APPLICATION OF A SATELLITE BASED RAINFALL-RUNOFF MODEL:A CASE STUDY OF THE TRANS BOUNDARY CUVELAI BASIN IN SOUTHERN AFRICA

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Abstract

Applications of distributed hydrological models are often constrained by poor data availability. Models rely on distributed inputs for meterorological forcing and land surface parameterisation. For this pilot study a satellite based rainfall-runoff model for large scale streamflow simulation is tested for the transboundary Cuvelai basin in Angola and Namibia. For this study the LISFLOOD hydrological model was selected and structure and data format of the model have been adapted. The model simulates river discharges in drainage basins as a function of spatial information on soils, topography and land cover. For rainfall estimation the TRMM 3B43 product has been selected wheareas for evapotranspiration estimation satellite products fom the LSA-SAF faciity have bene used. Other satellite products used are for elevation, leaf area index and land cover. Modelling focussed on simulation of the extreme high wet seasonal rainfall that caused major floodings in the area in 2009. The simulation period covered the food period (40 days). The model was manually calibrated by optimising five parameters. Model performance was assessed by the root mean squared error and Nash Sutcliffe coefficients. Results show that simulation of an extreme event that caused major floodings is possible thus indicating the effectiveness of use of satllite based model forcing data. Also the use of satellied based land cover data proved to be effective.

1 Introduction

In 2009 large scale floods in Cuvelai basin (Namibia) caused damage of over (USD) $500 million, (DWAF 2010). Intense and continuous rains throughout northern Namibia, southern Angola and western Zambia contributed to the flood. The floods led to the development of new hydrological conditions and drainage patterns as dried out lakes filled up (lake Liambezi) and fossil channels started to flow (Selinda river connecting to Kavango river), (NHS 2010). The floods caused emergency disaster conditions for one third of Namibia's population: 147 lives were lost, over 30 000 people displaced, agriculture and economic activities were disrupted, there was damage to infrastructure, and the government of Namibia declared a state of emergency (NHS 2010). Although there is an urgent need to develop adequate hydrological models to simulate andforecast events, there is significant lack of in-situ measurements (i.e. time series) of rainfall, evapotranspiration and stream flow. This lack of data probably constitutes the biggest challenge to the development of a hydrological model that serves stream flow simulation at first but eventually should serve forecasting of impacts of exteme meteorological events. Such model also could serve for early warning. Moreover, current

and rain gauges which are available are few and poorly distributed to represent the 167400km^2 size Namibia-Angola transboundary basin (Figure 1). Estimates of satellite based accumulated rainfall have to be assessed to better understand the spatio-temporal relationship between extreme rainfall inputs and floods. This study is an attempt to overcome the problem of data scarcity by use of satellite data, this particular for large scale and other transboundary river basins in Africa. The study aims to increase understanding of the applicability of satellite based rainfall estimation products as major inputs to rainfall-runoff models for flood simulation.

The pilot study assesses effectiveness satellite products so simulate stream flow of a large area with only very little in-situ data available. This study makes part of the ESATiger capacacity building programme,project 27. The aim of the project is not to deliver a suite of operational modleling tools but to build capacity in the field of remote sensing and

