Draft Report

Mozambique's Natural Capital

An assessment of the water source areas of Mozambique: Umbeluzi catchment, Niassa and Cabo Delgado Provinces

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1 Introduction

There is growing recognition of the interlinkages between human- and natural systems and that human well-being is both directly and indirectly dependant on the benefits they receive and derive from ecosystems. This growing understanding has led to the development of the concept of natural capital[1] as the stock of natural assets that generate (something a likened to interest in the form of) sustained flows of goods and services benefiting society (Costanza et al., 2014; Guerry et al., 2015; Naeem et al., 2015). More recently the concept of ecosystem services has been reframed as nature's contributions to people (NCP) as defined by the International Panel on Biodiversity and Ecosystem Services (Díaz, Demissew, Joly, Lonsdale, & Larigauderie, 2015).

Development strategies, policies and implementation linked through planning and management decisions, often fail to take into account, or undervalue the contributions made by natural capital, resulting in unsustainable utilization and management of resources and landscapes, and the destruction of these assets (Hein et al., 2016). The economics behind the dominant national models for growth and development do not acknowledge that there are limits to natural resources and that we live in a changing climate (Rockström et al., 2009; Steffen et al., 2015). This paradigm also largely disregards issues of social and political justice, with the result that the poor who typically are more highly dependent on natural resources and can be left ever worse off following development interventions (Cole, Bailey, & New, 2014; Dearing et al., 2014; Raworth, 2012). International recognition that the achievement of the Sustainable Development Goals and the goals of the Paris accord require a fundamental rethink of economic development models, appears to be gaining ground (Colglazier, Maskus, & Mungiu-Pippidi, 2015; Costanza, Fioramonti, & Kubiszewski, 2016; P. Dasgupta et al., 2015). So is the recognition that our use of many natural resources already exceeds sustainable levels and that active restoration or replenishment of the stock of natural capital is essential for human well-being, if not survival (Aronson & Alexander, 2013; P. S. Dasgupta & Ehrlich, 2013). One of the steps that has been taken is to get countries to account for their natural assets in the form of ecosystem or natural capital accounts[2] (Bartelmus, 2015; Hein et al., 2016; Lange, Hassan, & Alfieri, 2003; Pillarisetti, 2005). The UN recently initiated work on a system of ecosystem accounting that includes the measurement of stocks of ecosystem types; their condition; flows of services and goods provided by such ecosystem types; and the estimated value to communities, governments and businesses (based on either market transactions or non-market valuation) (UN, 2014) (**Figure 1**). The aim these accounts is to quantify and track changes in ecosystem types and associated ecosystem services over time as measure of national environmental and economic sustainability and environmental security and to inform policies, planning and management at national and sub-national levels (UNEP, 2017).

1.1 Purpose and aims of the report

Freshwater is a fundamental ecosystem service that enables human life and supports multiple aspects of our economic development. The natural capital that is fundamental to providing this benefit to people requires strategic management and careful planning so as to ensure the continued flow of these benefits. A critical first step is in understanding and defining those area, ecosystem and landscapes that are of critical importance in its provision, such that we may start to account for these benefits.

This report, which forms one of the initial step in the ecosystem accounting process, specifically focuses on identifying the water source areas in the Umbeluzi River basin and in Niassa and Cabo

[1] https://naturalcapitalforum.com
[2] https://seea.un.org/ecosystem-accounting

Delgado provinces in Mozambique because they comprise strategic ecological infrastructure (natural capital) for water security based on surface water provision (Draft Report on Natural Capital Assets in Mozambique dated 12 April 2016). The aim is to:

- Identify and locate (assess the extent of) the strategic water sources of these areas
- Describe the approach and methodology including data sources;
- Provide statistics and maps showing the estimated mean annual runoff in the study areas
- Provide some recommendations on the next steps

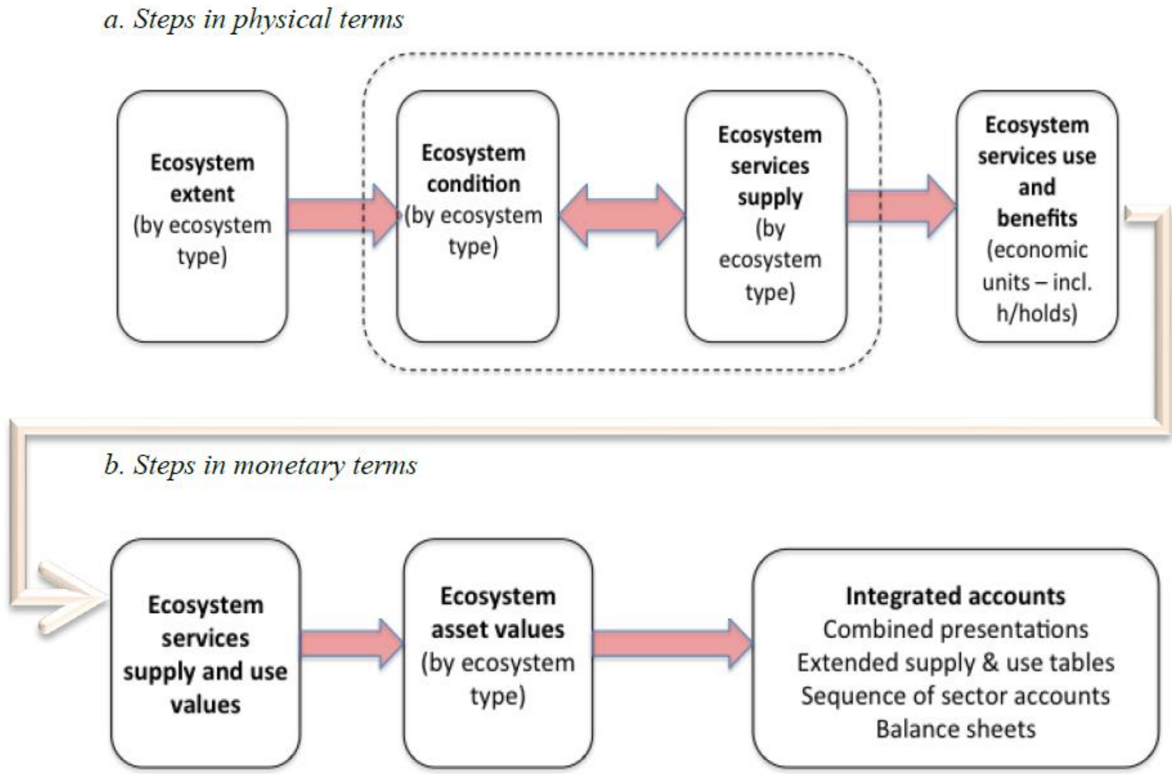

Figure 1: The relationships between the natural capital (ecosystems), ecosystem services and human well-being used in calculating the experimental ecosystem accounts (UNEP, 2017)

1.2 Water Source Areas

Water source areas are those areas that supply relatively large quantities of water, often ensuring water security far downstream from the source, even in other countries, and are pivotal in ensuring human livelihoods. They are also referred to as water towers or water factories (Messerli, Viviroli, & Weingartner, 2004; Meybeck, Green, & Vörösmarty, 2001; Viviroli, Dürr, Messerli, Meybeck, & Weingartner, 2007). Activities that have adverse impacts on the quantity and quality of water here may also have a disproportionally large impacts on downstream users. Protection of this ecological infrastructure to ensure that these areas continue to provide sustained yields of high quality water is, therefore, highly strategic (Brauman, Daily, Duarte, & Mooney, 2007; Harrison et al., 2016; Keeler et al., 2012). This critical dependence has been recognised in many parts of the world where downstream users are now supporting the implementation of water protection measures upstream, including restoration (Chichilnisky & Heal, 1999; Nduhiu, Gathenya, Mwangi, Aman, & Mutisya, 2016; Roumasset & Wada, 2013).

South Africa has recently undertaken an exercise in identifying its water source areas for surface water (Nel, Colvin, Le Maitre, Smith, & Haines, 2013; WWF-SA, 2013), and these have been integrated into the national water resources strategy (DWAF, 2013). Areas were identified and defined based on the spatial distribution of rainfall (Lynch, 2004; Schulze et al., 2008) and rainfall-runoff relationships (Nel et al., 2017; Scott, Le Maitre, & Fairbanks, 1998). These relationships were devised for estimating the pre-development runoff in ungauged catchments under natural vegetation (Midgley et al., 1994; Bailey and Pitman, 2015). These runoff estimates were calibrated by adjusting the mean annual runoff (MAR) for 4^{th} order (quaternary) catchments to match the values from the 2005 water resource assessment (Middleton & Bailey, 2008; Nel, Colvin, et al., 2013). This research found that 8% of the land area of South Africa, Lesotho and Swaziland produced 50% of the MAR. If the MAR for each part of South Africa is ranked from low to high, then areas receiving ≥135 mm are the surface water source areas. This work has subsequently been refined and extended to include groundwater and to identify those areas which were considered strategically important at the national level. These areas are now known as Strategic Water Source Areas (SWSAs) (Le Maitre et al., 2018). For the surface water SWSAs, this study used a technique which identified concentrations (high densities) of high yielding areas and defined boundaries for these areas based on the density contours.

For Mozambique, this kind of information on the baseline or pre-development runoff does not seem to exist. There are various sources of rainfall data but suitable datasets for estimating rainfall-runoff relationships are a limiting issue, especially in the northern provinces. There are reports which provide limited information on the runoff for some river systems and sub-basins of those river systems. Although WWF the team found information on the locations and the periods for which data were recorded (Estações Pluviométricas, Hidrométricas) for rain gauges and flow gauges, this dataset did not include the rainfall or runoff statistics themselves. The team also found some flow gauge records (Caudais, Niveis) but these were too incomplete to be of any value. The time and budget constraints on this project ruled out the setting up of hydrological models, so we tried various approaches as described below.

2 Approach and Methodology

2.1 Approach

The approach taken in this study is based on the fundamental hydrological concept of the water balance. This states that for any given area of land (e.g. a watershed or catchment) where there are no unaccounted for losses (i.e. no unknown subsurface leakage), the following equation holds:

Runoff = Rainfall – Evaporation ± ΔStorage

This means that the runoff over a period of time is the difference between the rainfall and the evaporation plus or minus the change in the water stored or retained in the catchment. Over long periods of time (usually at least 10 years) the increase and decreases in storage cancel each other out so that the net change in storage approaches zero. This means that if there are long term observations of any two of the other three components, the third one can be calculated from the other two using the water balance equation.

Historically, hydrologists relied on direct physical measurements of rainfall and runoff to determine the water balance because evaporation was difficult and expensive to measure and was only feasible for small areas. Many methods for estimating evaporation have been developed to get around this problem, some using data from evaporation pans and others using climatic information (R. Allen, Pereira, Raes, & Smith, 1998; Linacre, 1977; Moeletsi, Walker, & Hamandawana, 2013; Sumner & Jacobs, 2005; Thornthwaite, 1948). Most of them estimate potential evaporation because it was difficult to measure how much water vegetation was transpiring when soil moisture was limited. The develop of micro-meteorological techniques and, more recently, remote sensing methods for estimating evaporation has revolutionised studies of water balance (R. G. Allen & Kjaersgaard, 2008; Bastiaanssen, Menenti, Feddes, & Holtslag, 1998; Jovanovic, Mu, Bugan, & Zhao, 2015; Mu, Zhao, & Running, 2011; Tasumi & Allen, 2007).

Measurements of rainfall are available from various international databases and most countries have a national service which maintains weather stations and keeps long term records. Unfortunately these data are often not freely available and may be prohibitively expensive. Even when they are available, they are in the form of point data and which then needs to be translated into rainfall surfaces taking atmospheric circulation and terrain data (e.g. elevation) into account (Booth, Nix, Busby, & Hutchinson, 2014; Kriticos et al., 2012; Lynch, 2004). River flow gauge data are typically limited to a few sites in a country, and this data may also not be readily available. Although runoff data are available from the Global Runoff Data Centre (http://www.bafg.de/GRDC/EN/Home/homepage_node.html), the gauged river systems fall outside the area of interest. The next section discusses the datasets which were identified as potentially useful for this assessment.

It is important to emphasise that all these spatially extrapolated and remote-sensing based datasets are estimates and subject to errors and uncertainties and that their accuracy depends on a number of factors. One of the known weaknesses is the effects of shading of south, east and west facing slopes in rugged terrain, but most of the terrain in Mozambique is not rugged so we do not think this should be a big issue for this assessment. It is also important to recognise that this assessment is actually of relative water runoff, rather than absolute runoff. This does not mean that we ignore errors in the estimation of the runoff, in fact the estimates are adjusted to match runoff as accurately possible. What this means is: we are more interested in where most of the water is produced and that should not be strongly influenced by the accuracy of the volume estimates but rather by how accurately the spatial distribution of the driving variables, in this case the amounts of rainfall and evaporation, are captured.

2.2 Land cover

Land cover data for Mozambique were supplied by the WWF team. According to the notes, the dataset is based on Landsat images from about 2005 with the pixel classes standardised and converted to a polygon format which represents approximately a 1 in 100 000 mapping scale. The classes are based on the widely used FAO/UNEP Land Cover Classification System. The fact that this data was 10 year old was a concern for us, so too the fact that it did not incorporate Swaziland which we needed for the Umbeluzi catchment. These shortcomings/ resulted in us looking for alternatives.

