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Planning Urban Water System Responses to Megadrought

How looking back can help us look forward

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ABSTRACT

Drought, the 'creeping catastrophe', has been a recurrent feature of many parts of southern and eastern Australia over the last three decades. Yet, Australia is no stranger to prolonged drought periods, with the 1930s-40s period and the turn of the 20th century also characterised by widespread drought. Indeed, each drought experience has provided water managers the opportunity to update and implement new drought management strategies. However, the length of the instrumental record (~120 years at best) is inadequate to understand the full extent of drought risk in Australia and the question remains: are we actually planning for the worst drought possible? This deficiency can be somewhat overcome by using palaeoclimate archives of climate to extend the instrumental record. Importantly, such archives have revealed that climatologically similar regions to Australia have experienced megadroughts in the past (reduced rainfall periods lasting 20 years or more). However, the emerging risk of megadrought is yet to be quantified for our region. In response, this paper highlights how various palaeoclimate sources (in particular tree rings) can be used to update drought risk profiles and inform planning frameworks for drought response. We further emphasise that revised planning frameworks are required to examine the risks and options for mitigating those risks.

INTRODUCTION

Almost all urban water systems with significant surface and groundwater supplies in Australia have been designed to cope with droughts of varying lengths and severity. However, while some of these design droughts are more severe than any in the historical record, we do not know if these scenarios capture the full range of possibilities. Of concern is the (yet unquantified) risk of megadrought – defined as prolonged periods of aridity of multidecadal duration (Woodhouse and Overpeck 1998; Ault et al. 2014). The Millennium Drought, which impacted much of Eastern Australia between ~1997 through to 2010, is the longest drought on record for this region, coming close to, but not quite, satisfying the definition of megadrought.

Due to the shortness of the instrumental records, it is difficult to assess how the duration, severity and extent of droughts have changed across Australia. In long-populated coastal regions, Australia's rainfall and streamflow records are typically ~50-120 years in length while those in the arid zone are generally only ~40-60 years long. The brevity of the instrumental record hinders the calculation of return periods of extreme droughts we have experienced, such as the Millennium Drought, and negates the assessment of megadrought risk. This is of concern given that it has been demonstrated that rising temperatures have increased the risk of megadrought in the subtropical dry zones (Seager et al. 2007; Woodhouse et al. 2010) and model simulations (using fully coupled general circulation models) suggest that megadroughts could occur as a consequence of internal climate variability (e.g. Coats et al. 2015). That is, a megadrought may have simply not occurred in the last ~120 years, not because it is impossible, but rather because the various factors that contribute to megadrought have not aligned during the relatively short instrumental era. Could 21st century Australia experience a megadrought?

Evidence of past megadroughts is also contained within the global palaeo record. For example, tree-ring data indicates that five hundred years ago, the Western United States of America (USA) (with a climate comparable to that of eastern Australia, Verdon-Kidd et al. 2017a) experienced a megadrought that lasted ten times longer than anything observed in modern USA records (Stahle et al. 2011). Similarly, some Australian palaeoclimate studies have concluded that pre-instrumental droughts are likely to have been longer and more intense than the modern record (e.g. Vance et al. 2015; Allen et al. 2015; Ho et al. 2015; Verdon-Kidd et al. 2017b, Tozer et al. 2018).

The devastating consequences of drought on agriculture, the environment, communities and the economy mean it is crucial to establish the occurrence risk of droughts much worse than those in the Australian instrumental record. This risk needs to be incorporated into long-term drought resilience planning across Australia that facilitates precautionary management approaches for water resources that already becomes stressed during multi-year droughts. This will also further build on the significant water reforms initiated in the wake of the Millennium Drought experience. Against this background, we aim to inform water managers about the significant potential to extend the instrumental drought record through the development of palaeo records, with a focus on an expansion of the existing tree ring network across Australia. Importantly, the incorporation of the information offered by these kinds of records into water resource planning can help reduce vulnerability to megadrought conditions.

THE AUSTRALIAN PALAEO DROUGHT RECORD

Within the layers of natural climate archives, such as tree rings, sediments, corals and ice cores, are physical or chemical characteristics (proxies) that are directly influenced by the climate at the time the layer was formed/deposited and preserved. Various aspects of these layers can be used to reconstruct past hydroclimatic conditions. The most common hydroclimate reconstruction ‘targets’ include precipitation, streamflow (or storage inflows) and drought indices such as the Palmer Drought Severity Index (PDSI) or the Standardised Precipitation Evapotranspiration Index (SPEI).

In broad terms, there are two main ways of developing a pre-instrumental hydroclimate reconstruction from environmental archives:

(1) Using **remote** proxy data representative of large-scale circulation patterns known to have a significant relationship with the local (i.e. catchment) hydroclimate;

(2) Using **in-situ** environmental archives (e.g. trees within the catchment, corals at the outlet to a river, stalagmites within the catchment, etc.) and relating changes in their growth patterns to local climate.

