# The use of stable isotopes of water (D and $^{18}O$) in hydrological studies in the Jonkershoek Valley#

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## Abstract

We used stable isotopes of water in rainfall and streams in the Jonkershoek Valley to determine the relative contribution of new water (i.e. rain) during stormflow conditions. We found significant differences between rain and stream isotopic signatures which facilitated the use of a mass balance equation to calculate the components of stormflow. Analyses indicated that < 5% of the stormflow comprised direct runoff. This suggests that the rapid response of these streams to rainfall is mainly due to displaced groundwater.

## Introduction

Stable isotopes of hydrogen ($^2H$ or D) and oxygen ($^{18}O$) in water are excellent tracers of the origin and movement of water for use in studies of catchment hydrology. When a storm in a catchment produces rain with a significantly different isotopic signature to that of streams, it provides the opportunity to study the application of tracers on an enormous scale. By this approach isotopes have been used to determine the relative contribution of "new" (i.e. from a rain event) water to streamflow. To date such studies in catchments in Australia (Turner et al., 1987) and New Zealand (Pearce et al., 1986) have generally shown the somewhat surprising result that new water (i.e. direct contribution from a particular rain event) contributes less than 10% of the stormflow. In this paper we report on the use of this technology to analyse aspects of catchment hydrology in the Jonkershoek Valley of the SW Cape.

Here streams are quick to respond to rain events and within an hour of the beginning of a rain event, significant increases in the streamflow occur. On an annual basis, between 36% and 71% of rainfall (mean for 6 catchments is 51.1%) leaves the Jonkershoek catchments as streamflow (Van Wyk, 1987); however, the bulk of this runoff is as baseflow. This is reflected in low mean storm response ratios (quickflow as a proportion of stormflow) of between 1.9 and 18% (Scott, 1993). On the basis of an analysis of rainfall intensity and stormflow, Hewlett and Bosch (1984) argued that overland flow plays a minor role in flood production in streams from this area.

The stable isotope signature of particular rain events is largely determined by a "temperature-effect" (the colder the more negative) and to a lesser degree an "amount effect" (heavy storms result in greater depletion of heavier isotopes and thus a more negative isotopic signature) (e.g. Datta et al., 1991). The isotopic content of streams is an approximate long-term average of isotope concentration of precipitation in source catchments as well as reflecting a component of evaporative enrichment. Evaporative enrichment can be detected by comparisons with the local meteoric water line (MWL) (e.g Datta et al., 1991; Turner et al., 1987), the MWL merely being an empirical relationship between D and $^{18}O$ in the precipitation of an area.

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## Study area

Many streams in the Jonkershoek Valley (see map in Van Wyk, 1987) have been gauged and there is an extensive network of stations that monitor the climate of the valley (Hewlett and Bosch 1984; Van Wyk, 1987). We mainly studied the Bosboukloof and Lambrechtsbos B catchments, where mean rainfall is 1 296 and 1 472 mm respectively (Van Wyk, 1987). Most of the natural fynbos (macchia) vegetation has been replaced in both catchments by pine plantations. The geology of the catchments is mainly Table Mountain Sandstone (TMS), although the soils in both catchments are generally a talus TMS sandstone accumulation over a weathered granite mantle. They are usually structureless, deep and rocky. In places road cuttings indicate that soils are several metres deep. This suggests that the water holding capacity of the catchment is large, given that 1 m of soil can store 300 to 500 mm of water (Pearce et al., 1986). Also, soil characteristics are such that infiltration capacities are well in excess of normal rainfall intensities (Versfeld, 1981). In terms of the South African binomial system (MacVicar et al., 1977), Oakleaf and Glenrosa forms predominate in the lower reaches of these catchments, with Hutton and Clovelly forms also becoming important at upper elevations (Versfeld, 1993).

## Methods

An initial study of isotopic composition of rainfall and streamflow was made at Bosboukloof in July 1988. Thereafter a more detailed sampling programme was conducted in several catchments, but mainly Lambrechtsbos-B, in the period February to September 1992.

Rain was collected from rain gauges equipped with Nipher shields and stream water was collected in well-mixed sections of the streams above stilling ponds. After collection, samples were immediately placed in sealed bottles. Stable isotope analyses were performed by CSIR-Ematek in Pretoria on a VG SIRA24 mass spectrometer using an ISOPREP line. Equilibration was with $CO_2$ and for D the exchange reaction was catalysed with platinum. Values are given relative to standard mean ocean water (SMOW).

We calculated a local MWL using the isotope data for rainfall (Fig. 1) and we used a mass balance equation (Pearce et al., 1986) to determine the relative roles of old (stored) and new (current rain) water respectively. As integration period we used the full period for which stream isotopic values were collected (see Figs. 2 and 3).

