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Past and future changes to inflows into Perth (Western Australia) dams

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ABSTRACT

Study region: The city of Perth is located within the region referred to as south-west Western Australia (SWWA) defined as southwest of a line connecting 30° S, 115° E and 35° S, 120° E.
Study focus: SWWA has experienced a prolonged decline in rainfall since the early 1970s accompanied by serious reductions to inflows into the major storage systems. Consequent research questions include: What caused the decline in rainfall? Why have inflows decreased so dramatically? What can be expected over the coming decades? In this study, we consider these questions making use of recent observations and the latest generation of climate model results which attempt to simulate the effects of increased greenhouse gas concentrations.
New hydrological insights for the region under study: Recent observations show a continuation of dry conditions and confirm that a significant change in the relationship between rainfall and inflows appears to have occurred. There is little evidence that increasing local temperatures alone can explain this changed relationship which possibly represents long-term physical changes (e.g. groundwater levels) to the catchments. There is a strong consensus amongst recent model results that rainfall will decline further by the end of the 21st century. While this confirms findings from studies of previous model results, for the purposes of better estimating future changes to inflows it may now be more important to understand the reasons for the changed rainfall/inflows relationship.

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1. Introduction

Perth, located on the west coast of Western Australia (Fig. 1), is Australia's fourth most populous (∼2 million people) city and experiences a Mediterranean-type climate, dominated by wet winters and relatively dry summers. Long-term average annual rainfall is about 870 mm with over 85% falling in the 6 months between May and October. Rainfall averaged over the wider southwest region of Western Australia (SWWA) that encompasses Perth and its catchments declined significantly in the early 1970s and has not shown any signs of recovering to the values experienced during most of the 20th century (IOCI, 2002). This decline has been most evident in the early winter period (May to July) and has been linked to a decrease in the number of low pressure troughs and westerly frontal systems combined with a decrease in the amount of rainfall associated with rain bearing systems (Hope et al., 2006a; Raut et al., 2014). These changes have had a serious impact on the total amount of water held in Perth's major dams (Power et al., 2005; Hope and Ganter, 2010) located to the south and east of the city in the nearby Darling escarpment (Fig. 1).

Explaining the observed rainfall decline has been problematic. Many studies have investigated the role of the El Nino Southern Oscillation (e.g. Nicholls, 2009), the Southern Annular Mode (e.g. Meneghini et al., 2007; Hendon et al., 2007; Feng et al., 2010), and Indian Ocean sea surface temperature patterns (e.g. Smith, 1994; Smith et al., 2000; Risbey et al., 2009) without being conclusive. Smith and Timbal (2012) suggested that trends in southern Australia rainfall, including SWWA rainfall, were