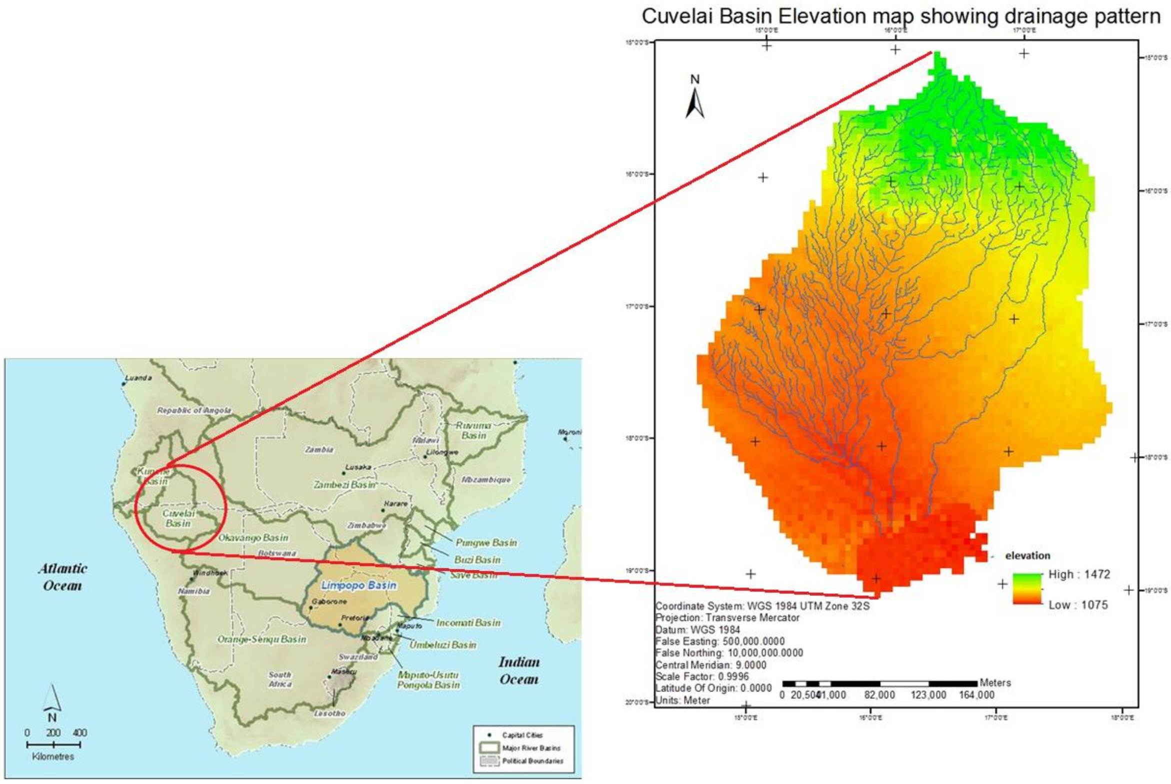


Figure 1: Location of Cuvelai Basin. (Source: http://www.limpoporak.com/en/river/geography/basins+of+southern+africa.aspx)

hydrological modelling in this specific project.

2 Satellite products

2.1 Digital elevation model (SRTM)

For representing elevation in our rainfall-runoff modeling approach we used the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with horizontal resolution of 90m at the equator. The data is projected in a Geographic (Lat/Long) projection, with the World Geodetic System 1984 (WGS84) horizontal datum and the Earth Gravitational Model of 1996 (EGM96) vertical datum [Farr and Kobrick, 2000; USGS 2006]. USGS (2006) report maximum elevation error of 16m. The existence of regions in a DEM without data (no-data regions) can cause significant problems in using SRTM DEMs, especially in the application of distrubuted hydrological models.The DEM for the study area is available from NASA/USGS and contained pixels where surface water bodies and/or heavy cloud shadow prevented the accurate estimation of elevation. To overcome this problem the Consultative Group on International Agricultural Research Consortium for Spatial Information(CGIAR-CSI) SRTM data product suggets a filling algorithm so to fill the data gabs. The interpolated DEM for the no-data regions was then merged with the original DEM to provide continuous elevation surfaces without no-data regions, (USGS 2006).

2.2 Rainfall estimation from space

For this study we evaluated the Multi-satellite Precipitation Analysis (TMPA 3B42) product from the Tropical Rainfall Measuring Mission (TRMM). This product is designed to combine precipitation estimates from various satellite systems and land surface precipitation from gauges. The product merges microwave (MW) infrared (IR) product and is available at 3-hourly temporal and 0.25° x 0.25° latitude–longitude spatial resolution (Huffman *et al.* 2007). For this study we used the post-real-time research-quality product that becomes available some fifteen days after the end of each month (research product), (Huffman *et al*. 2001). The product can be dowloaded at: http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3B42_Daily.

The research product of TMPA makes use of thee independent data sources: The TRMM Combined Instrument (TCI) estimate employs data from the TRMM Microwave Imager (TMI) and the TRMM precipitation radar (PR) as source for calibration. The resulting product is the TRMM Combined Instrument (TCI) 2B31 product (Haddad *et al.* 1997).The third source are the Global Precipitation Climatological Center (GPCP) monthly rain gauge analysis developed by GPCC (Rudolf 1993), and the Climate Assessment and Monitoring System (CAMS) monthly rain gauge analysis developed by the Climate Prediction Center (CPC) (Xie and Arkin, 1997). For extensive descriptions on the TMPA 3b42 product and its processing algorithm reference is made to (Huffman *et al.* 2007; NASA-GSFC, 2011; Acker and Leptoukh, 2007).

The TMPA 3B42 product algorithm V6

For estimation of rainfall intensity passive microwave fields of view (FOVs) from TMI, AMSR-E, and SSM/I are converted to precipitation estimates at the TRMM Science Data and Information System (TSDIS) with sensor-specific versions of the Goddard Profiling Algorithm (GPROF) (Kummerow *et al.* 1996; Olson *et al.* 1999). GPROF is a physics based algorithm that attempts to reconstruct the observed radiances for each FOV by selecting the "best" combination of thousands of numerical model generated microwave channel upwelling radiances, (Huffman *et, al.* 1995). The associated vertical profiles of hydrometeors are used to provide an estimated surface precipitation rate. The microwave data are screened for contamination by surface effects as part of the processing, with marginal contamination denoted as "ambiguous." Passive microwave FOVs from AMSU-B are converted to precipitation estimates at the National Environmental Satellite, Data, and Information Service (NESDIS) with operational versions of the Weng and Grody (2002) and Weng *et al.* (2003) algorithm.

