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Justin Costelloe: a champion of arid-zone water research

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1. Introduction

Justin Francis Costelloe (Fig. 1) was born in 1965. He grew up in the mining city of Bendigo (Victoria, Australia) before studying Earth Sciences at the University of Melbourne. He went on to work as an exploration geologist in the mining industry in the dryland regions of Australia and Chile. He developed a love of Australia's desert landscapes and returned to undertake Masters and PhD studies on arid zone hydrology at the University of Melbourne, before continuing as a research fellow and senior research fellow leading arid zone research projects. Justin was a leader in research aimed at understanding surface water and groundwater in Australia's arid zone and also made important interdisciplinary contributions linking the hydrology and ecology of the arid zone, with a focus on Australia's iconic Channel Country and the Great Artesian Basin (GAB). Drawing on his research and intimate field knowledge, he provided advice to government on management of the Lake Eyre Basin (LEB). Locations of the GAB and LEB, together with more detailed description of the GAB, are provided by Habermehl (2019, this issue). The LEB is the world's largest internally draining river basin, covering 1.2 million km^2 or 1/6 of Australia, and occupies parts of the states of Queensland, New South Wales, South Australia, and the Northern Territory. The main rivers rise in central Queensland and flow south-west to Lake Eyre, which is 16 m below sea level and located in South Australia. These rivers have intermittent to ephemeral flow regimes and the basin predominantly has semi-arid and arid climates and straddles the tropical and temperate zones (McMahon, et al., 2008a, McMahon, et al., 2008b).

Justin was also a great mentor to students. One of his students, White (2018), valued Justin's focus on evidence, questioning (to improve clarity of argument), commitment to feedback, emphasis on planning and being accountable for progress, attention to professional development, and availability, and his ability to lead by example. These multiple and diverse facets of “the best supervisor” go well beyond a narrow focus on science and are the mark of a well-rounded academic and mentor.

Justin’s research covered a range of topics. He contributed to quantifying the natural discharge components of the water balance of the GAB, one of the largest aquifers of the world and the main water resource for significant parts of the Australian arid zone. He was passionate about arid zone waterways and researched interactions between rivers and alluvial groundwater systems, transmission losses and the fate of water on the floodplains of arid river systems such as Cooper Creek and the Diamantina River, as well as the interactions between hydrology and aquatic ecology in the arid zone. During his PhD, a major contribution to the AridFlow project (Costelloe, et al., 2003, 2004) was characterising the hydrology of LEB rivers and, working with aquatic ecologists from a range of institutions (e.g. University of Adelaide, Griffith University, Arthur Rylah Research Institute, CSIRO Sustainable Ecosystems), building an integrated understanding of the interlinked hydrological and ecological systems of the basin. Arid catchment and stream systems are poorly studied globally, due to a lack of long-term observations (Wheater, 2007), compared with many other systems, particularly those from the perennial temperate zone. This makes Justin’s body of work important in a global context, even though he concentrated on the LEB for much of his work.

Justin took a range of approaches to his research, but field investigations were always central to his work. The LEB is a vast episodic and minimally monitored system that overlaps and interacts with the GAB, which has equally challenging data deficits. Justin met this challenge through targeted field research, monitoring rivers, water holes and groundwater discharge areas with a range of techniques. He deployed standard hydrometric monitoring of surface and groundwaters in remote areas. Hydrochemical techniques focussed on isotope- and solute- (major ions and others) based approaches. Dating of groundwater using chlorofluorocarbons (CFC), radio carbon and other techniques were also important. Using remote sensing, Justin and his students were able to map and quantify diffuse discharge from the GAB over a 500 km arc across the southwestern margin of the GAB, and the dynamics of the anastomosing flood plain systems of the channel country. To help interpret the data arising from field expeditions and the sparse long-term monitoring across the region, Justin also undertook hydrologic, groundwater and hydrochemical modelling studies.

2. Great Artesian Basin

Justin's arid zone eco-hydrology work demonstrated the presence of GAB groundwater discharge and associated salt deposition in catchments where waterholes and streams featured elevated salinity. This led to Justin working on the problem of quantifying the discharge fluxes of salt from the GAB to those waterholes and streams. An additional significant implication of this work was to further constrain vertical leakage rates from the GAB along its south-west margin, which remained a poorly understood component of the GAB's water balance.

Much of the groundwater flow throughout the GAB is focused towards discharge zones along the south-western margin (Habermehl, 1980), with water discharged by bores, natural springs (‘‘mound springs”) and vertical leakage. Due to the large spatial scale of the GAB, only modelling methods have been used to estimate the vertical leakage at a sub-basin scale (Welsh, 2000, 2006). Relatively few field measurements are available to constrain the rate or regional distribution of this vertical leakage. Where not constrained by observed data, uncertainty and bias can be high, undermining sustainable management of these important systems. Justin’s work was the first to quantify these discharge rates along the basin margin using direct measurements and then relating fluxes to a basin wide model. Discharge flux rates are commonly low and difficult to measure with field instruments, and long-term monitoring is problematic in remote locations. Additional challenges include the difficultly in representing the high spatial variability and temporal uncertainty of discharge processes. Justin’s approach was to apply multiple methods to measure or estimate the discharge rates, including chloride profile modelling to estimate discharge over decadal scales, micro-lysimeters to measure daily evaporation rates from discharge areas, and eddy-covariance to measure phreatic evaporation at hourly scale. Together these approaches were able to build a picture of temporal and spatial variability and also unravel complex processes such as the interaction between local meteoric recharge and assumptions about inter-aquifer flow.

