Case studies of groundwater – surface water interactions and scale relationships in small alluvial aquifers

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Abstract

An alluvial aquifer can be described as a groundwater system, generally unconfined, that is hosted in laterally discontinuous layers of gravel, sand, silt and clay, deposited by a river in a river channel, banks or flood plain. In semi-arid regions, streams that are associated with alluvial aquifers tend to vary from discharge water bodies in the dry season, to recharge water bodies during certain times of the rainy season or when there is flow in the river from managed reservoir releases. Although there is a considerable body of research on the interaction between surface water bodies and shallow aquifers, most of this focuses on systems with low temporal variability. In contrast, highly variable, intermittent rainfall patterns in semi-arid regions have the potential to impose high temporal variability on alluvial aquifers, especially for small ones. Small alluvial aquifers are here understood to refer to aquifers on rivers draining a meso-catchment (scale of approximately 10^1 – 10^3 km^2). Whilst these aquifers have lower potential storage than larger ones, they may be easier to access for poor rural communities – the smaller head difference between the riverbed and the bank can allow for cheap manual pumps. Thus, accessing small alluvial aquifers for irrigation represents a possibility for development for smallholder farmers. The aquifers can also provide water for livestock and domestic purposes. However, the speed of groundwater depletion after a rain event is often poorly understood. In this study, three small alluvial aquifers in the Limpopo Basin, Zimbabwe, were studied: (i) upper Bengu catchment, 8 km^2 catchment area on a tributary of the Thuli River, (ii) Mnyabeze 27 catchment, 22 km^2 catchment area on a tributary of the Thuli River, and (iii) upper Mushawe catchment, 350 km^2 catchment area on a tributary of the Mwenezi River. All three are ephemeral rivers. In each case, the hydrogeological properties of the aquifer were studied; the change in head in the aquifer was monitored over time, as well as any surface inflows. Results from each case are compared showing that scale imposes a lower limit on alluvial aquifer viability, with the shallowness of the Bengu aquifer (0.3 m) meaning it has effectively no storage potential. The much higher storage of the Mushawe aquifer, as well as the longer period of storage after a flow event, can be assigned partially to scale and partially to the geological setting.

Keywords: Alluvial aquifer, Groundwater – surface water interactions, Limpopo Basin, Scale

1. Introduction

An alluvial aquifer can be described as a groundwater unit, generally unconfined, that is hosted in horizontally discontinuous layers of sand, silt and clay, deposited by a river in a

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river channel, banks or flood plain. They are recharged either continuously if the river is fully perennial, or, more usually, annually (Barker and Molle, 2004). Because of their shallow depth and vicinity to the streambed, alluvial aquifers have an intimate relationship with stream flow. It can be argued that groundwater flow in alluvial aquifers is an extension of surface flow (Mansell and Hussey, 2005). Surface water bodies, or reaches thereof, can be classified as discharge water bodies if they receive a groundwater contribution to baseflow, or as recharge water bodies if they recharge a shallow aquifer below the streambed (Townley, 1998). In semi-arid regions, streams with alluvial aquifers tend to vary from discharge water bodies in the dry season, to recharge water bodies during the rainy season or under a managed release regime (Owen, 1991). Although there is a considerable body of research on the interaction between surface water bodies and shallow aquifers, most of this focuses on systems with low temporal variability. In contrast, intermittent rainfall patterns in semi-arid regions have the potential to impose high temporal variability on alluvial aquifers, especially small ones. For example, single high magnitude flows have been shown to have a greater influence on recharge than the more frequent, small to medium flows in the Kuiseb River in Namibia (Lange, 2005).

Small alluvial aquifers are here understood to refer to aquifers on rivers draining a meso-catchment (scale of approximately $10^1 – 10^3$ km^2; Blöschl and Sivapalan, 1995). Whilst these aquifers will have lower potential storage than larger ones – which are seen as good sources for irrigation water (Moyce *et al.*, 2006; Owen and Dahlin, 2005; Raju *et al.*, 2006) – small alluvial aquifers may be easier to access for poor rural communities – a smaller head difference between the riverbed and the bank can allow for cheaper or manual pumps. Thus accessing small alluvial aquifers for irrigation represents a possibility for development for smallholder farmers. However, little knowledge is available on the hydrogeological characteristics of small alluvial aquifers.

In this study, three small alluvial aquifers of different sizes in the Limpopo Basin, Zimbabwe are studied in order to establish (i) how much water can be stored in small aquifers of the three different scales, and (ii) for how long water is stored in the aquifer after the river ceases to flow at the three different scales.

