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Inherited drainage - paleochannels and preferential groundwater flow

Richard Owen · T. Dahlin

Abstract It is suggested that in a localized remnant of Kalahari sand at Dufuya, central Zimbabwe, groundwater flows in an integrated pattern inherited from the paleochannel network of the underlying gneiss. Contact springs occur at discrete localities along the Kalahari sand/gneiss boundary and are associated with spring sapping and land surface subsidence. Subsidence is presumed to be due to preferential solute removal by leaching and dissolution as a result of concentration of groundwater flow within the buried paleochannel network and the location of the springs is presumed to occur where the paleochannel network intersects the Kalahari sand/gneiss boundary. Over time the surficial Kalahari sand is preferentially removed along these buried drainage lines by spring sapping and headwards erosion, exposing the gneiss. Multi-electrode direct current resistivity profiling and radar have been used to map the subsurface, revealing the topography of the basement and nature of the Kalahari cover. Coincidence of gneiss basement depressions with the spring sites, leached sands and subsidence zones suggests inheritance of the gneiss fluvial paleochannel network pattern by the present day groundwater flow. Washed sand and gravel intersected in shallow boreholes in these areas provides further evidentiary support for the concept of inherited drainage.

Keywords Inherited drainage · Preferential groundwater flow · Geophysical methods · Kalahari · Zimbabwe

Introduction

This paper presents the results of hydrogeological and geophysical investigations carried out at Dufuya perennial contact spring located near Dufuya village in the central part of Zimbabwe, southern Africa (Figs. 1 and 2). The spring arises as a localized (50 m × 50 m) seepage zone in a small topographic depression occurring at the contact between the overlying unconsolidated Kalahari sand, which constitutes the aquifer, and underlying impermeable weathered basement gneiss. The spring discharges approx. 6 l/s, with little variation throughout the year. Reconnaissance investigations for comparison purposes were carried out at Sogwala and Makulambila, two similar contact springs located along the same contact (Fig. 2).

The purpose of the study is to investigate the hydrology of the Dufuya spring and the evolution of the groundwater flow system supplying the spring. Geophysical methods, supported by shallow auguring, have been used to determine whether the groundwater flow system is preferentially located within a buried paleochannel network in the gneiss basement, and therefore whether the groundwater drainage pattern has been "inherited" from a pre-existing surface drainage developed on the gneiss. The term "inherited drainage" has been used to describe this concept.

Outline of the hydrogeology of the study site

The key hydrogeological feature of the study area is unconsolidated permeable Kalahari sand overlying impermeable clay-rich weathered gneiss. This hydrogeological contrast produces numerous springs discharging at discrete localities along the contact zone. The Kalahari sand area is almost entirely without surface drainage, an indication that there is no surface run-off and suggesting that all precipitation infiltrates due to the high permeability of the surface. By contract the gneiss areas are characterized by a dense dendritic drainage pattern (Fig. 2). Groundwater flow to these contact springs provides an abundant perennial water supply and for this reason the evolution and distribution of the groundwater flow system in the Kalahari sand is of considerable significance.

Review of relevant literature

Geology

The geology in the study area consists of Archaean tonalitic and migmatitic basement gneiss, with subordinate younger granite intrusions, and locally preserved Permian

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Fig. 1 Location map showing the study area in Zimbabwe and the neighbouring countries

Karoo mudstones. These have been covered by a blanket of Tertiary to Recent Kalahari sand, which has subsequently been partially eroded to reveal the underlying basement. Around the edge of the Kalahari sand is a narrow rim of reworked and redistributed Kalahari sand. The Kalahari sand represents an outlier of a once continuous cover of largely aeolian sediments that are now preserved only on the watershed areas between the main rivers, where they form broad gentle rises of deep sand (Fig. 2; Harrison 1981; Stagman 1978).

The Kalahari sand at the study site lies at the eastern margins of the extensive Kalahari Group sediments of southern and central Africa that cover more than 2.5× 10^6 km^2 stretching from South Africa to the Democratic Republic of Congo and reaching a maximum thickness of more than 300 m in depo-centres such as the Okavango

