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Hydrology & Earth System Sciences

# Water flow pathways and the water balance within a headwater catchment containing a dambo: inferences drawn from hydrochemical investigations

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## Abstract

Dambos, seasonally saturated wetlands, are widespread in headwater catchments in sub-Saharan Africa. It is widely believed that they play an important role in regional hydrology but, despite research conducted over the last 25 years, their hydrological functions remain poorly understood. To improve conceptualisation of hydrological flow paths and investigate the water balance of a small Zimbabwean catchment containing a single dambo, measurements of alkalinity and chloride in different water types within the catchment have been used as chemical markers. The temporal variation in alkalinity is consistent with the premise that all stream water, including the prolonged dry season recession, is derived predominantly from shallow sources. The proposition that dry season recession flows are maintained by water travelling at depth within the underlying saprolite is not substantiated. There is evidence that a low permeability clay lens, commonly present in many dambos, acts as a barrier for vertical water exchange. However, the highly heterogeneous chemical composition of different waters precludes quantitative hydrograph splitting using end member mixing analysis. Calculation of the chloride mass-balance confirms that, after rainfall, evaporation is the largest component of the catchment water budget. The study provides improved understanding of the hydrological functioning of dambos. Such understanding is essential for the development and implementation of sustainable management strategies for this landform.

## Introduction

Dambos, defined as '*seasonally waterlogged, predominantly grass-covered, shallow linear depressions in the headward zones of rivers*' (Mackel, 1974), are a common landscape feature in sub-Saharan Africa. Their distribution corresponds approximately to the basement complex geology (i.e. hard, crystalline Precambrian rocks of intrusive or metamorphic origin) of the African and Post-African planation surfaces (Acres *et al.*, 1985). Situated in valley bottoms, dambos influence catchment hydrology, but their exact role in the hydrological cycle, remains a cause of controversy and debate (Bullock, 1992a).

A hydrological function commonly attributed to dambos is that they act as regulators of flow by storing water collected in the wet season and releasing it slowly during the dry season (e.g. Kanthack, 1945; Mackel, 1974; Perera, 1982). This idea, and similar beliefs about wetlands in general, has influenced both national and international wetland policy (Bullock, 1992a; Dugan, 1990). However, in relation to dambos, it is a phenomenon that has recently been questioned. Instead, it has been proposed that dry season river flows originate predominantly as hillslope groundwater that travels via the weathered bedrock (saprolite) beneath the dambo (McFarlane, 1987). Support for this hypothesis comes from a study of regional flow regimes in Zimbabwe that found, at the national scale, dambos do not significantly influence dry season flows. Indeed, where dambos occur in association with more deeply weathered regolith, their influence is one of baseflow reduction (Bullock, 1992b). However, other quantitative studies conducted over the last 25 years have produced contradictory results with some supporting the view that dambos increase dry season flows (e.g. Balek and Perry, 1973) while others (e.g. Hill and Kidd, 1980) have concluded that dambos promote evaporation and consequently decrease flows.

A prerequisite to greater understanding of the hydrological functioning of dambos is improved knowledge of flow pathways. Research, conducted in Europe and North America, has illustrated the usefulness of hydrochemistry for providing insights into catchment hydrology (e.g. Leibundgut, 1986). This research has highlighted, somewhat

unexpectedly, the importance of groundwater inputs to streamflow even in hard rock areas (e.g. Neal *et al.*, 1997; Soulsby *et al.*, 1998, 1999). However, very few comparable studies have been conducted in Africa. For regions of basement complex, there is a need for greater understanding of the relative contribution of deep groundwater to stream flow.

This paper reports findings from a one year hydrochemical investigation conducted in a Zimbabwean catchment containing a single dambo (McCartney, 1998). The principal aim was to aid the conceptualisation of hydrological flowpaths and to test the hypothesis that dry season recession flows are dominated by deep 'bedrock' groundwater. In addition, the data collected have been used to provide an estimate of evaporation from the catchment.

## Study area

The study catchment, located at the Grasslands Research Station, near Marondera in Zimbabwe makes up the headwaters of the Manyame River (Fig. 1). Located in a predominantly grassland region, it is typical of the Zimbabwean *highveld* (i.e. land at altitude > 1200m) where dambos are estimated to comprise 28% or more of the area (Whitlow, 1984). The crystalline geology and soils of the catchment are representative of large areas of sub-Saharan Africa. The stream channel starts approximately halfway along the length of the catchment, about 1 km from the catchment outlet and the catchment area is 3.33 km$^2$. It comprises two distinct zones; an upslope or interfluve region 2.12 km$^2$ in area and a dambo 1.21 km$^2$ in area (i.e. 36% of the catchment). Catchment relief is low, with slopes less than 4% and altitude ranging from 1654 to 1611 metres above sea level. Average annual rainfall and runoff are 859 mm and 86 mm respectively. Rainfall occurs predominantly during the summer (October to April) whilst the winter months (May to September) are usually dry. Mean summer and winter temperatures are 18.4 °C and 12.5 °C respectively. Average annual potential evapotranspiration, estimated by the Penman approach (Penman, 1948) is 1700 mm. Flow is seasonal, typically commencing in November or December and ceasing in July or August, but occasionally continuing until September.

