



LUND UNIVERSITY

Alluvial aquifers at geological boundaries: geophysical investigations and groundwater resources

Owen, Richard; Dahlin, Torleif

Published in:
Groundwater and human development

2005

[Link to publication](#)

Citation for published version (APA):

Owen, R., & Dahlin, T. (2005). Alluvial aquifers at geological boundaries: geophysical investigations and groundwater resources. In E. Bocanegra, M. Hernandez, & E. Usunoff (Eds.), *Groundwater and human development* (pp. 233-246). Balkema.

Total number of authors:

2

General rights

Unless other specific re-use rights are stated the following general rights apply:
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

CHAPTER 19

Alluvial aquifers at geological boundaries: Geophysical investigations and groundwater resources

R Owen

Department of Geology, University of Zimbabwe, Box MP 167, Mount Pleasant, Zimbabwe

T Dahlin

Department of Engineering Geology, Lund University, Box 118, S221-00, Lund, Sweden

ABSTRACT: Alluvial channel sands in active ephemeral streams are potentially highly productive aquifers that are normally fully recharged annually. The groundwater resource is constrained by the limited three-dimensional extent of these aquifers. Concepts are developed that propose an increase in alluvial aquifer dimensions at geological boundaries. Multi-electrode resistivity and ground penetrating radar are used to investigate the dimensions of an alluvial channel at a geological boundary with the more resistant lithology upstream. These investigations reveal that alluvial channel fill dimensions are increased in the overlying less-resistant lithology downstream of the boundary. Groundwater flow modelling has been used to determine aquifer potential and identify key fluxes, indicating that significant irrigation potential exists from these aquifers.

INTRODUCTION

Alluvial aquifers are widely used in the semi-arid regions of southern Africa, both for primary water supply and for irrigation development (Thomas & Hyde, 1972; Wikner, 1980; Nord, 1985; Owen & Rydzewski, 1991). These aquifers occur in the channels of active ephemeral rivers, sometimes called 'sand rivers' since they appear as dry sandy river beds during the dry season after river flow has ceased. Significant commercial irrigation development has taken place from the alluvial sediments of the Umzingwane, Runde and Limpopo rivers in southern Zimbabwe. This irrigated production coexists side by side and in contrast with low productivity dry land farming as practised by the local communal farmers. At Mazunga ranch on the River Umzingwane, an 800 ha block of commercial irrigation is developed by means of a suction lift well point system driven into alluvial channel sands upstream from a geological contact between resistant silicified sandstone downstream and less competent basalt upstream (Ekström et al., 1996). The neighbouring communal farmers live alongside the same river in abject poverty, practising dry land cultivation to try and provide for their basic food requirements.

This research has been carried out to determine whether there exists sufficient groundwater within this and other similar alluvial systems to provide for irrigation development capable of supporting the basic needs and improving the livelihoods of the communal farmers in these areas.

The key factors that govern the magnitude of exploitable groundwater resources in such alluvial aquifers in southern Africa have been identified and are listed below.

- In semi-arid climates, alluvial aquifers are totally recharged annually due to indirect recharge through river bed infiltration and may therefore be fully exploited on an annual basis. It has been shown that river flow only occurs after the aquifer channel sands have become fully saturated (Nord, 1985; Halcrow, 1982). Rivers are essentially natural rainwater harvesting systems, collecting run-off from large catchment areas and channelling this into narrow bounded river channels. The investigated site on the River Umzingwane has an upstream catchment of approximately 18,000 km².
- Aquifer dimensions are determined by the extent and thickness of the alluvial fill in the river channel and under the lateral alluvial plains, where these are developed. In general, alluvial aquifer dimensions are of the order of a few tens to a few hundreds of meters in width and a few to a few tens of meters in thickness, developed along the length of the alluvial channel, resulting in a long thin ribbon like aquifer. The geometrical extent of the saturated alluvial fill is a key limiting factor.
- The alluvial aquifer channel sediments are generally clean washed sands that have excellent hydraulic and storage characteristics, allowing for high well pumping rates. Hydraulic conductivity values ranging from 100–250 m/day and specific yield values ranging from 10–35 per cent have been recorded in Botswana and Zimbabwe (Nord, 1985; Owen, 1994).
- The flow through the channel sediments from upstream and downstream into the well field abstraction zone is identified as a critical factor controlling the productivity of the well field.
- Complete annual recharge ensures generally good fresh water quality.

Based on the foregoing, it can be seen that the three-dimensional extent of the saturated aquifer represents a key constraint for the development of groundwater resources from alluvial systems of this type. Localities where the alluvial fill dimensions have been naturally enhanced represent suitable sites for the optimum development of the groundwater resource in these aquifers. The geological map of Zimbabwe (1:1,000,000) shows that alluvial deposits tend to occur preferentially at geological boundaries (Owen, 1994). Knowledge of the bedrock geology and an understanding of the processes of alluvial deposition are helpful for determining localities with potentially enhanced alluvial aquifer dimensions. Such localities may host groundwater resources capable of supporting large-scale water development such as is required for commercial irrigation.

This paper focuses on the geometry of the alluvial fill at a geological boundary and models the groundwater resource potential of the associated alluvial aquifer. The data presented comes from a case study on the River Umzingwane in southern Zimbabwe (Figure 1).

