The delineation of alluvial aquifers towards a better understanding of channel transmission losses in the Limpopo River Basin

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Abstract

Understanding the impact of key hydrological processes on the availability of water resources is an integral component of equitable and sustainable integrated water resource management. Previous hydrological studies conducted in the Limpopo River Basin have revealed a gap in the understanding of surface water-groundwater interactions, particularly channel transmission loss processes. These studies, focused largely on the Limpopo River's main stem, have attributed the existence of these streamflow losses to the presence of significant alluvial aquifers and indicated that the losses account for about 30 percent (or 1000 $Mm^3\ a^{-1}$) of the basin's water balance. This paper reports on the delineation of alluvial aquifers across the Luvuvhu sub-basin using Landsat-8 imagery and the estimation of potential transmission losses based on the aquifer properties. To delineate alluvial aquifers, general land cover classes including alluvial aquifers were produced from Landsat-8 imagery through image classification. The areal extent of the delineated alluvial aquifers was calculated using ArcMap 10.3 Results indicate that the alluvial aquifers occur as relatively narrow channel alluvial deposits (32-124 m in width) and extensive vegetated floodplain deposits. In the Luvuvhu sub-basin, these are mostly located along the lower reach of the 200 km long meandering Luvuvhu River. The outcome of the delineation of the alluvial aquifer is seen to be consistent with existing regional hydrogeological maps. Based on the characteristics and size of the aquifer it is estimated that the capacity of the aquifer is approximately 9.34 Mm^3, which could be 'lost' from the Luvuvhu River system at any given point in time. The actual transmission losses however depend on a number of factors including the level of flow, the size of the aquifer in contact with the riverbed, regional slope for water loss into the adjacent areas, antecedent moisture content of the aquifer and riparian evapotranspiration.

Keywords: Alluvial aquifers, Hydrological Modelling, Luvuvhu sub-basin, Surface water-groundwater interaction.

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1 Introduction

1.1 Integrated water resources management in the Limpopo River Basin

Sustainable socioeconomic development within the Limpopo River Basin depends on the implementation of integrated water resources management during policy-making (). Integrated water resources management (IWRM) is based on the understanding that water, land and other natural resources are interlinked and need to be managed holistically (Malzbender and Earle, 2007). It is widely accepted as '*a process which promotes coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.*' (GWP, 2000). Understanding the impact of key hydrological processes on the availability of water resources has therefore been identified as an integral component of equitable and sustainable water resource management. A review of previous hydrological studies (Görgens *et al.*, 1991; Görgens and Boroto, 1997; JULBS, 1991; Meyer and Hill, 2013) conducted in the Limpopo River Basin has revealed a gap in the understanding of surface water-groundwater interactions, particularly channel transmission loss processes. These studies attribute the existence of streamflow losses to the presence of significant alluvial aquifers and indicated that the losses account for about 30 percent (or 1000 $Mm^3 a^{-1}$) of the basin's water balance. The focus of these studies, however, has been primarily on alluvial aquifers along the Limpopo River's main stem, and therefore streamflow loss processes in sub-basins remain largely unknown.

1.2 Alluvial aquifers

An alluvial aquifer is described as "an aquifer comprising unconsolidated material deposited by water, typically occurring adjacent to rivers and buried palaeochannels." (DWS, 2011). The distribution of alluvial deposits (aquifers) is determined by the river gradient, geometry of the channel, fluctuation of stream power as a function of decreasing discharge downstream due to evaporation and infiltration losses, as well as rates of sediment input due to erosion (Moyce *et al.*, 2006). The geomorphology of the Limpopo River is characterised by 100 m to 500 m wide alluvial deposits ranging in thickness between 5 and 10 m, as well as rocky outcrops and floodplains in the upper and middle reaches and extensive floodplains further downstream (Boroto and Görgens, 2003). The aquifers comprise mainly unconsolidated Quaternary sequences of clay, sand and gravel beds (CSIR, 2003; Gomo and van Tonder, 2013), and are sources of groundwater abstraction for multiple communities due to their high permeabilities (Owen and Madari, 2010) and good water quality (CSIR, 2003; Moyce et al., 2006). The alluvial aquifers along the Limpopo River are considered to have the potential for high yields, whereas those along tributaries such as the Luvuvhu River display much lower potential due to limited aquifer extent and less than optimum hydraulic characteristics (CSIR, 2003).

1.3 Delineation of alluvial aquifers

Traditional methods of identifying and marking the extent of alluvial aquifers have included field observations, the use of geological and hydrogeological maps as well as aerial photography (DWAF, 2005; Meijerink *et al.*, 2007). More recently, the application of remote sensing techniques and mapping using geographical information systems (GIS) to hydrogeology and other scientific fields, has proven more beneficial in terms of time and cost-efficiency for observing inaccessible locations, acquiring up-to-date imagery as well as covering larger geographical areas (Meijerink, 1996; Meijerink *et al.*, 2007; Campbell and Wynne, 2011). Studies that have delineated alluvial aquifers using remote sensing and GIS techniques have focused primarily on identifying groundwater recharge sites and groundwater potential development zones (Khan and Moharana, 2002; Solomon and Quiel, 2006; Javed and Wani, 2009; Saha *et al.*, 2010; Magesh *et al.*, 2012; Elbeih, 2015). Few others have looked at physiographical soil mapping (Afify *et al.*, 2010; Dobos *et al.* 2013) and characterising the soil, hydrogeological and physical characteristics of alluvial aquifers for water estimation purposes (Millaresis and Argialas, 2000; Moyce *et al.* 2006). The methods employed to locate, measure and characterise alluvial aquifers through remote sensing and GIS techniques have included the use of: multi-layer spatial analysis (Khan and Moharana, 2002), LiDAR-derived vegetation heights which give indication of the extent of alluvium along river systems (Levick and Rogers, 2011) and manual digitisation using Landsat 7 False Colour Composite (FCC) images (Moyce *et al.*, 2006). The study by Moyce *et al.* (2006) demonstrated the possibility of distinguishing channel alluvial deposits from floodplain alluvial deposits and similarly, the approach is applied in this study.

1.4 Channel transmission losses

Channel transmission losses describe surface water and groundwater interactions where streamflow is reduced by infiltration through the river bed, seepage into channel banks and flood plains (Walters, 1990). Compared to other hydrological processes, information on channel transmission losses remains largely lacking, however the dynamics between alluvial aquifers (alluvium) and channel transmission losses have been covered by several hydrological studies across the world (Walters, 1990; Hughes and Sami, 1992; Boroto and

Görgens, 2003; Smathkin, 2001; Lange, 2005; Hughes, 2008; Renard *et al.*, 2008; Morin *et al.*, 2009; Owen and Madari, 2010; Costa *et al.*, 2012; Jarihani *et al.*, 2015).

From these studies it is understood that, due to their water storage capabilities, the presence of alluvial aquifers results in significant channel transmission losses in ephemeral river systems found in semi-arid catchments such as the Limpopo River Basin (LRB) of southern Africa (Boroto and Görgens, 2003; LBPTC, 2010;). Figure 1 illustrates what is conceptually understood to occur in ephemeral channels when runoff traverses dry alluvial streambeds. In the LRB, as is similar in other semi-arid regions, factors that contribute to these losses typically include (Smakhtin and Watkins, 1997; Boroto and Görgens, 2003):

- Infiltration and extraction from bank storage,
- Recharge of storage in alluvial channel beds,
- Evaporation and evapotranspiration from the recharged beds and banks,
- Evapotranspiration from riparian vegetation, and
- Direct evaporation from the free water surface.

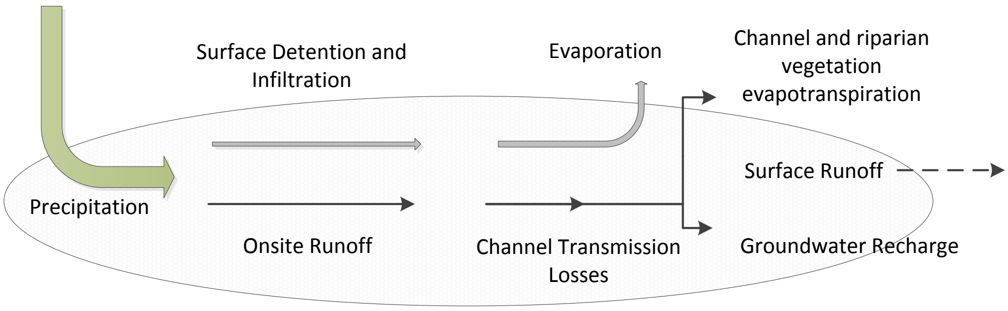

Figure 1. Illustration of what conceptually happens in ephemeral channels where runoff traverses dry alluvial streambeds. (Adapted from Renard *et al.*, 2008)

Further discussion of the hydrological processes involved in channel transmission losses can be found in Renard (1970), Abdulrazzak and Morel-Seytoux (1983), Knighton and Nanson (1994), Lange *et al.* (1998), Dunkerley and Brown (1999), Lange (2005), Konrad (2006), Dahan *et al.* (2007, 2008) and Dag´es *et al.* (2008), Renard *et al.* (2008) and Jarihani *et al.* (2015). The behaviour of channel transmission losses is summarised by Costa *et al.* (2012): "*…small sub-bank flows must firstly fill pool abstractions and channel filaments in order to propagate downstream; then bank-full flows infiltrate predominantly into bed and levees; and, at high stream discharges, overbank flows lose water for pools, subsidiary channels and floodplains, but once they become fully saturated, the most direct floodways become fully active and channel transmission losses decrease*." According to Costa *et al.* (2012) this behaviour is dependent on the seasonality of precipitation and runoff, the underlying groundwater system and flow and the (micro-)layered structure of alluvial and floodplain sediments.

