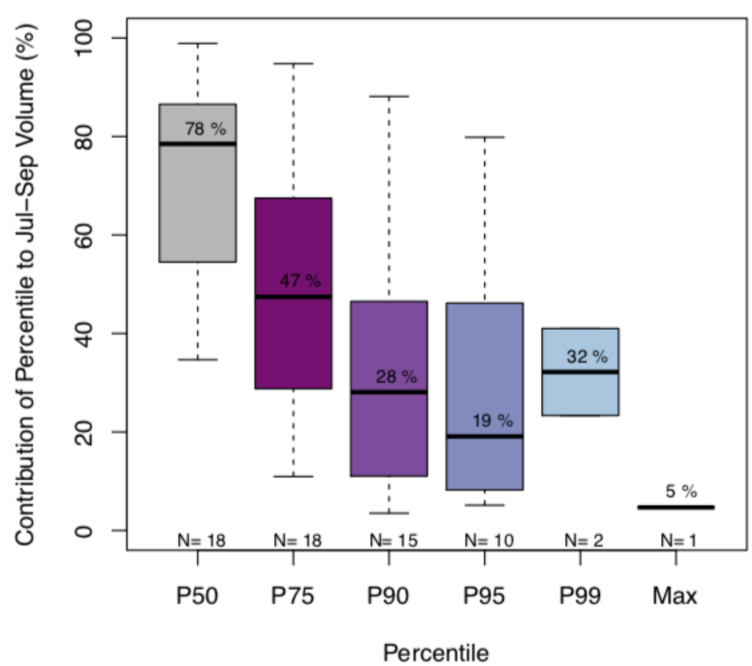

Figure 4. Proportion of monsoon (Jul-Sep) volume coming from daily inflows above each percentile-based flow index; P50 is the 50th percentile, P75th is the 75h percentile, and so on; Max is the maximum daily inflow. N is the number of years from which the daily inflows above the percentiles were observed.

2.2.3. Frequency and magnitude inflow characteristics partially explain interannual monsoon variability: We can also examine how well other inflow characteristics based on the percentile-based indices explain the interannual variability of monsoon reservoir volumes. Here we look at two characteristics: first, the frequency, or the number of days that the daily inflows were above the percentiles during the monsoon season. Figure 5 shows how the number of days above P50, P75, P90, and P95 relates to that year's monsoon reservoir volume. As we would expect, as the number of exceeding days increases, so does the total monsoon inflow volume. We see strong linear correlations, as measured by Pearson's r values, and find that the number of days above P75 has a stronger correlation (r=0.85) than P50 (r=0.62), showing the importance of the count of days in the upper quarter of the inflow distribution to total monsoon season volume. The number of days above P90 and P95 also have high correlations (r = .97 and .96, respectively), but here the linear correlations don't tell the whole story: the scatterplots reveal that there are several years with zero days above these thresholds. This relates to our previous point that these flows can be pivotal, but only in years in which they occur. The second characteristic that we examine is the annual magnitude, i.e., the value of the percentile index calculated annually for each monsoon season. For clarity, these are labeled $P50_{annual}$., $P75_{annual}$, and so on, indicating that these magnitudes are calculated from a flow duration curve like Figure 3, but for each year's monsoon season. The scatterplot in Figure 6 shows the association between the annual percentiles and that year's monsoon reservoir volume. These all exhibit very high linear correlations (r=0.95 to 0.98), indicating that these annual percentiles do a good job at explaining the interannual monsoon variability.

