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Insights into forecast-informed operation of the Hume Dam release

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The authors pay respect to the Traditional Owners and their Nations of the Murray−Darling Basin. We acknowledge their deep cultural, social, environmental, spiritual and economic connection to their lands and waters.

Project background

Project 8a of Theme 2 (T2.8a) of the Murray-Darling Basin Water and Environment Research Program (MD-WERP) aims to demonstrate the value of ensemble water forecasts for river operations decision-making in the Murray-Darling Basin (MDB). We hope the project outcomes will provide new understanding on how ensemble water forecasts can assist with river operations, particularly with quantifying and managing uncertainties.

This report is the project's fourth deliverable. It follows from the second deliverable report (Ng and Robertson, 2022). In the second report, we presented a case study of the Murray River between Hume Dam and Lake Mulwala for which we developed a prototype forecasting model to produce ensemble forecasts of the level of and outflow from Lake Mulwala, given the Hume Dam release and forecasts of tributary inflows and irrigation diversions. In the second report, we demonstrated the model for example events.

In this fourth report, we further refine the forecasting model from the second report. With the updated forecasting model, we develop decision rules governing the Hume Dam release for simulating the system on a rolling basis to investigate practical questions on using ensemble forecasts for operational decision-making. In the following, we describe the case study, our methods and the answers derived to the operational questions investigated.

Introduction

This case study is about how ensemble flow and demand forecasts can be applied to inform the release from Hume Dam, on the Murray River. The Hume Dam is operated by the Murray-Darling Basin Authority (MDBA) primarily for water supply. Release from the dam combines with tributary inflows – including those from Kiewa and Ovens Rivers – for delivery to Lake Mulwala, about four-five days downstream of the dam, and from there to: (i) Murray Valley Irrigation District, in Victoria, via Yarrawonga Main Channel, (ii) Murray Irrigation District, in New South Wales, via Mulwala Canal and (iii) other users further downstream. See Figure 1 for a schematic of the system.

The MDBA also operates Lake Mulwala, primarily as a point of diversion of the Murray River flow to the above irrigation districts but also as a small buffer storage for storing surplus water for later use. This buffering capacity of the lake allows for, to some degree, an over- or underestimation of the required Hume Dam release without significant consequences. However, the buffering capacity of the lake is limited as it is desired that the lake level remains within a range, 124.7-124.9 m, corresponding to the lake volume of 108,670-117,790 ML.

To decide on the Hume Dam release requires some forecast of the Kiewa and Ovens inflows and diversion demands from Lake Mulwala over the next several days. This is due to the four-five day travel time from the dam to the lake. However, to accurately generate the forecasts is not trivial. Both the Kiewa and Ovens are mostly unregulated; thus, their inflows can be highly variable depending on the weather and antecedent catchment conditions. The diversion demands from Lake Mulwala can also be highly uncertain due to the unpredictability of weather and thus, unpredictability of irrigators' water needs.

The problem is further complicated by the different travel times of the Hume Dam release and Kiewa and Ovens inflows to Lake Mulwala. The different travel times, ranging from one to five days, make it challenging to accurately amalgamate forecasts, especially ensemble forecasts, of the Kiewa and Ovens inflows and downstream demands for water with the Hume Dam release.

In real-time river operations, these factors can cause an over- or underestimation of the required Hume Dam release. An overestimation can lead to an excess in the outflow from Lake Mulwala and thus, less efficient operations. An underestimation can result in an inability to fully meet demands and therefore, a water supply shortage from the lake. Thus, this study aims to investigate how ensemble flow and demand forecasts can be used to improve river operations, in particular, to reduce the water excess and shortage from the lake.