DEVELOPMENT OF ALLUVIAL AQUIFER FILL AT A GEOLOGICAL BOUNDARY

Alluvial aquifer fill is deposited during periods of aggradation, due to a change in river flow regime or an increase in sediment supply to the stream (Richards, 1982). The alluvial sediments cover and fill the pre-existing river bed topography, normally giving rise to a planar gently sloping sand bed.

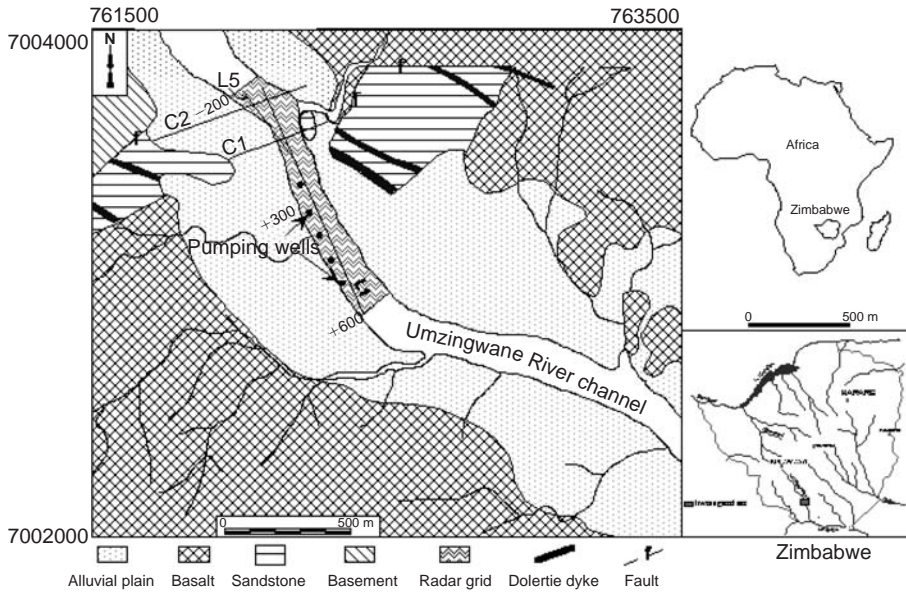


Figure 1. Geological map of the Umzingwane River site at Bwaemura. The positions of the resistivity profiles C1, C2, L1 and L5, and the area covered by the radar grid are shown.

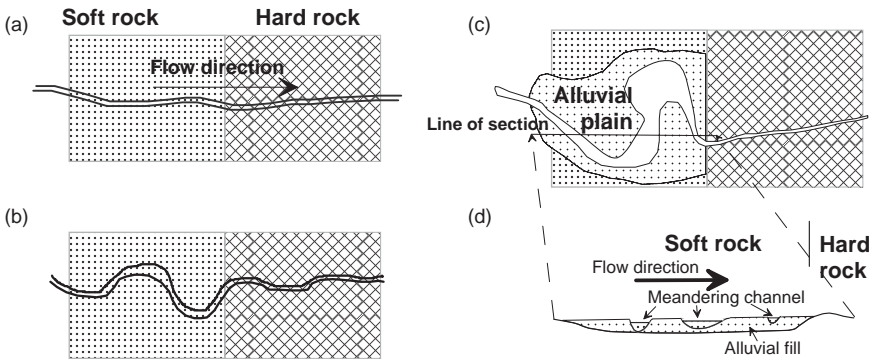


Figure 2. Alluvial development: resistant lithology downstream. Plan view: a) River channel cuts a narrow gorge through the hard rock downstream of boundary. b) Meanders develop upstream of boundary due to barrier effect of resistant downstream rock combined with erodibility of upstream soft rock. c) Meandering upstream of contact produces wide shallow alluvial valley, which is filled with alluvial sediments during periods of aggradation. Cross-sectional view: d) Channel meanders cut the shallow alluvial fill in the alluvial plain.

It is proposed that alluvial fill is augmented, in width and in thickness, at geological contacts. The effect of geological boundaries on the geometry and position of the alluvial fill depends on whether the resistant lithology occurs upstream or downstream. In the case with a downstream resistant rock barrier, a shallow meandering river channel occurs upstream of the geological boundary. A subsequent period of alluvial accumulation will give rise to a shallow laterally extensive alluvial fill, consisting of both channel and alluvial plain fill materials, as shown in Figure 2.

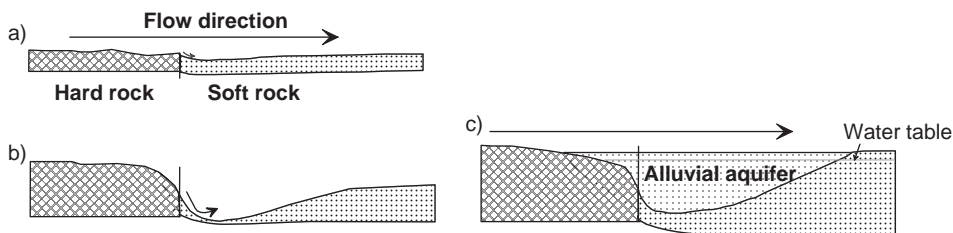


Figure 3. Alluvial development: less-resistant lithology downstream. Cross-sectional view: a) Flow over the boundary results in differential erosion; a small depression forms in the softer rock. Subsequent flow causes eddy currents, which scour out the softer rock. b) Further scour results in the development of a waterfall. c) Flow recession after flooding can result in alluvial aggradation, which fills up the channel, giving rise to an increased alluvial fill thickness downstream of the boundary.

