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Research papers

Estimating shallow groundwater availability in small catchments using streamflow recession and instream flow requirements of rivers in South Africa

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ABSTRACT

Groundwater is an important resource for multiple uses in South Africa. Hence, setting limits to its sustainable abstraction while assuring basic human needs is required. Due to prevalent data scarcity related to groundwater replenishment, which is the traditional basis for estimating groundwater availability, the present article presents a novel method for determining allocatable groundwater in quaternary (fourth-order) catchments through information on streamflow. Using established methodologies for assessing baseflow, recession flow, and instream ecological flow requirement, the methodology develops a combined stepwise methodology to determine annual available groundwater storage volume using linear reservoir theory, essentially linking low flows proportionally to upstream groundwater storages. The approach was trialled for twenty-one perennial and relatively undisturbed catchments with long-term and reliable streamflow records. Using the Desktop Reserve Model, instream flow requirements necessary to meet the present ecological state of the streams were determined, and baseflows in excess of these flows were converted into a conservative estimates of allocatable groundwater storages on an annual basis. Results show that groundwater development potential exists in fourteen of the catchments, with upper limits to allocatable groundwater volumes (including present uses) ranging from 0.02 to $3.54 \times 10^6\ \mathrm{m^3\ a^{-1}}$ ($0.10–11.83\ \mathrm{mm\ a^{-1}}$) per catchment. With a secured availability of these volume 75% of the years, variability between years is assumed to be manageable. A significant ($R^2 = 0.88$) correlation between baseflow index and the drainage time scale for the catchments underscores the physical basis of the methodology and also enables the reduction of the procedure by one step, omitting recession flow analysis. The method serves as an important complementary tool for the assessment of the groundwater part of the Reserve and the Groundwater Resource Directed Measures in South Africa and could be adapted and applied elsewhere.

1. Introduction

According to the National Water Act of South Africa (NWA, Act 36 of 1998), water-use licensing, including licensing of groundwater use, is to be granted only after defining and fulfilling the Reserve: the amount of water needed to supply basic human needs (BHN) and water needed to preserve ecological integrity (Xu et al., 2003). The objective of the NWA is to keep water, including groundwater, development within sustainable limits, while also adhering to efficiency and equity goals. In order to allocate water in accordance with the requirements of the NWA, it is imperative that the interdependencies between groundwater and surface water are realized and incorporated into the assessments and allocations of each resource (Kelbe and Germishuyse, 2010). Quantification of the 'groundwater component of the Reserve', i.e. the groundwater needed to fulfil BHN and ecological needs, is very important for the successful implementation of the NWA. However, estimating groundwater volumes and fluxes is a major challenge in South Africa due to large hydrogeological variability and complexity and limited groundwater data (Levy and Xu, 2012).

Acknowledging these facts, the generally accepted method for estimating the groundwater quantity part of the Reserve, as an element of defining the so-called Resource Directed Measures (RDM) of the NWA (DWAF, 1999; Xu et al., 2003), is to use estimates of groundwater recharge and stream baseflow as the upper limit for groundwater exploitation and the upper requirements for

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groundwater discharge to streams, respectively. According to Parsons and Wentzel (2007), the relationship to be solved is:

$$GW_{allocate} = (Re + GW_{in} - GW_{out}) - BHN - GW_{bf} \tag{1}$$

where

$GW_{allocate}$ = upper limit for groundwater allocation
Re = groundwater recharge
GW_{in} = lateral groundwater inflow (normally disregarded)
GW_{out} = lateral groundwater outflow (normally disregarded)
BHN = basic human needs
GW_{bf} = groundwater contribution to baseflow

This relationship has an aquifer or a hydrological unit as the base, normally the fourth-order (quaternary) catchments delineated for South Africa (1946 in total (Le Maitre and Colvin, 2008)) and evaluates fluxes on a long-term average annual scale (Parsons and Wentzel, 2007). Baseflow is that fraction of stream discharge that is not attributable to direct runoff from precipitation or melting snow. It is sustained on a more continuous basis, even under dry conditions, to an extent by groundwater discharge. As such, groundwater is critical in sustaining ecological functioning of many streams. GW_{bf} is here the minimum amount of groundwater discharge required to sustain the ecological integrity of groundwater dependent systems, like rivers, wetlands, and lakes (Levy and Xu, 2012). BHN is the part of the Reserve that caters for a minimum of water supply for human uses (e.g., 25 L/d/capita). The total groundwater Reserve is thus the sum of BHN and GW_{bf}. Any new development and allocation of groundwater ($GW_{allocate}$) has to be met from the possibly remaining surplus, which is the difference between the recharge and the total Reserve. The most uncertain parameters in this assessment are the recharge (Re) and the groundwater-derived minimum baseflow (GW_{bf}). The manual by Parsons and Wentzel (2007) has subsequently been updated by Dennis et al. (2012), including methods and cases for determination of the groundwater component of the Reserve.

