Development of short-range forecasts of weather-driven channel losses and gains to support Reclamation water management

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14. ABSTRACT
Unexpected water losses and gains on Lower Colorado River reach between Parker Dam and Imperial Dam challenge the Bureau of Reclamation's Yuma Area Office (YAO) daily operations, which aim at delivering water to irrigation districts while minimizing excess flow. This project investigated the origin of these losses and gains and explored the potential for calibrated precipitation forecasts to predict weather-related losses and gains at lead times of 1-5 days. Predictability was found to be low due to significant unexplained variance in the loss-gain time series unrelated to weather, as well as generally limited precipitation predictability in this area. However,

probabilistic forecasts were found to skillfully predict increased odds for all gains and medium-size gains. While specific to the domain of YAO, these results might be transferable to other Reclamation operations in need of short-term loss-gain forecasts.

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

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Cover image: All American Canal near Yuma. Credit: Flavio Lehner

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Executive Summary

Problem Statement

Reclamation's Yuma Area Office (YAO) in Yuma, AZ, manages the last stretch of the Lower Colorado River before it crosses the border with Mexico. YAO navigates the many complex dependencies on the river on a daily basis, from deliveries to regional irrigation districts to water quality and volume regulations under an international water treaty. Despite detailed accounting of water releases and diversions from upstream dams and water users, unexplained daily fluctuations in the amount water arriving in Yuma, termed 'losses' and 'gains', nonetheless occur. The unpredictable nature of these losses and gains complicates YAO's operations. Thus, forecasts of losses and gains could be of value to YAO's operations.

Research Activities and Results

This project aimed at investigating the main causes of unexplained daily fluctuations of losses and gains in the reach between Parker Dam and Imperial Dam on the Colorado River and to develop tools to forecast them. Using existing observational records, the project confirmed the existence of loss and gain events that rise above the baseline variability. It was revealed that a significant backwater effect exists in the lower part of the reach, closely tied to the weekly release schedule at Parker Dam. After correcting for this backwater effect, major precipitation events were found to be responsible for the most significant gain events, but that smaller precipitation events are usually not detectable against the baseline variability. Precipitation forecast skill on 3-day timescales was found to be moderate, even after locally calibrating the precipitation forecasts. Consequently, loss-gain forecast skill based on precipitation forecasts remains low, although probabilistic forecasts based on ensemble calibration might still offer value for operations planning purposes.

Future plans

Precipitation-based loss-gain forecasts could be incorporated into YAO's RiverWare implementation as a separate data stream, available to the scheduler on a by-need basis. In conversations with Hydros Consulting, who currently maintain the RiverWare implementation for YAO, plans were sketched out to develop test cases for such an implementation. Further, there were continuing conversations with Reclamation's Albuquerque Area Office, which serves the Middle Rio Grande and has similar forecasting needs as YAO, about leveraging the results and workflow from this project in their domain.

1. Introduction

1.1 Background and problem statement

The Bureau of Reclamation's Yuma Area Office (YAO) in Yuma, AZ, manages the last stretch of the Colorado River in the Lower Colorado Region (LCR) before it crosses the border with Mexico. Irrigation district managers and YAO operate with sub-weekly demand schedules for the delivery of water to their stakeholders. The Colorado River reach from Parker Dam to Imperial is subject to intense agricultural use, but also features essentially uninhabited and ungaged stretches.

The main operations area of concern for this project is thus water volume regulation. YAO receives weekly water orders, which are aggregated and used to request releases from Parker Dam, which dams Lake Havasu on the Colorado River (Fig. 1). Releases from Parker Dam travel on average for three days to Imperial Dam, the dam just upstream of Yuma, where they are diverted to the major irrigation districts having placed water orders with YAO. There are more minor diversions and agricultural return flows in the Blythe and Palo Verde area about half-way in between Parker and Imperial Dam.

YAO optimizes water delivery such that excess flow is minimized to close to the requirements under the international water treaty between the United States and Mexico (1.5 million acre feet per year (af/year); this total annual required delivery is subdivided into monthly amounts). The optimization is achieved by closely tracking orders and actual diversions, as well as using available reservoir storage. There are two small reservoirs in the Yuma area, which are used to buffer varying demand and supply: Senator Wash Reservoir (max. storage ~13,800 af) and Brock Reservoir (~8,000 af). However, the reservoir storage is small relative to the mean daily flow just above Imperial Dam (~19,000 af/day), as well as relative to its daily fluctuations (one standard deviation of daily flow ~4,000 af/day).

Despite detailed accounting of water releases and diversions from upstream dams and water users, unexplained daily fluctuations in the amount water arriving at Imperial Dam, termed 'losses' and 'gains', nonetheless occur. The unpredictable nature of these losses and gains complicates YAO's operations. It is hypothesized that strong convective precipitation events are partly responsible for these unexpected gains on the reach. Due to the lack of storage on this Colorado River reach, satisfying the stakeholder needs while keeping with delivery requirements to Mexico is a central operational challenge at the YAO.

Convective precipitation events are difficult to forecast, but have the potential to affect current water management operations in the LCR through unexpected and ungaged inflows and through increased water ordered, but not delivered; i.e., farmers and irrigation districts not diverting the water they ordered due to unexpected rain on their fields.

Currently, YAO operates reactively when it comes to management decisions affected by weather events. Water demand in the region is increasing, while monthly flow under the 1944 treaty with Mexico constrains the flexibility of operators in their effort to satisfy stakeholder needs. To improve water management efficiency under increasing system demands, research to support proactive planning and management with regard to weather influences was identified as a potentially beneficial area of study during a site visit in September 2016. In particularly, YAO and the stakeholders it serves would benefit from access to more accurate short-term weather and stream reach loss/gain forecasts. Improving the skill of weather, and channel loss/gain forecasts would lead to greater water management efficiency in the LCR.