Ultimately, channel transmission losses affect the availability of streamflow, hence it is imperative to understand their role in the alluvial aquifers of the LRB.

1.5 Estimation of channel transmission losses

Quantitative estimation of channel transmission losses through alluvial aquifers requires a conceptual understanding of the processes that govern water flow in the system and the hydraulic properties of these aquifers (Costa *et al.*, 2012). Several methods of estimating transmission losses and groundwater recharge using field-based applications are reviewed by Shanafield and Cook (2014). These include controlled infiltration experiments, monitoring changes in water content, using heat as a tracer of infiltration and conducting reach length water balances. Walter *et al.* (2012) investigate the estimation of aquifer recharge through visual analyses of satellite imagery, but indicate that the methods applied are best suited for explaining the spatial distribution of relative channel losses. For quantitative estimates of absolute losses, the study stipulates that in-stream flow measurements are required. According to Walter *et al.* (2012) and Shanafield and Cook (2014), streamflow losses into the underlying alluvium can be estimated by measuring discharge at two points in the channel system. If hydrometric data are available upstream and downstream of a channel reach, inflow and outflow volumes may be compared and transmission losses quantified (Tanner, 2013). Volumes of transmission loss may be related to flow and channel characteristics by means of regression analysis (Lange, 2005); however, this approach can be complicated by unknown lateral inflows (Tanner, 2013).The methods investigated by both Shanafield and Cook (2014) and Walter *et al.* (2012) do however indicate the importance of approaching transmission loss estimation holistically - "*Therefore, interdisciplinary studies linking the transmission losses (hydrology), infiltration (hydrology/soil physics), riparian response (ecology), and aquifer response (hydrogeology) would be extremely beneficial to the general, applied understanding of arid zone processes*" (Shanafield and Cook, 2014). In deriving a volumetric estimate of potential alluvial groundwater resources, Owen *et al.* (1989) utilised the product of the volume of the saturated aquifer and the specific yield of the aquifer. Moyce *et al.* (2006) used the product of the saturated aquifer thickness, the aquifer areal extents and specific yield to estimate water resources related to alluvial aquifers in the Mzingwane catchment of Zimbabwe.

To build on the knowledge of transmission loss processes in the Limpopo River Basin, this study delineates alluvial aquifers in the Luvuvhu sub-basin utilising Landsat 8 imagery and remote sensing techniques, and estimates the potential streamflow losses to the alluvial aquifer by using available hydrogeological data from previous regional studies as well as the derived aquifer extents.

2 Study Area

The Luvuvhu (Levuvhu) sub-basin (Figure 2) is one of the 27 sub-basins which make up the transboundary Limpopo River Basin (LRB) of southern Africa (Meyer and Hill, 2013). The sub-basin, which straddles the border between South Africa and Mozambique in the north of the Kruger National Park, is situated on the right bank of the Limpopo River between coordinates 22°17'57" - 23°17'31"S and 29°49'16" - 31°23'02"E, covering an area of 5 941 km^2 (Kundu *et al.*, 2014).

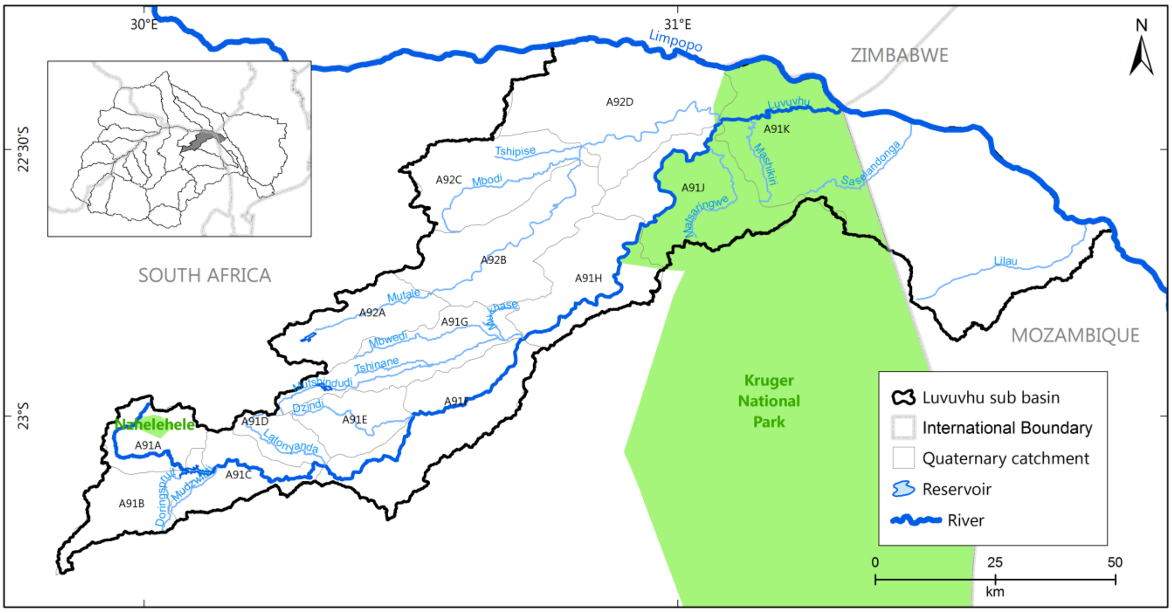

Figure 2. The location of the Luvuvhu sub-basin of the Limpopo River Basin

The Luvuvhu River rises in the Soutpansberg mountain range and flows for 200 km through a diverse range of landscapes before joining the Limpopo River at Crook's Corner near Pafuri, an area which marks the three-point boundary between Zimbabwe, South Africa and Mozambique (SoR, 2001). In South Africa the Luvuvhu sub-basin forms part of the Limpopo Water Management Area (WMA) (DWS, 2016). It is divided into 14 Quaternary catchments, namely A91A to A91K and A92A to A92D (DWAF, 2004). A Quaternary catchment is a fourth order catchment in a hierarchical classification system in which a Primary catchment is the major unit (DWS, 2011). It is used as the basic unit for water resource management in South Africa (Odiyo *et al.*, 2012).

The topography of the Luvuvhu sub-basin is characterised by mountainous highlands in the southwest, deep gorges across the length of the sub-basin which run parallel to the river channel and low-lying floodplains in the northeast (DWAF, 2004). In the Soutpansberg Mountains, which mark the headwaters of the Luvuvhu River, elevations are as high as 1587 metres above sea level (m.a.s.l.) and gently decrease through the steeply-incised Luvuvhu and Lanner Gorges before reaching 200 m.a.s.l at the Pafuri floodplain near the Limpopo River confluence (SoR, 2001; DWA, 2012).

The distinct change in topography gives rise to varied climatic conditions across the length of the sub-basin. Climate ranges from humid areas in the mountainous southwest to warmer, more arid areas in the north-eastern lowveld (DWA, 2012). The mean annual temperature ranges from about 18°C in the mountainous areas to more than 28°C in the northern and eastern parts of the sub-basin, with an average of about 25.5°C for the Limpopo WMA as a whole. Maximum temperatures are experienced in January and minimum temperatures occur on average in July (DWA, 2012).

Rainfall and evaporation in the Luvhuvu sub-basin is characterised by high spatial and temporal variation with the highest rainfall and lowest potential evaporation over the Soutpansberg mountain range, and the lowest rainfall and highest potential evaporation on the northeastern low-lying plains (Jewitt *et al.*, 2004). Rainfall occurs mainly during the summer months (October to March) and is strongly influenced by the topography (DWA, 2012; Odiyo *et al.*, 2015). The mean annual precipitation (MAP) varies from 450 mm on the low-lying plains to 1149 mm in the mountainous areas (Meyer and Hill, 2013). The combination of wetter, cooler conditions and steep slopes in the southwest contributes to this region providing the major component of the sub-basin's water resources (DWA, 2012). The mean total potential evaporation is 1678 mm (Jewitt *et al.*, 2004). Natural runoff in the basin is indicated as 560 mm a^{-1} (Meyer and Hill, 2013).