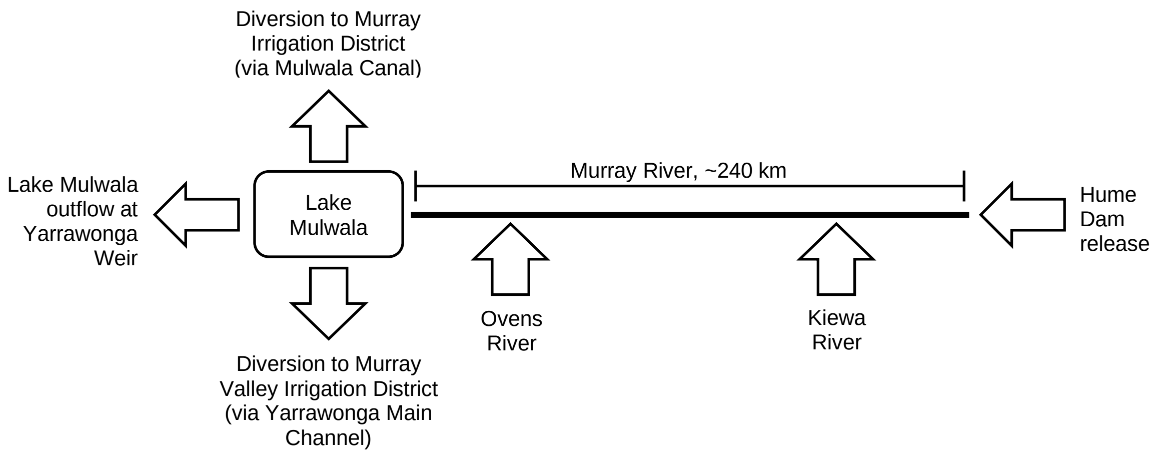

Figure 1. Section of Murray River from Hume Dam to Lake Mulwala and the tributaries Kiewa and Ovens Rivers to the Murray, diversions to Murray Valley Irrigation District (via Yarrawonga Main Channel) and Murray Irrigation District (via Mulwala Canal) from Lake Mulwala and Lake Mulwala outflow at Yarrawonga Weir

Methods

We develop a hydrologic model of the Murray River from Hume Dam to the inlet of Lake Mulwala using the SWIFT2 (Short-term Water Information and Forecasting Tool version 2) modelling platform (Perraud et al., 2015). The hydrologic model comprises the lag-and-route routing model, GR4H rainfall-runoff model and an error model, the Error Reduction and Representation in Stages model (ERRIS; Bennett et al., 2021). We calibrate and validate the model to over twenty sites, including the inlet to Lake Mulwala. The hydrologic model serves two purposes: (i) To generate retrospective ensemble forecasts of tributary inflows to the Murray, including the Kiewa and Ovens inflows, and (ii) to amalgamate the forecasts of the tributary inflows with the Hume Dam release to produce ensemble forecasts of the inflow to Lake Mulwala from the Murray.

We also develop statistical models to produce ensemble forecasts of the water demands from Lake Mulwala to Murray Valley and Murray Irrigation Districts. We predict the demands from orders provided four days in advance by the districts to the MDBA. To develop the models, we use a Bayesian Joint Probability (BJP) modelling approach (Robertson et al., 2013; Shrestha et al., 2015) with Yeo-Johnson transformation. We develop the models using historical MDBA data of daily demands and orders from 2010 to 2016. We apply the Schaake Shuffle (Clark et al., 2004) to the resulting ensemble forecasts to instil in them realistic spatial correlations.

We integrate the hydrologic and demand forecasting models developed with a mass balance model of Lake Mulwala. The integrated model serves to forecast, as a function of the Hume Dam release, the lake storage and level. We apply the integrated model to examine forecast-informed Hume Dam release strategies. For our analysis, we assume an allowable range of the lake level of 124.7-124.9 m and a target outflow from the lake of 9000 ML/day. (Under normal conditions, the outflow from Lake Mulwala is mostly governed by downstream demands and is limited to ~9000 ML/day by the Barmah Choke, a narrow section of the Murray River downstream of Yarrawonga.) The model also assumes that any exceedance of the lake level past 127.9 m will trigger an excess in the outflow from the lake, and conversely, any reduction in the lake level to below 124.7 m will trigger a shortage in the supply of water to meet demands.

With the integrated model, we develop three forecast-based decision rules to govern the Hume Dam release. Each rule receives as input ensemble tributary inflow and demand forecasts, and yields as output ensemble forecasts of the water excess (in the outflow) and shortage (in the supply) from Lake Mulwala and with that, a recommendation on the Hume Dam release.