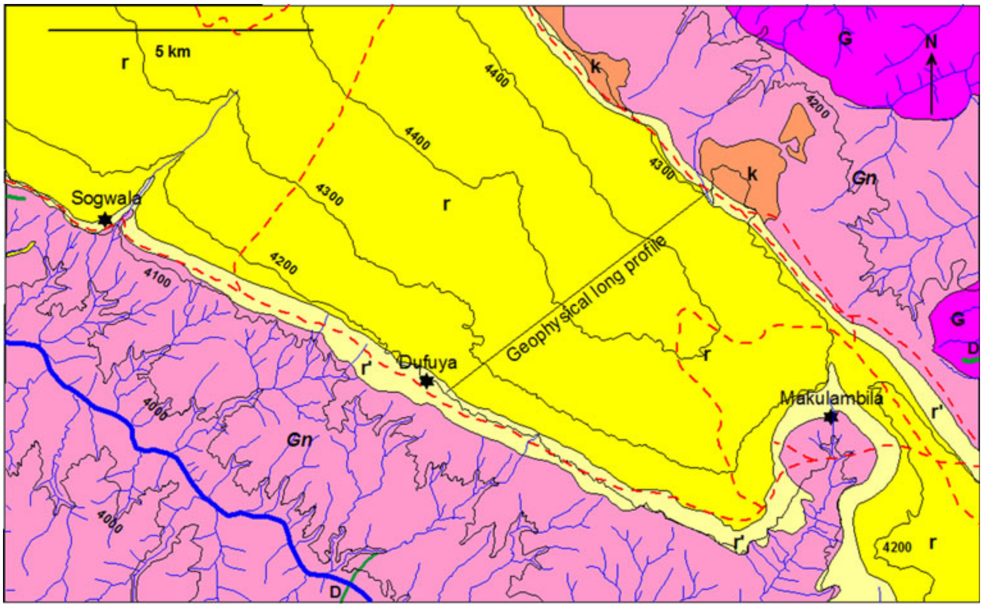

Fig. 2 The geology at the study site (modified from Harrison 1981). *Star* signifies spring sites: Dufuya, Sogwala, Makulambila, *r* Kalahari sand; *r'* redistributed Kalahari sand; *Gn* Gneiss; *G* granite; *k* Karoo sediments; *D* dolerite; *red dashed line* represents roads; *blue line* represents streams and river; topographic contours are in m asl. The position of the long resistivity profile is shown. The detailed resistivity survey was conducted at the Dufuya spring site

graben in Botswana and Etosha in northern Namibia (e.g. Haddon 2000; Thomas and Shaw 1991, etc.). There is far more to the Kalahari than the well known "Kalahari sand" and the complete succession is a complex sequence of sediments (Haddon 2000). Initial deposition of the Kalahari group sediments is widely accepted to have been initiated in the Late Cretaceous by tectonism resulting in basin development along a NW–SE axis. Subsequent tectonism along a NE–SW axis, continuing up to the present time, has modified the location and the ages of the principal deposition episodes of Kalahari group sediments (Wanke and Wanke 2007). Kalahari group sediments generally include widespread basal gravel and a fining upwards sequence with sedimentary facies ranging from coarse clastic proximal facies to distal fine grained mudstones and evaporites (e.g. Du Plessis and Le Roux 1995). The dominant depositional environment was fluvial, especially for lower units (Wanke and Wanke 2007), while the widespread upper unconsolidated sand is generally accepted to have an aeolian origin (e.g. Thomas 1987). Repeated tectonism, absence of fossils, the imprint of climate change, erosion, reworking, redeposition, and post depositional modification has resulted in a sequence that is complex and laterally inconsistent. Nevertheless, it is possible to recognize broad lithological units across the basin. Due to lack of outcrop, most attention has focussed on the uppermost units such as the unconsolidated sands, dunes, duricrusts and pan sediments. The Kalahari Group lithologies are diverse and varied and their origin, mode of deposition, age and environmental significance are still being debated (Haddon 2000).

Hydrogeology

One of the notable features of the Kalahari sand outcrop at the study site is the complete absence of surface drainage, due to the high infiltration rates on the sand. This lack of surface drainage is a general feature in the drier southern part of the Kalahari basin (Thomas and Shaw 1991). The location of the groundwater drainage system thus becomes of fundamental interest in the development and understanding of the water resources in the Kalahari sand.

Water boreholes drilled into the Kalahari sand in northwestern Zimbabwe often have very high yields in excess of 10 l/s with excellent quality groundwater (MacDonald 1970). By contrast, the water quality in many areas of the Kalahari sand in Botswana is so saline that the Botswana Geological Survey no longer considers the Kalahari sand as a useful source of potable groundwater (M. Magowe, Botswana Geological Survey, personal communication, 2006).

The average hydraulic conductivity measured from sandy parts of the Kalahari in the Okavango delta in Botswana ranged from 4 to 20 m/day (Wolski and Savenije 2006). Hydrogeology text books commonly ascribe porosities of 25–35% and hydraulic conductivities of 1–10 m/day to aeolian sand aquifers (e.g. Hamill and Bell 1986). The Kalahari sand is therefore potentially a very significant regional aquifer and improved knowledge and understanding of the groundwater flow processes operating within these sediments may provide an effective tool for development and sustainable management of the aquifer.

Investigations: methods

Field and geological mapping

Geological mapping and field observations were a key investigation method. The different drainage patterns developed over the Kalahari sand and basement gneiss reveal the permeability and infiltration capacity of the surface. The outcrop pattern and surface topography provide information on erosion and the geomorphological evolution at the spring sites. Observations at the springs reveal information about the geology and groundwater flow at the contact zones.

Geophysical investigations

Geophysics was used to investigate the subsurface to determine (1) the three-dimensional (3-D) extent of the Kalahari sand aquifer by identifying the depth to the Kalahari sand-gneiss interface and (2) the geo-electric characteristics of the Kalahari sand to infer the sediment types. The principal geophysical technique used was multi-electrode resistivity profiling using the Lund Imaging System with an ABEM SAS 300C Terrameter (Dahlin 1993). A ground penetrating radar RAMAC/GPR unit manufactured by Mala Geoscience, Sweden (Mala Geoscience 1995), was used in a localized area directly over the spring zone.

Shallow augering, soil sampling and analyses

The information obtained by geological mapping, field observations and geophysics was supported by shallow augering using a portable tripod mounted with a locally manufactured hand drill. Samples obtained from depths to maximum 15 m were used to test the hydraulic properties of the soil by sieve analyses, permeameter and Attergberg limits tests.

Hydrological measurements

Hydraulic conductivity values are assigned to each of the hydrogeologic units based on the soil tests and in situ testing such as slug, infiltration and pumping tests. The spring discharge at Dufuya was measured at weekly intervals with a 60° V-notch weir throughout an entire hydrological year. Water levels in the shallow boreholes were monitored on a weekly basis from September 1992 to March 1996.

