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Estimation of groundwater recharge in weathered basement aquifers, southern Zimbabwe; a geochemical approach

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ABSTRACT

Geochemical techniques have been used to estimate groundwater recharge and its spatial variability in basement terrain in a semi-arid area of southern Zimbabwe. Recharge rates estimated by chloride mass balance have been determined in the Romwe catchment, a small (4.6 km^2) headwater catchment underlain by banded gneisses, with good hydrological and geological control. The results support the findings from piezometric monitoring that there are significant differences in hydrogeological properties of weathered basement derived from different primary lithologies. Annual recharge estimates for shallow weathered aquifers derived from melanocratic bedrock (dominated by pyroxene gneiss), 22 mm, and leucocratic felsic bedrock, 6.7 mm, are 3.7% and 1.1% respectively of the long-term mean annual rainfall. The significant uncertainties associated with the chloride mass balance recharge estimates are discussed. Groundwater derived from each lithology generally has a distinctive geochemistry (Na/Cl, K/Na, Mg/Ca, Na/Cl, B, Ba). The information from the Romwe catchment control area was then scaled up using information from remote sensing images (which defined areas of dark and light soils above the banded gneiss) to confirm the higher recharge rates in the melanocratic lithology in the unexplored Greater Romwe (225 km^2) area. It is concluded that properly calibrated, remote sensing images could be further regionalized to site groundwater sources in basement terrain, providing a relatively inexpensive development tool.

1. Introduction

Groundwater is the main source of water for much of the rural population of sub-Saharan Africa, particularly those in the drought-prone semi-arid regions (Foster et al., 2000; JMP, 2008; MacDonald et al., 2009, 2012). The exploitation and sustainability of this resource is key to human survival and economic development. Large areas of sub-Saharan Africa are underlain by crystalline basement rocks and much research has been undertaken on groundwater storage and flow within this aquifer and how best to develop and protect water supplies (e.g. Wright, 1992; Chilton and Foster, 1995; MacDonald et al., 2005).

Crystalline basement rock in Africa is primarily of Precambrian age and granitic or gneissose in type (Clark, 1985). Basement aquifers are formed due to the effects of prolonged weathering and tectonic forces on the parent rock (Fookes, 1997). The aquifer can be simplified to a two layer system: the shallow weathered layer (regolith), and the underlying largely unweathered bedrock (Acworth, 1987). The regolith has a high storage in comparison with the bedrock; fractures within the bedrock provide permeability which can be high where a significant network of fractures exists (Chilton and Foster, 1995; Taylor et al., 2010). Boreholes completed in the bedrock are particularly productive where the fractures tap a large volume of overlying saturated regolith. The degree of weathering of the basement rock is dependent on a number of factors including: the mineralogy and texture of the parent rock (Jones, 1985; Courtois et al., 2010); fracturing that has occurred within the parent rock; the age of the erosion surface (Taylor and Howard, 2000); and the quantity of groundwater recharge and throughflow (Jones, 1985; Acworth, 1987). The weathering profile may vary considerably both on a regional and local scale.

An investigation of the control this variability in weathering can have on groundwater recharge and well productivity was undertaken between 1993 and 1998 as part of the work undertaken in southern Zimbabwe within the Romwe catchment study (RCS; Bromley et al., 1999). The Romwe catchment is a small basement-complex headwater catchment lying within the northern margins of the Limpopo Mobile Belt (Robertson, 1974). An aim of the RCS was to improve the understanding of hydrological processes, and particularly groundwater recharge mechanisms, in

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areas of crystalline basement geology having a land use typical of communal lands. A number of studies relevant to understanding the groundwater system within the RCS have been published (Macdonald et al., 1995; Butterworth, 1997; Bromley et al., 1999; Butterworth et al., 1999a,b,c; Moriarty, 2000).

The main objective of the study reported here was to investigate the use of chloride as a tool for estimating groundwater recharge in basement terrains. This technique has been successfully applied to sedimentary areas with deep unsaturated zones, such as in Australia (Allison et al., 1994), Senegal (Gaye and Edmunds, 1996) and China (Gates et al., 2008) but its application to basement areas and the weathered regolith has received little attention (Lapworth et al., 2013). In this paper, as well as Cl, major ions are used to characterise the hydrogeochemistry so as to infer the predominant aquifer units. The conclusions from work undertaken within the 4.6 km^2 Romwe catchment, used as a control, were applied to a larger area of 225 km^2 (Greater Romwe) to evaluate geochemical methods and remote sensing as tools for regional groundwater exploration. As well as addressing a gap in knowledge on the hydrogeological behaviour of basement aquifers, this study contributes towards the challenge of meeting the water requirements of rural populations in hard rock terrain.

