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Alluvial aquifers in the Mzingwane catchment: Their distribution, properties, current usage and potential expansion

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Abstract

The Mzingwane River is a sand filled channel, with extensive alluvial aquifers distributed along its banks and bed in the lower catchment. LandSat TM imagery was used to identify alluvial deposits for potential groundwater resources for irrigation development. On the false colour composite band 3, band 4 and band 5 (FCC 345) the alluvial deposits stand out as white and dense actively growing vegetation stands out as green making it possible to mark out the lateral extent of the saturated alluvial plain deposits using the riverine fringe and vegetation . The alluvial aquifers form ribbon shaped aquifers extending along the channel and reaching over 20 km in length in some localities and are enhanced at lithological boundaries. These alluvial aquifers extend laterally outside the active channel, and individual alluvial aquifers have been measured with area ranging from 45 ha to 723 ha in the channels and 75 ha to 2196 ha on the plains. The alluvial aquifers are more pronounced in the Lower Mzingwane, where the slopes are gentler and allow for more sediment accumulation. Estimated water resources potential ranges between 175,000 m^3 and 5,430,000 m^3 in the channels and between 80,000 m^3 and 6,920,000 m^3 in the plains. Such a water resource potential can support irrigation ranging from 18 ha to 543 ha for channels alluvial aquifers and 8 ha to 692 ha for plain alluvial aquifers. Currently, some of these aquifers are being used to provide water for domestic use, livestock watering and dip tanks, commercial irrigation and market gardening. The water quality of the aquifers in general is fairly good due to regular recharge and flushing out of the aquifers by annual river flows and floodwater. Water salinity was found to increase significantly in the end of the dry season, and this effect was more pronounced in water abstracted from wells on the alluvial plains. During drought years, recharge is expected to be less and if the drought is extended water levels in the aquifers may drop substantially, increasing salinity problems.

Keywords: Alluvial aquifer; Irrigated agriculture; Remote sensing; Limpopo basin

1. Introduction

1.1. Alluvial aquifers

Alluvial deposits are common in southern Zimbabwe, occurring as sand filled ephemeral rivers. The Mzingwane River is one such sand filled channel, with extensive alluvial aquifers distributed along its banks on the lower catchment and is the major northern (left bank) tributary to the Limpopo River in Zimbabwe, contributing around a quarter of the run-off in the Limpopo River (Gorgens and Boroto, 1997). These alluvial aquifers already sustain commercial citrus irrigation schemes, and are considered to have groundwater potential to support significant additional irrigation development, using infiltration galleries and well point systems to exploit the resource (Owen, 2000).

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

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due to evaporation and infiltration losses, and rates sediment input due to erosion (Richards, 1982). Alluvial deposits may be characterized by their position within the river valley, and occur as lateral accretion channel deposits, vertical accretion plains deposits, river terrace valley flat deposits and abandoned meander cut-off plain deposits (Owen, 1994). An enhancement of the thickness and area of alluvial aquifers is commonly observed associated with geological boundaries, and this enhancement occurs both upstream and downstream of the geological contact (Ekstrom et al., 1997; Beckman and Liberg, 1997). Such enhanced alluvial aquifers have been noted to have thickness of up to 20 m having a good water resource potential, e.g. Bwaemura Village aquifer has a potential capacity of 12,000 m^3/day, which could be used to develop 240 ha of irrigation (Owen, 2000). The lithologies on either sides of the geological contact will exhibit different degrees of resistance to fluvial erosion. The alluvium will accumulate over the less resistant lithology, regardless whether this lithology is upstream or downstream of the contact. However, the 3D geometry of the resultant alluvial deposits differ significantly dependant on which lithology is upstream and which is downstream (Owen, 2000).