Hydrogeological systems in the area are characterised by fractured and hard rock aquifers (Figure 3), and extensive areas of floodplain alluvium occur at the confluence of the Luvuvhu and Limpopo rivers (SoR, 2001). Soil types (Figure 4) are varied Leptosols (sandy loam) and Cambisols (clayey loam) most common in the lowlands (Ashton *et al.*, 2001; Batjies, 2004).

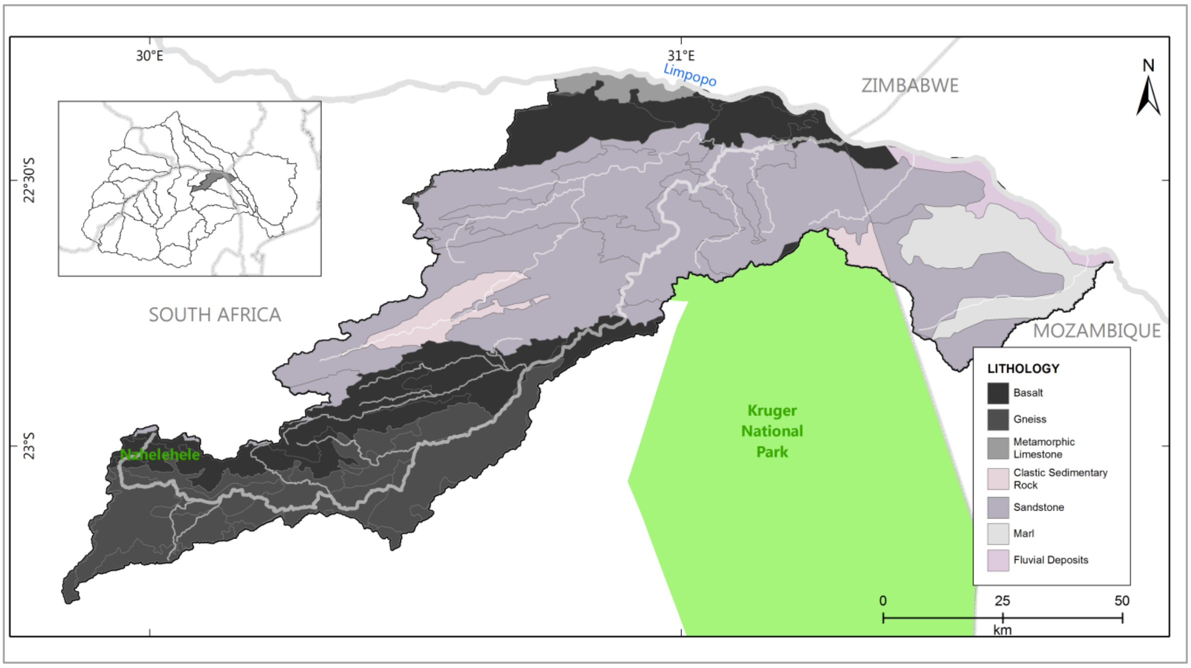

Figure 3. Dominant lithology in the Luvuvhu sub-basin (source?)

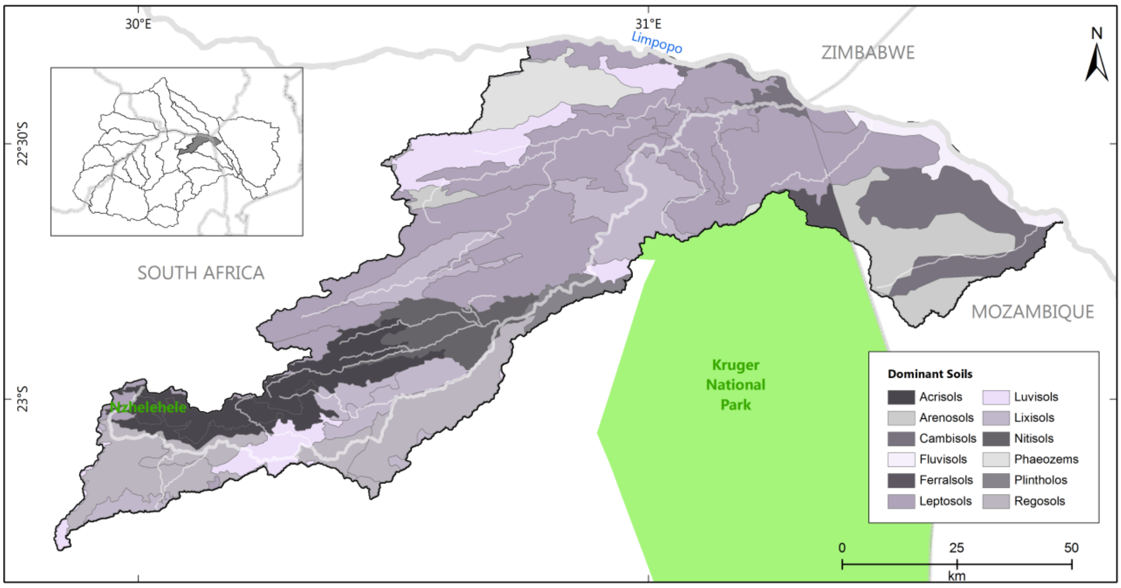

Figure 4. Dominant soil types across the Luvuvhu sub-basin (Batjies, 2004)

Groundwater contributes to baseflow throughout the catchment via subsurface seepage and springs (DWAF, 2004). Recharge was calculated as 4 percent of the MAP (Meyer and Hill, 2013). Aquifer productivity in the sub-basin ranges from 0.1- 0.5 L s^{-1} in the southern regions of the sub-basin, to 1-5 L s^{-1} in the north (MacDonald *et al.*, 2012).

Land-use activities in the Luvuvhu sub-basin include commercial forestry (4%) in the upper reaches of the Luvuvhu and Latonyanda rivers, commercial dry land agriculture (10%), commercial irrigation agriculture (3%), range land (50%), conservation areas (30%) and urban areas (3%) (Griscom, 2010; Odiyo *et al.*, 2015).

3 Methods and materials

3.1 Aquifer delineation

Remote sensing and GIS techniques were used to identify and delineate alluvial aquifers within the sub-basin, and existing literature and hydrogeological datasets consulted to verify the alluvial deposits and determine the hydraulic properties of the aquifer. Figure 5 illustrates the methods applied in delineating alluvial aquifers in the Luvuvhu sub-basin.

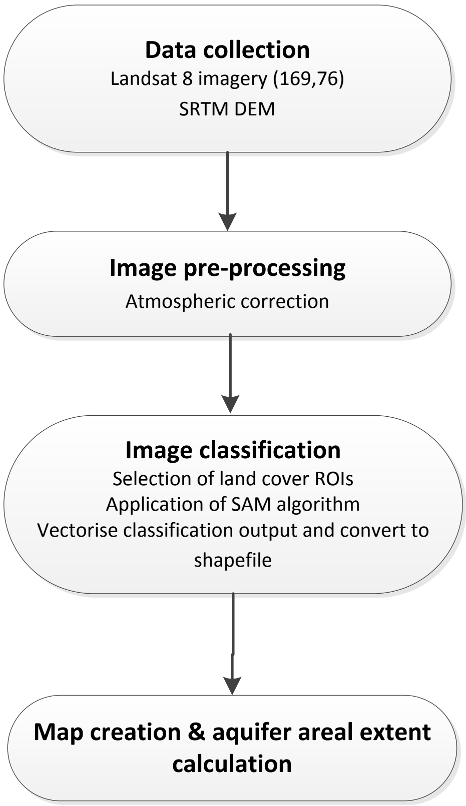

Figure 5. Approach applied to delineating alluvial aquifers in the Luvuvhu sub-basin

3.1.1 Data collection

The primary data used for alluvial aquifer delineation comprised georeferenced multispectral LandSat 8 Operational Land Imager (OLI) imagery and Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) Both datasets have global coverage, are well calibrated and processed and available freely from reliable sources. Landsat 8 imagery (Path 169, Row 76) (Figure 6) captured on 8 August 2015, were downloaded from the United States Geological Society (USGS) (https://glovis.usgs.gov/) download portal with geometric correction already implemented. In southern Africa, August represents the dry season and since alluvial plains deposits are often used for agricultural purposes in the Limpopo River Basin (Ashton *et al.*, 2001; Moyce *et al.*, 2006), it was important to use dry season image in order to maximise the spectral distinction between naturally-occurring and irrigated vegetation. Landsat-8 is a multispectral sensor with eight spectral bands in the visible, near infrared (NIR) and shortwave infrared (SWIR) regions and collects data at a spatial resolution of 30m. The 12-bit quantisation of data has enhanced the signal-to-noise radiometric performance of Landsat-8 thus increasing its utility for landcover mapping (Pervez *et al.*, 2016). A 30m SRTM DEM data was downloaded from the Remote Pixel download portal (https://remotepixel.ca/) and used in the atmospheric correction of Landsat-8 images. Landsat-8 images were atmospherically corrected using ATCOR-3 software which accounts for topographic effect. Ancillary data, to verify the location and extent of the identified alluvial aquifers, included literature (SoR, 2001; CSIR, 2003) and GIS spatial datasets (DWAF, 2001; Batjies, 2004) from previous hydrogeological studies conducted in southern Africa which detail the hydraulic properties of alluvial aquifers in the region. Table 1 indicates the description and sources of the data used.

