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Multi-decadal variability of drought risk, eastern Australia

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Abstract:

A number of previous studies have identified changes in the climate occurring on decadal to multi-decadal time-scales. Recent studies also have revealed multi-decadal variability in the modulation of the magnitude of El Niño–Southern Oscillation (ENSO) impacts on rainfall and stream flow in Australia and other areas. This study investigates multi-decadal variability of drought risk by analysing the performance of a water storage reservoir in New South Wales, Australia, during different climate epochs defined using the Inter-decadal Pacific Oscillation (IPO) index. The performance of the reservoir is also analysed under three adaptive management techniques and these are compared with the reservoir performance using the current 'reactive' management practices. The results indicate that IPO modulation of both the magnitude and frequency of ENSO events has the effect of reducing and elevating drought risk on multi-decadal time-scales. The results also confirm that adaptive reservoir management techniques, based on ENSO forecasts, can improve drought security and become significantly more important during dry climate epochs. These results have marked implications for improving drought security for water storage reservoirs. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS El Niño–Southern Oscillation (ENSO); La Niña; Inter-decadal Pacific Oscillation (IPO); Pacific Decadal Oscillation (PDO); hydrological impacts of ENSO; climate variability; drought risk; water resource management

INTRODUCTION

Stream flow is extremely variable in many parts of Australia, however, a strong relationship exists between stream flow and the El Niño–Southern Oscillation (ENSO) phenomenon (Simpson *et al.*, 1993; Chiew *et al.*, 1998). More importantly, it is possible to successfully forecast stream flow across many regions of Australia, using various ENSO indicators (Kiem and Franks, 2001; Piechota *et al.*, 2001). However, a number of previous studies have identified changes in the climate occurring on decadal to multi-decadal time-scales (Zhang and Casey, 1992; Allan *et al.*, 1995; Franks, 2002a; Franks and Kuczera, 2002). Recent studies have also revealed multi-decadal variability in the modulation of the magnitude of ENSO impacts on rainfall and stream flow in Australia and other areas (Gershunov and Barnett, 1998; Power *et al.*, 1999; Salinger *et al.*, 2001; Kiem *et al.*, 2003). These studies have used either the Pacific Decadal Oscillation (PDO, Mantua *et al.*, 1997) or the inter-decadal Pacific Oscillation (IPO, Power *et al.*, 1999) to assess long-term variability. It should be noted that although these indices were derived by independent approaches, marked similarities between the indices are apparent (Folland *et al.*, 2002; Franks, 2002b).

In particular, Power *et al.* (1999) have investigated marked temporal changes in ENSO correlations to Australian rainfall records. The temporal stratification of the rainfall sequences was achieved through the IPO index, representing anomalous warming and cooling in the Pacific Ocean. Power *et al.* (1999) showed how Australian ENSO correlations varied with the observed changes in persistent large-scale Pacific Ocean

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SST anomalies. Importantly, Power *et al*. (1999) demonstrated that individual ENSO events (i.e. El Niño, La Niña) had stronger impact across Australia during the negative phase of the IPO, implying that there exists a multi-decadal modulation of the magnitude of ENSO events. Therefore, long-term climate variability, and the associated modulation of ENSO impacts, may be of significant importance for the managers of water resource systems for whom the ability to forecast reservoir inflows is highly desirable.

This study investigates multi-decadal variability of drought risk by analysing the performance of a water storage reservoir in New South Wales (NSW), Australia, during different climate epochs defined using the IPO index. The performance of the reservoir during different climate epochs is also analysed under three adaptive management techniques and these are compared with the reservoir's performance using current 'reactive' management practices.

In the first section the method used to stratify the study period according to ENSO and IPO indices is presented. The following section describes the study reservoir and the current operational procedures of the reservoir. Also discussed is the variability of the study reservoir's major source of inflow in relation to both ENSO and multi-decadal climate states, defined by the IPO. The hydroclimatic data used in this study are then presented followed by the description and verification of the model used to simulate the performance of the study reservoir. The simulated performance of the reservoir during different climate states is then analysed. The analysis is performed first under current management conditions to evaluate the multi-decadal variability of drought risk and then utilizing the three adaptive management strategies to determine whether the drought security of the reservoir can be improved by using climate variability insight to make management decisions.

TEMPORAL STRATIFICATION ACCORDING TO ENSO AND IPO INDICES

The monthly NIÑO3 index of sea-surface temperature anomalies (Kaplan *et al*., 1998) was used as the ENSO index for this study. Every year from 1924 to 1999 was given an ENSO classification based on the six-month October to March average NIÑO3 value. This method and index combination has been demonstrated previously to be the most robust for the time period being investigated (Kiem and Franks, 2001).