There are several global and regional land cover datasets which are freely available. Unfortunately, the most recent and freely available land cover dataset for South Africa (GTI, 2015) does not extend into Swaziland or Mozambique. We also would prefer to work with raster data so, after an assessment, we chose to use a recent global dataset (2016) which seems to be a reasonable overall match to the 2005 dataset. This we sourced from the European Space Agency's Climate Change Initiative (https://www.esa-landcover-cci.org/?q=node/1) (Eberenz et al., 2016; ESA CCI LC, 2017). The dataset is designed for modelling the effects of climate change using plant functional types (PFTs) and has a spatial resolution of 300 m. It uses a very general classification of PFTs with just 10 broad classes but they do distinguish between woody-plant dominated vegetation (trees, shrubs) and herbaceous vegetation (grassland) and well as identifying croplands. The data are available as annual datasets for the period 1992-2015 (Li et al., 2018).

2.3 Rainfall data

The rainfall dataset that was used for the SWSAs in South Africa extends northwards to about 19.7°S and used rain gauges from southern Mozambique (Lynch, 2004). A visual comparison of the data with other datasets described below, suggests that the interpolated rainfall data are not very reliable except in the far south of Mozambique due to a lack of rain gauge records, but the reliable portion does include the Umbeluzi River basin.

There are several freely available sources of spatially gridded rainfall data for the world and portions of it (**Table 1**). The highest spatial resolution data that are readily available are those from the Worldclim site. We chose to use the CliMond data because of past experience with Worldclim which suggested that the higher spatial resolution was not necessarily a benefit, and the knowledge that the CliMond data are a refinement of Worldclim with additional data and quality testing (Kriticos et al., 2012). Ideally the accuracy of these datasets for Mozambique needs to be assessed against existing rainfall records data for Mozambique[3] to identify the most suitable dataset to use. Although the WWF team found a comprehensive record of the location of rain gauges and the periods for which data were recorded, this does not include the rainfall statistics themselves.

We also examined the possibility of using rainfall data made available through the Food and Agriculture Organisation's Water productivity assessment project website (for details see under evaporation) (FAO, 2017). The rainfall data are available in a database which contains daily rainfall estimated at a spatial resolution of about 5km and for the period from about 1983 to 2013 for the region from 50°N to 50°S. The database was generated by the Climate Hazards Research Group as part of their CHIRPS project (http://chg.geog.ucsb.edu/data/chirps/) and uses rainfall data derived from satellites, global models and measurements at local weather stations (Funk, Peterson, et al., 2015; Funk, Verdin, et al., 2015). The data were extracted for an area which covered the basins of the rivers in Mozambique including the Zambezi and Limpopo. Although the records covered a longer period we only extracted the annul data for the period 2009-2013 to match the evaporation data (see Section 2.4). Similar remote-sensing derived datasets are available from other sources, each of which has its weaknesses and strengths (Qi, Zhang, Fu, Sweetapple, & Zhou, 2016). We selected this one based on its use in the FAO water productivity study (FAO, 2017).

Table 1: Examples of spatial rainfall datasets that are readily available and suitable for this study.

Name or Institution	Description	Source
Climate Research Unit	Historical climate datasets of various kinds including long-term rainfall records; a source of the data used by Wordlclim and CliMond and reference datasets used for testing global climate models (Harris, Jones, Osborn, & Lister, 2014)	http://www.cru.uea.ac.uk/
Worldclim	Worldclim is a set of global climate layers (gridded climate data) for average monthly climate data for minimum, mean, and maximum temperature and for precipitation for 1970-2000. The spatial resolution ranges from 30" (about 1 km^2) to 10' (Fick & Hijmans, 2017)	http://www.worldclim.org/

[3] Examples of such datasets were extract from documents supplied by WWF and forwarded to Antonio and Herminio

Bioclim	A set of climate variables developed specifically for ecological and other modelling purposes derived from the Worldclim data and available from this site; a version is also available from the CliMond site; (Booth et al., 2014)	http://www.worldclim.org/bioclim
CliMond	The CliMond climate dataset consists of gridded historical climate data and some future climate scenario data at 10' or 30' spatial resolution. It is a refinement and combination of data from Worldclim and the 1961-1990 Climate Research Unit (CRU) (CL1.0 and CL2.0) datasets (Kriticos et al., 2012)	https://www.CliMond.org/ClimateData.aspx

Some official rain gauge records were obtained for Cabo Delgado province by the WWF team, with most of them having some records from 1987-2017 but there were many gaps. A spatial dataset with locations of rain gauges was also sources by the team. The spatial dataset indicates the province and district (Bacia) but does not name or describe the location itself, although it does include a Numero and a HYDROID. Unfortunately the records only give a name which could be the name for the District and for a town with the same name in the district. Assuming that that the name is the town name, we matched these records to gauge locations within or near to the town as indicated by the urban land cover and maps. We then extracted recent rainfall records to compare with the remote-sensing rainfall estimates to provide a form of ground-truthing.

2.4 Evaporation data

Daily evaporation data are available globally at a 1 km^2 resolution from the MODIS sensors and are typically made available as time-series composites (Mu et al., 2011). There are a number of sources of these time series including:

The National Aeronautics and Space Administration:

a) https://ladsweb.modaps.eosdis.nasa.gov/api/v1/productPage/product=MOD16A2
b) https://modis.gsfc.nasa.gov/data/dataprod/mod16.php

Land Processes Distributed Active Archive Centre:

c) https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod16a2_v006

These time series would have to be summarised to extract mean annual evaporation. In the end we chose the FAO Water Productivity Assessment for which annual data are available. This uses the SEBAL model (Bastiaanssen, Pelgrum, et al., 1998; FAO, 2017) rather than the MOD16 model (Jovanovic et al., 2015; Mu et al., 2011) to estimate Et but the results are comparable. The data were downloaded from:

http://www.fao.org/in-action/remote-sensing-for-water-productivity/database/database-dissemination-wapor/en/

Evaporation data were available at two resolutions: Level 1 at a 200 m resolution and Level 2 at a 100 m resolution. The Level 2 data are only available for a few countries globally, one of which happened to be Mozambique where annual data were available for 2009 to 2013. Level 1 data are available as single images roughly by continent. The data for Africa and the Middle-East are available for the years 2009-2017 but we decided to first try the Level 2 data.

The Global Runoff Data Centre (http://www.bafg.de/GRDC/EN/Home/homepage_node.html) maintains a database of river flow gauge records for most countries in the world including Mozambique. Some of these are on large river systems that extend far beyond Mozambique (e.g. Zambezi, Limpopo, Inkomati, Olifants) but others are more local (Pungo, Buzi, Save). The GRDC has data for the Limpopo, Zambezi and Save but not any of the other rivers. The team found a detailed monograph on the Save River (Anon, 2011) and a report is available on the Pungwe River (SIDA, 2008) but neither of these fall within in the current study area. However, the data in these reports may still be useful in future.

Spatially disaggregated runoff data from the South African SWSA study are already available for the portions of the Umbeluzi River basin that fall within Swaziland (Nel et al., 2017; Nel, Smith, & Le Maitre, 2013), so only the Mozambican runoff needs to be estimated. We estimated the runoff for Mozambique by applying the rainfall-runoff relationships used in Swaziland to similar catchments in the Mozambican portion, and then calculating the spatial runoff distribution in that part of the catchment. There is a report on the Umbeluzi catchments and the Pequenos Libombos dam (Droogers, Boer, & Terink, 2014) which includes data which is compared with the estimate of runoff from this study.

2.5 Using rainfall to estimate evaporation

In addition to using the rainfall and evaporation water-balance approach we used a generalised relationship between evaporation and rainfall derived from more than 300 long-term catchment studies which examined the effects of changes in the dominant vegetation in those catchments (Zhang, Dawes, & Walker, 1999, 2001). Their approach also is based on the fundamental water balance approach developed by (Budyko, 1974) which incorporates the realities that where rainfall is high, evaporation becomes limited by the available energy, and where rainfall is low evaporation is limited by water availability. They derived the following basic equation:

$$\frac{ET}{P} = \frac{1 + w\frac{E_o}{P}}{1 + w\frac{E_o}{P} + \frac{P}{E_o}}$$

Where ET = evaporation, P = rainfall and *w* = the plant available water coefficient (Zhang et al., 1999). They fitted regression models to the catchments with different vegetation types and found that E_0 could be replaced with a constant E_z. For herbaceous vegetation (e.g. pastures, grasslands) E_z was 1100 and for woody vegetation (trees, shrubs) E_z was 1410. The plant available water coefficient was 0.5 for herbaceous and 2 for woody vegetation due to the well-established fact that woody vegetation generally has deeper root systems than herbaceous vegetation (Canadell et al., 1996; Jackson et al., 1996). Estimates for mixtures of these two vegetation types can be derived by calculating the proportion of woody in a given area and summing them as follows: woody estimate x wood proportion + grassland estimate x grassland proportion (Zhang et al., 1999, 2001).

In our experience, these relationships have proved to be quite robust and appear to work for catchments sunder plantations and natural vegetation catchments in South Africa, although commercial forest plantations typically have higher evaporation than predicted by the woody vegetation model (Scott, Bruijnzeel, Vertessy, & Calder, 2004). This is not surprising given that these plantations are deliberately managed to maintain high growth rates and productivity unlike natural woody vegetation.

2.6 Umbeluzi catchment

As noted in the previous section on the data sources, we adopted a different approach for the Umbeluzi catchment because we had an estimate of the rainfall for the whole catchment from the same dataset that was used to identify the SWSAs in South Africa. The first task was to divide the Mozambican portion of the catchment into sub-catchments. The WWF team found some catchment and sub-catchment datasets that are used in Mozambique, including the catchment boundaries available from the HydroSHEDS database (http://www.hydrosheds.org/). The HydroSHEDS catchments or river basin boundaries are available at different levels from one (1st order) to twelve (12th order). After some experimentation the 6th order catchments proved to be a good match for the quaternary catchment boundaries used in South Africa (Midgley et al., 1994). The two sub-catchment datasets were combined an edited to produce a single set of sub-catchments for the entire river system.

The curve numbers used in the rainfall-runoff relationships for the SWSA study were already available for the quaternary sub-catchments within Swaziland. Only one rainfall-runoff curve number was use for all the Swazi and South African quaternary catchments which border on Mozambique so that curve number was also used for the Mozambican sub-catchments. The use of this curve is a reasonable approximation given that the climate in the Lowveld regions of Swaziland and South Africa is similar to that east of the Libombos mountains. The next step was to extract the spatial rainfall data for the entire catchment and calculate the runoff from the rainfall-runoff relationships using the following equation (Scott et al., 1998):

$$MAR = (MAP - B + 3) + \frac{C}{\exp(\frac{MAP - A}{C})}$$

Where MAR = Mean Annual Runoff, MAP = Mean Annual Precipitation, exp = e to the power of, A = 75+45Z, B=225+135Z, C = 150+90Z and Z = the curve number (1-9). The curve number is related to the rainfall, ranging from 1 for low rainfall areas to 9 for high rainfall areas.

The initial estimates of the runoff were then compared with published estimates of the runoff for the quaternary sub-catchments in Swaziland (**Table 2**).

Table 2: The relationship between the mean annual runoff from the most recent water resources assessment (Bailey & Pitman, 2015) ***and the estimated mean annual runoff from the rainfall-runoff relationships.***

Quaternary catchment	MAR mm	Estimated MAR (mm)	MAR Ratio
W60A	411.2	387.9	1.0601
W60B	439.0	410.2	1.0701
W60C	414.3	237.7	1.7431
W60D	206.0	102.0	2.0202
W60E	73.0	45.1	1.6197
W60F	71.5	37.8	1.8914
W60G	187.0	122.3	1.5294
W60H	70.0	31.5	2.2231
W60J	77.1	27.8	2.7755
W60K	75.3	32.4	2.3220

The data shows that there is a clear trend, with difference (MAR ratio) increasing as the mean annual runoff decreases. However, these relationships only apply to the sub-catchments in Swaziland and similar relationships need to be derived for the sub-catchments in Mozambique. Since runoff and rainfall are related, and rainfall data are available for all the sub-catchments, a linear regression was fitted to the mean annual rainfall in each catchment and to the correction factors (ratios). The regression equation was:

$$MAR\ Ratio = -0.0023 * Mean\ Annual\ Rainfall + 3.7496$$

The statistical analysis indicates that the relationship is significant ($R^2 = 0.7197$, $n = 10$ and $P < 0.01$) making this a reasonable relationship for estimating the correction factor (MAR ratio) for the Mozambican sub-catchments. The estimated corrections for the catchments were then applied to the sub-catchment runoff estimates to produce the final runoff estimates for the Umbeluzi catchment.

2.7 Niassa and Cabo Delgado

We used three different approaches for estimating the spatial distribution of runoff in these two provinces: (a) FAO water productivity data for rainfall minus the data for the actual evaporation using the 5-year mean data calculated form the annual data for the period 2009-13 as well as the differences for the individual years; (b) the CliMond mean annual rainfall minus the 5 year mean evaporation from approach (a) above after resampling the evaporation data to the same spatial resolution as the rainfall data; and (c) the catchment-data based model for estimating evaporation from rainfall with separate estimates for whether the dominant vegetation is herbaceous or woody plants.