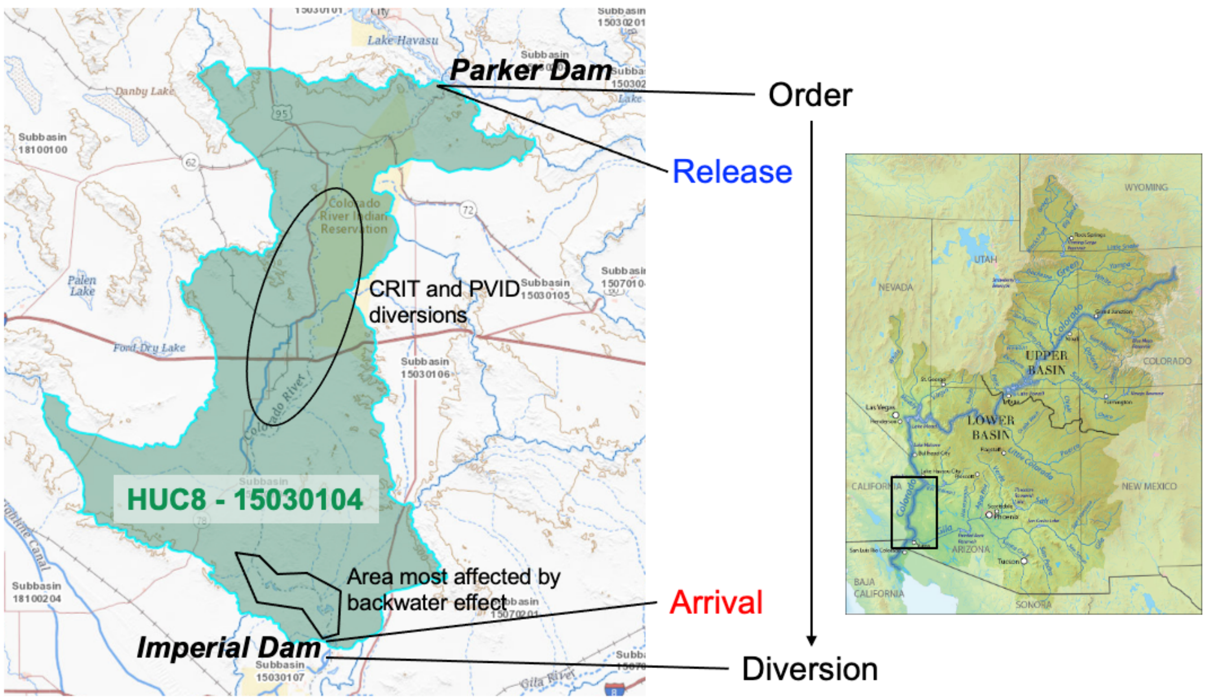

Figure 1: (Left) HUC8 domain used in this study. Objects and areas of interest are marked approximately (see text for details). (Right) Location of the study area, marked with a black box, within the Colorado River drainage.

1.2 Previous work

YAO operates a detailed implementation of RiverWare[1], built and maintained by Hydros Consulting, for their daily operational decisions. The model includes daily and sub-daily observational data on water orders, releases, diversions, return flows, and reservoir levels. It however does not include any weather information. YAO operators qualitatively consider local weather forecasts from standard weather apps and the National Weather Service website in their operations. The new National Water Model[2] was briefly considered by Reclamation for application to the YAO operational challenges, but lack of local calibration and lack of inclusion of scheduled reservoir releases rendered forecasted flows from the model too unrealistic for current use in this region.

[1] https://www.riverware.org/riverware/overview.html
[2] https://water.noaa.gov/about/nwm

1.3 Project scope

Reclamation requests support from NCAR (National Center for Atmospheric Research) and NOAA (National Oceanic and Atmospheric Administration) to assist in development of ensemble weather predictions for the YAO region and relevant drainage areas of the Colorado River basin. Reclamation also requests NCAR to develop a statistical gain/loss model for the reach between Parker and Imperial Dam, and then calibrate the model with measured flow over the historical period. Once the model calibration is complete, NCAR will develop gain/loss forecasts with 1-5 day lead times.

This project is guided by two overarching research questions:

1) What are the causes of losses and gains between Parker Dam and Imperial Dam?
   It is hypothesized that strong precipitation events can lead to gains through contributions from ungauged tributaries.

2) Can short-term weather forecasts be used to predict these losses and gains?
   It is hypothesized that locally calibrated precipitation forecasts together with records of releases, diversions, and return flows, can be used to develop a skillful forecast of losses and gains.

The study here focuses on the time period of overlap between different data sets used, which spans from 1 January 2003 to 31 December 2017. However, the workflow could be adjusted to run in real-time using continuous datasets. Necessary next steps are discussed in Section 4.

2. Data and Methods

2.1 Streamflow and precipitation data

We use daily streamflow data from the United States Geologic Survey (USGS), the Colorado River Indian Tribes (CRIT), and Palo Verde Irrigation District (PVID). The latter two are the main water users in between Parker and Imperial Dam. The gages are listed in Table 1.

Table 1: Streamflow gages used in this project.