The Inter-decadal Pacific Oscillation (IPO) is the coherent pattern of sea-surface temperature (SST) variability occurring on inter-decadal time-scales over the Pacific Ocean (Power *et al*., 1998; Folland *et al*., 1999; Power *et al*., 1999; Allan, 2000). In classifying the different IPO phases, Power *et al*. (1999) used the thresholds of $\pm 0{\cdot}5$ to distinguish positive, neutral and negative phases. Figure 1 shows the time-series of the IPO over the period analysed in this study. As can be seen, during this period there have been three major phases of the IPO: Two positive phases (IPO $> 0{\cdot}5$) between 1924 and 1943 and 1979 and 1997, and a negative phase (IPO $< -0{\cdot}5$) from 1946 to 1976. These three phases exclude the 10 years from 1958 to 1967 when the absolute value of the IPO index was less than 0·5.

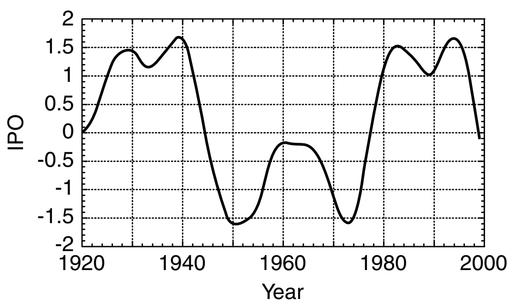

Figure 1. The inter-decadal Pacific Oscillation (IPO) index from 1920 to 1999

STUDY RESERVOIR—THE GRAHAMSTOWN RESERVOIR, NEW SOUTH WALES (NSW)

The reservoir used in this study is the Grahamstown Reservoir, which has been operating since 1963 and is located within the Williams River catchment near Raymond Terrace, NSW, Australia (see Figure 2). The Williams River catchment is of particular regional importance because it forms part of the conjunctive-use headworks scheme for potable water supply in the Newcastle region, the sixth largest residential region in Australia.

Grahamstown Reservoir has a relatively small catchment area (approximately 100 km^2 including dam surface area) in comparison with the size of the reservoir (approximately 25 km^2 on average). As a result of this, the runoff from the reservoir catchment area is insufficient to maintain water levels in the reservoir. Therefore, water is regularly extracted from the nearby Williams River and pumped into the Grahamstown Reservoir via a canal. It has been shown previously that seasonal rainfall and runoff volumes in the Williams River are highly correlated to ENSO events (Franks, 1998; Kiem and Franks, 2001; Wooldridge *et al.*, 2001).

Figure 3 shows the distributions of the total stream flow from December to May in the Williams River from 1924 to 1999 stratified according to (a) ENSO events and (b) the three different IPO phases irrespective of ENSO classification. Figure 3a clearly demonstrates the strong relationship between ENSO and stream flow in the Williams River. Figure 3b shows the high level of variability in the Williams River stream flow between the different IPO phases. As can be seen, markedly different distributions of stream flow are apparent