The TMI—AMSR-E and TMI—AMSU-B calibrations are set in the form of a single climatological adjustment for land and another for ocean. The rainfall estimates are calibrated for each satellite and audited for >40% "ambiguous pixels". Individual grids are populated by the "best" data from all available overpasses. The most likely number of overpasses in the 3-hr window for a given grid box is either one or zero. In the event of multiple overpasses, data from TCI, TCI-adjusted TMI, TCI-adjusted AMSR-E, and TCI-adjusted SSM/I are averaged, and TCI-adjusted AMSU-B estimates are used if none of the others are available for the grid box (Description after (NASA-GSFC, 2011), (Acker and Leptoukh, 2007)).

The research product uses two different IR datasets for creating the complete record of 3-hourly 0.25° grid box histogram is zenith-angle corrected, averaged to a single T_b value for the grid box gridded Tb's. Each, and plane-fit interpolated to the 0.25° grid. The CPC merged IR is averaged to 0.25° resolution and combined into hourly files as 30 min from the nominal. The result is to provide the high temperal resolution estimate that is typical when satellite data is corrected for small bias by gauge analyses over land. Detailed information on this algorithm is available at the link: http://pps.gsfc.nasa.gov/tsdis/Documents/ICSVol4.pdf.

In Huffman *et. al.*[2006] it is described that TMPA provides reasonable performance at monthly scales. NASA-GSCF, (2011) described that TRMM TMPA data has strong physical relationship to the hydrometeors that result in surface precipitation although it is shown to have some error due to lack of sensitivity to low precipitation rates over ocean in one of the input products namely AMSU-B. Other aspects that affect perfomance are that each individual satellite provides sparse sampling by course space reolutions so occurrence of precipitation is relatively poorly represented. In addition there are significant gaps in the current 3-hourly coverage by the passive microwave estimates even when images are combined and merged to improve spatial coverage (after NASA-GSCF, 2011). Performence asessments of the TRMM 3B42 satellite rainfall product in the Cuvelai basin that stretchs from Angola to Namibia are not known to the authors. Lack of verification is caused by the lack of in-situ menasurements and, as such, products must be considered uncertian.

Table 1: TRMM 3B42 data characteristics

Temporal Coverage	Start Date: 1998-01-01; Stop Date: -
Geographic Coverage	Latitude: 50°S - 50°N; Longitude:180°W - 180°E
Temporal Resolution	3-Hourly, Daily
Horizontal Resolution	0.25° x 0.25°; nlat = 400, nlon = 1440
Average File Size	Compressed: ~285 KB; Original: ~4.5 MB
Available formats	Ascii, HDF, NetCDF, Google Earth KMZ

Source (*Acker and Leptoukh 2007*)

The product 3B42 v6 is available from GIOVANNI TOVAS in four formats: HDF, NetCDF (NCD), ASCII (available only when the array size is within about half-million points), and Google Earth KMZ.