The interfluve soils are deep coarse-to-medium grained loamy sands overlying sandy clay loams. A key feature of the dambo is the presence of a well-defined, irregularly shaped clay lens embedded within sandy clay at generally less than 2.5 m depth. It varies in thickness from 0.05 m to 1.55 m and X-ray diffraction of auger samples indicates that 88% to 94% of the clay fraction comprises kaolinite

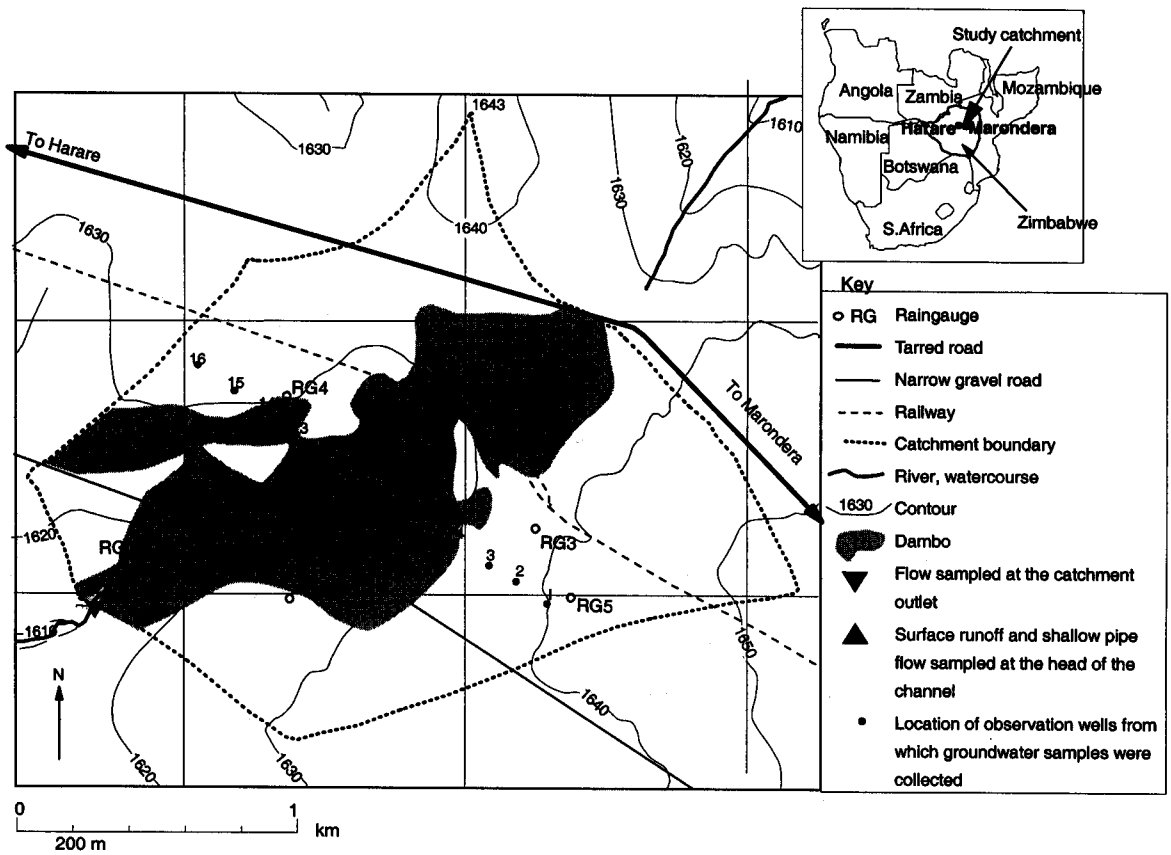


Fig.1. *The Grasslands Research Catchment (location and monitoring network).*

(McCartney, 1998). These heavy textured subsoils impede vertical drainage and the low slope angle reduces throughflow efficiency, so that the soil profile over much of the dambo is saturated for a large part of the wet season. Observations made in the current study showed that for prolonged periods during the wet season, water flowed over the ground surface into the stream at the head of the channel (hereafter, referred to as surface runoff). Water also entered the head of the channel from natural pipes (up to 5 mm in diameter) located, above the clay lens, at depths of approximately 20–40 cm below ground level (hereafter, referred to as pipe flow). A number of very small springs (< 1 cm in diameter) were found on the northern slope of the catchment, close to the dambo-interfluve boundary. These only flowed for a few days in late January and early February when the catchment was extremely wet. They were much smaller than the crescent springs described for dambos in Malawi (McFarlane, 1992).

There is some agriculture in the catchment (approximately 16% is cultivated and 24% is eucalyptus plantation). However, agrochemical inputs are believed to be small and direct anthropogenic influences on the chemical determinands measured in the current study are assumed to be negligible. In terms of the determinands measured, chemical composition of catchment water is controlled primarily by rainfall inputs and water-soil and water-rock interactions. Further details of the catchment are given in McCartney (1998) and McCartney *et al.* (1998a).

## Methods

### RATIONALE AND ASSUMPTIONS

The chemistry of soil and stream water is determined by a combination of physical and chemical processes associated with atmospheric inputs, chemical weathering and evaporation. These processes are both temporally and spatially variable. Hence, water collected from one location within a catchment may have a very different chemical signature to that collected from another location. The rationale underlying the use of chemistry in hydrological studies is that the stream water comprises water from a limited number of sources, each with a distinct chemical composition. These different sources are assumed to form the chemical boundaries of possible stream water observations and so are called 'end-members' (Hooper *et al.*, 1990). Steamwater is predicted to represent a mixture of these chemically distinct water types and so chemistry can be used to deduce information on water sources, hydrological processes and flow pathways.

In this paper reference is made to two natural tracers, namely alkalinity and chloride. Alkalinity provides an indicator of chemical weathering, bedrock reactivity and water residence times and provides a measure of within catchment variability. In contrast, chloride behaves as a conservative tracer and hence concentration changes reflect variation in inputs and evaporation.