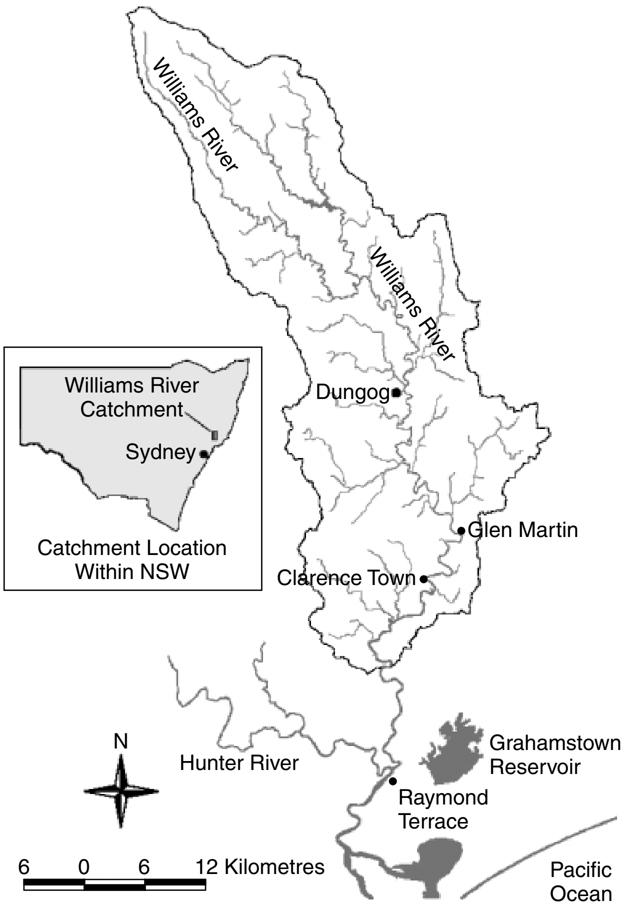

Figure 2. The Williams River Catchment

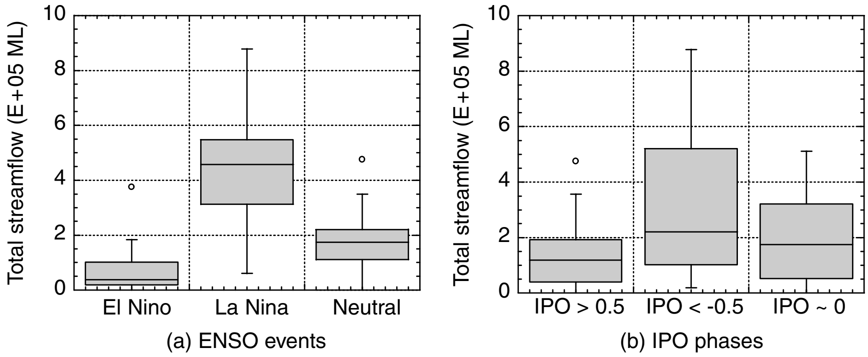

Figure 3. December to May total stream-flow distributions from 1924 to 1999 associated with (a) El Niño, La niña and neutral events and (b) the three different IPO phases

under the different IPO phases. Immediately obvious is the reduced seasonal stream flow under IPO positive conditions. It is therefore clear that Williams River stream flow is both highly correlated with ENSO processes and highly variable on multi-decadal IPO phase time-scales.

The Grahamstown Reservoir has a maximum storage capacity of 133 000 ML and is currently managed by the Hunter Water Corporation (HWC). As the runoff from the reservoir catchment is insufficient to maintain reservoir storage levels water is abstracted from the Williams River at the Balickera pumping station and pumped into the Grahamstown Reservoir. The reservoir subsequently supplies the majority of the water for the Newcastle region's population of approximately 500 000. The maximum amount of water that currently can be pumped from the Williams River into the reservoir is 1350 ML day^{-1} and this is achievable only when all six of the available pumps are operating 24 h a day. The river abstractions are also moderated by various water quality constraints that relate to salinity, phosphorous and turbidity in the Williams River. In addition, the need to maintain environmental compensation flows during dry periods also limits the amount of water allowed to be pumped from the Williams River, with no pumping allowed unless the stream flow is above 130 ML day^{-1}. Therefore, it is clear that an understanding of the effects of ENSO events on stream flow in the Williams River may aid in improving the operation of the Grahamstown Reservoir.

The current Drought Management Plan of HWC involves reducing the amount of water supplied by imposing water restrictions, if the reservoir falls below certain levels, that reduce the use of water by limiting or banning certain types of usage (HWC, 2000). In the case of extremely low storage levels, water usage is reduced through economic pressure by increasing the price of water. This type of Drought Management Plan is 'reactive' in that by the time restrictions are introduced the storage levels have already started to decrease.

Table I shows the storage levels at which HWC introduces the different restriction stages and when they are removed. Also shown in Table I is HWC's expected reduction in the amount of water supplied for each of the different restriction stages for residential, industrial (non-residential) and both residential and industrial combined.

HYDRO-CLIMATIC DATA

Continuous daily stream-flow data from the period June 1924 to May 2000 from the Williams River measured at Glen Martin (see Figure 2) were used. The daily stream-flow data collected at Glen Martin is of significant importance as the managers of Grahamstown Reservoir use it to decide when and how much water to pump into the reservoir via the Balickera pumping station. Daily rainfall data from Raymond Terrace, which is located close to the Grahamstown Reservoir (see Figure 2), was used to calculate the rainfall over the reservoir catchment for the period June 1924 to May 2000.