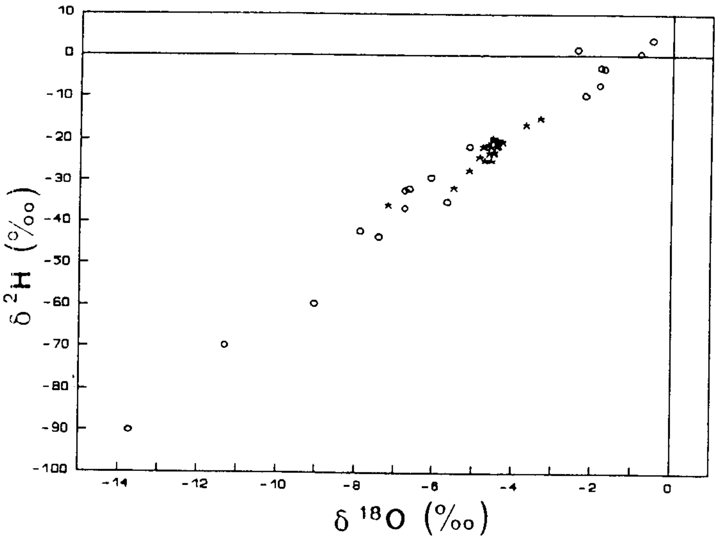


*Figure 1*
*The meteoric water line for Jonkershoek. Open circles represent isotope data from rainfall and stars represent streams*

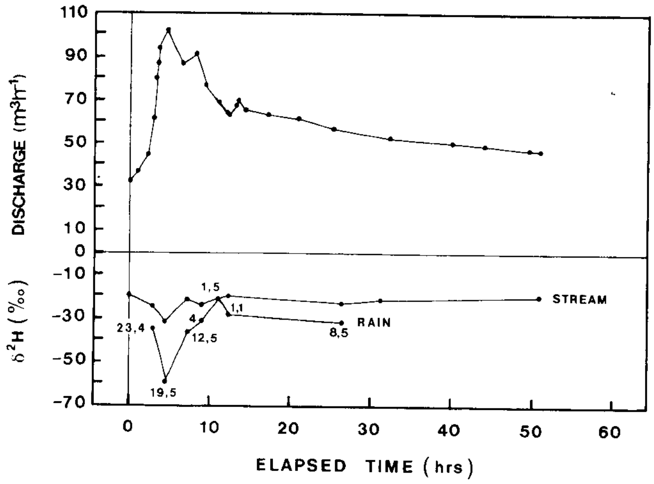


*Figure 2*
*Streamflow, precipitation and isotope concentrations for Lambrechtsbos B catchment during 21 to 23 September 1992. Values on the rainfall line indicate amount of rain (mm)*

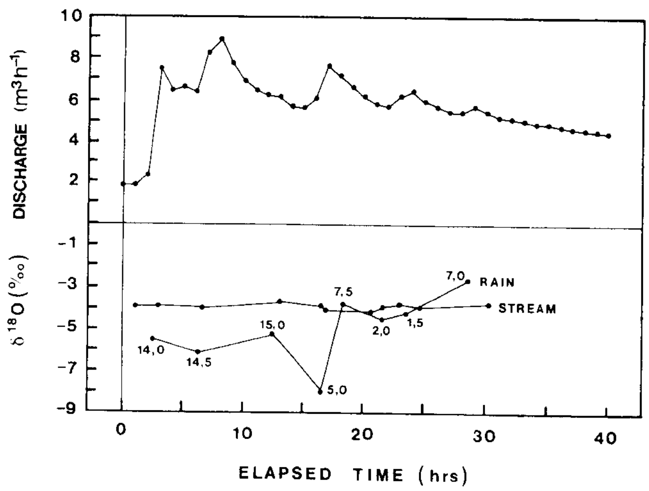


*Figure 3*
*Streamflow, precipitation and isotope concentrations for Bosboukloof catchment during 8-10 July 1988. Values on the rainfall line indicate amount of rain (mm)*

**TABLE 1**
**VARIATION IN ISOTOPIC SIGNATURE DURING RAIN EVENTS SAMPLED IN THE JONKERSHOEK VALLEY**

| Date | Time | $^{18}$O ‰ | D ‰ |
|---|---|---|---|
| 24/2/92 | | -3.1 | |
| 17/4/92 | | 1.5 | |
| 27/4/92 | 10:50 | | -89.8 |
| | 13:40 | | -69.5 |
| | 16:00 | | -42.1 |
| | 19:00 | | -43.3 |
| 2/6/92 | 8:30 | -6.4 | |
| | 10:30 | -7.0 | |
| | 12:00 | -9.4 | |
| | 15:30 | 3.8 | |
| 20/7 | | -3.2 | |
| 19/9/92 | | | -19.5 |

