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Reconstructing pre-instrumental streamflow in Eastern Australia using a water balance approach

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ABSTRACT

Streamflow reconstructions based on paleoclimate proxies provide much longer records than the short instrumental period records on which water resource management plans are currently based. In Australia there is a lack of in-situ high resolution paleoclimate proxy records, but remote proxies with teleconnections to Australian climate have utility in producing streamflow reconstructions. Here we investigate, via a case study for a catchment in eastern Australia, the novel use of an Antarctic ice-core based rainfall reconstruction within a Budyko-framework to reconstruct ~1000 years of annual streamflow. The resulting streamflow reconstruction captures interannual to decadal variability in the instrumental streamflow, validating both the use of the ice core rainfall proxy record and the Budyko-framework method. In the preinstrumental era the streamflow reconstruction shows longer wet and dry epochs and periods of streamflow variability that are higher than observed in the instrumental era. Importantly, for both the instrumental record and preinstrumental reconstructions, the wet (dry) epochs in the rainfall record are shorter (longer) in the streamflow record and this non-linearity must be considered when inferring hydroclimatic risk or historical water availability directly from rainfall proxy records alone. These insights provide a better understanding of present infrastructure vulnerability in the context of past climate variability for eastern Australia. The streamflow reconstruction presented here also provides a better understanding of the range of hydroclimatic variability possible, and therefore represents a more realistic baseline on which to quantify the potential impacts of anthropogenic climate change on water security.

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1. Introduction

Rainfall and streamflow reconstructions from paleoclimate proxies indicate that the instrumental climate record does not capture the full range of climate variability (e.g. Meko et al., 1995; Cook et al., 1999; Woodhouse and Lukas, 2006a,b; Allen et al., 2015b; Vance et al., 2015; Ho et al., 2016; Tozer et al., 2016). Importantly, Thyer et al. (2009) showed that instrumental climate records, on which water resource management plans are based, produce high parameter uncertainty in stochastic models and that longer records are required to reduce uncertainty and enable proper stochastic model identification. Where paleoclimate data is used, longer wet and dry sequences are observed, allowing for the development of more realistic statistics on which to design water infrastructure and develop catchment management plans (Biondi et al., 2002; Verdon and Franks, 2007; Biondi et al., 2008; Prairie et al., 2008; Henley et al., 2011; Patskoski and Sankarasubramanian, 2015). As such, researchers are investigating the incorporation of paleoclimate reconstructions, and more specifically, streamflow reconstructions, into water management and planning (e.g. Thyer et al., 2006; Woodhouse and Lukas, 2006b; Prairie et al., 2008; Patskoski and Sankarasubramanian, 2015). However, knowledge gaps still exist and, in practice, the uptake of insights from paleoclimate research remains limited, especially in Australia where water resources management is primarily based on short (~100 years at best) instrumental rainfall and streamflow records (e.g. Kiem et al., 2016).

High resolution streamflow reconstructions are traditionally developed from tree ring records given their high temporal resolution and ability to represent local hydroclimatic behaviour (Elshorbagy et al., 2016; Razavi et al., 2016). In North America, a

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broad network of tree ring records (see Fig. 5 in Cook et al. (2010)) has afforded the development of numerous streamflow reconstructions in water catchments across the region (e.g. Meko et al., 1995; Meko et al., 2001; Woodhouse and Lukas, 2006a,b; Ho et al., 2016). In Australia, however, there is a lack of in situ, high resolution (e.g. at least annual) paleoclimate proxy records, particularly in the densely populated eastern seaboard. Of the existing eastern Australian-based streamflow reconstructions (Table 1), two (from the island of Tasmania) utilise local proxy (tree ring) records (4 and 5, Fig. 1a) (Allen et al., 2015a; Allen et al., 2015b; Allen et al., 2017). The remaining reconstructions use proxy records that are remote from the water catchments of interest and therefore rely on climatic teleconnections between the proxy location and the region of interest. McGowan et al. (2009) produced a streamflow reconstruction for the River Murray (2, Fig. 1a) based on a reconstruction of the Pacific Decadal Oscillation (PDO) which in turn was developed from flood-drought records in eastern China. Gallant and Gergis (2011) produced a streamflow reconstruction for the same location as McGowan et al. (2009) (3, Fig. 1a) but used a network of tree ring and coral records from New Zealand, Indonesia, the tropical Pacific region and Australia (outside of the River Murray catchment). Finally, Lough (2007) produced streamflow reconstructions for four rivers in northeastern tropical Australia from coral records from the Great Barrier Reef (1, Fig. 1a).