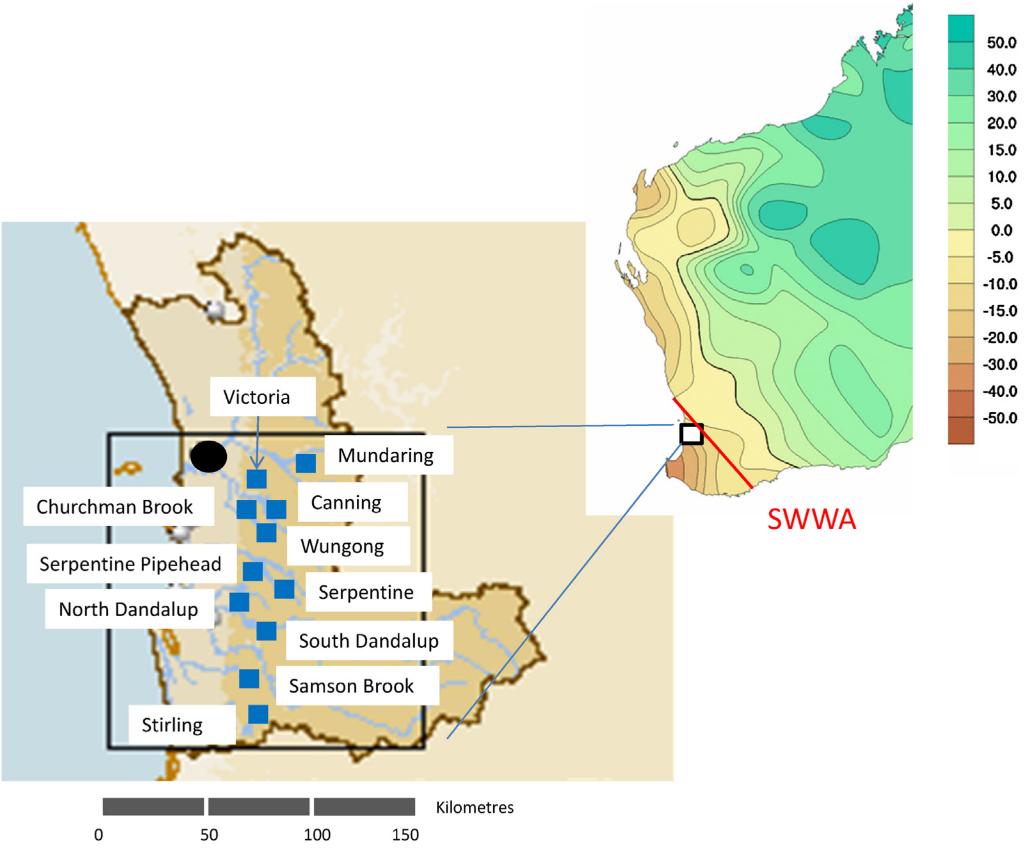

Fig. 1. Location of Perth (filled black circle) and major dams (blue squares). Also shown is a map indicating the region referred to as south-west Western Australia (SWWA) and long-term (1970–2013) trends in annual rainfall (units mm per decade). *Source*: Bureau of Meteorology (http://www.bom.gov.au/climate/change/).

more likely to be explained by large scale shifts in atmospheric circulation patterns rather than by regional SST changes. This is also indicated by the fact that early climate model experiments based on prescribed SST anomalies tend to have no real effect on simulated rainfall unless the anomalies are made unrealistically large (Frederiksen et al., 1999). Other evidence that the rainfall trends are primarily linked to large-scale atmospheric circulation changes is provided by Verdon-Kidd and Kiem (2014) who noted that the period over which the SWWA dry spell occurred coincided with rainfall changes over several continents including Australia, New Zealand and southern and western Africa, and van Ommen and Morgan (2010), who identified an apparent inverse relationship between precipitation records in East Antarctica and SWWA. Analyses of climate model simulations have also been inconclusive since, although it has been possible to detect simulated declines in rainfall over similar time scales, these are generally only half the amount observed (Timbal et al., 2006). For example, Hope and Ganter (2010) noted that recent declines in winter rainfall and increases in winter mean sea level pressure are similar to those projected by climate models forced by increases in atmospheric greenhouse gas concentrations, but only for the end of the 21st century. Bates et al. (2008) concluded that the observed decline most likely comprised some anthropogenic signal combined with some (unexplained) multi-decadal scale variability.

In addition to the problem of understanding the rainfall decline, the relatively large decline in annual streamflows is not well understood (Kinal and Stoneman, 2011) with various studies proposing a range of possible causes. Rising temperatures may have been a factor as has been suggested for eastern Australia over recent time (Nicholls, 2004; Cai et al., 2009). However, both observational evidence (Roderick et al., 2009) and theoretical arguments (Lockart et al., 2009), suggest that temperature is not a strong driver of evaporation. Bates et al. (2010) concluded that the decline in annual inflows was consistent with a decline in average rainfall accompanied by decreases both in the frequency of daily precipitation occurrence and in wet day amounts. Declining groundwater levels (Petrone et al., 2010; Petheram et al., 2011; Hughes et al., 2012) are also likely to be a factor since these have been observed in some of the catchments (Kinal and Stoneman, 2011).

Finally, while the observed rainfall changes are not fully understood, projected changes to rainfall over the SWWA region have tended to be relatively unambiguous. Over 30 years ago it was suggested that a warmer world would lead to a decrease in SWWA rainfall (Pittock and Salinger, 1982). Since then most modeling studies using a range of greenhouse gas emissions scenarios have tended to indicate decreases in rainfall (Hope, 2006b) and runoff for later this century (Charles et al., 2007; Bates et al., 2008; Islam et al., 2013; Silberstein et al., 2012). A question here is whether the more recent set of climate model simulations (referred to as CMIP5) still exhibit this degree of consensus.

In this study we revisit some of these questions using (a) updated (to the end of 2013) observations of inflows and (b) simulations from the latest generation of climate model results (CMIP5) which have been assessed in the latest (Fifth) IPCC Assessment Report (Stocker et al., 2013). We examine the relationship between annual rainfall and inflows and consider recent changes in this relationship with a focus on the role of temperature. We also synthesize CMIP5 model results for both the recent past and for later this century under a high-end greenhouse gas emissions scenario (RCP8.5). The findings are discussed in terms of the relative importance of generating climate projections versus a better understanding of changes to the rainfall/inflows relationship.

2. Data

Inflows into the 11 major dams have been measured since the early 20th century and Fig. 2 shows the long-term (1911–2013) time series of total inflows. (*Source*: WA Water Corporation, http://www.watercorporation.com.au/water-supply-and-services/rainfall-and-dams/sources.) This shows that inflows declined rapidly after 1974 and possibly again around 2000 (Bates et al., 2008). Prior to the 1970s, the annual average was about 350 gigalitres (GL) but since then has declined by more than half with only 12 GL recorded in 2010 during an extremely dry year.