## Results

### Meteoric water line

Rainfall (collected at 300 m) varied significantly in isotopic signature from -89.8 (27/4/92) to 3.8 (2/6/92) for D and from -0.48 to -13.7 for $^{18}$O (Table 1 and 2). Regression analyses of D and $^{18}$O from rainfall samples collected throughout the study period yielded an MWL for the area of D= 9.63+ 6.989 *$^{18}$O (Fig. 1; $r^2$=0.974, n=18). Similar analyses for stream water yielded D= 5.059+ 6.051* $^{18}$O ($r^2$=0.871, n=23), suggesting that a degree of evaporative enrichment had occurred. In total 8 rain events were studied and there did not appear to be a seasonal trend towards more negative isotopic signatures in winter. This lack of seasonality and the MWL equation itself are very similar to the results obtained

TABLE 2
VARIATION IN THE ISOTOPIC COMPOSITION OF STREAMS IN THE JONKERSHOEK VALLEY
(ALTITUDE DATA FROM VAN WYK, 1987)

| Catchment | Sample altitude | Max altitude | Mean altitude | Date 21/2 - D | Date 20/3 - $^{18}O$ | Date 15/4 - D | Date 16/4 - $^{18}O$ (8:00) | Date 16/4 - $^{18}O$ (16:00) |
|---|---|---|---|---|---|---|---|---|
| Langrivier | 366 | 1 460 | 950 | -20.2 | -4.30 | -22.6 | -3.29 | -3.74 |
| Lambrechtsbos-B | 300 | 1 067 | 660 | -21.9 | -4.60 | -23.3 | -3.38 | -4.01 |
| Bosboukloof | 274 | 1 067 | 543 | -18.7 | -4.38 | -20.6 | -3.83 | -4.04 |
| Biesievlei | 280 | 580 | 396 | -19.4 | -4.40 | -23.0 | -3.20 | -3.74 |
| Lambrechtsbos-A | 366 | 1 067 | 690 | -23.7 | -4.46 | -22.8 | | |
| Abdolfskloof | 270 | 430 | 350 | -22.3 | -4.24 | -21.6 | -4.07 | -4.38 |
| Swartboskloof | 320 | 1 100 | 833 | -21.0 | -4.38 | -18.4 | -3.58 | -4.30 |
| Eersterivier | 360 | 1 300 | | -23.0 | -4.26 | -17.5 | -3.44 | |
| Tierkloof | 280 | 1 530 | 900 | -23.3 | -4.53 | -22.8 | -3.60 | -3.63 |

21/2 - only 0.5 mm of rain had fallen over the previous 60 d
20/3 - 49.6 mm of rain had fallen since the previous sampling (21/2); no rain had fallen in the previous 20 d
15/4 - after sampling 10.4 mm of rain fell
16/4 - 21.7 mm fell in the morning before the afternoon sampling

in an area of similar rainfall and climate in the Salmon Catchment of Western Australia (Turner et al., 1987). Variation in streamflow isotopic content was less marked than that of rainfall and except for dips during storms, ranged from about -17.5 to -23.3 for D and -3.2 to -4.6 for $^{18}O$ (Table 2).

### Temperature and amount effects

Bulked monthly rainfall samples collected at a range of altitudes yielded an altitude effect of about 0.32 ‰ $^{18}O$ per 100 m (Table 3; $r^2$=0.801; n=7). Samples taken simultaneously from the same stream (Langrivier) but at different altitudes gave values of -24.0 for D at 670 m and -20.2 for D at 366 m. In the intensively sampled rain events no progressive depletion of heavier isotopes was observed (Table 3; Figs. 2 and 3), nor was this so-called "amount effect" detectable in the data presented in Table 1 ($r^2$=0.314). This suggests that the dominant factor controlling variations in isotopic signature in the study area is temperature. Rain which falls at lower elevations has a greater isotopic content because of greater levels of evaporative enrichment.

Isotopic signatures of different streams varied in a complex fashion, with considerable change in rank amongst the sampling dates (Table 1 and 2). This is maybe not surprising given that isotope concentrations will depend on the complex interplay of altitude effects, degree of storage and evaporation. However, there is isotopic evidence of leakage of rainfall that falls at higher elevations (and therefore having a more negative signature), into the relatively small and low elevation adjacent catchments of Abdolskloof and Biesievlei. The isotopic content of the streams from these catchments appears to be as low as that for higher elevation catchments. This is of interest because the research catchments are normally assumed to be watertight.