Alkalinity, defined following the methodology of Gran (1952), is a measure of the acid buffering compounds in natural water less the hydrogen ion concentration. For circumneutral waters such as those encountered in this study, where organic acid buffering, carbonate and calcium carbonate, bicarbonate and hydroxide complexes are not significant, a good first approximation is:

$$[ALK_{Gran}] = [HCO_3^-] - [H^+] \quad (1)$$

where the units of concentration are $\mu eql^{-1}$.

Within a catchment, the alkalinity increases with increased contact between water and weatherable material, and it is commonly found that water following deeper groundwater pathways has a much higher alkalinity than water following surface and near-surface pathways. Hence, variation in alkalinity may be used to indicate the relative contribution to stream water of different end-members with changes in flow. However, in this paper, alkalinity is used in only a semi-quantitative manner. It is utilised to infer possible water pathways, but is not used to assign values to proportion of mix, because to do so would require much greater information on volumetric storage and reactivity for different hydrological processes than is presently available.

Chloride is a conservative tracer the concentration of which is only affected by evaporation. In catchments where there are no anthropogenic sources and there is no seawater intrusion, the principal input of chloride is from the atmosphere, primarily in rainwater. Under these circumstances, chloride can be used to determine the precipitation-to-recharge ratio from a simple mass balance (Lerner, 1997):

$$GWR = (P\ T_P)/T_R \quad (2)$$

where GWR is recharge (mm), P is precipitation (mm), $T_R$ is the concentration in groundwater ($mgl^{-1}$) and $T_P$ is the concentration in precipitation ($mgl^{-1}$). The method assumes that all chloride in groundwater is derived from precipitation and that chloride concentration occurs by evaporation prior to recharge. It integrates recharge in time and space so is well suited to areas, such as Grasslands, where there is a great deal of spatial and temporal variation in precipitation.

### EXPERIMENTAL DESIGN AND MONITORING

Catchment runoff has been measured at a compound weir, comprising a 45° V-notch and six rectangular angle-iron crests since 1956. Stage is recorded continuously with a chart recorder. The charts are digitised and daily flow computed using a theoretical rating equation. For the current study, additional hydrometric and hydrochemical monitoring was conducted in the catchment (McCartney, 1998). The monitoring reported in this paper was carried out between October 1995 and September 1996 (i.e. hydrological year 1995, hereafter referred to as HY1995).

Throughout this period, in addition to the geochemical monitoring described below, groundwater levels and rainfall were measured daily and soil water content was determined approximately weekly using a neutron probe. In the discussion that follows day numbers relate to the start of HY1995 (i.e. 01/10/95).

As part of the hydrochemical investigations, rainwater, stream water, surface runoff, shallow pipe flow and shallow groundwater samples were collected for determination of alkalinity and chloride. Rainwater was collected from 4, of the 5, raingauges located in the catchment (i.e. RG1—RG4) when the daily catch exceeded 10 mm. Analysis indicates that in HY1995, 93% of the total rainfall input into the catchment occurred in events exceeding 10 $mmd^{-1}$ (McCartney, *et al.*, 1998b). Initially water was collected from RG5, but chemical analyses indicated that it consistently had a very different composition to the water obtained from the other raingauges. Although not directly below them, this may have been a consequence of the proximity of RG5 to trees on the interfluve crest. Research has shown that deposition of atmospheric particulate matter and fine mist is greater close to a forest edge (Neal *et al.*, 1994). Consequently, the chemical data obtained from RG5 were discarded and water quality sampling of this gauge ceased. Stream water was collected daily at the weir, from the day after flow commenced (13/12/95) until 14/06/96, and thence twice weekly until 29/08/96, a few days before flow ceased. Samples of surface runoff and shallow pipe flow were collected at the head of the channel on all days when there was sufficient volume for it to be collected simply by holding a bottle to the flow. Water samples were also collected from the small springs on the few days that they flowed.

Groundwater samples were collected approximately every two months from shallow (i.e. less than 6.0 m deep) observation wells situated along a transect across the widest part of the catchment (Fig 1). Daily observations of water-level within each well indicate that samples were obtained across a range of groundwater levels, that in most wells included the seasonal maximum and minimum. Wells at locations 1, 2 and 16 stayed dry for much of the year and so only a very few samples (from locations 3 and 15) were obtained from the interfluve. However, there was adequate spatial coverage for hydrochemical sampling from the dambo (i.e. locations 4 to 14). At locations 7 to 14, water was collected from 2 observation wells; one penetrating through, and one augered just to the top of, the clay lens. All wells were made of PVC pipe with a diameter of 3.6 cm and had slots cut every 10 cm over their entire length. No attempt was made to seal the base of the pipes. The tops were capped with rubber bungs and the tops of the auger holes were sealed with concrete to prevent infiltration of rain from the surface. Samples were obtained using a hand operated vacuum pump (Nagle Company, Rochester, NY, USA) and teflon tubing. To obtain an indication of deep groundwater chemistry, a single sample was obtained from each of two deep boreholes located at the Horticultural Research Centre, some 1.5 km from the catchment. These boreholes, HRC2 and HRC3, were 57 m and 47 m deep respectively.

### LABORATORY ANALYSES

To minimise carbon dioxide degassing (which increases water pH) all samples were collected in filled, sealed glass bottles and analysed for alkalinity as soon as possible (usually within two to three hours of collection). Gran alkalinity was determined, after filtering the water samples through 45 mm filters, by acidimetric titration over pH range 3.0 to 4.0. pH was measured using a combination electrode (Radiometer Ltd.). Selected samples representing spatial and temporal variability in waters collected were returned to the Institute of Hydrology. Here, chloride concentrations were determined using automated colorimetry (Zall, *et al.*, 1956).

