Delineation of the Luvuvhu Headwater Catchment using high-resolution Digital Elevation Models (DEMs)

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Abstract

Hydrological studies pivot on the proper understanding of the drainage system that is under investigation. It is imperative to delineate the catchment and better visualise the area, especially in headwater catchment assessments. Advances in technology have improved how catchments are delineated and visualised. This has become integral to understanding how the river system is distributed and the basis for hydrological studies. Against this background, this research delineated the Luvuvhu Headwater Catchment (LHC) using high-resolution Digital Elevation Models (DEMs). The Shuttle Radar Topography Mission (SRTM) Global DEMs with a cell size of 30m resolution were used. Four DEMs covering the study area were mosaicked before analysis and processed to 10m x 10m resolution. The research results were compared against the conventionally used maps in similar studies. The delineated map showed a highly defined stream network that was more detailed than the previously used maps. The use of high-resolution DEMs thus produced a detailed stream distribution of the LHC. Coupling catchment delineation with ground-truthing will enhance the understanding and sustainable management of headwater catchments.

Keywords: Catchment area, GIS, hydrological modelling, spatial resolution, strategic water sources concept.

1. Introduction

The hydrologic regime of every catchment is unique to its location, topography, vegetation, and prevailing climatic conditions (Clark *et al.*, 2014). The origin of water flow has become critical to understanding river characteristics. Recently, much attention has been placed on water source areas of rivers in South Africa (Nel *et al.*, 2011; Nel *et al.*, 2017). Headwater catchments, as they are commonly referred to, are unique water source areas of a river that contribute to the initial streamflow and do not have an upstream catchment (Richardson, 2020). These catchments are located at the furthest, most elevated part of the river from its low-lying mouth. However, several headwater catchments exist within the same river catchment connecting to the major river at different locations. The spatial collection of headwater catchments within a river catchment accounts for 60-80% of the total river catchment area (Richardson, 2020).

Water collected in headwater catchments is usually from aquifer overflow (springs) or melting ice and snow (Barua *et al.*, 2022). The water is generally cooler because of the melting ice in colder climates and the presence of dense forests that provide shade to the flowing river in warmer temperatures. Headwater catchments have a hard-to-access terrain which gives them ecological and hydrological autonomy (Gumbo *et al.*, 2021). Unique and endemic flora and fauna are prominent in headwater catchments, and their interactions provide goods and services carried to the far reaches of the river (Gumbo *et al.*, 2021). The quality and quantity of water that a headwater catchment produces are essential to the characteristics of the major river (Alexander et al., 2007). These small catchments' contribution determines the river's streamflow type (i.e., perennial, intermittent, and ephemeral) and the purity of the water (Storey et al., 2011). Recently water resource availability has been threatened by anthropogenic activities that promote urbanisation, pollution, and population increase, taking a toll on the resource (Mishra et al., 2021). The impact of climate change exacerbates the pressure on water resource availability (Gumbo and Kapangaziwiri, 2021). Understanding these pressures on water resources and the critical functions of headwater catchments have become a priority in water resources management.

Research work to identify strategic water source areas has been undertaken, and the sites have been demarcated (Nel *et al.*, 2013). This has opened an opportunity for implementing scientific research to explicitly understand these areas' linkages, goods, and services. This is a relatively new approach in water resources management for South Africa. Still, countries like the United States of America (USA) have researched and incorporated headwater catchment management into federal water management policies (Nadeau and Rains, 2007). Lessons from countries incorporating headwater catchment management into their management policies have shown how invaluable these areas are to natural resource management. As South Africa strives to cover this deficit in water resource management, headwater catchment studies have become a priority.

Information gaps exist in headwater catchment management in the African context, such that research relies on case studies in developed nations. This brings about uncertainties in policy adoption based on studies that do not mimic African conditions. Identifying representative case studies addressing issues typically experienced by African communities becomes a priority. Therefore, carefully selected study sites provide a starting point for developing locally relevant strategies (Gumbo et al., 2022) for natural resources management. The headwater catchments of the Luvuvhu River Catchment (LRC), A91A and A91B, were selected based on the research protocol developed by Gumbo et al. (2022).

This site is data-scarce with a large rural population that depends on natural resources for livelihood. These are common characteristics of catchments in Africa, and a study carried out in such environments can be easily adopted for most parts of Africa. The survey of headwater catchments requires knowledge of their spatial extent and drainage system. This can be achieved through catchment delineation that utilises high-resolution digital elevation models (DEMs).