While much of inland Western Australia has experienced an increase in annual rainfall over recent decades, a significant decline has occurred over the south-west corner which includes Perth (Fig. 1). This is evident in the time series for rainfall averaged over the SWWA region defined as southwest of a line connecting 30° S, 115° E and 35° S, 120° E (Fig. 1). Fig. 3a shows the long-term

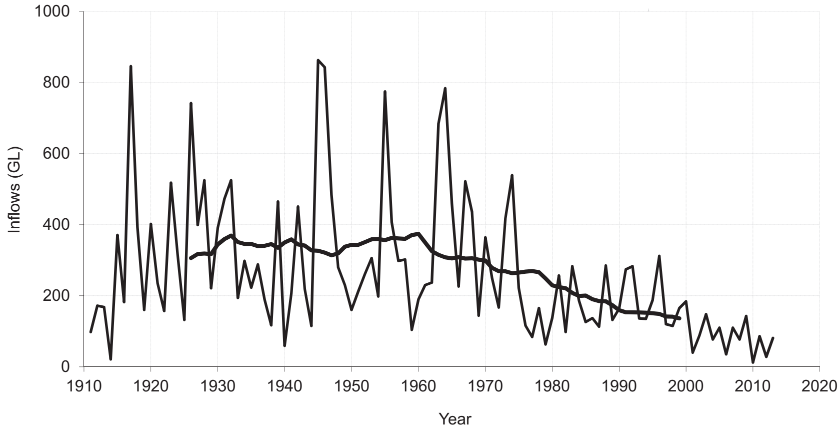

Fig. 2. Time series of total annual inflows to Perth Dams (1911–2013). 31-year running averages are indicated.

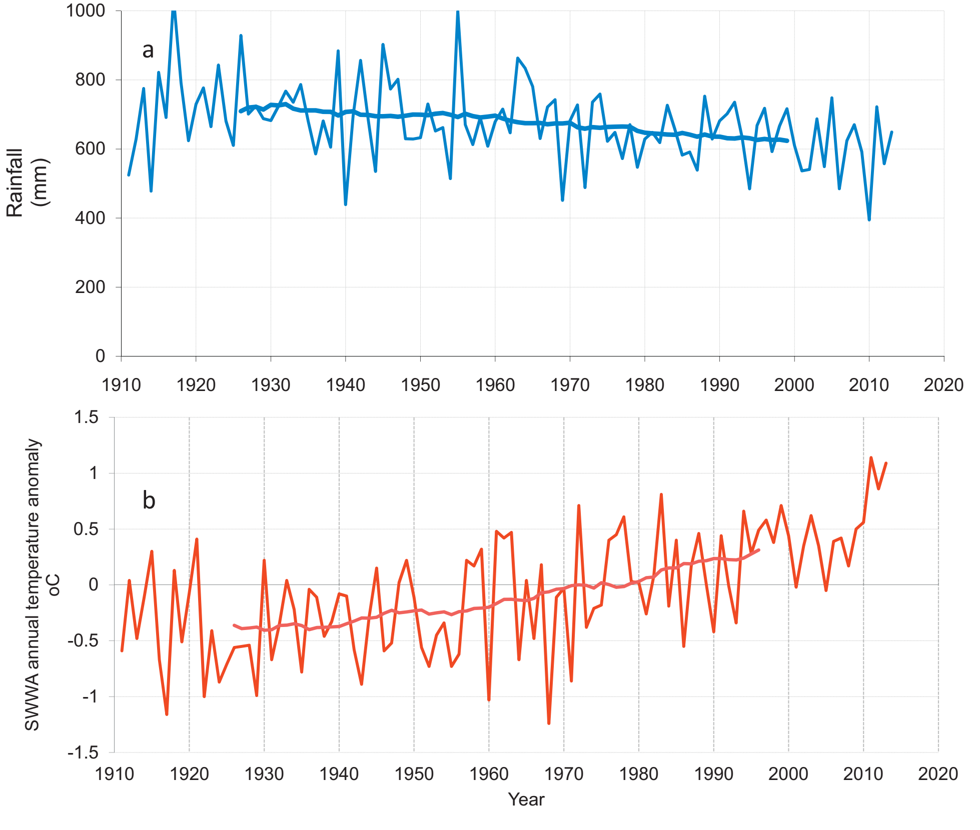

Fig. 3. As for Fig. 2 except for SWWA: (a) annual rainfall and (b) annual average temperature (expressed as deviations from the long-term (1961–1990) average value).

(1911–2013) time series of SWWA annual rainfall values as provided by the Bureau of Meteorology (http://www.bom.gov.au/climate/change). The rainfall decline is characterized by an absence of values above 800 mm after 1965 with only 400 mm recorded in 2010 – the lowest value on record. At the same time, SWWA annual mean temperatures have exhibited a positive trend of about +0.8 °C per century with 2011 being the warmest year on record (Fig. 3b).

We also consider the results for simulated SWWA rainfall from climate model simulations which attempt to account for past and projected factors which affect global and regional climate. Specifically, we analyze the results from the Coupled Model Intercomparison Project-Phase Five (CMIP5) which involves a range of experiments based on uniform inputs for atmospheric greenhouse gas, aerosol and ozone concentrations (Taylor et al., 2012). These include "historical" (1850–2005) runs which are forced by observed atmospheric composition changes and changes in land cover, and "projection" (2006–2100) runs forced with specified concentrations (referred to as "representative concentration pathways" or, RCPs). The projections of interest here are those which involve the relatively high RCP8.5 emissions scenario. We have analyzed a total of 38 model results (one run per model) that were available at the time of the study (see Table A1).