Some attempts to apply Method 1 for Australian catchments have used a single proxy to reconstruct hydroclimate (e.g. Verdon and Franks 2007; McGowan 2009; Vance et al. 2015). In the two former cases, the researchers exploited the strong relationship between streamflow and remote Pacific Ocean climate modes (e.g. the El Niño/Southern Oscillation, ENSO). More recent approaches have adopted a multi-proxy network to resolve the maximum amount of variability in the record of interest (e.g. Gallant and Gergis 2011, Ho et al. 2015). For example, in the absence of any local palaeoclimate archives, Verdon-Kidd et al. (2017b) developed a 507-year reconstruction of rainfall and streamflow for the monsoonal northwest of Australia. In this study the authors used six remote records that represented of a range of circulation patterns known to influence the region to reconstruct catchment scale rainfall and streamflow (Figure 1). Importantly their results highlight the likelihood of events more extreme than observed in the limited instrumental record. In particular, the maximum run length of below median rainfall is far greater (twice as long) for the reconstruction compared to the observed (Figure 2).

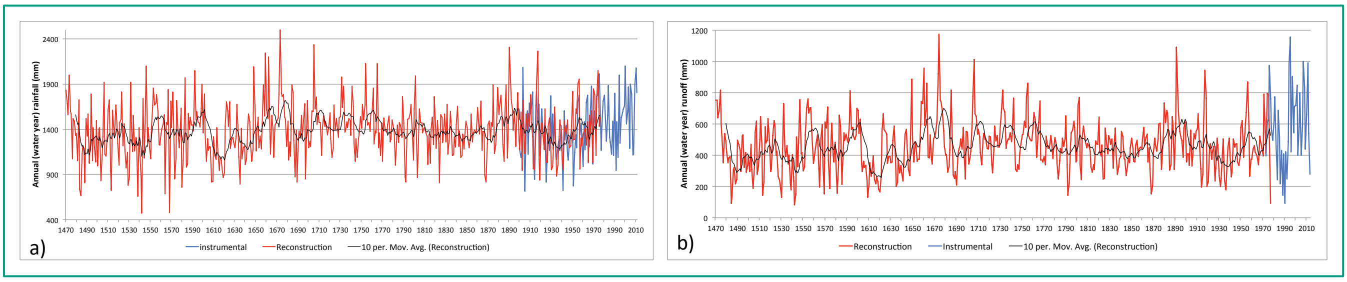

Figure 1: Multi-proxy based 507-year a) rainfall and b) streamflow reconstruction for the monsoonal northwest Australia (Source: Verdon-Kidd et al. 2017b).

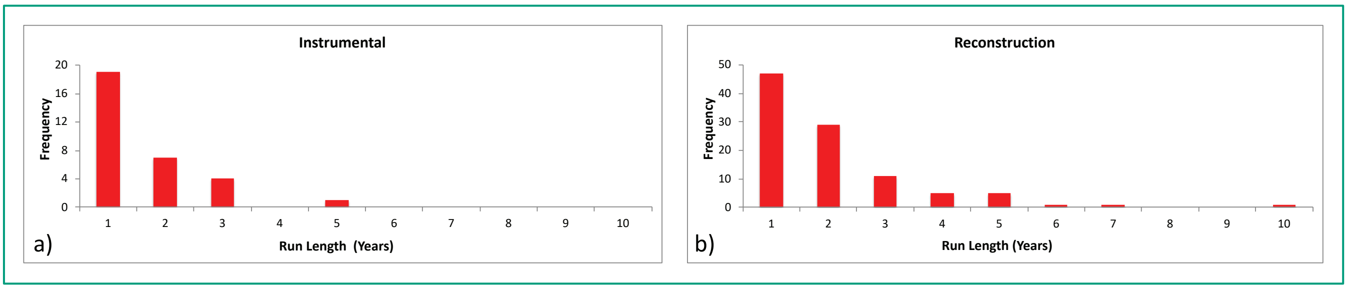

Figure 2: Run length of dry spells in instrumental record and reconstruction (adapted from Verdon-Kidd et al. 2017b).

The newly developed Australia and New Zealand Drought Atlas (ANZDA) is another example of the use of relatively remote proxies and is the first attempt to reconstruct a spatial picture of pre-instrumental drought history for the last 500 years. It uses a network of 176 tree ring records (mostly in New Zealand and Tasmania) and one coral record (Palmer et al. 2015) to reconstruct summer PDSI, successfully capturing the settlement drought of 1791-2 (Figure 3). Although not a rainfall/runoff reconstruction that would be of direct interest to water managers, it is still a useful tool for assessing past hydroclimate and will most certainly be extended in the future.

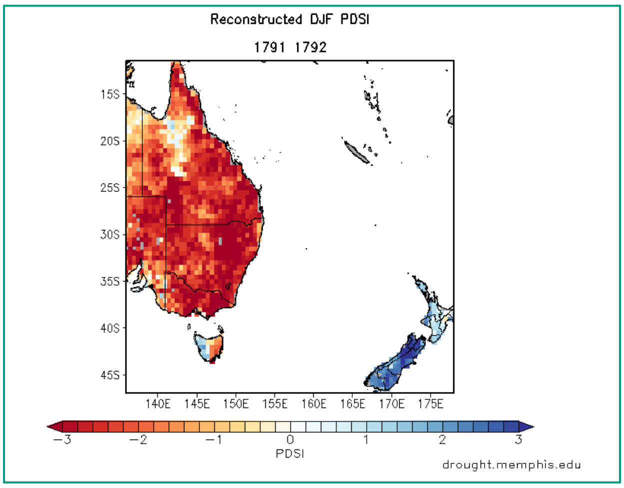

Figure 3: Extent of the Settlement Drought (1791-2) based on the PDSI (negative values indicate extreme drought) Source: http://drought.memphis.edu/ANZDA/Default.aspx.