2. Methods

2.1. Study Area

The alluvial aquifers of the Mzingwane Catchments are the most extensive of any tributaries in the Limpopo Basin (Görgens and Boroto, 1997). Alluvial deposits are present in the lower reaches of most of the larger rivers and some of the minor tributaries. They are narrow bands, typically less than 1 km in width on the largest rivers, too several metres on smaller river. The distribution of these aquifers is determined by the river gradient, geometry of channel, fluctuation of stream power as a function of decreasing discharge downstream due to evaporation and infiltration losses, and rates of sediment input due to erosion (Owen, 1991). Infiltration rates are fairly constant, due to the physical homogeneity of alluvium. An enhancement of the thickness and areal extent of alluvial aquifers is commonly observed associated with geological boundaries, and this enhancement occurs both upstream and downstream of the geological contact. Recharge of the alluvial aquifers is generally excellent and is derived principally from river flow. No river flow occurs until the channel aquifer is saturated and such full recharge normally occurs early in the rainy season (Owen and Dahlin, 2005). Three meso-catchments were selected for field study, at different spatial scales (figure 1 and table 1).

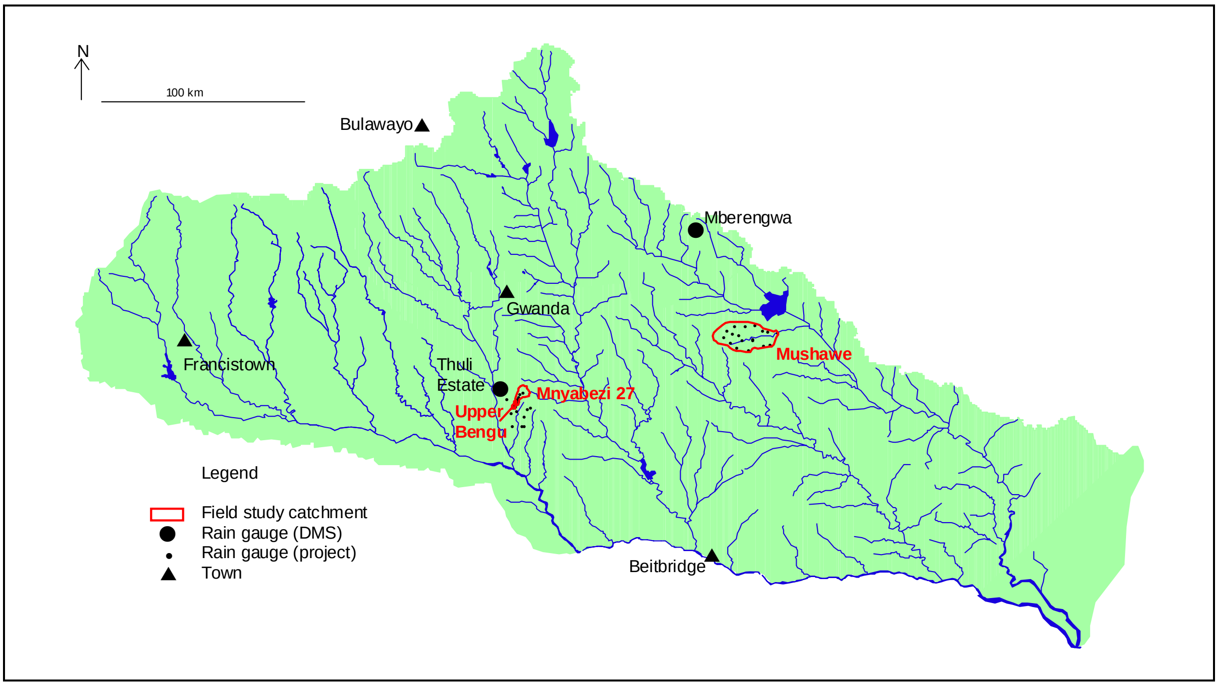

Figure 1. Location of rainfall stations and discharge stations used in this study. DMS = Department of Meteorological Services. Inset: location of study area within southern Africa (shaded).

Table 1. Characteristics of field study catchments.

Characteristic	Upper Bengu	Mnyabezi 27	Mushawe	Source
Catchment area (km^2)	7	22	350	Derived from 1:50,000 topographic mapping
Length of river (km)	4	8	35	Derived from 1:50,000 topographic mapping
Catchment geology	Weathered older gneisses	Weathered older gneisses	Granitoids: Limpopo Belt North Marginal Zone	Mineral Resources Centre, 2007; Field observations
Geological age (Ga)	2.90	2.90	2.72-2.52	Mineral Resources Centre, 2007
Land use	Rangeland 60% Fields 40 %	Rangeland 95% Fields 5 %	Rangeland 60% Fields 30 % Bare rock 10 %	Derived from 1:50,000 topographic mapping, ground-truthed with field observations
Mean annual rainfall, 1987-2000 (mm/a)	445	445	472	Own analyses; data from Department of Meteorological Services
Reference rainfall station	Thuli Estate	Thuli Estate	Mberengwa	Department of Meteorological Services

2.2. Data Collection

The channel width and slope were surveyed in the field and the depth of sand determined by physical probing with a steel probe (Mansell and Hussey, 2005). Composite samples of alluvial material were collected from each aquifer.