Gage name	ID	Record used
Colorado River below Parker Dam	USGS 09427520	01/01/2003-12/31/2017
Colorado River above Imperial Dam	USGS 09429490	01/01/2003-12/31/2017
CRIT diversion	N/A	01/01/2003-12/31/2017
CRIT return flow	N/A	01/01/2003-12/31/2017
PVID diversion	N/A	01/01/2003-12/31/2017
PVID return flow	N/A	01/01/2003-12/31/2017

We use precipitation observations from NOAA's Climatology-Calibrated Precipitation Analysis (CCPA), which is a 6-hourly precipitation product that combines a gage-based analysis with Stage IV multisensory observations (Hou et al., 2014). The data was aggregated from 6-hourly to daily for the purpose of this study. The original spatial resolution of CCPA is 2km, but after testing the sensitivity of our results to spatial resolution, the data was aggregated to the HUC-8 (Hydrologic Unit Code) 15030104 domain, which exactly encompasses the drainage area between Parker and Imperial Dam.

2.2 Loss-gain time series

Losses and gains were calculated as the differences between the flow at Colorado River below Parker Dam (henceforth "release") and Colorado River above Imperial Dam (henceforth "arrival"). Thereby, the arrival values are lagged by 3 days, which was confirmed (via lag correlation) to be the average travel time between Parker and Imperial Dam. Further, diversions and return flows from CRIT and PVID in the Blythe and Palo Verde area are incorporated at a lag of 1 day, yielding the loss-gain time series for the reach between Parker and Imperia Dam (Fig. 2). There exists a distinct annual cycle in the release data originating from systematically varying agricultural demand. The loss-gain time series, on the other hand, does not exhibit a clear annual cycle.

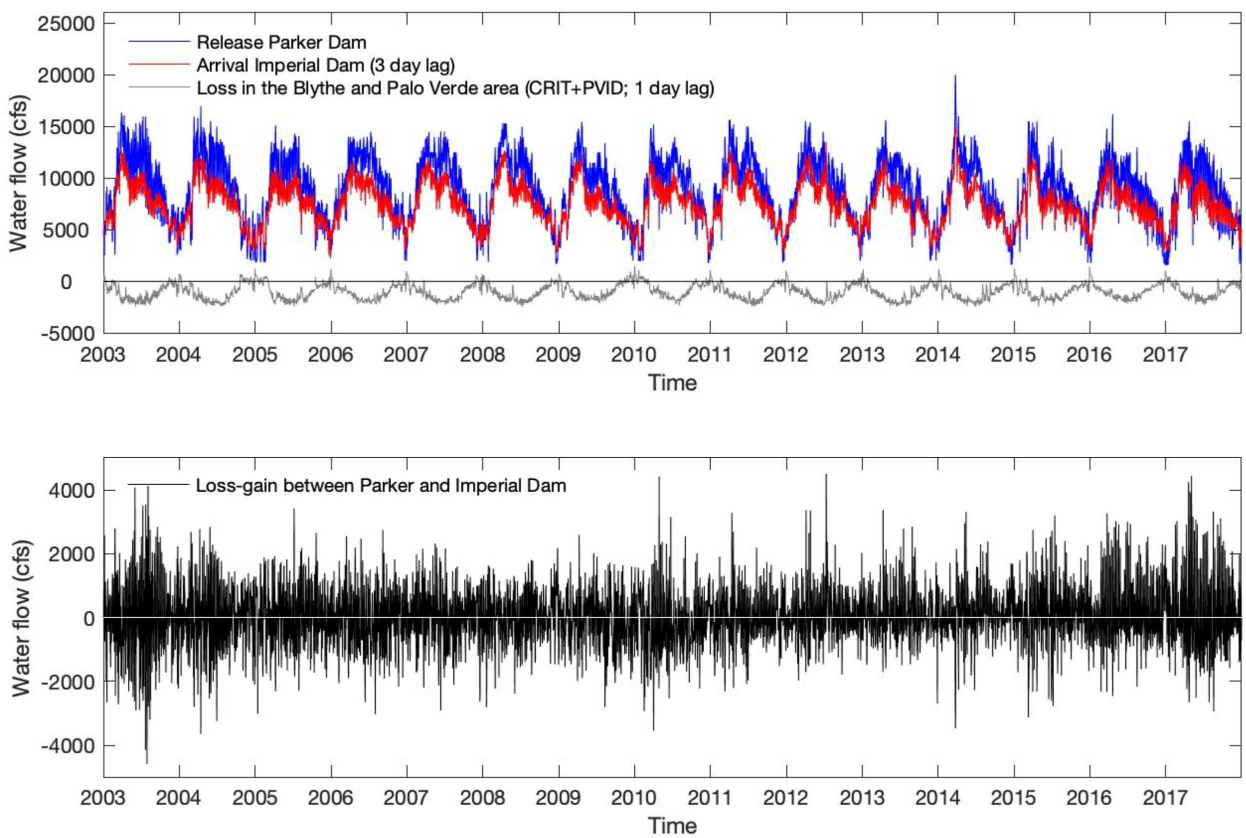

Figure 2: (Top) Daily releases from Parker Dam, arrivals at Imperial Dam, and losses (return flows minus diversions) in the Blythe and Palo Verde area in cubic feet per second (cfs).

2.3 Orders and diversions at Imperial Dam

We use daily total orders and diversions at Imperial Dam provided by Reclamation's YAO over the period 2012-2017 to investigate whether periods of water-ordered/not-delivered (WOND) are associated with precipitation events.

2.4 Precipitation forecasts and calibration

We use daily precipitation forecasts from a reforecast data set created for NOAA's Global Ensemble Forecast System (GEFS). Forecasts were extracted on a 0.5°x0.5° Gaussian grid for the period from January 1, 2002, to December 31, 2017. Reforecasts are available for 11 ensemble members. Further details about this data set can be found in Hamill et al. (2013).