Following the minimax regret principle, the rules seek to identify the Hume Dam release that best minimises the potential worst-case water excess or shortage from Lake Mulwala. A given Hume Dam release will yield a potential for water excess and shortage from the lake. The worst outcome for the given release will be the maximum of this potential shortage and excess. The minimax principle seeks to find the release that minimises this worst outcome. The first and second rules model this potential worst outcome according to the expectations (means) and medians, respectively of the output ensemble excess and shortage forecasts. The third rule models it according to the risks of an excess or shortage as estimated by the output forecasts. In all three rules, the estimate of the worst outcome is averaged over lead time.

The decision rules rely on simulations of the system. They operate by simulating the system for several scenarios of the Hume Dam release, then interpolating between the scenarios to identify the best Hume Dam release. For easy interpolation, we set the Hume Dam release constant through the forecast horizon when simulating the system. An advantage of such a simulation-based approach (as opposed to an optimisation approach) is its simplicity and thus ease of operationalisation.

The decision rules impose a limit on the day-to-day change in the Hume Dam release. We consider two cases of the limit, 1300 ML/day (15 m^3/s) and 6500 ML/day (75 m^3/s). The first case represents a strict case where the limit is frequently binding, and roughly corresponds to the limit imposed on the dam release by the ‘six-inch rule’ (Department of Environment, Land, Water and Planning, 2015). The second case represents a more relaxed case where the limit is mostly non-binding.

We implement the decision rules on a rolling basis to simulate the Hume Dam release and inflow to Lake Mulwala over time and ensuing water excess and shortage from the lake. We model each new iteration as representing the start of a new day. With each new iteration, we rerun the decision rules with new input tributary inflow and demand forecasts to yield new recommendations on the Hume Dam release over the next several days but retain and apply only the recommendations for the first day. In this manner, we simulate, day by day, the system performance under the different rules.

Operational questions

We analyse the results to gain new insights into the questions below.

(a) Which of the decision rules developed is best for managing Hume Dam for water supply and under what conditions?

(b) How far ahead of inflow and demand forecasts should Hume Dam operators adopt?

(c) How do constraints on the day-to-day change in the Hume Dam release influence the value of forecast operations?

(d) What value is there, in terms of the system performance, of improved diversion demand forecasts?

Which of the decision rules developed is best for managing Hume Dam for water supply and under what conditions?

Figure 2 shows the realised system performance, from 2010 to 2014, under each rule in terms of the total excess outflow (left) and total supply shortage (right) from Lake Mulwala, summed over September to April. The top and bottom panels are for the limit on the day-to-day change in the Hume Dam release of 1300 ML/day (15 m^3/s) and 6500 ML/day (75 m^3/s) respectively. Both panels assume up to 8 days ahead tributary inflow and demand forecasts informing the decisions rules. The results are normalised to the expectation-based rule. Thus, they represent the differences of the three rules from the expectation-based rule. Where the difference is negative, the expectation-based rule is inferior and where it is positive, the expectation-based rule is superior.

From the left side graphs in Figure 2, we find in general, the expectation-based decision rule best for minimising the excess outflow from Lake Mulwala, or in other words, for managing high flows. This is as expected as streamflow is bounded by zero on the lower end but unbounded on the upper end. This can cause the tributary inflow forecasts informing the decision rules to be skewed upwards by high ensemble members, especially in times of high flow. When this is so, we can expect inflated forecast expectations and thus, increased reductions in the Hume Dam release when computing the release using the expectation-based rule in the face of high flows. Note however, where the limit on the change in the Hume Dam release is low (1300 ML/day), the expectation-based rule can sometimes fail to produce the least excess outflow (such as in 2010 and 2011). This is because where the limit is low, it can sometimes act to prevent the Hume Dam release from adapting fast enough, thus curtailing the usual behaviours of the different rules, for better or worse.

From the right side graphs in Figure 2, we observe that the risk-based decision rule is best for minimising the water supply shortage from Lake Mulwala. This is true for both cases of the limit on the change in the Hume Dam release considered. The risk-based rule is best here as it considers only the forecast probabilities of a water excess or shortage and not their potential magnitudes. It is thus unaffected by high forecast ensemble members that can unduly influence the behaviours of the other two rules (the expectation- and median-based rules). This allows the risk-based rule to give greater priority, as compared to the other two rules, to minimising the water supply shortage from Lake Mulwala.