The alluvial sediments have estimated hydraulic conductivity (K) values of between of 40 and 200 m/day based on the Hazen's (1911) method (the sand sieve analysis). Seepage losses have been noted to be insignificant and that the water will have moved 1.5 km downstream over a 300-day dry season (Nord, 1985). The evaporation losses from the channel sand decrease up to 1 m depth and then there is no further loss through evaporation. Yield ranges from 40 to 5200 m^3/day. The alluvial plain and channel deposits have specific yield values of between 5–7% and 15%, respectively (Owen, 1994; Nord, 1985; Wikner, 1980).

Recharge of the alluvial aquifers is generally excellent and is derived principally from river flow. Nord (1985) found that no river flow occurs until the channel aquifer is saturated and such full recharge normally occurs early in the rainy season. By contrast for lateral plains aquifers, recharge depends on the permeability of the aquifer, the distance from the channel and the duration of river flow (Owen, 1994). In Zimbabwe recharge is seasonal occurring in the rainy season (November–February) and aquifer losses due to evaporation, transpiration, vertical seepage losses to bedrock and downstream flows are all sources of aquifer losses during the dry season (April–October). Some alluvial aquifers may be recharged by dam releases during the dry season, such as the Zhove dam on the Mzingwane in southern Zimbabwe.

Evaporation losses from the channel sand beds are initially high, but decline as the water table declines to approximately 90 cm below the sand bed surface (Wipplinger, 1958). On the alluvial plains with finer grained soil, the evaporation extinction depth may be somewhat deeper, but it is transpiration from the thick lush forests that develop on the saturated alluvium under the riverine fringe that are likely to extract the most groundwater from the aquifers in the dry season.

The water quality is relatively good due to regular recharge and flushing out by flood waters and dam releases in the catchment (Owen, 1994; Owen, 2000). The salinity increases with distance from the channel and there is increase in salinity during the dry season mostly in the semi-arid parts of the catchment. Salinity has been noted to be a more general problem mostly in the plain deposits in the semi-arid areas of the area, which is the Lower Mzingwane (Moyo et al., 2005; Nare et al., 2005). Hoko (2005) reported conductivity levels of up to 9800 $\mu S\,cm^{-1}$ from shallow groundwater in Mwenezi district, immediately to the east of Lower Mzingwane.

Studies have shown that the groundwater in alluvial aquifers above granitic areas is of low salinity and that from basalts is of high salinity, e.g. conductivity of 520 $\mu\Omega\,cm^{-1}$ on granite compared to 1450 $\mu\Omega\,cm^{-1}$ on basalt, and sodium absorption ratio of 0.6 on granite compared to 2.3 on basalt (Owen, 1994).

In this paper, the distribution of alluvial aquifers in the Mzingwane Catchment will be identified and water resource potential calculated using data from the literature and satellite imagery identified alluvial aquifers extents. The current alluvial groundwater usage and possible irrigation potential will be analysed.

1.2. Study area

The Mzingwane Catchment is made up of the Mzingwane River and the Ncema, Inyakuni and Insiza tributaries (Fig. 1). The Mzingwane (Umzingwani) River rises near Bulawayo and flows south to the Limpopo, with Insiza as its major tributary. The Upper Mzingwane, Ncema, Inyakuni and Insiza Rivers are all dammed in the Esigodini area, and these dams supply the City of Bulawayo. The lower Insiza is dammed at Silalabuchwa and lower Mzingwane is dammed at Zhove, near Mazunga (Fig. 1). Generally, rainfall in the catchment is erratic and decreases from the north to the south, with annual rainfall at Esigodini ranging from 1200 to 200 mm over the last 70 years, and at Beitbridge from 500 to 50 mm for the same period. The land use in the Upper Mzingwane catchment is mainly commercial farming, private and resettlement land, while the Lower Mzingwane is mainly communal lands. The main settlements are Gwanda Town and Esibomvu, Esigodini, West Nicholson and Colleen Bawn. Commercial irrigated agriculture is a major water user in areas north of Gwanda, while in the southern parts of the catchment agriculture is mostly subsistence farming in the poverty stricken communal lands and extensive livestock management in the commercial areas (ZSG, 1998).