In the case with the more resistant geology located upstream, a waterfall is commonly developed by scour of the more easily eroded downstream lithology. If there is a subsequent period of alluvial aggradation, the waterfall and associated downstream plunge pool are buried, thus becoming the locus of enhanced alluvial fill thickness as shown in Figure 3.

Such conceptual models, which illustrate the deposition and accumulation of alluvial fill material, may be used as a guide for locating sites in sand rivers where greater volumes of alluvial fill can be expected to occur. In this study, only one alluvial aquifer site is investigated. This site has the more resistant geology upstream and a significant increase in the saturated thickness of the alluvial fill downstream of the geological boundary was anticipated.

These 'buried waterfall'-type sites are considered to be more favourable for groundwater development than the laterally extensive sites, due to greater saturated thickness of the alluvial fill, increased available drawdown for wells and reduced water losses to evaporation.

RIVER UMZINGWANE ALLUVIAL AQUIFER

The alluvial fill at a geological boundary (Figure 1) along the River Umzingwane in southern Zimbabwe was investigated using multi-electrode resistivity and ground penetrating radar, in order to obtain information on the bedrock profile and on the dimensions of the alluvial fill. There are two boundaries in close proximity along the river channel at the selected locality. Gneiss occurs in the northern upstream reach of the channel in faulted contact with the downstream Karoo sandstone, which is heavily silicified within the fault zone. The sandstone dips gently to the south and is overlaid by Karoo basalt downstream. Although the basalt normally overlies the sandstone conformably, the contact between the two at this locality has been mapped as an inferred fault.

Based on outcrop evidence at this locality, it is suggested that the gneiss and silicified sandstone in the fault zone are more resistant to erosion and weathering than the sandstone downstream, which in turn appears marginally more resistant than the downstream basalt. With regard to the concepts of alluvial fill development proposed in the previous section, both boundaries have weaker rock downstream, and deeper alluvial sections may

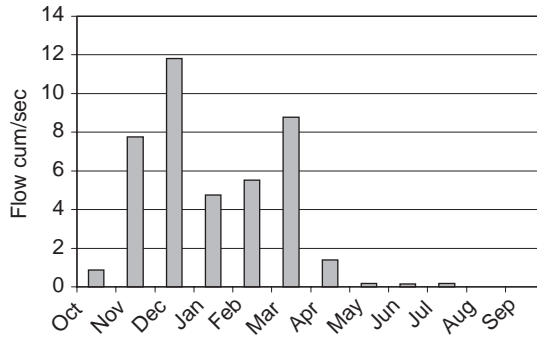


Figure 4. Mean monthly river flow records for Kwalu gauging station, Umzingwane River – average of 7 years of available flow records.

be expected to occur at and just downstream of these boundaries. However, the major contrast in competence is between the upstream gneiss/silicified sandstone fault zone and the downstream sandstone, and a more significant enhancement of the alluvial fill was expected just downstream of this boundary.

For the alluvial channel sands, aquifer parameter values for hydraulic conductivity, specific yield and porosity were measured using a constant head permeameter and by laboratory gravimetric measurements respectively. Based on these measured values and values obtained from other alluvial channels in the region (Nord, 1985; Owen, 1994), average hydraulic parameter values have been assigned to the alluvial channel sediments as follows: hydraulic conductivity: 200 m/day; specific yield: 20 per cent; and porosity: 35 per cent.

As indicated previously, recharge to semi-arid alluvial aquifers is completely dominated by river flow. A gauging weir exists 7 km downstream from the investigated aquifer and the flow data indicate that there is river flow greater than 1 m³/sec for 6–7 months each year (Figure 4). It can therefore be assumed that the aquifer is fully saturated for this period, provided that abstraction rates from the aquifer are less than the measured river flow. Depletion of the alluvial groundwater resource only begins to occur once river flow has ceased (Nord, 1985; Halcrow, 1982).

GEOPHYSICAL INVESTIGATIONS

Initially, electrical resistivity profiling was used to determine the subsurface structure at the study site. The field data were collected by Ekström et al. (1996) as continuous vertical electrical soundings (CVES) using the ABEM Lund Imaging System (Dahlin, 1996) with the Wenner array selected in order to depict the anticipated horizontal nature of the alluvium/bedrock boundary. Protocol files with ten different electrode spacings in the range 5–120 m were used to provide a compromise between time required for field data acquisition, depth penetration and resolution of the shallow subsurface environment. The resulting apparent resistivity sections were processed by means of inverse numerical modelling to provide estimates of the true resistivity distribution, using the software Res2dinv (Loke, 1999).