### Details of intensively studied storms

We intensively sampled stream and rain isotopic content during 2 storms, one in each catchment. During the storm of 21 to 23 September 1992 at Lambrechtsbos B (see also Fig. 2), 70.6 mm (measured at 300 m amsl) fell over a 20 h period. Based on the standard fixed slope technique of hydrograph separation of Hewlett and Hibbert (1967), stormflow amounted to 2.32 mm (3.28% of precipitation) and quickflow amounted to only 0.77 mm (1.09% of precipitation, 33.25% of stormflow). The duration of stormflow was 22 h.

TABLE 3
VARIATION IN $^{18}O$ WITH ALTITUDE AND AMOUNT OF RAIN IN THE JONKERSHOEK VALLEY. VALUES ARE FOR BULKED MONTHLY RAINFALL FOR MAY 1993.
$^{18}O$ VALUES ARE MEANS OF 2 MEASUREMENTS

| Altitude (m) | Total rainfall (mm) | $^{18}O$ ‰ |
|---|---|---|
| 409 | 358 | -5.7 |
| 579 | 240 | -5.6 |
| 655 | 247 | -6.9 |
| 898 | 265 | -7.3 |
| 937 | 322 | -8.4 |
| 1 219 | 573 | -8.1 |
| 1 234 | 530 | -8.2 |

At Bosboukloof (Fig. 3), 65.5 mm fell over the 30 h period during 8 to 10 July 1988. Stormflow amounted to 7.02 mm (10.7% of precipitation) and quickflow to 3.22 mm (4.9% of precipitation, 45.8% of stormflow). Stormflow conditions lasted for 40 h.

### Components of streamflow

It is clear that "new" water has almost no impact on stream isotope concentrations (Figs. 2 and 3). Both the storms we studied were of a reasonable magnitude and in both there was a considerable depletion of heavier isotopes in the rain relative to the stream.

TABLE 4
MASS BALANCE ANALYSIS OF 2 STORM EVENTS IN JONKERSHOEK VALLEY. VALUES ARE ‰

| Site | Weighted isotope values | | | | | | % Stormflow which is rain | |
|---|---|---|---|---|---|---|---|---|
| | Pre-event streamflow | | Rain | | Event streamflow | | | |
| | $^{18}O$ | D | $^{18}O$ | D | $^{18}O$ | D | $^{18}O$ | D |
| Lambrechtsbos-B | -4.44 | -20.1 | -6.95 | -41.5 | -4.61 | -22.46 | 6.4 | 8.5 |
| Bosboukloof | -3.95 | | -5.6 | | -3.9 | | <1.0 | |

However, this depletion resulted in only a small decrease in stream isotopic signature during the storm.

By using the mass balance equations we determined that less than 10% of the storm event streamflow is due to recent rain (Table 4). These values can be refined by adjusting for orographic effects on rainfall and elevation effects on isotope concentrations. According to the Van Wyk (1987) model of orographic effects on rainfall in the Jonkershoek Valley, on average 21.25% more rain should fall on the Lambrechtsbos B catchment than was measured at our rain gauge at 400 m because the mean altitude for the catchment is 660 m. Similarly, accepting that isotopes are depleted with increasing altitude (Table 3), suggests that mean isotopic signature for rain falling in the catchment will be 16.5% more negative than determined at 400 m. When these 2 factors are taken into account, the contribution of new rain to the streamflow decreases from 8.5 % to 5.4% based on D for Lambrechtsbos B. It thus seems that only the rain falling in the channel contributed to stormflow.

## Conclusions

Sufficient variation exists in isotopic signature of different rainfall events for the isotope method to be applicable to these catchments. In both catchments it was clear that recent rain contributes only minimally to isotope content of coincident runoff. This suggests that the groundwater reservoir is sufficiently large to be well-buffered against inputs having different isotopic signatures.

From this it can be concluded that stormflows in the Jonkershoek streams are generated by the rapid displacement of groundwater. Sklash et al. (1986) hypothesise that a shallow groundwater ridge, alongside the stream, generates the rapid streamflow response to infiltrating rainfall. This could also apply to these humid catchments of the Cape.

Our study confirms that overland flow is definitely not a stormflow generating mechanism in the Jonkershoek Valley. These catchments do not appear to differ greatly from other humid mountain catchments studied in South Africa which yield a high proportion of the rainfall over the year, but which have a low storm response (Hewlett and Bosch, 1984). We predict that in these catchments stormflow is mainly composed of "old" water.

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