DERIVING RIVER NETWORKS FOR THE NOSSOB AND AUOB RIVERS IN THE KALAHARI DESERT FROM THE SRTM DEM AND LANDSAT 8 IMAGERY

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ABSTRACT

The catchment area upstream of the confluence of the Nossob and Auob Rivers intersects three countries namely Namibia, South Africa and Botswana. Most of the catchment receives only 150 mm to 300 mm of annual rainfall. The rivers in the part of the catchment that falls in the Kalahari Desert do not have tributaries. This is mainly due to the low rainfall, the relatively flat terrain and presence of sand dunes. Small streams do occur in dune streets, but often terminates in interdune depressions or in the numerous pans in the area. In contrast, the upper reaches of the catchment have dense drainage networks including several dams. These variations complicate the development of an accurate and representative drainage network for the catchment. This study demonstrates how river lines can be derived from a digital elevation model (DEM) to provide a consistent dataset in a highly variable catchment spanning three different countries. Flow paths were derived from a hydrologically-improved DEM by applying a flow accumulation threshold of 100. However, flow paths could not directly be interpreted as stream lines as the drainage density in the study area varies considerably. The landscape was consequently stratified according to drainage density (DD) taking into consideration areas that are homogeneous in terms of environmental conditions (e.g. precipitation, landcover, soils and terrain). The potential DD layer was used along with Strahler stream order to select streams. Visual interpretation of Landsat 8 imagery was used to verify and modify the selection to produce the final drainage network.

INTRODUCTION

According to Vogt et al. (1) a spatial database of rivers and catchments and their characteristics, is critical for monitoring natural hydrological processes and for the sustainable management of water resources. The recent availability of two global DEMs namely the SRTM DEM (2) and ASTER Global DEM (3) provides the opportunity to automatically extract flow paths and catchment boundaries for large areas. However, many challenges still remain. This includes the conversion of flow paths to river lines and the correct delineation of catchment boundaries. Other complications include: paleo drainaige channels filled by eolian and alluvial material that are visible on satellite imagery and DEMs, but not relevant in terms of current conditions; the modification of river flow regimes due to anthropogenic influences such as land-use changes, water abstraction and relocation, as well as water storage (4, 5); and dry catchment areas (e.g. the Nossob basin) with numerous inter dune depressions, resulting in unrealistically short streams. Consequently, the research question is:

How can environmental data sets such as geology, soils, terrain, vegetation and rainfall be used to improve the automated delineation of rivers from DEMs?

METHODS

River networks were selected from flow paths, taking into consideration homogeneous areas with respect to drainage density and environmental variables such as climate, soils and terrain. This task was therefore based on the conjunctive use of digital elevation data and environmental parameters in a grid-based GIS environment which facilitates the delineation of areas of homogeneous drainage density. The landscape was stratified into drainage density classes. This process was guided by the premise that the purpose is not to derive a physical value of drainage density but to define areas with specific environmental conditions. After the delineation of areas with homogeneous drainage density channel networks were extracted from the different source areas.

In a similar study, Colombo et al. (6) defined homogeneous drainage areas on the basis of environmental factors influencing channel initiation and, therefore, governing drainage density (DD). The authors assumed that low DD is favoured in regions of highly resistant or highly permeable subsoil material, under dense vegetation cover and where relief is low, while high DD is favoured in regions of weak or impermeable subsurface material, sparse vegetation cover and mountainous terrain.

Study area

The catchment area upstream of the confluence of the Nossob and Auob Rivers intersects three countries namely Namibia, South Africa and Botswana. Most of the catchment receives between 150 mm and 300 mm of annual rainfall with the exception of the western part in Namibia, which receive between 300 mm and 450 mm rainfall annually. The rivers in the part of the catchment that falls in the Kalahari Desert do not have tributaries. This is mainly due to the low rainfall, the relatively flat terrain and presence of sand dunes. Small streams do occur in dune streets, but often terminates in interdune depressions or in the numerous pans in the area. The large rivers are, however, well defined with wide sand beds, often deeply carved into the landscape which indicates that there were previously significantly more water flow than is currently the case. In contrast, the upper reaches of the catchment have dense drainage networks including several dams.