Environmental isotopes and water chemistry

Oxygen-18 and Deuterium isotope samples were collected in the dry season, July 1992, from the Dufuya spring and the downstream weir; in the wet season, January 1993, further samples were collected from the spring, the weir and BH 5-11 in the Kalahari sand.

Investigations: results

Field observations and geological mapping

The Kalahari sand at Dufuya and the surrounding area is an outlier from the main body of the Kalahari that persists further west. The sand occurs as a gentle rise on the interfluve between the surface drainage, which flows over gneissic basement exposed in the valleys (Harrison 1981). The Kalahari sand on the interfluve is a poorly sorted orange buff fine silty sand with occasional gravel, while the "redistributed" Kalahari sand along the contact zone is a clear white fine-to-medium quartz sand without silt and has a washed appearance (Fig. 3).

The most striking hydrogeological feature is the occurrence of numerous springs along the Kalahari sand/ basement gneiss contact zone, the most prominent being located at Dufuya (Fig. 4), Sogwala and Makulambila. The springs are discrete localized seepage zones occurring as marshy areas over the Kalahari sand, becoming progressively more channel-like downstream over the gneiss. The marshy areas are topographic depressions at the edge of the Kahalari sand, and may be triangular, as at Dufuya (Fig. 4), or elongate, as at Sogwala (Fig. 5). Sub-rounded coarse basal gravel is observed at the lithological contact at both Dufuya (Fig. 4) and Sogwala springs. At Makulambila, much of the Kalahari sand has been removed by erosion (Fig. 2), and a stream flows from the Kalahari sand remnant over exposed basement. The groundwater level is perennially at a shallow depth along the entire length of the contact zone.

The Kalahari sand at the study site

It is known that the Kalahari Group sediments are highly variable (e.g. Haddon 2000), and within the study area several units are observed: basal gravel along the contact, reworked leached quartz sand in the actual spring sites and along the contact zone, mixed cohesive sandy clay gravel and fine orange silty sand in the interfluve areas. This suggests a variety of depositional environments.

Fig. 3 Kalahari Sand. At *left*: Highly leached well sorted clean quartz sand leached by concentrated groundwater flow from BH5 at the spring site. At *right*: Semi-cohesive poorly sorted unleached Kalahari gravely clayey sand from BH 9, ~120 m upslope of the spring

The shallow tube-wells (Fig. 6) drilled upslope of the Dufuya spring site exhibit some of this variation: Fig. 3 shows two samples: a clean white non-cohesive quartz sand from BH5 at the edge of the marshy spring zone; and a poorly sorted cohesive mixed sample with particles ranging from gravel to clays, with sand as the dominant fraction from BH9 on the interfluve area. Samples collected from the tube-wells 5 to 12 show a gradation between these two samples, as indicated by the Atterberg limits (Fig. 7), which indicate a decrease in clay content approaching the spring, presumed due to progressive leaching by increased groundwater flow velocities and volumes towards the spring. Other tube wells (BH 14–16) drilled southwest of the road that marks the contact between the Kalahari sand and the gneiss (Fig. 6) intersect a thin layer (<1 m) of redistributed Kalahari sand before intersecting weathered gneiss.

Hydrogeology

For the purpose of assigning hydraulic conductivity values, four sediment classes have been recognized (Table 1). These are (1) poorly sorted mixed Kalahari sands, silts and gravels that characterize the upper interfluve area of the Kalahari sand. These are very variable ranging from surficial silty sands to conglomeratic silty and clayey sands intersected in several tube wells. The second class (2) is clean reworked white quartz sands that occur in the spring sites. These are texturally and compositionally highly mature sands that most likely were of aeolian origin and have been reworked and

Fig. 4 Dufuya spring. Photograph illustrating four features: (1) spring sapping in the centre of the photo, just upslope of the cattle trough in the reed beds, (2) the gentle depression in the gneiss basement as marked by the base of the fence line, (3) the modest depression in the Kalahari sand area covered by reeds, and (4) the basal Kalahari gravel next to the cattle trough and in the bare ground in the middle of the photo

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Fig. 5 Sogwala spring. Spring discharge occurs at the tall reeds in the *mid-photo* on the horizon. Leached Kalahari sand and the shallow water table are shown in the foreground well. The difference between the far blue and near green horizons shows the land surface subsidence along a linear zone from the shallow well to the spring. The grassy plain in the foreground is devoid of surface erosion features, suggesting that the lowered land surface is subsidence due to sub-surface leaching and solute removal by groundwater drainage

leached by groundwater flow. They are hydraulically significant since the bulk of the groundwater flows through them. A similar class (3) is the reworked Kalahari sand that occurs all along the contact zone. They are also well sorted sands, although significantly less leached than the spring facies. The final hydraulic conductivity class (4) is the clay derived from the weathered gneiss that forms the hydrogeological basement.