2. Background

2.1. Romwe catchment study

The Romwe catchment is located in the Save River Basin, within the northern margins of the Zimbabwean Lowveld, at an altitude of ~800 m asl. The site (20°45′S, 30°46′E) is 390 km south of Harare (Fig. 1). The catchment (Fig. 1) which had a dispersed population of 200–250 at the time of the study (49 persons/km^2), is typical of many headwater catchments in the communal lands of Zimbabwe, in that it is underlain by crystalline basement and has mixed land use consisting of rainfed farming and woodland vegetation. Gentle slopes along the valley floor, drained by an ephemeral stream, are flanked by steep rocky hills, dissected at intervals by steep saddles. Cultivation is restricted to the valley floor, while steep valley sides are covered by Miombo woodland (Cowling et al., 1997). Rainfall usually occurs only in the summer months from October to April. The annual average rainfall is 591 mm (std dev 253 mm), based on a 45 year record at Chendebvu Dam (Mugabe et al., 2007), 12 km to the north of the catchment; the inter-annual variability for this period ranges from 83 mm to 1191 mm. The annual rainfall measured in the Romwe catchment over the period of the study was: 1993/1994, 538 mm; 1994/1995, 501 mm; 1995/1996, 866 mm; 1996/1997, 719; 1997/1998, 673 mm.

The Romwe catchment is located in an area of strongly-banded granulite gneiss (Bromley et al., 1999). The gneissic foliation dominates the trend of the topography in the catchment (Figs. 1 and 2). The gneisses range from dark-coloured pyroxene gneisses to light-coloured quartzo-feldspathic granulites. Between these extremes of composition is a wide range that grades imperceptibly from one to the other. The various types are interbanded at scales from a few centimetres to several hundred metres, however, the north side of the low-lying cultivated areas of the catchment is dominated by melanocratic pyroxene gneisses, while leucocratic pyroxene gneisses banded together with subordinate amounts of quartzo-feldspathic gneiss are more common on the southern side (Bromley et al., 1999). The high ground within the catchment is primarily quartzo-feldspathic gneisses with subordinate pyroxene amphibolite and biotite gneisses although this also underlies some of the lower-lying cultivated areas in the south of the catchment. Within the leucocratic pyroxene gneisses, pyroxene is usually the dominant mafic mineral though occasionally amphiboles or biotite may be more abundant; these mafic minerals constitute up to 25% of the rock. Hypersthene is the dominant mafic mineral in the pyroxene gneisses, often forming up to 70% of the rock.

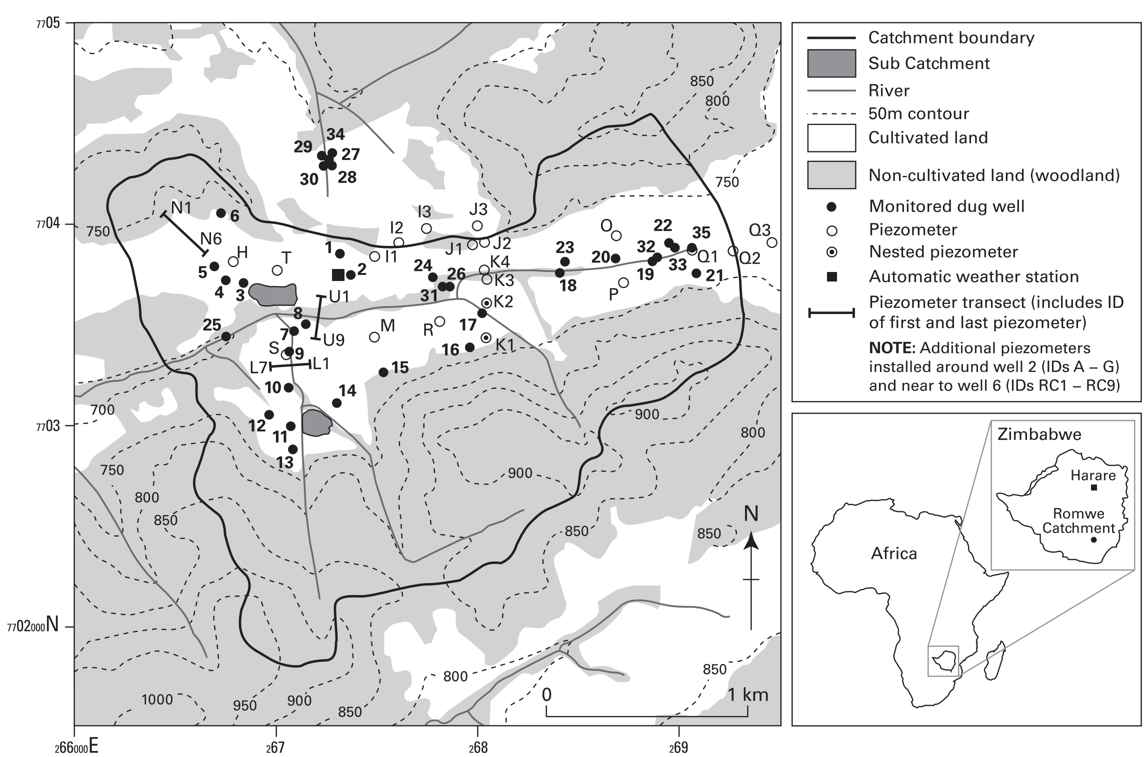

Fig. 1. Romwe catchment, topography, hydrology, land use and location of wells and piezometers. Coordinate system used is UTM grid, Zone 36K Modified Clarke 1880 (S.A.) Spheroid.