Previous research (Lin et al., 2006; Kundu et al., 2014, Limpopo River Awareness Kit, 2022) in headwater catchment management have used different resolutions in their delineations based on the available DEMs at that time. Recently, finer resolution and free DEMs have eased the delineation of catchments and increased confidence in the results. It is anticipated that high-resolution DEMs can produce a complex drainage system whose stream order numbers should be verified through ground-truthing. Several studies within the LRC (Nkuna and Odiyo; 2011, Odiyo et al., 2015; Ramulifho et al., 2019) used conventional maps to show the drainage system of the catchment. These maps are basic and do not fully represent the river network. In headwater catchment studies, their spatial extent is small and requires the greatest detail. Delineating the Luvuvhu Headwater Catchment (LHC) is essential and becomes a necessary undertaking in headwater studies. The drainage system should be well defined to classify the stream orders. This paper delineated the LHC using high-resolution DEMs and assessed them against those used in similar studies in the LRC.

2. Study area

The LRC is located within the Vhembe Biosphere Reserve (VBR). The river originates in the south-easterly slopes of the Soutpansberg Mountains, as shown in Figure 1. The catchment area covers 5941 km^2 with 14 sub-catchments. The catchment receives mean annual precipitation (MAP) of 608 mm. The rainfall ranges between 400mm − 1800 mm yearly, with the furthest part west of the catchment receiving the most and declining towards the east. Mean annual evaporation of 1678 mm is experienced, higher than the MAP for most areas within the catchment. This explains the semi-arid nature of the LRC and the need for good water resources management. Before joining the Limpopo River in the Kruger National Park, the Luvuvhu River travels approximately 200 km through different topography (Kundu et al., 2015). Different river sections have unique hydrological characteristics, with the headwater streams having steep, narrow rivers with occasional pooling.

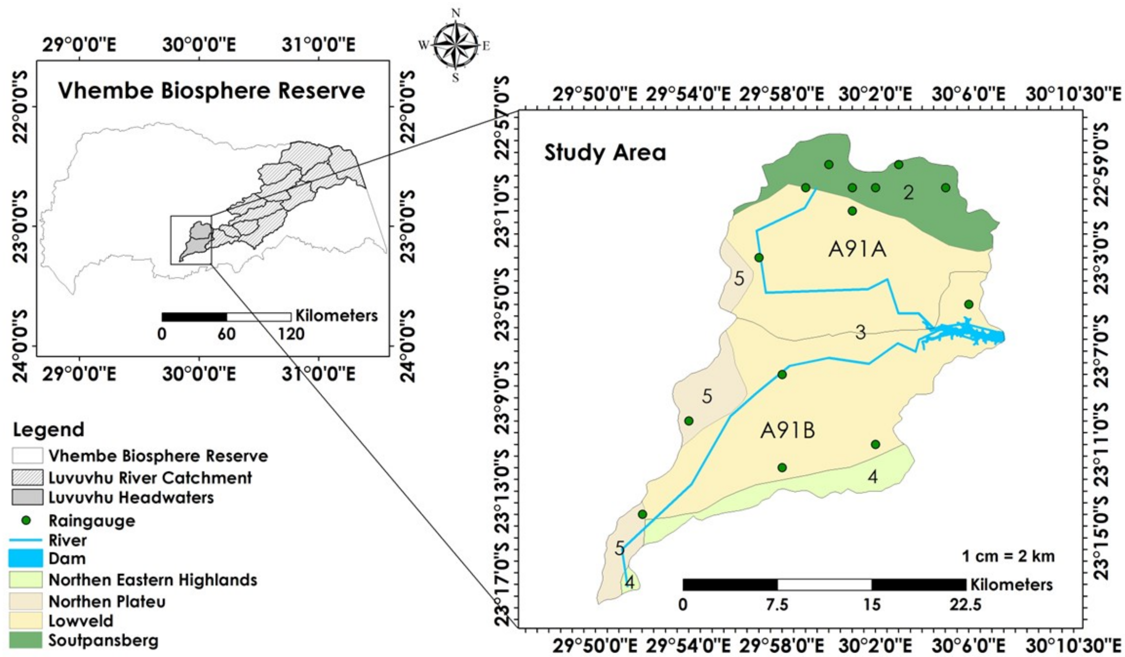

Figure 1: Map showing the location of Vhembe Biosphere Reserve in the Limpopo Province, South Africa, and the location of the Luvuvhu headwaters within the biosphere.