Based on the results, we recommend a mixed use of the decision rules. We recommend using the risk-based rule in times of low to medium flow, which is the majority of the time. And in times of high flow (or expected high flow), we recommend the expectation-based rule. Bear in mind though, that where there is a strict limit on the change in the Hume Dam release, the expectation-based rule is not always best for minimising the excess outflow from Lake Mulwala. This is because where the limit is strict, it can act to curtail the system performance, thus affecting the relative behaviours of the different rules.

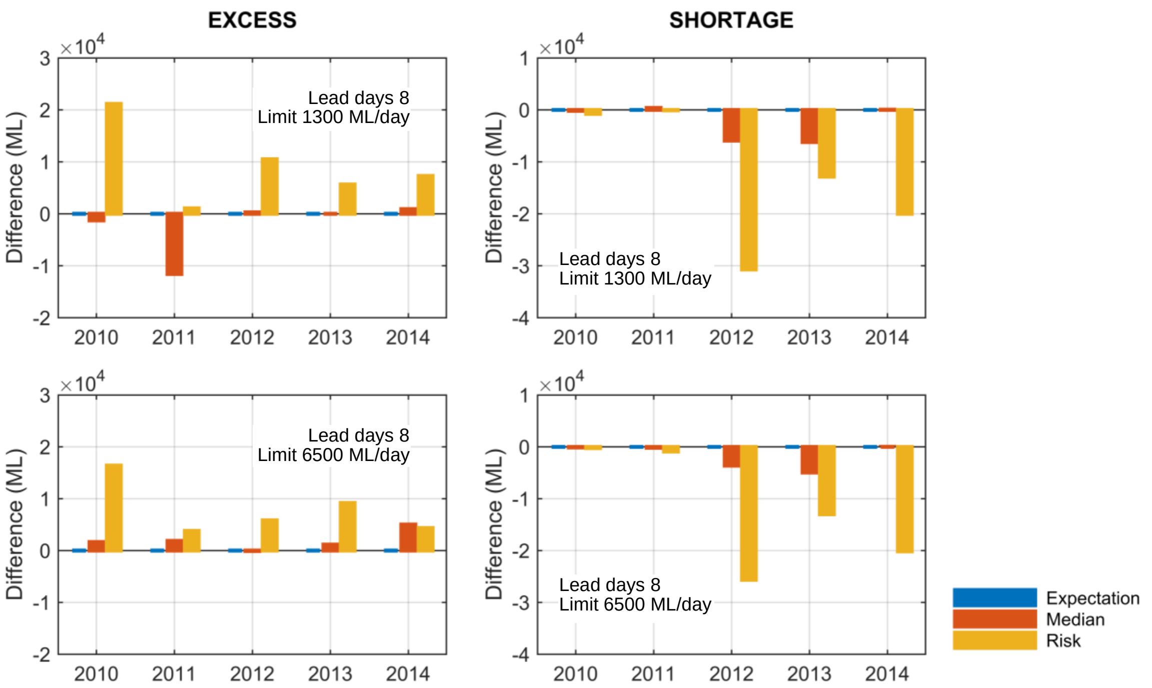

Figure 2. Relative performances of the expectation-, median- and risk-based decision rules developed in terms of the total excess outflow (left) and total supply shortage (right) from Lake Mulwala; the results are normalised to the expectation-based rule; top and bottom panel results are for the limit on the change in the Hume Dam release of 1300 and 6500 ML/day respectively; both panels assume up to 8 days ahead forecasts

How far ahead of inflow and demand forecasts should Hume Dam operators adopt?

Figure 3 gives the realised system performance under the risk-based rule assuming different lead time lengths of the input tributary inflow and demand forecasts to the decision rules. For brevity, we give only the results for the risk-based rule as the trends are the same for the other rules. We show the results for six scenarios of lead time length, from 5 to 10 days ahead. We have selected these scenarios on the basis that the travel time from Hume Dam to Lake Mulwala is ~4-5 days.

The results are in terms of the sum of the total excess outflow and total supply shortage from Lake Mulwala, over eight months from September to April. The left and right graphs give the results for when the limit on the day-to-day change in the Hume Dam release is 1300 ML/day (15 m^3/s) and 6500 ML/day (75 m^3/s) respectively. The results are normalised to the first lead time scenario of 5 days ahead and thus, represent the differences of the various lead time scenarios from the first. A negative difference denotes a better overall system performance, compared to the first lead time scenario, while a positive difference denotes a poorer overall system performance.