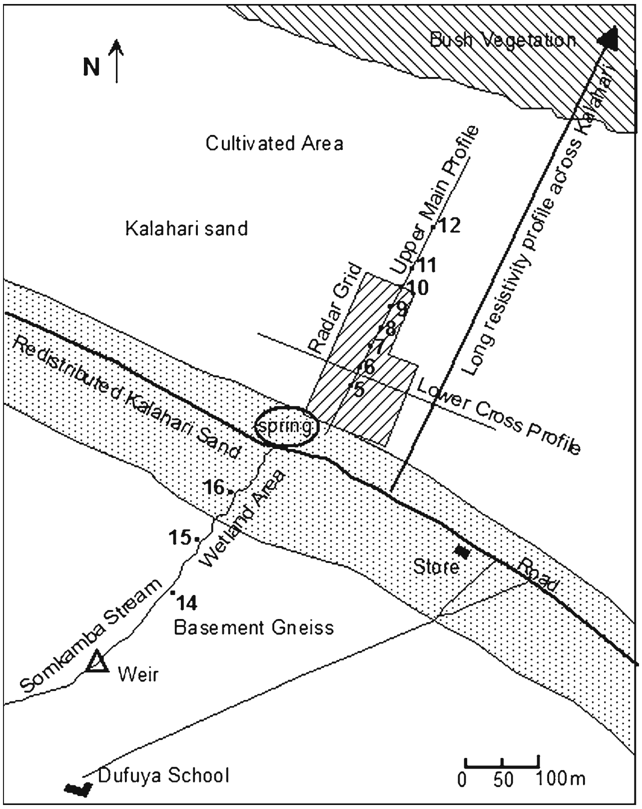


Fig. 6 The location of the geophysical surveys and shallow boreholes at Dufuya. The Upper Main Profile and Lower Cross Profile resistivity surveys are shown in Fig. 9a and b, and the radar grid is shown in Fig. 9c. The boreholes are numbered from 5–16 (*black dots*). The samples in Fig. 3 were taken from boreholes 5 and 9

Drainage

The drainage is completely dominated by the geology. Over the Kalahari sand surface streams and run-off channels are almost entirely absent confirming that the drainage system is dominated by groundwater flows to the spring sites, as characterized by the Dufuya spring. The spring discharge at Dufuya has been measured as between 5.5 and 6.9 l/s throughout an entire hydrological year (1993/1994) with no observable response to short-term climatic events. The bulk of the discharge occurs from the Kalahari sand and redistributed Kalahari sand above the road at the "eye" of the spring, which is about 0.25 ha in extent. This spring water flows both by overland flow and by subsurface seepage through the redistributed Kalahari sand and over the gneiss to form a wetland 63 ha in extent, down-slope of the spring. Approximately 28 ha are perennially cultivated principally as vegetable gardens and small orchards. The total watershed area feeding the wetland is estimated at 724 ha (Andreini et al. 1995).

The surface drainage on the gneiss is dominated by two major structurally controlled rivers, which both flow towards the north-west on both sides of and parallel to the elongate Kalahari sand body (Fig. 2). The tributary drainage on the gneiss exhibits a dense network of ephemeral streams with a typically dendritic pattern.

Geophysical investigations

To obtain an overview of the Kalahari sand geometry, a 7-km long low resolution NE–SW resistivity profile crossing the

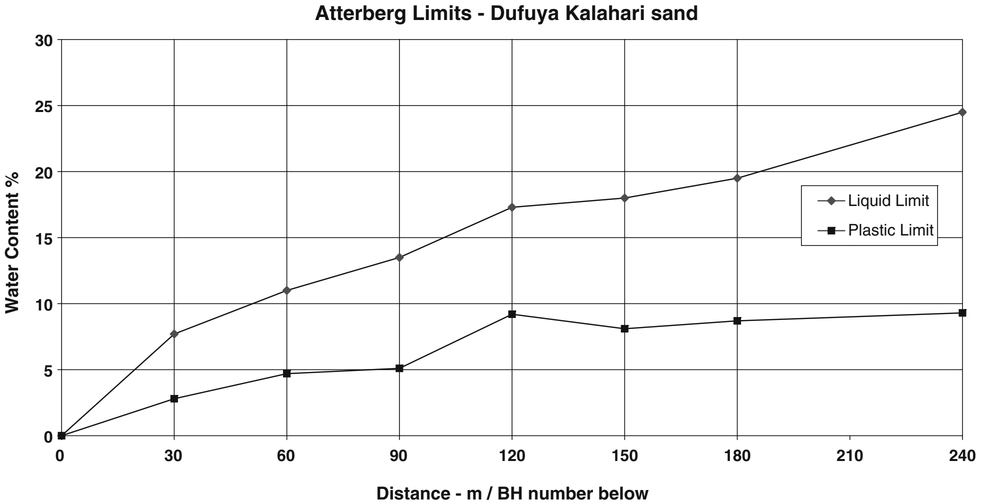


Fig. 7 Atterberg limits for soils from BH5 at the spring to BH12 upslope. The liquid limit (LL) and plastic limit (PL) decrease steadily towards the spring, indicating progressive leaching of clays closer to the spring

entire Kalahari outcrop was acquired (Fig. 2), revealing a mantle of resistive sand (maximum thickness 60 m) overlying a low resistivity basement (Fig. 8). Electrode spacing between 5 and 20 m was used, with the closer spacing used at the ends of the profile, where the Kalahari sand pinches out and the springs occur. An approximate water table has been estimated from the resistivity survey (Einarsson et al. 1994).

Detailed multi-electrode resistivity profiling with 2 m electrode separation has been done in the vicinity of the Dufuya spring (Fig. 6). Two detailed resistivity profiles are presented:

1. The upper main profile orthogonal to the basement/Kalahari contact line over the spring and crossing the contact (Fig. 9a)
2. The Lower Cross Profile parallel to the contact within the Kalahari sand just upslope of the spring (Fig. 9b).

In addition, ground penetrating radar (GPR) with continuous reading along a 12.5 m×25 m line-spacing grid has been acquired around the spring site (Fig. 9c). The resistivity profiles reveal significant detail about the geometry and geology at the spring. The Kalahari sand has very high resistivity at the actual discharge site (>3,000 Ωm) where the sand is a medium grained clean white quartz sand. The Kalahari sand further upslope from the spring has a much lower resistivity signature between 100 and 500 Ωm, suggesting a different composition and texture. In this area, buff coloured poorly sorted “mixed” Kalahari sand with both fines and pebbles in a dominantly sandy matrix is observed on the surface and in the borehole spoil. It shows little sign of leaching as the fines are still present and the quartz grains are stained (Fig. 3).

