Flood Risk Mapping in Africa: Exploring the Potentials and Limitations of SRTM Data in the Lower Limpopo, Mozambique

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Examensarbete vid Institutionen för geovetenskaper
Degree Project at the Department of Earth Sciences
ISSN 1650-6553 Nr 379

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Abstract

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Many regions in Africa are presently faced with an increasing flood risk due to impending climate change and population growth. One useful mitigation strategy to decrease this risk would be to map it, so that urban planning, warnings systems and emergency response subsequently could be designed to reduce societal vulnerability. This is, however, not widely feasible on the African continent, as developing countries often lack access to the topography and discharge data required to produce high-quality flood risk maps. To seek a way around this problem, on-going research is investigating the possibility of obtaining alternative model inputs, by using global datasets of elevation, derived from remote sensing, and methods to estimate flood flows. This thesis presents a case study within this context where the aim was to determine the accuracy of an African catchment-scale flood map, produced with the satellite product SRTM (Shuttle Radar Topography Mission) as topography input, and to explore the potentials and limitations of such a model scheme. Two high-magnitude floods, occurring in year 2000 and 2013 in the Lower Limpopo Basin (Mozambique), were modelled for inundation extent, using a no-channel 2D model built for the LISFLOOD-FP flood modelling software. Flood water levels were also simulated to assess the models vertical performance. Model outcomes were evaluated against satellite imagery and recordings of high watermarks, adjusting the value representing the roughness of the floodplain to optimize flood extent correspondence. Due to different hydrograph dynamics, simulations of the two floods required different values of roughness (0.02 and 0.09 s m$^{-1/3}$) to reach maximum accuracy ($F = 0.59$ and 0.64, respectively). However, the results also indicated that a model calibrated with a flood of relatively low return period potentially could be used to map rare flood events. Simulation inaccuracies were mainly attributed to (1) reservoirs and streams, temporarily connecting to the river system during high flow conditions, (2) limitations of the topography data, in terms of recognizing riverbed geometry and floodplain micro-topography, and (3) cloud cover, reducing the accuracy of flood extent reference data. The vertical simulation accuracy, with an average error of ± 2 m, was well within the uncertainty bounds of input data. Errors were in this case ascribed the SRTM’s representation of high slope terrain and possible radar speckles in urban areas. The findings of this study indicate that there is high potential in using SRTM data for mapping of high-magnitude flood risk in Africa, but also that consideration to river system complexity is crucial.

Keywords: Flood inundation modelling, Africa, SRTM, LISFLOOD-FP, quality analysis

Degree Project E1 in Earth Science, 1GV025, 30 credits
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ISSN 1650-6553, Examensarbete vid Institutionen för geovetenskaper, No. 379, 2016

The whole document is available at www.diva.org
Populärvetenskaplig sammanfattning

Kartläggning av översvämningsrisk i Afrika: En undersökning av möjligheter och begränsningar med SRTM-data i Nedre Limpopobassängen, Mocambique

Paulina Bastviken

Många områden i Afrika står för närvarande inför en ökad översvämningsrisk på grund av klimatförändringar och befolkningstillväxt. En användbar strategi att minska denna risk skulle vara att kartlägga den, så att stadsplanering, varningssystem och respons vid nödsituationer därefter skulle kunna utformas till att begränsa samhällets sårbarhet. Detta är dock inte möjligt på bred front över Afrikas continent, då utvecklingsländer ofta saknar det data av topografi och vattenflöde som behövs för producera högkvalitativa översvämningsriskkartor. För att försöka hitta ett sätt att kringgå detta problem undersöker pågående forskning möjligheten att generera alternativa modellingsinput, från globalt tillgängligt höjddata, insamlat av satelliter, och metoder att uppskatta översvämningsflöden. Denna uppsats presenterar en fallstudie inom denna kontext där syftet var att bestämma kvalitén hos en översvämningskarta över ett Afrikanst avrinningsområde, producerad med satellitprodukten SRTM (Shuttle Radar Topography Mission) som topografiinput, och att utforska möjligheterna och begränsningarna med en sådan karteringsmodell. Två stora översvämningar, vilka inträffade år 2000 och 2013 i Nedre Limpopobassängen (Mocambique), simulerades för utbredning med hjälp av en 2D-model utan flodfåra byggt för modellingsprogrammet LISFLOOD-FP. Vattenivåer simulerade också för att kunna bedöma modellens vertikala prestation. Resultaten jämfördes med satellitbilder och dokumenterade höga vattenmärken (observerade på t ex. husfasader), samtliga som flodplanets flödesmotstånd justerades för att optimera överensstämmelsen. Då översvämningsarna var av olika karaktär behövdes olika flödesmotstånd (0.02 and 0.09 s m$^{1/3}$) för att maximal kvalité på respektive översvämningskarta skulle uppnås. Denna kvalité beräknades till 0.59 och 0.64, på en index-skala (F) där 1.00 motsvarar en perfekt simulering. Trots olika optimala flödesmotstånd antydde resultaten även att en modell kalibrerad med en relativt frekvent återkommande översvämnning möjligtvis kan användas till att kartlägga sällsynta översvämningar. Avvikelsen mellan dokumenterad och simulerad översvämningsutbredning tillskrevs i huvudsak: (1) sjöar och vattendrag som temporärt ansluter till flodsystemet under höga flöden, (2) begränsningar i topografidatat gällande att fånga flodens geometri och flodplanets mikro-topografi samt (3) moln som skygger översvämningsarna i referensdatabas och minska dess sanningshalt. Vattenivåer simulcerades med ett genomsnittligt fel av ±2 m, vilket med marginal ligger inom inputdatats totala osäkerhetsram. Avvikelsen troddes i detta fall bero på SRTM-datats representation av slutande terräng och möjliga radarfläckar (reflektioner) i urbana områden. Resultaten i denna studie indikerar att det ligger stor potential i att använda SRTM-data för att kartlägga risken för stora översvämnningar i Afrika, men belyser också vikten av att uppmärksamhet ges till flodsystems komplexitet.

Nyckelord: Översvämningsmodellering, Afrika, SRTM, LISFLOOD-FP, kvalitetsanalys

Examensarbete E1 i geovetenskap, 1GV025, 30 hp
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ISSN 1650-6553, Examensarbete vid Institutionen för geovetenskaper, Nr 379, 2016

Hela publikationen finns tillgänglig på www.diva.org
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1 Introduction

Floods are the most frequently occurring natural hazards of modern times and, as a significant portion of the world’s population is settled in floodplains and coastal areas, damages can be disastrous (Karlsson and Arnberg, 2011). Globally, floods account for approximately 50% of all casualties, 70% of all homelessness and 30% of all economical losses caused by natural disasters (INGC, 2003); and in average 100 million people are affected each year (CRED, 2016).

Climate models indicate that flood events might become more recurrent and severe in the future, as a consequence to sea level rise and increased storm frequency induced by climate change (Nicholls, 2004). One continent projected to experience a high and widespread increase in flood frequency is Africa (Hirabayashi et al., 2013), which is also suffering from a rising vulnerability to floods. During the last 50 years, population growth and urban development of flood prone areas have been observed to cause a dramatic increase of flood induced fatalities and economical losses in Africa (Di Baldassarre et al., 2010a). This trend is highly worrying, since the population on the continent will continue to grow rapidly in the near future (Engelman, 2016), and settlement in floodplains present many advantages to support human livelihood for rural societies (Spaliviero et al., 2014).

To limit the impacts of future high magnitude floods events, different defensive strategies can and should advisedly be pursued. For the African continent, effective and sustainable such strategies would be to establish reliable flood-forecasting systems, increase public awareness, plan urban development to discourage human settlements in flood-prone area and to strengthen the institutional response capacity on the local scale (Di Baldassarre et al., 2010a). Providing guiding information for all these measures, flood risk maps play an important role. However, the production of high-quality flood risk maps requires access to fine resolution topography and reliable discharge data, which is a problematic matter for many data-poor regions in Africa (Yan et al., 2015; Stokstad, 1999). To deploy large amount of resources to establish national dataset of digital elevation and extensive networks of river gauging stations is simply not feasible for many developing countries.