2.8 Defining the Water Source Areas

We planned to use the kernel density method used in the South African study (Le Maitre et al., 2018) in this assessment, but this is highly time consuming and does not work well with the coarse spatial resolution of the data and the relatively small sizes of the study areas. So we converted the raster runoff data to point values and used a function that builds polygons from points to delineate the water source areas on the maps.

3 Results

3.1 Umbeluzi catchment

The headwaters of the Umbeluzi catchment are located within Swaziland. The dominant vegetation is a mosaic of trees (15.0%), shrubs (48.2%) and grassland (18.6%) with some areas of cultivated land (16.0%) (**Figure 2**). Open water accounts for 0.9% and the remaining classes 1.4%. Based on the FAO water productivity land cover (FAO, 2017), the cultivated land is virually all dryland production except for the subcatchments downstream and to the south-east of the Mnjoli dam in Swaziland which are irrigated sugar cane. This dam was built to secure the water for this extensive area of irrigated sugarcane (Droogers et al., 2014). The Lebombo mountains are characterised by a high proportion tree of cover. There are further cultivated lands, mostly dryland but with some irrigation around and below the Pequenos Libombos. The lowland areas of Swaziland are known to be severely invaded by *Chromoalena odorata* (Triffid weed) and the there are extensive invasions of *Acacia mearnsii* and some pines in the upper catchments. These latter invasions account for some of the tree cover in those catchments. Urban areas such as Mbabane and Maputo occur mainly outside the catchments although there are smaller towns within the catchment. Mbabane is supplied with water from the Hwane dam which is sitiuated in the headwaters of this catchment. Abstraction of river flows for irrigation and for town water supplies via the dams and other abstraction points will influence the amount of runoff in the catchment compared with pre-development conditions.

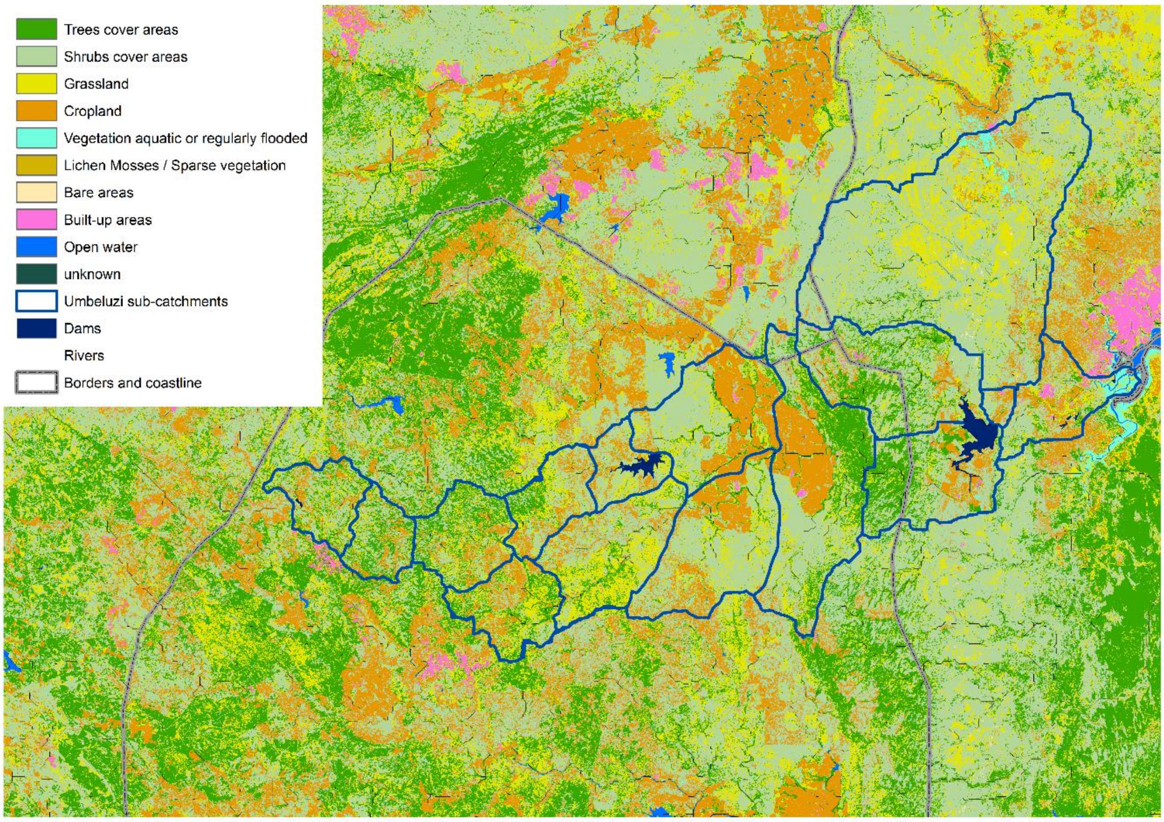

Figure 2: Land cover in the Umbeluzi catchment based on 2016 data from the European Space Agency Climate Change Initiative (https://www.esa-landcover-cci.org/?q=node/1)

Most of the rainfall in the Umbeluzi catchment occurs along the escarpment in western Swaziland where the annual total rainfall exceeds 1200 mm (**Figure 3**). Relatively little rainfall occurs in the sub-catchments in Mozambique where the annual rainfall ranges from 510 to about 700 mm. The main reason for the increase in rainfall from east to west is the increase in elevation from east to west. The top of the catchment is at about 1800 m above sea level while the Mozambican plains east of the Libombos are less than 100 m above sea-level. The rain bearing winds come mainly from the east and north-east and create this strong orographic gradient with the highest rainfall on the seaward slope of the escarpment. There is a small area with slightly higher rainfall at the mouth of the Umbeluzi River in Maputo Bay.

The spatial distribution of the rainfall has a direct influence on the distribution of the runoff with parts of the headwater catchments having a MAR of more than 400 mm (4000 m^3/ha) (**Figure 4**). The runoff intervals were chosen to match percentiles of the runoff from the whole catchment. Areas producing ≥199.0 mm of MAR account for 50% of all the MAR in the catchment, and areas with ≥410 mm account for 25% of all the runoff. Areas with ≤ 66 mm produce 25% of the runoff. These data make it clear that the areas producing 50% of the MAR are essentially all located within Swaziland rather than Mozambique (**Figure 5**), especially if the location of the Pequenos Libombos (the lowest dam in the catchment, **Figure 4**) above the confluence with the Movene River is taken into account. If only the Mozambican portion of the catchment is considered (**Figure 6**), then there are two water source areas. One extends across the valley between the Lebombo mountains and a ridge to the east between Pequenos Libombos and Moamba, and the other lies in the northern part of the Movene River catchment near Chai-Chai.

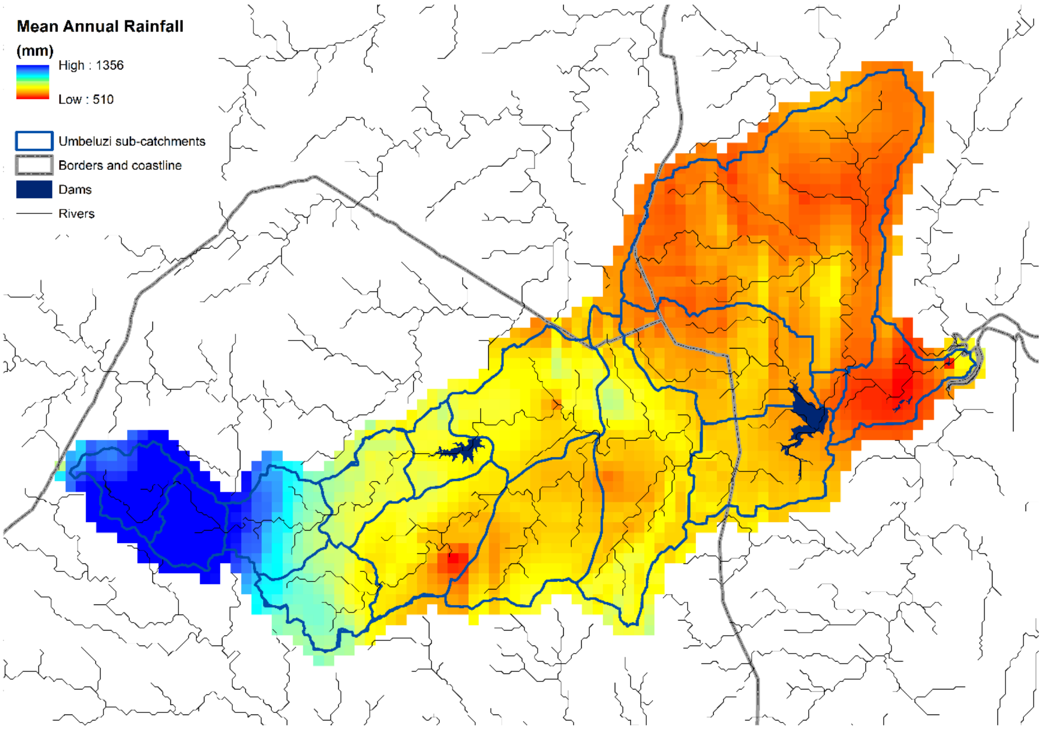

Figure 3: The spatial distribution of the mean annual rainfall in the Umbeluzi catchment estimated by Lynch (2004) based on medium to long-term rain gauge data for South Africa, Swaziland and Mozambique.

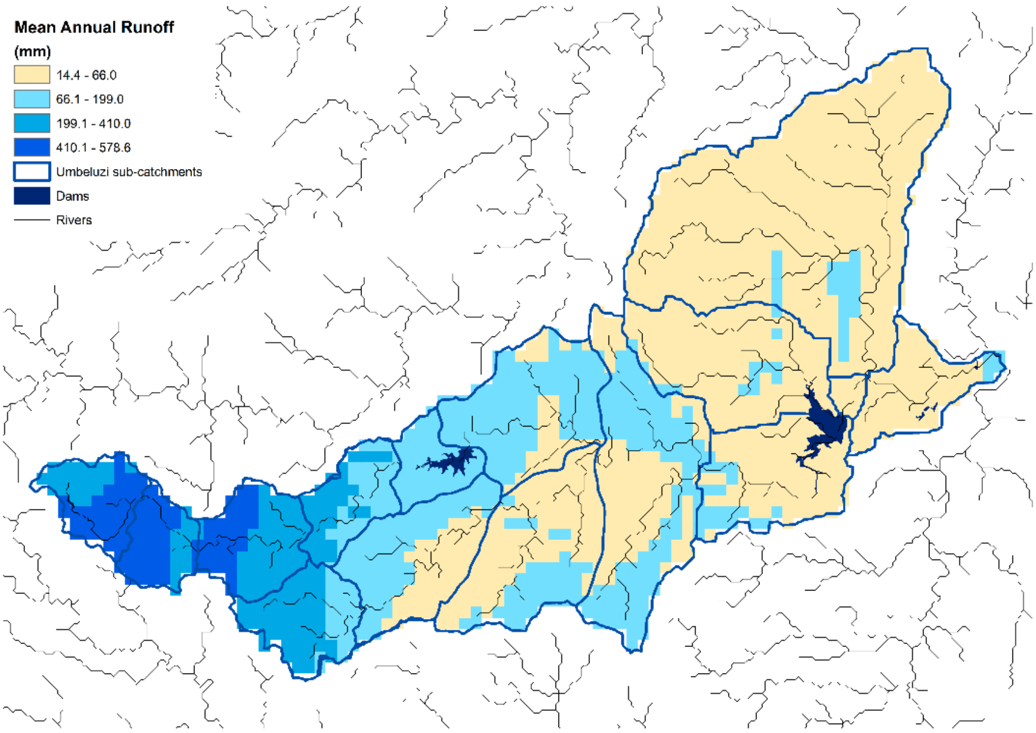

Figure 4: Estimated mean annual runoff for the Umbeluzi catchment based on the rainfall and rainfall-runoff relationships used in the South African Strategic Water Source Area study (Nel et al., 2017)***. Areas with ≥199 mm of runoff produce 50% of the runoff.***