## Results

### HYDROLOGY

Catchment average rainfall (determined using the method of Theissen polygons (Theissen, 1911)) for HY1995 was 1085 mm. Annual runoff, which commenced on 12/12/95 (after a total of 315 mm of rainfall), was 99 mm. Most runoff occurred in January and February when the soil profile across the dambo was saturated. Frequency analysis highlights the very 'flashy' nature of flow from the catchment, with two-thirds of the total annual runoff occurring on just 15 days out of the 269 with flow (McCartney *et al.*, 1998b). Although, the dry season flow (i.e. that occurring after 01/04/96) accounted for just 5.6% of the total annual runoff it was extremely prolonged and only ceased on 05/09/96 (Fig. 2). Water levels measured in the observation wells indicated that throughout HY1995 the hydraulic gradient was towards the stream channel on both sides of the catchment. During the dry season water levels close to the valley bottom were maintained by a downslope flux of groundwater. This decreased as the season progressed resulting in accelerated decline of water levels in the valley bottom. Cessation of flow from the catchment coincided approximately with the watertable in the two wells closest to the stream channel dropping below the top of the clay lens.

### CHEMISTRY OF DIFFERENT WATER TYPES

The temporal variation in alkalinity and chloride within rainfall, stream water, surface runoff and pipe flow and the frequency distribution of the alkalinity in each water type are shown in Figs. 2 and 3.

Throughout HY1995, rainfall was characterised by having generally low chloride and low alkalinity concentrations although there was a great deal of non-systematic

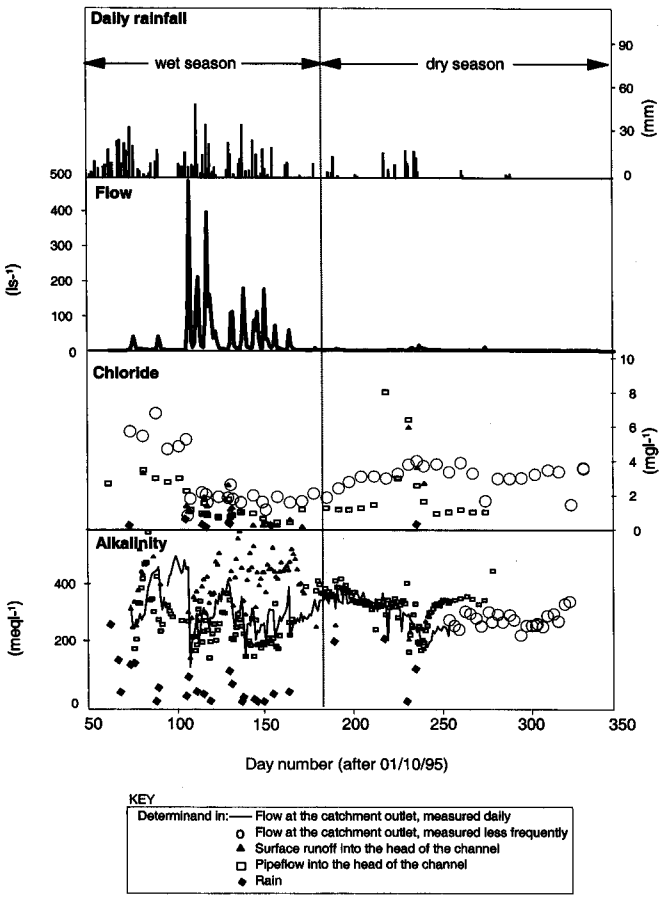


Fig. 2. *Temporal variation in alkalinity and chloride in rainfall, stream flow, surface runoff and pipe flow.*

variation in the chemistry of water catches between different raingauges from one event to another (Table 1). The rainfall alkalinity distribution was skewed towards values lower than 50 $\mu eql^{-1}$ (Fig. 3a).

Surface runoff entering the stream at the head of the channel was characterised by having consistently higher, but a greater range of alkalinity than the rainfall. In contrast, the pipe flow entering the stream at the head of the channel usually had alkalinity concentrations that were generally intermediate between those of the rain and the surface runoff (Table 1). The waters of both the pipe flow and the surface runoff show an approximately normal frequency distribution in alkalinity but with a higher mean for the surface runoff (Fig. 3). The higher alkalinity of the surface runoff in comparison to that of the pipe flow was not anticipated: pipe flow would be expected to have higher, rather than lower, alkalinity because it generally has a longer residence time and more contact with weathered material than surface runoff. The most plausible explanation for this observation is that the surface runoff comprises, at least in part, return flow that has come into contact with weathered material.

The stream water generally had alkalinity values intermediate between the surface runoff and pipe flow entering at the head of the channel. These values are in the range 121 to 501 $\mu eql^{-1}$. In contrast the chloride concentration in the stream water was generally higher concentration and less variable than that in either the surface runoff or the pipe flow (Table 1). Following the very high rainfall of a tropical storm on day 107 (15/1/96) there was a substantial drop in the concentration of both determinands. Although there was a general trend of increasing concentrations of alkalinity and chloride as the dry season progressed, neither returned to the pre-storm values before flow from the catchment ceased in September (Fig. 2). Higher stream flows were generally associated with a dilution of alkalinity, but there was much less variation in chloride concentration.

The much higher chloride concentrations in the surface runoff, pipe flow and stream water than in rainfall are indicative of high evaporative demand. Surface runoff and pipe flows are normally relatively quick flowpaths that provide little time for evaporation. Hence, the high values are further evidence that these water types comprise a component of return flow. The very high 'spikes' in chloride concentration in pipe flow and surface runoff on day 221 (08/05/96) and day 234 (21/05/96) coincide with unseasonably high rainfall for this time of year. In May, total rainfall was 89.4 mm compared to the monthly average of 12.5 mm.