Table I. Hunter Water Corporation Drought Management Plan (HWC, 2000). Storage levels at which restrictions are introduced/removed and also the expected water savings at each restriction stage

Restriction stage	Restriction imposed (%)	Restriction removed (%)	Expected reduction in supply		
			Residential (%)	Industrial	Total (%)
1	60	70	10	Minimal	5
2	50	60	20	Minimal	10
3	40	50	30	Minimal	15
4	30	40	30	20%	25

THE GRAHAMSTOWN RESERVOIR MODEL

A model to calculate the amount of water stored in Grahamstown Reservoir at the end of each day was constructed based on the following water balance equation

$$S(d) = S(d-1) + B(d) + R(d) + r(d) - E(d) - D(d)$$

Where d is day, S is volume in storage (ML), B is Balickera Pumping (ML), R is runoff from reservoir catchment (ML), r is rainfall in the reservoir catchment (ML), E is evaporation (ML) and D is water supplied or demand (ML). Figure 4 shows a schematic diagram of the Grahamstown reservoir model.

The amount of water pumped from Balickera each day is firstly dependent on the level of stream flow in the river and also the available space in the reservoir. The amount of water that can be available for pumping is the lower out of available space and stream flow above 130 ML day^{-1}, which is the minimum amount of stream flow needed before pumping is allowed. However, this is limited to a maximum of 1350 ML day^{-1} owing to the pumping capacity at Balickera. A variety of water quality issues also affect the amount of water available for pumping. After analysing daily water quality data it was found that water quality issues reduced the amount of water available for pumping by about 70% on average. Therefore, the amount of water pumped from Balickera was calculated as 30% of that which was available or allowed to be pumped.

Demand was calculated for each month based on the average values of the actual supply data from 1990 to 2000. Daily demand was then obtained by dividing the monthly values by the number of days in the corresponding month.

Hunter Water Corporation provided formulae to calculate the daily volume of water contributed to the reservoir by rainfall and runoff in the reservoir catchment (Berghout, 2001). In order to determine the amount

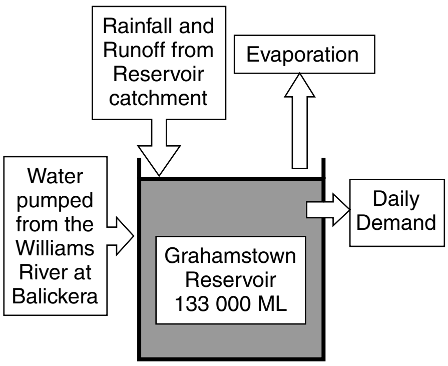

Figure 4. Schematic diagram of the Grahamstown Reservoir model

of rainfall and runoff received in the Grahamstown catchment on each day between June 1924 and May 2000 daily rainfall data from the Raymond Terrace rain gauge was used. Hunter Water Company also provided a formula that estimated the amount of water lost from Grahamstown Reservoir each day owing to evaporation (Berghout, 2001). Losses resulting from evaporation are based on HWC relationships dependent on the surface area of the reservoir, the time of year and the amount of rain that had fallen in the reservoir catchment on the current and previous days.

Storage levels of the Grahamstown Reservoir from January 1976 to October 2000 were obtained from HWC. Also obtained were the amounts of water taken from the Williams River at Balickera and the amount of water supplied to the community from Grahamstown for each month from January 1976 to May 2001. These data were used to validate the model used in this study. Figure 5 shows a scatter plot and a time-series from January 1976 to October 2000 comparing the measured storage volume and the storage volume simulated by the model. The storage volumes are expressed as a percentage of the reservoir's capacity. Figure 5 confirms that the model satisfactorily reproduces the storage levels of the reservoir with the scatter plot showing a high degree of correlation with $R^2 = 0{\cdot}80$. Importantly, it should be noted that the model parameters have not been derived by calibration and yet the model successfully reproduces the periods of marked drawdown of the reservoir, which is key to this current analysis.

METHOD

In order to simulate the reservoir's performance in different climate states 1000 replicates of 1000-year rainfall and stream-flow sequences were created for each of the positive, negative and neutral IPO phases, based on the rainfall at Raymond Terrace and the stream flow at Glen Martin occurring within each phase.

Seasonal distributions were based on the 6-month periods from December to May (summer) and June to November (winter) in recognition that ENSO processes only affect summer rainfall and stream-flow totals, whereas winter totals are uncorrelated to ENSO conditions (Kiem and Franks, 2001). No significant correlation between the winter and summer distributions is apparent in the observations and therefore no measure of autocorrelation between consecutive seasons was included in this study.