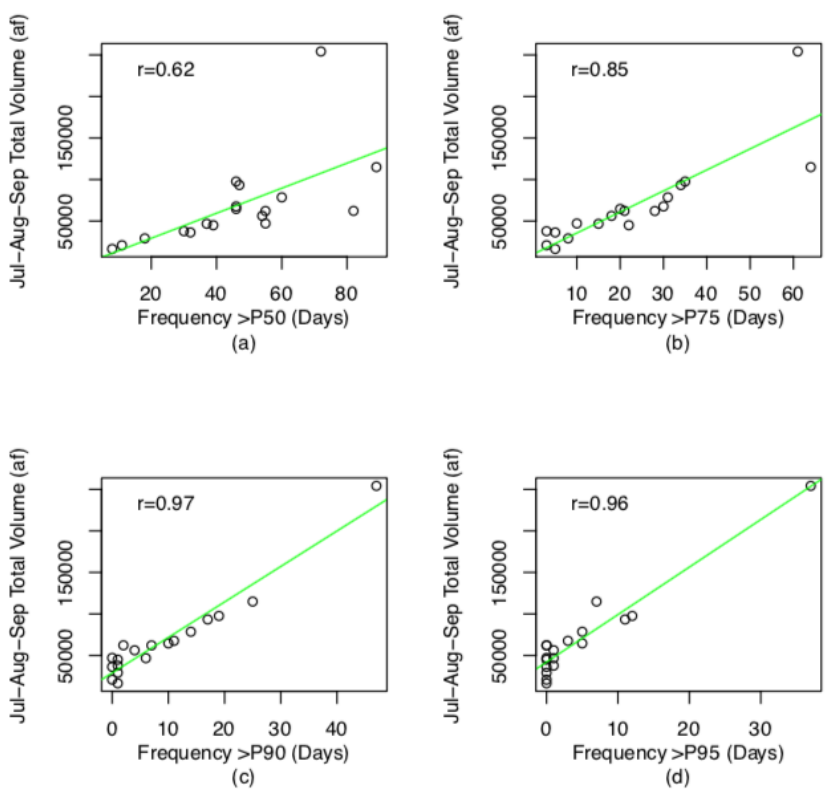

Figure 5. Frequency of days with inflows above select percentile-based indices versus monsoon (Jul-Sep) volumes in acre-feet (af); r is Pearson's linear correlation.

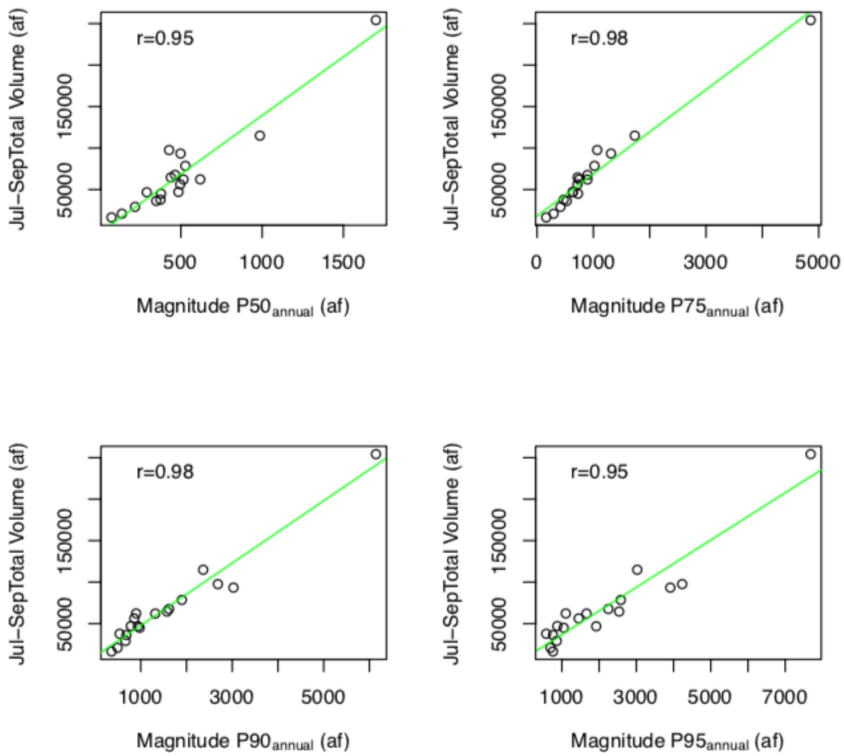

Figure 6. Inflow magnitudes of annual percentile-based indices versus monsoon (Jul-Sep) volumes in acre-feet (af); r is Pearson's linear correlation.

