Negative Indian Ocean Dipole drives groundwater recharge in southeast Australia

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Abstract

Understanding how Australian groundwater recharge is affected by the Pacific and Indian Ocean climate drivers is crucial for water resource planning and management, especially in semi-arid environments. This will allow for assessment of the impact of climate change on the occurrence and timing of groundwater recharge and the sustainable management of this resource into the future. Measuring groundwater recharge is difficult as it occurs in the subsurface. However, caves situated in the unsaturated zone give us the opportunity to observe these subsurface processes. Here we show good agreement between the recharge events measured in a cave system and groundwater bores at a nearby site. We also show that the most significant recharge event during a decade of observations occurred during a particularly strong negative Indian Ocean Dipole period. Through further analysis of recharge events dating back 1900 we show for the first time a significant link with negative Indian Ocean Dipole events.

Introduction

Groundwater is an essential source of water especially in semi-arid to arid regions. Understanding groundwater recharge processes is essential for water resource management and improving our understanding of groundwater dependent ecosystems and the hydrological cycle. Groundwater recharge is the “downward flow of water reaching the water table, adding to groundwater storage”\(^1\). Recharge can be diffuse (precipitation-generated infiltration, occurring over large areas, here termed ‘rainfall recharge’) or focused (from losing or ‘leaking’ rivers, wetlands and lakes)\(^2\). However, the scarcity of surface water bodies in many water-limited environments means that rainfall is the main source of groundwater recharge.

Rainfall recharge in water-limited environments is event-specific and will only occur once the rainfall recharge threshold is exceeded. This is the amount of precipitation that is required to overcome a combination of evapotranspiration losses and sub-surface moisture deficits which control the initiation of vertical drainage of water. Quantifying this threshold, and understanding how often it is exceeded, its spatial variability, and how it varies with climate and environmental changes, is crucially important for the sustainable management of groundwater and is currently a major challenge\(^3\).

However, groundwater recharge is difficult to measure directly (experimentally) because it is taking place in the subsurface and is highly variable in space and time. Existing techniques available to quantify recharge thresholds, for example using water isotopes and chlorine mass balance aggregate information over time and are typically limited to monthly or lower resolution, and the water table fluctuation method is unable to distinguish if the groundwater response is new water from the rainfall event or represents a hydraulic response from previously infiltrated water or changes in lateral groundwater flow\(^4,5\).

Here, we use limestone caves situated in the unsaturated zone as observatories for the movement of water from the surface to the aquifer. Previously, we have demonstrated the success of this approach using automated drip-loggers deployed in caves over a five-year period in the Macleay region (mid-north coast NSW);\(^6\) and six-years at the Snowy Mountains (NSW)\(^3\). Importantly, continuous hydrological time series of cave percolation waters can provide the necessary observational data to constrain rainfall recharge thresholds at the scale of individual events, allowing the quantification of temporal and spatial heterogeneity of recharge.

To date, no comparisons have been made between diffuse recharge events recorded by cave-based monitoring and those recorded in nearby groundwater bores (wells). Here this is undertaken for the first time for bores located in both karstified and non-karstified lithologies and cave observatory data for the period 2012–2020 for the water-limited Wellington region of New South Wales, Australia. The cave-based monitoring quantifies rainfall recharge thresholds for individual recharge events, and this is compared to water table fluctuations in nearby bores at the Wellington Research Station. These bores are unaffected by groundwater abstraction and are representative of recharge to a range of fractured-rock and alluvial aquifers. Based on these times of recharge the climate drivers can be determined and an assessment made on how recharge in these environments is likely to change in the future.

ENSO and IOD are significant drivers for rainfall in Australia though their influence is highly seasonal and region specific\(^7\). For southeast Australia, IOD tends to influence rainfall during the period June-October, and ENSO spring for the region of this study\(^8,9\). La Niña and/or negative IOD events typically increases the amount of rainfall for east Australia. Conversely, dry conditions is generally observed during El Niño and/or negative IOD events\(^10\).