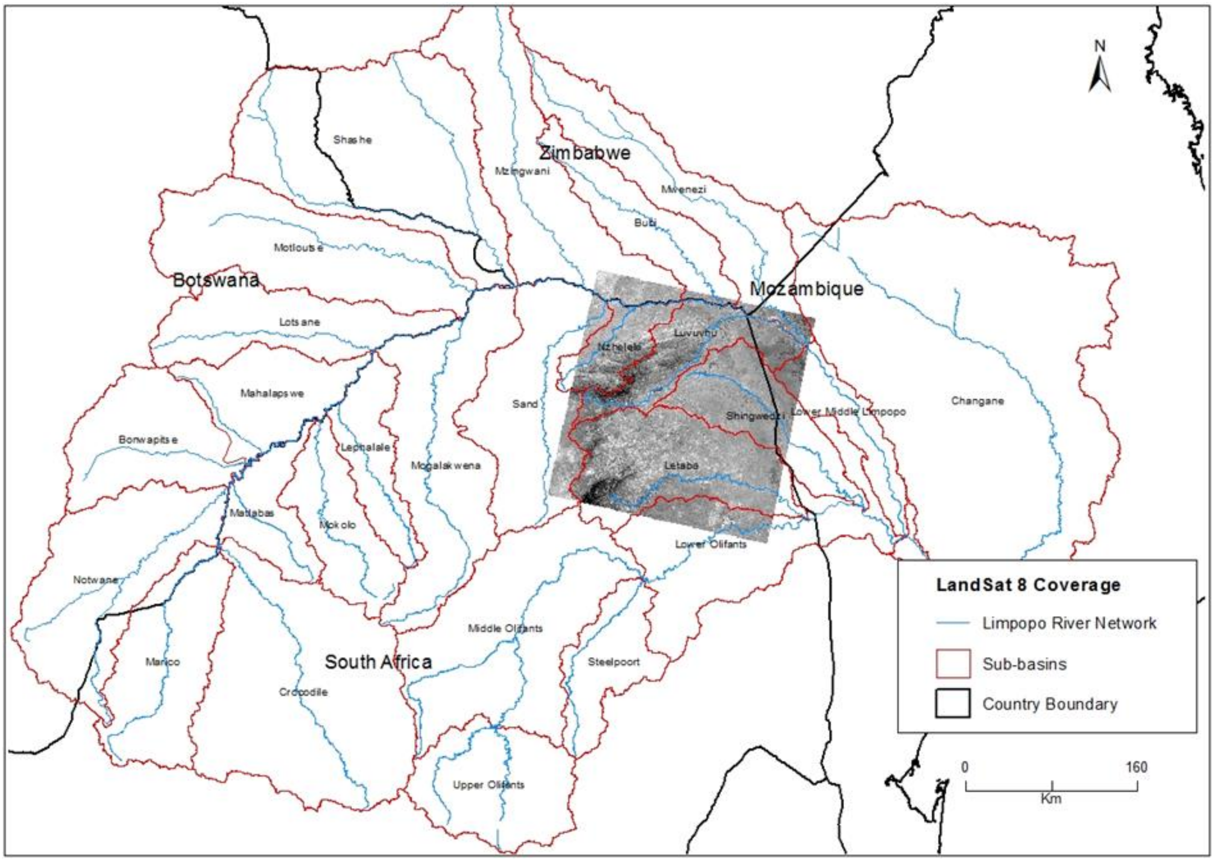

Figure 6 Landsat 8 OLI coverage of the Luvuvhu sub-basin.

Table 1. Spatial data collected and used in the study

Data set	**Description**	**Spatial Resolution**	**Source**

Satellite imagery	LandSat 8 OLI[a] coverage of study area	30 m	USGS, 2015
Elevation	SRTM[b] digital elevation model	30 m	Jarvis, 2008
Terrain slope	SRTM digital elevation model	30 m	Jarvis, 2008
Soil types	Regional soil classification	1:2 000 000	Batjies, 2004
Dominant lithology	Messina 2127 hydrogeological map	1:500 000	DWAF, 2002
River Network	Delineation of Limpopo River Basin river network	1:5 000 000	Howard *et al.*, 2013
Land cover and use	Google Earth coverage of study area	30 m	Google Earth, 2016

[a]*OLI Operational Land Imager*
[b]*SRTM Shuttle Radar Topographic Mission*

3.1.2 Image classification

To delineate alluvial aquifers, general land cover classes including alluvial aquifers were produced from Landsat-8 imagery through image classification. Image classification was implemented using Spectral Angle Mapper (SAM). Essentially, SAM is a similarity measure that computes the level of similarity between two spectra and is insensitive to illumination-induced differences among spectra. A high angle between spectra indicates that the two objects are spectrally separable (Keshava, 2004). SAM has been used successfully in other studies (Cho *et al.*, 2010; Madonsela *et al.*, 2017) and we expected it to classify alluvial aquifers accurately. Interpretation of the Landsat 8 image was based on supervised classification and analysis of panchromatic Band 8 and false colour composites produced from Band 4, Band 5, and Band 6, using ENVI 4.8. Alluvial deposits stand out as bright white areas within the extent of the river channel on a panchromatic band (Figure 7). In the FCC RGB 456 image, the dry alluvial deposits are also white with moist sands reflecting an off-white pink hue. Sands that are more saturated reflect a brighter pink and regions where surface flow is prominent are a bright to deep red (Figure 8). The floodplain alluvial deposits are identified by the green riverine zone that lines the channel boundary, representing naturally vegetated deposits.

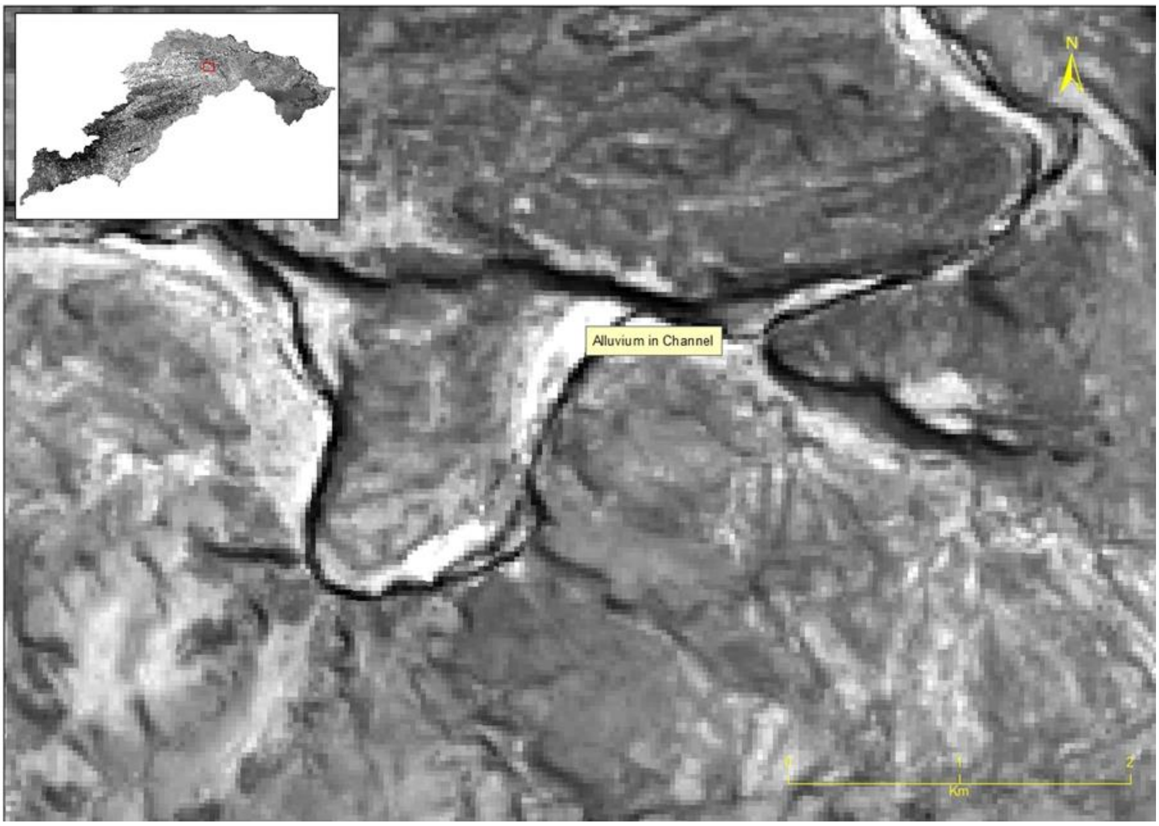

Figure 7 On the panchromatic image of LandSat 8 (169, 76), channel alluvium stands out as bold white deposits within the extent of the river channel.