The northern half of the Mzingwane Catchment is underlain by crystalline granitic and gneissic rocks, with mineralised greenstone belts (Bulawayo, Gwanda and Filabusi Greenstone Belts) and intruded by various dolerite dykes and sills (Zimbabwe Geological Survey, 1994 and

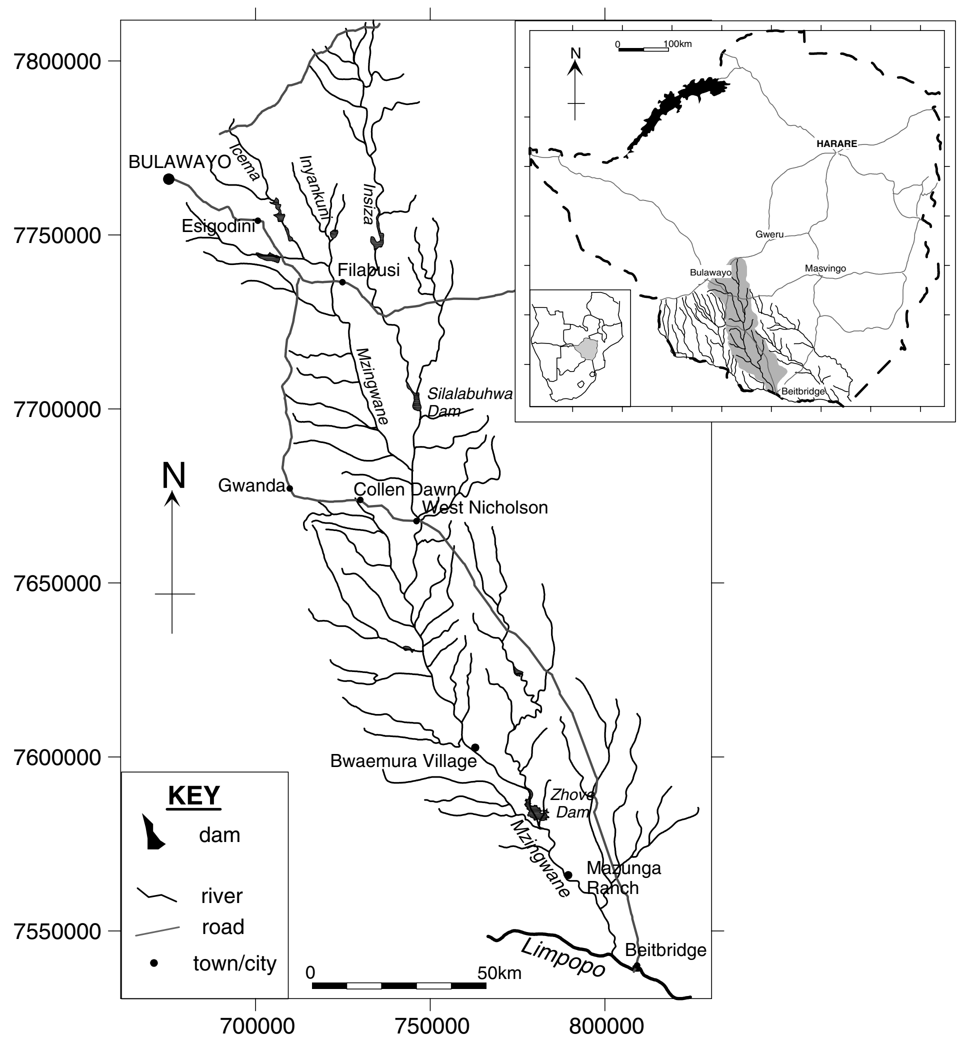

Fig. 1. Map showing the Mzingwane Catchment and its location in the Limpopo Catchment.

Ashton et al., 2001). The southern half is underlain by Limpopo Belt gneisses, except for the area around Mazunga, which is underlain by Karoo System rocks (mainly basalt) with recent alluvium along the rivers (Rollinson, 1993; Van Reenen et al., 1992).