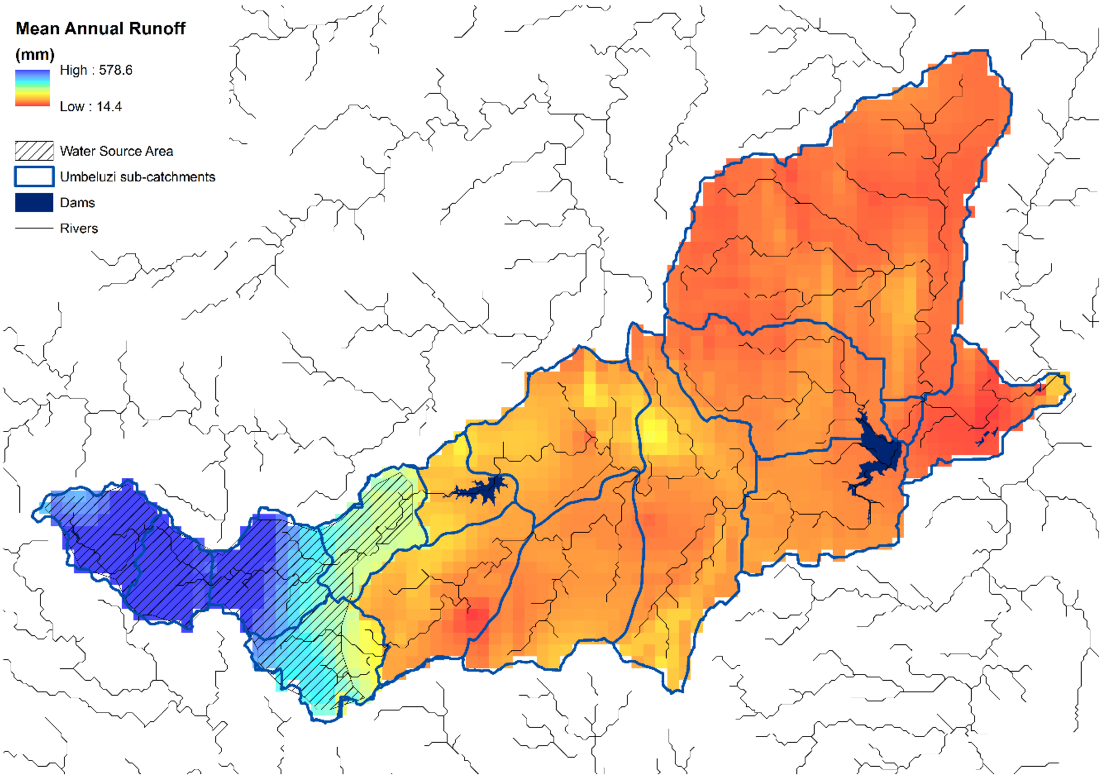

Figure 5: Mean annual runoff in the Umbeluzi catchment showing the water source area (i.e. the area that generates 50% of the runoff) for the whole catchment.

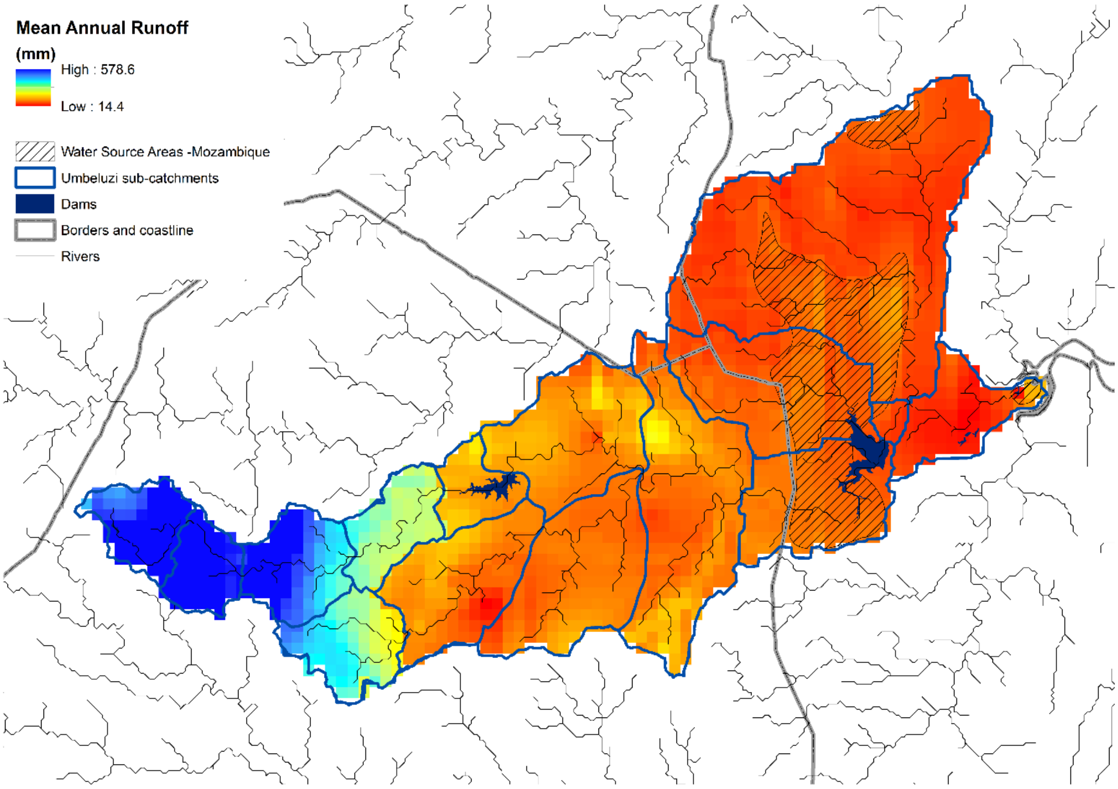

Figure 6: Mean annual runoff in the Umbeluzi catchment showing the water source area (i.e. the area that generates 50% of the runoff) for the Mozambican portion of the catchment.

3.2 Niassa and Cabo Delgado

As discussed under the approach and methods, the rainfall dataset that was used for the South African study of SWSAs is limited to the far south of Mozambique. The northern part of Mozambique also has a very different climate to the south, so the South African rainfall-runoff relationships would not be appropriate. So three approaches were tested:

a) Using estimates from remote sensing of the spatial distribution of the rainfall and evaporation from the FAO water productivity study (FAO, 2017) to estimate the runoff
b) Using information from spatially interpolated rainfall records and the FAO estimates of evaporation to estimate the runoff
c) Using a general model for estimating the runoff based on the rainfall and the dominant vegetation type.

The two provinces are situated adjacent to each other and comprise two main river basins: the Rovuma which is shared with Tanzania with the Rovuma River forming the border; and the Lurio River which is shared with Nampula province in the south. They also share the Messalo River which has its headwaters in Niassa but is mainly within Cabo Delgado. The rest of Cabo Delgado includes a numerous smaller rivers, including the Montepuez, Megaruma and Uncindi (**Figure 7**).

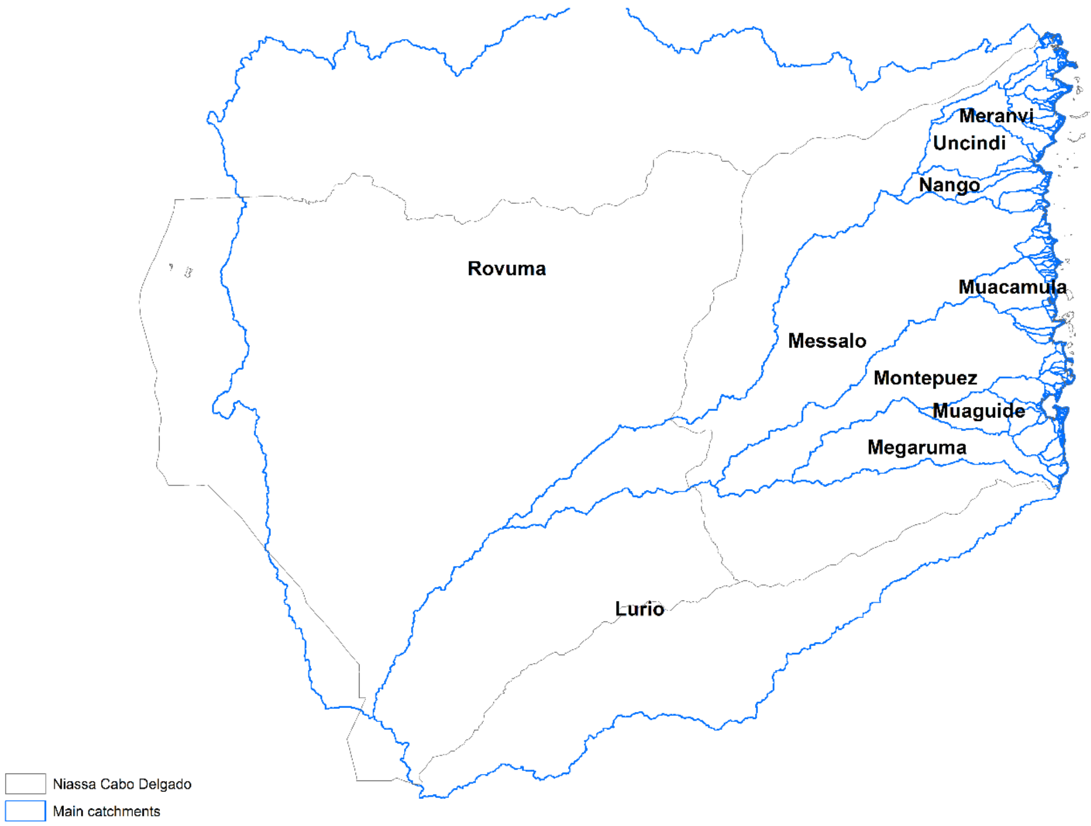

Figure 7: The river catchments overlapping and within Niassa and Cabo Delgado provinces. Only the main ones have been labelled.

The land cover is characterised by a mixture of tree (44.3% of the area) and grassland dominated areas (37.0%) with only 5.9% under shrubland and 3.5% under waterbodies and wetlands (including mangroves). Sparse vegetation, bare areas and open water account for about 0.2% (**Figure 8**). There are dryland cultivated areas (in total 9%) in the headwaters of the Rovuma and Lurio River basins and in smaller areas around settlements and small towns, with some very small irrigated areas along some of the rivers in the coastal plains and hinterland. The limited degree of transformation of the land cover in the catchments in these provinces means that the current day runoff in these river systems should be close to the pre-development runoff.

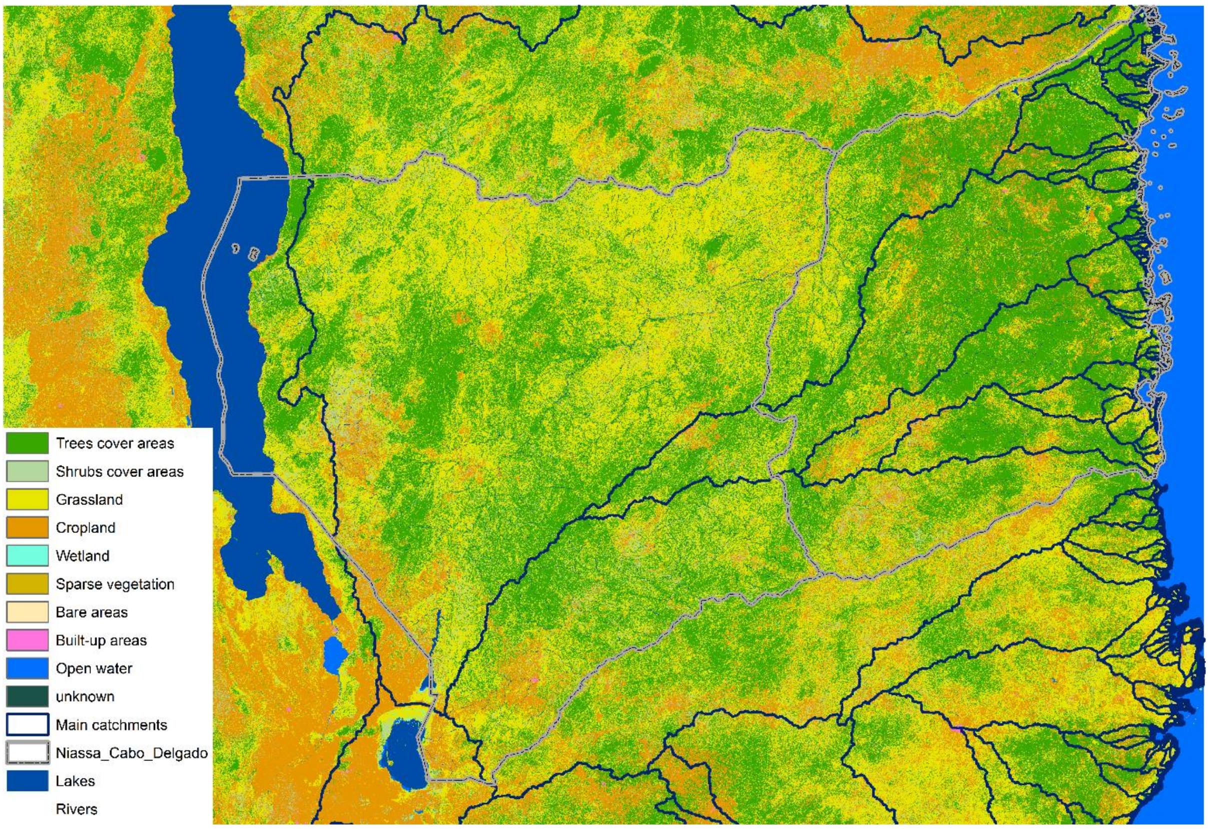

Figure 8: Land cover in Niassa and Cabo Delgado based on 2016 data from the European Space Agency Climate Change Initiative (https://www.esa-landcover-cci.org/?q=node/1)

Spatially interpolated data from long-term rainfall records show that the highest rainfall in these two provinces occurs in the relatively high-lying areas to the east of Lake Malawi and in the far south near Lake Chilwa in Malawi (**Figure 9**). The southern coastal and hinterland and a portion of the Lurio River catchment get the lowest rainfall.

