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Long-term annual groundwater storage trends in Australian catchments

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ABSTRACT

The period of direct groundwater storage measurements is often too short to allow reliable inferences of groundwater storage trends at catchment scales. However, as groundwater storage sustains low flows in catchments during dry periods, groundwater storage can also be estimated indirectly from daily streamflow based on hydraulic groundwater theory; this idea was applied herein to 17 selected Australian catchments to examine their long-term (half a century or longer) groundwater storage trends. On average, over past 45 years, groundwater storage exhibited negative trends in all the selected catchments, except in the Katherine River catchment located in the Northern Territory. These negative trends persisted over longer periods, close to 100 years in some catchments and the strongest decreasing trend of 0.241 mm per year was observed in the Barron River catchment in New South Wales. However, groundwater storage exhibited different trends over the different shorter periods. Thus, while during the period of 1997–2007, 15 out of the 17 catchments showed negative trends in groundwater storage, during the period of 1980–2000, 12 out of the 17 catchments exhibited positive trends in groundwater storage; this underscores the fact that record lengths of one or even two decades are inadequate to derive meaningful trends. Strong consistencies in the trends exist across most catchments, indicating that groundwater storage is affected by large-scale climate factors.

1. Introduction

Groundwater represents a large proportion of readily available freshwater resources on a global scale and is the only available water resource in some areas [1]. During prolonged dry periods, groundwater sustains low flows in streams and changes in climate and land use can significantly affect groundwater storage and low flow regimes [2,3]. Characteristics such as the magnitudes and durations of low flows have been widely used to determine water allocation and ecological water requirements [2]. It is predicted that increasing human consumption and climate change will have profound effects on future water resources, although the predictions are associated with large uncertainties [4–7]. Most studies of these impacts on hydrology have focused on surface water and much less is known about the impact on groundwater [8,9]. In any event, the identification of trends in groundwater requires long time series of observations (viz. at least half a century to a century). Unfortunately, long-term direct measurements of groundwater levels are rare and often too short to make reliable inferences of groundwater trends at regional scales. This is certainly the case for many regions in Australia, where groundwater monitoring started in the 1970s and 1980s with discontinuous measurements. There is also the issue of scale; measurements of groundwater level in single isolated wells represent local scale, whereas water resources management requires information at the catchment scale, so that a wide network of many wells would be needed but is rarely available.

As noted, during dry periods low flows of a river derive primarily from water released by the upstream groundwater aquifers. Consequently, on the basis of hydraulic groundwater theory, this principle has been applied [10] to develop a method that estimates groundwater storage changes using daily streamflow data from a catchment. Because streamflow measurements typically commenced much earlier than groundwater records, this method can provide regional estimates of groundwater storage for much longer time periods than for those obtainable from groundwater wells. Applications have already been made to catchments in Mongolia [11], Japan [12] and USA [3,13] to study trends in groundwater storage. Over the past 50 years, many catchments in Southern Australia have experienced declines in annual streamflow, mostly due to reductions in annual rainfall [14–16] but also due to reductions in groundwater storage [17]. Significant changes in low flows have been observed in these catchments with some perennial streams

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even becoming ephemeral [15]. In Australia many regions are dependent on groundwater resources for irrigation and domestic water use, and a number of the regions comprise significant groundwater-dependent ecosystems. A better insight into how groundwater systems in Australia have been changing will be critical in developing sustainable water resources management plans. The objectives of this study are (1) to test the groundwater storage trends derived from baseflow observations [10] against observed groundwater level data and (2) to examine long-term groundwater storage trends during the past century in selected catchments in Australia.

2. Catchment description and data

This study selected 17 catchments that have at least 45 years of unregulated daily streamflow records and the area of the catchments ranges from 196 to 8358 km^2 (Fig. 1). Unregulated streamflow is defined as streamflow that is not affected by human control or diversion. The selection of the catchments was also based on consideration of availability of continuous daily streamflow records, if possible though not absolutely necessary, groundwater level data, and a distribution of hydroclimatic conditions. The daily streamflow data were made available to us thanks to the state agencies and quality checks were performed. The first step in the quality check was to scan data quality codes for any missing and poor-quality data. Once identified, missing values were calculated from streamflow data observed on previous and following days. The second step was to plot values of daily rainfall and streamflow to check for inconsistencies and to identify errors in the streamflow data (e.g. irregular or unusual spikes, identical streamflow value over a significant period of time). The data quality controls ensured that only good quality streamflow data were considered.