A remote climate proxy record that has also been utilised for Australia is the millennial-length summer sea salt record from the Law Dome ice core in East Antarctica (Vance et al., 2013, 2015; Tozer et al., 2016). Law Dome annual sea salt concentrations are a function of wind speed over the Southern Ocean, which are connected with large-scale climate processes operating at annual to decadal scales that also influence Australia's climate (Souney et al., 2002; Vance et al., 2013, 2015). Tozer et al. (2016) recently used the sea salt proxy record to develop a 1013-year rainfall reconstruction for the Williams River (WR) catchment on the eastern seaboard of Australia (Fig. 1b). The proxy record is annually resolved and accurately dated (discussed in Section 3.1.2), enabling precise dating of extreme events. This record is also significantly longer than other proxy records (and the instrumental period) used in existing Australian streamflow reconstructions (Table 1), and has the potential for extension to 2000 years (Roberts et al., 2015). This proxy record is unique for hydroclimate studies where accurate event timing and high data resolution are needed and thus shows potential for future streamflow reconstruction in Australia.

The streamflow reconstructions presented in Table 1 are based on regression techniques. These techniques may be suitable for rainfall reconstructions, given that rainfall is directly linked with atmospheric and oceanic processes, or for tree ring based streamflow reconstructions, because tree growth is a response to local hydrologic conditions. However, for streamflow reconstructions using remote proxies, regression techniques frequently ignore other processes affecting catchment water balance (e.g. evapotranspiration, soil moisture, catchment storage, vegetation, topography, groundwater recharge) (Solander et al., 2010; Gallant and Gergis, 2011; Saito et al., 2015).

An alternative option is to develop a hydrological model that uses proxy-derived inputs to produce a streamflow reconstruction (e.g. Saito et al., 2008; Gray and McCabe, 2010; Solander et al., 2010; Saito et al., 2015). This approach incorporates catchment processes into the streamflow reconstruction development. For example, Gray and McCabe (2010) and Saito et al. (2015) reconstructed preinstrumental streamflow in two catchments in the western United States using conceptual hydrological models with tree ring-derived precipitation and temperature as inputs. However, a drawback of this approach is the need to calibrate multiple model parameters (e.g. four and six parameters in the case of Gray and McCabe (2010) and Saito et al. (2015) respectively) and the consequent assumption that optimised parameters remain valid over the reconstruction time period (i.e. over multiple centuries). A change in mean rainfall can reduce parameter transferability (Vaze et al., 2010; Coron et al., 2012), and this issue is likely to magnify when using reconstructed rainfall as a model input where multiple regime shifts occur over the last 1000 years (e.g. Tozer et al., 2016).

The zero-parameter, non-linear Budyko (1974) curve provides another option for streamflow reconstruction. Widely used in the hydrological community, the Budyko curve is a simple water balance model that describes the partitioning of rainfall into streamflow and evapotranspiration (Zhang et al., 2008; Greve et al., 2015). The Budyko curve is used to model streamflow in Australian catchments (Zhang et al., 2008; Potter and Zhang, 2009) but, to our knowledge, has not been used to reconstruct preinstrumental streamflow in eastern Australia.

In this study we use the Budyko (1974) curve and an associated single parameter Milly's β curve for comparison (Milly, 1993) (discussed further in Section 4.1), which require rainfall and potential evapotranspiration (PET) inputs, to reconstruct preinstrumental

Table 1
Current published eastern Australian streamflow reconstructions.

Reference	Description	Region	Proxy used	Record availability	Reconstruction method
1. Lough (2007)	Annual (Oct-Sep) freshwater flow into Great Barrier Reef (from reconstructions of Herbert, Burdekin, Pioneer and Fitzroy River flow)	Northeast QLD	Coral luminescence indices from corals in Great Barrier Reef region	1631–1983 (353 years)	Linear regression
2. McGowan et al. (2009)	Annual River Murray inflows	Southeast Australia	Pacific Decadal Oscillation reconstruction (developed based on flood-drought records from eastern China, (Shen et al., 2006))	1474–1994 (521 years)	Piecewise polynomial interpolation
3. Gallant and Gergis (2011)	Annual (Aug-Jul) River Murray inflows	Southeast Australia	Tree rings (from New Zealand, Indonesia, Western Australia and Tasmania) and corals (from Fiji-Tonga, Great Barrier Reef, Indonesia)	1783–1988 (206 years)	Principal component analysis and multiple linear regression
4. Allen et al. (2015b)	Dec-Jan reconstruction of a streamflow index for central-west Tasmania and inflows to the Lake Burbury impoundment	Tasmania	Tree rings (from Tasmania)	1530–2007 (478 years)	Nested point-by-point regression
5. Allen et al. (2017)	Jul-Aug inflows to the Lake Burbury impoundment	Tasmania	Tree rings (from Tasmania)	1731–2007 (277 years)	Principal component regression

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