The drainage systems in the arid to semi-arid areas of the study area have become defunct. These characteristics reflect the long and varied climatic and tectonic history of the continent and its distinctive topographic arrangement. In arid environments trees are often confined to the banks of ephemeral rivers. Apart from short-lived surface waters that remain after rainstorms, most water resources are underground and are therefore difficult to map using remote sensing.

The dominant soils in the arid and semi-arid parts of the catchment comprise Arenosols, or soils developed on transported soils in which the degree of soil formation and horizon differentiation is either weak or absent. Particular characteristics of Arenosols are low reserves of weatherable minerals and low silt-clay ratios. Colours are usually red in upland sites and dune ridges, yellow in flat areas, and grey in bottomland sites (in the major drainage lines). The parent material of Arenosols is aeolian sand or sand derived from aeolian processes or through the deposition of extensive sheets of pedisediment or hillwash as escarpments receded and pediments came to dominate the landscape.

Studies have shown that a combination of the relatively low permeability of the Kalahari sands and the low rainfall prevalent in the study area precludes recharge of groundwater aquifers by rainfall where sand cover exceeds about 15 m. It is therefore assumed that the relatively good aquifers formed by the lower units of the Kalahari Group are recharged laterally from distant sources. In some areas, such as around Stampriet in Namibia, artesian conditions are present and analysis of these waters indicates slow replenishment over tens of thousands of years (7).

Data collection

Landsat 8 imagery were downloaded for the study area using EarthExplorer (http://earthexplorer.usgs.gov/). Landsat 8 was launched on 11 February 2013 and its data as well as data from other satellites in NASA's Landsat series of satellites are provided free of charge. With the first Landsat satellite being launched in 1972 this dataset provides a wealth of information for future research.

A continuous DEM was created by Weepener et al. (8) for southern Africa by filling voids in the SRTM DEM, version 2.1 (http://dds.cr.usgs.gov/srtm/), using 20 m contour lines and the ASTER Global DEM. The resulting DEM covered the area between 19ºS and 35ºS and 12ºE and 36ºE. It includes the whole of South Africa, Swaziland and Lesotho and large parts of Namibia, Botswana, Zimbabwe and Mozambique. The void filled DEM contained 4 203 626 sinks (areas surrounded by higher elevation values) which made the DEM unreliable for delineating flow paths and catchment areas. To overcome this limitation, the DEM was hydrologically improved by applying an automated impact reduction approach. The impacts of sink filling and channel carving were compared for each sink to choose the appropriate method.

The World Soils and Terrain (SOTER) database (9) provides a uniform resource map for the southern African region at a scale of 1:1 000 000. SOTER units consist of a distinctive, often repetitive, pattern of land form, lithology, surface form, slope, parent material and soil. The dominant major soil groups that can be found in the study include Arenosols, Calcisols, Cambisols, Leptosols and Regosols.

The Global Land Cover 2000 map for Africa was used to evaluate land cover in the study area (10). The land cover classes in the study area include closed grassland, deciduous woodland, deciduous shrub land with sparse trees, open grassland with sparse shrubs, open grassland and sparse grassland.

New et al. (11) constructed a dataset of a 10' lat/lon mean monthly climatology of surface climate over global land areas, excluding Antarctica. The surfaces were interpolated from station means for the period centred on 1961 to 1990. Variables in the dataset include: mean temperature, diurnal temperature range, relative humidity, sunshine, ground-frost frequency, wet-day frequency, wind speed, and precipitation data. Of specific interest to this study is the total annual precipitation surfaces that were prepared by New et al. (11).

Data analyses

The Strahler stream order (12) was calculated and used to select actual streams from the flow paths at different levels of drainage density (DD). The drainage density was chosen by visually interpretating the Landsat 8 imagery and a map indicating potential DD. This map was stratified into different density classes by means of a scoring system of factor maps that determine drainage density. The layer has values ranging from 1 (low DD) to 5 (high DD). Table 1 shows the relationship that was applied between the DD rank and the Strahler stream orders.