A possible alternative approach, currently being investigated within research, is to use global datasets of topography acquired by remote sensing (e.g. Sanders, 2007) and methods to estimate discharge (e.g. Padi et al., 2011; Pappenberger et al., 2012). The usefulness of global elevation data for large-scale flood modelling has been showed, but there is still a strong need for more research to clarify potentials, limitations and associated uncertainties (Yan et al., 2015). As for flood flow estimations, methods still need refinement (Yan et al., 2014). If it can be shown that sufficient simulation accuracy can be reached with these easily obtained datasets, flood risk mapping in Africa could potentially be extended to reach continental coverage, with inclusion of data-scarce areas. This would lead to a more widespread awareness, and with spatially distributed risk information at hand, resource management and flood mitigation could be designed to reduce societal vulnerability. Such a cascade of measures could possibly lessen the
consequences of future floods on the African continent, and other flood-prone and data-poor regions of the world.

2 Aim

The objective of this thesis was to perform a quality analysis of a flood inundation map, which presently can be produced for catchments on the African continent at low cost. On the basis of that flood mapping in Africa is heavily hampered by limited access to fine resolution topography, the following two research questions were formulated:

- To which level of accuracy can a modelled flood inundation map over an African catchment be produced, with topography data that freely available for the entire continent?
- What are the most significant sources of inaccuracies in such a map?

In the attempt to answer these questions, the lower part of the Limpopo Basin in Mozambique, one of Africa’s most flood-prone catchments (Karlsson and Arnberg, 2011), was chosen for a case study of flood extent modelling. Besides the Limpopo Basin’s frequent exposure to floods, this choice was founded on the availability of inundation extent reference data and discharge records needed for model calibration and validation. Two large floods in 2000 and 2013 had been captured on satellite imagery as well as at monitoring river stations in the Lower Limpopo. LISFLOOD-FP (Bates and De Roo, 2000; hereafter abbreviated to LISFLOOD) was chosen to be the software tool of the study, since it is a free and relatively simple flood inundation modelling program, suitable for large scale simulations (Pender, 2006). The objective's condition of potential continental coverage led to the selection of the SRTM dataset (a satellite derived, globally available digital elevation model) as topography input. By performing flood inundation modelling, according to the described scheme, and analysing the quality of the result, this study aimed to provide increased knowledge on the potential and limitations of using SRTM data to map flood risk in Africa.
3 Background

In this chapter background information of the case study is presented. The first section summarizes some finding of previous studies, exploring the potentials and limitations of the SRTM data for flood mapping applications. Thereafter follows a description of the study area, the Lower Limpopo, and the two floods (from year 2000 and 2013) used as model calibration and validation events.

3.1 Previous Research

Several studies have investigated the usefulness of the SRTM product for different flood modelling applications. Sanders (2007), for instance, evaluated the potential of different on-line Digital Elevation Models (DEMs) as terrain input in inundation models and especially highlighted the utility of the SRTM data. However, he also pointed out that non-physical relief is present in the data and that these artificial spikes and wells might affect simulation outcomes.

Yan et al. (2013) explored the potential of SRTM in flood inundation modelling in a case study of the Po River, Italy, using outcomes obtained with high quality topography as reference data. Differences were found significant, but within the range of accuracy that is commonly associated with large-scale flood studies.

Over the Lower Limpopo Basin specifically, Karlsson and Arnberg (2011), performed a quality assessment of two global datasets of topography, SRTM and HYDRO1K, for use in a simple static flood inundation model. The authors concluded that both DEMs could be used on a local scale for this purpose, but that incorporated inadequacies in the data can result in simulated flood extent being both under- and overestimated.

Neal et al. (2012) used the SRTM product as topography input to model inundation extent and flood levels by the use of different model structures. The authors could in their study demonstrate the significance of river connectivity for good simulation result.

In addition to serving as topography in inundation extent modelling, the SRTM product has been shown to be useful for deriving several river parameters, such as slope and discharge (LeFavour and Alsdorf, 2005), water surfaces (Alsdorf et al., 2007), cross-sections (Patro et al., 2009) and flood wave profiles (Schumann et al., 2010). Jung et al. (2011) furthermore demonstrated that SRTM could be used to explore intra- and inter annual flooding variations.

Many studies have also been dedicated to characterize the inaccuracies incorporated in the SRTM during data acquisition. These inaccuracies have been related to, for instance, high relief terrain (Falorni et al., 2005), vegetation (Baugh et al., 2013) and surface reflections (Farr et al., 2007) and will be accounted for more in detail in section 4.1.1.

In summary, while many publications indicate high potential in the use of SRTM for flood modelling applications, limitations are still present and it is indicated that catchment characteristics
and flood dynamics might influence how sensitive flood modelling outcomes are to those limitations. To this end, more case studies, evaluating the quality of simulated flood events of various magnitudes in different environment in Africa, will provide highly useful information for a future large-scale mapping campaign of the flood risk on the continent.

3.2 Study Area

3.2.1 The Lower Limpopo, Mozambique

The Limpopo Basin (Fig. 1) is located in southeast Africa, with its river outlet in the Indian Ocean. It has a total area of 412 000 km², shared between South Africa (47.0%), Mozambique (19.3%), Botswana (17.7%) and Zimbabwe (16.0%) (INGC, 2003). Differences between the countries, regarding hydrological conditions and the level of societal development, are reflected in the character of the catchment. Generally, upstream regions are urban and dry while areas downstream tend to be rural and wet; a pattern that poses a challenge for the water resource management in the basin (INGC, 2003).

The Limpopo River is the second longest African River draining into the Indian Ocean. It flows 1750 km along the north border of South Africa before entering the Lower Limpopo, the most downstream sub-catchment of the Limpopo Basin, in Mozambique (WMO, 2012). Two large tributaries join the main river during its course in the Lower Limpopo: the Changane River from the northeast and the Elephant River from the southwest. The Limpopo River then meanders for about 70 km, forming a circular alluvial valley with a diameter of approximately 15 km, before it finally reaches the Ocean (Maposa et al., 2015).

The main river channel is completely unregulated, unlike its tributaries. In total, 47 dams exist within the Limpopo Basin, the largest one being the Massingir Dam with its storage capacity of 2840 Mm³ (Mohamed, 2014). The Massingir Dam regulates the flow of the Elephant River, near the upstream boundary of the Lower Limpopo. Several Inter-Basin Water Transfer Schemes also exist, in total transferring 695 Mm³ of water per year into the Limpopo River (Mohamed, 2014).

The floodplain of the Lower Limpopo is generally low-lying and flat, with the entire subbasin being located at elevations less than 100 m above sea level and the general terrain only slightly dipping towards the southeast (INGC, 2003). The vegetation cover is dominated by savannah and cultivated areas, intermixed with grassland and woodland, (INGC, 2003) and the main soil types are sand and sandy clay (Karlsson and Arnb erg, 2011).

In terms of socio-economic aspects, the Lower Limpopo is fertile and heavily populated. The floodplain has approximately 860 000 inhabitants (INGC, 2003) and supports a substantial part of Mozambique’s economy through agriculture and other activities (Maposa et al., 2015). Several
communities, including the two major cities Xai-Xai and Chokwe, are located in direct vicinity of the river channel.

The Limpopo Basin is regularly exposed to extreme weather conditions, with 95% of the annual precipitation (on average 530 mm) being received during October to April, and the rest of the year being hot and dry (WMO, 2012). This strong seasonality is connected to the alternating positions of the Inter-Tropical Convergence Zone (ITCZ). Migrating south, the ITCZ brings cold fronts to the Limpopo region while, on the opposite, dry weather is associated with its northward movement (INGC, 2003). The climate of the Limpopo Basin is also affected by the Mozambique Current, which transports warm water and humid air from the equator, and the El Niño Southern Oscillation phenomenon (ENSO) (INGC, 2003). Extreme weather events, already frequently and causing both floods and droughts in the Lower Limpopo, are projected to become more recurrent in the future as climate change progresses (Hulme, 1996).

Figure 1. Overview map of the Limpopo Basin and River. The red square marks the geographical extent of study area (the Lower Limpopo).
3.2.2 The 2000 and 2013 flood events

Mozambique has a long record of being affected by water related disasters (Venton et al., 2013) and is ranked the most flood prone country in southern Africa (Karlsson and Arnberg, 2011). The reasons behind the many flood disasters are the region's exposure and vulnerability to tropical cyclone activity, intensive local rainfall and poor management of upstream reservoirs (INGC, 2003).