Several headwater catchments contribute to the Luvuvhu River (Luvuvhu, Sterkstroom, Latonyanda, Dzindi, Mukhase, Mbwedi, and Mutshindudu). The Luvuvhu (A91B) and Sterkstroom (A91A) rivers are associated with an extensive reedbed where the rivers converge. The two rivers feed into the Albasini Dam, which supports the agricultural activities of the local community. Indigenous trees dominate the area, with land-use activities dominated by agriculture and forestry. The Luvuvhu River is host to forestry plantations covering a more significant area. However, the riparian vegetation has been affected by alien invasive species and clearing to create orchards (VBR, 2021).

The Sterkstroom River is characterised by intensive orchards that have been set up along the river, leaving a narrow riparian vegetation strip (River Eco-status Monitoring Programme, 2019). Water quality is negatively affected by herbicides and insecticides in the plantations and farmed lands. Land-use changes within these rivers can negatively alter the hydrological regime of the entire river catchment (River Eco-status Monitoring Programme, 2019). The health of these rivers is currently in an appropriate state though such areas need to be kept in their most pristine condition to provide streamflow of adequate quantity and quality to the downstream reaches.

3. Methodology

The Shuttle Radar Topography Mission (SRTM) Global DEM datasets with a cell size of 30m resolution were acquired from the ViewFinder Panorama data interface (http://www.viewfinderpanoramas.org). Four DEMs covering the entire study area were mosaicked before analysis. To delineate the headwater catchment, the mosaicked dataset was resampled to 10m x 10m resolution. Higher resolution grids visualise better the headwater catchment delineated (Walker *et al.*, 2021). The DEM processing was done using ArcGIS (ESRI ® ArcGIS Desktop: Release 10.8, Redlands, California, USA). The dataset sinks were filled using the hydrological monitoring tools. Then, the flow direction for each cell was determined using the flow direction grid calculation. The drainage network was generated using the flow accumulation function from the selected pour points. The catchments were automatically delineated using the Snap Pour point tool to ensure the selection of high accumulation flow points. The hydrological tools and the Stream Order Function with the Strahler method were used to determine the stream order from the river networks.

4. Results and discussion

This paper sought to delineate the headwater catchment of the LRC. This process relied on high-resolution digital maps that were processed and analysed in ArcGIS. Several tools (ArcSWAT, WEAP, QGIS) can be used to delineate catchments. Ray (2018) examines the effectiveness of some of these tools in delineating a catchment. He concluded that the SWAT model performs better than the other tools. However, the results obtained from ArcGIS gave satisfactory results. This minimised uncertainty arising from limited knowledge of the model/software being used.

The procedure carried out in this research was guided by the recommendations of Ray (2018) as a guide to good practice in such undertakings. The DEMs used in this study were treated to make them sink-free for use in ArcGIS. Filling in sinks is a necessary procedure that must be carried out initially to have results that genuinely represent the drainage system to be studied, as expressed by (Dąbrowska et al., 2018). The limitations to automatic catchment delineation are mainly centred around sinks/pits present within the DEM. These sinks result from errors in the sampling, interpolation, data entry, observation density and biases related to remote sensing data (Ray, 2018). The sink filling process becomes crucial before the drainage system is established although several errors might occur. It can be helpful to employ other software (e.g., ArcSWAT) that can automatically fill the sinks on the DEM. In other cases where the DEM may not delineate the entire area, patching up to cover the study area becomes necessary. This brings about different challenges when using DEMs in catchment delineation. The limitations explained were addressed during the delineation process and produced a useable map for the study.

Though the delineation of catchments and presentation of drainage systems has been made easy by using and improving geoinformatics technologies, there is a need to carefully apply these techniques in environmental studies (Ray, 2018). As such, the delicate nature of headwater streams in environmental studies requires carefully extracted catchments to understand the complex interactions in these areas. Hydrological studies depend heavily on catchment delineations that are close to representing the catchments under investigation. This is important in data-scarce catchments that lack observed hydrological datasets. Studies in such areas require techniques for generating data that can be used in research. Lack of data discourages research from being carried out in these areas though these areas are usually populated by communities that would benefit from climate change knowledge. Hydrological models play a significant role in generating this missing information for use in climate change studies. Catchments delineated from high-resolution DEMs have a more defined drainage network showing stream order numbers for the different rivers within the catchment. The detailed information coupled with hydrological models can be used in the generation of streamflow data. Catchment responses to precipitation events can be derived with the help of detailed maps. It is from high-resolution DEMs that much information can be shown on a map.