For each IPO phase, the 1000 years that made up the sequences were sampled randomly from the years within the relevant IPO phase. A stochastic modelling approach based on Monte Carlo sampling was used to determine the ENSO classification of each year being sampled, based on the probability of an El Niño, La Niña or neutral event occurring within each IPO phase. This method accounts for the uncertainty associated with the frequency at which different ENSO events occur within each IPO phase (Kiem *et al*., 2003). A similar approach was used to determine the summer season rainfall and stream-flow totals associated with the different ENSO events within each IPO phase. Distributions of expected seasonal rainfall and stream-flow totals were derived according to observed ENSO impacts (i.e. resultant rainfall and stream flow in El Niño, La

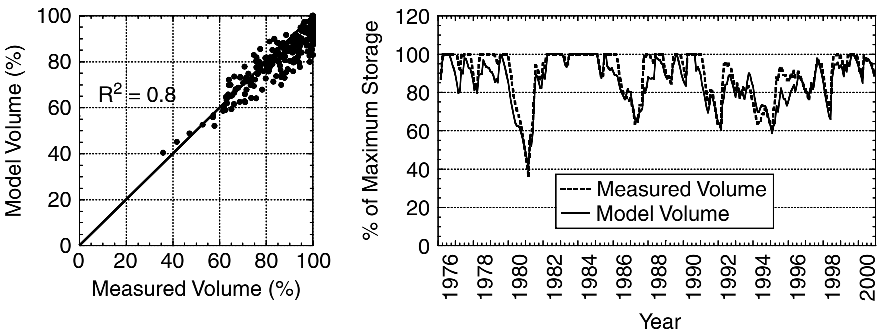

Figure 5. Comparison of measured and simulated storage levels of the Grahamstown Reservoir from January 1976 to October 2000

Niña or neutral events depending on the type of year sampled) within each IPO phase. Where few observations of El Niño impact were available, a lower bound on each of the distributions was set as the lowest recorded seasonal total (cf. Sanso and Guenni, 1999).

To derive daily time-series for each replicate, ENSO event specific daily rainfall and stream-flow patterns were sampled on a monthly basis and then rescaled to provide the correct sampled seasonal total. In this way, the derived replicate series implicitly accounts for the known differences in intensity and timing of rainfall and stream flow under different ENSO phases (Franks, 1998; Wooldridge *et al.*, 2001). Although many different methods are available for the stochastic generation of rainfall series, for the purpose of this study it should be noted that the method is applied equally to each of the IPO phases and to the different management strategies assessed for comparative purposes.

The different 1000-year replicates for each IPO phase were run through the Grahamstown Reservoir model using current reactive HWC management practices and the resultant daily storage levels were obtained. In each case it was assumed that the initial storage in the reservoir was at the maximum capacity. No ENSO insight was taken into account for these runs of the model.

Three alternatives to the current 'reactive' management procedures are then investigated to determine whether climate variability insight can be used to increase the drought security of the reservoir. The three alternative adaptive management techniques are:

1. Increasing the storage level at which the various restriction stages are introduced if an El Niño event is forecast or being experienced.
2. Increasing the amount of water pumped into the reservoir, if an El Niño event is forecast or being experienced, by relaxing the water quality constraints currently in place.
3. Increasing the amount of water pumped into the reservoir by increasing the maximum pumping capacity of the pumping station.

Only the first two adaptive management options attempt to make use of ENSO insight. In this study it has been assumed that ENSO events can be consistently forecast at least 6 months in advance following a historical analysis of index-based ENSO prediction schemes (Kiem and Franks, 2001). The three adaptive management techniques were used in conjunction with the reservoir model and 1000-year replicates to calculate the daily storage level for each of the alternative management strategies under each of the three IPO phases.

A critical time for HWC is when the storage level of Grahamstown Reservoir drops below 30% of capacity as this is when extreme and costly measures are undertaken in order to ensure drought security (HWC, 2000). Therefore, drought risk during the different IPO phases, and also when using the different adaptive management procedures, was assessed by analysing the total number of times the reservoir storage levels fell below the critical level of 30%.

RESULTS

Figure 6 shows the average probability, and 90% confidence intervals, of a critical event (30% storage) during the different IPO phases using HWC's current management procedures. As can be seen, when the IPO is positive the average probability of a 'critical event' is 0·038 compared with 0·002 when the IPO is negative (a 95% decrease) and 0·020 during the neutral IPO phase (a 47% decrease). Therefore, the risk of falling below the critical level when IPO is positive is almost 20 times higher than it is during the negative IPO phase, indicating that the risk of drought is significantly higher when the IPO is positive.