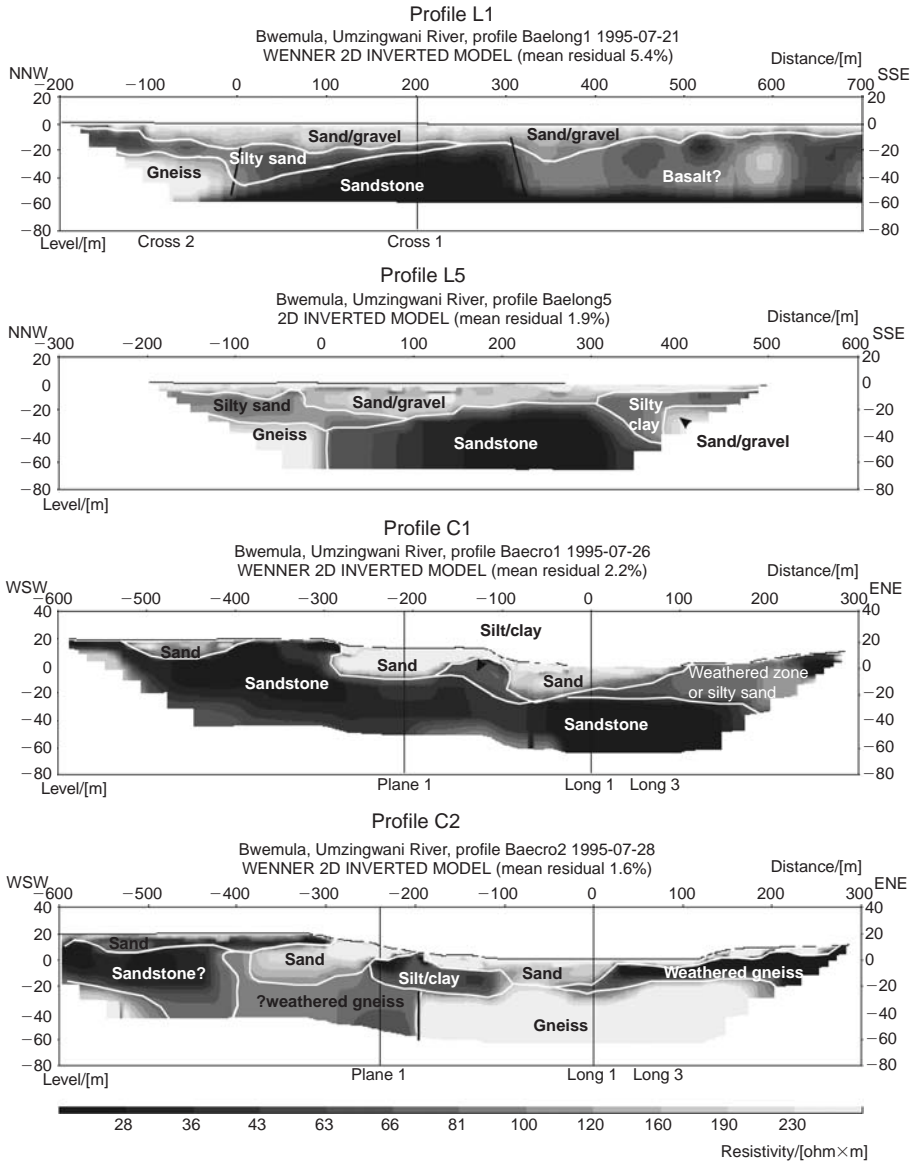


Figure 5. Multi-electrode resistivity profiles across the contact zones. L1 and L5 are profiles along the river and C1 and C2 are profiles across the river. Alluvial channel fill has a high resistivity signature and this helps to distinguish it from the other earth materials in the section. The interpreted geology is marked on to the sections.

Four of the measured CVES profiles have been selected to illustrate the effect of the observed geological boundaries on the geometry of the alluvial fill (Figure 5). Profiles L1 and L5 were measured along the length of the channel from north-west to south-east and positioned so as to intersect the geological boundaries, while profiles C1 and C2 were measured across the channel and extended to cover the full width of the lateral alluvial

plains (Figure 1). Figure 5 shows the inverted electrical resistivity sections of all these profiles with the interpreted geology marked directly on to the images.

The alluvial channel fill has a high resistivity signature and this makes it relatively easy to distinguish from underlying bedrock, except where the bedrock is fresh gneiss, which is also highly resistive. Profile L1 shows an increase in alluvial fill thickness between 0–150 m, in the vicinity of the gneiss/sandstone boundary, and again at 300–400 m, at the sandstone/basalt boundary. Profile L5 shows a similar pattern, but the thickening of the alluvial fill downstream of the gneiss/sandstone boundary at 0 m is less striking. Profiles C1 and C2 cross the channel and clearly show the presence of a paleo-channel at a higher elevation and to the west of the active channel.

The maximum thickness of alluvium occurs at the gneiss/sandstone contact (0 m on L1), where the alluvium appears to attain a thickness up to 40 m. The thickness of the alluvial fill declines in a downstream direction moving away from the geological boundary until it remains only as a thin (~5 m) surficial layer.

In addition to the resistivity profiles, Beckman and Liberg (1997) carried out a ground penetrating radar survey across the geological boundary area. A radar grid was surveyed within the active river channel where good penetration was expected. The grid extends across the full channel width and along the same length of channel as the resistivity line L1 (Figure 1). It consists of eight parallel lines 25 m apart, aligned along the channel and nine parallel lines across the channel approximately 100 m apart. The radar grid was not extended on to the alluvial plains due to poor access as a result of the dense riverine vegetation in these areas. In addition, there was concern that radar signals would suffer from severe attenuation in silts and clays that can be expected as over-bank deposits on alluvial plains.

The data were collected with a Malå Geoscience RAMAC/GPR, using antennas with a centre frequency of 50 MHz. The distance between each trace was 20 cm. The radar results were plotted as standard radargrams, where the depth axis shows reflection time. True depths were estimated from WARR (wide angle refraction and reflection) measurements at four selected points. The primary reflector was digitized from the radargrams and the digitized depths merged into a three-dimensional depth map (Figure 6), which has the same grid coordinates as the resistivity profiles (Figure 5).