3. Results

In this section we investigate simple linear relationships between observed total inflows and both observed SWWA annual rainfall and annual mean temperature. The direct effect of rainfall is quite clear but, in order to identify the role of temperature, we firstly remove the direct effect of rainfall on inflows and then correlate temperature with the inflow residuals. Secondly, in order to assess the statistical significance of the relationship, we remove the effect of long term trends in temperature and residual inflow data by considering only first-order difference values.

3.1. Rainfall and inflows

A plot (Fig. 4a) of total inflows versus SWWA annual rainfall (1911–2013) reveals a significant ($p < 0.01$) linear fit (correlation coefficient $r = +0.80$) that can explain 63% of the total variance in the data. This is particularly useful since it indicates that interannual rainfall changes at the relatively large (i.e. SWWA) scale are relevant to changes that take place at the relatively small (i.e. catchment) scales. This implies that, while often desirable, it may not be necessary to downscale coarse, large scale climate model results in order to make estimates of impacts at smaller scales.

The regression coefficient indicates that inflows increase by about 137 GL for each 100 mm increase in rainfall above 500 mm. Fig. 4b shows the same data but highlights the different linear fits that apply to the data over the early period 1911–1976 compared to the later period 1977–2013. The most recent data highlight a possible change in the relationship since it indicates that recent (post-1976) inflows tend to be much less for a given rainfall amount than was the case previously.

Fig. 5a shows the result of using the linear relationship with rainfall derived from the full record to reconstruct the observed inflows. The reconstruction tends to underestimate the maxima while overestimating the minima, reflecting the fact that a simple statistical fit to real world data will always underestimate the observed variance to some degree. The reconstruction is also characterized by a tendency to overestimate inflows over recent decades. This indicates suggests that another factor, apart from rainfall, may be involved. Otherwise, it provides reasonable estimates characterized by a root mean square error of 110 GL. The differences between the reconstructed and observed inflows (Fig. 5b) represent residual values and, even though not Gaussian, simple *t*-tests indicate small (i.e. $p < 0.0001$) probabilities that the values after 1976 could have come from the same population before 1976. While this also suggests a break-point around 1976, it is also worth noting that values at the start of the time series (i.e. between 1911 and 1920) resemble the most recent values. It is quite possible that the hydoclimatic regime could be described as a shift to relatively wet conditions around 1920, followed by a shift to relatively dry conditions after 1976. Shifts in the climate regime have been suggested by Hope and Ganter (2010) who indicated that the time series of May to July total rainfall for the SWWA region can be characterized by break-points (dry to wet) around 1900 and (wet to dry) around 1968.

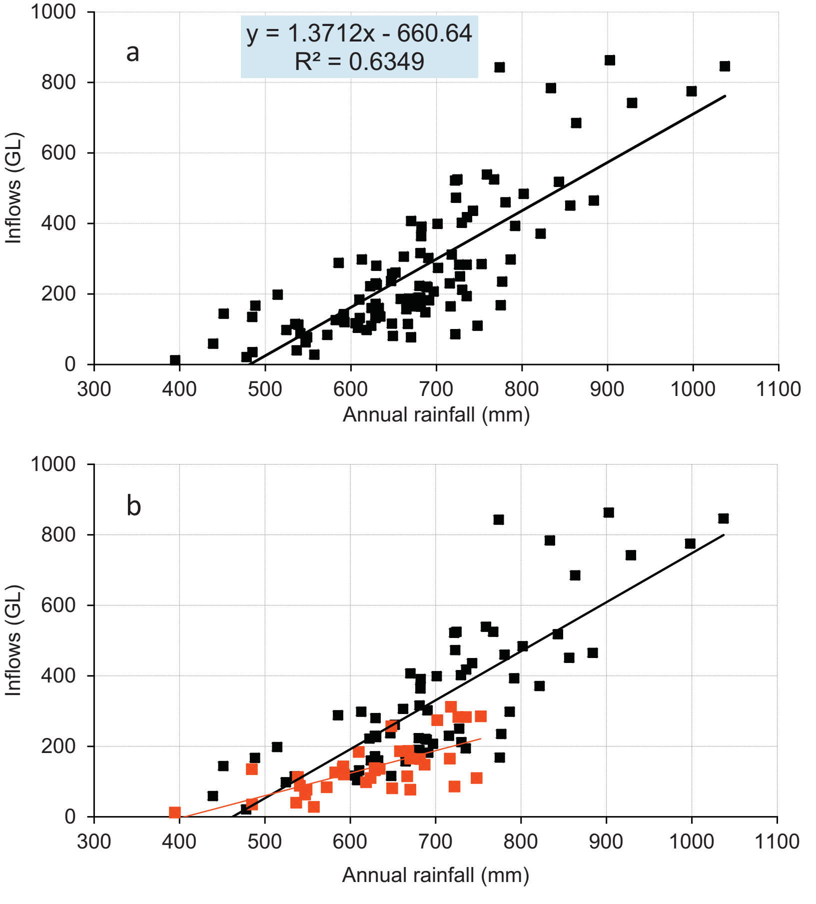

Fig. 4. The relationship between Perth total inflows and SWWA annual rainfall: (a) over the full period (1911–2013), (b) over the two sub-periods (1911–1976, black) and (1977–2013, red).