Table 1 Hydraulic conductivity of formations in the vicinity of Dufuya Spring

Hydrogeologic unit	Hydraulic conductivity (m/day)
Mixed Kalahari sand	2
Redistributed Kalahari sand	5
Leached spring facies, Kalahari sand	10
Basal gneiss aquitard	0.2

Both resistivity profiles indicate a degree of pseudo-stratification in the Kalahari sand, with a high resistivity upper layer, a lower resistivity intermediate layer and high resistivity basal layer. The resistivity profiles and the radar image all show a land surface depression overlying and coinciding with a depression in the gneiss basement.

Environmental isotopes

The oxygen18-deuterium plot shows that both the Kalahari groundwater and the spring water fall on the global meteoric water line indicating that infiltration has been rapid before significant evaporation loss has taken place. This is in agreement with the high infiltration rates measured on the Kalahari sand surface. The similar isotopic signatures suggest that the spring water originates from the Kalahari groundwater. By contrast, the oxygen-18/deuterium values for the weir water below the marsh are less negative, suggesting a concentration of the heavier isotopes in the marshland due to evaporation losses (Fig. 10).

Interpretation and conceptual model of the Kalahari sand

A conceptual model for groundwater flow in the investigated part of the Kalahari sand is developed in this section.

Groundwater/surface water interactions

The relative abundance of groundwater in the Kalahari sand may be readily explained by the physical and hydraulic

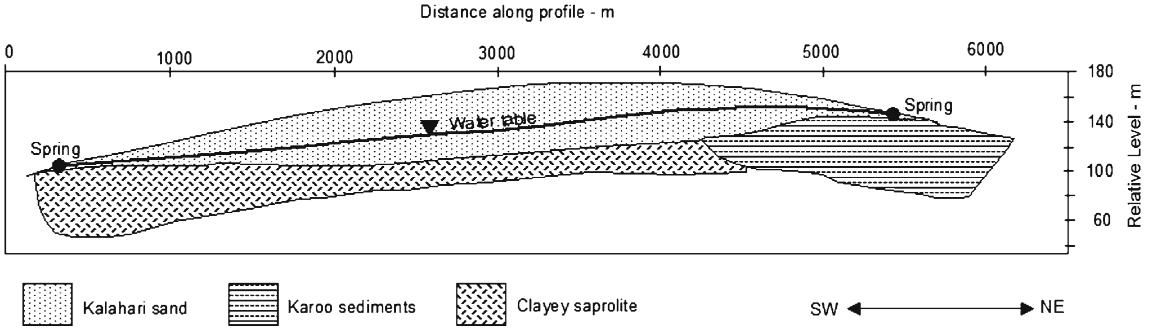


Fig. 8 Geological interpretation of the long resistivity profile across the entire outcrop of the Kalahari sand (Fig. 2). The horizontal scale (0–6,000 m) shows the position along the profile and the vertical scale the relative investigation depth. The water table is estimated from the variation in resistivity values (Einarsson et al. 1994)

properties of the Kalahari sand, which has high porosity (25–35%) and high hydraulic conductivity (2–10 m/day; Table 1). Almost all the rainfall infiltrates directly into the loose unconsolidated sand resulting in the absence of surface drainage, leading to high recharge rates. De Vries and Von Hoyer (1988) proposed the concept of a "recharge threshold" for the Kalahari sand, estimated as 400 mm for Botswana. Early season precipitation infiltrates directly into the sand, replacing the soil moisture lost from the root zone to active evapotranspiration during the preceding season. Once the soil moisture has been replenished to field capacity, the recharge threshold has been reached and the balance of precipitation, since it is not lost to run-off, percolates into the deep loose sand to become groundwater recharge, estimated as 180–200 mm/year at Dufuya (Owen 2000).

As a result of these high recharge rates, the Kalahari sand areas are characterized by numerous perennial springs occurring at discrete localities along the Kalahari sand-gneiss contact. The groundwater flow at the Dufuya spring varies little throughout the year and appears independent of individual rainfall events and short term climatic variables. By contrast, the adjacent gneiss areas are characterized by numerous closely spaced ephemeral streams (Fig. 2). Flow from the mixed Kalahari sand-gneiss catchment at Dufuya has a very high seasonal variability (Andreini et al. 1995).

Groundwater flow in the Kalahari sand

Interpretation of the geophysical data provides an indication of the possible groundwater flow pattern in the Kalahari sand. The pseudo-stratification observed in the Kalahari sand resistivity profiles (Fig. 9a and b) has been interpreted as a dry surface layer, a second layer with accumulated fines leached down from the top layer and a basal layer leached by pseudo-channelling of groundwater flow towards the spring site.

The extremely high resistivity values at the spring site are attributed to aggressive leaching caused by concentrated groundwater flow towards the discharge end of the flow paths, resulting in the clean quartz sand observed there. Solute and fines removal due to advanced leaching with the consequent volume reduction gives rise to the depression observed at the Dufuya spring site. Such land surface subsidence and insetting is observed at other spring sites, notably Sogwala.