2.3. Step 3. Identify key climatic and atmospheric drivers of the hydrologic opportunity

Understanding the key factors that drive the potential opportunity is critical to understanding its possible role in water management. In step 2, we examined several aspects of the interannual variability of Elephant Butte Reservoir monsoon season volumes. Next we seek to understand the key climate and atmospheric drivers. We recognize that other factors, such as land use and management, are important as well; and though not examined here we discuss this point in the discussion and conclusions. Step 3 analyses rely on several datasets:

- Average precipitation: We use daily precipitation data from PRISM Gridded Climate Data Group (prism.oregonstate.edu), downloadable from http://www.prism.oregonstate.edu/documents/PRISM_downloads_FTP.pdf. Average precipitation is calculated by 1) averaging the daily values over each year's monsoon season (Jul-Sep), and 2) spatially averaging over the Rio Grande watershed contributing to Elephant Butte Reservoir within New Mexico. The data are available through 2014, so the overlapping period with the Elephant Butte Reservoir monsoon volumes is 2000-2014.
- Average large-scale variables: Prein (2018) identifies three potential predictors of monsoon season precipitation anomalies based on weather patterns over New Mexico: sea level pressure, wind speed, and precipitable water; these are from ECMWF's Interim Reanalysis (Dee et al. 2011) (ERA-Interim) Average values are calculated by 1) averaging the daily values over each year's monsoon season (Jul-Sep), and 2) spatially averaging over the entire state of New Mexico.

In this step, we first examine the runoff efficiency of the Elephant Butte Reservoir monsoon volumes with precipitation (2.3.1). Second, we examine the above 4 predictors (basin-average precipitation, sea level pressure, wind speed, and atmospheric precipitable water) and their linear correlation (Pearson's r) with several monsoon inflow characteristics examined in Step 2 (Section 2.3.2).

2.3.1. Runoff efficiency exhibits interannual variability. Runoff efficiency is calculated as the fraction of runoff, here the Middle Rio Grande monsoon volume (measured as the inflow to Elephant Butte Reservoir), divided by precipitation. Then, we normalize the value (i.e., we divide all values by the maximum runoff efficiency). Figure 7 shows the interannual variability of the runoff efficiency: the black line is calculated using the monsoon total precipitation, and shows that 2006 has the highest normalized efficiency within the years analyzed. To get a sense of the efficiency of the upper part of the distribution and extremes, the efficiency is also shown by using two percentile-based indices derived from the precipitation: PR_P75_{annual} and PR_P99_{annual}, corresponding to the magnitude of the 75^{th} and 99^{th} percentiles of daily precipitation in a given year's monsoon season. All three lines show similar patterns, but the PR_P99_{annual} line (purple) is lower for most years, showing that these heavier precipitation events may be less efficient in most years, except in the most extreme years (e.g., 2006). The $P75_{annual}$ line (orange) is above the black line in some years, indicating the relatively higher efficiency of the top quarter of precipitation days, and is just below the black (and purple) lines in 2006, the most extreme year. This underscores the point that when extremes occur, they can be quite efficient, but that more moderate extremes (e.g., P75) contribute more reliably in any given year.