According to a digital atlas for disaster preparedness and response in the Limpopo Basin (INGC, 2003), the extensive flood in the beginning of year 2000 was triggered by a succession of three cyclones (Eline, Gloria and Hudah), hitting the east coast of Southern Africa with great force. Over a 100 km stretch, the width of the Limpopo River grew from 100 m to 10-20 km, inundating 1400 km² of agricultural land (WMO, 2012). The water levels exceeded the highest observed in over 150 years (INGC, 2003) and it took over six weeks for the accumulated water to retreat (Venton et al., 2013). The consequences of the flood became devastating, with reports of 800 casualties, 4500 000 people affected and widespread destruction to buildings and infrastructure (CRED, 2016). In monetary terms, the losses were estimated to a cost of 600 million US$, a sum that at the time corresponded to 20 % of Mozambique’s GDP (INGC, 2003). The 2000 flood was an event of magnitude and severity rarely experienced in the Lower Limpopo Basin. Its return period was estimated by Maposa et al., (2014) to exceed 200 years.

The flood in 2013 had an inundation extent similar to the 2000 flood, but its dynamic character was very different (Venton et al., 2013). Heavy rain in January 2013 created a flood peak with a steep rise and fast recession. The overall duration of the flood disaster in 2013 was therefore significantly shorter than the flood in 2000, which was caused by multiple cyclones. In terms of relative stage differences between the two floods along the Limpopo river, the flood in 2013 led to higher (+1.5 m) water levels upstream but lower (-3 to -4.5 m) in the downstream area around Chokwe (Venton et al., 2013). The impact of the flood in 2013 was also different, since the experience 13 years earlier had motivated developments in the flood disaster management of the area. These developments included improved flood forecasting, early warning systems and transboundary cooperation, which all helped to limit the damage (Venton et al., 2013). The event, nevertheless, claimed 119 lives, affected 240 000 people and led to economical losses to a cost of 3 million US$ (CRED, 2016). One additional problematic consequence of the 2013 flood, more unusual in its type, was that 15 000 crocodiles were released into the wild from a farm close to the Limpopo River (Smith, 2013).
4 Datasets

In order to build a flood model, three different types of data are required. These are: (1) topography for estimation of river channel and floodplain geometry, (2) discharge data for definition of appropriate initial and boundary conditions and (3) flood reference data for model calibration and validation (Di Baldassarre, 2012). The quality of the final model result will consequently be a reflection of the availability, resolution and accuracy of these datasets. This chapter gives an overview of the three aforementioned data types, and provides a description of the specific datasets used to simulate the 2000 and 2013 flood events in the Lower Limpopo Basin.

4.1 Topography

The spatial distribution of a flood in a landscape can be estimated based on the principle of gravity and the approximation that floodwater, under the influence of gravity, accumulates in low-lying areas. Topography therefore constitutes a highly important input dataset in hydraulic inundation modelling. Nowadays, a commonly used form of topographic data is DEMs derived from remote sensing. DEMs are provided from many different sources with various resolution, quality and spatial coverage. Fine resolution data with high accuracy can offer very detailed information, but their acquisition is accompanied by high costs that limit the access for developing countries (Yan et al., 2015). This is especially the case when topography over large areas is required, as in many flood studies. The low-cost alternatives are DEMs with global coverage, which in spite of relatively low resolution and accuracy have been proven to be useful for many purposes (Yan et al., 2015). Because this study aims to employ data with high availability, a global DEM was selected as topography input. The choice fell on Shuttle Radar Topography Mission 1 Arc-Second Global (SRTM) since this elevation model has the highest accuracy and resolution (30m) of all DEMs that currently offer full coverage of the African continent for free (Farr et al., 2007).

4.1.1 SRTM

The Space Radar Topography Mission was launched in 2000 by the National Aeronautics and Space Administration (NASA), National Geospatial-Intelligence Agency (NGA), German Aerospace Center (DLR) and the Italian Space Agency (ASI) (Farr et al., 2007). The aim of the mission was to produce a near-global topographic dataset with consistent and quantified errors. Data collection took 11 days to complete and was conducted with the use of Interferometry Synthetic Aperture Radar technology (InSAR) mounted on the space shuttle Endeavour (Rabus et al., 2003).

The general principle of InSAR is that electromagnetic radiation (in the microwave frequency range) is sent from a satellite towards the Earth and then recorded when returning, after being
backscattered at the surface. The recorded signal return time enables the distance between the satellite antennas (which positions are known) and the point of scattering to be calculated. Multiple recordings at different phases then provide information about terrain altitude and angles, from which a 3D topographic model can be built. For full description of the InSAR technology, see Bamler (1999).

Between the raw data and the offered SRTM product layed processing steps of SAR focusing, motion compensation, co-registration, interpolation, interferogram formation, filtering, phase unwrapping, geocoding and mosaicking (Rabus et al., 2003). Regridding was also performed to smooth out errors, and filling-in to eliminate data gaps (Farr et al., 2007).

The SRTM product offers elevation data over all land area between 60°N and 56°S, corresponding to 80% of the Earth’s terrestrial surface, to a spatial resolution of at best 1 arc second, or approximately 30 m (Farr et al., 2007). Over the African continent the SRTM is estimated to incorporate errors of ± 5.6 m in absolute height (total mission vertical error), ± 9.8 m in relative height (vertical error within local scale of 200 km) and ± 11.9 m in absolute geolocation (horizontal circular accuracy) (Rodriguez et al., 2006).

The vertical height error in the SRTM data is composed by inaccuracies from several different sources. One is radar speckles, or random noise, caused by radiation reflections, and visible as spikes or wells in the topography (Sanders, 2007). Another source is voids, which are created by terrain relief and later filled by interpolation. Both of these errors are generally larger and more frequent in high-relief areas (Falorni et al., 2005). A third source of vertical inaccuracy is the height of land surface cover, which currently is incorporated in the SRTM data and causes a positive elevation bias in regions where vegetation is tall and dense (Baugh et al., 2013). However, since the radar beams can penetrate some distance into the canopies before reflection occurs, this bias is generally negligible in sparsely vegetated areas (Van Niel et al., 2008). Water nevertheless constitutes a fully impenetrable medium for the SAR technology. This results in geometries of water bodies being unrecognized by the SRTM model, which instead shows the surface elevation of water surfaces at the time of satellite overpass. For rivers, bank elevations will add height to this bias, when the river channel is less wide than raster pixels (Farr et al., 2007).

4.2 Discharge

The magnitude of a flood is determined by the amount of water entering the system and the time period during which high flow prevails. When performing a flood simulation, one common way to define the incoming water volume is to let the hydrograph at one or several upstream locations in the study area form the inflow boundary condition of the model (Di Baldassarre, 2012) The access to time-series of discharge, representing suitable inflow points, is therefore an important parameter when designing a flood model.
Discharge can be measured directly, but is more often obtained indirectly by established stage-discharge relationships, or so called rating curves (WMO, 2008). The main advantage with using the rating curve method is that the data collection is automatic, after the curve equation has been determined. The method, however, does require the presence of gauging stations where the water level of the river is monitored. In the absence of monitoring river stations, a technique for estimating discharge has to be applied. Such a technique can for example be inflow regionalisation where flood peak flows are estimated based on a statistical relationship to drainage area (Padi et al., 2011), or physical cascade modelling (Pappenberger et al., 2012).

4.2.1 SADC-HYCOS

In the Limpopo catchment a system of automated river-monitoring stations, SADC-HYCOS (Southern Africa Development Community-Hydrological Cycle Observation Systems), was installed to collect hydrological data (INGC, 2003). The observed flow data, used in this thesis to model for the 2000 and 2013 flood events, consisted of daily discharge recordings at Combombune and Massingir river stations. The recordings had been collected by the governmental agency Adimistração Regional de Águas do Sul (ARA-Sul) in Mozambique and were kindly provided by Omar Khan at Eduardo Mondlane University. To translate hydrographs from one location to another, information in the station catalogue compiled by the Global Runoff Data Centre (GRDS) was used in combination with an assumption of hydrological similarity (see section 5.2.1).

The accuracy of water level observations is in the range of 2-5 cm, which in comparison to other sources of uncertainty can be assumed negligible (Pappenberger et al., 2006). Errors incorporated in the rating curve (from individual measurements, presence of unsteady flow and high flow extrapolation) have a more significant effect. Such errors can, during unfortunate circumstances, add up to an uncertainty of up to 40% of the reading (Di Baldassarre and Montanari, 2009).