While still valuable, the limitation of the remote proxy approach is that the final reconstruction will always contain a mix of local and remote signals contained within the data source (i.e. utilising tree ring information sourced from north and south America will inherently contain a signal specific to that region as well as the larger scale ENSO signature). This inherently limits the amount of variability resolved by the reconstruction (typically ~25%). Further, an underlying assumption of this approach is that the remote teleconnections (e.g. the ENSO impact on Australian rainfall) are stationary through time (see section 5 for further discussion). Developing reconstructions from local material (i.e. Method 2) can help to reduce this uncertainty and increase the skill of the reconstruction at the catchment scale. Some notable examples of this approach for the Australian region include the south-west Western Australia autumn-winter rainfall reconstruction (Cullen and Grierson 2009) derived from tree rings, a 337-year reconstruction of the Burdekin River (QLD) flow based on corals (Lough 2007), the 277-year cool season dam inflow reconstruction for Western Tasmania (Figure 4) and the accompanying warm season reconstruction based on a network of tree rings (Allen et al. 2015; Allen et al. 2017).

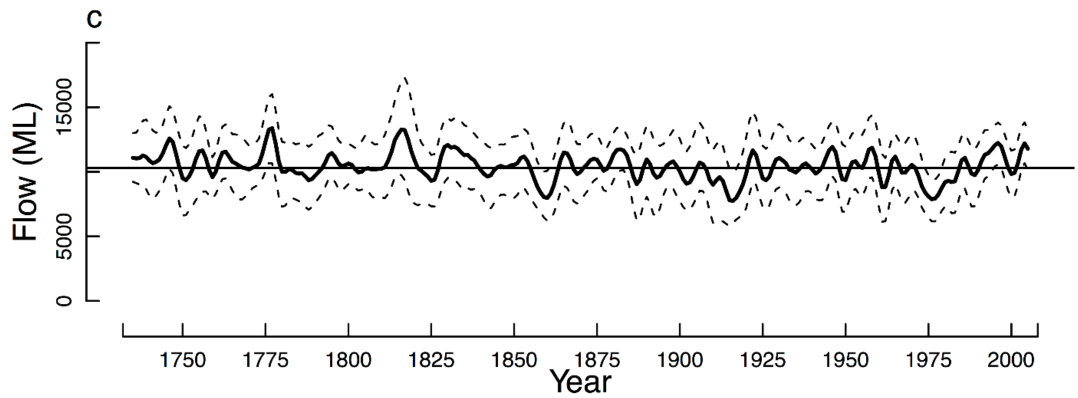

Figure 4: Smoothed July-August (20-year smoothing spline) dam inflows for Lake Burbury, western Tasmania. Dark dashed lines are 90% bootstrapped intervals (Source: Allen et al. 2015).

Unfortunately, only a few local hydroclimate (rainfall or streamflow) reconstructions exist in Australia (see Haines et al. 2016 and Ho et al. 2015b for a review). These reconstructions do not represent the full Australian spatial domain, nor do any of them include the catchments of major east Australian cities. This is in contrast to the volume of such information available for USA and Europe. One of the prime barriers in Australia has been a lack of readily accessible and easy to analyse sources of palaeoclimate data in the populated regions (especially the coastal zone), where much of our water infrastructure exists. However, emerging methods may reveal new sources of palaeoclimate data, mitigating some existing barriers. This 'new found' potential with respect to tree rings is discussed in the following section and highlights the potential availability of a range of data that can help improve estimates of the risk of drought.

USING TREE RINGS TO RECONSTRUCT AUSTRALIAN HYDROCLIMATE

The temporal resolution (annual/seasonal) and time period over which tree ring-based reconstructions can be developed (last ~1000 years) is particularly attractive for developing water management scenarios (see Ho et al. 2015b for a comparison of proxy data resolution). Importantly, the annual resolution allows for a direct calibration of tree-ring data with instrumental climate records (Figure 5) to develop practically useful reconstructions of past hydroclimate (discussed further in Section 4).

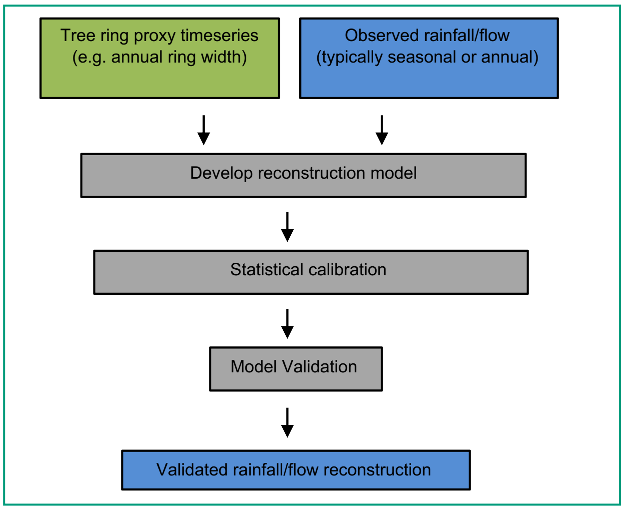

Figure 5: Overview of reconstruction methodology.