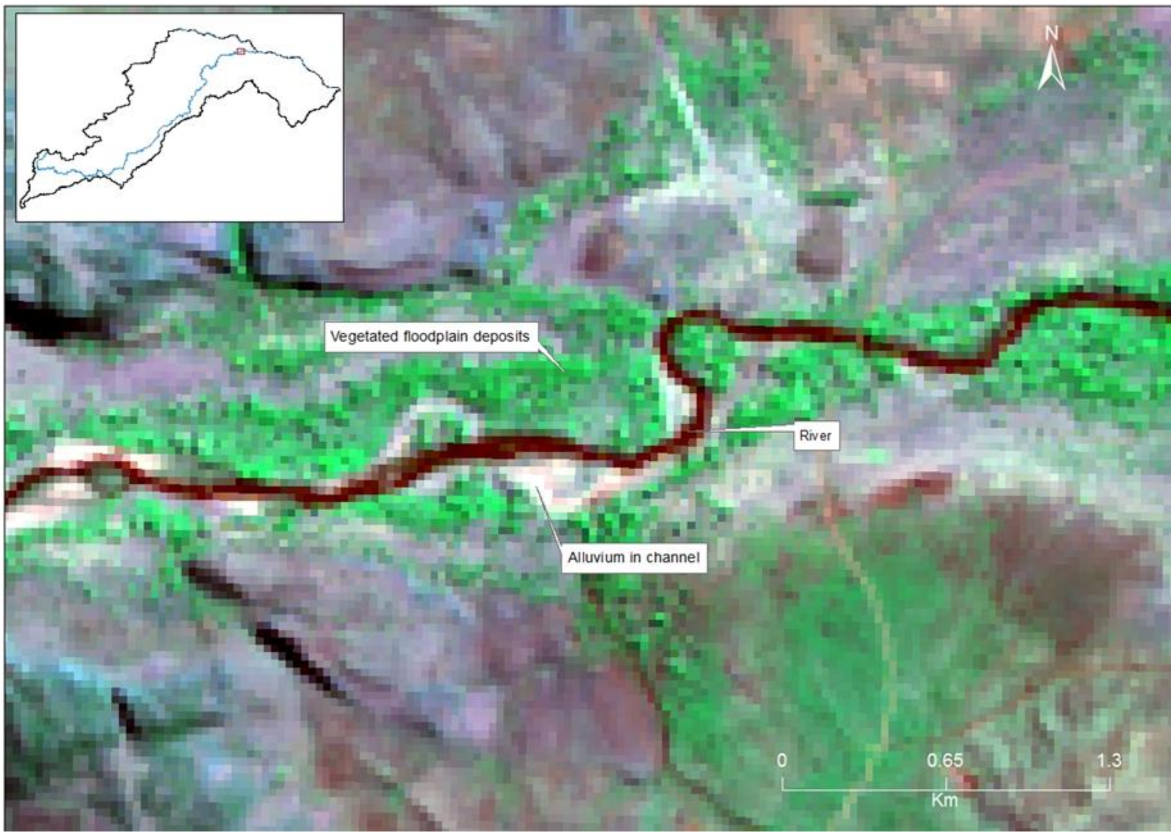

Figure 8 On the false colour composite image (RGB 456) of LandSat 8 (169, 76), the contrast between channel alluvium, vegetated floodplain deposits and river (with streamflow) can be observed.

Land cover classification involved the identification of 8 land cover classes (Table 2) and collection of regions of interest (ROIs) in the Landsat scene; an average of 33 pixels was assigned to each ROI. The chosen land cover classes were based on land cover and land use characteristics verified with existing land cover studies (Kundu *et al.*, 2015) and 2016 Google Earth image. Each class had 40 ROIs that were used for training the classifying algorithm i.e. SAM. The algorithm was applied with a pixel angle of 0.15 to obtain the land cover classification results (Figure 9). An accuracy assessment of the land cover classification was conducted using an unprocessed Landsat image as reference data. A collection of 10 ROIs per class was used to classify regions on the reference data that correspond to the 8 classes identified in Table 2, and to compute a confusion matrix that reveals the accuracy of the classification.

Table 2. Description of classes chosen for land cover classification

Class name	Description
Channel alluvial deposits	Alluvial deposits confined within the boundary of the river channel; river bed alluvium
Vegetated floodplain deposits	Naturally vegetated riverine zone that lines the river channel
River	Areas indicating streamflow within the river channel
Dams	Artificial (man-made) water bodies
Built-up areas	Urban residential areas and industrial sites including shopping complexes, mines/quarries
Rural settlements	Open cleared fields with isolated buildings
Cultivated areas	Irrigated and non-irrigated agricultural lands, centre pivots and forest plantations
Open grassland	Bare land with no fences/boundaries

Post image classification, three classes i.e. channel alluvial deposits, vegetated floodplain deposits and river which define alluvial aquifers were vectorised and converted to shapefiles for the areal extent to be determined using the GIS software, ArcMap 10.3. In ArcMap 10.3, the areal extent of identified alluvial deposits was calculated by manually digitizing the boundary determined by the classification. This process was implemented to ensure that misclassified or missing pixels within the boundary of alluvial deposits could be accounted for. Other studies (Griscom *et al.*, 2010; Kundu *et al.*, 2015) in the region have successfully characterised the land use and cover of the Luvuvhu sub-basin with some indication of the location and extent of alluvial deposits however, they do not report the actual size and characteristics of the deposits.

3.1.3 Estimation of saturated aquifer volume

The volume of water that can be stored in the alluvium was calculated from estimated saturated aquifer thickness, the derived areal extents and the effective porosity of the soil material making up the alluvial deposit. The method applied is discussed by Masike (2007). The equation used is as follows:

$$V_w = A \times b \times \tilde{n} \qquad \text{Equation 1}$$

where: V_w = Aquifer Capacity, A = Areal extent of aquifer, b = Estimated Aquifer Thickness and $\tilde{n}$ = average porosity

The estimated saturated aquifer thickness and effective porosity are based on previous hydrogeological work conducted in southern Africa for similar alluvial aquifer environments in neighbouring sub-basins. Field results from Love *et al.*, (2007), McCormick, (2010) and Cobbing *et al.*, (2008) respectively recorded saturated alluvial aquifer thicknesses of 1.60 m to 2.45 m for the Mushawe alluvial aquifer in the Mwenezi sub-basin, 0.5 m to more than 2.00 m for an upper stream alluvial aquifer in the Letaba sub-basin and an average of 3.5 m for the alluvial aquifer underlying the main stem of the Limpopo River. While, the effective porosities recorded in the region are 32.5% (McCormick, 2010), 39% (Masvopo, 2008) and 43% (Love *et al.*, 2007). For the Luvuvhu alluvial aquifer a maximum thickness of 3.5 m was used with an average effective porosity of 38%. The thickness was based on the proximity of the Luvuvhu channel to the Limpopo main stem and the similar slope element. The effective porosity was averaged from the effective porosity range of 25% to 50%, given by Freeze and Cherry (1979) for unconsolidated sand deposits.

4 Results and Discussion

4.1 Alluvial aquifer delineation

Results from image classification (Table 3) shows that the overall accuracy of the SAM classified image (Figure 9) is 75.20%, while the average producer's and user's accuracies are 69.75% and 70.19%, respectively. This indicates that a high proportion of the reference data was accurately mapped, therefore validating the accuracy of the land cover classification. This evaluation is further supported by the Kappa coefficient which shows that the classification was efficiently performed. With regards to the 3 classes (channel alluvial deposits, vegetated floodplain deposits, river) that were vectorised for estimation of alluvial areal extent and volume, high accuracy is observed with the channel alluvium, while the vegetated floodplain deposits and river classes respectively show moderate and low accuracies. Majority of the errors for vegetated floodplain deposits are due to misclassified rural settlements and cultivated areas classes and are resultant of low spectral separability between the classes affected; water was observed to be most misclassified with unclassified pixels and built-up areas. Nonetheless, visual assessment of the classified alluvial aquifer location shows a satisfactory agreement with the existing hydrogeological maps (Figure 10 and 11).