A major challenge of the research was to interpolate and scale field discharge measurements, collected at the meter and hundreds of meter scales, to produce estimates of discharge over an area of 1000s km^2. Remote sensing data provide the only feasible means to characterise diffuse discharge processes over the large spatial scales occurring along the south western margin. With colleagues, he developed a conceptual framework to relate surface expressions of discharge to subsurface discharge rates to facilitate a basin margin-wide classification of discharge rates.

Justin's work significantly refined ranges of estimated diffuse discharge and improved the understanding of the water balance for the GAB's South Australia portion. Water flows to the south-west margin from two distinct directions, the north-east (to the eastern part of the SW margin) and the north-west (to the western part of the SW margin) (Costelloe, et al., 2015). A key finding was that in the eastern portion of the GAB south-west margin a significant proportion of diffuse discharge is likely to be occurring distal to the margin, whereas along the western portion it is likely that the majority of discharge is occurring along the high discharge zones mapped in the research. This has consequences when attempting to establish a sustainable yield for harvesting groundwater since the western portion will be more sensitive to groundwater abstractions, where the groundwater would otherwise flow to shallow water discharge areas, feeding springs and maintaining the groundwater dependant ecosystems of discharge zones.

3. Surface-water/groundwater interactions

Much arid zone hydrology is episodic due to strong evaporative demands that dry surface water from the landscape together with infrequent precipitation events. In the LEB, both local rainfall events in catchments draining to Lake Eyre from the west and runoff from the semi-arid tropics in the headwaters of the Cooper Creek and Diamantina River bring water to the flood plains of the lower reaches of the basin. In addition, the GAB overlaps with the LEB and transports water from remote recharge beds to discharge zones in the south-west of the GAB which coincides with the lower reaches of the LEB. The arid nature of the basin means that evapoconcentration of solutes and transport of solutes within the water systems are important processes that influence water quality in the flood plain sediments, aquifers, rivers and water holes. Overall the region can be viewed as a complex system of interactions between artesian groundwater, fluvial and lacustrine waters and pluvial sources interacting to varying degrees spatially and temporally within shallow groundwater systems.

Justin’s work was able to identify a series of interactions between river waters and GAB waters that typically occur in shallow alluvial groundwater systems around the rivers and lakes of the region (Costelloe, et al., 2005b). Spatial patterns of salinity indicate that mound springs and areas of diffuse discharge from the GAB are major sources of salt in the Neale’s/Peak river systems. The salt is mobilised into the stream system through surface and near-surface processes leading to trends of increasing salinity through GAB discharge zones. This mobilisation includes bank storage and recession flows towards the end of flow events.

In the Coongie Lakes system of the Cooper Creek, the lakes typically recharge the shallow groundwater systems during periods of inundation but that shallow groundwater evaporates through the lake beds during dry periods leading to salinization of the lake bed sediments in the more ephemeral lakes (Costelloe, et al., 2009). Justin found that the more ephemeral lakes experience recharge through preferential flow paths. Consequently, solutes that moved into those sediments by groundwater evaporation during dry periods remain within the lake bed sediment matrix following recharge. Recharge from the more perennial lakes appears to be by matrix flow resulting in low solute concentrations in bed sediments. As the basin moves between dry and wet epochs associated with Pacific (e.g. El Nino-Southern Oscillation – ENSO) and Indian Ocean variability

(Indian Ocean Dipole), the balance of these processes can vary within individual lakes. It is speculated that these spatial variations between lakes may also be linked to variations in groundwater age with older water found under more ephemeral lakes, and more enrichment of stable water isotopes under the more perennial lakes because they are subject to longer periods of active lake evaporation during recharge.

The hydrochemistry of groundwater, particularly the dominance of either sulphate or bicarbonate, proved to be a useful tool in distinguishing between GAB, fluvial and pluvial sources of groundwater recharge to shallow systems (Costelloe, et al., 2012). Modelling of the hydrochemical evolution of waters subject to evapoconcentration and subsequent mineral precipitation was able to identify some areas where GAB water was the dominant source, other areas where it was a minor contributor and some areas where either a mixture of sources was required to produce the observed chemical characteristics or water sources were ambiguous, demonstrating the complex variation of recharge sources for shallow groundwater systems throughout the region.