The majority of tree-ring based climate reconstructions are derived from measurements of ring width. This is based on the well-established theory that when a tree is growing in favourable environmental conditions the annual growth layers are large, whereas under stressed conditions (e.g. drought) growth layers tend to be narrow. In addition, variables such as wood density, isotopic composition and wood anatomy (e.g. vessel characteristics) are sensitive to climate variations. However, many of the species that have been investigated on mainland Australia do not produce regular annual rings, historically hampering the application of dendrochronology in these regions (Heinrich and Allen, 2013).

Tasmania is the exception, where long-lived conifers with clear annual rings such as Huon Pine have already yielded reliable climate reconstructions. Promisingly for the mainland, recently developed methods, which do not necessarily rely on the visual presence of annual ring boundaries (e.g. isotopic variations, variation in anatomical details such as wood density, vessel density or tracheid size and spatial arrangement), have increased the potential of some tree species previously discounted for dendrohydrology (e.g. Poussart et al. 2006; Haines et al. 2018). These methodological advances open up possibilities to produce long records from additional species. Some notable examples of species that have already shown potential (ring widths) include Eucalyptus pauciflora (Snow Gum; Brookhouse et al. 2008), Eucalyptus diversicolor (Karri; J. Oliver UWA pers. comm.), Callitris intratropica (Blue Cyprus; Baker et al. 2008), Callitris columellaris (White Cyprus; Cullen and Grierson 2009; O'Donnell et al., 2015; 2018) and Toona ciliata (Red Cedar; Heinrich et al. 2008; 2009). Density variation in Araucaria cunninghamii (Hoop Pine; Haines et al 2018) and the isotopic composition, wood density, and vessel arrangements in the widespread and potentially long-lived (~700yrs) Avicennia marina (Grey Mangrove; Santini et al., 2013, Goodwin et al., 2019) are also revealing the potential of these species.

There is significant untapped potential to expand the network of tree-ring records across Australia (and hence hydroclimatic reconstructions) adjacent to both agricultural regions and major population centres where a better understanding of drought risk is required. Figure 6 highlights the opportunity to expand the existing dendrochronology network to new sites.

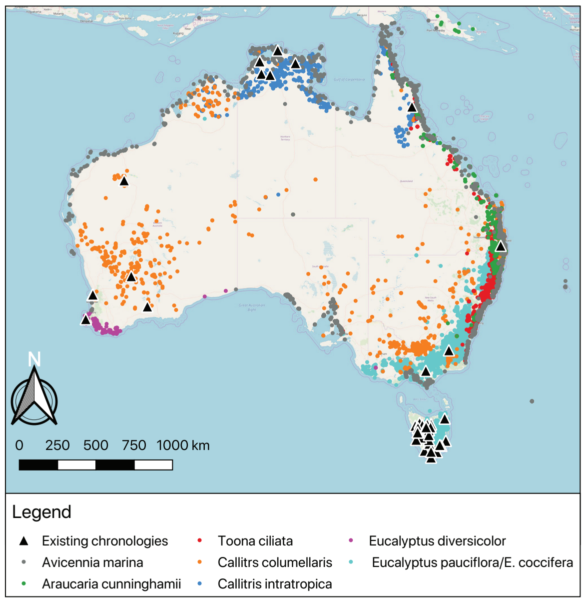

Figure 6: Location of existing chronologies (black triangles) and distribution of species which are currently being investigated for dendroclimatological potential (not exhaustive).

FROM TREE-RING BASED RECONSTRUCTION TO DROUGHT RISK ANALYSIS AND RESPONSE PLANNING

The development of long rainfall or streamflow proxy records is only a first step in improving estimates of hydrological risk and uncertainty. The information available from these records still needs to be placed into a 'drought' context. There are many kinds of drought including meteorological, agricultural, hydrological, and socio-economic drought. Prolonged drought such as the Millennium Drought and megadrought crosses all these categories – the longer the drought the greater the impact.

Possibly most significant, and most relevant to water managers, is the impact on water available in storages and rivers (hydrological drought). Therefore, water managers are most likely to require information in a form suitable for input to water systems models that simulate storage levels, allocations, transfers, demand, etc. Management options then need to respond to such events so they can be simulated (discussed further in the following section).

A suggested flow path for developing, assessing and managing drought scenarios based on palaeo records is presented in Figure 7.