Methods

Site description

The two study sites are located near Wellington NSW, Australia and are approximately 7 km apart. The geology at the Wellington Caves site (32.621535°S; 148.939984°E) consists of massive and thinly bedded karstified Devonian limestone, with a thin (< 1 m) but variable soil cover consisting of aeolian red clay\(^11\). The Wellington Research Station (WRS) site (32.572480°S; 148.985090°E) sits in a river valley partly filled with Quaternary alluvial and colluvial sediments varying from clays to cobbles\(^12\). A portion of the research monitoring bores at WRS are installed in the unconsolidated sediments in the Macquarie River valley and the remaining bores are drilled into the bedrock of the upper slopes of the valley. The bedrock consists of mainly Devonian meta-basalts, with a variable soil regolith (0.5-1 m) grading into thicker colluvium and alluvium further down the slope\(^12,13\). Below the soil zone bedrock at both sites are characterised by fracture and conduit flow as the primary (matrix) porosity of both the meta-
basalt and limestone is low\textsuperscript{13}. Both sites are characterised by cleared (WRS) or remnant degraded box grass woodland (Wellington Caves) with sparse tree-cover.

Wellington is characterised by a semi-arid climate, and experiences a hot dry summer and cold winter climate with roughly uniform, but episodic rainfall throughout the year\textsuperscript{14} (Fig. S1). The annual average rainfall is 621.1 mm (1991 – 2020) with annual average evaporation of 1679 mm (1991 – 2020) recorded at the Wellington (D&J Rural) Bureau of Meteorology station\textsuperscript{15}.

Cave recharge data from Cathedral Cave has been collected since 2010 from a network of 20 loggers\textsuperscript{11}. Drips at 25 m below ground surface were used, as these are close to the modern groundwater level, which is only a further ~ 5 meters below. The drip logger locations therefore represent diffuse recharge events to the groundwater table. Rainfall recharge thresholds to initiate recharge is determined through comparison of the timing of recharge events detected in the cave with antecedent precipitation using daily precipitation timeseries from the Wellington Bureau of Meteorology station. For the past modelling of groundwater recharge the timeseries of daily potential evapotranspiration was obtained from SILO\textsuperscript{16}.

The UNSW Wellington Research Station contains a network of bores, where groundwater levels have been monitored since 2012. Bores that showed groundwater fluctuations similar to the fluctuations in the nearby Macquarie River as shown in\textsuperscript{12} were excluded from this study; so that only diffuse recharge was considered. The bore details are given in Table S1. Some of the selected bores are located in fractured rock and are uncased bores without screens.

**Climate Indices**

The Dipole Mode Index (DMI) is used here to identify Indian Ocean Dipole (IOD) events\textsuperscript{17}. The DMI index is calculated as the difference between the sea surface temperature anomalies averaged in the west (50°E - 70°E, 10°S - 10°N) and east (90°E - 110°E, 10°S to 0°S) Indian Ocean regions, with data obtained from Global Climate Observing System (GCOS) Working Group on Surface Pressure (WG-SP)\textsuperscript{18}. A negative IOD event is identified when the DMI index is below one standard deviation (approximately -0.5°C), which means that the eastern Indian Ocean is warmer than normal, and the western Indian Ocean is cooler than normal. A positive IOD event occurs when the opposite sea surface temperature pattern is above one standard deviation.

El Niño Southern Oscillation events are identified using the Niño3.4 index, which is calculated using the averaged sea surface temperature anomalies in the central Pacific between 5°N - 5°S and 170° - 120°W. We classify La Niña events when the central Pacific is cooler than average and the Niño3.4 index is below one standard deviation. El Niño events are identified when the central Pacific is warmer than normal, and the index is above one standard deviation (approximately 1.1°C).

**Results and Discussion**

**Climate and Rainfall**

The years of 2010–2012 were marked by a double-dip La Niña event and record-breaking rainfall in several parts of Australia\textsuperscript{19–21}. The consecutive occurrence of the La Niña events contributed to placing April 2010 to March 2012 as Australia's wettest two-year period on record. The rainfall surplus in the study region led to a pronounced groundwater recharge event at the first half of 2012 (Fig. 2-middle panel). This was followed by a period of around average rainfall (on a yearly basis) for 2012 through to 2015. Though in early 2013, heavy rainfall led to floods in several catchment areas of interior NSW (Fig. 2a), however those events were more localised and intermittent than the persistent rain associated with the previous La Niña event.