To further demonstrate this, annual (April to March) stream-flow totals from 1924 to 1999 were obtained from the Williams River at Glen Martin and stratified into three distributions based on the phase of the IPO. The mean annual stream-flow total for the IPO positive distribution was 246 747 ML, for the IPO negative phase the mean was 425 666 ML and when the IPO was near zero the mean was 381 407 ML. Student's

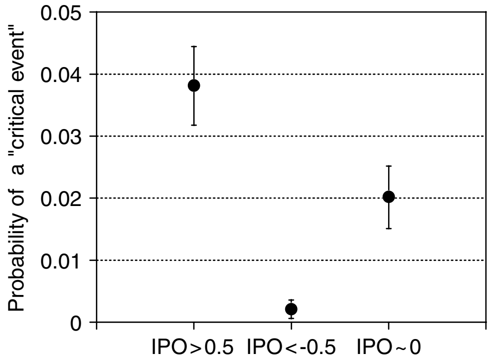

Figure 6. Average probability of a 'critical event' during each of the three IPO phases using current HWC management practices. The error bars represent the 90% confidence intervals in each case

t-test was then used to determine whether there was a significant difference between the annual stream-flow distributions for the positive and negative IPO phases. The *t*-test resulted in a very low *p* value of 0·012, which is the probability that the mean of the annual stream flow in the IPO positive distribution is equal to the mean of the IPO negative distribution. Therefore, as the *p* value is less than 0·05 (the standard level for significance) the hypothesis that the mean of the annual Glen Martin stream-flow totals when IPO is positive is equal to the mean when IPO is negative is rejected. Hence, it would be concluded that the mean annual stream-flow total when IPO is positive is significantly lower than the mean when the IPO is negative. This is despite the fact that the positive IPO periods tend to be associated with suppressed ENSO impacts in Australia, and therefore El Niño events that are not as dry as IPO neutral or negative El Niño events (Power *et al.*, 1999).

An explanation for this is that the IPO, in addition to modulating the impacts of ENSO, also appears to modulate the frequency at which the ENSO extremes occur. Table II shows the IPO phases, as defined earlier in this paper (with 1924–43 denoted IPO $> 0{\cdot}5(1)$ and 1979–97 denoted IPO $> 0{\cdot}5(2)$), that have occurred from 1924 to 1999 and also the number of El Niño, La Niña and neutral events that occurred within each IPO phase.

Immediately apparent from Table II is that IPO negative phases tend to be biased towards an increased frequency of La Niña events. It therefore appears that the multi-decadal processes as represented by the IPO may modulate the frequency of ENSO events as well as the magnitude of their impact.

To test the statistical significance of the dependence of ENSO event frequency on IPO phase a simple test of proportions was applied (Hogg and Tanis, 1988). It is assumed that the sampling distribution of the proportion of El Niño events occurring within any IPO phase can be approximated by a normal distribution with a mean of p and a variance of $p(1-p)/n$. Where p is the proportion of El Niño events that have occurred within each IPO phase, calculated using $p = y/n$, where y is the number of El Niño events that have occurred and n is the total number of years in the IPO phase being investigated. This was repeated for La Niña and neutral events.

Table II. Number of El Niño, La Niña and neutral events occurring within each of the inter-decadal Pacific Oscillation (IPO) phases

	IPO $> 0{\cdot}5(1)$	IPO $> 0{\cdot}5(2)$	IPO $< -0{\cdot}5$	IPO ≈ 0
El Niño	4	6	4	3
La Niña	4	1	10	7
Neutral	12	12	7	6
Total	20	19	21	16

In order to determine whether the probability (P_1) of a given ENSO event occurring during one IPO phase was significantly different to the probability (P_2) of the same ENSO event occurring during a different IPO phase the following statistical test was used. Let y_1 represent the number of El Niño events, for example, that occurred in the n_1 years when IPO was positive and y_2 the number of El Niño events that occurred in the n_2 years when IPO was negative. Hogg and Tanis (1988) define a test statistic used to test the hypothesis that P_1 equals P_2 as:

$$z = \frac{|p_1 - p_2|}{\sqrt{p(1-p)(1/n_1 + 1/n_2)}}$$

where $p_1 = y_1/n_1$, $p_2 = y_2/n_2$, $p = (y_1 + y_2)/(n_1 + n_2)$ and $z \approx N(0, 1)$.