Table 3. Producer's and user's accuracy

Class	**Producer's accuracy (%)**	**User's accuracy (%)**
Channel alluvial deposits	88.24	69.82
Vegetated floodplain deposits	65.25	40.31
River	34.30	29.50
Dams	88.20	99.88
Built up areas	70.07	92.78
Rural settlements	78.22	69.06
Cultivated areas	75.45	89.96
Open grassland	58.32	70.19
Total		
Overall accuracy	75.20%	
Kappa co-efficient	0.7054	

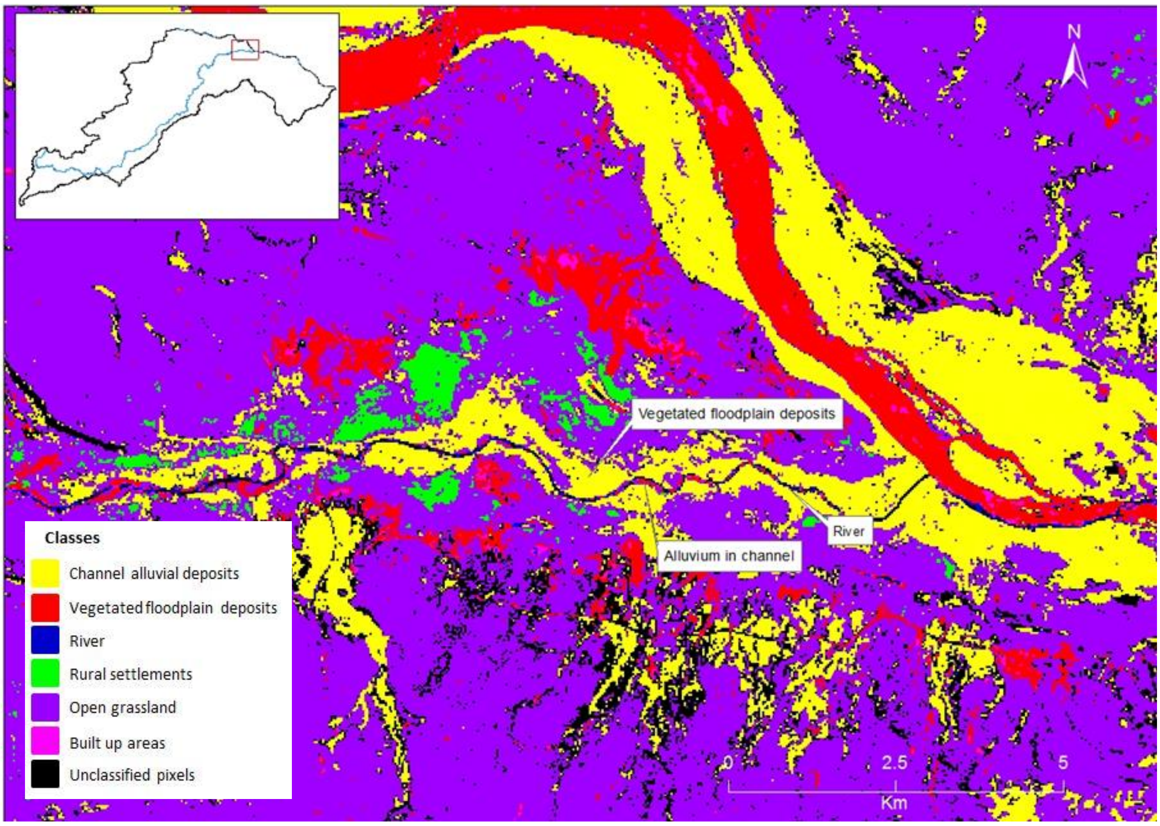

Figure 9. Output from the LandSat land cover classification using Spectral Angle Mapper. The image indicates the confluence between the Luvuvhu River and the lower reach main stem of the Limpopo River. Some regions of misclassification (marked by unclassified pixels and rural settlements) are also noted in the output as one moves further away from the current river course.

The location of alluvial deposits is observed along the lower reach of the Luvuvhu River, a low-lying area that marks the confluence between the Luvuvhu River and the main stem Limpopo River. The area is conventionally known as the Pafuri floodplain (Griscom et al., 2010) due to the extensive floodplain alluvium deposited there. From the land cover classification (Figure 9), extensive vegetated floodplain deposits are observed on either side of a relatively narrow strip of channel alluvium. The channel alluvium occurs as 32 m to 124 m wide deposits covering an areal extent of 1.92 km^2 while the vegetated floodplain deposits range in width from 26 m to 892 m covering an areal extent of 7.8 km^2(Table 4); the total alluvial aquifer extent is therefore an estimated 9.72 km^2. The length of the aquifer zone measures 14.5 km. The Messina 2127 1:500 000 hydrogeological map (DWA, 2002) (Figure 10) and the SOTWIS-SAF soil classification (Batjies, 2004) (Figure 11) validate the alluvial aquifer delineation in the area. According to the Messina 2127 1:500 000 hydrogeological map, alluvium occurs as unconsolidated sand deposits with a borehole yield of ≥5 l s^{-1} in the region. The soil types constituting the alluvial deposits are described as a Eutric Cambisol and Leptosol (Batjies, 2004).

Table 4. Hydrogeological characteristics of the Pafuri alluvial aquifer in the Luvuvhu sub-basin

Channel alluvial aquifer	
Channel type	Meandering along old and current river course
Channel slope (regional)	0.00%
Channel width (range)	32 m – 124 m
Approximate areal extent of channel deposits	1.92 km^2
Natural barriers	Vegetated floodplain (wetland)
Alluvial sediments characteristics	Cambisols (clayey loam), Leptosols (sandy loam)
Estimated saturated volume of channel alluvium	2.36 Mm^3
Alluvial plains	
Plains width (range)	26 m – 892 m
Approximate areal extent of alluvial plains (range)	7.80 km^2
Alluvial sediments characteristics	Cambisols
Estimated saturated volume of plains aquifer	6.98 Mm^3

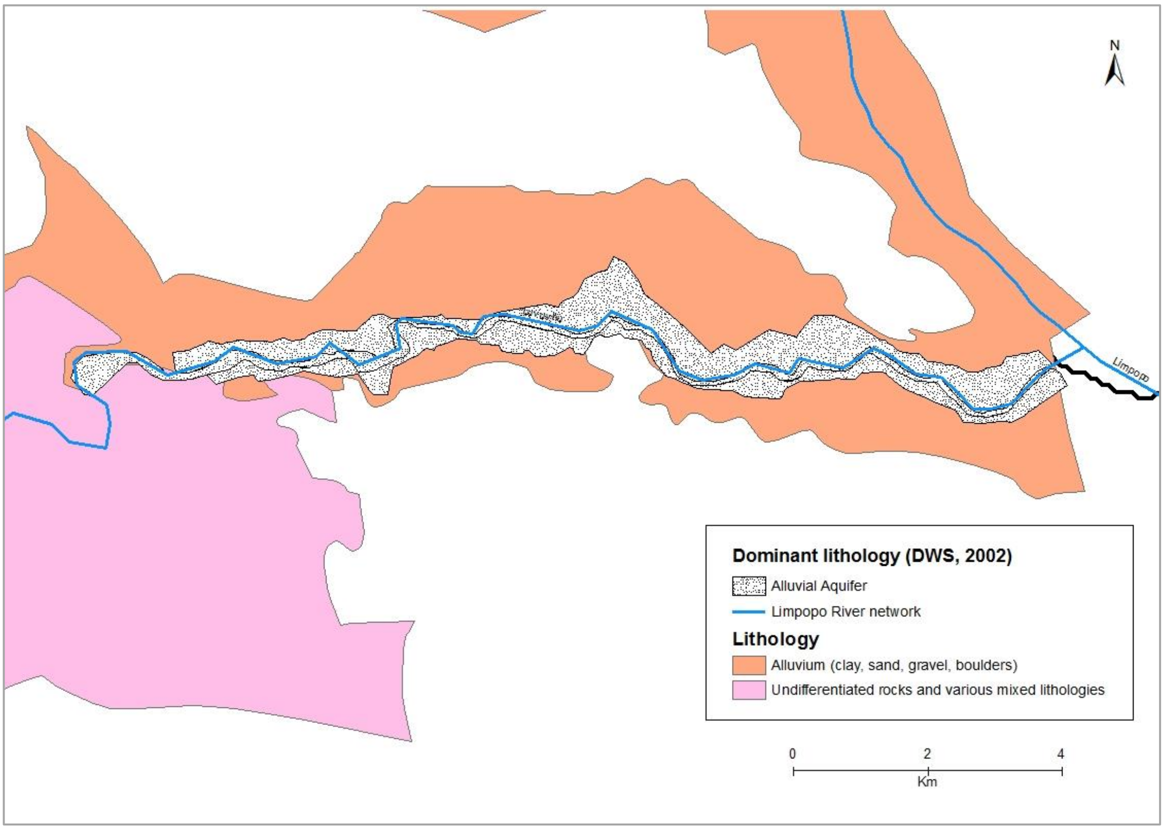

Figure 10. The delineated alluvial deposits are overlain on top of the Messina 2127 1:500 000 hydrogeological map (DWAF, 2002) to illustrate the consistency of the delineated alluvial aquifers with existing hydrogeological maps. The white areas indicate the extent of the sub-basin.