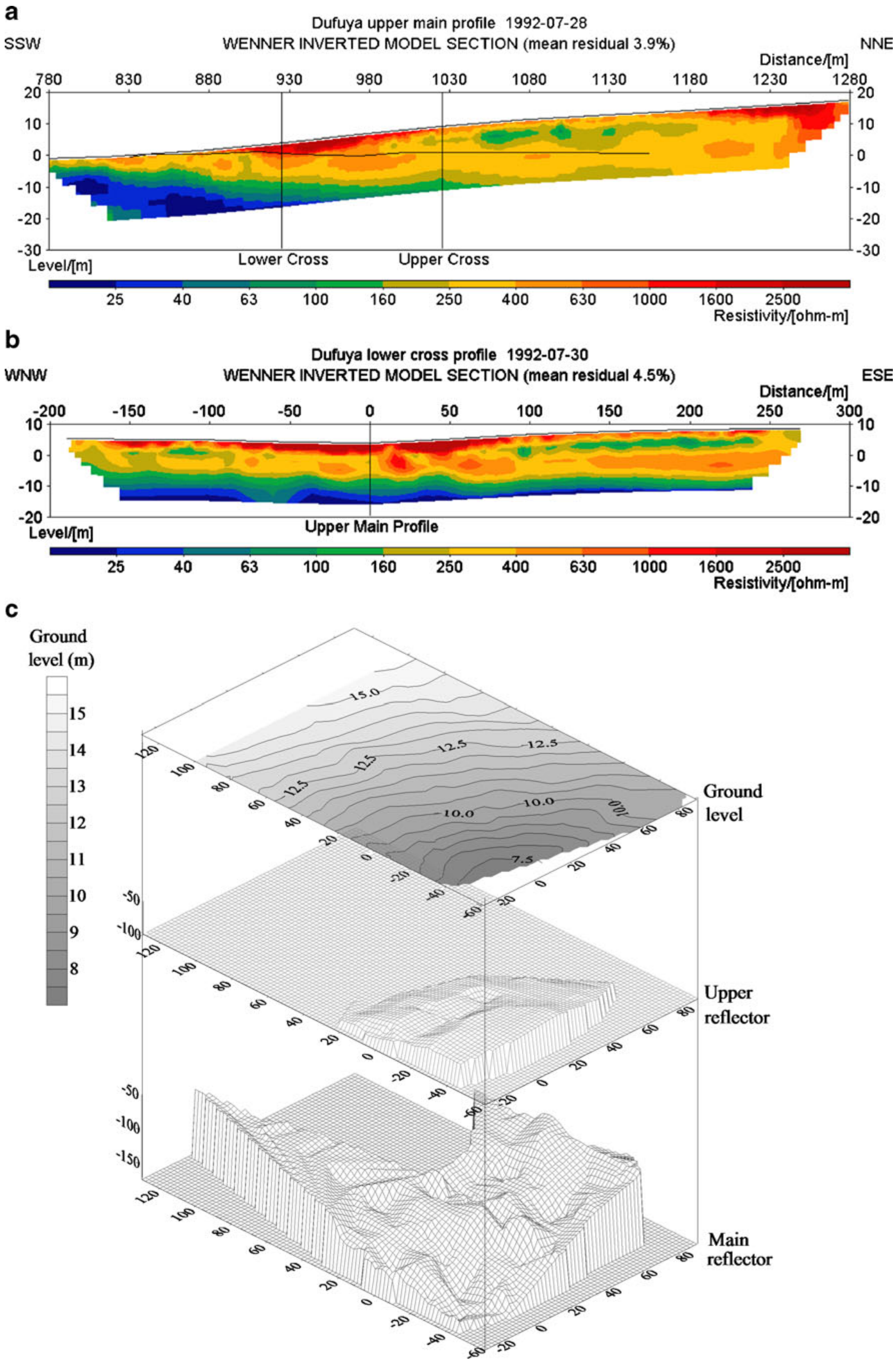
At Dufuya, the resistivity and the radar images show a depression in the basement gneiss underlying the surface depression as discussed previously. This coincident depression in the basement must pre-date the spring and as a topographic low, it is presumed to represent an element of the paleo-drainage in the pre-existing gneiss land surface. The photograph of the spring at the contact zone (Fig. 4) shows that the gneiss surface forms a channel, mimicking the land surface, with a central depression and slightly elevated flanks.

Erosion sequence at the Kalahari sand-gneiss contact

The outcrop pattern and drainage at three Kalahari sand contact springs, Makulambila, Sogwala and Dufuya, has been compared (Fig. 2). These three localities portray an evolutionary sequence of progressive erosion within the Kalahari sand and hence provide insight into the erosion mechanism and the role played by the groundwater drainage system.

Erosion of the Kalahari sand at Makulambila has exposed the bedrock in a circular shaped basin with Karoo arkoses to the north east and tonalitic gneisses to the south west leaving only a thin Kalahari sand remnant on the crest of the interfluve (Fig. 2). The outcrop pattern indicates that ongoing erosion and removal of the Kalahari sand has exposed the pre-existing gneiss drainage channel, which is now occupied by the Makulambila stream and its tributaries.