The three-dimensional radar image (Figure 6) shows a reflector underlying the alluvial channel sediments, which is interpreted as bedrock beneath the alluvial fill. The maximum depth of penetration attained by the radar survey was 16 m and the reflector is lost as the bedrock depth increases towards the western side of the channel. There is no bedrock reflector on the western edge of the alluvial channel (Figure 6), suggesting that a paleo-channel extends beyond the western edge of the active channel, an interpretation that is corroborated by resistivity profiles C1 and C2 (Figure 5).

The lateral extent of this buried paleo-channel can be estimated from the vegetation signature on the alluvial plains (Figure 6). Aerial images show a strongly bimodal vegetation signature along the banks of the river, consisting of a belt of lush thick vegetation with large riverine trees such as *Acacia galpinii* and fig species such as *Ficus sycomorus* occurring closer to the channel, and a more sparse open woodland with smaller non-riverine trees occurring further away from the channel. The lush vegetation signature on the alluvial plain is indicative of the availability of a perennial water supply to the root zone and is interpreted as saturated alluvial fill in the buried paleo-channel, which is in hydraulic contact with and is recharged from the active river channel.

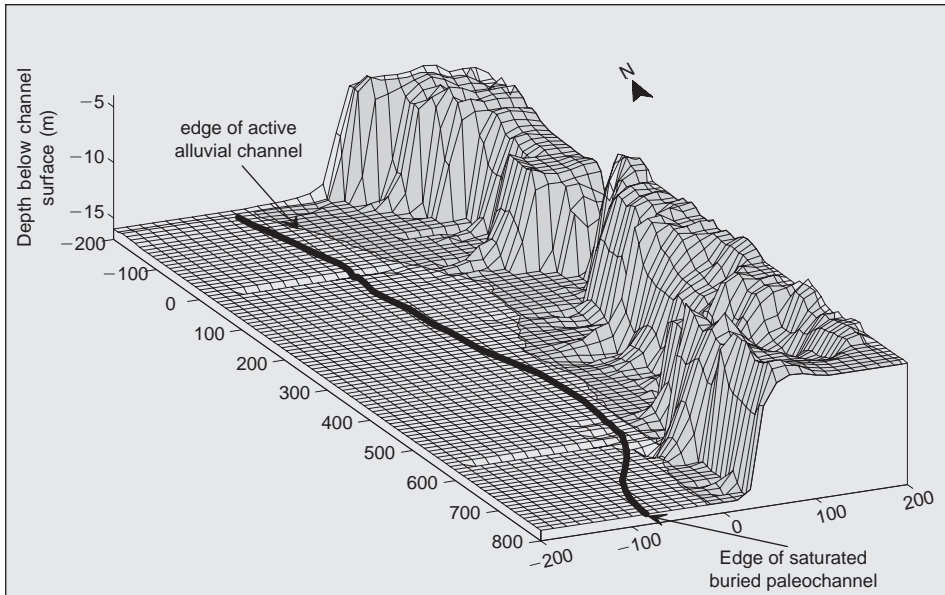


Figure 6. Three-dimensional radar image of the Umzingwane River channel. The image shows the bedrock surface beneath the alluvial channel. The riverbed surface is at 0 m on the vertical scale in the figure. The maximum penetration depth attained was 16 m, which is insufficient to locate bedrock in the western portion of the channel. The edge of the saturated alluvial fill to the west (solid dark line) has been identified from the riverine vegetation signature on satellite images. The position of the grey radar grid is shown in Figure 1.

EFFECT OF GEOLOGICAL BOUNDARIES ON ALLUVIAL FILL DIMENSIONS

The site geological map (Figure 1) indicates that there has been dextral displacement of the gneiss/sandstone boundary beneath the alluvial fill in the Umzingwane valley. As a result of this displacement, it is difficult to determine from the map the exact position of the geological boundaries where they are obscured by the alluvial cover. The radar grid (Figure 6) has been divided into two equal sections: the northern section from -200 m to $+300$ m and the southern section from $+300$ m to $+800$ m. The map (Figure 1) shows that the northern radar section extends across the gneiss/sandstone boundary. However, due to this dextral displacement, the position of the sandstone/basalt boundary beneath the alluvial channel cover is not clear from the map, but the resistivity sections L1 and L5 indicate that this boundary occurs at approximately $+300$ m. The southern section of the radar grid from $+300$ to $+800$ m therefore does not cross any geological boundary, but has a low competence contrast geological boundary at the start of the section.

The three-dimensional radar image (Figure 6) shows that the alluvial fill dimensions are both wider and deeper in the northern portion of the channel, as compared to the southern channel section, which is largely filled with bedrock. The relative dimensions of the alluvial fill have been estimated from the radar image. If the bedrock reflector persists westwards at 16 m depth to the edge of the buried paleo-channel (Figure 6), then the upstream northern section comprises 65 per cent and the downstream southern section 35 per cent of the aquifer. If the bedrock reflector were to rise to the surface just

at the edge of the active channel, then the upstream sector would comprise 64 per cent and the downstream sector 36 per cent of the aquifer. These values support the proposal (Figures 2 and 3) that alluvial fill volumes are significantly increased at geological boundaries.