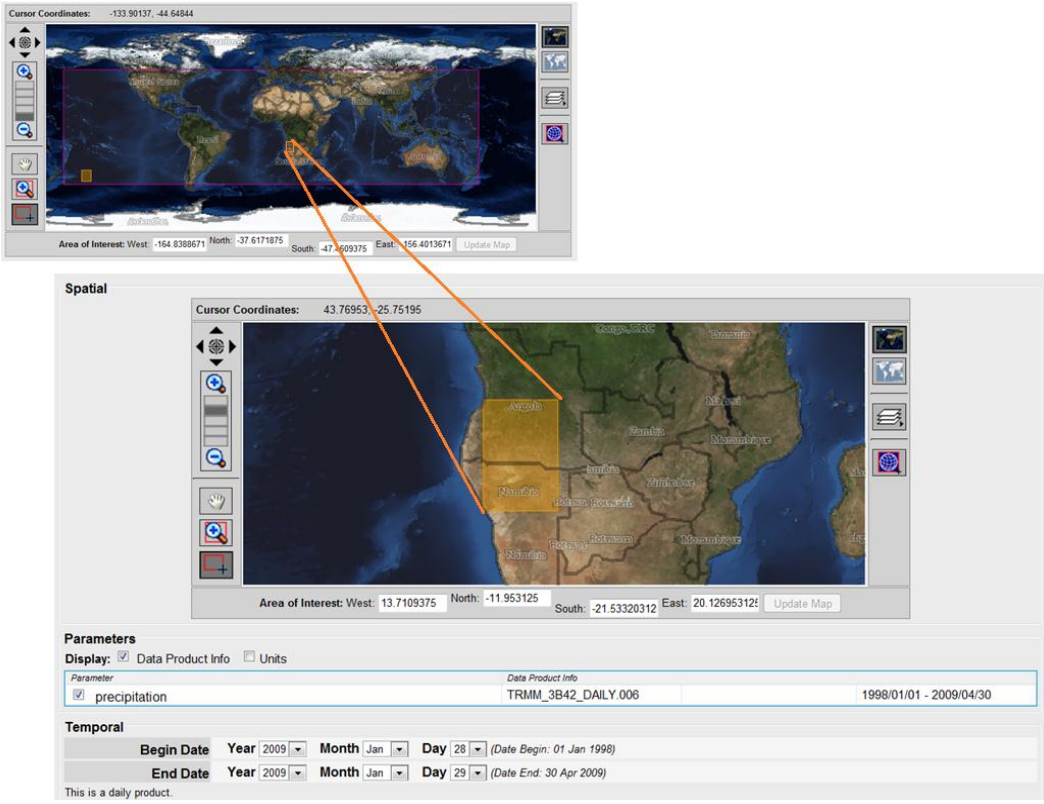


Figure 2: GIOVANNI TOVAS interactive interface. (Source: http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3B42_Daily)

2.3 LSA-SAF Evapotranspiration (ET)

The evapotranspiration (ET) product is derived from EUMETSAT Land Surface Analysis Satellite Application Facility (LSA SAF). Two products from the EVIRI radiometer on board the MSG satellite are produced. These are the instantaneous ET (30 minutes) and the daily ET both at spatial resolution of 3 km^2. The ET algorithm targets the quantification of the flux of water vapour from the ground surface (soil and canopy) into the atmosphere using input data derived from Meteosat Second Generation (MSG) satellite. The product used for Cuvelai basin was taken from Southern Africa (SAFr) geographical area within the Meteosat disk, covering the African continent south of the equator. Detailed information on the ET product is available at the following link: http://landsaf.meteo.pt.

The procedure follows a physical approach which can be described as a combination of the Soil-Vegetation-Atmosphere Transfer (SVAT) scheme and Tiled Land-Surface Scheme (TESSEL) land surface model. To simplify the estimation, the SVAT scheme is modified to accept satellite remote sensing derived data combined with data from numerical weather prediction (NWP) as forcing. Detailed information on the TESSEL model is available at the

following link:
http://www.ecmwf.int/research/EU_projects/GEOLAND/CTESSEL/index.html.

The TESSEL land surface model is a physical model based on soil moisture. In practice, the combined model is run on MSG images. Each pixel is considered as a mix of homogeneous entities.(i.e tiles) representing a particular coverage type (bare soil, grassland, crops, and forests). Some parameters are defined at the pixel level and are thus shared by the tiles composing the pixel, while others are defined at the tile level (i.e. overlay by a single tile), most of them being extracted from the ECOCLIMAP database (Masson *et al.* 2003). The resulting ET estimate for each pixel is obtained through the weighted contribution of each considered tile in the pixel [Description after Gellens-Meulenberghs *et al.*(2007)].

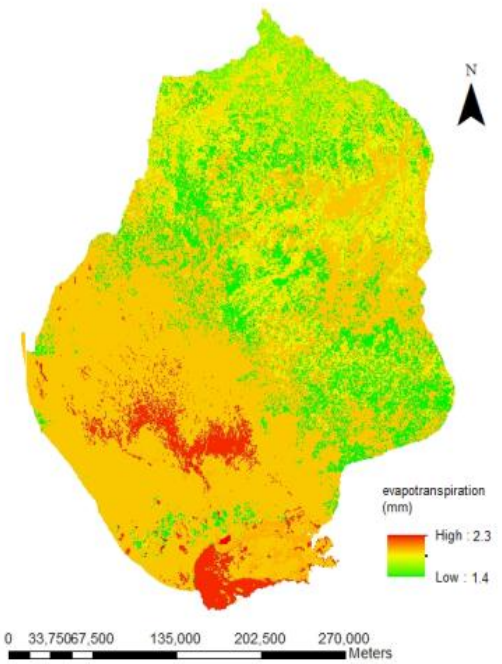


Figure 3: Evapotranspiration estimate 11th februari, 2009.

2.4 GLOBCOVER land-use map

The land use map of Cuvelai basin was extracted from the GLOBCOVER global map, at a spatial resolution of 300 meters. The GLOBCOVER project was launched 2004 as an initiative of ESA. It has now evolved to an international collaboration between ESA, FAO, UNEP, JRC, IGBP and GOFC-GOLD. The objective of GLOBCOVER is to produce a global land-cover map for the year 2005 at high resolution (300 m × 300 m) using data from MERIS sensor on-board ENVISAT satellite. The GLOBCOVER product intends to complement and update other existing comparable global products, such as the global land cover map for the year 2000 (GLC 2000) with a resolution of 1 km × 1 km produced by the JRC. Appropriate approaches for the validation of the land cover products are planned to be defined in consultation with Centre for Earth Observation Science (CEOS). Details of the GLOBAL cover map are available at http://geoserver.isciences.com:8080/geonetwork/srv/en/metadata.show?id=228. Figure 4 gives a flow chart on the processing of the landuse maps. Figure 5 show maps of the Cuvelai area as available through GLOBCOVER and reposessed following teehclassifcation of the corine data base.