El Niño is generally associated with dry conditions in east Australia, however, despite the occurrence of the extreme 2015–2016 El Niño event, rainfall was not atypical that year\textsuperscript{22}. Instead, the region experienced significant rainfall surplus in 2016 due to the appearance of a record negative Indian Ocean Dipole event in the same year. There was significantly above average rainfall in 2016, caused by the occurrence of this record negative Indian Ocean Dipole event. In the following three years, east Australia suffered from significantly below average winter rainfall which led to a severe drought across the Murray Darling Basin from 2017 to 2019\textsuperscript{23}, and the subsequent devastating 2019/2020 Black Summer bushfires\textsuperscript{24}. An additional La Niña event also occurred over the 2017/2018 summer, albeit too weak to alleviate the dry conditions in the region. The 2017–2019 Murray Darling winter drought finally broke in 2020 after the return of wet conditions following the development of a La Niña event. The region experienced significantly above average rainfall, including heavy rain events and floodings in 2020 that contributed to the observed groundwater recharge (Fig. 2c). The La Niña-related wet conditions persisted through spring and 2020/2021 summer, rising soil moisture, runoff and water storage levels and increasing the risk of floods in the region. Heavy rainfall and floods affected many parts of southeast Australia in March 2021\textsuperscript{25}, which was exacerbated by the appearance of a weak negative Indian Ocean Dipole event in winter 2021. November 2021 was the wettest November in 122 years for New South Wales and Australia as a whole\textsuperscript{26}.

**Groundwater Recharge**

Despite all the heavy rainfall associated with the climate indices over the 9-year period of study, there was only one large recharge event detected in all groundwater bores, in 2016. This reinforces that diffuse recharge is episodic and in water limited environments, such as Wellington, infrequent. This
further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model further confirms that Australian Water Landscape Model...
At present, it is unclear how the frequency and strength of negative IOD events will change in the future, though strong positive IOD events are projected to become more frequent in a greenhouse warming scenario. It is also unclear whether less strong negative IOD events would generate conditions conducive to the rainfall recharge of groundwater at our fractured rock sites and elsewhere. This is obviously a very important question to answer to predict the impacts of climate change on groundwater resources that support remote communities, farming and groundwater dependent ecosystems in southeast Australia and other semi-arid environments.

References


Bureau of Meteorology. Special Climate Statement 75 - Australia's wettest November on record. (2022).


Figures
Figure 1

The study areas including the bore locations at the Wellington Research Station.
Figure 2

A: Rainfall measured at the BOM weather station in Wellington including the Cumulative Rainfall Departure (CRD), B: the cave drip timeseries at Wellington Caves and C: groundwater timeseries at the UNSW Wellington Research Station. Groundwater levels are reported as elevation in metres with respect to Australian Height Datum (mAH). The identified groundwater recharge events are shown with dashed black lines.
Figure 3

The amount of rainfall 7, 14, and 21 days prior to the identified recharge events. # indicates the recharge event was only observed in the GW bores, and * in the caves only.

Figure 4

Timeseries of Wellington recharge events (blue), IOD represented by the Dipole Mode Index (red), and ENSO represented by Niño3.4 index (yellow).
Figure 5

A: Scatter plot of Wellington recharge events versus Dipole Mode Index. Recharge events are accumulated by months. Negative (positive) Dipole Mode Index is colored blue (red). Stars represent recharge events above 1 standard deviation (35.3mm). Light grey dashed lines indicate the thresholds for negative and positive IOD events. At the top, the frequency of recharge events are quantified. B: Scatter plot of Wellington recharge events versus ENSO represented by the Niño3.4 index.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- WellingtoncaveandGWrechargepaperSupplementary.docx
- TableS1.docx