At Sogwala (Fig. 2), headwards erosion has lead to an upslope retreat of the Kalahari sand/gneiss contact by approx. 300 m. The extensive spring zone is characterized by widespread spring sapping giving rise to irregular collapsed surfaces, leached sand, and basal gravel with exposed gneiss bedrock downstream. Discharge from the Sogwala spring has been estimated at +10 l/s (Owen 2000). Above the spring, a shallow linear topographic valley, remarkable for the complete absence of surface



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◀ **Fig. 9** **a** Multi-electrode resistivity upper main profile from the spring orthogonal to the gneiss-Kalahari contact (Berner et al. 1993). Note: (1) *SSW* end of profile from 780 to 900 m shows low resistivity (<40 Ωm) and weathered clay gneiss at base of the profile. (2) Very high resistivity (>1,000 Ωm) from 900 and 970 m: highly leached clean quartz sand in spring zone. (3) Pseudo-stratification of the profile: higher resistivity (±500 Ωm) found in the dry sandy upper layer; lower resistivity (±150 Ωm) found in the second layer, with leached clays translocated from the top layer; intermediate resistivity (±250 Ωm) found in the third layer below the water table, interpreted as the groundwater flow layer. **b**. Multi-electrode resistivity lower cross profile within the Kalahari sand parallel to the gneiss-Kalahari contact (Berner et al. 1993). Note: (1) Pseudo-stratification as in Fig. 9a. (2) Very high resistivity at spring site between –50 and +50 m; (3) Higher resistivity mid-layer from +10 and +70 m, interpreted as a groundwater flow channel; (4) Surface depression from –80 to +60 m due to land surface subsidence; (5) Vestigial paleochannels in weathered gneiss at –60 m and at –10 to +20 m. **c**. Relief map based on interpretation of GPR data (Beckmann and Liberg 1997). Image shows ground surface level relative to the drinking trough overflow pipe at the spring discharge (see Fig. 4), upper reflector (groundwater level) and main reflector (gneiss bedrock), as a function of the reflection time (ns). The model is viewed from the south-west, with the eye of the spring in the fore-ground. The clear depression in the gneiss bedrock under the spring is interpreted as a buried paleochannel that controls groundwater flow through the overlying Kalahari sand

run-off features, has developed in the Kalahari sand (Fig. 5). This depression is formed by land surface subsidence due to leaching and removal of soluble materials by groundwater flow and its shape is expected to mimic the underlying groundwater flow, which appears to follow in a linear fluviatile pattern.

The third locality at Dufuya spring shows limited erosion. A small, basin-shaped depression in the Kalahari sand has formed immediately above the spring discharge but there has been no headwards retreat of the Kalahari sand-gneiss contact. However spring sapping and land surface collapse is evident at the discharge site (Fig. 4).

In terms of the progression of erosion, the Sogwala locality shows an intermediate form of erosion between Makulambila and Dufuya. The mechanism is similar throughout, which is subsurface removal of material by aggressive leaching along the groundwater flow paths, leading to thinning of the Kalahari sand cover and subsidence of the land surface. Once the Kalahari sand cover is too thin to accommodate the groundwater flow, then surface flow commences, resulting in channel formation, with spring sapping and headwards erosion. Thereafter, the contact between the Kalahari sand and the gneiss migrates gradually upslope into the Kalahari sand, exhuming the paleo-drainage. The fact that the springs occur at discrete intervals suggests control derived from the basement topography. These three spring sites, when studied together, exhibit an evolutionary geomorphic time series and reveal an interaction of simultaneous surface and subsurface erosional processes.

Groundwater flow in an inherited drainage system

Based on the available surface and sub-surface data, it is proposed that the groundwater flow occurs in preferential flow paths inherited from the gneiss paleo-drainage. Assuming a fluvial drainage system existed on the pre-Kalahari surface, these paleo-stream channels would (1) exhibit favourable topography and (2) contain permeable

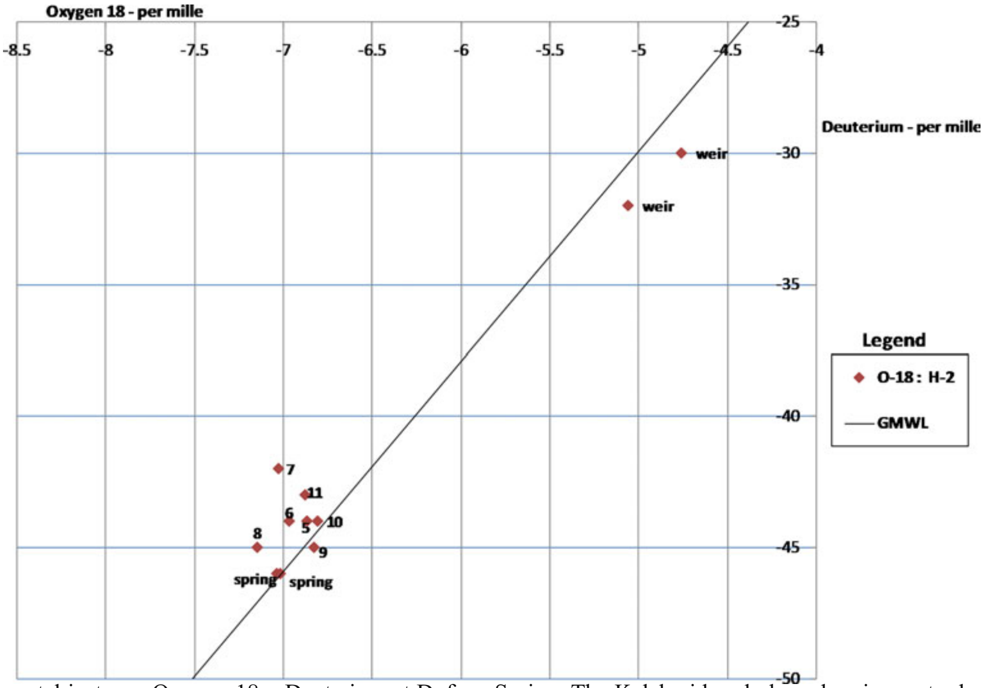

Fig. 10 Environmental isotopes Oxygen-18 v Deuterium at Dufuya Spring. The Kalahari borehole and spring water have similar isotopic signatures, suggesting that they have similar origin. These samples fall on the global meteoric water line (*GMWL*) suggesting infiltration before significant evaporation loss. The $^{18}O/^{2}H$ value for the downstream weir water does not fall on the GMWL and this water is relatively enriched in heavy isotopes suggesting preferential loss of the light isotope fraction by evaporation