The newly created land use polygon dataset was reclassified from the GLOBCOVER land cover classes to match the land cover classification of the CoRINE data base (see http://www.ceh.ac.uk/data/LCM1990Categories.html) used by LISFLOOD.

2.5 MODIS Leaf Area Index

LAI is an important input for the LISFLOOD model, since it is used as input to estimate interception, evaporation of intercepted water, evapotranspiration and evaporation from the

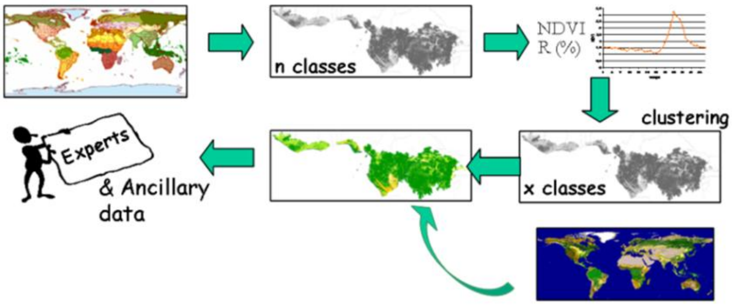


Figure 4: GLOBCOVER landuse classification process Source: http://postel.mediasfrance.org/en/BIOGEOPHYSICAL-PRODUCTS/Land-Cover/

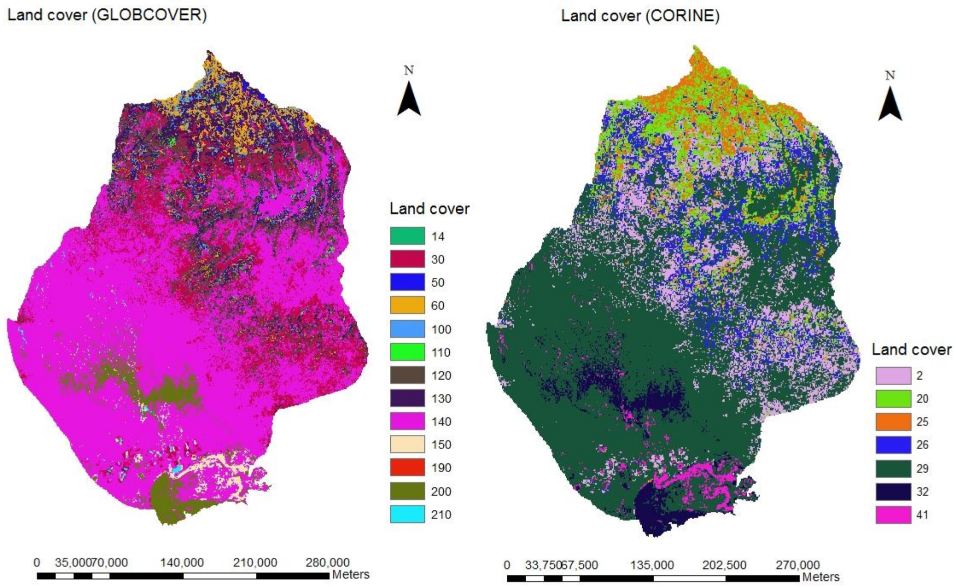


Figure 5: CORINE land cover classes and GLOBCOVER land cover classes.

soil surface.For this study we used the MODIS product that is available at https://lpdaac.usgs.gov/lpdaac/products/modis_products_table. The product algorithm uses sun and view angle directions of the MODIS satellite to estimate LAI values based on Bidirectional Reflectance Factor (BRF) for each MODIS band, band uncertainties, and six biome land cover classes, (Ranga *et al.* 2000). Imaages are available at dailly basis.The processing is done by NASA and daily LAI values are composited over an eight day period. The products are distributed from the EDC Data Center as 1 km 8-day products. The flow chart (figure 6) shows a summary of the estimation proceddure. The closed loop between product analysis, validation and algorithm refinement is a key element for improving product