4.3 Flood Reference

When constructing a flood model, reference information about the dimensions (e.i. extents or stages) of at least two flood events has to be known so that the procedure of calibration and validation can be performed. Flood reference data can be obtained in different ways. Satellite imagery can capture the extent of on-going floods from space, while preserved traces of flood water levels (high watermarks) can be observed during in situ field campaigns. In this study, the main flood reference data consisted of various satellite images of the Lower Limpopo, taken during the time of the 2000 and 2013 floods. High watermarks, available for the flood in 2000, were also used to explore the model's ability to simulate flood levels.
4.3.1 Satellite Imagery

Since the smooth surfaces of water bodies efficiently reflect electromagnetic radiation of many different wavelengths, satellite imagery is a very valuable tool for deriving reference data of flood extent (Di Baldassarre et al., 2011). Especially useful are the images obtained by Synthetic Aperture Radar (SAR) sensors, which can collect data independently of daylight and cloud cover (Aplin et al., 1999). Optical sensors are heavily limited by these two factors, but can, under the right conditions, provide very valuable information (Marcus and Fonstad, 2008). Some issues which may affect SAR data are, for example, reflections from urban structures or standing vegetation (i.e. speckles) and dark areas (Karlsson and Arnberg, 2011). The speckles might appear dry and cause an underestimation of the flood extent, while dark areas might be wrongly interpreted as flooded.

Before being used as evaluation data, satellite images of flood extent have to be classified to display identify the border between dry and wet areas. This can be done by various methods with different potentials and limitations. Some commonly used methods are visual interpretation, histogram thresholding and modelling of image contour or texture; and the representation of the flood mask can be either deterministic or probabilistic (Di Baldassarre, 2012). To use probabilistic approach is more statistically robust, but requires access to multiple SAR images of the flood at similar overpass times (Schumann et al., 2009). Due to lack of time and material in this study, readily processed deterministic flood extent reference data were acquired from two reliable sources (details of datasets are given below). The uncertainty of flood extent maps varies according to the quality in the data used to derive the map. For flood extent maps derived from SAR imagery, Schuman et al. (2009) estimated the uncertainty to 150 - 300 m.

2000 flood reference

The reference data used for the 2000 event in the Lower Limpopo consisted of a polygon shapefile of the flood extent kindly provided from Karlsson and Arnberg (2011). The inundated area had been extracted from two remote sensing images, recorded on the 1st of March by the Landsat 7 and Radarsat 1 satellites (data details listed in Table 1). To derive the flood mask, Karlsson and Arnberg (2011) used thresholding and visual analysis. The authors reported speckles, in the area of Xai-Xai for the radar data. However, as these reflections are only visible at very high resolution they were not a major issue for the accuracy of the flood extent outline. Some dark areas were also identified, but removed during data processing. Figure 2 displays the two satellite images, overlaid over the study area, beside the derived flood extent reference.
Table 1. Details of the source data used to derive the delineation of the 2000 flood extent in the Lower Limpopo. Information obtained from Karlsson and Arnberg (2011).

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Resolution (m)</th>
<th>Date</th>
<th>Provider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat-7 (Optical)</td>
<td>30</td>
<td>20000301</td>
<td>German Aerospace Center</td>
</tr>
<tr>
<td>Radarsat-1 (SAR)</td>
<td>15</td>
<td>20000301</td>
<td>Canadian Space Agency</td>
</tr>
</tbody>
</table>

2013 flood reference

As a reference for the 2013 flood event, polygon shapefiles, representing the flood extent during different phases, were provided by United Nations Institute for Training and Research (UNITAR). The products had been developed within the framework of United Nations Operational Satellite Application Programme (UNOSAT), which offers imagery analysis and satellite solutions to organisations working with humanitarian relief, human security, strategic territorial and development planning (UNITAR, 2016). The source data of the UNOSAT shapefiles were radar and optical satellite images, of various resolutions and coverage, acquired between 24th of January and 2nd of February 2013 (UNITAR, 2013). Because of the variety of spatial and temporal coverage of the images, the shapefiles were merged into a single dataset. Details of the source data are listed in Table 2 and the shapefiles, merged into one polygon, are displayed in Fig. 3. Information, describing the specific processing approach was unfortunately not provided with the data.

Table 2. Details of the source data used to derive the delineation of the 2013 flood extent in the Lower Limpopo. Information obtained from UNITAR (2013).

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Resolution (m)</th>
<th>Date</th>
<th>Provider</th>
</tr>
</thead>
<tbody>
<tr>
<td>TerraSAR-X (SAR)</td>
<td>8.25</td>
<td>20130124</td>
<td>German Aerospace Center</td>
</tr>
<tr>
<td>SPOT-5 (Optical)</td>
<td>10</td>
<td>20130124</td>
<td>French Space Agency</td>
</tr>
<tr>
<td>TERRA (Optical)</td>
<td>250</td>
<td>20130125</td>
<td>National Aeronautics and Space Agency</td>
</tr>
<tr>
<td>SPOT-5 (Optical)</td>
<td>10</td>
<td>20130129</td>
<td>French Space Agency</td>
</tr>
<tr>
<td>Radarsat-2 (SAR)</td>
<td>28</td>
<td>20130202</td>
<td>Canadian Space Agency</td>
</tr>
</tbody>
</table>
4.3.2 High Watermarks

One type of trace that a flood leaves behind in the field is marks on house walls and other urban structures. These marks are created by the water surface when the flood is at a standstill. Measurements of the highest marks, the so-called high watermarks, have been estimated to represent the maximum flood height to an accuracy of 30-40 cm (Neal et al., 2009; Horritt et al., 2010).

A campaign to gather high watermark data, corresponding to the 2000 flood in the Lower Limpopo, was conducted by Karlsson and Arnberg (2011) During the campaign, 13 different locations in the basin were investigated (Fig. 2), with the purpose to obtain a reference of the maximum flood extent. The record consisted of coordinates and elevation of visible high watermarks (Table 3), measured with folding rules and geolocated with a GPS device. At sites were marks were sparse (due to for example repainting of houses), observations were complemented by interviews with the local population.

Table 3. High watermarks collected in the Lower Limpopo after the 2000 flood. Table is reconstructed after Karlsson and Arnberg (2011). Sites with flood heights of 0 m equals locations of maximum flood extent. Flood heights are given in meters above ground level and site number is increasing in downstream direction.

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Latitude (E)</th>
<th>Longitude (S)</th>
<th>Flood Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chokwe</td>
<td>33°00´02´´</td>
<td>24°32´11´´</td>
<td>2.54</td>
</tr>
<tr>
<td>2</td>
<td>Guiju</td>
<td>33°0307</td>
<td>24°30´43´´</td>
<td>3.75</td>
</tr>
<tr>
<td>3</td>
<td>Sousuanine</td>
<td>33°06´01´´</td>
<td>24°32´06´´</td>
<td>3.85</td>
</tr>
<tr>
<td>4</td>
<td>Lionde</td>
<td>33°03´43´´</td>
<td>24°35´21´´</td>
<td>1.34</td>
</tr>
<tr>
<td>5</td>
<td>Cohane</td>
<td>33°05´18´´</td>
<td>24°40´23´´</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td>Chacate</td>
<td>33°07´50´´</td>
<td>24°44´39´´</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Chibuto</td>
<td>33°31´50´´</td>
<td>24°42´18´´</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Xai-Xai North</td>
<td>33°41´29´´</td>
<td>24°54´03´´</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>Xai-Xai/Chicumbane</td>
<td>33°33´19´´</td>
<td>24°59´38´´</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Xai-Xai City</td>
<td>33°38´31´´</td>
<td>25°02´37´´</td>
<td>3.66</td>
</tr>
<tr>
<td>11</td>
<td>Xai-Xai City</td>
<td>33°38´25´´</td>
<td>25°02´39´´</td>
<td>3.6</td>
</tr>
<tr>
<td>12</td>
<td>Xai-Xai City</td>
<td>33°38´20´´</td>
<td>25°02´38´´</td>
<td>3.54</td>
</tr>
<tr>
<td>13</td>
<td>Xai-Xai/Chongoene</td>
<td>33°39´01´´</td>
<td>25°03´26´´</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 2. Reference data for the 2000 flood inundation extent in the Lower Limpopo. The map to the left displays the satellite images collected during the flood, while the derived inundated area (blue) and measured high watermarks (red circles) are shown to the right.