GROUNDWATER MODEL

Groundwater flow modelling has been used as a guide for determining the various fluxes into and out of the model domain, and the optimum pumping rate and well field spacing for an alluvial aquifer of the type described here.

The aquifer is modelled as a single layer, 200 m wide and 1000 m long and consists of 20 columns and 50 rows with uniform grid block dimensions of 10×20 m. The aquifer dimensions for the active channel are taken directly from the three-dimensional radar image (Figure 6). The saturated alluvial fill in the buried paleo-channel west of the active channel is not included in the model, since its lateral extent is only inferred from the vegetation signature on aerial images and its thickness is not known. The model therefore underestimates the groundwater resource in the aquifer, potentially by as much as 40 per cent, and the values derived from the modelling may be treated as the minimum aquifer potential for this section of river. The model design presumes no fluxes occur through the lower (alluvium/bedrock) boundary.

The assigned aquifer parameter values for hydraulic conductivity and storage are discussed in a preceding section. These values remain unchanged for all the modelled scenarios.

There are potentially major fluxes into and out of the model space through the river bed boundary and through the upstream and downstream boundaries. Recharge to the aquifer occurs mainly from river bed infiltration, which predominates over the direct rainfall recharge. This indirect recharge is modelled as a river boundary, with the water level elevation above the channel surface during periods of river flow. Once the river flow ceases during the dry season, the river boundary is turned off. Direct recharge is estimated at 10 per cent of average annual precipitation (55 mm) for all scenarios and occurs entirely during the period river flow.

This river boundary is a transient boundary covering the entire model surface, set with the river stage elevation 0.5 m above the channel surface for 180 days, and then turned off for the remainder of the year. To allow for water transfer from the river into the aquifer, a conductance value of $500 \text{ m}^2/\text{day}$ has been assigned to all cells in the river bed. The boundary and conductance values for all the modelled scenarios do not at all limit the required inflows during the period of river flow. Drawdown within the aquifer only occurs after the end of period of river flow and this is the critical stress period for the groundwater resource.

In addition to the flux through the river bed, water may also enter or leave the model through the upstream and downstream boundaries, which are designated as general head boundary cells. The flow through these boundary cells is controlled by the conductivity and saturated aquifer thickness in the boundary cells. Figure 6 shows that the western side of the aquifer has greater depth (15 m) of alluvial fill than the eastern side (5 m) and this is reflected in the assigned conductance values in the boundary cells on the west and east sides of the model, which are set at 1500 and $500 \text{ m}^2/\text{day}$ respectively.

Table 1. Assigned head/time and conductance values for general head boundaries.

Time start	Time end	Scenario 1 (Low head m)	Scenario 2 (Med head m)	Scenario 3 (High head m)	16 m thick (Cond m ² /d)	5 m thick (Cond m ² /d)
0	180	0	0	0	1500	500
180	210	-1	-0.5	-1	1500	500
210	240	-2	-1	-1	1500	500
240	280	-3	-1.5	-1	1500	500
280	320	-4	-2	-1	1500	500
320	365	-5	-2.5	-1	1500	500

The saturated thickness at the boundary cells will decline as a result of pumping, evaporation and other outflows from the aquifer. The actual saturated thickness is not known and to cover the possible range of boundary cell head values, four different scenarios have been modelled; zero flux with the general head boundary turned off, low flux with a small saturated thickness assigned to the boundary cells, moderate flux with a medium saturated thickness assigned to the boundary cells and high flux with the boundary cells fully saturated except for a dry top 1 m, which is annually lost to evaporation (Wipplinger, 1958). Transient boundary heads are assigned in all model scenarios and are set at river bed level during the period of river flow and decline with time during the period of no flow. For all assigned boundary head values, the model has been adjusted for maximum pumping discharge.

Table 1 shows the general head boundary input values for time, head and conductance for all the modelled scenarios. The first time period, 0–180 days, represents the period of river flow (Figure 4) and during this time period the head values at the boundary cells are set at 0 m, which is the river bed surface. Subsequently, the head values are lowered by equal increments of either 0.5 m or 1.0 m for each time period for the medium and low head scenarios respectively as shown in Table 1. The time periods are arbitrarily set at 40 days each, except for the two time periods immediately after the end of river flow (day 180–210 and day 210–240), which are set at 30 days each. The rationale for assigning shorter time interval per fixed drawdown in the 60 day period immediately after the end of river flow is that during this period head changes are subject to an additional outflow flux due to evaporation losses as well as the pumping and general head boundary fluxes, which persist throughout the hydrological year. For the high head case, only two time intervals have been used: the period of river flow with the head set at 0 m and the period of no river flow with the head set at -1.0 m.

Six pumping wells have been placed in the model (Figures 1 and 7) and the pumping rate from these wells has been increased incrementally to obtain the maximum discharge for each model scenario.

MODEL RESULTS

The model flow budget (Table 2) shows that during the period of river flow (day 1–180), inflow through the river bed boundary completely dominates the inflow water budget and provides water not only for the pumping wells, but also surplus water which flows out of the aquifer via the upstream and downstream general head boundaries. As the general

Table 2. Water Budget for alluvial aquifer models.