Table 1: Relationship between DD rank and Strahler stream order

DD	Strahler stream order
5	All flow paths
4	Flow paths with stream order greater than 1
3	Flow paths with stream order greater than 2
2	Flow paths with stream order greater than 3
1	Flow paths with stream order greater than 4

A visual inspection of the dominant major soil group in the SOTER database showed that the Arenosols group only has main river beds, while the other soil groups also include minor tributaries.

The separation of mountainous areas from the many sand dunes in the study area proved challenging. The following procedure was followed to calculate mountainous areas:

- Calculate the maximum and minimum elevation values of the 3x3 and 6x6 neighbouring cells for each cell in the DEM.
- Subtract the minimum elevation values from the maximum elevation values to create new grids called Diff3 and Diff6, respectively. These grids contain the maximum relative height difference of the neighbouring cells. The grid derived from 6x6 neighbouring cells is used to ensure that only significant features are selected, while the grid with the 3x3 neighbouring cells is used to define the boundary of the feature. (Only using 3x3 neighbouring cells would also capture dunes.)
- Create a third grid by taking the median values of the 5x5 neighbouring cells for each cell in Diff3 (for the purposes of this study called median_grid). This is done to derive smoother boundaries of the features.
- Mountainous areas were then calculated as all areas where median_grid is greater than 20 m and where Diff6 is greater than 40 m.

It is important to note that this procedure will not only extract mountains, but also large valleys/gorges. For the purposes of this study both mountains/hills and large valleys/gorges will result in higher density stream lines. If the two types of features have to be separated, a final step can be added to the procedure which also incorporates the calculation of curvature.

Annual precipitation and land cover did not show as strong relationships with DD as mountainous areas and arenosols. Nevertheless, Tables 2 and 3 were prepared, using land cover and rainfall, respectively, to get an indication of DD for areas that do not fall in either mountainous areas or arenosols.

Table 2: Proposed DD rank for land cover classes

Global Land Cover 2000	Rank (1 = low DD; 5 = high density DD)
Deciduous woodland	3
Deciduous shrubland with sparse trees	3
Closed grassland	3
Open grassland with sparse shrubs	3
Open grassland	4
Sparse grassland	4

Table 3: Proposed DD rank for annual precipitation classes

Annual precipitation (mm)	Rank (1 = low DD; 5 = high density DD)
100-200	2
200-300	3
300-400	4
>400	5

The following rules were applied to derive the potential DD map:

- DD = 5 for all mountainous areas;
- DD = 1 if the major soil group in the SOTER database (9) is Arenosols; and
- Use the average of the rank between land cover and annual precipitation for all other areas.

RESULTS

Figure 1 illustrates the streams in the Nossob catchment area as derived from flow paths, taking the drainage density of different areas into consideration.