There was high temporal and spatial variability in the chemistry of water samples obtained from all the shallow observation wells installed in the catchment. The variation between wells was not congruent. A statistical comparison shows a higher mean and wider range in both the alkalinity and the chloride concentration of water obtained from those wells that penetrated through the clay than from those that did not (Table 1). At low to moderate alkalinity there is a very similar distribution for water taken from both types of well. However, there is a much longer tail to high values for water taken from the wells penetrating the clay (Fig. 3). More samples were obtained from the wells penetrating the clay, but nevertheless if the two distributions were the same, then on a statistical basis, some high values (ca. 5) would be expected for the water obtained from the wells not penetrating the clay.

The wells penetrating the clay were slotted over their entire length so some mixing of water from above and below the clay would be expected. This may explain the similarity in the low to moderate alkalinity distributions. However, the high alkalinity water indicates either a high degree of localised chemical weathering or an input of much deeper groundwater. Examination of the timings and water levels at times of high alkalinity revealed no systematic pattern for the wells penetrating the clay lens. Lower groundwater levels were not associated with higher alkalinity in the deeper system, so the possibility of greater weathering immediately below the clay is uncertain.

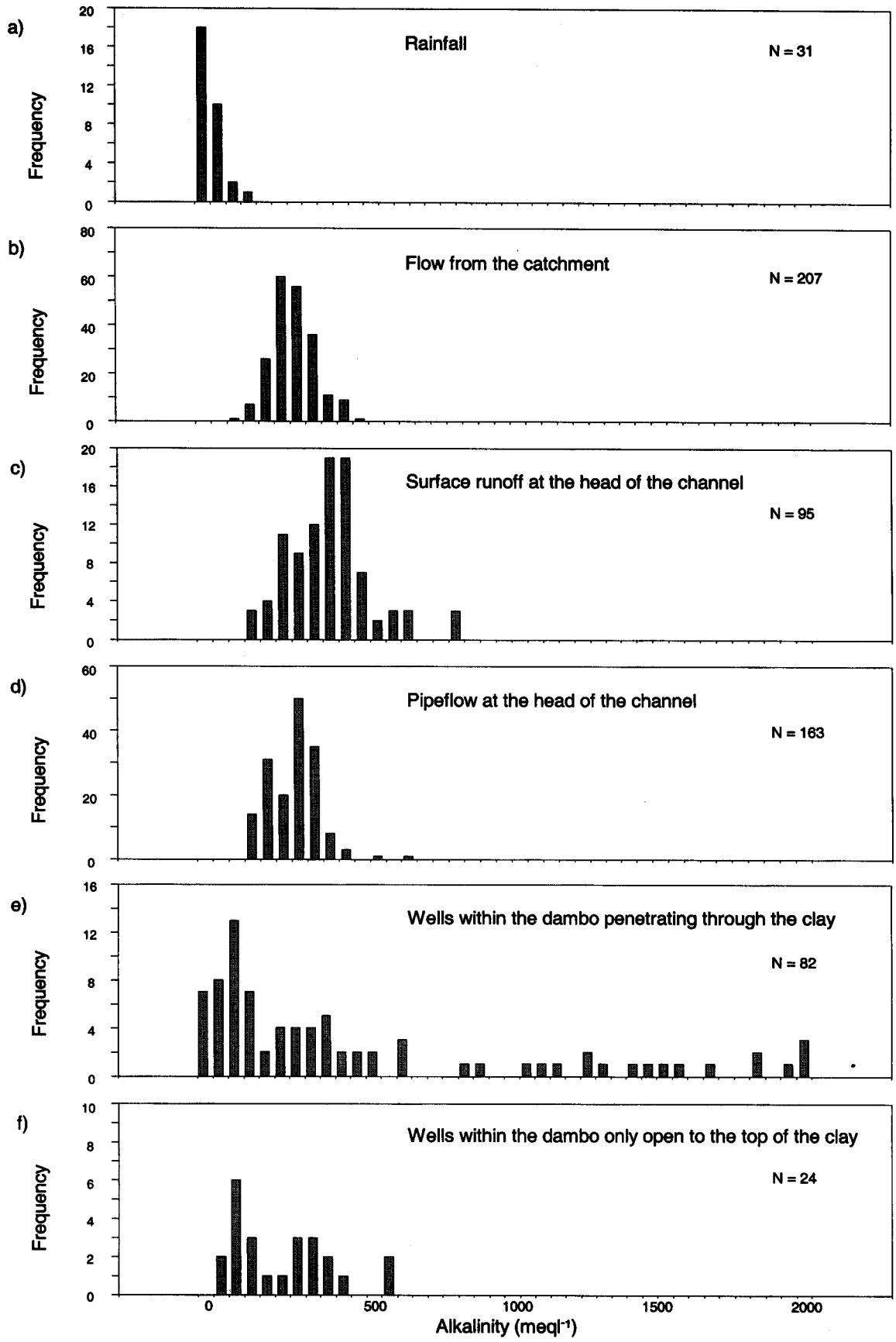


Fig. 3. *Frequency distribution of the alkalinity in each water type.*

*Table 1.* Alkalinity and chloride concentration in rainfall, surface runoff, pipe flow, groundwater and stream water, collected in the Grasslands Research Catchment in HY1995