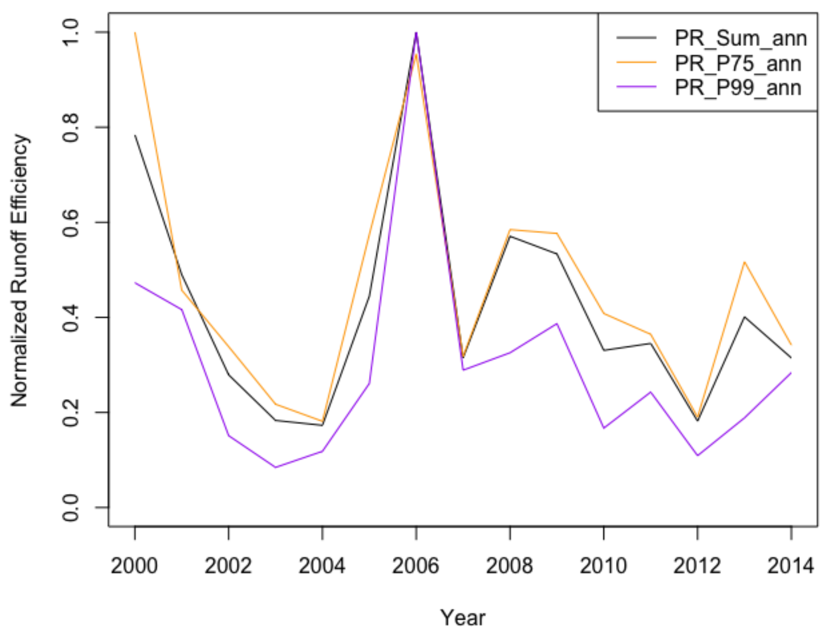

Figure 7. Normalized runoff efficiency of monsoon reservoir volumes using monsoon total precipitation (PR_Sum_ann), and two percentile-based precipitation indices, the magnitude of the year's 75^{th} and 99^{th} percentile precipitation day (PR_P75_ann and PR_P99_ann).

2.3.2. Most monsoon inflow characteristics show strong linear correlations with precipitation and precipitable water. Table 1 shows the linear correlations between the precipitation and large-scale predictors and the monsoon inflow characteristics:

total volume and maximum annual inflows, as well as the percentile-based frequency exceedances and annual magnitudes. Table 1 shows that total volumes are most highly correlated with average precipitation over the contributing watershed (r=0.73), and followed by precipitable water (r=0.61). Annual maximum values are most strongly correlated with higher average wind speeds (r=0.52), followed by precipitable water (r=.43), and not significantly correlated with average precipitation, indicating that predictors for averages versus maximums can be quite different. In terms of the frequency characteristics, average precipitation and precipitable water are both important, though as we get to higher percentiles, precipitable water becomes more important. For the frequency of days above P99, sea level pressure also shows a relatively strong association. These initial diagnostics show predictive promise, and the next step is to develop a statistical model to identify the best combination of significant predictors and the associated predictive skill. The appropriate statistical model that will be explored for each characteristic is shown in the last column of Table 1.

Table 1. Pearson's linear correlations (r) between climate and atmospheric predictors and monsoon inflow characteristic predictants for Elephant Butte (EB) Reservoir, as well as the appropriate statistical model form.

Predictant	**Predictors**				**Appropriate Statistical Model Form**
Monsoon EB Inflow Characteristic	**AvgPrecip NM Rio Grande**	**NM Avg Sea Level Pressure**	**NM Avg Precipitable Water**	**NM Avg Wind Speed**	
Total Volume	**0.73**	0.21	**0.61**	-0.26	Linear Regression
Max Annual Inflow	-0.04	-0.15	0.43	0.52	Generalized Extreme Value
Frequency P50	0.53	0.29	0.50	-0.36	Poisson
Frequency P75	**0.73**	0.46	**0.75**	-0.25	Poisson
Frequency P90	**0.77**	0.52	**0.79**	-0.14	Poisson
Frequency P95	**0.83**	0.32	**0.80**	0.11	Poisson
Frequency P99	-0.10	0.47	**0.66**	0.17	Poisson
Magnitude P50_Annual	**0.66**	0.23	0.59	-0.37	Linear Regression
Magnitude P75_Annual	**0.79**	0.28	**0.69**	-0.25	Linear Regression
Magnitude P90_Annual	**0.78**	0.28	**0.63**	-0.05	Linear Regression
Magnitude P95_Annual	0.59	0.23	**0.60**	0.10	Linear Regression
Magnitude P99_Annual	0.24	0.12	0.47	0.25	Linear Regression

2.4. Step 4. Explore the opportunity-management nexus

The fourth step is to explore the opportunity-management nexus, i.e., to identify quantitative and/or qualitative entry-points to test if and how the changing hydrology could impact management decisions. Managers often use local operations models to understand how changes will affect their water storage and key water operations, which can be used to guide their management decisions. In short, it is critical to collaborate with local water managers to understand their decision and modeling context to explore the potential opportunity-management nexus.