Figure 3. Reference data for the 2013 flood inundation extent in the Lower Limpopo. The map to the left displays one of the satellite image collected during the flood (TERRA), while the derived the inundated area (blue) is shown to the right.
5 Methods

The focus of this chapter is to describe the structure, assumptions and limitations of LISFLOOD, the modelling software used in this study, and provide an account for how the Lower Limpopo flood model was constructed and evaluated. The technical information related to LISFLOOD is taken from the user manual of the software, code release 6.0.4 (Bates et al., 2013), unless otherwise indicated.

5.1 LISFLOOD-FP: Structure, Assumptions and Limitations

LISFLOOD was designed at the University of Bristol as a software tool for research dealing with inundation modelling (Bates and De Roo, 2000). The program is freely available and simulates flood events by solving different simplified versions of the shallow water equations in a raster environment. The shallow water equations describe the propagation of a flood wave, by the assumption that momentum and mass are conserved. In 1D, these two conservation equations for shallow water are written as:

\[
\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q_x^2}{A} \right) + gA\frac{\partial (h+z)}{\partial x} + \frac{g n^2 Q_x^2}{R^2 A} = 0 \quad (1a)
\]

\[
\frac{gA}{\partial x} + \frac{\partial Q_x}{\partial x} = 0 \quad (1b)
\]

where:

- \( Q_x \) = Flow in Cartesian x direction
- \( A \) = Cross sectional area of flow
- \( h \) = Water depth
- \( z \) = Bed elevation
- \( g \) = Gravitational constant
- \( n \) = Manning’s coefficient of friction/Roughness coefficient
- \( R \) = Hydrometric radius
- \( t \) = Time
- \( x \) = Distance in Cartesian x direction

The chosen method by which these equations are solved is determined by the characteristics of the system to be modelled and the availability of data and time. To simulate flooding in the Lower Limpopo, the acceleration solver was chosen as the most appropriate. The other solvers, provided by LISFLOOD, are either less complex in their structure, more time consuming, not considered robust or require more data.
The acceleration solver applies the 1D shallow water equations (eq. 1a and 1b above) on a 2D grid (with friction terms in both Cartesian directions), to simulate the wave propagation in both the river channel and on the floodplain. From one cell to another, the flow is determined by the local acceleration, the friction slope and the water slope whereas the convective acceleration term is neglected. To avoid the problem of cells becoming filled with water and disturbing the flow paths, the solver calculates adaptive time steps. The calculation is performed according to the Courant-Friedrich-Lewy condition, which scales the time steps to cell size and water depth. The optimal time step, derived by this method, decreases linearly. One drawback of the adaptive time step mode is that it can increase simulation times considerably for high resolution DEMs.

As with any modelling approach, a number of assumptions and limitations are present using LISFLOOD and the acceleration solver. The mass and momentum of the water are, as previously mentioned, considered constant, and the floodplain is treated as being a series of storage cells, with flow solely occurring in Cartesian directions. The flood flow is further assumed to be gradually varied (i.e. the water depth is presumed to vary with longitudinal distance) and any effect of lateral friction is neglected. At conditions of extremely low roughness and/or high water turbulence the wave propagation can be underestimated. Using the acceleration solver, in particular, low roughness can also cause model instabilities. Such instabilities can be resolved by the inclusion of a diffusion term in the shallow water equations, which however requires more data. The fundamental data, required by the acceleration solver, are discharge at inflow points and floodplain topography. With these inputs and the flow across the domain edge (i.e. the general slope of the topography) defining the downstream boundary condition, flood simulations can be simulated in either steady state or dynamic mode (i.e. with fixed or varied discharge input).

When a model has been properly built, to be run by LISFLOOD, it can be calibrated to reach maximum correspondence with the chosen reference by adjusting the value of Manning’s roughness coefficient \( n \). This coefficient represents the landscape’s general resistance to flood flow, caused by for example surface roughness, topography, vegetation and loose debris (Arcement and Schneider, 1989). In LISFLOOD, separate \( n \)-values can be used for the river channel and the floodplain; and the floodplain \( n \) can also be set to vary in space. Since the Lower Limpopo has a relatively homogeneous land cover and in order to keep the model structure simple, one single \( n \)-value was used to calibrate the model in this study.

### 5.2 Model Setup

To model flood inundation extent with LISFLOOD practically means that several individual files have to be constructed. These files define the study area, the flood event, and control the parameters and actions of the model code. The model setup used in this study consisted of a controlling file (.par), a
processed version of the SRTM (.dem.asc), a file with the water levels of the river (.start), defined boundary conditions (.bci), flood hydrographs at upstream boundary conditions (.bdy) (hydrographs), times of satellite overpass (.opts) and a stage file with the coordinates of the high watermark recordings (.stage). An additional, automatically generated, output file (.max) was also used in the analysis. In the following sections the detailed process of creating these files will be described, according to function of being input data or defining output data.

5.2.1 Model Input

The SRTM images, used to derive the topography of the study area (.dem.asc), were acquired from USGS Earth Explorer and processed in ArcGIS. After merging the images into one dataset, the resolution was aggregated from 30 to 90 m by averaging neighbouring cells. This was done in order to remove noise and reduce the model computation time, as suggested by Neal et al. (2012). The resulting DEM was thereafter clipped to only display the floodplain of the Lower Limpopo. The exact geographical extent was chosen with respect to Cartesian directions, the high watermark record, river station locations, and the spatial coverage of the SAR data. A suitable spatial reference system was then applied to the DEM before it was exported as an ascii file. The projection used was WGS 1984 in UTM Zone 36S.

During the data processing, the general topographic trend of the Lower Limpopo floodplain was found to be flat with a slight dip to the SE, similarly to terrain information reported by INGC (2003). The apparent dips were calculated to be 0.005 m/m to the East and 0.003 m/m to the South. Both theses slopes were defined as free boundaries conditions in the model setup (.bci).

Three points on the DEM were selected as inflow boundary conditions (.bci). Two of these, Massingir and Combonume, were chosen as they represent approximate locations of river stations upstream of the area flooded in 2000 and 2013, where discharge data were available. The third inflow point was added to include the Changane tributary in the model. Hereafter, this inflow point will be referred to as Point 3 (P3). The DEM raster and the three inflow points are displayed in Fig. 4.

Before the constructed model was used to simulate the 2000 and 2013 floods, it was fed with fixed flows, corresponding to the average discharges at the river stations. This procedure provided a state of the Lower Limpopo Basin with water in the river channel, which was used as the initial condition for the flood simulations (.start). By including an initial condition in the model setup, the computation times of upcoming simulations could be reduced and complete river system connectivity assured. A simulation time of 310 days was required to fill up the river network with average flow.

To simulate the two flood events, the LISFLOOD model was run with time-varying flows as upstream boundary conditions (.bdy). The duration of the floods were defined as the time from average flow to the largest flood peak, with some eventual extra days to include satellite overpass times. This meant 54 days for the flood in year 2000 (8th of January to 3rd of March) and 18 days for
the 2013 flood (16th of January to 2nd of February). For Massingir and Combomune, the hydrographs corresponding to these time periods, were made into two different flood-flow input files (.bdy). At P3, where no discharge was available, the flow for these files had to be estimated by assuming hydrological similarity. This meant, multiplying the specific discharge hydrograph at Combomune (the flow at Massingir was not chosen since being regulated) with the drainage area upstream of P3. The P3 drainage area was manually determined by using the DEM and river network data from HydroSHEDS (Lehner et al., 2008). All discharge values were divided by cell width, as it is a requirement to use the unit m$^3$/s for dynamic flows in LISFLOOD. Figure 5 displays the hydrographs used as model input when simulating the 2000 and 2013 events (in m$^3$/s). The flood dynamics visible coincide with the description given by Venton et al. (2013).

4.2.2 Model Output

Two files in the model setup were created with the purpose to acquire simulation outputs comparable with the reference data. These files included the times of satellite overpasses (.opts) and coordinates of high watermark sites (.stage). For the overpass times the water levels in each pixel of the DEM were retained as results, while the stage file requested recordings of the water depths for the geographical points defined (Fig. 4) at each saved time step. The maximum water levels recorded in the stage file were assumed to best correspond to the high watermark data. The third type of output, which was used in this study, is created by LISFLOOD as a default setting. This output file (.max) contains the maximum water level reached in each raster cell during the simulation.