Porosity was determined from the volume of water retained by a 500 ml beaker of alluvial material and specific yield was derived from porosity. Potential storage was calculated for a unit length of river from the river cross-section and specific yield. Wipplinger (1958) and Nord (1985) have shown that evaporation following saturation dries generally to 0.9 m below the aquifer surface. This datum was used to determine the potential storage below the evaporation line.

Hydraulic conductivity was determined for the Mnyabezi 27 alluvial aquifer using two methods: (i) Slug test, using a 1.00 m long and 0.07 m diameter slotted and closed PVC pipe which was driven into the aquifer 0.165 m and filled with water. The time taken for the water level in the PVC pipe to attain the initial water level (of the alluvial aquifer) was recorded and the hydraulic conductivity computed. (ii) Permeameter test, using a 60 dm^3 bucket with a 25 mm outlet, which was completely filled with alluvial material and a constant head maintained by continuous inflow. The time taken to fill a 5 dm^3 bucket was recorded and the hydraulic conductivity computed (De Hamer, 2007). A grain size analysis was carried out on alluvial material from each site and the similarity in results suggests that the three sites have similar hydraulic conductivities (Shephard, 1989).

Piezometers, driven to bedrock, were placed in the alluvial aquifers at Mnyabezi 27 and Mushawe. Piezometers were not installed at Bengu, since water level monitoring was carried out on a daily time step and the Bengu aquifer dried up in less than 24 hrs.

3. Results and discussion

The main hydrogeological parameters determined are shown in Table 2. The potential storage increases in proportion to the cross-sectional area of the aquifer. However, the two shallower aquifers have no storage below the evaporation line of 0.9 m depth.

Table 2. Characteristics of field study aquifers.

Parameter	**Upper Bengu**	**Mnyabezi 27**	**Mushawe**
Average width of channel	4 m	10 m	50 m
Average channel slope	0.25 %	0.28 %	0.17 %
Average depth of sand	0.30 m	0.90 m	2.23 m
Average porosity		0.33	
Specific yield		0.27	
Potential storage per 100 m length of river	32 m^3	243 m^3	3,010 m^3
Potential storage below the evaporation line per 100 m length of river	0 m^3	0 m^3	1.796 m^3
Hydraulic conductivity (slug test)		61.3 m day^{-1}	
Hydraulic conductivity (permeameter test)		62.8 m day^{-1}	

The Upper Bengu aquifer dried out within 24 hrs and the Mnyabezi 27 aquifer within 17 days of a flow event (figure 2). However, the Mushawe aquifer had not dried out more than a month after the last flow event of the rainy season.

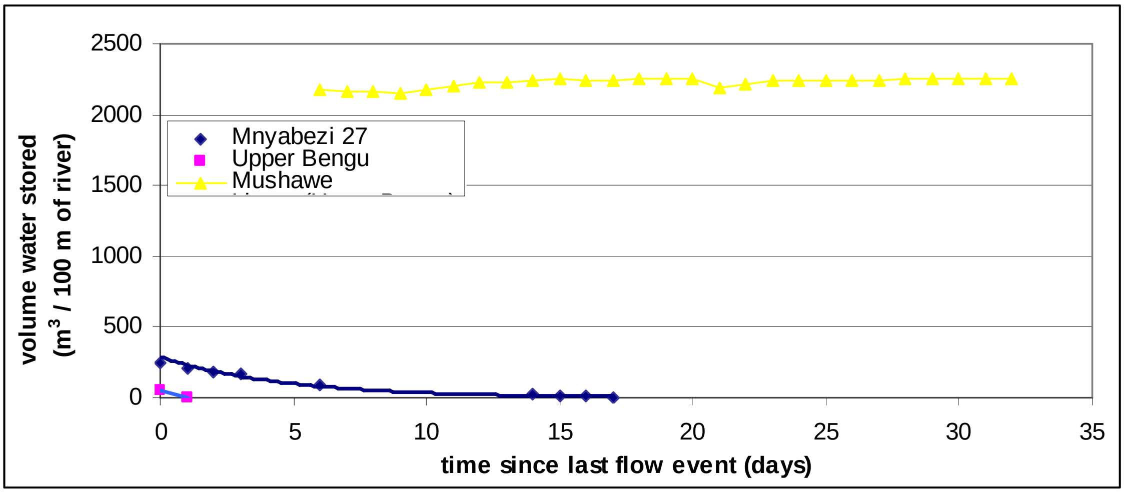

Figure 2. Drying curves for the three alluvial aquifers studied.