Statistical post-processing is performed to correct systematic biases in the forecasts and to adjust the representation of forecast uncertainty by the ensemble. Forecasts were calibrated against the aggregated CCPA data described above. For the first post-processing step we use a variant of the distributional regression approach proposed by Scheuerer & Hamill (2015), which calculates summary statistics of the ensemble forecasts (ensemble mean, a measure of ensemble spread, etc.) and links them to the parameters of a parametric forecast distribution that models the forecast uncertainty. This yields calibrated probabilistic forecasts for each lead time (here: daily precipitation accumulations up to seven days ahead) in the form of probability distributions. To turn these back into a (calibrated) ensemble with a realistic serial correlation structure, a new variant of the Schaake shuffle (Clark et al., 2004) proposed by Scheuerer et al. (2017) was employed. A nice side effect of this 2-step statistical calibration procedure is that it allowed us to increase the ensemble size to 30 members, which permits a better representation of the forecast distribution.

2.5 Loss-gain forecasts

We use a linear regression model with 3-day average quantitative precipitation forecast ($\overline{QPF_{t-2:t}}$) as a predictor to forecast losses and gains at time t with lead times of up to 5 days. α, β, and ε are regression coefficients and residual, respectively.

$$Q_t = \alpha + \beta\overline{QPF_{t-2:t}} + \varepsilon$$

Since precipitation forecasts are zero-bounded, we only forecast gains, no losses:

$$Q_t = \begin{cases} Q_t, & if\ Q_t > 0 \\ 0, & if\ Q_t \leq 0 \end{cases}$$

It is conceivable that strong precipitation events themselves would be able to cause gains and subsequent losses involving the backwater effect (see Section 3.1), but this was not investigated and the backwater effect was assumed to be entirely driven by the Parker Dam release schedule.

In practice, gain forecasts were interpreted in a conditional sense, such that a certain probability p_1 and magnitude of forecasted precipitation θ_{QPF} was equated with a probability for a certain magnitude of gains θ_Q, ranging from 0 (any gains) to >2σ (gain of more than 1,475 cfs):

$$P\left(\overline{QPF_{t-2:t}} > \theta_{QPF}\right) > p_1 \sim P\left(Q_t > \theta_Q\right).$$

3. Results

3.1 Backwater effect and correction

Over the course of the study it was discovered that a significant backwater effect exists on the reach between Parker and Imperial Dam, between approximately 10 and 20 miles upstream of Imperial Dam. In that area several small side arms of the Colorado River (Martinez Lake, Ferguson Lake, Taylor Lake, Adobe Lake) fill and drain depending on the water level in the main stem. When filling, these backwaters temporarily consume water from the main stem, such that less water arrives at Imperial Dam than anticipated from the release at Parker Dam 3 days earlier, leading to an apparent, albeit not real, loss of water. Analogously, when backwaters are draining due to reduced main stem flow (due to reduced releases at Parker Dam), the backwaters will drain into the main stem, leading to more water arriving at Imperial Dam than anticipated from the release at Parker Dam 3 days earlier, leading to an apparent gain of water (see Fig. 3 for an example, the apparent gains are well visible in the loss-gain time series).

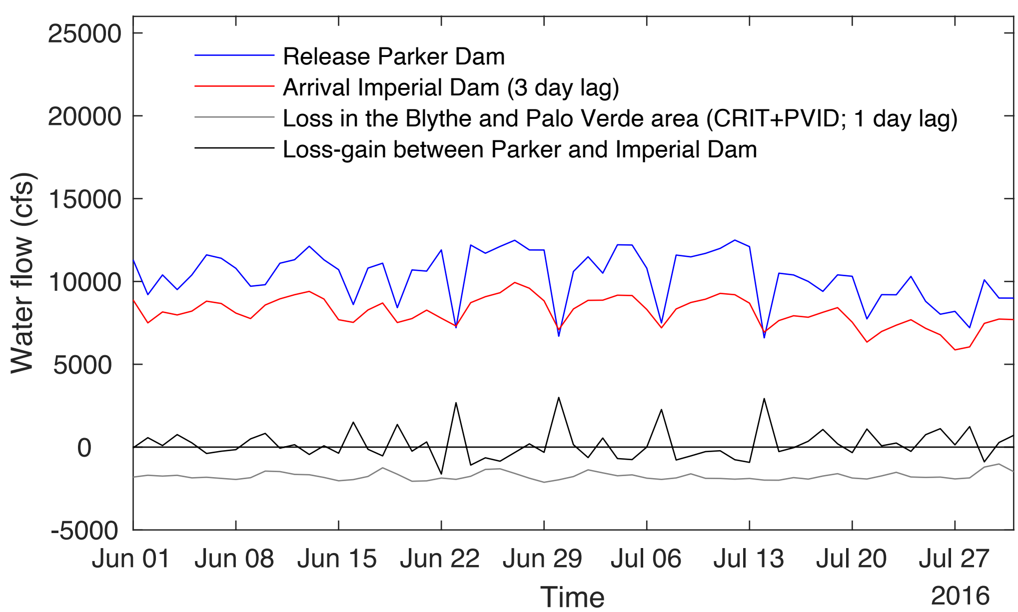

Figure 3: Daily releases from Parker Dam, arrivals at Imperial Dam, losses (return flows minus diversions) in the Blythe and Palo Verde area, and the overall loss-gain time series in cubic feet per second (cfs) during June-July in 2016.

It is also visible in Fig. 3 that the backwater effect occurs particularly pronounced when releases from Parker Dam drop sharply from one day to the next. This would be a case when backwaters drain due to a sudden drop in the main stem water level, leading to an apparent gain at Imperial Dam. After consultation with YAO operators, it was indicated that releases are usually lower on Thursdays, in anticipation of reduced irrigation on Sundays in the Yuma area. This is confirmed by looking at the day-to-day changes in Parker Dam releases, where there is a significant drop in release from Wednesdays to Thursdays and a concomitant increase from Thursdays to Fridays (Fig. 4 top).