| Determinand | | Rainfall * | Surface runoff at the head of the channel | Pipe flow at the head of the channel | Groundwater† | | | | Stream water |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | A | B | C | D | |
| Alkalinity N ($\mu$eq $l^{-1}$) | | 31 | 95 | 163 | 24 | 82 | 1 | 1 | 207 |
| | mean | 50 (54) | 421 | 309 | 255 | 547 | 1488.1 | 991.2 | 313 (263) |
| | max | 153 | 817 | 672 | 613 | 2676 | — | — | 501 |
| | min | 4 | 153 | 153 | 50 | 34 | — | — | 121 |
| | CV | 0.73 | 0.31 | 0.26 | 0.53 | 0.90 | — | — | 0.22 |
| Chloride N (mg $l^{-1}$) | | 9 | 22 | 37 | 23 | 58 | 1 | 1 | 47 |
| | mean | 0.37 (0.35) | 1.51 | 1.79 | 3.00 | 3.50 | 2.3 | 0.8 | 2.90 (1.93) |
| | max | 0.60 | 5.90 | 8.00 | 6.40 | 12.40 | — | — | 6.70 |
| | min | 0.20 | 0.20 | 0.40 | 1.30 | 0.90 | — | — | 0.90 |
| | CV | 0.31 | 0.89 | 0.85 | 0.49 | 0.70 | — | — | 0.46 |

* Rainwater chemistry presented for average of raingauges RG1 to RG4.
† Groundwater from different locations:

A—groundwater collected from observation wells installed to the top of the clay
B—groundwater collected from observation wells penetrating through the clay lens
C—groundwater collected from borehole HRC2 at the Horticultural Research Centre (depth 57 m)
D—groundwater collected from borehole HRC3 at the Horticultural Research Centre (depth 47 m)
(both HRC2 and HRC3 were located 1.5 km from the catchment and cased in the regolith)

Numbers in brackets are the volume-weighted averages over the wet season i.e. ($\Sigma c_i v_i / \Sigma v_i$) where $c_i$ = measured concentration and $v_i$ = volume of flow or rainfall on day i.

Instead, the elevated alkalinity may indicate an input of deeper groundwater at certain times. The lack of high alkalinity water above the clay lens is consistent with the lens acting as a semi-impermeable barrier to deeper groundwater.

Both the alkalinity and chloride concentrations in the water samples collected from the two boreholes located at the Horticultural Research Centre are very different (Table 1). Both samples were collected on the same day so the differences indicate the high spatial variability in the chemical characteristics of deep groundwater. The chloride concentrations of both samples lay within the range determined for water taken from observation wells in the catchment located both above and penetrating the clay lens. In contrast, the alkalinities determined for the borehole waters lay outside the range observed in the wells located above the clay, but within the range observed in the wells penetrating the clay. Although far from conclusive this finding supports the hypothesis that deep groundwater may, at times, be upwelling beneath the clay.

The alkalinity of water samples collected from the small springs on the north slope of the catchment showed considerable spatial variability and no temporal trend (Table 2). The ambiguity in the data means that it is not possible to determine whether the water is predominantly deep or shallow in origin. No chloride measurements were obtained for any spring water.

## TEMPORAL VARIATION IN ALKALINITY

This study revealed no clear systematic difference in the chemistry of water collected from above and below the dambo clay. The large variability in the solute chemistry of all water types, including spring water, indicates a complex flow routing system with considerable differences in residence times and soil water sources. Quantitative hydrograph splitting, using end-member-mixing analysis for the alkalinity, could not be undertaken with any conviction because of the large variability in water chemistries. Nevertheless, temporal variation in stream water, surface runoff and pipe flow chemistry does provide qualitative insights into possible hydrological pathways. Alkalinity characteristics of these waters indicate that the flow regime during HY1995 can be divided into four distinct periods (Table 3).

### *Period 1 (day 73–107)*

During this period the alkalinity of the three water types varied considerably from day to day but was, on average, higher than observed throughout the rest of the year. A reasonable interpretation of these data is that this was effectively a transition period in which rainwater mixed with water remaining in the catchment from the HY1994 wet season. It is probable that during this period there was considerable spatial variability in the extent of mixing of

Table 2. *Alkalinity of water collected from the small springs located on the north slope of the Grasslands Research Catchment*

| Spring | Date | Alkalinity ($\mu$eq $l^{-1}$) |
|---|---|---|
| SP01 | 21/01/96 | 184 |
| | 25/01/96 | 208 |
| | 27/01/96 | 202 |
| SP02 | 25/01/96 | 9 |
| | 09/02/96 | 300 |
| SP03 | 25/01/96 | 56 |
| | 27/01/96 | 37 |
| SP04 | 25/01/96 | 346 |
| | 27/01/96 | 311 |
| | 29/01/96 | 275 |
| | 09/02/96 | 341 |

high and low alkalinity water; reflected in the variable alkalinity of the stream water over this period.

*Period 2 (day 108 to 174)*

This period commenced immediately after the tropical storm on day 107 (15/01/96) and continued until close to the end of the wet season. Throughout this period, the alkalinity of the stream water consistently lay between that of the surface runoff and the pipe flow, but in general lay closer to the pipe flow than the surface runoff (Fig. 4). Regression of alkalinity and log flow confirms that all three water types, but particularly the surface runoff, were diluted during high discharge events. The three water-types are most similar at high flows in terms of alkalinity (Fig. 4). These data are consistent with the interpretation that the stream water is dominated by pipe flow and surface runoff.

*Period 3 (day 175 to 242)*

Throughout most of this period, the initial part of the dry season recession, there was no surface runoff into the stream, but the pipe flow continued. The alkalinity of the stream water was almost constant and was very similar to that of the pipe flow. This is consistent with the pipe flow being the over-ridingly dominant end member contributing to the flow. However, because of the lack of a distinguishing chemical fingerprint for the groundwater from below the clay, the possibility of deeper groundwater originating from below the clay contributing to stream flow cannot be ruled out conclusively.