3.2. Temperature and inflows

If we plot raw inflows versus temperature (not shown) we also find a moderately strong correlation ($r = -0.37$). However, this partly reflects the fact that rainfall and temperature tend to be inversely correlated, i.e. when it is dry temperatures tend to be above average and vice versa. Therefore, any such correlation may be misleading, since it will tend to indirectly reflect the influence of rainfall on inflows through its association with temperature. The direct effect of temperature can be estimated by plotting temperature against the inflow residuals (shown in Fig. 5b). The resultant partial correlation is weaker ($r = -0.23$) but still suggests that temperature may be a factor. However, this correlation may not be statistically significant if it simply reflects long-term trends in the data. If this is the case then the number of effective degrees of freedom in the data will be less than the sample size and the statistical significance correspondingly smaller. If we consider just first order difference values (i.e. the difference between the value one year ahead and the value one year previously), then this effectively removes any long-term trends (Smith and Timbal, 2012) and allows us to investigate the relationship at short time scales. When this is done the correlation between inflow residuals and temperature ($r = -0.02$) effectively disappears. From this analysis we conclude that the direct relationship between inflows and temperature is misleading because (a) rainfall and temperature tend to be inversely related and

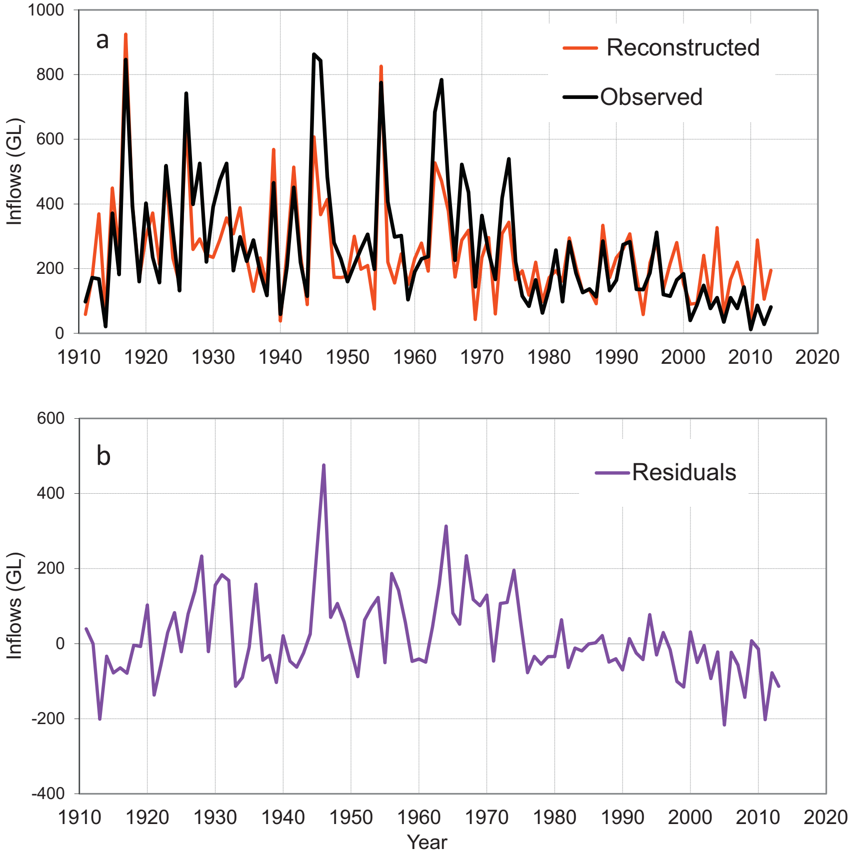

Fig. 5. (a) A comparison of observed and reconstructed Perth total inflows based on SWWA annual rainfall. (b) Residual values inflows calculated as the difference between observed and reconstructed inflows.

(b) there exist long-term trends in the data sets. Once these have been accounted for, there is no evidence that SWWA temperature has any significant effect on total inflows to Perth dams.