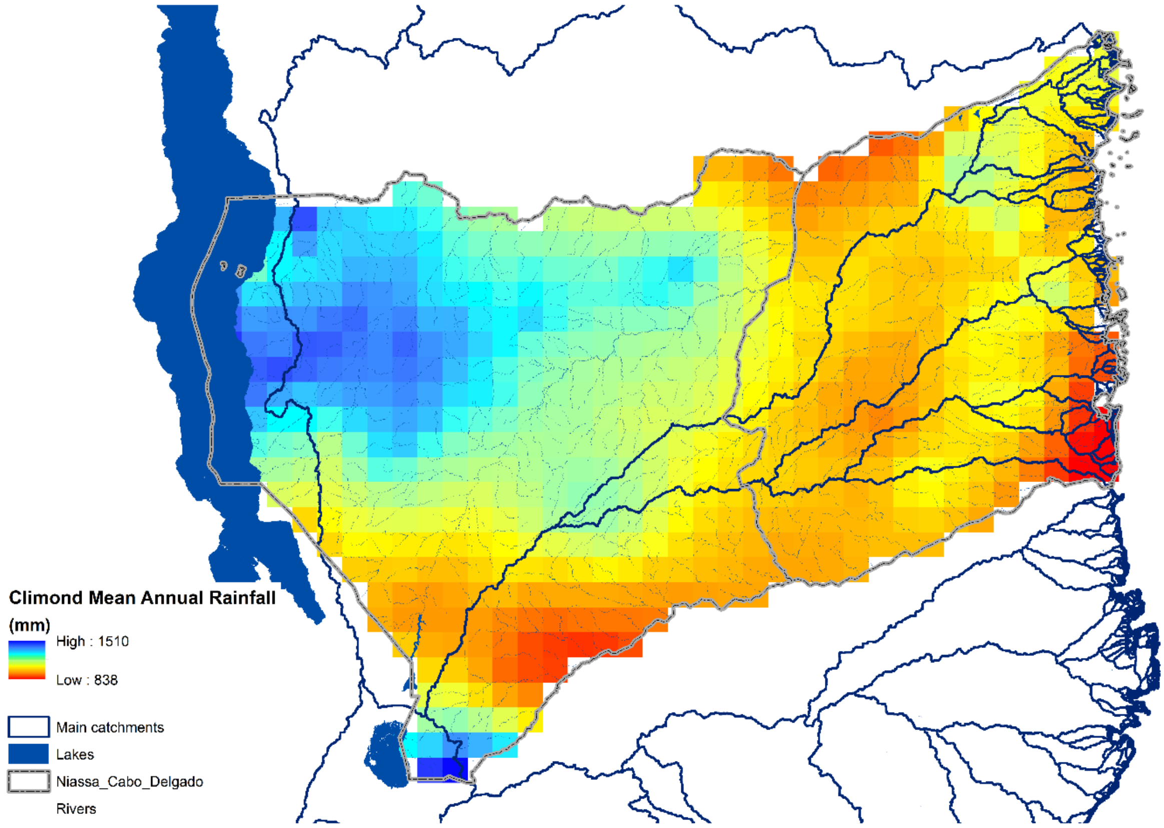

Figure 9: The mean annual rainfall in Niassa and Cabo Delgado provinces based on the CliMond dataset interpolated from weather station rainfall records (Kriticos et al., 2012).

Both the rainfall amount and distribution differs markedly from the remote sensing based estimates whose mean annual rainfall for the years from 2009 to 2013 is about 45-48% lower than the long-term datasets (**Figure 10**). There is higher rainfall in the west near Lake Malawi and also in the coastal portions of the Lurio and Megaruma River systems. The area of higher rainfall near Lake Chilwa is not evident in this dataset. Although satellite based rainfall estimates are known to underestimate rainfall they normally represent the spatial distribution fairly accurately. Some reasons for these substantial discrepancies are dealt with in the discussion. However, the marked differences in the amounts and spatial distributions suggest that the lack of publically accessible rainfall data from representative stations in Mozambique may be adversely affecting the calibration of the remote-sensing based estimates of the actual rainfall in this area.

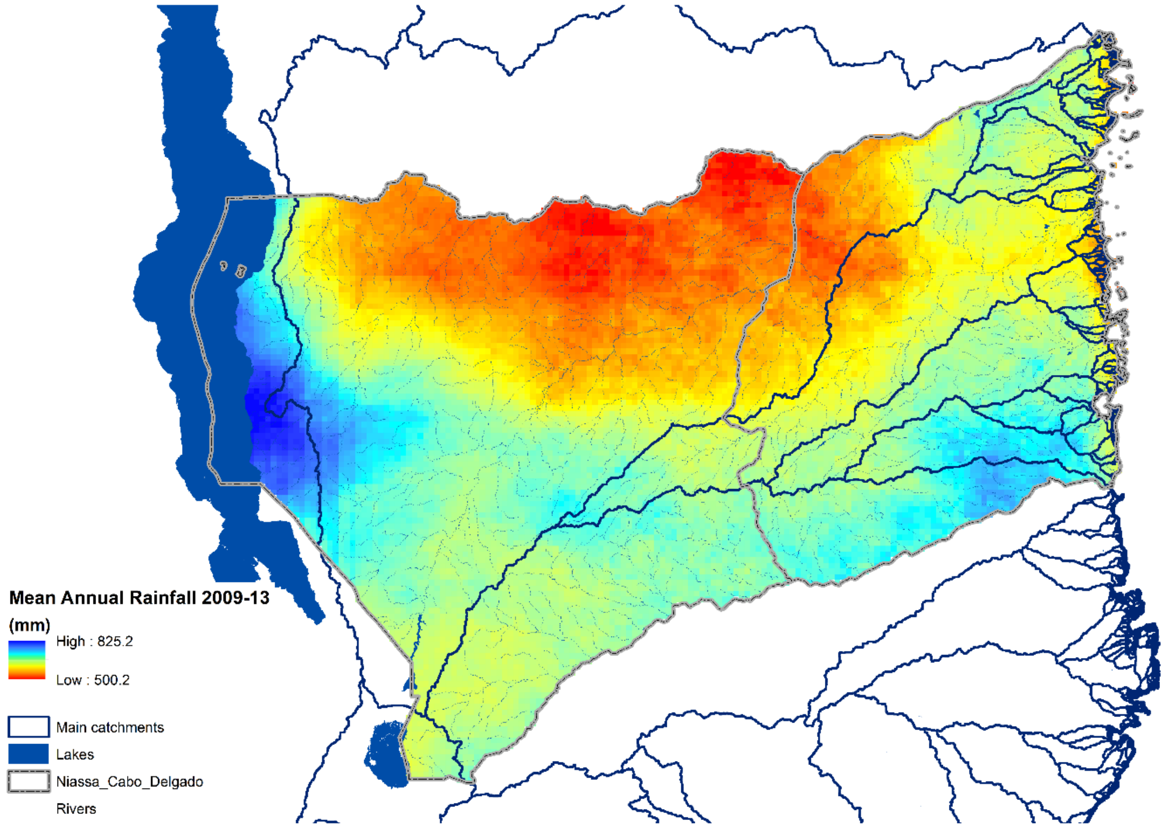

Figure 10: The mean annual rainfall in Niassa and Cabo Delgado provinces based on estimates from remote sensing for the period 2009-2013 (data from the CHIRPS project, see the Methods)

The mean annual evaporation for the period 2009-2013 showed very high values for Lake Malawi itself (>2 000 mm) which has very high evaporation because it is open water (**Figure 11**). There are some areas with higher evaporation on the eastern side of Lake Malawi (1 400-1 600 mm) but most of Niassa and Cabo Delgado have an annual evaporation between 400 (orange) and 1 100 mm (cyan).

Approach (a) is based on the water balance and assumes that rainfall minus evaporation = runoff over a long-enough period. However, when the remote-sensing based rainfall and evaporation were subtracted from each other most of these two provinces had zero or negative runoff with limited areas of low runoff being located in the southern portions of the provinces. It is not clear whether this is due to an overestimate of the evaporation or an underestimate of the rainfall but the latter seems more likely given the substantial discrepancies between the rainfall record-based data (**Figure 9**) and the remote-sensing based estimated of the rainfall (**Figure 10**). Also, since the evaporation data are extensively used in the water productivity study and, if incorrect, would show up as anomalous productivity values, it is likely they would be reasonably close to the actual evaporation.

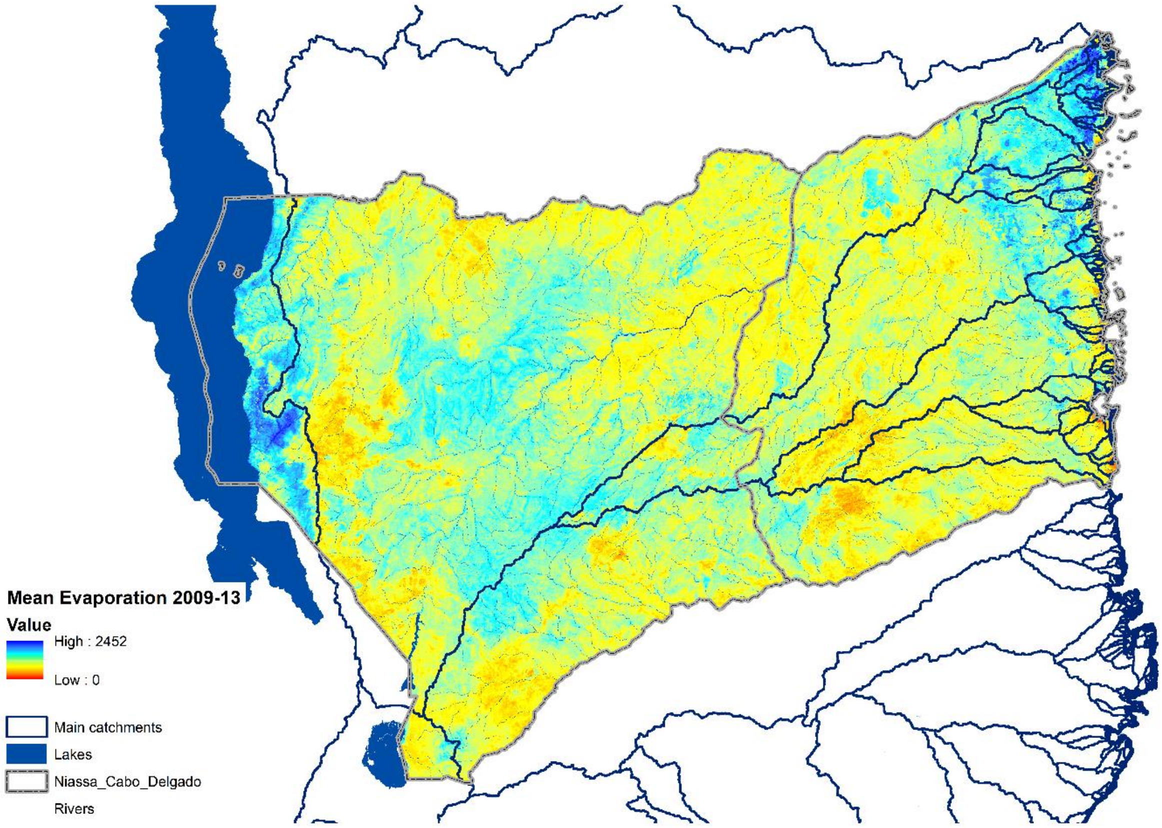

Figure 11: Mean annual actual evaporation values for Niassa and Cabo Delgado provinces based on data for 2009-2013 from the FAO water productivity study (FAO, 2017).

The problems with approach (a) led us to try approach (b) which uses the remote-sensing evaporation estimates and interpolated rain gauge rainfall records. We first extended the period over which the mean annual evaporation was calculated to 2009-2016[4] to use all the available data. Then we resampled these datasets to the same spatial resolution as the CliMond dataset and calculated the mean evaporation for the period. We then subtracted the evaporation from the rainfall. This still led to some negative runoff values but the negative values were generally close to zero and confined to just a few locations, mainly single pixels. The map still shows that a large part of these two provinces has a very low mean annual runoff (<10 mm) (**Figure 12**) with the highest runoff being generated in the high-lying areas in the headwaters of the Rovuma River basin and in the south of Niassa in the Lake Chilwa basin and the headwaters of the Lurio River basin. These figures seem unreasonably low given the relatively high rainfall experienced throughout these two provinces based the data from the CliMond database (**Figure 9**), so we tried approach (c).

[4] We did this by using level 1, 200 m spatial resolution evaporation data which are available for a longer period.