Scenario ↓ Flux boundary	Period of river flow (0–180 days)					Period of no river flow (180–365 days)				
	Inflow		Outflow			Inflow (average)		Outflow (average)		
	River	Rechg	Wells	G.h.b.	E.t.	Storage	G.h.b.	Wells	G.h.b.	E.t.
Zero flux	3267	55	2500	0	822	2500	0	2500	0	0
Low flux	10471	55	3500	6204	822	1154	2482	3500	71	64
Medium flux	13377	55	7500	5110	822	909	6628	7500	0	37
High flux	15870	55	10000	5103	822	28	9997	10000	0	25

Rechg = recharge, G.h.b = general head boundary and E.t. = evapotranspiration. The average values for the period of no river flow reflect the transient modelled head changes at the general head boundaries.

head boundaries are adjusted to allow for greater fluxes, pumping rates are increased and these increases are met by increased inflow through the riverbed boundary. For all scenarios with active general head boundaries, the outflow flux remains reasonably steady, which presumably is conditional on the number and position of pumping wells. The fact that these outflow fluxes are so similar suggests that the maximum pumping rate has been attained for these model scenarios. For the period of river flow, model convergence occurs readily.

The model period of no river flow (day 180–365) is less robust and in many cases well discharge had to be reduced in order to achieve model convergence.

The model indicates that the key outflow is to pumping wells and that this demand is balanced by a combination of inflow across the general head boundaries and water taken from storage within the modelled aquifer. As the boundary conditions are adjusted to allow for higher fluxes, so the quantity of water taken from storage declines, while the inflow across the boundaries increases. In the case with the high flux boundary, very little water is taken from storage and all the water required for pumping enters the aquifer through the general head boundaries. The values of the various fluxes for the different boundary conditions are summarized in Table 2. For the medium flux scenario at time 365 days, plan and cross-section views (Figure 7a) of the channel show water levels in the aquifer, dry cells and velocity vectors converging towards the wells. Drawdown levels within the aquifer range from 2–8 m and groundwater flows occur through the general head boundaries at the up and downstream ends of the modelled channel.

The zero flux boundary may be regarded as a special artificial case, where no water is allowed to enter the aquifer during the period of no river flow (day 180–365). The pumping rate has been increased incrementally until no further model convergence can be obtained. Since there is no inflow or outflow from the zero flux model, the model results provide information about the quantity of water that can be pumped from available storage in the model domain. The total volume pumped in the dry season is 462,500 m³, which is considered to be the maximum exploitable groundwater stored in a 1-km river reach, without any inflow, as may be the case in periods of extreme drought. Provided that the channel is fully saturated at the start, a maximum pumping rate of 2500 m³/day can be sustained for the entire dry season. For the zero flux scenario, Figure 7b illustrates plan and cross-section views at 365 days of the channel showing dry cells where the aquifer is thinner and drawdown of 9–11 m within the deeper aquifer zones. Comparing Figures 7a and b provides a view of the importance of the fluxes into

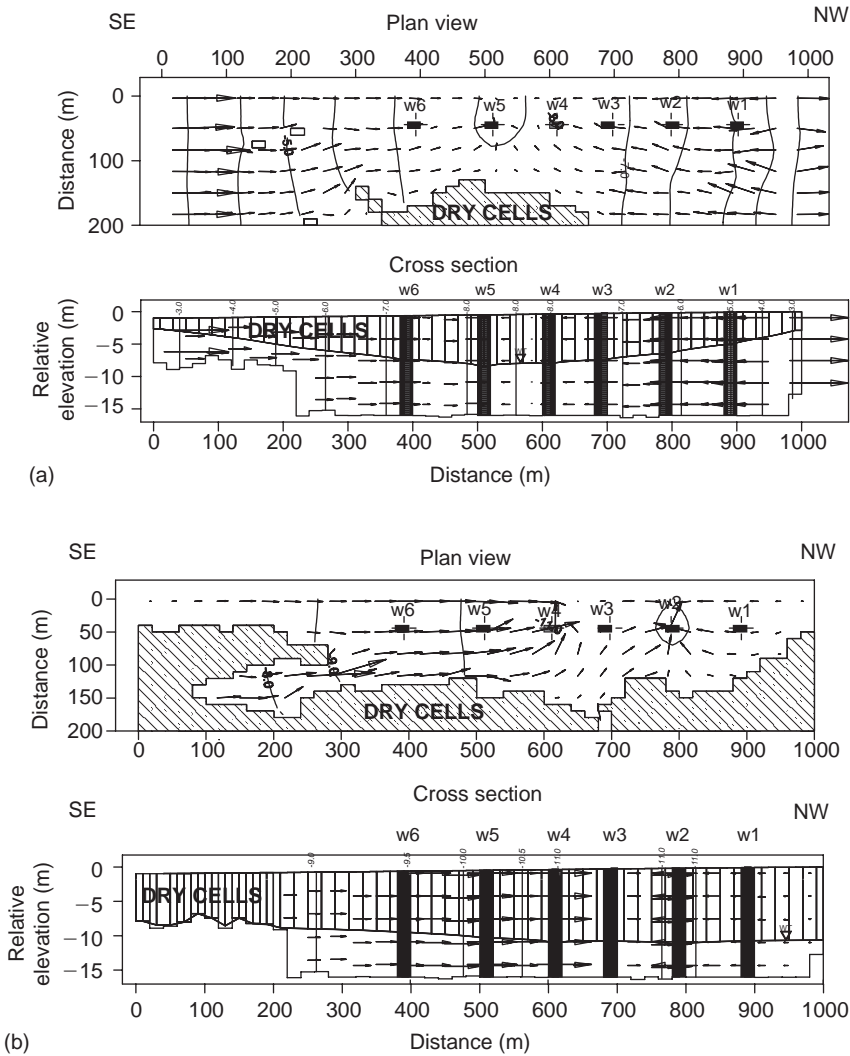


Figure 7. Plan and cross-section (column 5) views of aquifer showing location of pumping wells, water levels, dry cells and velocity vectors at 365 days for: a) intermediate drawdown medium flux general head boundary and b) zero flux boundary condition.

the aquifer through the general head boundaries. These inflows reduce the drawdown in the aquifer and allow for higher pumping rates. Such information may be used for optimization of the well field design.