From the left graph in Figure 3, we observe that where the limit on the change in the Hume Dam release is low (1300 ML/day), there is no one scenario of lead times that consistently outperforms. Instead, what is best varies year to year. This is not unexpected as longer forecast lead times mean a longer foresight and therefore, a greater ability for the decision-maker to hedge for the future, but at the same time, longer lead times can also mean poorer forecast skill overall and therefore, poorer operational decisions. Thus, the ideal length of lead times is not usually obvious and can vary depending on circumstances.

The right graph in Figure 3 shows that where the limit on the change in the Hume Dam release is high (6500 ML/day), the system performs best with 5 days ahead forecasts. This is true for all five years examined except 2010. For 2010, 6 days ahead forecasts are better but their advantage over 5 days ahead forecasts that year is relatively minor. 5 days ahead forecasts are best when the limit on the change in the Hume Dam release is high because a higher limit allows for quick adaptability of the dam release to changing conditions, e.g., a fast-approaching storm event. When the Hume Dam release is allowed to rise and fall as needed, there is little need for longer lead times as no advanced hedging of the system with the early ramping up or down of the dam release is usually necessary.

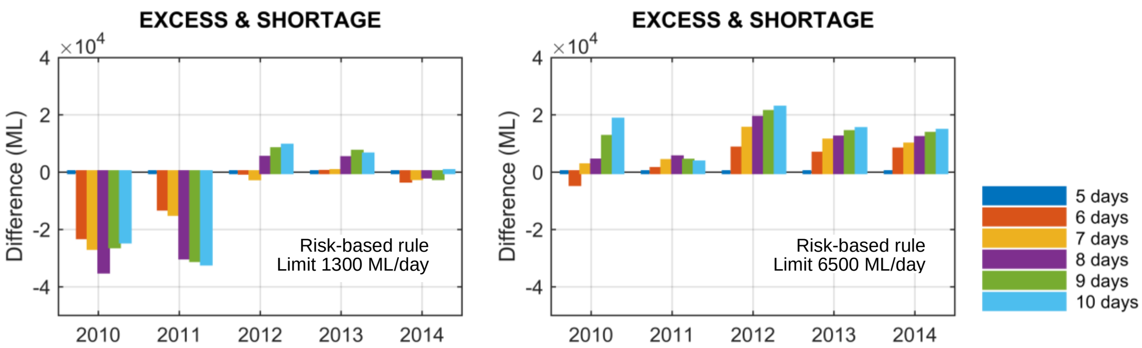

Figure 3. The system performance under the risk-based rule for forecast lead times from up to 5 to 10 days in terms of the sum of the total excess outflow and total supply shortage from Lake Mulwala; left and right graphs give the results for the limit on the change in the Hume Dam release of 1300 and 6500 ML/day respectively; the results are normalised to first lead time scenario of 5 days ahead

How do constraints on the day-to-day change in the Hume Dam release influence the value of forecast operations?

In the previous sections, we examine the effects of this limit on the relative performances of the decision rules developed and its interplay with the forecast lead time length. In this section, we investigate how changing the limit from 1300 ML/day (15 m^3/s) to 6500 ML/day (75 m^3/s) affects the system performance.

Figure 4 gives the results in terms of the total water excess (left) and shortage (right) from Lake Mulwala, summed over September to April. The results are normalised to the first case where the said limit is set to 1300 ML/day and thus, represent the differences of the two cases from the first case. To be concise, we show only the results for the risk-based decision rule with 8 days ahead forecasts.

From the figure, we find that increasing the limit on the change in the Hume Dam release improves the system performance. This is because, as discussed in the previous section, increasing the limit gives greater flexibility to the system to raise or lower the Hume Dam release as needed in response to changing conditions. This enables more optimal decisions and consequently, better system performance.