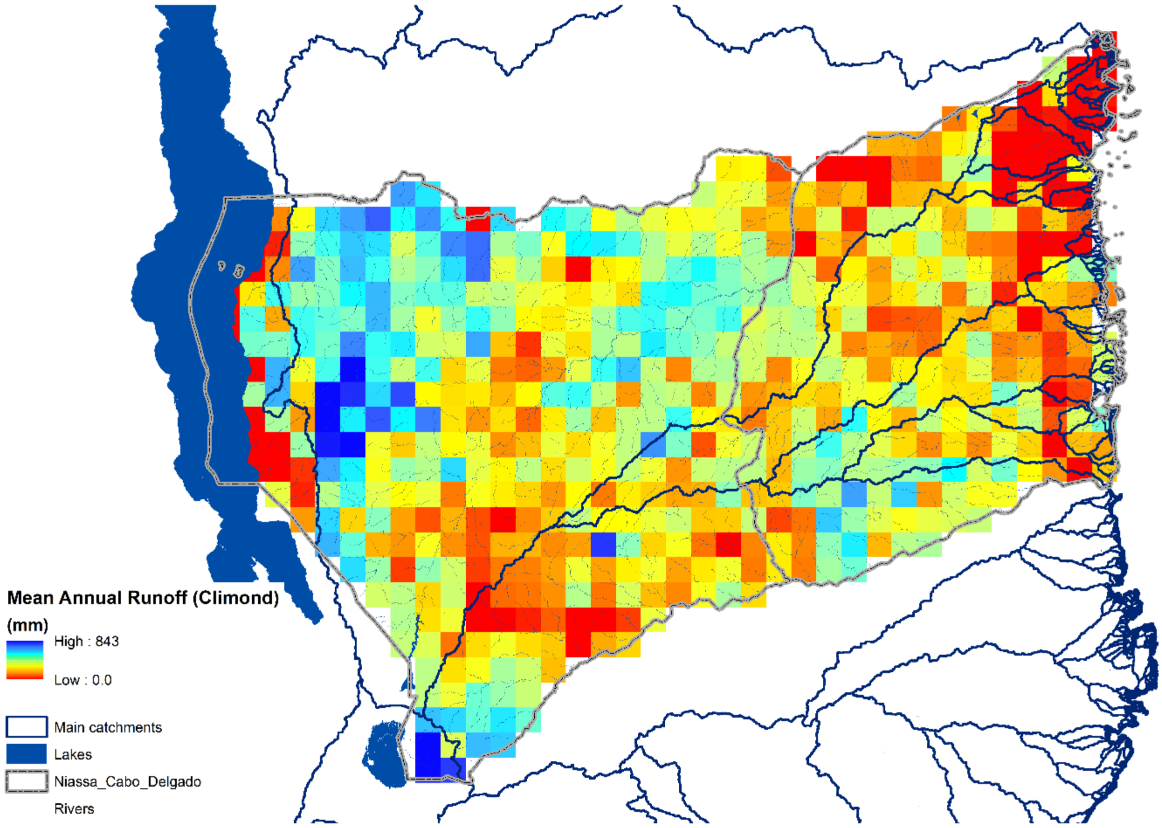

Figure 12: Mean annual runoff for Niassa and Cabo Delgado provinces based on the difference between the mean annual rainfall estimated from rainfall records (Figure 9) and the mean annual evaporation for the period 2009-2016 (FAO, 2017)

Approach (c) estimates the spatial distribution of the runoff using rainfall-evaporation models for woody and grassland (herbaceous) dominated vegetation types (Zhang et al., 1999). For this analysis we used the CliMond rainfall dataset which we believe to be more reliable than the CHIRPS (see the Discussion for more on this issue). Since this model uses rainfall to estimate evaporation (Zhang et al., 1999) the rainfall and the evaporation surfaces are similar. In the wettest parts of these provinces (near Lake Malawi in the north-west and Lake Chilwa in the far south), the mean annual evaporation exceeds 1 000 mm, or about 66% of the mean annual rainfall. The grassland evaporation, not shown, is substantially lower, with estimates ranging between 574 and 753 mm per year compared with 738 to 1100 mm for the woody vegetation. If the vegetation was mainly woody plant dominated, the estimated mean annual runoff in these two provinces would range from 100 to 411 mm per year, or 1 000-4 110 m^3/ha/year in terms of volume (**Figure 14**) whereas it would range from 264-757 mm if grasslands were the dominant vegetation.

Whether the dominant cover is grassland or woody vegetation, the highest runoff is clearly generated in the headwaters of the Rovuma River and the other headwater tributaries. In the Lurio River basin the highest runoff is concentrated in the headwaters near Lake Chilwa, and in the Movene River there is slightly higher rainfall in the headwaters. In the other rivers the runoff is very evenly distributed. The estimated total MAR under grassland vegetation for the river basins, and portions of river basins in Niassa and Cabo Delgado is about 94 337 million m^3 under grassland which more than twice that for the woody vegetation at 42 803 million m^3 (**Table 3**). The differences vary between the basins with the greatest differences being in the basins with the highest runoff, such as Niassa which drains into Lake Malawi via a number of small rivers and streams.

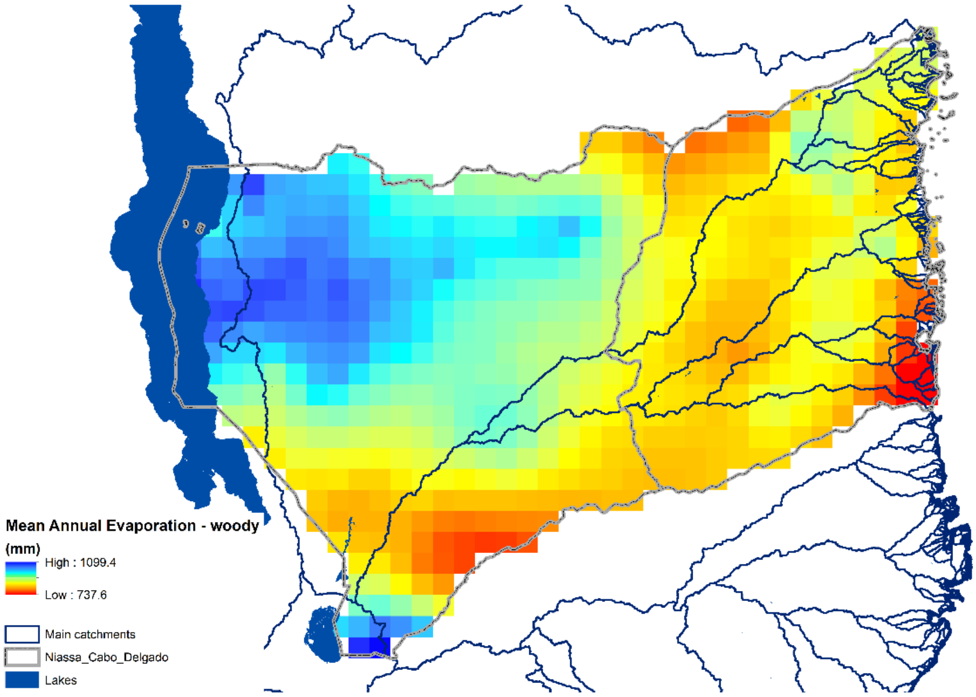

Figure 13: Mean annual evaporation values for woody vegetation Niassa and Cabo Delgado provinces based on the generalised model for estimating evaporation from rainfall (see section 2.5) and the CliMond spatial mean annual rainfall dataset (Kriticos et al., 2012) (Figure 9).

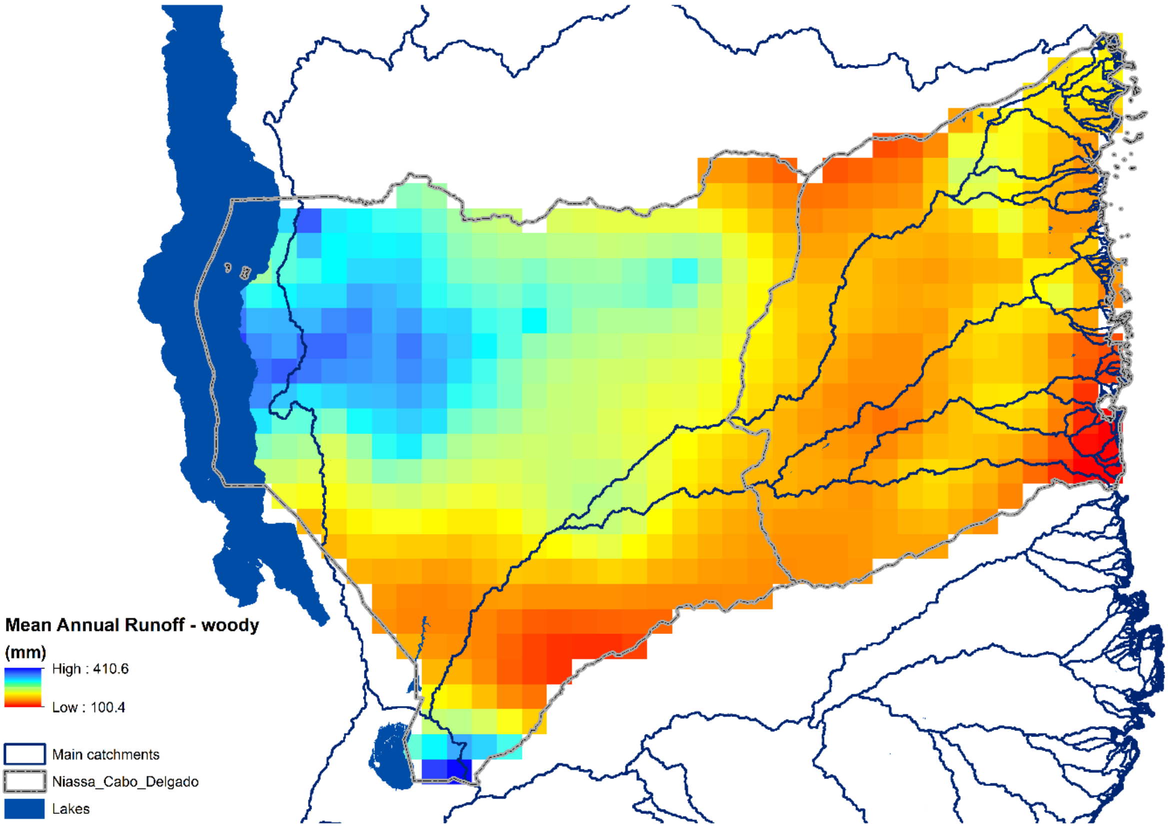

Figure 14: Mean annual runoff values for woody vegetation in Niassa and Cabo Delgado provinces based on the difference between the estimated evaporation (Figure 13) and the CliMond spatial mean annual rainfall (Kriticos et al., 2012) (Figure 9).

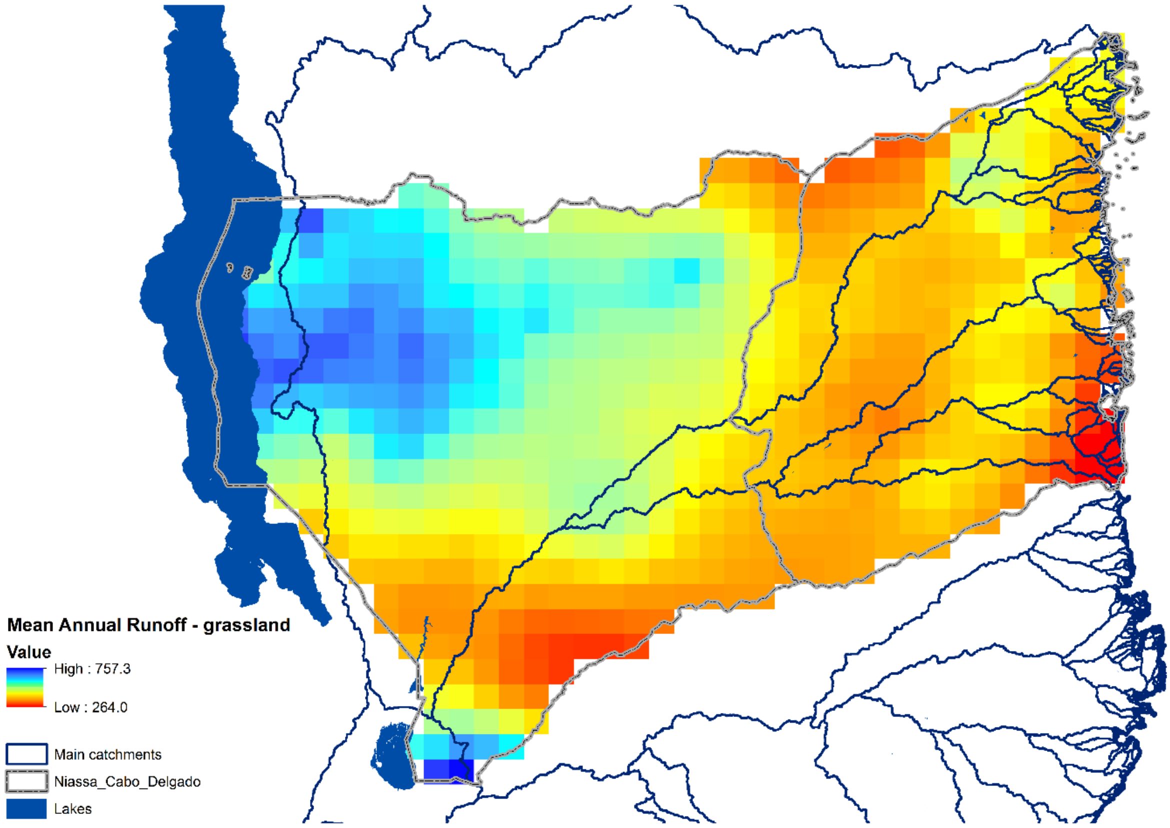

Figure 15: Mean annual runoff values for grassland vegetation in Niassa and Cabo Delgado provinces based on the difference between the estimated evaporation (Figure 13) and the CliMond spatial mean annual rainfall (Kriticos et al., 2012) (Figure 9)

Table 3: Summary of the runoff for the river basins and portions of river basins in the Niassa and Cabo Delgado provinces based on the data in Figures 11 and 12.