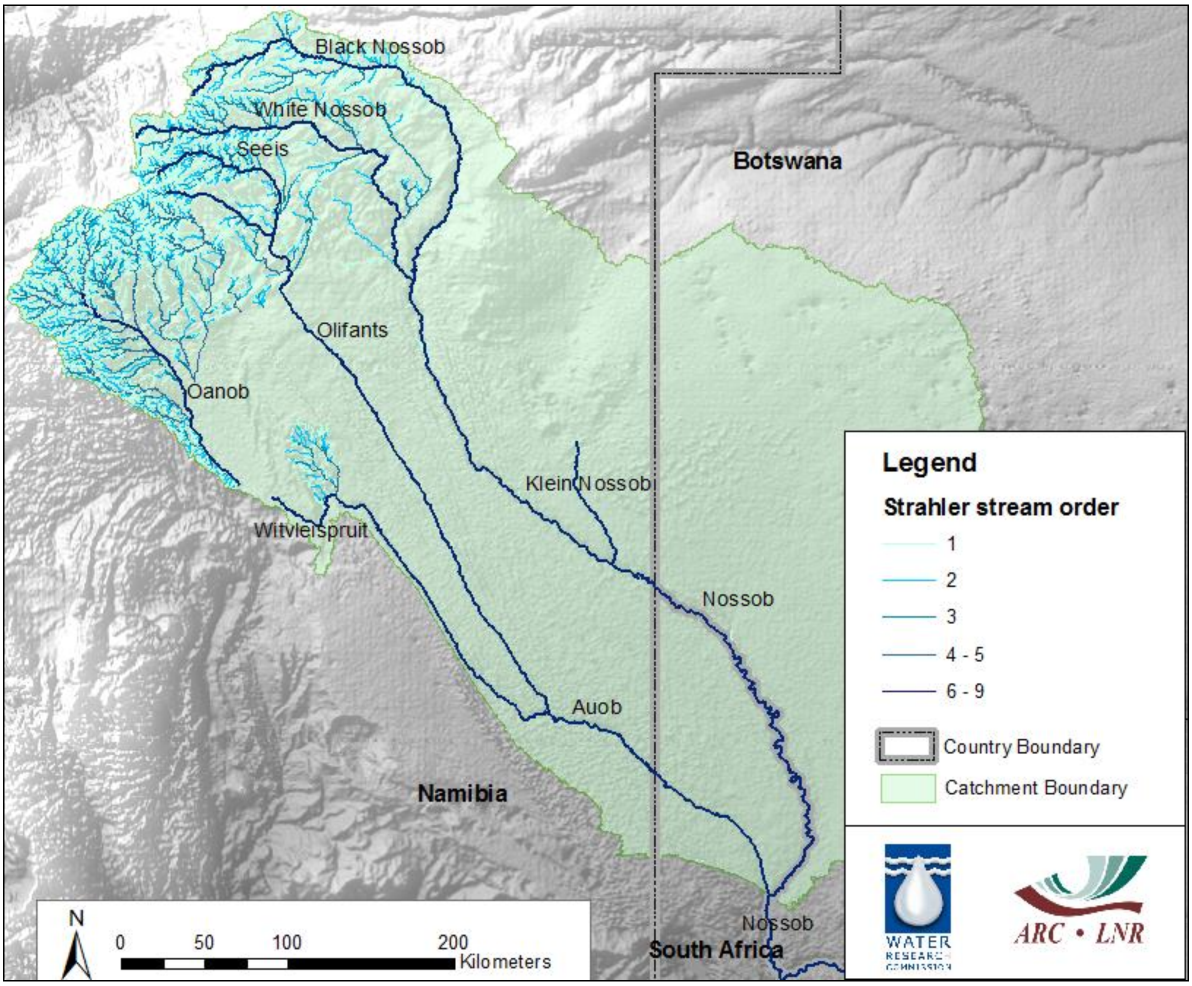

Figure 1: Stream lines in the Nossob catchment area.

CONCLUSIONS

This study demonstrates how river lines can be derived from a digital elevation model (DEM) to provide a consistent dataset in a highly variable catchment spanning three different countries. A hydrologically-improved DEM covering southern Africa was used for this purpose. Flow paths, derived from the DEM could not directly be interpreted as stream lines as the drainage density in the study area varies considerably. The landscape was consequently stratified according to drainage density (DD) and by taking into consideration areas that are homogeneous in terms of environmental conditions (e.g. precipitation, landcover, soils and terrain). Two parameters that showed a high correlation with DD were the Arenosols soil group and mountainous areas. Particular characteristics of Arenosols are low reserves of weatherable minerals and low silt-clay ratios. The mountainous areas, derived from the SRTM DEM, had a high DD while Arenosols had a low DD. All other areas were ranked according to rainfall and vegetation with sparser vegetation and higher rainfall areas resulting in higher DD. These relationships were used to generate a potential DD layer which was, along with Strahler stream order, used to select streams. Visual interpretation of Landsat 8 imagery was used to verify and modify the selection to produce the final drainage network.

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