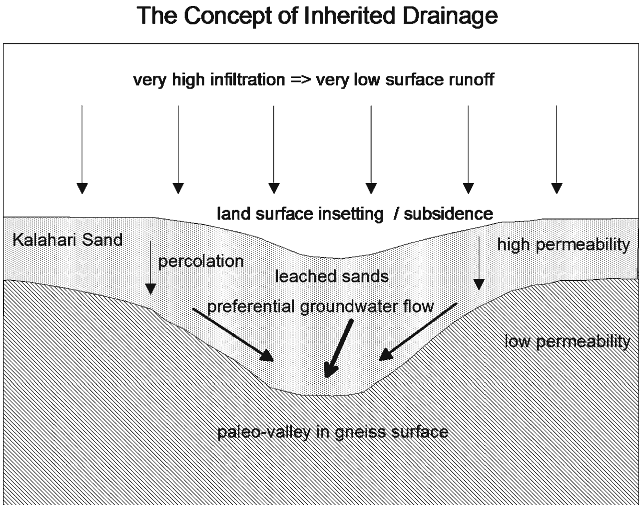

Fig. 11 Diagram of inherited drainage. The key elements are: (1) the high hydraulic conductivity of the unconsolidated sediments resulting in high infiltration rates; (2) the hydraulic conductivity contrast between the basement and the surficial unconsolidated sands; (3) the basement topography or paleo-drainage, which controls the groundwater flow. The anticipated features of this concept such as land surface insetting, leached sands at the springs and the localized/channelized nature of the seepage zones, are all observed at the study site

channel sediments. Kalahari sand deposition buried the existing gneiss land surface with its drainage network, establishing a condition with highly permeable unconsolidated surficial material, Kalahari sand, overlying low permeability basement gneiss. During recharge events, rapid infiltration into the Kalahari sand occurs, with water percolating down until it reaches the low permeability bedrock. At the Kalahari-bedrock interface, water flows down the maximum slope of the buried paleo-surface and hence into the buried paleochannel network. This type of groundwater flow system development may be aptly called "inherited drainage" since the groundwater flow pattern is inherited from the pre-existing surface drainage developed on the basement (Fig. 11).

The concentration of flow along a specific flow path results in locally increased leaching and improved hydraulic conductivity along that flow path. The dissolved material is discharged at the springs resulting in volume loss and land surface insetting, creating a surface depression overlying the preferential flow path. Such depressions *potentially* enhance ponding and local groundwater recharge, although the lack of surface runoff over the Kalahari sand in this study area precludes this effect. These effects may work in tandem setting up a positive feedback loop that enhances preferential groundwater flow along the paleo-drainage lines. Groundwater flow modelling of the Dufuya aquifer does show increased flow velocities and preferential flow in the area upslope of the spring zone (Owen 2000).

The process of headwards erosion described previously would follow the course defined by the buried paleo-drainage. It is suggested that this was and remains a principal mechanism in the removal of the Kalahari sand cover, which formerly covered the lower Gweru area and beyond (Lister 1987). By inhabiting an inherited drainage network, groundwater flow preferentially exhumes and rehabilitates the pre-existing drainage system.

Conclusions

This paper proposes a theoretical model whereby groundwater flow may occur in an integrated pattern inherited from a pre-existing paleochannel network formerly active on the underlying buried land surface. The Dufuya spring site is a contact spring at the interface between basement gneiss and Kalahari sand. Key aspects are the relatively uniform highly permeable surficial aquifer material with a low permeability underlying layer. Since the sand pinches out at this locality, key features of the contact spring are exposed. Such features include local coincident depressions in both the overlying aquifer and the basement, leaching of the spring sediments leading to locally enhanced permeability, and discharge of spring water with dissolved solutes leading to sediment volume reduction and land surface subsidence.

The study of the Dufuya contact spring and associated springs raises the possibility that the location of such springs is controlled not only by the position of the contact but also by the buried topography in the bedrock. Groundwater flow to such springs may be channelled along pre-existing paleo-drainage lines in the bedrock, and hence is described as "inherited drainage". The implications of such a flow system may be significant.

As indicated previously, the Kalahari sand occupies a vast area across south-western Africa, and potentially constitutes an important aquifer in much of Botswana, western Zambia, south-eastern Angola and north western Namibia, as well as parts of western Zimbabwe. However, well yields in the Kalahari are erratic, ranging from more than 50 l/s to less than 1 l/s, and the water quality is highly variable, from saline brines to excellent quality fresh water.

It is suggested that the mechanism/process of inherited drainage described in this paper may also function in other areas covered by deeper Kalahari sand, and the concept of inherited drainage may provide a useful theoretical approach for groundwater exploration in the Kalahari sand. If such a mechanism controlling groundwater flow is valid, then the implications are that:

1. Such inherited groundwater drainage channels are likely to be the locus of enhanced permeability and hence higher well yields
2. Inherited groundwater paleo-drainage is likely to be a locus of increased flow, leading to more rapid replenishment from upstream sources and hence a fresher water quality
3. The proposed conceptual model may be useful for the design of groundwater exploration strategies in unconsolidated sediments.

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