2. Materials and methods

Geo-referenced LandSat imagery was used to identify alluvial channel and plains deposits. ER Mapper 6.3 and ILWIS 3.2 were used for the different image processing techniques. Different False Colour band combinations were employed. Further image processing techniques such as contrast enhancement and clustering were employed to bring out more information. Aerial photos and geological maps were used to verify the deposits, which were mapped and located by satellite imagery at selected locations. The identified aquifers were digitised and their area determined.

River gradient, channel width and river course were used to determine the types of alluvial aquifers (Birkeland and Larson, 1989). Gradients of <1:500 were classified into upper catchment aquifers and those 1:500 in to the lower catchment aquifers. Using the current river course, the alluvial deposits were classified into channel alluvial deposits and plain alluvial aquifers. The channels alluvial aquifers are characterised by the current river flow and the plain alluvial aquifers the abandoned river channels with riverine vegetation. In terms of channels width they were classified into <15 m wide channels (narrow channel aquifers) and >15 m wide channel (broad channel alluvial aquifers). Geological maps, drainage maps and aerial photos helped in the classification. The minimum alluvial water resources were determined from estimated saturated aquifer thickness, the area extents and the specific yield. The equation is as follows:

$$\text{Estimated water resources} = \text{area} \times \text{estimated saturated aquifer thickness} \times \text{specific yield}$$

Saturated alluvium thicknesses and the specific yield were estimated based on data from previous aquifer work in

Zimbabwe (Owen, 1994, 2000) and in Botswana (Nord, 1985; Wikner, 1980), the data reliability is uncertain. The resultant estimated water volumes were then converted into irrigation potential based on a 5 mm daily water requirement for a 200-day irrigation period (Owen, 1994). A three-dimensional terrain model was designed from digitised topographic contour lines to show the distribution of the aquifers spatially and in relation to the topography.

3. Results and discussion

Alluvial channels sands were easily observed on panchromatic images as bold white deposits in the river channels. On the false colour composite band 3, band 4 and band 5 (FCC 345) the alluvial deposits stand out as white and dense actively growing vegetation stands out as green, making it possible to mark out the lateral extent of the saturated alluvial plain deposits using the riverine vegetation and in addition on the basalt the plains stand out in a purplish tint (Fig. 2). In addition FCC 543 and FCC 534 are good in outlining drainage and alluvium in the basaltic terrain. FCC 543 is also useful in marking out different geological lithologies.

Alluvial aquifers in this catchment were classified into upper and lower catchment alluvial aquifer (Lower Mzingwane and Upper Mzingwane), and channel and plain alluvial aquifers (Fig. 3). The channels deposits were further split into broad channel alluvial aquifers, narrow channel alluvial aquifers. River channel alluvial aquifers can be found along the riverbed on most of the tributaries but thicker aquifers occur in the Lower Mzingwane as broad channel aquifers. (The occurrence of thin alluvium in most of the tributaries is attributed to decreased stream flow velocity at the end of the rainy season and high evaporation rates.) Plain alluvial aquifers and broad alluvial aquifers are more pronounced in the Lower Mzingwane, where the slopes are gentler with gradients of about 1:500 and even 1:1000 (Fig. 3). The alluvial aquifers in the Upper Mzingwane could have developed due to stream flow velocity reduction caused by change in gradient, rapids and cataracts aiding sediment deposition and accumulation. In the Lower Mzingwane the alluvial aquifers form extensive ribbon shapes covering about 20 km (Fig. 3), which is a result of gentle gradients influenced by the basalts. This allows for sediment accumulation on both sides of the channels hence plain alluvial channels in both ends of Mzingwane River. Different resistance competence in lithologies at lithological boundaries has allowed for sediment accumulation in some areas in the Lower Mzingwane namely Mazunga Ranch and Bwaemura Village (Ekstrom et al., 1997; Beckman and Liberg, 1997).