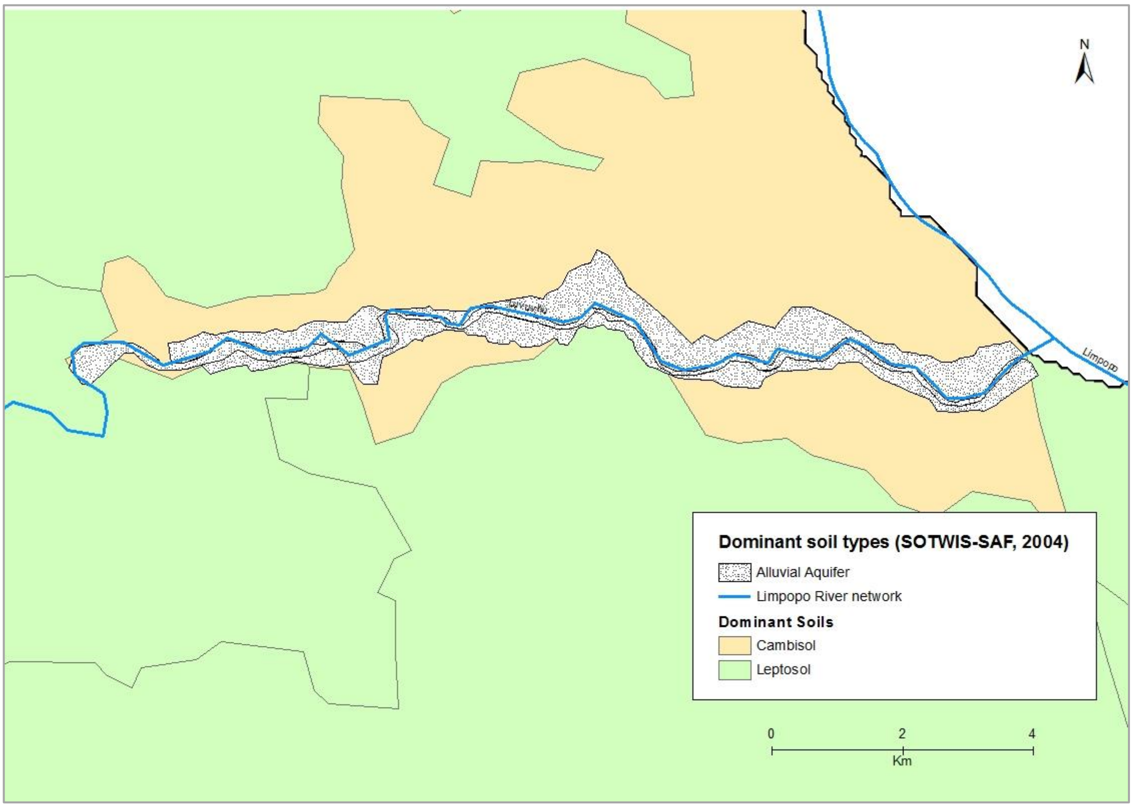

Figure 11. The delineated alluvial deposits are overlain on top of the SOTWIS-SAF soil classification (Batjies, 2004) to illustrate the consistency of the delineated alluvial aquifers with existing hydrogeological maps.

Figure 12 illustrates the appearance of the channel alluvium and vegetated floodplain deposits on a Google Earth image. A study by Ashton and Turton (2009) illustrates the possible extension of this alluvial aquifer and considers it to be a transboundary aquifer; however no scaled measurements are provided regarding the areal extent of the deposit.

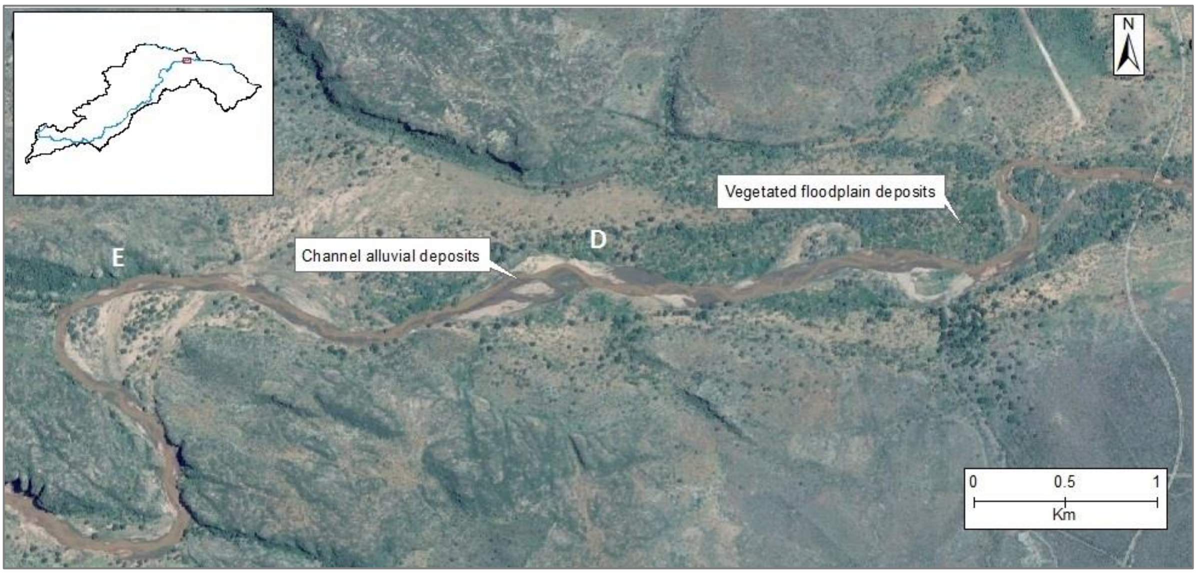

Figure 12. Google Earth image of the Pafuri alluvial deposits. Reaches E and D (Figure 13) are displayed. The image indicates the current course of the Luvuvhu

River as well as alluvial deposits which occur along the riverbed (old and current) and vegetated floodplains.

4.2 Estimation of aquifer volume

The estimation of the hydraulic properties of the alluvial aquifer was based on available spatial datasets as well as literature pertaining to general hydraulic characteristics of the soil types, Cambisol and Leptosol. Although several boreholes have been noted in the aquifer zone, only data on the yield capacity are reported. According to the spatial dataset of the Messina 2127 1:500 000 hydrogeological map (DWAF, 2002), yields within the channel boundary range from 6.34 l s^{-1} to 1.27 l s^{-1}, decreasing towards the mouth of the Luvuvhu River. Yields along the vegetated floodplain alluvial deposits range between 6.31 l s^{-1} to 4.99 l s^{-1}, also decreasing towards the confluence of the Luvuvhu River and the Limpopo main stem.

The delineation of the alluvial aquifer is illustrated in Figure 13, along with the reach segments used in calculating the total potential alluvial aquifer water resources along the lower Luvuvhu River.