Further confirmation of this pattern is obtained from analysis of the whole time series, which shows that the largest gains tend to be associated with the largest day-to-day drops in release, and that the largest losses tend to be associated with the largest day-to-day increases in release (Fig. 4 bottom). The relationship, measured by correlation, between day-to-day change and loss-gain exists on all week days, but is strongest for the Wednesday-to-Thursday and Thursday-to-Friday changes, consistent with the general narrative.

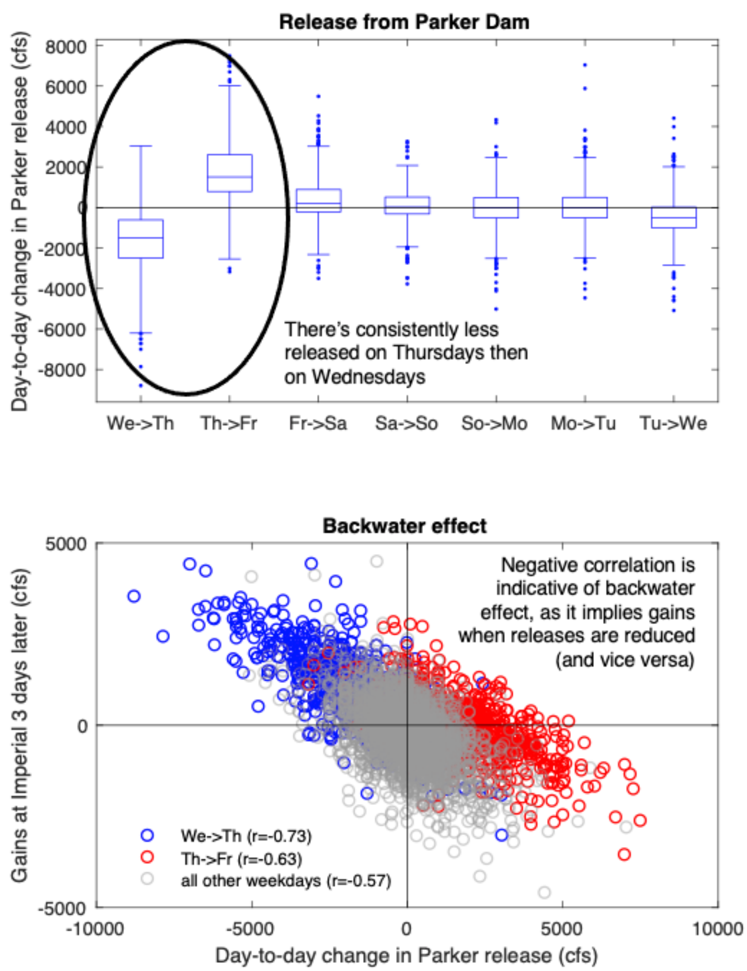

Figure 4: (Top) Day-to-day change in Parker Dam release over the years 2003-2017. Box plots give the median, inter-quartile range, 5th and 95th percentile, and outliers. (Bottom) Gains at Imperial Dam as a function of day-to-day change in Parker Dam release.

Since the backwater effect is largely unrelated to precipitation and thus complicates the identification of the precipitation influence on the loss-gain time series, we attempt to remove it with a linear regression between day-to-day changes in release and loss-gain. Other backwater models are possible and were discussed with Hydros Consulting, who have developed the routing from Parker to Imperial Dam in RiverWare (Steve Setzer, personal communication, June 2021).

The backwater correction reduces the daily variability in the loss-gain time series by 20% (measured by standard deviation). The correction appears to be most effective in reducing variability during days with little to no precipitation, as measured by observed 3-day precipitation totals from CCPA (Fig. 5), which is as intended, since we want to avoid removing variability that is in fact associated with precipitation events.

At the same time, Fig. 5 underscores that only the strongest precipitation events cause a discernable shift of the loss-gain probability distribution towards more gains and that there exists no obvious linear or even lower-order nonlinear relationship between precipitation and losses and gains. Indeed, the largest gains (and losses) of the record occur during days with no precipitation.

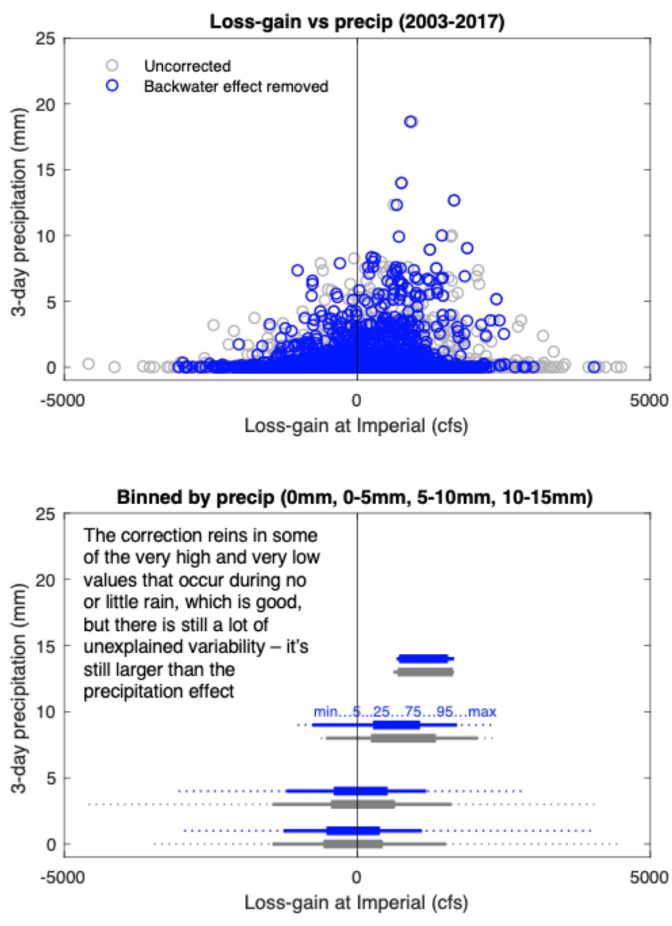

Figure 5: (Top) Relationship between daily loss-gain values and 3-day precipitation values from CPAA aggregated over the HUC8 domain between Parker and Imperial Dam for uncorrected and backwater effect-corrected loss-gain time series. (Bottom) Same as (Top), but as box plots binned according to precipitation levels 0mm, 0-5mm, 5-10mm, 10-15mm.