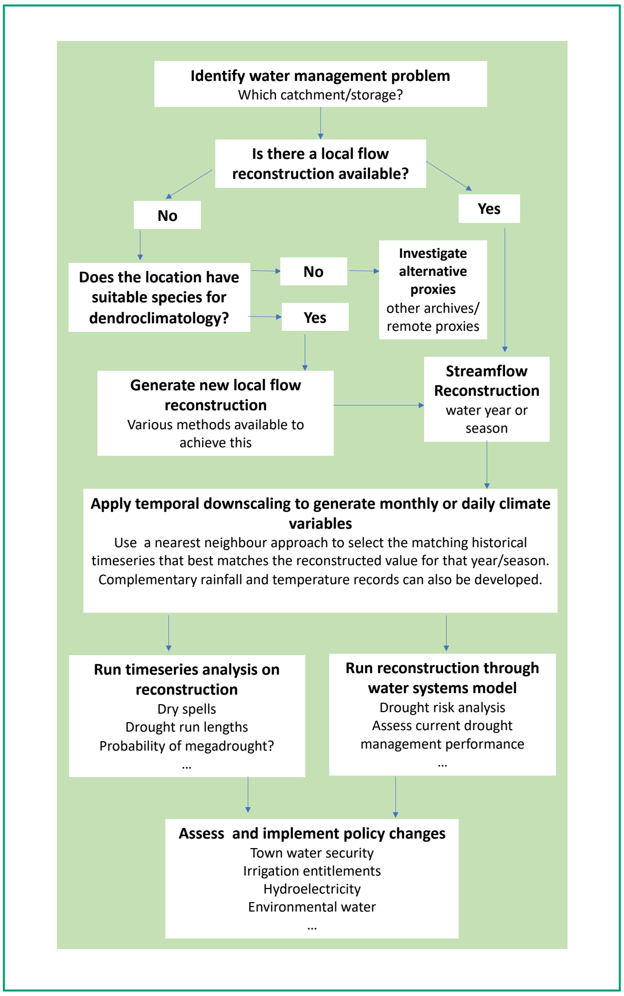

Figure 7: Flow chart describing the process from developing the tree ring-based reconstruction through to informing policy.

The final step in Figure 7 represents the culmination of information into a megadrought response plan. At the core of such plans is the fact that water use is a fundamental input to a functioning urban economy and healthy society. Indeed, the United Nations Sustainable Development Goal Six (SDG6) specifically states "clean, accessible water for all is an essential part of the world we want to live in". For Australia and elsewhere, the scenario where the water supply distribution system ceases to function, and water is distributed by other means would almost lead to the complete shutdown of industry, commerce and associated employment. The 'Cape Town Water Crisis' is a stark reminder of this possibility, where the city had to plan for "Day Zero" (Sousa 2019; LaVanchy et al. 2019).

As a minimum, the reticulated supply system needs to continue to function during prolonged and severe drought. In a water supply system, the quickest recovery occurs when there is an ability to switch to an alternative supply source. This is neatly explored via several global case studies in a recent book published by the International Water Association (IWA) titled "Resilient Water Services and Systems: The Foundation of Well-being". However, significant parts of many urban water systems across Australia are reliant on a single source of supply and even in cases where alternative supply options do exist, their capacity is typically insufficient to meet demand. A further complication arises from our inability to recognise the onset of a sustained drought until the drought has sufficiently progressed to affect human activity (Maybank et al. 1995). Therefore, plans need to be flexible, responsive and adaptive as droughts progress.

Based on the above we propose the following stages to follow in the development of a drought plan (summarised by Figure 8):

1. *Palaeoclimate and hydrology assessment*. As per Figure 7, develop megadrought scenarios;

2. *Determine emergency system demands*. The minimum demand for a functional supply. These demands will be much lower than those achieved by the restrictions on water use typically used during droughts. The plan would include very specific actions targeting water use across all customer sectors plus water system leakage.

3. *Adopt drought scenarios*. May involve adopting multiple scenarios (with the goal of testing the cost implications). These could be sequences from the palaeo record, or lower – zero inflow for example.

4. *Identify critical supply situations*. This will require the examination of the vulnerability of each part of the water supply system and determine escalating zones of failure. Situations could involve the failure of a single supply source, multiple supply sources and even all supply sources.

5. *Develop a long list of emergency supply options*. These will include transfers from other parts of the supply system, manufactured water such as desalination or recycled wastewater.

6. *Develop short list of emergency supply* options

7. *Evaluate lead times and triggers*. Checking whether the lead times afforded by trigger levels have time for delivery of options. If not, it will be necessary to bring forward some of the planning or construction.

8. *Costing of options*; and

9. *Assessment of options*, including a consideration of the compatibility of the emergency supply option with longer term supply options.

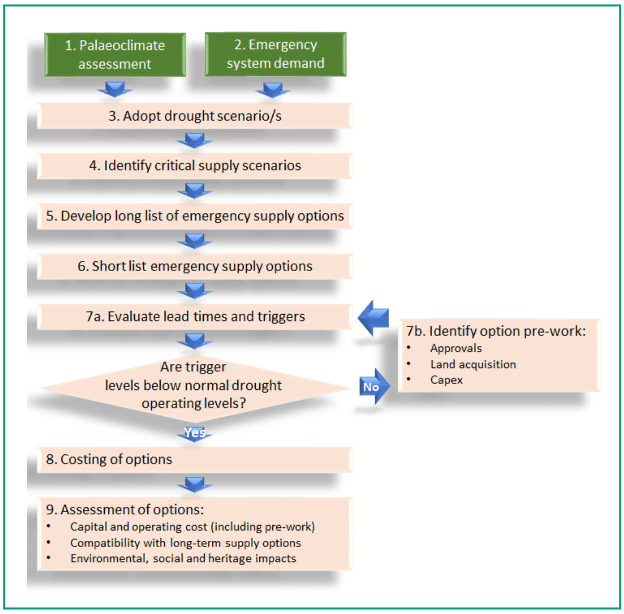

Figure 8: Mega Drought Infrastructure Response Planning Framework that includes incorporation of information available from palaeoproxies