Table III shows the results obtained when the probability of El Niño, La Niña and neutral events occurring in different IPO phases were compared. The p value in Table III indicates the probability that the frequency at which a given ENSO event occurs in one IPO phase is equal to the frequency at which the same ENSO event occurs in a different IPO phase.

Table III shows that when the negative IPO phase is compared with the positive IPO phases, the frequency at which La Niña events occur is significantly higher when the IPO is negative. Table III also demonstrates that the number of neutral events that occur when the IPO is positive is significantly higher than when the IPO is negative, indicating a higher rate of occurrence of the ENSO extremes (El Niño or La Niña) when the IPO is negative.

It also can be seen from Table III that when the two different positive IPO phases are compared the probability of the frequency at which El Niño events occur being equal is 0·204. Therefore, the rate at which El Niño events occur in the two positive IPO phases is not significantly different. Similar results were found for the frequency at which La Niña and neutral events occur in the two different positive IPO phases, in that there is no significant difference between the two IPO positive phases.

It is therefore apparent from these results that the IPO negative phase is associated with a statistically significant increase in La Niña events, which tend to be wetter than the average La Niña owing to the inter-decadal modulation of ENSO impacts (Power *et al*., 1999; Kiem *et al*., 2003). Although El Niño events during the negative IPO phase tend to be drier than average El Niño events, the increased likelihood of strong La Niña events under IPO negative conditions appears to mitigate the occasional enhanced El Niño.

Table III. Results obtained when the frequency at which El Niño, La Niña and neutral events occur in the different inter-decadal Pacific Oscillation (IPO) phases are compared. Significance at the <5% and <1% level is represented by * and ** respectively

Event	Period being tested		y_1	n_1	p_1	y_2	n_2	p_2	z	p value
El Niño	Period 1	Period 2								
	IPO > 0·5 (1)	IPO > 0·5 (2)	4	20	0·20	6	19	0·32	0·828	0·204
	IPO > 0·5 (1)	IPO < −0·5	4	20	0·20	4	21	0·19	0·077	0·469
	IPO < −0·5	IPO > 0·5 (2)	4	21	0·19	6	19	0·32	0·914	0·180
	IPO > 0·5 all	IPO < −0·5	10	39	0·26	4	21	0·19	0·576	0·282
La Niña	Period 1	Period 2								
	IPO > 0·5(1)	IPO > 0·5(2)	4	20	0·20	1	19	0·05	1·376	0·084
	IPO > 0·5(1)	IPO < −0·5	4	20	0·20	10	21	0·48	1·864	0·031*
	IPO < −0·5	IPO > 0·5(2)	10	21	0·48	1	19	0·05	2·996	0·001**
	IPO > 0·5 all	IPO < −0·5	5	39	0·13	10	21	0·48	2·969	0·001**
Neutral	Period 1	Period 2								
	IPO > 0·5(1)	IPO > 0·5(2)	12	20	0·60	12	19	0·63	0·203	0·420
	IPO > 0·5(1)	IPO < −0·5	12	20	0·60	7	21	0·33	1·712	0·043*
	IPO < −0·5	IPO > 0·5(2)	7	21	0·33	12	19	0·63	1·886	0·030*
	IPO > 0·5 all	IPO < −0·5	24	39	0·62	7	21	0·33	2·085	0·019*

Therefore, the drought risk during the negative IPO phase appears to be significantly decreased owing to the predominance of the recharging La Niña events under IPO negative conditions.

Conversely, there tends to be significantly less La Niña events in the positive IPO phase compared with when the IPO is negative. In addition, the recharging effects of the La Niña events that do occur are suppressed during the positive IPO phase. Therefore, the decreased frequency of recharging La Niña events results in a period of significantly increased drought risk when the IPO is positive. Thus the multi-decadal variability of drought risk for the Grahamstown Reservoir appears to result from IPO-induced modulation of both the magnitude and frequency of ENSO impacts, in particular La Niña events that have a recharging effect on the reservoir.

Figure 7 shows the average probability of a 'critical event' for each of the 1000-year sequences under the three adaptive management strategies during the different IPO phases. In Figure 7 a zero increase in restriction introduction level, Balickera Pumping or Pumping Capacity corresponds to HWC management practices as they are now.

Figure 7 shows that there is a marked difference in reservoir performance during the different IPO phases for all three of the different management techniques and that the adaptive reservoir management techniques have the greatest effect during the positive IPO phase. The adaptive management strategies that perform the best, with respect to decreasing the probability of a 'critical event', incorporate pumping extra water into the reservoir, either by decreasing water quality constraints in advance of El Niño events (Figure 7b) or increasing the pumping capacity at Balickera (Figure 7c).