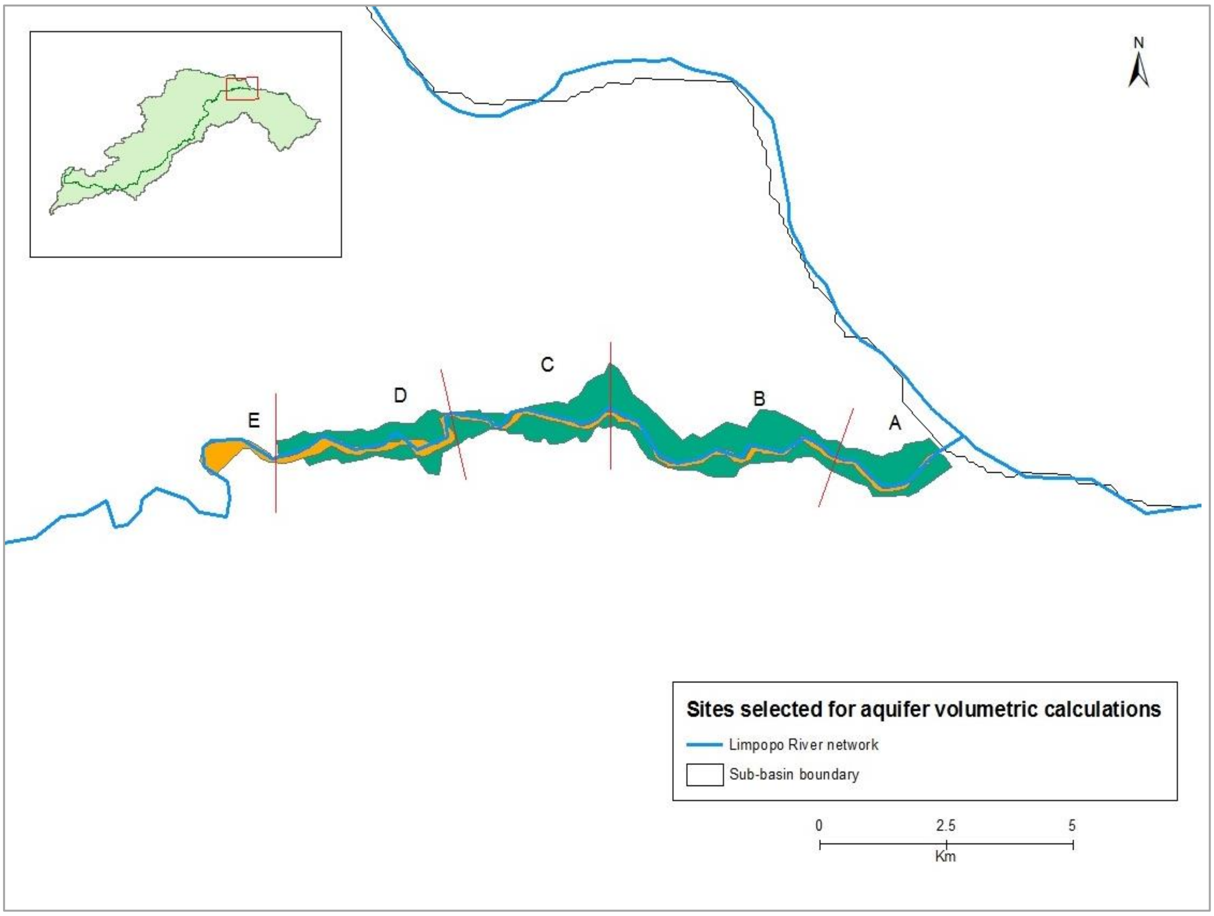

Figure 13. Alluvial aquifer discretisation for aquifer volume estimation..

Table 5 indicates the estimated area, soil type, average thickness and porosity of each reach segment along the alluvial aquifer extent. The estimated volume of water stored is based on Equation 1. The volume of water that can be stored in the alluvial aquifer, at a given point in time, amounts to an estimated 2.36 Mm^3 and 6.98 Mm^3 for channel deposits and vegetated floodplain deposits, respectively. These values are, however, uncertain due to the paucity of groundwater-related data in the area (e.g. streamflow discharge, groundwater level series) - a typical situation in semi-arid basins (Hughes, 2008; Costa *et al.*, 2013; Tanner and Hughes, 2015) and do depend on the measured dimensions of the alluvial aquifer.

Table 5. Estimated saturated volume of the alluvial aquifer

Sites	**Channel Deposits**					**Plains Deposits**				
	Estimated Area (km^2)	Soil type	Average saturated thickness (m)	Average effective porosity	Estimated volume of water stored (Mm^3)	Estimated Area (km^2)	Soil type	Average saturated thickness (m)	Average Effective Porosity	Estimated volume of water stored (Mm^3)
A	0.20	Cambisol	3.5	0.38	0.26	1.38	Cambisol	2.5	0.38	1.31
B	0.42	Cambisol	3.4	0.38	0.55	3.12	Cambisol	2.4	0.38	2.85
C	0.26	Cambisol	3.3	0.38	0.32	1.68	Cambisol	2.3	0.38	1.46
D	0.58	Cambisol Leptosol	3.2	0.38	0.71	1.62	Cambisol	2.2	0.38	1.36
E	0.45	Cambisol	3.0	0.38	0.52					
Total	1.92				2.36	7.80				6.98

4.3 Conceptual understanding of channel transmission losses in the Luvuvhu sub-basin

To gain a broader conceptual understanding of channel transmission loss processes along the delineated alluvial aquifer in the Luvuvhu sub-basin a schematic of the water budget (Figure 14) is considered. The climatic characteristics (Section 2) of the Luvuvhu sub-basin indicate that the low-lying plains are dominated by a semi-arid climate consistent with low rainfall and high evaporation, therefore it is expected that evaporation will play a significant role as part of the channel transmission loss processes. Furthermore, the alluvial deposits are relatively shallow in depth compared to the 15 m thickness reported (Busari, 2008) further downstream along the Limpopo River hence evaporation is likely to impact the capacity of water stored by the alluvial aquifer, especially during the dry season. The other dominant process expected to influence the capacity of water stored by the alluvial aquifer, is evapotranspiration; the floodplains of the identified alluvial aquifer are significantly vegetated with riverine forests which increase the potential for evapotranspiration. Although not indicated on the schematic, the streamflow regime in the Luvuvhu is highly impacted with several large dams and farms dams storing water for commercial forestry and agriculture. Furthermore, groundwater abstraction (from fractured aquifers) for domestic use and irrigation is reported however the quantity is uncertain (DWS, 2016b). These reduce the amount of natural flow in the channel which decreases the amount of water seeping into the local aquifer system.

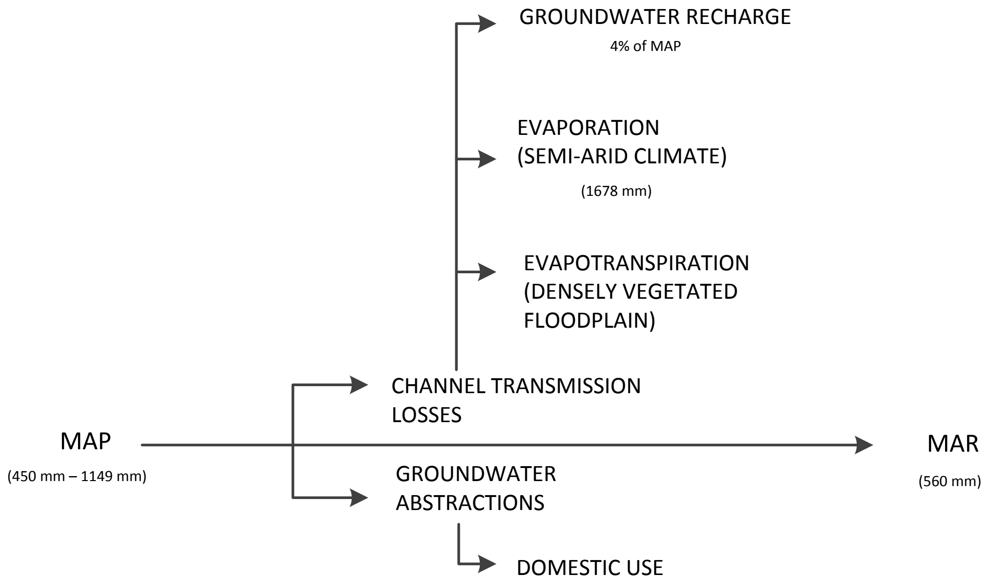

Figure 14. Conceptual understanding of channel transmission losses in the Pafuri alluvial aquifer of the Luvuvhu sub-basin. MAP and MAR respectively denote the mean annual precipitation and mean annual runoff (Meyer and Hill, 2013).

5 Conclusion

Equitable and sustainable integrated water resources management requires a holistic understanding of the impact of key hydrological processes on the availability of water resources in any hydrological basin. In the semi-arid Limpopo River Basin of southern Africa, the dynamics between channel transmission losses and alluvial aquifers has been noted to impact significantly on the basin's water balance. An improved understanding of these processes is therefore considered integral to advancing knowledge of water resource estimations in semi-arid regions. To facilitate the understanding and quantification of transmission losses and hence determine the impact on the water resources of the Luvuvhu sub-basin of the transboundary Limpopo River Basin, the study located and delineated alluvial aquifers in the sub-basin using LandSat 8 imagery and remote sensing techniques. Alluvial channel and floodplain deposits were identified in the lower reach of the Luvuvhu

River proximate to the confluence with the Limpopo River main stem. This area is commonly known as the Pafuri floodplain. The total area measured for channel alluvial deposits is 1.92 km^2 while a larger extent of 7.80 km^2 was recorded for the floodplain deposits, giving a total alluvial aquifer extent of 9.72 km^2. These extents are based on the outcome of the land cover classification which presented, in itself, a few misclassifications. The estimation of the hydraulic properties of the alluvial aquifer was based on available spatial datasets as well as literature pertaining to similar alluvial aquifer environments in neighbouring sub-basins. Based on the physical and hydraulic properties used, the capacity of the alluvial aquifer was estimated to be approximately 9.34×10^6 m^3. This value is however uncertain as evaporative losses due to vegetation were not included in the calculation. Furthermore, field data relating to groundwater and alluvial deposits in the Luvuvhu sub-basin were found to be sparse, therefore estimates based on work conducted in other catchments were used. Despite the uncertainty regarding transmission loss estimation, consistency was observed between the results of the delineation of the Pafuri alluvial aquifer and the existing regional hydrogeological maps. Furthermore the study was able to conceptualise the dynamics of channel transmission loss processes in the sub-basin based on an understanding of the climatic influences and the properties of the alluvial aquifers delineated. Qualitatively, it is understood that water is likely to be 'lost' from the alluvial aquifers than gained, with evaporation and evapotranspiration from the vegetated floodplains being the dominant channel transmission loss processes.

The Luvuvhu sub-basin is one of 27 sub-basins in the Limpopo River Basin, therefore to expand knowledge on the dynamics between channel transmission losses and alluvial aquifers in the basin it is recommended that similar studies are conducted in each of the other sub-basins, with the inclusion of uncertainty analysis for the loss estimations.

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