While the concept of megadrought planning may be somewhat new to Australia, we can look elsewhere (in particular the USA) for successful examples of water authorities that have followed this approach to Figure 8. An excellent example is outlined by Gober et al (2016), who details a study conducted for the future water management of metropolitan Phoenix, one of the fastest growing urban areas of the southwest. The goal of their study was to "stress test water resources in Phoenix, using the direst hydroclimate conditions in the pre-historical record as an analogue for the increasingly likely megadroughts expected to hit the region in the coming decades". The authors then trialled a set of drought management policies to see if they could prevent unsustainable groundwater use. It is this specific concept of scenario development, followed by stress testing and then option assessment that we advocate here.

A NOTE ON UNCERTAINTY IN CLIMATE RECONSTRUCTIONS AND BEST PRACTICE

Uncertainty in palaeoclimate reconstructions typically arises from a) dating, and b) temporal variability in the physical relationships. The degree of uncertainty is dependent on the source material (e.g. corals, ice cores, tree rings, speleothems) and whether the proxies are local or remote proxies (Section 2). For absolutely dated and annually resolved proxies like tree rings, dating uncertainty is not a problem. A further source of uncertainty relevant to reconstructions based on remote proxies is the assumption that relationships between variables do not change over time. This assumption relies on non-changing teleconnections between large-scale atmospheric patterns. For reconstructions based on local proxies, this is much less of a concern. Another factor to consider in relation to tree ring widths is that the strength of the relationship between tree ring width and hydroclimate conditions will typically be asymmetrical. That is, tree rings width will better reflect drier than wetter conditions because once moisture availability has reached a certain threshold, the tree is unlikely to respond to additional moisture. Hence, tree-ring widths are likely to be more sensitive to drought conditions. Other aspects of tree rings – e.g. other wood properties (see Allen et al. 2017) or cellular damage may indicate adversely wet conditions that may either quantitatively or qualitatively complement the information available from ring widths.

Within the context of uncertainty, it is important to remember that reconstructions are statistical, not deterministic. Successful calibration and validation of models against the instrumental data ensures that, from a palaeoclimatic point of view, useful estimates can be derived from the model. There will always be uncertainty around those estimates, and a growing number of tree ring reconstructions explicitly show this by including interval estimates (e.g. Allen et al 2015; 2017). The uncertainty in proxies originates from a proxy's response to its whole environment, and climate is just one part of that. In developing a reconstruction, only proxies with a sufficiently strong hydroclimate signal are included. What is crucial to understand is that a successfully validated model will provide information superior to simple reliance on a climatology gained from short-term instrumental records. If a palaeoclimate model cannot be statistically validated against instrumental data, it should not be relied upon to make inferences. No reconstruction is perfect, but it is known that information from palaeoproxies can improve uncertainty and risk estimates in regard to flood (Australian Rainfall and Runoff http://arr.ga.gov.au; Ball et al., 2019), and undoubtedly also in relation to drought.

The uncertainty inherent in palaeoclimate records will present some challenges to engineers and hydrologists who may not be familiar with this kind of data. However, the use of estimation intervals (uncertainty bounds) will help provide useful guidance. Although not common practice, documented uncertainty present in the reconstructions can be propagated through hydrological records, with output used to assess whether the use of the palaeo-record has improved its performance. Assessment of how to deal with the uncertainty inherent to palaeohydrological reconstructions in hydrology is a growing research area (currently the topic of a PhD project) and at present there is relatively little literature available (pers. comm. N. Ballis, PhD student, University of Melbourne). The relative lack of information about how uncertainty in palaeoclimate records is best dealt with in hydrological modelling, combined with the problems of simply relying on short instrumental records presents an important opportunity for plaeoclimatologists, hydrologists and engineers to work closely together to better appreciate the issues involved in the development of palaeoclimate records. It is also an opportunity to consider how to best deal with uncertainty such that best use is made of the records. This paper aims to promote such discussions that will subsequently underpin significant advances in this area.

DISCUSSIONS AND CONCLUSIONS

There are well-founded concerns about water security for town water, irrigators and the environment across much of the Australian mainland. Given that drought management plans are currently premised on probabilities of low inflows based on a limited instrumental record, it is timely to explore and develop pre-instrumental water histories. There is significant potential to expand the tree ring network across Australia through targeted investment in this research. Initial scoping studies have identified species with potential to yield climate information, without the reliance on clearly visible annual growth rings (which previously has hampered the application of tree ring analysis in Australia). An ideal outcome of future tree ring research in Australia would be the development of a high-density network of tree ring chronologies similar to the USA. However, a starting point would be to specifically target regions where effective management of water supply is crucial, particularly those regions with increasing demand pressures.

Tree ring reconstructions of past climate cannot be used to predict the future, but they do tell us the range of drought conditions that have occurred in the past, and which could be expected to occur in the future under natural climate conditions. These records document the natural climate variability that will be superimposed on changes that may come about with warming temperatures in the future.