3.2 Water-ordered/not-delivered (WOND)

There is anecdotal evidence that water users do not divert water they previously ordered if a strong precipitation event causes natural irrigation, thereby at short notice eliminating the need to divert water for irrigation. These water-ordered/not-delivered (WOND) events are common, since there are no penalties for not diverting/using water that has been ordered, hence there is no incentive on the user side to avoid WOND. This is reflected in an average WOND of 640 cfs, which is well above zero (Fig. 6 left). Here we use 2 standard deviations as a threshold to identify the largest 40 WOND events over the period 2012-2017. We then collect precipitation for the same dates and find that the WOND events indeed occur predominately during anomalous precipitation events, events that themselves exceed 2 standard deviation of daily precipitation (Fig. 6 top row). The inverse is confirmed as well, that is, during strong precipitation events WOND events are more likely to occur (Fig. 6 bottom row). This serves as a confirmation of the influence of precipitation on water user behavior and illustrates the challenges for YAO to deal with such excess water at short notice.

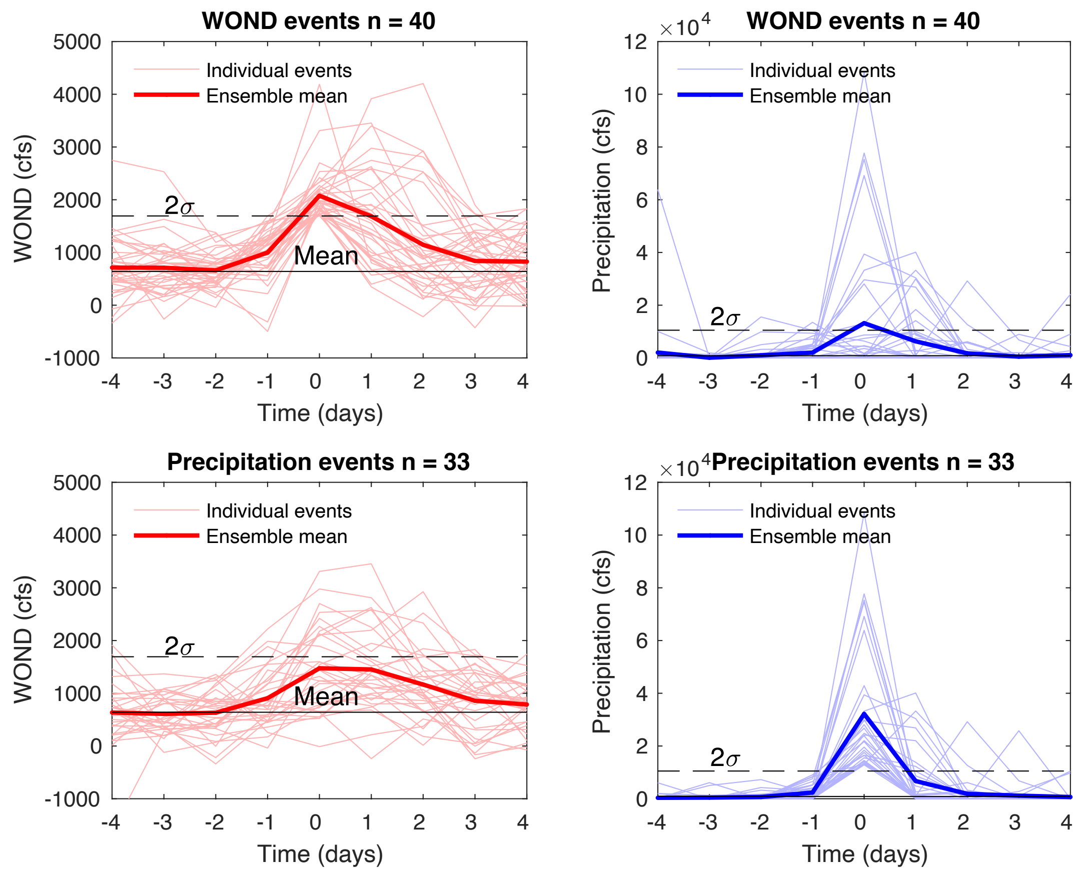

Figure 6: (Top left) Water-ordered/not-delivered (WOND) events, defined as exceeding 2 standard deviations (σ) of the full WOND time series. The long-term mean and 2σ threshold are indicated. Individual events and their mean are given in thin and bold lines respectively. (Top right) Daily precipitation during the WOND events. (Bottom left) WOND events during 2σ daily precipitation events. (Bottom right) 2σ daily precipitation events.