Average values of 7% for the plain deposits and 15% for channel deposits form the basis of the calculated minimum estimated water resources (Table 1). The specific yield values for plain deposits are lower than channel deposits due to the heterogeneous nature of the deposits and the high amount of fine materials present in plain deposits (Owen, 1994). The estimated water volumes of the river channel

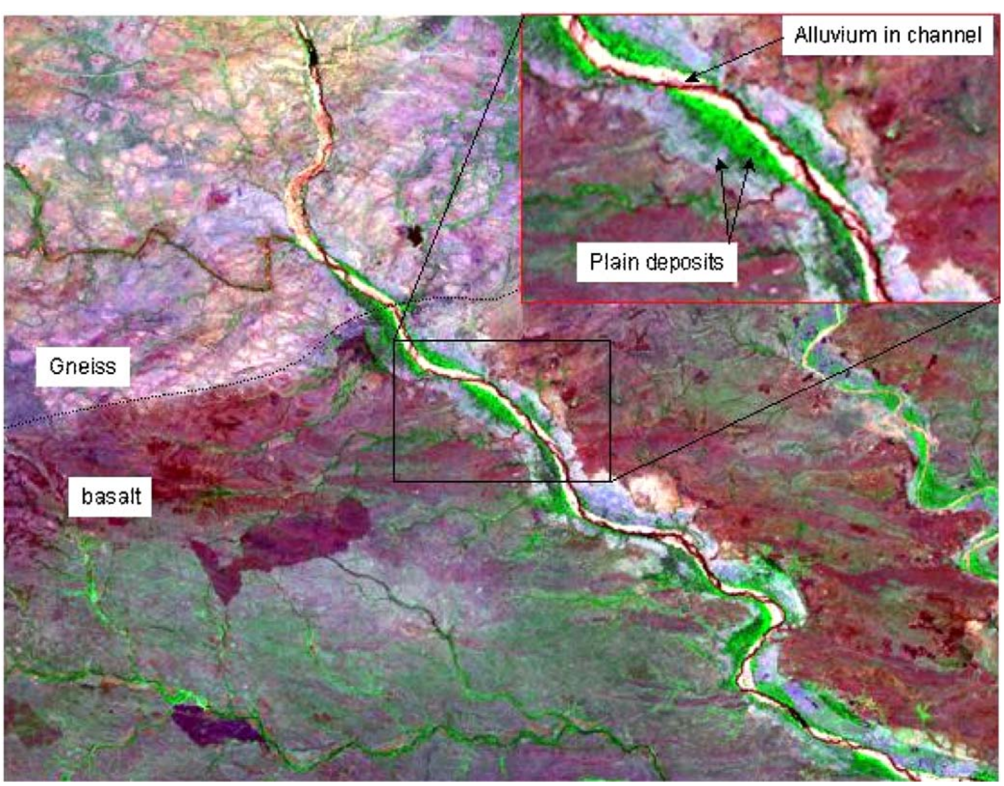

Fig. 2. GIS-based hydrogeological analysis of a portion of the lower Mzingwane River, using a false colour composite (bands 3, 4 and 5) of Landsat scene p170r075t2000, acquired on 2000-06-01.