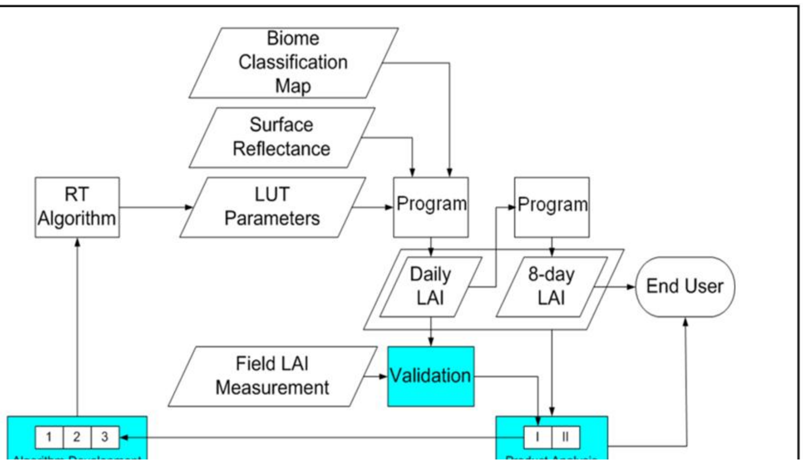
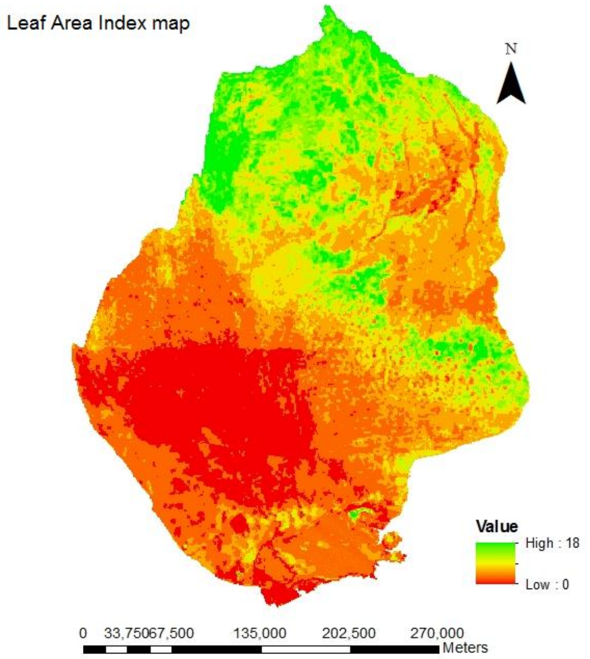


Figure 6: Algorithm for MODIS LAI data (Source: http://www.ntsg.umt.edu/project/modis#data-product)

quality in each successive reprocessing of LAI. Figure 7 shows LAI of the Cuvelai area for the 9th of 2009. Note that LAI changes over time depending on crop growth stages and soil water availability. For this pilote study we used averaged LAI at monhtly base.

Figure 7: Leaf Area Index map of the Cuvelay area (24 February 2009).

Since each satellite product is affected by aspects that relate to the specifc sensor technology, time-sapce resolution, sub-grid variability, sateliite observation algorithm and its specifc



parameters (just to mention a few) each product must be assesessed for its acccurracy. Table 2 reports on the quality aspects an d assessments performened on the satellite products.

Table 2: Quality assessment of satellite data

Satellite imagery	Quality assurance / accuracy levels
SRTM DEM	The SRTM DEM has an average error of 8 m as opposed to 20 m for the TOPO DEM. In area specific studies around the world systematic errors were identified in the SRTM data, related to aspect. The errors were found to be highest in northeast-facing slopes, attributed to the effect of incidence angle of the original radar images used to produce the SRTM DEM. http://srtm.csi.cgiar.org/PDF/Jarvis4.pdf
Precipitation TRMM v6-3B42	All TRMM products are provided with random error estimates. The data record have gaps in the record dueto processing errors and down time on receivers related to satellite imagery shortcomings. TMI error detection and correction is done by deleting all pixels with non-physical Tb and local calibration errors. ftp://precip.gsfc.nasa.gov/pub/trmmdocs/3B42_3B43_doc.pdf
Evapo-transpiration (ET)	The error estimate is the most general quality indicator operationally delivered by the algorithm. Automatic quality control (QC) is performed on each product and the quality information is provided on a pixel basis. Dark pixels (uncertainty < 0.1), green (uncertainty 0.1-0.15), yellow pixels (uncertainty 0.15 -0.20), red pixels correspond to unusable areas. http://www.earsel.org/symposia/2009-symposium-Chania/09EARSEL_garciaharoetal_LSASAF.pdf
MODIS Leaf Area Index	Science data quality flag was inferred as 'passed'on 17/04/2002, but the following is to be observed: Over inland water bodies (rivers, lakes, etc...) surface reflectance inputs and VI values are not be stable and should be used with caution. Users are advised to examine the per-pixel product quality to screen poor data before applying it to project-applications, science, and research. http://landweb.nascom.nasa.gov/cgi-bin/QA_WWW/detailInfo.cgi?prod_id=MYD13Q1&ver=C5
GLOBECOVER Land use	The final product has a relative RMSE of <50 mand <80 m absolute RMSE. Corrections have been implemented to diminish the influence of the atmosphere.In orderto minimise the bi-directional reflectance effects a simple composition averaging (BRDF correction) was used. http://due.esrin.esa.int/prjs/Results/20110202183257.pdf