To make the model setup complete a controlling file (.par) was created. The purpose of this file is to provide information of where the data of a certain model parameter is found, and to define the model solver, n-value, simulation time parameters and result directory.
Figure 4. Map visualizing the model setup with the SRTM topography input (classified in 50 m height intervals), inflow points (light blue circles), stage output/high watermarks (red circles) and initial conditions (blue area). The ocean pixels in the lower right corner of the DEM (diagonally striped triangle) were removed in order to reduce computation time.

Figure 5. Flood hydrographs used as model input at inflow points. Hydrographs at Combomune and Massingir are derived from observations while P3 is calculated, using the Combomune discharge and hydrological similarity. * Day 0 refers to first day with Q > Qmean (i.e. 88 m$^3$/s) prior to flood peak at Combomune River Station.
5.3 Calibration and Validation

The model was calibrated using the 2013 flood, since its hydrograph had the shortest duration. The n-parameter was initially set to the minimum, maximum and three intermediate values (0.06, 0.09 and 0.12 s m$^{-1/3}$) within the recommended literature range of 0.03 – 0.15 s m$^{-1/3}$ (Chow, 1959; Arcement and Schneider, 1989). However, in order to obtain an optimized model performance, the range was later expanded to also include 0.02 and 0.01 s m$^{-1/3}$. The calibration was performed manually and the runs were limited in numbers because of long simulation times.

The accuracy of each calibration result was evaluated through a contingency table approach, a method commonly used in flood modelling literature (Di Baldassarre, 2012). In this approach, simulation results and reference data are made into binary flood extent maps, composed by wet and dry pixels, which then are compiled to obtain a spatial distribution of the model performance. In this study, since the UNOSAT shapefiles (composing the reference of the 2013 event) covered various parts of the flood extent during different overpass times, the best option to derive compliable datasets was to merge the shapefiles into one single polygon layer, and use the result file of maximum water level in each raster cell (.max). The binary maps were created in ArcGIS by classifying the raster pixels as flooded or dry, according to a system of ID numbers. A threshold value of 0.1 m water height was chosen for classifying the cells in the simulated result files as flooded, based on the assumption that the satellites sensors would fail to capture water levels lower than this. The two binary maps (simulated and reference) were then compiled, by summing their different ID numbers pixel by pixel. As a result, a new map with four different pixel categories (A-D) visualised areas being captured, overestimated or underestimated as flooded by the LISFLOOD model. The number of pixels in each category was then used to calculate the accuracy, or F-index, (eq. 2), the Bias (eq. 3) and the Flood capture (eq. 4) of each simulation run.

\[
F = \frac{A}{A+B+C} \quad (2)
\]

\[
\text{Bias} = \frac{A+B}{A+C} \quad (3)
\]

\[
\text{Flood Capture} = \frac{A}{A+C} \quad (4)
\]

where:

- $F$ = Quality Index
- $\text{Bias}$ = Aggregated value of under- and overpredictions
- $\text{Flood Capture}$ = % of flood extent being captured in simulation
- $A$ = Number of pixels being flooded according to both reference data and simulation
- $B$ = Number of pixels being dry according to reference data but simulated as flooded
- $C$ = Number of pixels being flooded according to reference data but simulated as dry
- $D$ = Number of pixels being dry according to both reference data and simulation
After the calibration procedure, the 2000 event was used for model validation. However, since the 2000 flood was so dynamically different from the flood in 2013 it was not only modelled once, with the best-fit \( n \), but also with remaining values of \( n \) tested during the calibration process. The point of this was to investigate if the two floods, due to their differences, needed different \( n \)-values to be modelled with optimized outcome.

The quality of the validation simulations was evaluated in the same way as the calibration results, by calculating the F-index, Bias and Flood extent capture. For the 2000 event, the output files with the inundated area at satellite overpass were merged and compared to the reference shapefile provided by Karlsson and Arnberg (2011).

To also investigate the performance of the model in the vertical direction, a supplementary validation analysis was performed on the simulated stage file. The maximum water levels simulated were compared to the high watermarks data, by calculating the mean error (ME), mean absolute error (MAE), root mean square error (RMSE) and standard deviation (STD). The ME (eq. 5) provides a measure of the bias in the model result, whereas the MAE (eq. 6) and RMSE (eq. 7) describe the accuracy (RMSE giving higher weight to larger errors) and the STD (eq. 8) the precision (Karlsson and Arnberg, 2011). All individual stage errors were also calculated and plotted, as indicators of eventual spatial differences in the model performance.

\[
ME = \frac{\sum_{i=1}^{n} (S_{M_i} - S_{HW_i})}{n} \tag{5}
\]

\[
MAE = \frac{\sum_{i=1}^{n} |(S_{M_i} - S_{HW_i})|}{n} \tag{6}
\]

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_{M_i} - S_{HW_i})^2}{n}} \tag{7}
\]

\[
STD = \sqrt{\frac{\sum_{i=1}^{n} ((S_{M_i} - S_{HW_i}) - ME)^2}{n}} \tag{8}
\]

where:

- \( S_{HW_i} \) = High watermark stage at location \( i \)
- \( S_{M_i} \) = Modelled stage at location \( i \)
- \( n \) = Number of stage locations
6 Results

In this chapter the outcomes of the model calibration and validation are presented. The findings are separated into sections according to flood variable modelled (flood extent or flood level).

6.1 Flood Extent

The initial calibration of the constructed LISFLOOD model, performed with the 2013 flood event, revealed a tendency of better correspondence between simulation and reference being obtained with decreasing n. However, since no maximum value of performance was observed, the range of investigated n-values was extended downwards. This resulted in an optimized model performance, with a general accuracy of $F = 0.59$, being achieved with $n = 0.02 \text{ s m}^{-1/3}$. In total, 75% of the inundated area was correctly captured as flooded during this simulation, and the bias was calculated to 1.02, meaning that the total area modelled as inundated was 2% larger than the reference flood extent. Using values of n outside the literature range did not cause any model instabilities.

The validation run with the n-parameter set to $0.02 \text{ s m}^{-1/3}$ resulted in a slightly higher accuracy ($F = 0.61$) than obtained during the corresponding calibration run. In this simulation a similar part of the flood extent was captured (73%), but in total the modelled inundated area was underestimated by 9% compared to the reference data (Bias = 0.91). The model reached an even higher correspondence with the 2000 flood by increasing the n-value. For n-values between 0.03 and 0.15 $\text{ s m}^{-1/3}$ the model performed very similar, with all simulations receiving an accuracy rounded to $F = 0.64$. The maximum F-value was obtained with the n-parameter set to $0.09 \text{ s m}^{-1/3}$. During this simulation, 83% of the flooded area was captured and the Bias of the result was calculated to 1.13. Looking at the general pattern of all calibration and validation simulations, higher accuracy was obtained when modelling the 2000 flood, independent of the value on n. Fig. 6 displays the F-index, Bias and Flood capture for each flood simulation performed during the calibration and validation procedure.

In addition to determining the general accuracy of the flood simulations, the spatial correspondence between model results and reference data were analysed. The findings of this analysis are visualized by the inundation maps in Fig. 7-10, in which the distributed model performance of the two most accurate flood simulations (2000 and 2013) and their corresponding calibration/validation runs are displayed. Remaining simulations can be found, as similar flood maps, in appendix A and B. For both flood hydrograph and all n-values used, discrepancies between modelled flood extent and reference data were mainly located in three areas; (1) along the upstream part of both river channels (flood extent overestimated), (2) in the region where the Changane River (flow from P3) drains into the Limpopo River (flood extent underestimated) and (3) in the southwest part of the basin, towards the watershed boundary (flood extent overestimated). The primary differences between calibration and
validation results were that the model, to a larger extent, overestimated the 2013 flood in area 3 and, with the n-parameter set to 0.02 s m$^{-1/3}$, failed to capture larger parts of the 2000 flood in region 2.