3.3. *Simulated rainfall*

Estimates of SWWA annual rainfall from each model were made by averaging the results from grid squares representing the wider SWWA region and generating continuous time series over the period 1901–2100. For a variety of reasons (e.g. different model resolutions, physical parameterizations, and overall skill) model results for regional rainfall tend to differ (both in means and variability) from observations. Fig. 6 shows an example of a time series of raw values from one particular CMIP5 model (MPI-ESM-LR) which is characterized by a consistent underestimate of both the mean and interannual variance. While it is tempting to discriminate amongst the model results depending on their skill at reproducing these fundamental characteristics of rainfall there is little evidence that this has much of an effect on projections (e.g. Smith and Chandler, 2009). Instead, we assume in the first instance that all model results are of equal value but transform them to remove any biases relative to observations. If Y denotes a model value for rainfall, O denotes an observed value, overbars denote averages over

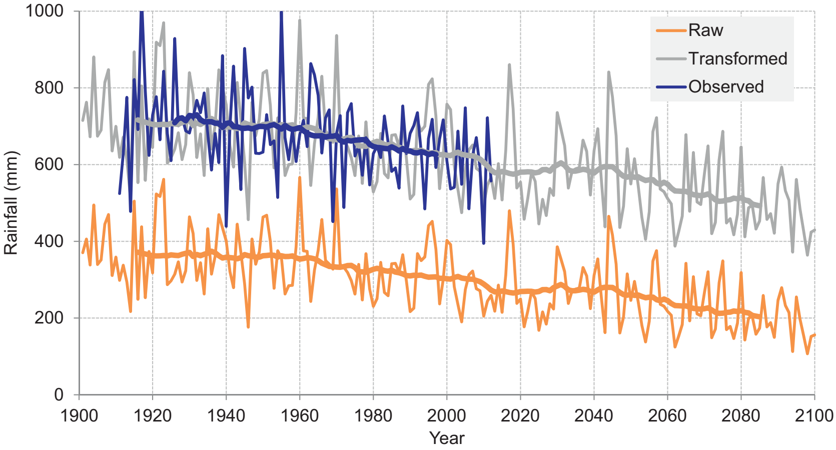

Fig. 6. A comparison of observed (blue), simulated (MPI-ESM-LR, orange) and transformed (gray) annual SWWA rainfall. 31-year running average values are indicated.

the 20th century (1901–2000) and σ denotes the associated interannual standard deviation, then the transformation

$$Y^* = (Y - \bar{Y})\frac{\sigma_o}{\sigma_y} + \bar{O} \quad (1)$$

provides a bias correction and makes the projected values from the different models comparable (Smith et al., 2013). Note that it is not necessary to use observations for the transformation since setting $\bar{O} = 0$ and $\sigma_o = 1$ yields time series with zero mean and unit variance. A potential problem with this type of linear transformation is that it can sometimes lead to small, physically unrealistic, negative values for rainfall. However, these situations are rare and replacing any such occurrences with zeroes has negligible impact on the findings presented in this study. While other techniques exist for transforming model time series to obtain a closer match with observed time series (e.g. quantile–quantile matching), this is usually done at the daily time scale (c.f. Bennett et al., 2012; Kokic et al., 2013) where there can be relatively large discrepancies between model and observed values. Climate model values can sometimes differ substantially from observational-based estimates, but because we are mainly dealing with large-scale annual averages, these differences are not often very large. Consequently, we assume that a relatively simple bias correction and scaling as represented by (1) is sufficient for synthesizing the model rainfall projections. Fig. 6 also shows the result of transforming the MPI-ESM-LR model results. Note that the while the transformation preserves the 20th century mean and interannual variability, it does not necessarily preserve variability at decadal and longer time scales. However, in this particular case, it can be seen that the transformed MPI-ESM-LR model results are very similar to the observations in terms of the long term trend (of the 31-year running averages).

Fig. 7 provides a synthesis of the CMIP5 38-member ensemble results by showing, for each year, the minimum, median and maximum 31-year running averages (1916–2086) compared to the observed 31-year running average. As has been found in several previous studies, the model projections all tend to agree that rainfall will decline (e.g. Charles et al., 2007; Bates et al., 2008; Islam et al., 2013; Silberstein et al., 2012) with not one model result (raw or transformed) indicating an increase between the late 20th century and the late 21st century. Median values decrease by about 25%, maximum values by about 14% and minimum values by about 47%.

In addition to showing the synthesis of the full ensemble, Fig. 7 also shows the results from a sample of seven models (ACCESS1-3, BNU-ESM, CMCC-CESM, IPSL-CM5B-MR, IPSL-CM5B-LR, MPI-ESM-LR and NORESM1-M) that tend to be characterized by maxima during the early part of the 20th century, followed by declines from between about 1950–1970 – somewhat similar to that seen in the observations. This behavior is mainly the result of internal variability on multi-decadal time scales