Comparing the left and right graphs in Figure 4, we find that increasing the limit on the change in the Hume Dam release has significant benefit only in terms of the total water excess from Lake Mulwala but little benefit in terms of the total water shortage from the lake. This is because the water excess is caused mostly by high flow events that can develop suddenly and quickly. Whereas the water shortage is caused mainly by receding or low flows that are usually more gradual. Thus, the increased flexibility from increasing the said limit has more value for managing the water excess than for managing the water shortage.

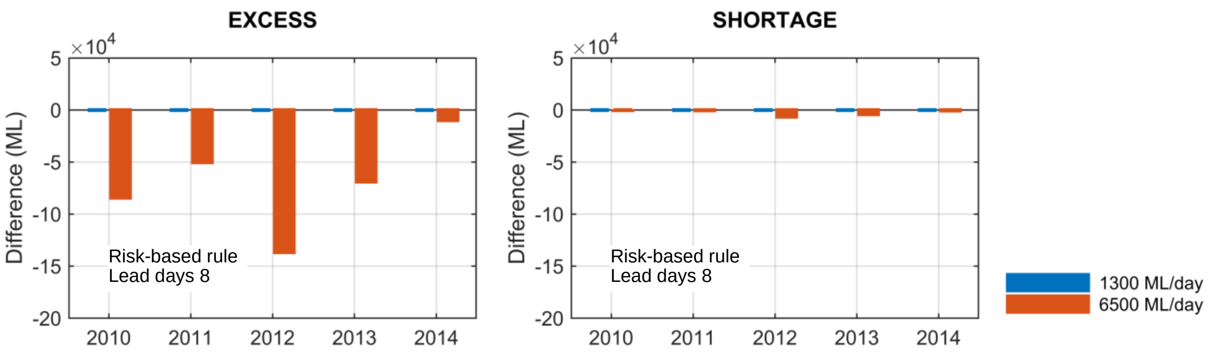

Figure 4. Effects of increasing the limit on the change in the Hume Dam release from 1300 to 6500 ML/day under the risk-based rule assuming up to 8 days ahead forecasts; the results are in terms of the total excess outflow (left) and total supply shortage (right) from Lake Mulwala and are normalised to the first case of the said limit of 1300 ML/day

What value is there, in terms of the system performance, of improved diversion demand forecasts?

In this section, we evaluate the potential benefit of more accurate forecasts of the diversion demands from Lake Mulwala to Murray Valley and Murray Irrigation Districts. This question is of interest as the demand forecasts are a direct factor in the decision-making for the Hume Dam release and improving their accuracy can potentially reduce the uncertainties affecting the decision-making process, leading to more optimal release decisions.

To answer the question, we rerun our simulations assuming perfect forecasts of the demands and compare the results with our original results assuming uncertain forecasts of the demands. Figure 5 shows the results in terms of the total water excess (left) and shortage (right) from Lake Mulwala, from September to April. The figure gives the differences of the new results (assuming perfect demand forecasts) from the original results assuming (uncertain demand forecasts). For brevity, we show and discuss only the results for the risk-based rule with 8 days ahead forecasts and the limit on the day-to-day change in the Hume Dam release set at 1300 ML/day (15 m^3/s).

The negative differences in Figure 5 indicate, as expected, that the system performs better with perfect demand forecasts, in terms of both reduced water excess and reduced water shortage from Lake Mulwala. From the left graph in the figure, we find applying the perfect demand forecasts to reduce the total excess outflow from Lake Mulwala by ~40,000-130,000 ML or 4.4-14.4 times the target daily outflow from Lake Mulwala of 9000 ML/day. From the right graph, we find applying the perfect demands forecasts to reduce the total shortage in the supply from Lake Mulwala by up to 90,000 ML or 10 times the target daily outflow from Lake Mulwala.

These reductions may or may not be worth the cost of improving the diversion demand forecasts. Regardless, practically, the actual reductions in the water excess and shortage from Lake Mulwala that can be potentially realised from improving the demand forecasts are likely lower than the estimates here. This is because in the real world, perfect forecasts are not possible and whatever improvements to the forecasts that can be had are unlikely to lead to the same level of benefit as obtained here.