An alternative approach, omitting the need to assess Re is based on the premise that the baseflow component of streamflow in unregulated and relatively pristine basins is a good indicator of shallow groundwater storage and availability in the basin. Groundwater abstraction or factors impacting groundwater recharge will alter the groundwater storage and consequently the natural baseflow regime. Hence, it is assumed that the amount of water that is available for groundwater development for use like BHN, agriculture and industry in a catchment, is the groundwater storage required to generate the baseflow in excess of 'environmental baseflow requirements' (McClain et al., 2013). In order to relate baseflow to groundwater storage, recession flow analysis is applied. Assuming that the recession flows, in the absence of precipitation and direct surface runoff, consist of the cumulative outflow from all upstream phreatic aquifers representing a linear reservoir, the analysis of these flows can infer information on storage of groundwater in these aquifers through a proportionality factor, the characteristic drainage time scale (Brutsaert and Sugita, 2008). Similarly, the 'river ecological reserve' or instream flow requirement, when less than river baseflow, can be converted to a groundwater storage in the catchment necessary to maintain them, constituting part of the 'groundwater ecological reserve'. By extrapolation, any baseflow in excess of this instream flow requirement represents, when converted to groundwater storage, the groundwater volume allocatable to all human uses.

The study proposes to apply this approach for the first time in South Africa as part of the determination of the Reserve and the Resource Directed Measures (RDM) (Dennis et al., 2012). The method was initially proposed by Smakhtin (2001a) and trialled in Africa, more specifically for a catchment in Tanzania (Shu and Villholth, 2013). While the methods of baseflow separation, recession flow analysis and estimation of instream flow requirements have been tested and applied in the literature for various purposes, their combined and integrated use for estimating groundwater availability has not been reported extensively.

The overall aim of the study is to develop and test an integrated method for assessing allocatable groundwater from streamflow recession and instream flow requirements. The advantages of this method include:

(i) no *a priori* information on hydrogeology and recharge is required
(ii) it enables initial assessments of available groundwater storage integrated at the catchment scale
(iii) it is based on ecological criteria related to the river
(iv) it incorporates assessment of temporal (inter-annual) variability of groundwater availability.

2. Theoretical background

2.1. Estimating drainage time scale from recession flow analysis

The Boussinesq equation describing outflow into a fully penetrating empty stream channel from an initially saturated homogenous unconfined rectangular aquifer placed on a horizontal impermeable layer and with no flux at the boundary is shown in Brutsaert and Nieber (1977), when making use of the Dupuit assumptions, to be expressed as a power law function:

$$\frac{dQ}{dt} = -aQ^b \tag{2}$$

where Q [L^3/T] is the river discharge during recession (t > 0), $(-\frac{dQ}{dt})$ is the rate of change of discharge, and a [unit depends on b] and b [–] are parameters.

By linearizing the Boussinesq equation and retaining the fundamental harmonic in the Fourier expansion to describe outflow from the aquifer, the constants in Eq. (2) can be shown to be (Brutsaert and Lopez, 1998):

$$b = 1 \tag{3}$$

$$a = \frac{\pi^2 k_o p D l^2}{n A^2} \tag{4}$$

where k_o [L/T] is the hydraulic conductivity, n [–] is the drainable porosity, D [L] is the total aquifer depth, l [L] is the total length of upstream channels in the watershed, and A [L^2] is the drainage area of the catchment. Drainable porosity is the pore volume of water that is removed (or added) when the water table is lowered (or raised) in response to gravity and in the absence of evaporation.[1] According to Brutsaert and Lopez (1998), the parameter p [–] is a constant (introduced to compensate for the approximation resulting from linearization), which can be estimated to be 0.346.

Basically, a [T^{-1}] in Eq. (4) is the inverse of the characteristic drainage time scale (K [T]) given by Brutsaert (2008):

$$K = \frac{0.1n}{D_d^2 T_e} \tag{5}$$

where D_d [L^{-1}] is the drainage density given by l/A, and T_e [L^2/T] is the effective hydraulic transmissivity of the aquifer given by $T_e = k_o\, p\, D$.

Brutsaert and Lopez (1998) and Brutsaert (2008) have shown that the behaviour of hydrograph recession during low flow is best described with Eq. (2) using a value of b = 1. The flow recession in

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[1] http://nrcca.cals.cornell.edu/soil/CA2/CA0212.5.php, (accessed on 05 September, 2015)