4. Conclusions

Comparison of the Bengu and Mnyabezi 27 aquifers shows that scale imposes a lower limit on alluvial aquifer viability. The shallowness of the Bengu aquifer (0.3 m) means it has effectively no storage potential. The deeper Mnyabezi 27 aquifer (0.9 m) can store water for slightly over two weeks.

The much higher storage of the Mushawe aquifer, as well as the longer period of storage after a flow event, can be assigned partially to scale and partially to the geological setting. (i) With a depth of over 2 m, the Mushawe aquifer has over half of its depth below the evaporation line, decreasing losses substantially when compared to the shallower aquifers. (ii) The Mushawe aquifer sits on younger and less weathered rock (Table 1). This reduces seepage losses.

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References

Barker, R. and Molle, F. 2004. Evolution of irrigation in South and Southeast Asia. *Comprehensive Assessment Research Report* **4**, International Water Management Institute, Colombo, 39p.

Blöschl, G., and Sivapalan, M. 1995. Scale issues in hydrological modelling: a review. *Hydrological Processes*, **9**, 251-290.

De Hamer, W. 2007. *Potential Water Supply of the Mnyabezi Catchment: A case study of a small reservoir and alluvial aquifer system in the arid region of southern Zimbabwe.* MSc dissertation (unpublished), Department of Water Engineering and Management , University of Twente.

Görgens, A.H.M. and Boroto, R.A. 1997. Limpopo River: flow balance anomalies, surprises and implications for integrated water resources management. In: *Proceedings of the 8th South African National Hydrology Symposium*, Pretoria, South Africa.

Lange, J. 2005. Dynamics of transmission losses in a large arid stream channel. *Journal of Hydrology*, **306**, 112–126.

Love, D., Moyce, W. and Ravengai, S. 2006. Livelihood challenges posed by water quality in the Mzingwane and Thuli river catchments, Zimbabwe. 7th WaterNet/WARFSA/GWP-SA Symposium, Lilongwe, Malawi, November 2006.

Mansell, M.G. and Hussey, S.W. 2005. An investigation of flows and losses within the alluvial sands of ephemeral rivers in Zimbabwe. *Journal of Hydrology*, **314**, 192-203.

Mineral Resources Centre. 2007. Geology of the Limpopo River Basin. *WaterNet Challenge Program PN17 Activity Report* **7** (draft).

Moyce, W., Mangeya, P., Owen, R. and Love, D. 2006. Alluvial aquifers in the Mzingwane Catchment: their distribution, properties, current usage and potential expansion. *Physics and Chemistry of the Earth*, **31**, 988-994.

Nord, M. 1985. *Sand Rivers of Botswana, Results from phase 2 of the Sand Rivers Project*. Unpublished report, Department of Water Affairs, Government of Botswana, Gaborone.

Owen, R.J.S. 1991. *Water Resources for Small-Scale Irrigation from Shallow Alluvial Aquifers in the Communal Lands of Zimbabwe*. M.Phil. thesis (unpublished), Department of Civil Engineering, University of Zimbabwe.

Owen, R. and Dahlin T. 2005. Alluvial aquifers at geological boundaries: geophysical investigations and groundwater resources. In: Bocanegra E, Hernandez M. and Usunoff E. (Eds.) *Groundwater and Human Development*, AA Balkema Publishers, Rotterdam, pp233-246.

Raju, N.J., Reddy, T.V.K. and Munirathnam, P. 2006. Subsurface dams to harvest rainwater – a case study of the Swaranamukhi River basin, southern India. *Hydrogeology Journal*, **14**, 526-531.

Shephard, R.G. 1989. Geology and ground water in Door Country, Wisconsin, with emphasis on contamination potential in the Silurian dolomite. *United States Geological Survey Water Supply Paper* **2047**.

Surveyor General of Zimbabwe and Forestry Commission, 1996. 1:250,000 Vegetation Map Series. Surveyor General of Zimbabwe, Harare.

Townley, L.R. 1998. Shallow groundwater systems. In: Dillon, P. and Simmers, I. (Eds.) *International Contributions to Hydrogeology 18: Shallow Groundwater Systems*. Balkema, Rotterdam, pp3-12.

Wipplinger, O. 1958. Storage of Water in Sand. South West Africa [Namibia] Administration Water Affairs Branch, Windhoek, Namibia.