River Basin Name	Catchment Area (km^2)	Grassy vegetation			Woody vegetation		
		Mean Annual Runoff (mm)	Standard deviation (mm)	MAR (million m^3)	Mean Annual Runoff (mm)	Standard deviation (mm)	MAR (million m^3)
Lurio*	34734.87	403.9	47.2	14030.79	174.9	18.9	6073.46
Mandimba**	2868.74	398.4	25.2	1142.90	206.9	14.2	593.63
Megaruma	5606.61	401.1	33.6	2248.54	173.2	14.8	970.87
Menembo	3014.96	634.8	53.5	1914.09	185.4	17.4	558.89
Meranvi	2471.05	432.8	18.2	1069.55	193.1	21.0	477.02
Messalo	22794.55	414.2	22.0	9441.14	145.6	29.9	3318.36
Montepuez	9588.47	407.4	25.1	3906.31	278.8	45.9	2673.45
Muacamula	2931.61	419.2	29.23	1228.86	193.4	10.8	566.82
Muaguide	3918.27	348.4	54.1	1365.07	182.3	13.1	714.44
Nango	2351.37	431.9	35.0	1015.66	324.1	36.7	762.13
Niassa**	8489.22	566.9	70.9	4812.45	178.4	14.6	1514.49
Rovuma*	101211.16	504.2	75.4	51033.34	238.5	47.7	24141.23
Uncundi	2479.13	455.3	23.3	1128.65	176.8	28.3	438.30

* Part of the basin only; ** Mandimba drains into Lake Chilwa and Niassa into Lake Malawi

Data on the flows in the Rovuma River basin are available from runoff data collated by the Global Runoff Data Centre (http://www.bafg.de/GRDC/EN/Home/homepage_node.html) but only for the full river and not for just the Mozambican portion. There is a study which used modelling to estimate flows in the Rovuma River system with inputs from various resources but the estimates were still subject to a high degree of uncertainty (Minihane, 2012). This study included a graph showing historical flow measurements on the Lugenda River, the major tributary of the Rovuma River within Mozambique (op cit. Figure 2). No statistics were given with this figure but it gives a mean annual flow figure of 195 m^3/second (6 154 million m3/year). The size of this catchment is given as 40 300 km^2 so the volume is equivalent to a runoff of about 152.7 mm/year. The location of the gauge on the Lugenda River is not given and the dataset of river flow gauges provided by the WWF team lists 18 gauges on this river but does not identify any of them using the gauge code given in the flow study (Q202). If this location can be confirmed we could then compare these data with runoff estimates from this study.

The runoff estimates can be adjusted to values between the grassland and woody vegetation depending on the relative cover of these two vegetation classes. We have not done this step of the analysis because the focus here is primarily on where most of the runoff comes from rather than estimating the volume, although we clearly want to match the volumes as closely as possible to observed flows. An analysis of the water sources areas for these two provinces and the main river basins found that for the provinces, about 25% of the MAR (MAR ≥ 544 mm) is generated by about 20% of the area and 50% of the runoff (MAR ≥ 461 mm) by about 43% of the area (**Table 1**, **Figure 16**). There are three water source areas in these two provinces (**Figure 17**): an extensive one in the northern part of Niassa, extending eastwards from Lake Malawi past Maruppa and including the headwaters of the Messalo River; and two smaller ones, one near Lake Chilwa and one in north-eastern Cabo Delgado, roughly centred on Mueda.

The patterns for the individual river basins would be similar with the thresholds differing depending on the runoff generated in that basin and how evenly it is distributed. In the case of the Rovuma about 25% of the MAR is generated by about 21% of the area and 50% of the MAR by 44% of the area and in the Lurio the corresponding values are 22% and 56% of the area.

Table 4: The mean annual runoff thresholds for water source areas for the main river basins and the provinces of Niassa and Cabo Delgado.

River basin or Provinces	MAR thresholds (percent) 25	50	75
Lurio	424	398	385
Messalo	428	411	401
Montepuez	430	415	394
Rovuma	574	514	461
Provinces	544	461	408

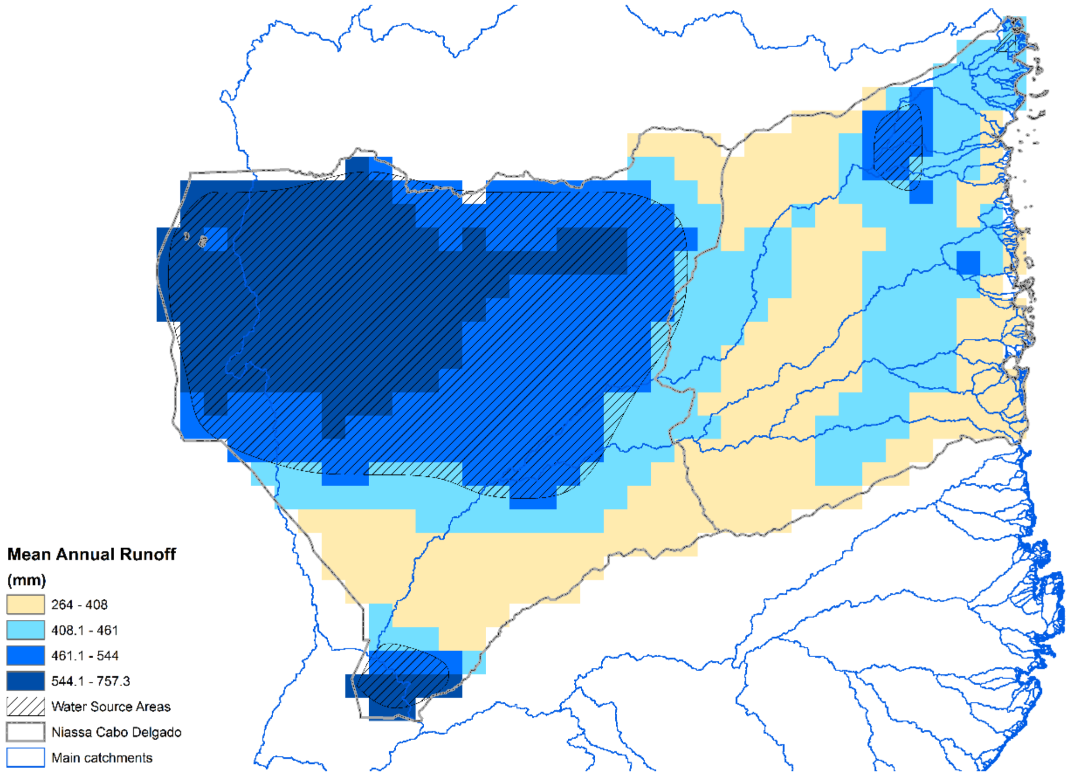

Figure 16: Estimated mean annual runoff for Niassa and Cabo Delgado provinces based on the grassland evaporation estimate (Figure 15).

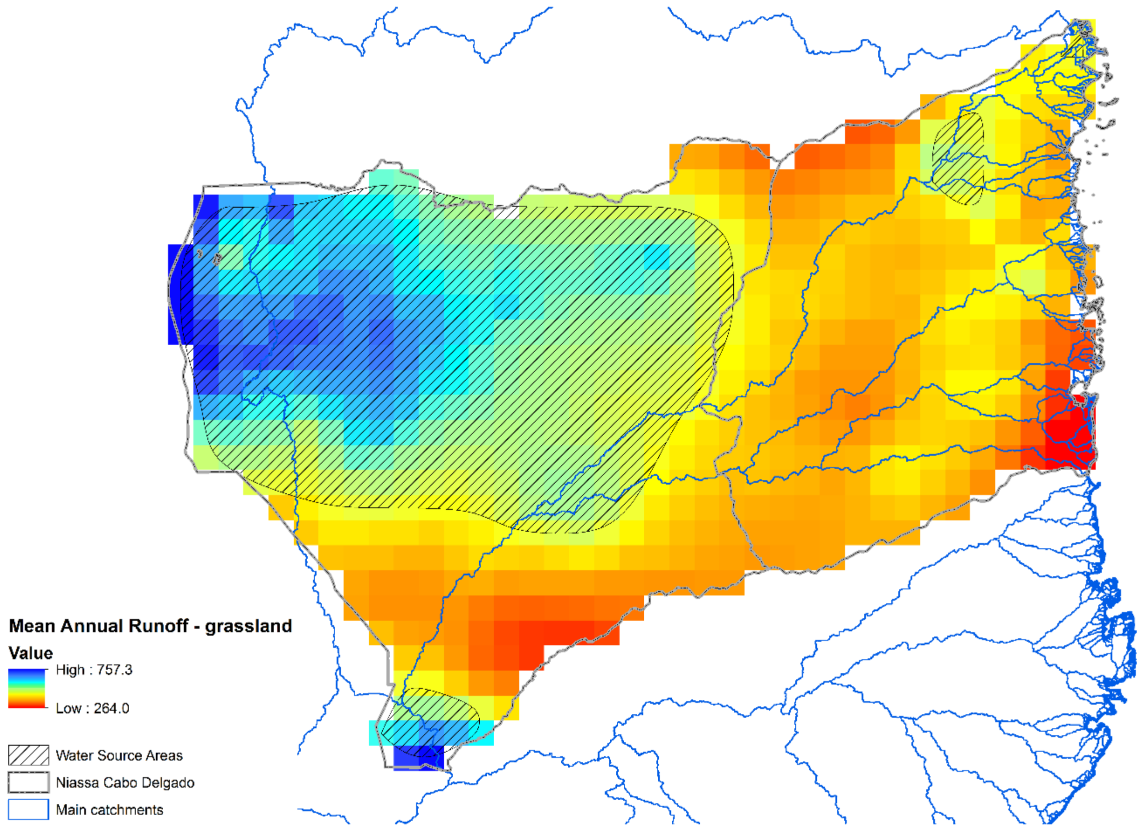

Figure 17: Water source areas and the mean annual runoff (mm per year) under grasslands in Niassa and Cabo Delgado. The three water source areas generate 50% of the mean annual runoff for these provinces.

4 Discussion

Although there are some issues in relation to the data and the findings as described above, this assessment has been able to identify water source areas in the Umbeluzi catchment and in the Niassa and Cabo Delgado provinces (Figures 5, 6 and 17).

4.1 Umbeluzi catchment

In the case of the Umbeluzi the relationship is based on an approach which has been applied and tested in South Africa (Nel et al., 2017; Nel, Smith, et al., 2013) using a rainfall surface developed for the area including southern Mozambique and Swaziland (Lynch, 2004). We were also able to apply the curves and apply adjustments to the estimated runoff to match estimates from other data sources for sub-catchments in Swaziland (Bailey & Pitman, 2015) as well as estimating adjustments for the sub-catchments in Swaziland. It is clear from this assessment that the main water source areas are located primarily within Swaziland with close to 50% of the total MAR being generated in that country (**Figure 4**). The picture is rather different for the portions within Mozambique itself which include the Movene River, a portion of the Calichare River, and a portion of the lower Umbeluzi River above and below the Pequenos Libombos. Within Mozambique, the highest runoff is found near the mouth of the Umbeluzi (**Figure 4**) with areas of slightly higher rainfall associated with an escarpment (150-250 m high) on the eastern side of the valley extending northwards from the Pequenos Libombos, and with the Lebombo mountains on the western side of that valley.

We have not been able to obtain definitive data on the flows in the sub-catchments in Umbeluzi system. There are studies that have assessed the hydrology of the system but they comment on their low confidence in their data because of a lack of gauged records, leaving them to rely on estimated inflows into the Pequenos Libombos to calibrate the models (Droogers et al., 2014; Juízo & Lidén, 2010). Under natural conditions the available water in the system is estimated to be about 535 million m^3/year. This is not the total flow, just the amount that could be used assuming various methods of storage and abstraction (e.g. dams, direct from river flow). At present irrigation in the whole catchment is estimated to be reducing the flows by about 350 million m^3/year but it is not clear if this accounts for the return flows (excess irrigation water which returns to the nearest river). The modelling estimated that the evaporation accounts for about 3 628 million m^3/year (89% of the rainfall) so that the mean annual runoff is about 558 million m^3/year with a marked year to year variations, with outflows to the sea ranging from near zero to 2000 m^3/year (Droogers et al., 2014). This study estimated the total runoff, pre-development, to be about 572 million m^3/year at the Pequenos Limbobos and about 648 million m^3/year at the river mouth, with both figures falling with the hydrologically modelled range. One concern is that the rainfall data that were used in the rainfall surface are from the beginning of the available record till 1999 or 2000 (Lynch, 2004) so they may not represent current rainfall (for more see section 4.2).