The Millennium Drought alerted us to the fact that our water supplies could be more vulnerable than informed by our limited 120-year record of rainfall. The current conditions across much of NSW are once again a stark reminder of this. There are significant populations at risk of potential dire economic and social consequences as a result of megadroughts.

In palaeoclimate and hydrology assessment, we have a tool that can be applied to give us an understanding of the types of scenarios that we might be facing, and to improve risk estimates, and hence infrastructure. We also have the water infrastructure strategy approaches to do the necessary pre-emptive planning and infrastructure development work. These investments in research and water supply system resilience will most likely be modest in comparison to the adverse outcomes that occur in the event of being unprepared.

REFERENCES

Allen, K. J., Nichols, S. C., Evans, R., Cook, E. R., Allie, S., Carson, G., ... & Baker, P. J. (2015). Preliminary December–January inflow and streamflow reconstructions from tree rings for western Tasmania, southeastern Australia. Water Resources Research, 51(7), 5487-5503.

Allen, K.J., Nichols, S.C., Evans, R., Allie, S., Carson, G., Ling, F., Cook, E.R., Lee, G. and Baker, P.J., 2017. A 277 year cool season dam inflow reconstruction for Tasmania, southeastern Australia. Water Resources Research, 53(1), pp.400-414.

Ault, T.R., Cole, J.E., Overpeck, J.T., Pederson, G.T. and Meko, D.M., 2014. Assessing the risk of persistent drought using climate model simulations and paleoclimate data. Journal of Climate, 27(20), pp.7529-7549.

Baker, P. J., Palmer, J. G., & D'Arrigo, R. (2008). The dendrochronology of Callitris intratropica in northern Australia: annual ring structure, chronology development and climate correlations. *Australian Journal of Botany, 56*(4), 311-320.

Ball J., Babister, M., Nathan, R., Weeks, W., Weinmann, E., Retallick, M., Testoni, I., (Editors), 2019. Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia.

Brookhouse, M., Lindesay, J., Brack, C. 2008. The potential of tree rings in *Eucalyptus pauciflora* for climatological and hydrological reconstruction. Geographical Research 46(6), pp. 421-434

Coats, S., Cook, B.I., Smerdon, J.E. and Seager, R., 2015. North American pancontinental droughts in model simulations of the last millennium. Journal of Climate, 28(5), pp.2025-2043.

Cullen , L.E. and Grierson, P.F. 2009. Multi-decadal scale variability in autumn-winter rainfall in south-western Australia since 1655 AD as reconstructed from treer ings of *Callitrtis columellaris. Climate Dynamics* 33:433-444.

Gober, P., Sampson, D. A., Quay, R., White, D. D., & Chow, W. T. (2016). Urban adaptation to mega-drought: Anticipatory water modeling, policy, and planning for the urban Southwest. *Sustainable cities and society*, 27, 497-504.

Goodwin, M (2019) Assessing the Dendroclimatic Potential of the Grey Mangrove (Avicennia marina (Forssk.) Vierh.) in New South Wales, Australia. University of Newcastle Honours thesis.

Haines, H.A., Olley, J.M., Kemp, J. and English, N.B., 2016. Progress in Australian dendroclimatology: Identifying growth limiting factors in four climate zones. Science of the Total Environment, 572, pp.412-421.

Haines, H.A., Olley, J.M., English, N.B., Hua, Q. 2018. Anomalous ring identification in two Australian subtropical *Araucariaceae* species permits annual ring identification and growth-climate relationship development. Dendrochronologia 49, pp. 16-28

Heinrich, I., Weidner, K., Helle, G., Vos, H., Banks, J.C.G. 2008. Hydroclimatic variation in far north Queensland since 1860 inferred from tree rings. *Palaeogeography, Palaeoclimatology, Palaeoecology* 270: 116 - 127

Heinrich, I., Weidner, K., Helle, G., Vos, H., Lindesay, J., Banks, J.C.G. 2009. Interdecadal modulation of the relationship between ENSO, IPO and precipitation: insights from tree rings in Australia. *Climate Dynamics* 33: 63 – 73.

Heinrich, I. and Allen, K., 2013. Current Issues and Recent Advances in A ustralian Dendrochronology: Where to Next?. Geographical Research, 51(2), pp.180-191.

Ho, M., Kiem, A.S. and Verdon-Kidd, D.C., 2015a. A paleoclimate rainfall reconstruction in the Murray-Darling Basin (MDB), Australia: 2. Assessing hydroclimatic risk using paleoclimate records of wet and dry epochs. Water Resources Research, 51(10), pp.8380-8396.

Ho, M., Kiem, A.S. and Verdon-Kidd, D.C., 2015b. A paleoclimate rainfall reconstruction in the Murray-Darling Basin (MDB), Australia: 1. Evaluation of different paleoclimate archives, rainfall networks, and reconstruction techniques. Water Resources Research, 51(10), pp.8362-8379.

Gallant, A.J. and Gergis, J., 2011. An experimental streamflow reconstruction for the River Murray, Australia, 1783–1988. Water Resources Research, 47(12).

Kiem, A.S., Johnson, F., Westra, S., van Dijk, A., Evans, J.P., O'Donnell, A., Rouillard, A., Barr, C., Tyler, J., Thyer, M. and Jakob, D., 2016. Natural hazards in Australia: droughts. Climatic Change, 139(1), pp.37-54.