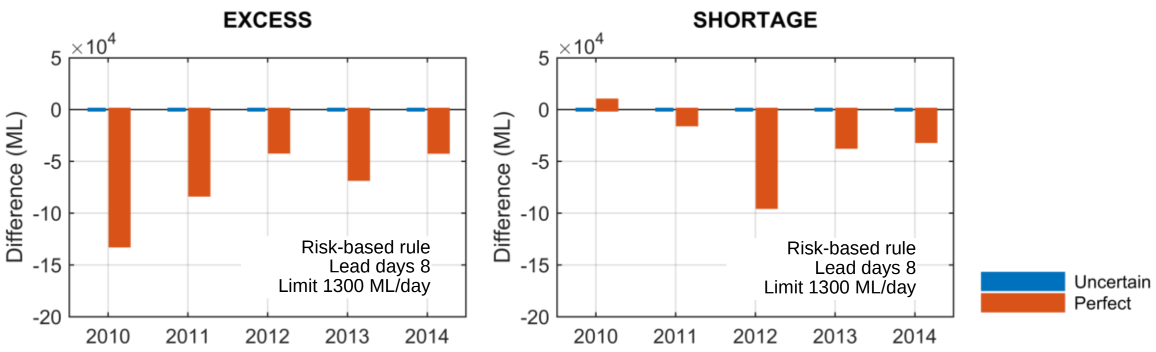

Figure 5. Value of perfect forecasts of the diversion demands from Lake Mulwala under the risk-based rule assuming 8 days ahead forecasts and the limit on the change in the Hume Dam release of 1300 ML/day; the results are in terms of the total excess outflow (left) and total water shortage (right) from Lake Mulwala and are normalised to the base case of uncertain demand forecasts

Summary and conclusions

In this report, we demonstrate how ensemble flow and demand forecasts can be used to inform the release from Hume Dam for delivery of water to Lake Mulwala. We develop and compare three forecast-based decision rules to govern the Hume Dam release. The rules receive as input ensemble tributary inflow and demand forecasts and yield as output ensemble forecasts of the water excess and shortage from Lake Mulwala and given that, a recommendation on the Hume Dam release. The first and second rules are based on the expectations and medians respectively of the output excess and shortage forecasts, while the third rule is based on the risks of an excess or shortage as per the output forecasts.

The decision rules impose a limit on the day-to-day change in the Hume Dam release. We consider two cases of the limit: a strict case where the limit is frequently binding and a more relaxed case where it is mostly non-binding. We implement the rules on a rolling basis to simulate the Hume Dam release and inflow to Lake Mulwala over time and ensuing water excess and shortage from the lake. We analyse the results to gain new insights into key operational questions, as summarised below.

(a) Which of the decision rules developed is best for managing Hume Dam for water supply and under what conditions?

In general, the risk-based rule is best for minimising the water supply shortage from Lake Mulwala, while the expectation-based rule is best for minimising the excess outflow from the lake. However, where the limit on the change in the Hume Dam release is strict, the expectation-based rule is not always best for minimising the excess outflow from Lake Mulwala. This is because where the limit is strict, it can act to curtail the system performance, thus affecting the relative behaviours of the different rules.

(b) How far ahead of inflow and demand forecasts should Hume Dam operators adopt?

The best forecast lead time length to adopt depends on the limit on the change in the Hume Dam release. Where the limit is low, the ideal length of lead times is not fixed but varies between 5 and 10 days depending on conditions. Where the limit on the change in the Hume Dam release is high, the system performs best with 5 days ahead forecasts. The difference between the two cases is because the higher the said limit, the quicker the adaptability of the Hume Dam release to changing conditions and hence, the lesser the need for advanced hedging of the system with the early ramping up or down of the dam release.

(c) How do constraints on the day-to-day change in the Hume Dam release influence the value of forecast operations?

Increasing the limit on the change in the Hume Dam release improves the system performance as doing so gives the system greater flexibility to adjust the Hume Dam release as needed in response to changing conditions. However, increasing the said limit has significant benefit only in terms of the reducing the excess outflow from Lake Mulwala but little benefit in terms of reducing the supply shortage from the lake.

(d) What value is there, in terms of the system performance, of improved diversion demand forecasts?

Improved forecasts of the diversion demands from Lake Mulwala have the potential to reduce both the excess outflow and supply shortage from the lake. However, the potential reductions are not large, relative to the total volume of flow passing through Lake Mulwala, and may not be worth the cost of improving the forecasts.

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