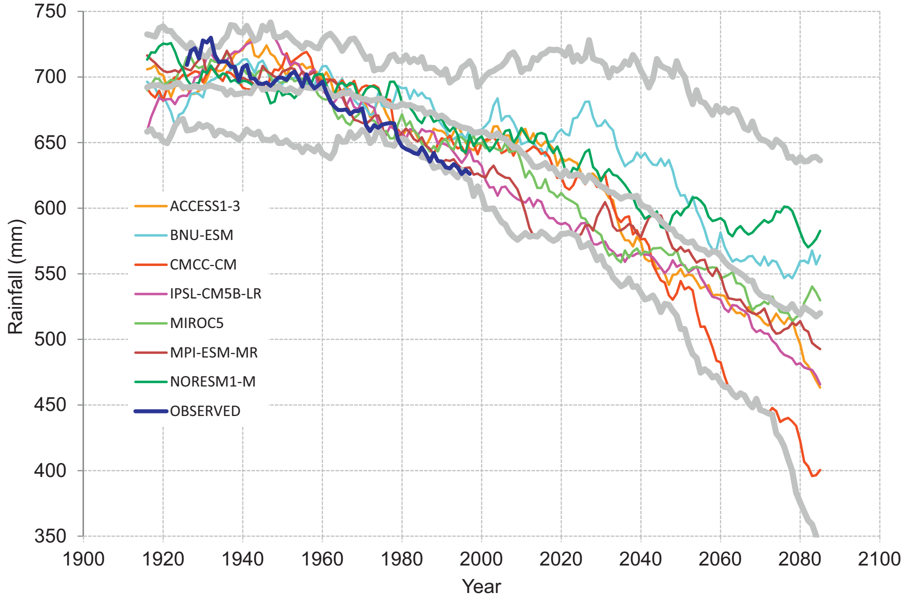

Fig. 7. A comparison of observed (dark blue) and CMIP5 multi-model results for SWWA annual rainfall (31-year running averages). The 38-member ensemble minimum, median and maximum values are indicated by the gray lines. The results from seven individual models are indicated by the colored lines.

since the effect of the prescribed external forcings tends to be most evident after about 1980 as seen in the ensemble median values. It is also worth noting that, despite selecting this sample of model results based on their approximate similarity with the observations over the 20th century, the sample ensemble results for projected changes are not much different to those for the full ensemble in terms of median and value and spread. The fact that the observed rainfall decline can be partly matched by at least some of the models lends weight to the explanation put forward by Bates et al. (2008) – namely that it (the decline) most likely comprises some anthropogenic signal combined with some multi-decadal scale variability. The relative contributions are not explored here and would require a more detailed attribution study.

3.4. *Projected inflows*

The projected changes to rainfall from the CMIP5 models can be used to estimate possible changes in total inflows using the long-term (i.e. 1911–2013) relationship evident in Fig. 4a. This is a simple linear relationship with the proviso that minimum values for inflows must be zero or greater. However, application of this simple formula assumes that the relationship is constant and it has already been noted that this may not be the case according to the most recent data. Note that the transformed model rainfall values preserve the observed mean rainfall over the 20th century while the simulated inflows preserve the observed mean inflow.

Fig. 8 summarizes the results for projected inflows. It compares the observed 31-year average inflows with the full ensemble results based on the rainfall simulations from all the models. It can be seen that ensemble maximum values match the observations for the early part of the 20th century but it is not possible to match the relatively low observed values over the latter part. This is not caused solely because of differences in rainfall, since these are reasonably well estimated during the first part and are only moderately overestimated during the second part. This is further demonstrated by comparing the results from the seven selected models whose rainfall time series partly match the observed time series. None of the simulated inflows from these models matches the relatively

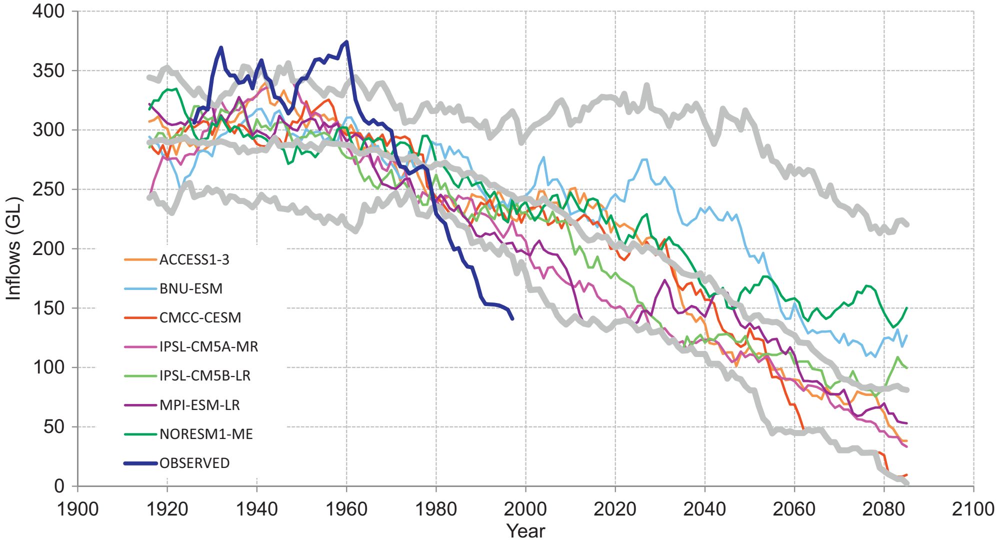

Fig. 8. As for Fig. 7 except for observed and simulated inflows.

extreme decline in observed inflows after 1960. The most likely explanation is that the rainfall inflow relationship used does not adequately represent the real relationship that appears to apply over recent decades, i.e. there appears to be another (effectively unknown) factor involved. As a consequence, it is likely that any long-term inflow projections will tend to be overestimates.