Figure 6. (a) Accuracy $F$, (b) Bias and (c) Flood Capture (%) of flood extents simulated with different n-values. Calibration simulations (Flood 2013) are displayed by black dots and solid lines, while validation simulations (Flood 2000) with white dots and dashed lines.
Figure 7. Flood map showing the spatial performance of the model in the most accurate inundation extent simulation obtained during calibration. Calibration was performed with the 2013 flood hydrograph.
Figure 8. Flood map showing the spatial performance of the model when simulating the validation event (the 2000 flood) with calibrated n-value.
Figure 9. Flood map showing the spatial performance of the model in the most accurate inundation extent simulation obtained during validation. Validation was performed with the 2000 flood hydrograph.
Figure 10. Flood map showing the spatial performance of the model when simulating the calibration event (the 2013 flood) with n-value of best validation run.
6.1 Flood Levels

To evaluate the model’s ability to simulate the vertical extent of the flood, the performance was assessed against the high watermark record. Table 4 summarizes the general results. Generally, the errors of the simulated stages were on the order of a meter. High accuracy (MAE and RMSE) and precision (STD) were obtained with a low n (0.01 and 0.02 s m$^{-1/3}$) while intermediate n-values (0.06 and 0.09 s m$^{-1/3}$) led to a low systematic error (ME).

Table 4. General vertical model performance, calculated from the difference between maximum flood levels simulated for the 2000 event and the high watermark record.

<table>
<thead>
<tr>
<th>n (s m$^{-1/3}$)</th>
<th>ME (m)</th>
<th>MAE (m)</th>
<th>RMSE (m)</th>
<th>STD (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>-1.12</td>
<td>1.87</td>
<td>2.40</td>
<td>2.12</td>
</tr>
<tr>
<td>0.02</td>
<td>-0.78</td>
<td>1.88</td>
<td>2.28</td>
<td>2.41</td>
</tr>
<tr>
<td>0.03</td>
<td>-0.54</td>
<td>1.91</td>
<td>2.44</td>
<td>2.38</td>
</tr>
<tr>
<td>0.06</td>
<td>0.13</td>
<td>1.95</td>
<td>2.50</td>
<td>2.49</td>
</tr>
<tr>
<td>0.09</td>
<td>0.17</td>
<td>2.00</td>
<td>2.57</td>
<td>2.57</td>
</tr>
<tr>
<td>0.12</td>
<td>0.36</td>
<td>1.99</td>
<td>2.59</td>
<td>2.57</td>
</tr>
<tr>
<td>0.15</td>
<td>0.39</td>
<td>1.94</td>
<td>2.56</td>
<td>2.53</td>
</tr>
</tbody>
</table>

To detect possible spatial patterns in the model performance, the residual errors were plotted individually along an upstream-downstream gradient (Fig. 11). The pattern over the system was consistent through all simulations, but a positive relationship between the n-value and water level heights could be observed. The residual error from site to site, however, was highly variable.

A map of the Lower Limpopo (Fig. 12), displaying elevation and slope, shows that many of the high watermark sites (7-9 and 13) are situated in locally high-relief terrain along the valley sides; site 7 even close to a local high point. In addition, the positions of several sites (1 and 10-13) coincide with the most highly populated cities in the region, Xai-Xai and Chokwe.

Figure 11. Individual water level errors simulated during validation (Flood 2000) at the sites where high watermarks were recorded. Values of n (s m$^{-1/3}$) are seperated by different shades of grey.
Figure 12. Map displaying the locations of high watermark sites in relation to the terrain (approximated to relative difference in elevation and slope) of the Lower Limpopo.
7 Discussion

This chapter provides a discussion of the flood modelling results, with a focus on explaining observed inaccuracies. The sections are, just as in previous chapter, divided according to simulated flood variables (flood extent or flood level).

7.1 Flood Extent

The constructed inundation model produced flood maps with an accuracy of approximately $F = 0.60$ for both the 2000 and 2013 floods, using the calibrated n-value of $0.02 \text{ s m}^{-1/3}$. An optimal fit was however not achieved for the 2000 flood with this n, but with the n-value increased to $0.09 \text{ s m}^{-1/3}$. An accuracy of $F = 0.64$ was then obtained. This outcome might be explained by the different dynamics of the two floods. The rapid and extreme flood peak of the 2013 event could have flushed through the catchment, without being significantly affected by the system resistance expressed by the n-parameter. For the 2000 flood, on the other hand, the roughness of the floodplain would have had a larger influence, since the inflowing water was more distributed over time (i.e. the 2000 flood hydrograph having multiple peaks with long duration). Findings from this study therefore agree with previous research that suggest the need of different calibration coefficients for floods of different magnitudes (Romanowicz and Beven, 2003; Horritt et al., 2007; Di Baldassarre et al., 2009). However, as quite good results were obtained through the whole spectra of tested n-values the result also suggest that a model calibrated with a flood of a relatively low return period might sufficiently capture the inundation extent of rare, extreme flood event. If true, this could potentially have high importance for flood risk mapping on the African continent, since extreme magnitude floods are few in historic data records but will become more frequent with climate change.

Spatially, the inaccuracies of simulations were concentrated in three regions, irrespective of flood and n-value. The upstream part of river channels and the southwest part of the floodplain showed tendencies for the flood extent to be overestimated, while it was significantly underestimated in the area where Changane River joins the Limpopo River. The latter fact highlights one important limitation of the model setup, namely its inability to account for the impact of reservoirs and temporary streams that may join the river system during conditions of high flow. Instead of diverting flow from the Limpopo River into Changane River, which would have inundated a larger area, the model used this water to fill the lake located west of the Changane River (Fig. 3). The reference data from the 2013 flood (Fig. 3) also indicates that several temporary streams added water into the lake and subsequently into the river system. Discharge data from such small streams is unlikely available, but solely by incorporating the lake in the fill-up might have significantly improved simulation accuracy in the model. Hence, one strong recommendation for future similar modelling studies is to
give thorough attention to river system complexity, including adjacent reservoirs that potentially could be reached by water during high magnitude floods.

Another factor, possibly contributing to flooded regions not being accurately captured by the model, is the assumption of hydrological similarity used to estimate the flow at P3. Changane River is generally characterized by low flow (Maposa et al., 2015) but, at the same time, its drainage area receives higher annual precipitation than Limpopo (WMO, 2012) and it is located closer to the coast. It is thus possible that the assumption of equal specific discharge at Combomune and P3, during weather conditions of heavy rainfall and cyclones originating in the Indian Ocean, might have led to an underestimated flood flow hydrograph at P3.

The overestimated flood extent modelled in the southwest part of the basin is attributed to different causes for calibration and validation flood simulations. The reference data of the 2013 event, the floodwater did not, to any large extent, flow into the southwest part of the basin. The model result probably differed in this respect, due to the inability of the SRTM data to recognize channel bed geometry and micro-topography. This loss of accommodation space, preferential flow path and small surface irregularities, combined with the floodplain in itself being extremely flat, and overestimated flood water levels in this region mainly ranging between 0.1 and 2 m, could have made the water spread out in the model. One alternative, but less likely, reason for the overestimated flood region in the 2013 flood map, could be a change of local roughness between year 2000 and 2013.

Due to the large water volume of the 2000 flood event, the generalized representation of small variations in the landscape would have a low influence on the model capacity to simulate the inundation extent. On the other hand, for many parts of the 2000 flood mask, the outline coincides with the widespread cloud cover in the Landsat 7 image (Fig. 13). It is very likely that the flooded area could have extended beyond this outline and the overestimations in 2000 flood simulations (along river channels and in the southwest area) were therefore rather ascribed to these reference inaccuracies than to limitations of the SRTM.

In terms of the general usability of the SRTM data to model flood extent, the results of this are encouraging, especially considering the low level of details used by the model of this study and how several improvements could easily be made. Nonetheless, some case specific aspects shaping the result have to be remembered.

First of all, the terrain of the study area has a low relief and incorporates a profound river valley. This means that the SRTM data is relatively accurate, and that floods are somewhat confined by the landscape's geomorphology. Mapping flood risk in catchments with either higher, or with flatter terrain without any distinct geological features, might therefore result in higher simulation errors.