IRRIGATION POTENTIAL OF ALLUVIAL AQUIFERS

If the average daily irrigation requirement is arbitrarily set at $50 \text{ m}^3/\text{day}/\text{ha}$, then a pumping rate of $2500 \text{ m}^3/\text{day}/\text{km}$ reach of river should be sufficient to irrigate 50 ha. If pumping rates are increased, this will deplete the water resource in the aquifer upstream

and downstream. Using six pumping wells a modelled pumping rate of 10,000 m³/day, sufficient to irrigate 200 ha, is sustainable for the 185-day period of no river flow and would deplete the water in storage from a 4-km river reach of the aquifer. Based on this, it is clear that the Umzingwane alluvial aquifer is highly under-utilized and that irrigation could be developed far more extensively from the alluvial sediments within the river channel.

CONCLUSIONS

A conceptual geological model that supports a significant increase in the geometrical extent of alluvial aquifers at geological boundaries is suggested. Geological maps and geological site investigations support this model. Geophysical surveying confirms increased thickness and lateral extent of alluvial channel sediments at faulted geological boundaries in the Umzingwane River in southern Zimbabwe. Such channel sediments constitute an excellent aquifer, which is generally fully recharged every year.

The employed geophysical techniques proved suitable for mapping the alluvial aquifer. Resistivity imaging gave valuable results inside the present-day stream channel as well as the flood plains and surrounding terrain. GPR only yielded useful results within the coarse channel sediments, with a maximum depth penetration of 16 m and depth penetration was reduced by clay or silt lenses. The geophysical results were used to delineate the three-dimensional geometric extent of the aquifer used for designing the groundwater model space. The geophysical data would provide excellent guidance for drilling.

The groundwater model indicates that the Umzingwane alluvial aquifer is under-utilized and that significant irrigation potential exists. These results are expected to be applicable to similar river channels, which could presumably provide irrigation water to alleviate both the risks and the low yields associated with dry land farming in similar semi-arid areas, both within Zimbabwe and elsewhere.

ACKNOWLEDGEMENTS

We wish to thank to Sida/SAREC for funding the research. We thank students Kristina Ekström, Camilla Prenning, Zodwa Dladla, Marianne Beckman and Maria Liberg for field data collection and Peter Ulriksen for input as supervisor for the GPR survey. Thanks to Tom Blenkinsop and Paul Dirks for review comments and to Julius Muzuva for help with the illustrations.

REFERENCES

- Beckman M and Liberg M. (1997) Ground Penetrating Radar Mapping of Shallow Aquifers in Zimbabwe. MSc thesis, Lund University, ISRN: LUTVDG/TVTG-5056-SE.
- Dahlin T. (1996) 2D resistivity surveying for environmental and engineering applications. *First Break*, 14 (7).
- Dahlin T and Owen R. (1998) Geophysical investigations of alluvial aquifers in Zimbabwe. *Proceedings of the 4th Meeting Environmental and Engineering Geophysics, Barcelona, Spain, 14–17 September, 1998.*

- Ekström K, Prenning C and Dladla Z. (1996) Geophysical Investigations of Alluvial Aquifers in Zimbabwe. MSc thesis, Lund University, ISRN: LUTVDG/TVTG-5035-SE.
- Halcrow, Sir William and Partners. (1982) North-west Somalia refugee water supply consultancy. Oxfam project report.
- Loke MH. (1999) *Res2dinv ver 3.4 for Windows 3.1, 95 and NT. Rapid 2-D resistivity & IP inversion using the least squares method.* Software manual, <http://www.abem.se>.
- Nord M. (1985) *Sand Rivers of Botswana, Phase 2.* Department of Water Affairs, Government of Botswana.
- Owen RJS. (1994) Water resources for small scale irrigation from shallow alluvial aquifers in the communal lands of Zimbabwe. MPhil thesis, Department of Civil Engineering, University of Zimbabwe.
- Owen RJS and Ryzewski JR. (1991) Shallow groundwater as a resource for small-scale irrigation development. In: *Techniques for Environmentally Sound Water Resources Development.* Wooldridge R. (ed.) Pentech Press.
- Richards K. (1982) *Rivers. Form and Process in Alluvial Channels.* Methuen, ISBN0416749003.
- Thomas EG and Hyde LW. (1972) Water storage in the sand rivers of eastern Botswana. Technical note 33, UNDP. Government of Botswana.
- Visual Modflow v 2.8.2, (2000) User's Manual, Waterloo Hydrogeologic Inc.
- Wikner T. (1980) *Sand Rivers of Botswana, Phase 1.* Department of Water Affairs, Government of Botswana.
- Wipplinger O. (1958) The Storage of Water in Sand. Water Affairs Branch. South West Africa Administration.