For the Rio Grande of New Mexico, the Upper Rio Grande Water Operations Model (URGWOM) includes reservoirs and operation rules to make hydrologic data relevant to management. URGWOM uses streamflow forecasts to select historical hydrographs to calculate inflows into its reservoirs, include Elephant Butte Reservoir. To date, streamflow forecasts are provided by the

Natural Resources Conservation Services (NRCS), and are based primarily on snowpack measurements, aiming to predict snowmelt runoff. One potential intersection with this framework is to use the understanding gained here as a launching point to predict a suite of monsoon inflow characteristics. It is hoped that these characteristics could be used as guidance for altering the predicted hydrograph during the monsoon season. The tradeoffs between the best predicted monsoon inflow characteristics (such as the total volume versus the magnitude or frequency attributes) and the ability to integrate with and utility for the URGWOM system need to be evaluated. However, even if the information could not be explicitly integrated in the modeling system, even qualitative information on monsoon inflow characteristics may be useful, and would be more than what is currently provided.

3. Discussion and Conclusions

This study offers a 4-step generalized approach to understanding potential opportunities from changing hydrology, including extremes. We provide a specific a case study example of the Middle Rio Grande basin in New Mexico. The goal is to provide both a general approach and a specific example that can be tailored to other watersheds and management systems.

In this investigation, we examined inflows to Elephant Butte Reservoir during the summer monsoon season, as well their association with average basin precipitation and other large-scale variables. However, we note that water resources in the Western US, including New Mexico, are often over-allocated and tightly managed. With full recognition of this fact, we note that we only focus on climate and atmospheric predictors. We recognize a priori that they will only partially explain the variability in the monsoon inflow characteristics, and presumably some of the remaining, unexplained variability would come from groundwater extraction, land-use changes, land surface characteristics, direct management, as well as other factors not examined here. However, we do note that this approach is more suited to looking at the upper percentiles and extremes, as compared to looking at the lower flows of the distribution, where the non-climate signals would likely be more prevalent.

Demonstrating the generalized framework for the Middle Rio Grande basin in New Mexico offers a successful application of the generalized framework, but we note that there could be other applications that yield less useful, though still informative, results. For example, we also stepped-through parts of the framework for the Pecos River basin, New Mexico, which in terms of infrastructure, is already well set-up for collecting extreme precipitation and subsequent runoff along the system. Here, we were interested in not reservoir inflows, but a decision-relevant variable for this watershed, which is the annual allotment to Carlsbad Irrigation District (CID), a Reclamation Project. The CID allotment is the amount of water the farmers are allowed to take per acre of land irrigated. However, when we examined the connections between the CID and Pecos watershed precipitation and the large-scale circulation variables, we did not find strong associations. This indicates that either a) different explanatory variables may need to be examined for the CID allotment, or b) different decision-relevant variables more closely associated with climate could be examined (e.g., reservoir inflows for this basin).

The provocative question posed in this study was “Extremes of Opportunity?” and the results here suggest several conclusions relevant to water managers. First, it depends on what you define as “extreme”. Here, we examine the entire upper half of the flow distribution, and do find that all the upper percentiles contribute a disproportionately higher fraction of the monsoon reservoir volume relative to their occurrence. In the 18-year record examined here, the maximum day contributed 5% of the monsoon flow in that year, and the days that exceeded P99 (or 1% of the days) contributed a median of 32% in the two years that they occurred. Hence, the higher extremes (e.g., maximum and >P99) could certainly provide opportunities in the years they occur. The more moderate extremes (P75-P90) also provide median contributions that are skewed higher than their occurrence, but there is much more variability in these contributions. Nevertheless, we also examined several predictors, including basin-average precipitation and large-scale variables, which showed significant correlations, especially basin-average precipitation and atmospheric precipitable water. These suggest that there is scope for providing outlooks on monsoon inflow characteristics, either from seasonal climate forecasts of the predictor variables, or in terms of downscaling from climate model output. Future work will develop statistical modeling tools to investigate these different applications and to test their ability to integrate with current management in the system.

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