Using the median values as a rough guide, Figs. 7 and 8 indicate that an approximate 25% reduction in rainfall between 1916 and 2085 translates into an approximate 72% reduction in inflows. The ratio (2.9) or "elasticity" factor is consistent with estimates based on analyses of earlier model projections and detailed hydrologic modeling. For example, Islam et al. (2013) estimated a reduction (for later this century) of 74% in runoff associated with a decrease in rainfall of 24% for single catchment within SWWA – a ratio of 3.0. Silberstein et al. (2012) investigated the effect of projected rainfall changes on 13 basins within SWWA – a key feature being that the percentage change in runoff can be up to a factor of three times the percentage change in annual rainfall. However, if the relationship between rainfall and inflows has recently changed, it is quite feasible that, assuming the rainfall projections are realistic, the actual declines could be greater than those simulated here.

4. Discussion and conclusions

It is apparent that the protracted dry episode experienced by SWWA since the 1970s has continued up to the present (2013). Secondly, it is also apparent that it is possible to use large-scale average (i.e. SWWA) rainfall to estimate total inflows to Perth dams. This is particularly useful since it implies that climate model results, which are typically only meaningful at these scales, can be directly used to estimate the impacts of projected rainfall changes on inflows, i.e. while downscaling (either statistical or dynamical) of climate model results can add value, in the first instance it may not be necessary in order to obtain plausible first order estimates.

While a simple linear relationship between inflow and (SWWA) rainfall is sufficient to describe much of the variability in observed inflows, the most recent data confirms that the relationship appears to have changed after 1976, with less inflow for a given rainfall amount. The role of temperature in this changed relationship has been investigated but we find that any apparent correlations reflect the fact that rainfall and temperature tend to be inversely related and that temperature and inflow data exhibit long-term variability. When these factors are accounted for there is no evidence that local temperature changes have any direct effect on inflows. This suggests that other explanations for the changed relationship between rainfall and inflows are more likely. For example, the combined effects of changes in timing of rainfall events throughout the year, the absence of very heavy rainfall events and long-term changes in the physical character of the catchments – most likely changes to ground water levels.

As was found in analyses of previous climate model experiments, the latest set of climate model results (CMIP5, RCP8.5) all project a decline in annual rainfall by the end of the century accompanied by relatively large uncertainty. Some models (ACCESS1-3, BNU-ESM, CMCC-CESM, IPSL-CM5B-MR, IPSL-CM5B-LR, MPI-ESM-LR and NORESM1-M) exhibit time series that exhibit similarities to the observed SWWA time series in terms of a late 20th century decline. This confirms early interpretations that suggested that both natural variability and the enhanced greenhouse effect have contributed to the rainfall decrease.

The climate change projections continue to indicate a pessimistic outlook for rainfall – a finding consistent with those presented in previously published studies. Despite the consensus amongst the models, there is still a relatively wide range in the magnitude of the projected decline by the end of the century. Given this range, plus the fact that we have only considered the results associated with a single emissions scenario, we have made no attempt to deal with this uncertainty. The fact that the CMIP5 projections do not differ substantially from previous model projections suggests that further modeling experiments will not yield much more extra information. However, some climate-related questions still deserve attention. For example, are the projected rainfall decreases accompanied by similar changes to mean sea level pressure patterns and the frequency of rain-bearing systems? Is it possible to narrow the uncertainty in the projections by discriminating between models and/or downscaling the result? Otherwise it is apparent that changes in the rainfall/inflow relationship could be just as important, if not more so, than changes to rainfall. It may therefore be more useful to better understand the nature the of long-term relationship between rainfall and inflows in order to better estimate the future for Perth water supplies.

Conflict of interest

None declared.

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Appendix.

Table A1
List of CMIP5 model acronyms. The sample of seven models whose results for rainfall show similar declines to that seen in observations over recent decades.

ACCESS1-0	
	ACCESS1-3
BCC-CSM1-1-M	
BCC-CSM1-1	
	BNU-ESM
CANESM2	
CCSM4	
CESM1-BGC	
CESM1-CAM5	
	CMCC-CESM

Table A1 (*Continued*)

CMCC-CM	
CMCC-CMS	
CNRM-CM5	
CSIRO-MK3-6-0	
EC-EARTH	
FGOALS-G2	
FGOALS-S2	
FIO-ESM	
GFDL-CM3	
GFDL-ESM2G	
GFDL-ESM2M	
GISS-E2-H	
GISS-E2-R	
HADGEM2-AO	
HADGEM2-CC	
HADGEM2-ES	
INMCM4	
IPSL-CM5A-LR	
	IPSL-CM5A-MR
	IPSL-CM5B-LR
MIROC5	
MIROC-ESM-CHEM	
MIROC-ESM	
	MPI-ESM-LR
MPI-ESM-MR	
MRI-CGCM3	
NORESM1-ME	
	NORESM1-M

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