Land surface temperature (LST) (LST only serves snowmelt calculations)	Errors in the data such include individual pixel count errors, missing parts of scan-lines, wrong geo-location and missing periods. There are also unknown errors in ECMWF re-analysis. http://postel.mediasfrance.org/IMG/pdf/CSP-0350-ATBD_LST-I1.00.pdf

3 Hydrological modelling

For this study the LISFLOOD model was selected that serves for large scale stream flow and inundation modelling. LISFLOOD is a spatially distributed and physically-based hydrological model (De Roo *et al*. 1989, De Roo (1996). The model simulates river discharge in a drainage basin as a function of topography, model focing data, soil properties and land cover. The model's primary output product is channel discharge whereas internal rate and state variables can also be written as output. For the LISFLOOD training version that was received from the JRC only the streamflow output was activated and as such time series on internal states and flood inundation was not available for the similation period. All output can be written as grids, or time series at user-defined scales, points or areas.

The structure of the LISFLOOD (see figure 8) van be characterised as follows:

a) a 2-layer soil water balance sub-model serves as basic modelling enteties for the shallow subsurface

b) sub-models are used for the simulation of groundwater and sub-surface flow

c) a sub-model for the routing of surface runoff to a river channel

d) a sub-model for the routing of channel flow to the catchment outlet.

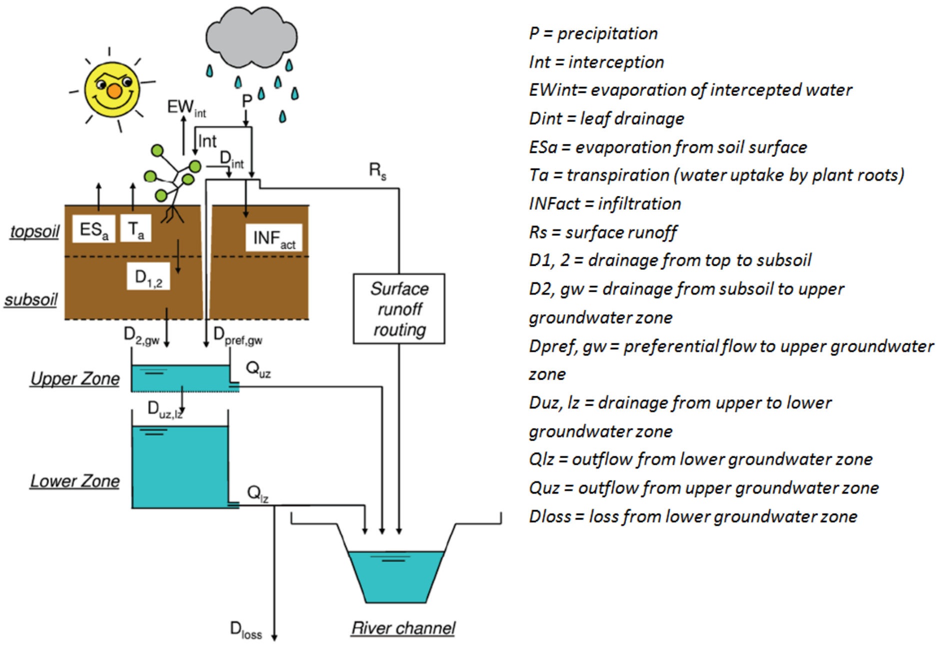


Figure 8: The LISFLOOD model structure (van der Knijff and de Roo, 2008)

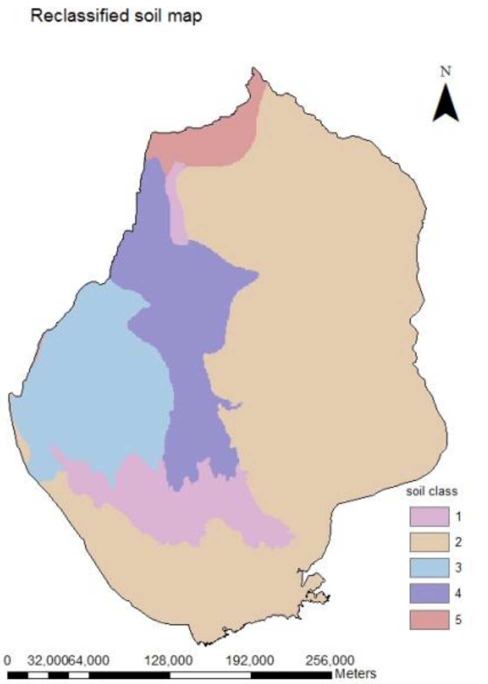
The processes simulated by LISFLOOD are precipitation, interception, soil freezing, snow melt, infiltration, percolation, capillary rise, ground water flow and surface runoff. Surface runoff and channel routing are routed separately using a GIS based kinematic wave routing module as the Manning equation, (De Roo *et al*. 2000). All satellite product s used in this study that served as inputs are decribed in Section 2. Below a short description is added on the non-satllite model inputs.