*Period 4 (day 243 to 341)*

During this period, there were only four days, at the start, when there was surface runoff. However, sufficient pipe flow for it to be collected for analyses continued until day 282. The alkalinity of the stream water was lower than that measured in the pipe flow indicating that during this period the discharge from the catchment was dominated by another source of water. The low alkalinity of the stream water, compared with the pipe flow, indicates that this end member had little contact with weathered material. It is highly unlikely that the recession flow during this period was dominated by water from a deep 'bedrock' source. However, without additional information on the spatial variability of the chemical composition of water above and immediately below the clay lens, it is not possible to say where this water originated. Some insight into this might be gained by sampling chemistry along the length of the stream but time and resource constraints meant this was not possible in the present study.

**Table 3:** *Alkalinity characteristics of stream flow, surface runoff and shallow throughflow in the Grasslands Research Catchment, during four periods*

| Period* | Average flow ($ls^{-1}$) | Average alkalinity ($\mu$eq $l^{-1}$)† in streamflow mean | streamflow CV | streamflow N | surface runoff mean | surface runoff CV | surface runoff N | pipe flow mean | pipe flow CV | pipe flow N |
|---|---|---|---|---|---|---|---|---|---|---|
| 12/12/95 (73)—15/01/96 (107) | 8.31 | 395 | 0.19 | 33 | 505 | 0.37 | 17 | 354 | 0.31 | 24 |
| 16/01/96 (108)—22/03/96 (174) | 49.26 | 289 | 0.19 | 67 | 435 | 0.20 | 65 | 242 | 0.22 | 54 |
| 23/03/96 (175)—29/05/96 (242) | 2.00 | 328 | 0.14 | 68 | 235 | 0.10 | 9 | 341 | 0.16 | 62 |
| 30/05/96 (243)—05/09/96 (341) | 0.96 | 259 | 0.14 | 39 | – | | | 333 | 0.14 | 23 |

* Number in brackets is the day number after 01/10/95

† N is the number of observations from which the mean and CV were determined

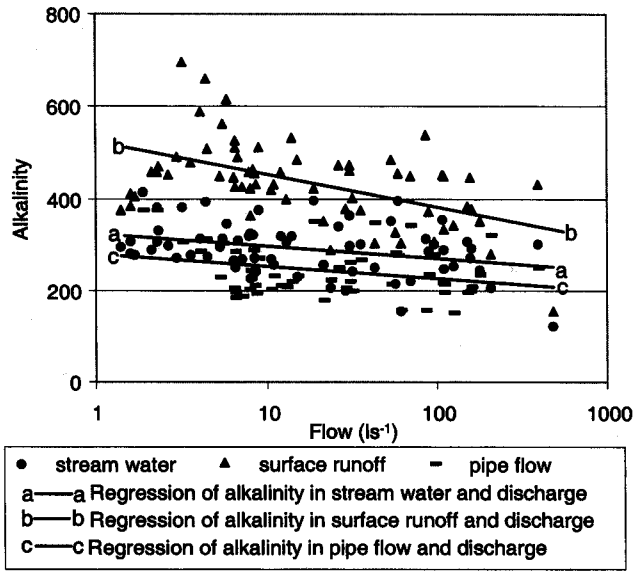


Fig. 4. *Variation in alkalinity in stream water, surface runoff and pipe flow with changes in discharge ($ls^{-1}$) at the catchment outlet for days 108–174.*

WATER BALANCE

During HY1995, the volume-weighted concentration of chloride in rainfall ($T_p$) was 0.35 mg $l^{-1}$. The volume weighted concentration of chloride in the recession flow between 01/07/96 and 05/09/96, used as an estimate of the groundwater tracer concentration (i.e. $T_R$), was 2.79 mg $l^{-1}$. Substituting these values into Eqn. 2 provided an estimate of the average groundwater recharge across the catchment of 136 mm. This, used in conjunction with the rainfall (1085 mm), measured outflow (99 mm) and estimated deep drainage (80 mm), provide an estimate of the average annual evaporation across the catchment of 772 mm (McCartney, 1998). This result compares to 751 mm derived from estimates of groundwater hydraulic gradient and a conceptual model of the fluxes along the instrumented transect across the catchment (McCartney, 1998). It indicates that after rainfall, evaporation is the largest element of the catchment water balance.

## Discussion

Although uncertainty remains, the temporal variation in the alkalinity of different water types provides insight into the possible flow paths within the catchment. Figure 5 indicates an interpretation that is consistent with the data obtained. The data indicate that groundwater systems in the catchment comprise a complex mixture of soil and groundwater sources.

During the wet season solute chemistry is consistent with the stream water comprising, predominantly, a mixture of shallow pipe flow and surface runoff. The data also indicate that surface runoff comprises a mixture of return flow and saturation overland flow. Isotopic analyses have shown that during the wet season, considerable volumes (up to 70%) of storm runoff is 'new' water (i.e. water derived directly from rainfall generating the runoff event) produced on the dambo as saturation overland flow (McCartney *et al.*, 1998a). However, during HY1995, the surface runoff generated upstream of the head of the channel continued for 10 days after the cessation of heavy rainfall. For this reason, as well as the relatively high alkalinity of this water, it is believed that a proportion of the surface runoff was caused by lateral groundwater fluxes, forced to the surface as a consequence of the thin regolith in this part of the catchment. A study of a wetland in a headwater catchment in southern Ontario indicated that on average half of the groundwater entering the wetland was transported over the wetland's surface (Roulet, 1990). However, in the current study it is not possible to quantify the fraction of surface runoff that is return flow.