Several maps exist (Figure 2) that could have been used but do not give enough detail on the drainage systems being studied. This is especially true in headwater catchment studies which require high-resolution spatial detail. The study of headwater streams depends heavily on the knowledge of the stream ordering and size of the catchment being studied. These studies must be informed initially by well-defined drainage systems using geoinformatics techniques (Kundu et al., 2013). Kundu et al. (2013) carried out similar research within the LRC, and their results are displayed in Figure 3. This produced a branched river network that was better than the existing maps of that time. However, comparing Figure 3 with the map generated for this study (Figure 4) shows a more complex drainage system. This is attributed to the use of high-resolution DEMs for the delineation. The methods used by Kundu et al., 2013 and those for this study are similar with a distinct difference in the DEMs used. As a result, the map delineated for this study presents a more complex drainage system that will require classification through ground proofing to determine the characteristics of the delineated rivers.

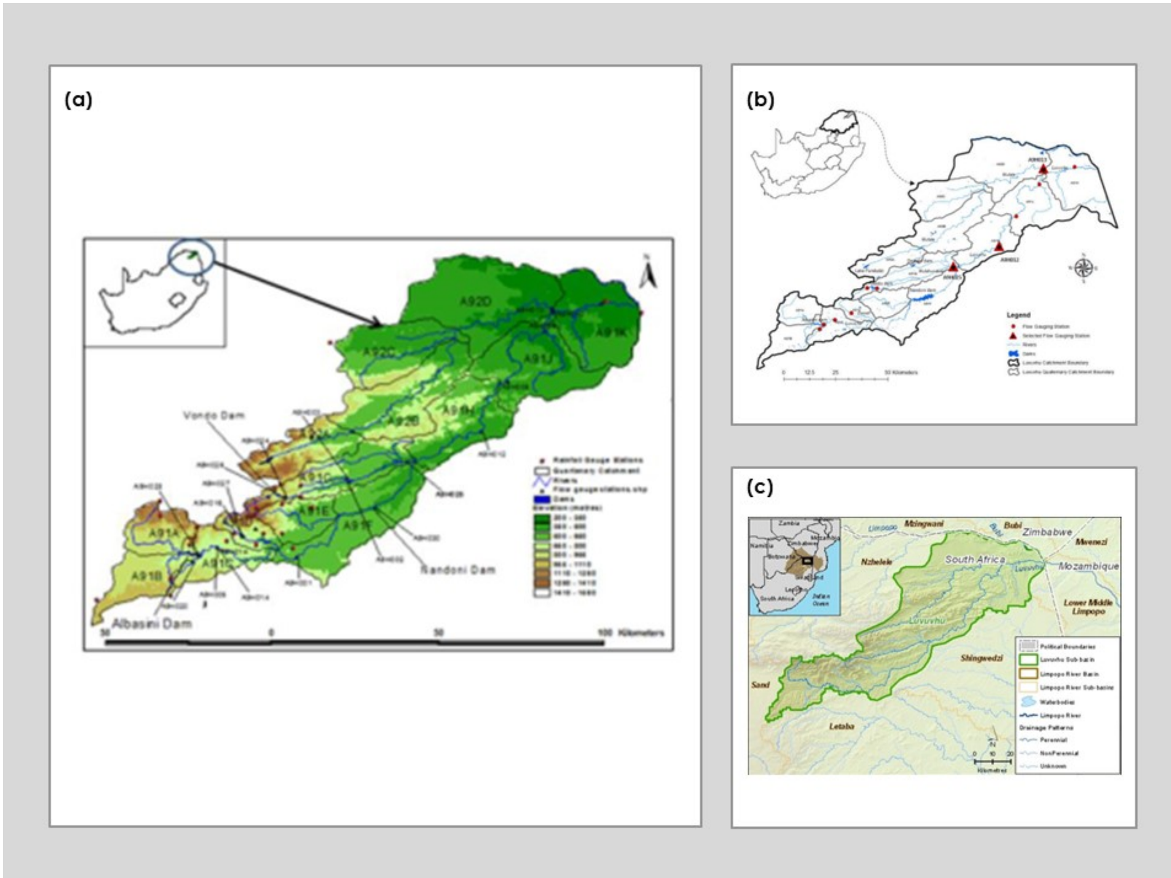

Figure 2: Maps used to compare with the delineated catchment in the Luvuvhu River (a) Kundu *et al.* (2014), (b) Ramulifho *et al.* (2019) and (c) Limpopo River Awareness Kit (2022).