It is also clear from the studies cited above and the land-cover data on cultivated areas (**Figure 2**) that Swaziland is using a lot of the water from the Umbeluzi River system before it gets to Mozambique (Droogers et al., 2014; Juízo & Lidén, 2010). However, there are also some more factors that need to be considered. Vegetation degradation through overgrazing, which leads to increasing soil loss and erosion, as well as reducing infiltration and increasing surface runoff is well known phenomenon globally and in southern Africa (Le Maitre et al., 2007; Turnbull, Wainwright, & Brazier, 2008; Wilcox, Le Maitre, Jobbagy, Wang, & Breshears, 2017; Wilcox & Newman, 2005). Unfortunately, the current methods of identifying and quantifying land degradation do not effectively and reliably detect it until it has reached the stage of exposing the soil through extensive sheet, rills and gully (donga) erosion (García et al., 2008; Le Roux, Newby, & Sumner, 2007; Rouget, Cowling, Vlok, Thompson, & Balmford, 2006; Thompson et al., 2009; Wessels et al., 2013). We do not expect this kind of change to have affected the accuracy with which we can identify water-source areas but still need to recognise that erosion in such areas can have substantial impacts on water security downstream, both through changes in flow regulation and thus flow regimes, and in sediment loads which affect water quality and can fill dams with sediment. Another factor is the increase in density of woody plant species, notably trees either due to changing fire-regimes or atmospheric CO2-enrichment or both which is a well document phenomenon in South Africa (O'Connor, Puttick, & Hoffman, 2014; Skowno et al., 2017; Wigley, Bond, & Hoffman, 2010). The final issue is invasions by alien plant species, especially trees, which have a higher water use than the natural vegetation and decrease the runoff from the invaded areas (Le Maitre, Gush, & Dzikiti, 2015; Le Maitre, Scott, & Colvin, 1999). Many of the invading species are the same as those used in plantations and the impacts of invasions would therefore be similar to those of commercial plantations. Unfortunately, the land cover data available for Mozambique and Swaziland do not distinguish plantations from other tree cover but a visual inspection of the upper Umbeluzi using Google Earth suggests that there are some plantations but they are quite limited in extent. Alien plant invasions are far more pervasive in these catchments, mainly Black wattle (*Acacia mearnsii*) and pines in the upper catchment, Triffid weed (*Chromolaena odorata*), Lantana (*Lantana camara*) and many others in the lower catchments based on data from the South African National Invasive Alien Plant Survey for 2007 (Kotzé, Beukes, van den Berg, & Newby, 2010) which included Swaziland. Altogether at least 32 356 ha have been invaded, the average density is about 55% which is relatively high. These invasions are estimated to have reduced the mean annual runoff by about 34.3 million m^3 or 7.5% with a maximum of about 15.9% in one of the headwater catchments (Le Maitre, Forsyth, Dzikiti, & Gush, 2013). This is a substantial loss and will continue increasing as these invasions expand. Clearing these invasions would make a large volumes of water available in perpetuity for the citizens of both countries.

4.2 Niassa and Cabo Delgado

The assessment in Niassa and Cabo Delgado provinces could not use the same approach as was used for the Umbeluzi River catchment because no rainfall-runoff curves are available. The initial approach (a) involved using spatial datasets on rainfall and evaporation and to estimate the runoff based on the water balance. This approach was not successful as the difference was too high and often resulted in a negative runoff. This we interpret as being largely due to an underestimation of the rainfall which is a known issue with remote-sensing rainfall estimates (Milewski et al., 2009; Wang, Guan, Gutiérrez-Jurado, & Simmons, 2014; Zambrano-Bigiarini, Nauditt, Birkel, Verbist, & Ribbe, 2017). However, an analysis of the multi-year MODIS-based evaporation estimates for South Africa found that this gave a runoff estimate that is about 15% different from the MAR estimates from other sources (Jovanovic et al., 2015). This is much less than the difference found in this assessment. It is also known that the amounts of evaporation, rainfall and runoff may not balance in models, especially when they are not explicitly designed to produce a water balance (López López, Sutanudjaja, Schellekens, Sterk, & Bierkens, 2017; Odusanya et al., 2018; Veldkamp et al., 2018).

The second approach (b) of subtracting remote-sensing based estimates of evaporation from interpolated rain gauge data gave more realistic results but was still believed to be understating the runoff. The led to the third approach (c) of estimating the runoff from relationships between rainfall and evaporation developed for different dominant vegetation types. This appeared to give the best estimates of the runoff but, although there is an estimate of the river flows in the Lugenda River, we have not been able to test whether these estimates are reasonable because we do not have the location of the flow gauge. We used the results of this approach to identify three water source areas in these provinces with the most extensive being in the northern part of Niassa.

We undertook a further examination of the rainfall data by comparing the actual records for four weather stations in Cabo Delgado with the rainfall estimated from the remote sensing datasets and found that the rain gauge data generally gave substantially higher values (**Table 5**), which is in line with the differences between the CHIRPS and CliMond datasets. All the evidence points towards rainfall underestimation in the CHIRPS data which can also be attributed, in part, to the lack of freely available rain gauge data for Mozambique to use in calibrating a modelling exercise like CHIRPS.

Table 5: A comparison of the mean rainfall from gauge records in the following towns in Cabo Delgado and for the CHIRPS datasets for the period indicated.

Station	**Gauge record 2009-2013**	**Chirps 2009-2013**	**Notes**
Montepuez	805	662	Value for matched cell
Mocimboa da Praia	958	647	Mean of nearest cells
Mueda	1423	638	Value for matched cell
Pemba	751	611	Value for nearest cell

However, the CHIRPS dataset does provide some useful insights into the marked discrepancy between the CliMond and CHIRPS rainfall estimates of the spatial distribution of the rainfall in these two provinces (**Figure 9**, **Figure 10**). A study of the future climates and disease risk in Mozambique provides a summary of the rainfall from 1989-2014 in its description of the current climate (**Figure 18**) (USAID, 2018). This map shows that the long-term mean annual rainfall pattern from the CHIRPS data matches the CliMond data in these two provinces well (**Figure 9**). There is high rainfall in the area of Niassa bordering on Lake Malawi as well as higher rainfall near Lake Chilwa, and much higher rainfall across the northern part of the province (**Figure 18**) than in the recent CHIRPS data (**Figure 10**).

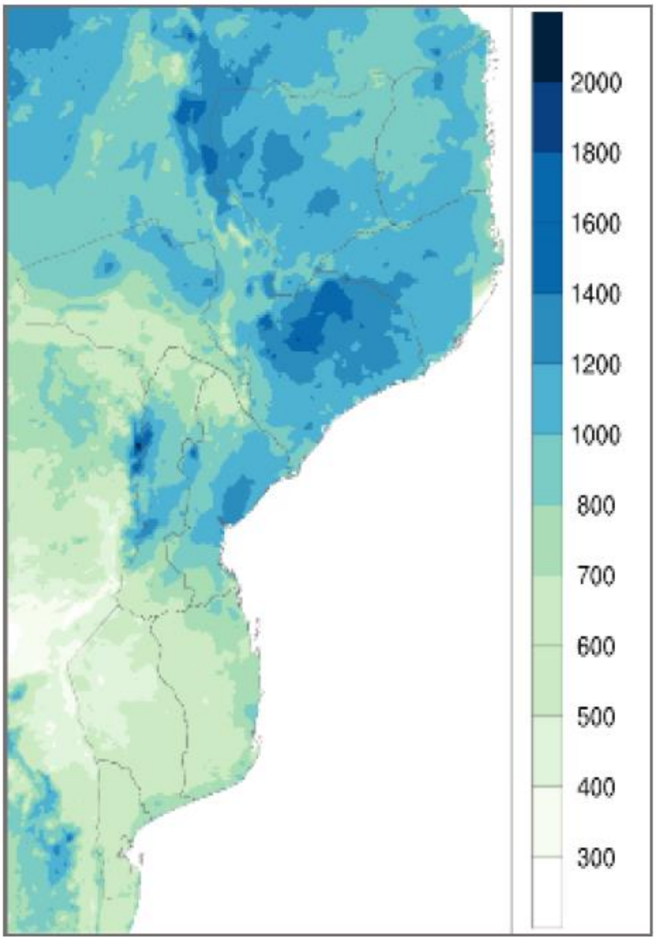

Figure 18: Mean annual rainfall (mm) 1981-2014 (USAID, 2018).

The overall pattern in the rainfall from 1981-1999 (**Figure 19**) is very similar to the longer-term summary (**Figure 18**) but, when the differences between the rainfall during this period and the period from 2000-2014 are examined, it is clear that some areas of Mozambique have been receiving much less rainfall since 2000 (USAID, 2018). In particular the pattern of the rainfall in northern Niassa for these two periods is very similar to the discrepancy between the CliMond and the CHIRPS rainfall estimates (**Figure 9**, **Figure 10**). This could be interpreted as a climate-change induced shift in the rainfall but when the long-term data are examined it becomes very clear that the spatial distribution and amount of rainfall over Mozambique varies very markedly between years and shows no consistent patterns or trends (USAID, 2018). This study concluded, therefore, that it is too soon to decide whether this is indeed a climate change induced shift rather than natural variability. An independent climate change study for the South African Development Community also concluded that there would be little change in the rainfall over most of Mozambique but there might be a decrease in south-central Mozambique (Davis-Reddy & Vincent, 2017). Nevertheless, the studies do indicate that shifts in the spatial distribution of rainfall can persist for periods of a decade or more and this should be taken into account in water resource planning.

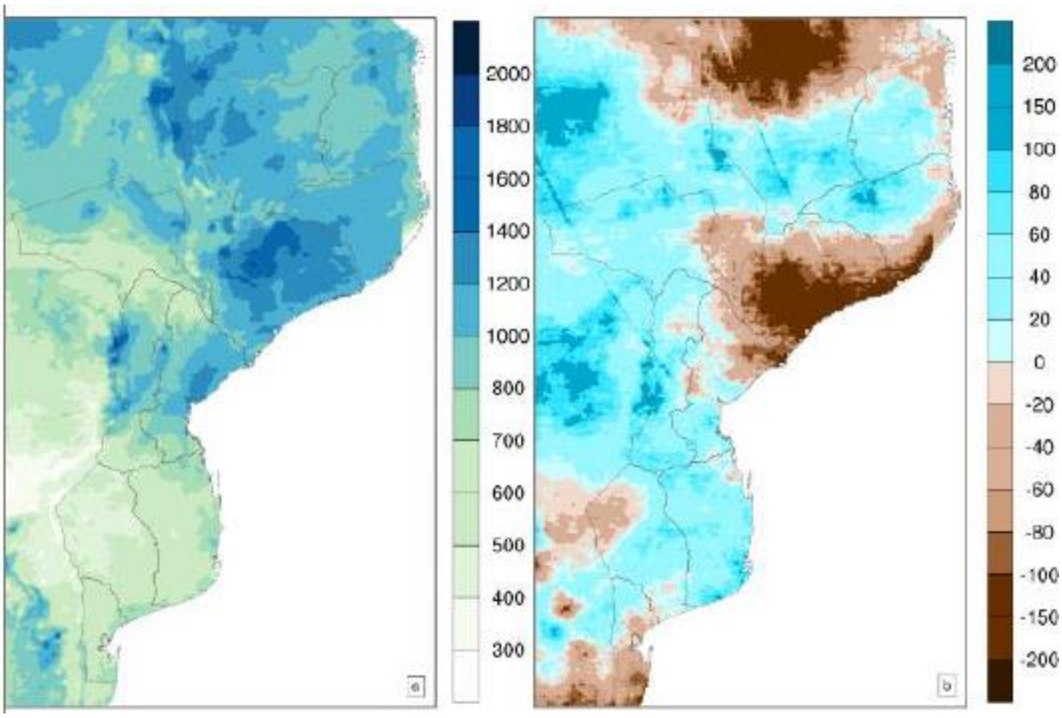

Figure 19: Mean annual rainfall 1981-1999 (left) and difference between 1981-1999 and 2000-2014 (right) (USAID, 2018).

The concerns about vegetation and land degradation, woody plant density increases and alien plant invasions that were discussed under the Umbeluzi catchment apply in these provinces as well. We have not found any studies that have assessed land degradation or woody plant density increase in Mozambique but there is no reason to assume that the same drivers and processes are not having the same effects in Mozambique as they are in South Africa. We have not been able to locate suitable information on the distribution and density of invasions for this region of Mozambique but, based on our knowledge of the potential invaders, the species would include Triffid weed, Lantana and probably a number of other tropical and sub-tropical species. These species are understood to use more water than the vegetation they invade (Meijninger & Jarmain, 2014) but not as much as species such as the Black Wattle (Dye & Jarmain, 2004; Everson et al., 2014) which is a major invader in the Umbeluzi catchment. We do not know if Black wattle occurs within these provinces but, if it does, it would be most likely to occur in the high-lying areas to the east of Lake Malawi as it is not suited to the tropical climates of the lower lying areas. If this species was invading these areas it could have important implications for water security in this river basin together with the other species probably invading these areas.

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