Secondly, as the Lower Limpopo is rural and vegetation cover is low, sparse and evenly distributed, the potential positive elevation bias in the SRTM model was neglected. For flood modelling in other parts of Africa, where the character of the land cover is different, a procedure to identify the ground surface (e.g. Baugh et al., 2013) might be needed to obtain satisfying results.
A third important aspect is the reference data. In this study the reference data for calibration and validation were obtained from separate sources. As slightly different processing methods could have been used in these datasets, some uncertainty is brought into the results. The deterministic nature of the used reference, i.e. that the flooded area is defined by as a clear outline, can also be questioned. Several studies has suggested a probabilistic evaluation method, using fuzzy flood reference maps showing multiple possible flood extents of different probability, as being more statistically robust (Schumann et al., 2009; Di Baldassarre et al., 2010). However, within the scope of this thesis it was not feasible, by neither a deterministic or probabilistic method, to derive new reference data and the readily available dataset were moreover considered sufficiently accurate and similar to serve the aim of the quality analysis.

As a last remark, one has to underline that even though global topography seems to be able to provide a useful alternative to costly high-resolution elevation data, it is still only one of two constraints that limit flood risk mapping in the data-scarce areas of Africa. The lack of discharge records still remains a difficult challenge, as estimation methods often fail to predict high flows (Yan et al., 2014).

**Figure 13.** Illustrations of the cloud cover impact on flood extent reference data. Reference shapefile (red line) is superimposed on the Landsat 7 satellite image over areas overestimated in the 2000 flood simulations. Upstream part of Limpopo River is displayed to the left and the southwest part of basin to the right.
7.1 Flood Levels

The analysis of the simulated flood water levels revealed that, independent of chosen n, errors were on the order of a meter (ME = 0.17 m, MAE = 2.00, RSME = 2.57 m and STD = 2.57 m for best fitted flood extent). This accuracy is not adequate for detailed use, but considering the possible errors incorporated in the high watermark recordings, discharge data, DEM and model assumptions, all simulations performed well within this uncertainty range. A comparison to findings by Neal et al. (2012) also suggests that the model performed as well as could be expected. The researchers of that study likewise used SRTM data (aggregated to 905 m resolution) and a no-channel 2D-model, constructed for LISFLOOD, to simulate flood water levels in an African catchment (the Blue Nile). The ME and the RMSE of their best-fitted simulation of surface water levels were quantified to 2.54 and 3.34 m (Neal et al, 2012).

During the investigation of the individual stage error, a tendency of the simulated water levels being positively related to the value of the n-parameter was observed. This outcome is reasonable and reflects the impact of the roughness on the flow in the system. At low resistance, flow along the main path of the river channel is easy and water therefore also easily drains into the sea. On the contrary, high roughness retains water upstream and increases flow in lateral directions.

The high variability of errors on the simulated flood extent is probably related to the lack of micro-topography in the 90 m resolution SRTM raster. Especially so, since many of the sites were located in the steep terrain on the valley sides (the elevation in site cells and adjacent pixels could differ by as much as 24 m) and the simulated stage values, each representing the area of one cell, are compared to a reference dataset of point values. It should also be noted that a simulated water level with no error at 0 m elevation, as obtained at site 7, does not represent a perfectly captured water stage. The reference data define 0 m elevation as corresponding to maximum flood extent, while sites in the DEM grid could be located well above this height. This is probably the case at site 7, as its position is close to a local high point and no variation of water stage with change in n is seen.

For sites 10-13, Karlsson and Arnberg (2011) had reported discrepancies between the data from Radarsat 1 and the high watermark record. Speckles from surfaces in the urban area of Xai-Xai made these sites appear dry on the radar image, while the ground observations reported them as flooded. A similar issue in SRTM data could explain the underestimated stage values in the Xai-Xai area, and possibly also at Chokwe (site 1).

Vegetation is, just as for flood extent simulations, a potential source of error when modelling water levels, but its impact in the Lower Limpopo Basin is assumed low.
8 Conclusions

In this study, two large-scale floods in the Lower Limpopo Basin in Mozambique (occurring in year 2000 and 2013) were modelled for inundation extent using LISFLOOD, with the use of the global dataset of elevation SRTM as topography input. Flood extent simulations were evaluated against reference data extracted from various satellite images. High watermark recordings, available for one of the flood events, also allowed for an analysis of the vertical model performance.

During the model calibration procedure, the best simulation was obtained with an n-value of 0.02 s m$^{-1/3}$. Calibration and validation simulations with this specific n reached accuracies of $F = 0.59$ and 0.61, respectively. However, to obtain an optimal accuracy ($F = 0.64$) for the validation flood, the n-value needed to be increased to 0.09 s m$^{-1/3}$. This result was attributed to the different dynamics of the two flood events used for the calibration-validation procedure, and their respective sensitivity to system roughness. The study therefore line up behind previous research highlighting the insufficiency of using one calibration coefficient to reach maximum simulation correspondence of different magnitude floods, at the same time as it shows that a model calibrated with a flood of relatively low return period potentially can be used to map rare flood events with adequate results.

Spatial analysis of the flood extent simulations revealed inaccuracies being concentrated in three locations. The main causes were thought to be (1) unfilled reservoirs and streams, temporarily connecting to the river system during high flow conditions, (2) lack of riverbed geometry and floodplain micro-topography in the topography data and (3) cloud cover influencing the outline of the flood extent reference.

The vertical accuracy of water level simulations incorporated an average error of ± 2 m, indicating that the model, based on SRTM topography, is unsuitable to make detailed stage predictions but performs well within uncertainty bounds of input data. The source of the errors was believed to be in the SRTM’s representation of landscape morphology; which influence results for sites located in high slope terrain. In urban areas, underestimated flood levels could also have been due to radar speckles in the DEM.

The general findings of this study indicate that there is high potential in using the SRTM for large-scale mapping of high magnitude flood risks in Africa. Such maps could possibly provide highly valuable information for the future development hazard mitigation and water management. However, the results also highlight the importance of considering catchment specifics during the mapping procedure. The river system character, with adjacent geomorphological features and water bodies, could have a large influence on map accuracy and should therefore be carefully studied and kept in mind during model design. To apply a method to fill basin depressions beyond the main river reach might, for example, be needed when establishing the initial conditions of the model. To increase the knowledge of basin complexity impact and limit of input data usability, further case studies focusing on catchments of various character and smaller magnitude floods would be highly beneficial.
Lastly, one has to point out that even though inundation modelling based on global topography data can give encouraging results the lack of discharge records remains a challenge to be solved before catchment-scale flood maps in Africa can reach continental coverage.

9 Acknowledgements

The warmest gratitude is given to Giuliano Di Baldassarre. Thank you so much for all guidance, inspiration and encouragement. Thanks also to Johanna Mård Karlsson, Kun Yan, Diana Fuentes, Omar Khan and Patricia Trambauer for sharing material and/or your expertise knowledge on different aspects of the project and to Christian Zdanowicz and Elin Hultin Eriksson for useful comments on the text.

Nino and Audrey, I could not imagine nicer people to share an office with, thank you so much for inviting me into your lovely work environment. Romain, for all your support I owe you a lifetime ration of cinnamon buns.
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Appendix A: Calibration simulations

Figure A1. Flood map showing the spatial performance of the model when simulating the 2013 flood event with $n = 0.01 \text{ s m}^{-1/3}$
**Figure A2.** Flood map showing the spatial performance of the model when simulating the 2013 flood event with $n = 0.03 \text{ s m}^{1/3}$
Figure A3. Flood map showing the spatial performance of the model when simulating the 2013 flood event with $n = 0.06 \text{ s m}^{-1/3}$
Figure A4. Flood map showing the spatial performance of the model when simulating the 2013 flood event with $n = 0.12 \text{ s m}^{-1/3}$
Figure A5. Flood map showing the spatial performance of the model when simulating the 2013 flood event with $n = 0.15 \text{ s m}^{-1/3}$
Appendix B: Validation simulations

Figure B1. Flood map showing the spatial performance of the model when simulating the 2000 flood event with $n = 0.01 \text{ s m}^{-1/3}$
Figure B2. Flood map showing the spatial performance of the model when simulating the 2000 flood event with $n = 0.03 \text{ s m}^{-1/3}$
Figure B3. Flood map showing the spatial performance of the model when simulating the 2000 flood event with $n = 0.06 \text{ s m}^{1/3}$
Figure B4. Flood map showing the spatial performance of the model when simulating the 2000 flood event with $n = 0.12 \text{ s m}^{-1/3}$
Figure B5. Flood map showing the spatial performance of the model when simulating the 2000 flood event with $n = 0.15 \text{ s m}^{-1/3}$