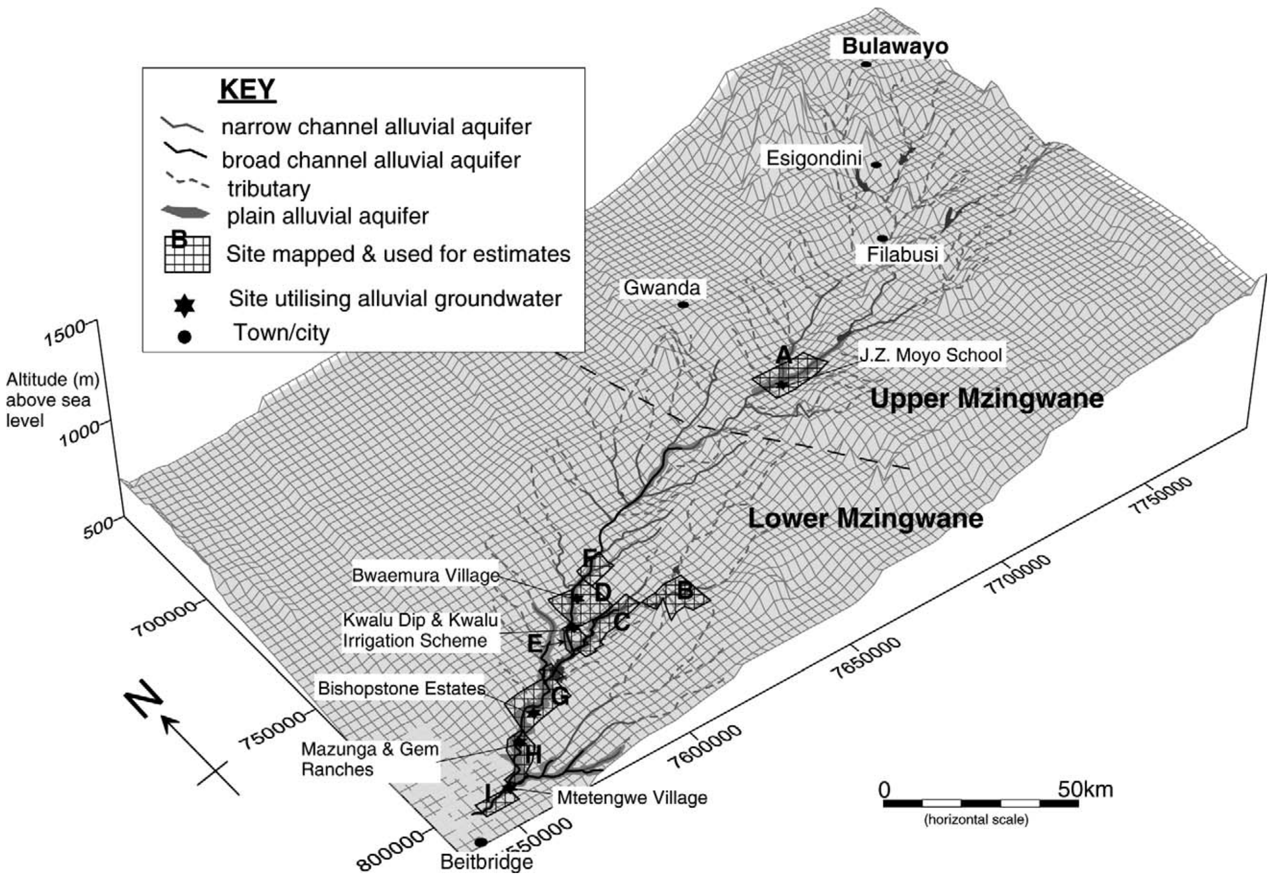

Fig. 3. Three-dimensional map of the Mzingwane Catchment showing the sites mapped out for estimating water volume and irrigation potential and current sites utilising alluvial groundwater and the different types of alluvial aquifers (*N.B. Vertical scale exaggerated*).

Table 1
Minimum estimated water volume and irrigation potential of alluvial river channel and plain aquifers in the Mzingwane Catchment using digitised alluvium from satellite imagery

Sites	Channels						Plains				
	Channel type	Area (ha)	Specific yield value (%)	Saturated thickness (m)	Estimated volume of water (m^3)	Irrigation potential (ha)	Area (ha)	Specific yield value (%)	Saturated thickness (m)	Estimated volume of water (m^3)	Irrigation potential (ha)
A	Straight	131.67	15	1	2×10^5	20	171.69	7	1	1.2×10^5	12
B	Meander	116.63	15	1	1.75×10^5	17.5	75.53	7	1.5	8×10^4	8
C	Meander	286.12	15	2	8.6×10^5	86	1537.7	7	3	3.23×10^6	323
D	Straight	44.51	15	4	2.67×10^6	267	1073.79	7	5	3.76×10^6	376
E	Straight	179.83	15	5	1.35×10^6	135	969.61	7	5	3.39×10^6	339
F	Straight	136.11	15	3	6.1×10^5	61					
G	Straight–meander	723.45	15	5	5.43×10^6	543	2196.27	7	4.5	6.92×10^6	692
H	Straight–meander	478.79	15	4.5	3.23×10^6	323	1203	7	5	4.21×10^6	421
I	Meander	252.89	15	3	1.14×10^6	114	248.2	7	3	5.2×10^5	52
Total		2350			1.5665×10^7	1566.5	7475.79			2.223×10^7	2223