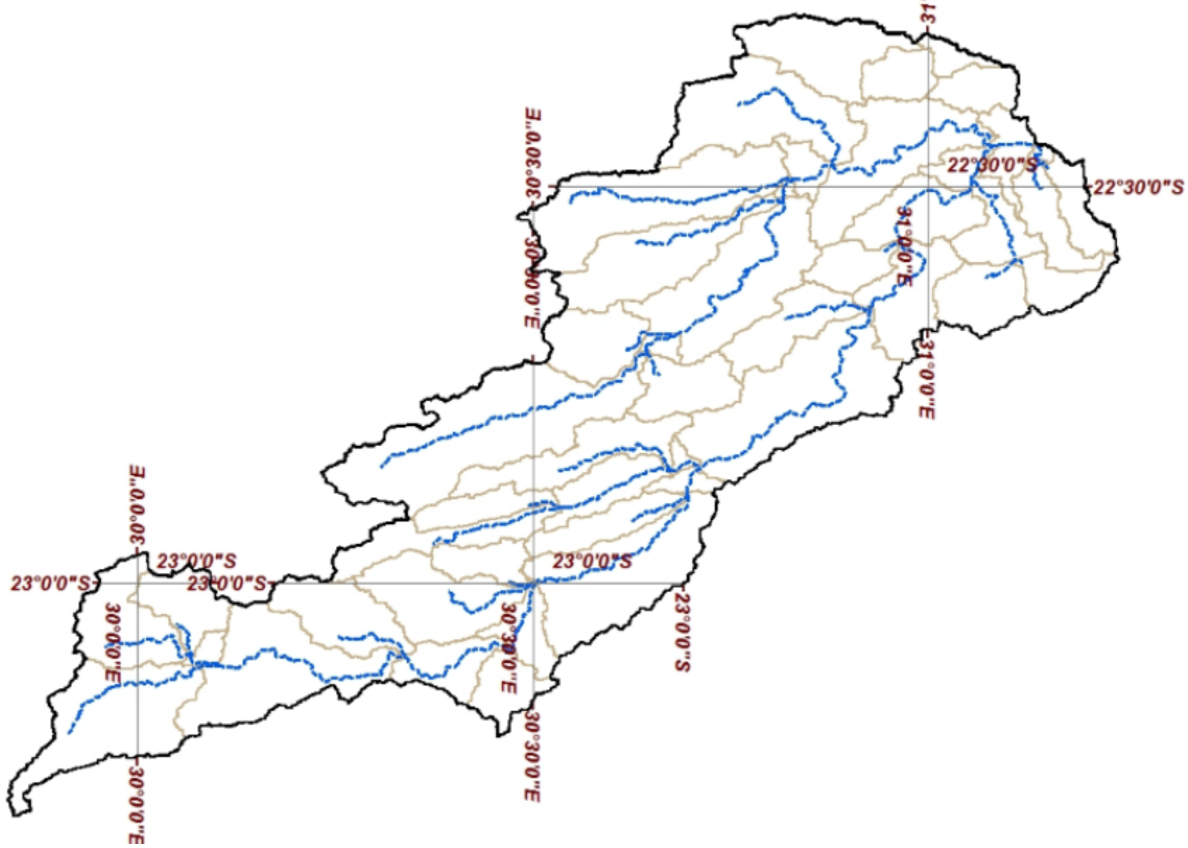

Figure 3: The resulting map of the extraction and analysis of morphologic and hydrologic properties for Luvuvhu River Catchment (Kundu et al., 2013).