In a study of a dambo in Malawi, the hydraulic conductivity of the clay was determined to be just $10^{-5}$ $md^{-1}$ (McFarlane, 1992). In the current study, slug tests were conducted in the observation wells using the methodology of Bouwer and Rice (1976) to estimate hydraulic conductivity (McCartney, 1998). These indicated that, across the dambo, hydraulic conductivity was extremely variable, but averaged 0.16 $md^{-1}$ with a coefficient of variation (CV) of 1.07. This compares with an average of 0.42 $md^{-1}$ (CV = 0.42) for measurements made on the interfluves. The high CV for the dambo may reflect the variable thickness of the clay lens and the fact that the tests induced changes in water level above the clay at some locations. Nevertheless, the fact that much higher hydraulic conductivity values were determined than in Malawi means that further investigation is required to determine the full extent to which the dambo clay acts as a barrier to vertical water movement.

The small springs only flowed when the catchment was very wet. The high variability in the alkalinity of the spring water may reflect large differences in the chemistry of near surface soils. It is possible that the springs are derived from perched water occurring in temporarily saturated soils, as shown in Fig. 5. Alternatively, it may indicate that the springs, although very similar in physical form, have different sources. Those with very low alkalinity water may comprise return flow that has had very limited contact with weathered material, while those with higher alkalinity water may have a component of return flow from deeper in the system. At present it is not possible to state which of these hypotheses is the more likely, but the high temporal variability is indicative of complex processes.

During the dry season, stream water alkalinity was never significantly greater than that of either the shallow pipe flow or the surface runoff. In addition, the stream stopped flowing when the water-table dropped below the

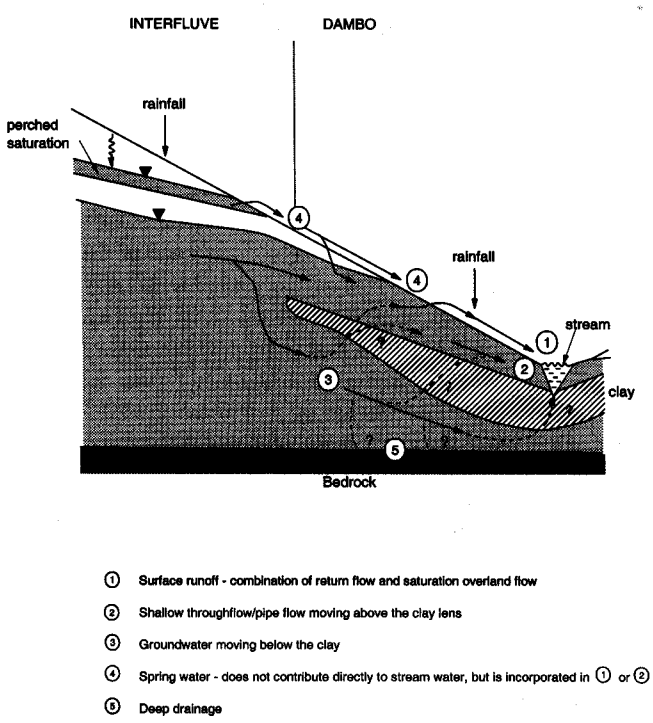


Fig. 5. *A conceptual model of flow paths that provides an interpretation that is consistent with the hydrochemical data.*

top of the clay. Therefore, a significant contribution of deep 'bedrock' groundwater to the stream seems unlikely. Although in many headwater catchments deep groundwater has been found to contribute significantly to baseflow, even in hardrock areas (e.g. Mulholland, 1993; Hill and Neal, 1997), having the dominant contribution from shallow soils is a phenomenon that has been observed elsewhere (e.g. Hewlett and Hibbert, 1963). However, because the groundwaters above and immediately below the clay lens were not completely distinguishable in terms of solute chemistry, the possibility of a contribution of below-clay groundwater to stream flow during the dry season cannot be completely ruled out.

During HY1995, the water table continued to drop after flow from the catchment had ceased and although this may be due entirely to evapotranspiration, it is possible that it represents deep drainage that leaves the catchment via fractures in the bedrock. The best estimate of deep drainage, derived by comparison of changes in soil water content above and below the water table (deduced using the neutron probe data) was 80 mm, averaged over the catchment (McCartney, 1998). Of course, this water may eventually discharge to the stream at some downstream location, thus maintaining downstream river flow by the method proposed by McFarlane (1987). Further studies are required, investigating water chemistry at different downstream locations, to determine more exactly the regional contribution of deep groundwater to stream flow.

# Conclusion

The data obtained in the current study indicate large spatial and temporal variability in the composition of different water types. Despite the uncertainties, the data remain of value since, as demonstrated in this paper, they provide a simple method for determining, at least at the broad level, water sources and hydrological pathways within the catchment. The high variability of the shallow groundwater and spring water chemistry is indicative of changing flow circumstances, suggesting that there is only limited storage and minimal transport within the catchment.

The results of this study do not confirm the hypothesis of McFarlane (1987) that dry season recession flows originate as hill slope water by-passing the dambo through the saprolite. Rather they indicate that flow from the catchment, which is representative of many in the area, is dominated by shallow water sources. The alkalinity data are consistent with recession flow originating from slow drainage of shallow soils only; there is no evidence of a significant 'bedrock' contribution. Differences in baseflow chemistry may be attributable to alternative flow pathways and varying contributions from the near surface soil horizons. Further study is required to confirm these findings and identify how variable such systems are.

The chloride mass balance confirms that evaporation is the largest component of the water budget after rainfall. The analysis is based on limited data and errors in the estimated recharge rate may be large. Nevertheless, the finding adds to the growing body of evidence that, during the dry season, depletion of dambos is dominated by evapotranspiration rather than by contribution to river flow. Direct measurement of dry season evaporation from dambo grasses, for example using the bowen-ratio technique (Malek and Bingham, 1993), would provide valuable additional insight into the magnitude of dry season water fluxes.

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