aquifers along the Mzingwane River, as measured using satellite imagery, range between 175,000 m^3 and 5,430,000 m^3 and the plains between 80,000 m^3 and 6,920,000 m^3 (Fig. 3 and Table 1). These values are an underestimate since they are based on the minimum saturated aquifer thickness. The 5 mm daily requirement is an average figure and it equates to 50 m^3/day/ha water requirement for irrigation. For 200 days per year of irrigation, this requires 10,000 m^3/ha/yr. The remaining 165 days of the year are during the rainy season or immediately following the rainy season and water abstracted for irrigation during this period is considered to be the expense of river flow and not aquifer storage. With a 50 m^3/day/ha irrigation requirement the alluvial aquifers of the Mzingwane Catchment have an irrigation potential ranging from about 18 ha to 543 ha and plain alluvial aquifers from 8 ha to 692 ha (Table 1).

Currently, some of the aquifers are being used to provide water for domestic use – J.Z. Moyo School and Mtetengwe Village, livestock watering and dip tanks – Kwalu, commercial irrigation – Mazunga and Gem Farms, food security scheme – Kwalu Irrigation Scheme and market gardening – Bwaemura Village (Fig. 3). Mazunga Ranch, Gem Ranch and Bishopstone Estates are overabstracting from the alluvial aquifers in the dry season leading to salinity problems in the citrus plantations. This salinity can affect the citrus plantations yield and subsequently the soil properties. More irrigation schemes utilising the groundwater resources can be set up along the Mzingwane River and better irrigation potential would be achieved if abstraction points are spread out over the length of the river (Owen, 2000). During drought years, recharge is expected to be less and if the drought is extended (as in the 2003–2004, 2004–2005 seasons) water levels in the aquifers may drop substantially. Salinity intrusions from older lithologies can be experienced if there is overabstraction from the aquifers – or during drought years when there is less recharge.

4. Conclusion

Alluvial aquifers in the Mzingwane can be divided into narrow and broad river channel deposits and plain deposits. Even though river channel aquifers occur almost everywhere on the vast length of Mzingwane their storage capacity is limited in the upper catchment due to steep slopes. The Lower Mzingwane has thicker and more extensive aquifers because the slopes are gentle (1:500 or even 1:1000), which is good for sediment accumulation. Landsat False Colour Composites can be used to map out alluvium deposits and panchromatic images are best used for the river channel deposits. Satellite based groundwater estimates need supporting data since the resolution of the images is not good enough to give confidence in the results. A large irrigation potential lies in the alluvial aquifers mostly in the Lower Mzingwane, with the best water quality from the river channel aquifers. Lithological boundary controlled aquifers have the potential to store more groundwater. Salinity is a problem in the Lower Mzingwane mostly in the plain deposits. To avoid salinity problems, integrated water management is needed to utilise the plains and river channel aquifers conjunctively. Well point systems with the pump house on the riverbank and infiltration galleries will be less prone to destruction by flooding. Abstraction rates and water quality should be monitored to avoid salinity problems of the river channel aquifers during the dry season. Artificial alluvial dams can be constructed to increase the storage capacity of the aquifer and thereby store enough freshwater for the dry season. Farmer-based programmes on water and crop management, along with careful management of abstraction rates can improve productivity of the available water and safeguard against depreciation in water quality.

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