LaVanchy, G. T., Kerwin, M. W., & Adamson, J. K. (2019). Beyond 'Day Zero': insights and lessons from Cape Town (South Africa). *Hydrogeology Journal*, 1-4.

Lough, J.M., 2007. Tropical river flow and rainfall reconstructions from coral luminescence: Great Barrier Reef, Australia. Paleoceanography and Paleoclimatology, 22(2).

Maybank, J., Bonsai, B., Jones, K., Lawford, R., O'brien, E. G., Ripley, E. A., & Wheaton, E. (1995). Drought as a natural disaster. *Atmosphere-Ocean, 33*(2), 195-222.

McGowan, H.A., Marx, S.K., Denholm, J., Soderholm, J. and Kamber, B.S., 2009. Reconstructing annual inflows to the headwater catchments of the Murray River, Australia, using the Pacific Decadal Oscillation. Geophysical Research Letters, 36(6).

O'Donnell, A. J., Cook, E. R., Palmer, J. G., Turney, C. S., Page, G. F., & Grierson, P. F. (2015). Tree rings show recent high summer-autumn precipitation in northwest Australia is unprecedented within the last two centuries. *PloS one*, *10*(6), e0128533.

O'Donnell, A.J., Cook, E.R., Palmer, J.G., Turne,y C.S.M., Grierson, P.F. 2018. Potential for tree rings to reveal spatial patterns of past drought variability across western Australia. *Environmental Research Letters* 13 024020, DOI: 10.1088/1748-9326/aaa204.

Palmer, J.G., E.R. Cook, C.S.M. Turney, K. Allen, P. Fenwick, B.I. Cook, A. O'Donnell, J. Lough, P. Grierson, and P. Baker. 2015 Drought variability in the eastern Australia and New Zealand summer drought atlas (ANZDA, CE 1500-2012). Environmental Research Letters, 10, doi: 10.1088/1748-9326/10/12/124002.

Poussart, P. M., Myneni, S. C. B., & Lanzirotti, A. (2006). Tropical dendrochemistry: A novel approach to estimate age and growth from ringless trees. *Geophysical Research Letters*, 33(17).

Santini, N. S., Hua, Q., Schmitz, N., & Lovelock, C. E. (2013). Radiocarbon dating and wood density chronologies of mangrove trees in arid Western Australia. *PloS one, 8*(11), e80116.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H.P., Harnik, N., Leetmaa, A., Lau, N.C. and Li, C., 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science, 316(5828), pp.1181-1184.

Sousa, P. M., Blamey, R. C., Reason, C. J., Ramos, A. M., & Trigo, R. M. (2018). The 'Day Zero'Cape Town drought and the poleward migration of moisture corridors. *Environmental Research Letters, 13*(12), 124025.

Stahle, D.W., Diaz, J.V., Burnette, D.J., Paredes, J.C., Heim, R.R., Fye, F.K., Soto, R.A., Therrell, M.D., Cleaveland, M.K. and Stahle, D.K., 2011. Major Mesoamerican droughts of the past millennium. Geophysical Research Letters, 38(5).

Tozer, C.R., Kiem, A.S., Vance, T.R., Roberts, J.L., Curran, M.A.J. and Moy, A.D., 2018. Reconstructing pre-instrumental streamflow in Eastern Australia using a water balance approach. Journal of Hydrology, 558, pp.632-646.

Vance, T.R., Roberts, J.L., Plummer, C.T., Kiem, A.S. and Van Ommen, T.D., 2015. Interdecadal Pacific variability and eastern Australian megadroughts over the last millennium. Geophysical Research Letters, 42(1), pp.129-137.

Verdon, D. and Franks, S.W., 2007. Long-term drought risk assessment in the Lachlan River Valley–A paleoclimate perspective. Australasian Journal of Water Resources, 11(2), pp.145-152.

Verdon-Kidd, D.C., Hancock, G.R. and Lowry, J.B., 2017b. A 507-year rainfall and runoff reconstruction for the Monsoonal North West, Australia derived from remote paleoclimate archives. Global and Planetary Change, 158, pp.21-35.

Verdon-Kidd, D.C., Scanlon, B.R., Ren, T. and Fernando, D.N., 2017a. A comparative study of historical droughts over Texas, USA and Murray-Darling Basin, Australia: Factors influencing initialization and cessation. Global and Planetary Change, 149, pp.123-138.

Water Corporation 2012. Water Forever, Whatever the weather, Drought-proofing Perth. www.watercorporation.com.au/-/media/files/residential/about-us/planning-for-the-future

Woodhouse, C.A., Meko, D.M., MacDonald, G.M., Stahle, D.W. and Cook, E.R., 2010. A 1,200-year perspective of 21st century drought in southwestern North America. Proceedings of the National Academy of Sciences, 107(50), pp.21283-21288.

Woodhouse, C.A. and Overpeck, J.T., 1998. 2000 years of drought variability in the central USA. Bulletin of the American Meteorological Society, 79(12).

The R Core Team (2018) R: A Language and Environment for Statistical Computing Version 3.5.1 (2018-07-02).

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