4. Floodplains in the arid zone

Arid zone floodplains play a key role in streamflow transmission losses as floodwaters move downstream. In the LEB, a combination of low gradients, anastomosed channels and arid climate can significantly reduce the size of a flood pulse as it moves through the middle to lower reaches of the basin. Early work on the spectacular changes brought by flooding in the LEB and filling of Lake Eyre by Kotwicki and co-workers (Kotwicki, 1986, Kotwicki and Allan, 1998, Kotwicki and Isdale, 1991) motived Justin. Building on previous work in Cooper Creek (Knighton and Nanson, 1994), Justin investigated the non-linear relationship between flood pulse discharge and the magnitude of transmission losses in the middle Diamantina River (Costelloe, et al., 2003, McMahon, et al., 2008a). Between Diamantina Lakes and Birdsville, he found transmission losses averaged 77%, which means on average only 23% of a flood pulse leaving Diamantina Lakes arrived at Birdsville. He also noted that transmission losses tend to increase with discharge up to a threshold value (~1500 x 10^6 m^3 for this reach of the Diamantina); whereas for discharges above this threshold, the transmission loss percentage declined for larger flood pulses.

Justin identified three main processes: (1) evaporation; (2) infiltration; and (3) terminal storage as contributors to the non-linear and threshold behaviour of transmission losses with discharge in these systems. Low channel gradients in the LEB mean that flood pulses move slowly downstream in this region, which facilitates loss of water via evaporation at the potential rate from the water surface. Infiltration losses can also occur through the bed and banks of the channel. As flood magnitude increases, then when the flood pulse exceeds the channel capacity and spreads onto the floodplain, the losses to evaporation and infiltration across a larger area can increase significantly. Losses due to terminal storage also increase once the flood moves onto the floodplain, due to water moving into the anastomosed channel network and becoming disconnected from the main channel flood pulse. Once disconnected from the main channel, this water can remain as a series of waterholes that slowly evaporate and infiltrate away and are lost to the downstream network. From a hydrological perspective, inundation of the floodplain contributes to terminal storage transmission losses. However, that water on the floodplain has great ecological, indigenous and social significance (Gibbs, 2009, Silcock, 2009). To understand the relative contribution of these three processes to transmission loss dynamics, Costelloe, et al., (2003) modelled the Diamantina Lakes to Birdsville reach and concluded that losses due to terminal storage were the largest contributor, followed by evaporation and then infiltration (see also McMahon, et al., 2008b).

5. Arid zone ecohydrology

It is trite but also somewhat misleading to say that water availability is a key limiting resource to ecosystems in the arid zone. Particularly for major river systems such as the Cooper Creek and Diamantina River, and associated lake and wetland systems, episodic influxes of water lead to boom and bust ecology (Arthington and Balcombe, 2011). Understanding hydrologic dynamics therefore becomes a critical underpinning for understanding and predicting impacts of change on arid zone ecosystems.

The episodic flow regime is a key feature of these systems, together with an anastomosing channel morphology in many of the streams. This leads to highly variable water availability and Justin's work in extrapolating information from a very small number of stream gauges spatially throughout the systems using models of the floodplain inundation (Costelloe, et al., 2005a) provided an important base for investigating the links. This enabled questions of environmental flow management to be examined with a rigorous evidence base and demonstrated the sensitivity of flow regimes to any future water extraction or indeed climate change (Costelloe, et al., 2003). The ephemeral nature of LEB and many other arid zone streams make ecological refugia critical, motivating Justin and others to examine the implications of hydrologic patterns for the ecological diversity and processes within the rivers, waterholes and lakes of the LEB (Costelloe and Russell, 2014, Puckridge, et al., 2010, Puckridge, et al., 2000). These studies clearly demonstrated the important role of hydrologic variability to the aquatic ecology.

Justin also worked on ecohydrological problems in the arid zone including examining the source of water used by riparian *E. Coolabah* trees that typically grow within meters to tens of meters of channels in the region (Costelloe, et al., 2008). That work demonstrated Coolabah combined use of soil and groundwater even in the presence of surface water. Working with ecologists he also examined questions of whether alien fish are disadvantaged by the episodic flow regime of these rivers, the diversity of algae, the role of salinity fluctuations in macroinvertebrate diversity, and the diversity of zooplankton in LEB rivers.

6. Reprise

Justin's research on the hydrology and ecohydrology of Australia's drylands, specifically the Lake Eyre Basin, was wide ranging and impactful. He was able to collaborate successfully across disciplines resulting in a much more rounded understanding of these fantastic natural systems. Justin's papers have influenced studies in many other contexts from modelling of ephemeral rivers in Africa (e.g. Wolski, et al., 2006) and elsewhere, informing earth observation studies of major wetlands (e.g. Heimhuber, et al., 2016), and global studies of groundwater use by vegetation (Evaristo and McDonnell, 2017). Most importantly Justin made a significant contribution to the multidisciplinary understanding of Australian dryland systems, notably the LEB and GAB (Habeck-Fardy and Nanson, 2014). He passed away in 2018.

7. Acknowledgements

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FIGURE CAPTION:

Figure 1. Justin Costelloe in 2011, at Cooper Creek, which flows into Lake Eyre Basin. Photo Graham Tomlinson.