CONCLUSION

This study has investigated the multi-decadal variability of drought risk by analysing the performance of the Grahamstown Reservoir in NSW, Australia. Multi-decadal drought risk was assessed by calculating the probability of the reservoir storage level falling below 30% during three different phases of the IPO. The study has also sought to determine whether adaptive management strategies could be used to reduce drought risk when compared with the current 'reactive' management procedures.

It was found that the risk of the reservoir storage level falling below the critical level of 30% was almost 20 times greater during the positive IPO phase than it was when the IPO is negative. This is despite the fact that the IPO positive phase has been shown to be associated with less severe ENSO impacts in Australia. An explanation for this is that in addition to the IPO modulating the impacts of ENSO it also modulates the frequency at which the ENSO extremes occur. When the IPO is positive the decreased frequency of La Niña events combined with a reduction in the recharging effect of the La Niña events that do occur, results in a period of significantly increased drought risk. Conversely, although extremely dry El Niño events are still possible when the IPO is negative, drought risk is significantly reduced owing to the predominance of

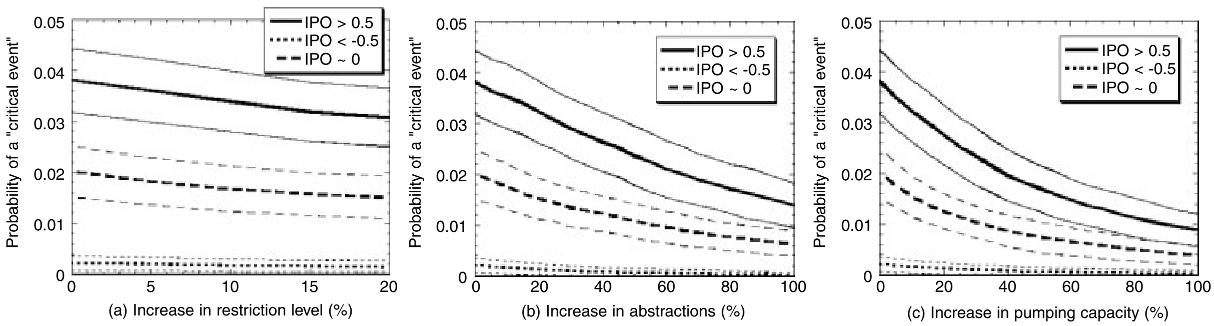

Figure 7. Average probability of a 'critical event' during each of the three different IPO phases using the three adaptive management strategies. The finer lines represent the 90% confidence intervals for each IPO phase

strong recharging La Niña events, provided the reservoir is large enough to endure the dry events that do occur, as is the case at Grahamstown. Thus the multi-decadal variability of drought risk appears to result from IPO-induced modulation of both the magnitude and frequency of ENSO events. Recent research has indicated that the dual modulation of ENSO events also has the effect of reducing and elevating flood risk on multi-decadal time-scales, with the negative IPO phase having a significantly higher flood risk than the positive IPO phase (Franks, 2002a; Kiem *et al*., 2003).

It was also found that drought security could be improved through the use of adaptive management strategies, with the greatest improvements obtained when the water pumped into the reservoir was increased, either by decreasing water quality constraints in advance of El Niño events or increasing the pumping capacity. More importantly, it was discovered that adaptive reservoir management techniques had the greatest impact on improving drought security when the IPO was positive, when drought risk is at its highest.

These results have a number of implications. It is clear from this and other studies that climate variability in eastern Australia varies significantly as a result of multi-decadal climate processes. As noted by Franks (2002b), both PDO and IPO indices are inextricably linked to the variable periods of Pacific Ocean (and indeed global) warming and cooling observed over the past 100 years. At present, it is unclear whether these variable multi-decadal epochs are a result of internal ocean–atmosphere interactions (e.g. Latif and Barnett, 1994; McPhaden and Zhang, 2002) or externally forced by ultraviolet solar variability (e.g. White *et al*., 1997; Reid, 2000; Franks, 2002b). Nonetheless, the identification of the role of the IPO phase in modulating ENSO processes offers novel insight into drought risk assessment as well as providing a useful leading indicator that in conjunction with ENSO predictions can be used to assess drought risk on seasonal through to multi-decadal time-scales. Most importantly, it is clear that seasonal/annual stream flow cannot be assumed to arise from a single distribution, thus negating the application of purely empirical approaches to the estimation of drought security.

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