Spatially averaged annual rainfall was calculated for each catchment using gridded SILO daily rainfall [18]. The gridded daily rainfall data were obtained by interpolating point measurements from over 6000 rainfall stations across Australia. The spatial pixel size of the rainfall data is approximately 5 $\times$ 5 km. The spatial coverage of the rainfall stations is reasonably good, particularly in the south-eastern Australia. Ordinary kriging technique was applied to interpolate monthly rainfall data. The method takes into account rainfall variations with elevation. Then daily rainfall data for each SILO pixel were generated from the monthly rainfall data based on daily rainfall distribution in the nearest station [18]. Catchment average rainfall was obtained by aggregating the SILO interpolated rainfall surfaces.

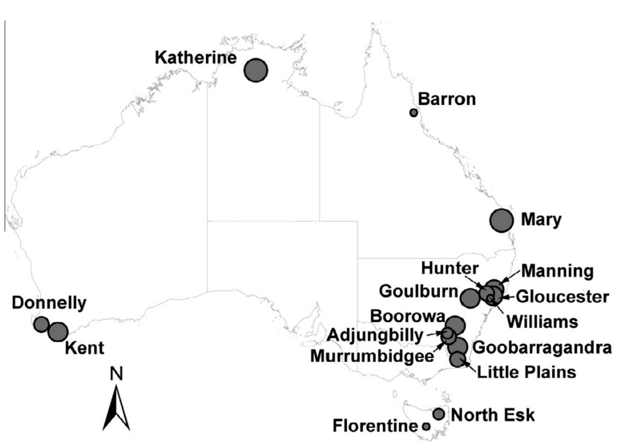

Fig. 1. Location map of the catchments. The size of circles indicates the relative catchment areas.

Table 1 lists the area, location, climatic and aquifer characteristics of the selected catchments, which represent different conditions and groundwater systems. The mean annual rainfall ranges between 664 and 1616 mm and the aridity index (i.e. potential evaporation divided by rainfall) varies from 0.64 to 2.07. For the selected catchments, the mean slope ranges from 0.6° to 8.6° and the surface soil types include sandy loam, loam, and clay with large local differences in saturated hydraulic conductivity and water holding capacity. The vegetation in the catchments includes crops, grass, woodlands, and forest. According to Coram et al. [19], local flow systems are the dominant groundwater systems in the selected catchments with intermediate flow systems existing in some of them (Table 1). The geology of the catchments includes Tindall limestone, Silurian limestone and sandstone, Atherton basalts, Mareeba granite and various other metamorphics and alluvials. In 12 of the 17 catchments, observation wells had been installed so that groundwater table levels have been observed for some time; these well observations allow a comparison with the results of the present method. The groundwater observation wells were selected based on consideration of their locations (i.e. proximity to streamflow gauging stations), length of records, and effect of pumping. However, as listed in Table 1, these available records are much shorter than those of the streamflow records. The potential evaporation data listed in Table 1 were obtained from the SILO data base based on Morton's modification [20] of the Priestley and Taylor method [21]; these catchment values were calculated from the gridded SILO data base in the same manner as the listed catchment rainfall values.

3. Methods

3.1. Groundwater storage trends estimated from base flow

The low flow hydrograph can be expressed as a function of time, as:

$$Q = Q(t) \tag{1}$$

where Q is the rate of flow [L^{3}T^{-1}] and t is the time [T]. For convenience of comparison with other fluxes in the water cycle such as rainfall and evaporation, in what follows, Q is transformed to flow per unit of drainage area [LT^{-1}], and denoted by $y = Q/A$, in which A is the area of the catchment.

Probably the most commonly used functional form of $y(t)$ in hydrology is of the exponential type, namely

$$y = y_0 \exp(-t/K) \tag{2}$$

where K is the characteristic time scale of the catchment drainage process [T], also commonly known as the storage coefficient, and y_0 is the value of y at the selected time origin $t = 0$. Eq. (2) was originally proposed on the basis of empirical evidence; however, some useful insight in its physical nature can be gained by examining how it can be derived by means of hydraulic groundwater theory. As shown elsewhere (e.g. [10,22]), the "long-time" solution of the linearized Boussinesq equation describing the outflow from a homogeneous and horizontal aquifer with the appropriate boundary conditions, yields the following for the characteristic drainage time scale

$$K = 0.10 n_e \Big/ \left(D_d^2 k_0 \eta_0\right) \tag{3}$$

where k_0 [LT^{-1}] is the hydraulic conductivity, n_e the drainable porosity, η_0 is the average vertical thickness [L] of the layer in the soil profile occupied by flowing water, $D_d = L/A$ is the drainage density, where L is the total length of upstream channels in the catchment. Eq. (3) is based on the assumptions that the river channel network