3.3 Precipitation forecasts

Fig. 7 shows the evolution of forecast skill with lead time at different times of the year. Forecast performance is measured via the continuous ranked probability score (CRPS) and put into context by relating it to the CRPS of a climatological forecast. Values of the resulting skill score ('CRPSS') larger than zero suggest that the calibrated forecasts provide potentially useful information, whereas values below zero indicate that one is better off with using climatological precipitation scenarios as input to the loss-gain model. A perfect forecast would achieve a CRPSS of 1.0. The curves in Fig. 7 suggest that forecast skill is relatively low during most times of the year. A notable exception is fall, where good forecast skill is obtained for up to five days ahead. Calibrated forecasts still show some amount of skill during spring, but in summer and winter the CRPSS is very close to zero, so the utility of this forecast information is limited.

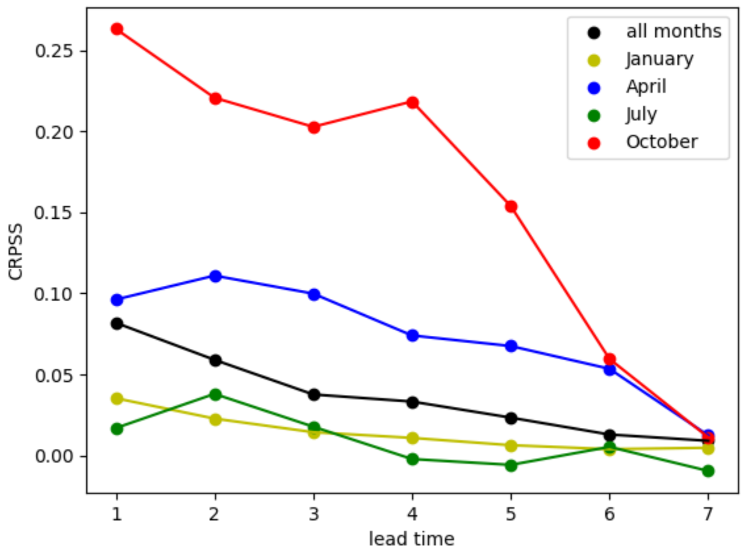

Figure 7: Continuous ranked probability skill scores (CRPSSs) as a function of lead time, calculated separately for each month. One month is depicted for each season to illustrate the differences in skill over the course of the year.

3.4 Loss-gain forecasts

As alluded to in Section 3.1, only the strongest precipitation events are associated with a discernable shift of the loss-gain probability distribution towards more gains (Fig. 5). Consequently, only strong and successfully forecasted precipitation events might provide potential for skillful gain forecasts.

Due to the lack of a robust linear or non-linear model for the relationship between precipitation and the loss-gain time series, we focus on conditional forecasts. Specifically, we test whether different magnitudes of forecasted 3-day precipitation are associated with different odds of correctly forecasting an observed gain within a 3-day period after the forecasted precipitation peak.

Forecast performance is assessed through contingency tables to understand how frequently significant gains are (1) forecasted and observed, (2) forecasted but not observed, (3) not forecasted but observed, and (4) not forecasted or observed. Example cases for scenarios (1)-(3) are illustrated in Fig. 8.

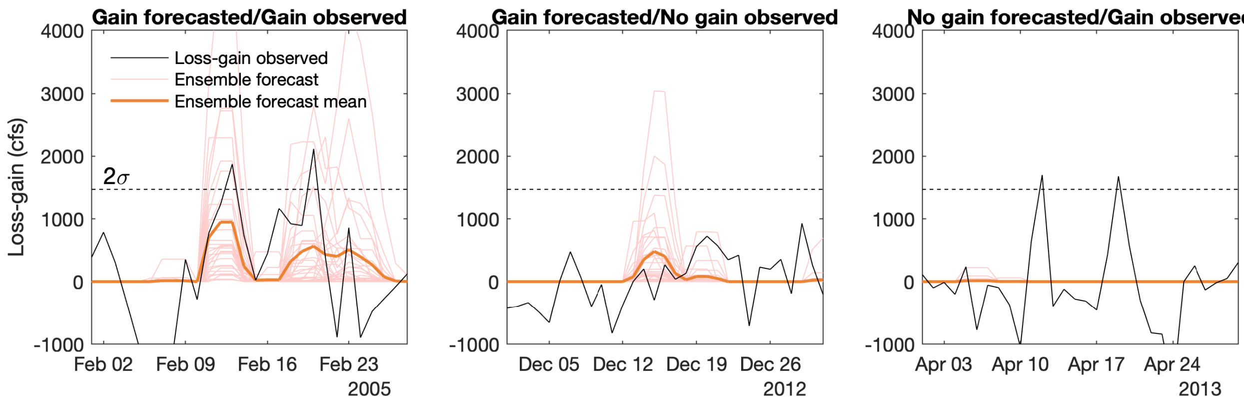

Figure 8: Illustrative cases of (left) a successful forecast and (middle, right) unsuccessful forecasts. Shown is the observed loss-gain time series and the 30 ensemble members of the precipitation forecast (arbitrarily scaled to match the y-axis) and its ensemble mean at lead time 1 day. The two standard deviations (2σ) threshold of the loss-gain time series is given as a dashed line.

Given that the Yuma area is very dry with only infrequent precipitation, we focus on scenario (1), the "true positive" forecasts, as those are most likely to be of practical use. In other words, weather-based gain forecasts are likely only considered by the operator when a chance of precipitation is actually forecasted. Scenario (2), "false positives", can then be inferred from the inverse probabilities.