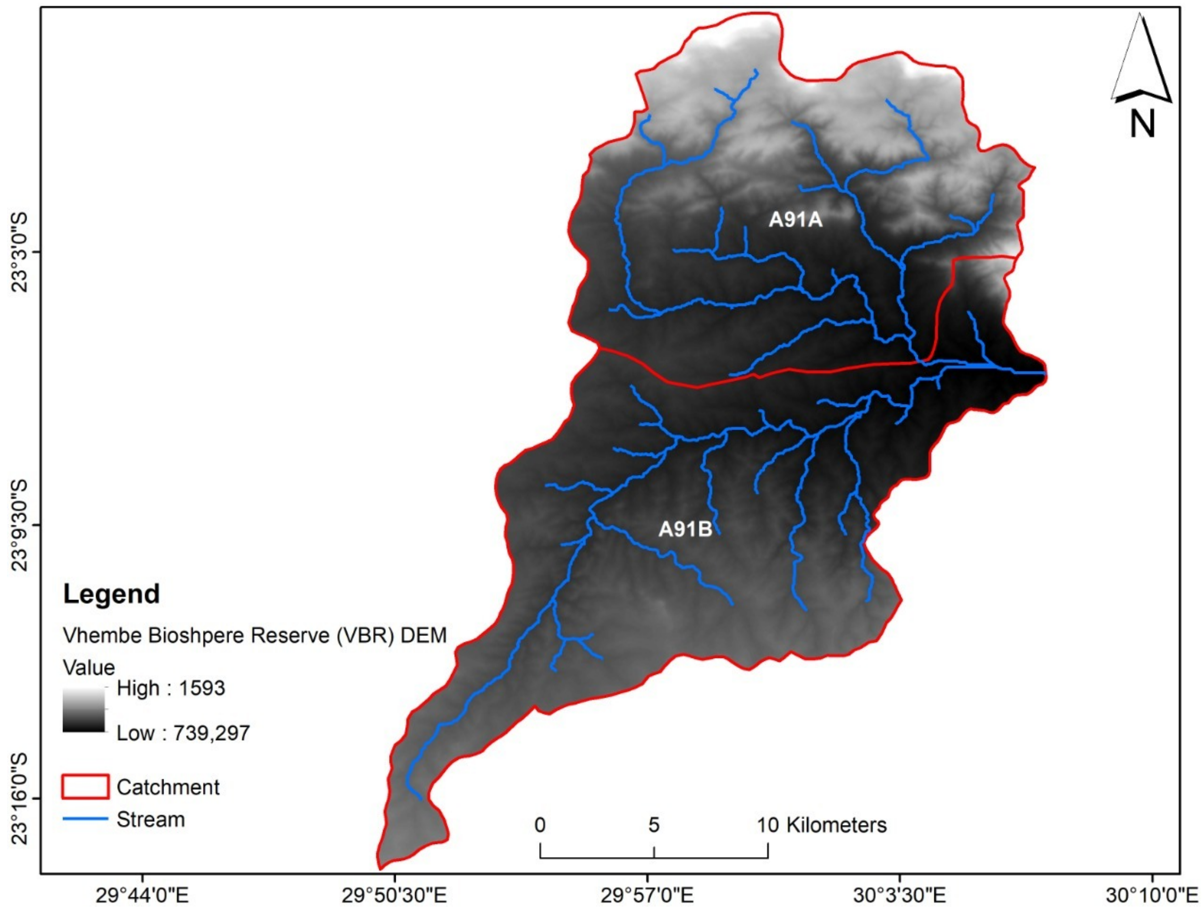

Figure 3: The delineated Luvuvhu Headwater Catchment.

5. Conclusion

Hydrological studies require delineation of the area which the river/s discharge into. Catchment studies, especially in headwater regions, require proper delineation that shows the spatial extent to which the study is implemented and how the drainage system is branched. The study briefly explained the importance of headwater catchments in river hydrology and how proper delineation using the available geoinformatics techniques produces complex drainage systems. These drainage systems backed with field visits can give the stream order numbers with a higher degree of accuracy to initial hydrological studies. This study's delineation of the headwater catchment becomes the initial stage in grander research to determine the environmental flows for the Luvuvhu headwater catchment for livelihood enhancement as the climate changes. High-resolution DEMs were treated for sinks and incorporated into the ArcGIS software, where a complex drainage system was produced using the hydrologic toolkit within the software.

The resulting delineated catchment showed a well-detailed drainage system different from the conventional maps available in the literature and contributed new information to the hydrology of the catchment. High-resolution DEMs showed better results as compared to other delineations that have been carried out in the area. Technological advancement in software and resources used in catchment delineation proved increased efficiency in catchment delineation. This was evident in the comparison of Figures 2 and 3 against the results of this research. This research aimed to delineate the headwater catchment of the LRC, and the results show a highly branched headwater catchment. This information sets up good ground for the grander research to determine environmental flows in this delineated catchment. As a finer resolution is achieved on DEMs, it is highly recommended that a similar analysis be carried out to understand the drainage system of the LRC fully.

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