Figure 9 shows the fraction of correctly forecasted gain events above various thresholds. In the scenario where we forecast *any* gains (loss-gain time series > 0), the precipitation-based gain forecast is skillful out to about 3 days lead time. That is, if a chance for precipitation, P(pr > 0 mm/day) > 0, is used as a criterion to predict gains, the forecast is correct between 80% and 100% of the time. For lead times greater than 3 days, there is no benefit from the forecast beyond the climatological chance of seeing a gain in any 3-day period (dashed black line in Fig. 9). There is an intuitive gradation across the different strength of precipitation forecasts: if there is a chance for stronger precipitation events, the chance for a correct gain forecast increases. This confirms that the *observed* relationship – that stronger precipitation events are typically associated with larger gains – translates to *forecasted* precipitation. In other words, the precipitation forecast skill discussed in Section 3.3 is sufficient to extend to skillful gain forecasts, skillful here refers to the ability to correctly predict the occurrence of gains of any magnitude, but not any specific magnitude (see next paragraph).

If we focus on forecasting gains >1σ (738 cfs), forecasts are also skillful for lead times of 3 days, but only the strongest precipitation forecasts still yield correct gain forecasts >60% of the time. For gains >2σ (1,475 cfs), the fraction of correct forecasts drops to <20%. This is consistent with the results from Section 3.1, where it was shown that the largest gains (and losses) occur during periods without precipitation, thus while strong precipitation events do increase the chance for gains, the strongest gains are typically not associated with or predictable from precipitation.

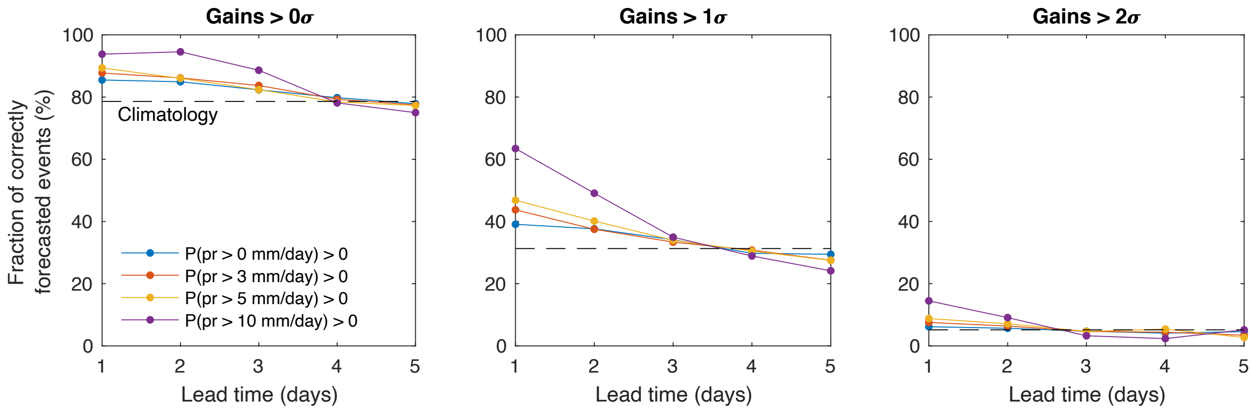

Figure 9: Fraction of correctly forecasted categorical events for (left) gains >0, (middle) gains >1σ, and (right) gains >2σ. Forecasts and climatology are calculated as the probability to predict a particular threshold exceedance in any of the 3 days including and following the forecast time.

The low skill in predicting large gains notwithstanding, the forecasting approach explored here could provide useful guidance regarding the operator's expectation for precipitation-driven gains. There is a robust increase in the probability for gains for any precipitation forecast with up to 3-day lead time. Stronger precipitation forecasts (or forecasts with higher probability) are robustly associated with a higher probability for gains.

4. Discussion

This study aimed at identifying the main drivers of losses and gains on the Colorado River reach between Parker and Imperial Dam. It confirmed that strong precipitation events can lead to gains at Imperial Dam. It was also revealed that there is substantial variability in the loss-gain time series unrelated to precipitation. Part of this variability originates from a pronounced backwater effect in the lower part of the reach and is tied to the release scheduling at Parker Dam. However, substantial loss-gain variability unrelated to precipitation remains even after empirically removing the backwater effect, thus leaving the door open for other possible drivers such as routing and gage biases (a topic investigated by Hydros Consulting).

The residual loss-gain variability makes it challenging to develop a skillful precipitation-based forecast model for large gains. Further, precipitation forecast skill is low in this region in general, in particular in summer, although strong events at short lead time are better forecasted. Precipitation-based gain forecasts are skillful in indicating increased odds for gains in general in the days following a forecasted precipitation event.

These results might not immediately support a reliable and sharp forecast of the largest gains, as was hoped for at the onset of the project. Large gains are of greater interest than small gains due to the challenges they pose for YAO operations and its limited reservoir storage. However, there might still be value in conditional forecasts that provide guidance on the probability of gains over assuming climatology. The intermittency of precipitation in the Yuma area suggests that these conditional gain forecasts could be considered on a case-by-case basis by the operators, supplementing or replacing the more ad hoc consideration of other weather forecasting products.

This study raises several additional questions and potential future avenues of research. Routing and accounting for backwater effects could potentially be improved by using hourly data where available. Although originally part of the project scope, we did not investigate additional precipitation forecast products beyond GEFS. It is conceivable that higher-resolution deterministic forecasts provide more accurate precipitation forecast at shorter lead times (1-1.5 days) during the convectively active season. A newer version of GEFS (v12) has recently been released and would be the product of choice when transitioning the gain forecast model to operations.

5. Data location

Certain code and data used in this project are contained in online repositories, including:

- GEFS precipitation forecast calibration and evaluation (Michael Scheuerer): https://github.com/mscheuerer/PrecipitationFields
- Loss-gain forecast and evaluation scripts (including data used in this study): https://github.com/flehner/yuma_project

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Metric Conversions

Provide metric equivalents for non-metric units used in the text:

Unit	Metric Equivalent
1 acre foot (af)	1233.48 cubic meters per second
1 cubic foot per second (cfs)	0.028316847 cubic meters per second