Non-satellite based model inputs

Soils

By its physical base, for simulation of the soil moisture storage and movements of the unsaturated zone, the LISFLOOD model uses a so called Richards type flow equation. This equation is parameterised by the, so called, 'Van Genuchten' reelattions which calculates soil moisture based on saturated volumetric soil moisture content ($\boldsymbol{\theta_s}$), residual volumetric soil moisture content ($\boldsymbol{\theta_r}$), a pore size index ($\boldsymbol{\lambda}$), saturated conductivity ($\boldsymbol{K_s}$) and the Van Genuchten parameter Alpha($\boldsymbol{\alpha}$). For eachof these parameters vakues need to be defined that reflects on the actual soils in the study area.

The project area was extracted from the regional soils map of Africa using the Cuvelai basin boundary file 'Cuvelai.shp' created in the ArcMAP spatial analyst tools. The vector-based soils data files were then reclassified from the FAO/UNESCO classes to match the LISFLOOD-USGS classes for which related tables are available in the LISFLOOD manual. Soil parameters are linked to the soil texture and land use maps through look-up tables.



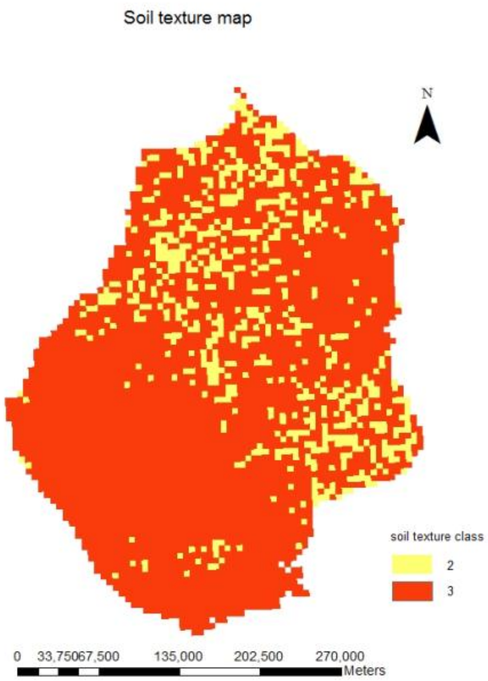


Figure 9: LIFLOOD input table for soil texture

Where code 1 is solonchacks, code 2 is solonetz, code 3 is acrisol, code 4 is chermozem and code 5 is luvisols. The soil texture map to the right is a typical PRCaster type map, where code 2 represents silt and code 3 represents clay portions of the upper soil horizon.

The LISFLOOD model requires soil depth and soil texture to be defined for two horizons.

Table 3: Soil texture characteristics at 1 m depth for LISFLOOD simulation [Horizon A]

Order	Soil texture				
	θ_s	θ_r	λ	α	K_s [cm/day]
Acrisol	0.439	0.01	0.1804	0.0314	12.061
Chernozem	0.52	0.01	0.1012	0.0367	24.8
Luvisols	0.403	0.025	0.3774	0.0383	60
Solonchacks	0.614	0.01	0.1033	0.0265	15
Solonets	0.430	0.01	0.2539	0.0083	2.272

(Source: Rawls *et, al.* 1982)

Channels

For tranfer of runoff water to the basin outlet, a strahler order drainage network is used. The nework evolves from upstream element mapping. Runoff from any grid element is simulated based on a kinematic wave approximation and requires that channles need to parameterised at pixeel level. In this study fixed properties are defined for each respective strahler order. In this study channel properties such as bank width, bank height, dimensions for the respective strahler orders increase from upstream to the downstream with largest values at the outlet. A major constrain to this approach in the Cuvelai area in Namibia is that flow behavour in the ochannas cannot be similated. Moreover, the DEM resolution (5 km × 5 km) is much to coursce to represent conveyance characteristics of the ochannas.

Stream flow measurements

For this study, stream flow data was not available and constrained model calibration. To overcome this problem information on water levels from radassat flood maps was used and stream flow was estimated by considering the the total accumulated cross/secttional area of the ochannas that drain the water. Clearly, this procedure must be considered `rudimentary` and results of estimated stream flow must be considered very inaccurat e and thus unreliable. Results of the inversely established stream flow hydrolgraph are shown in the section on model calibration.

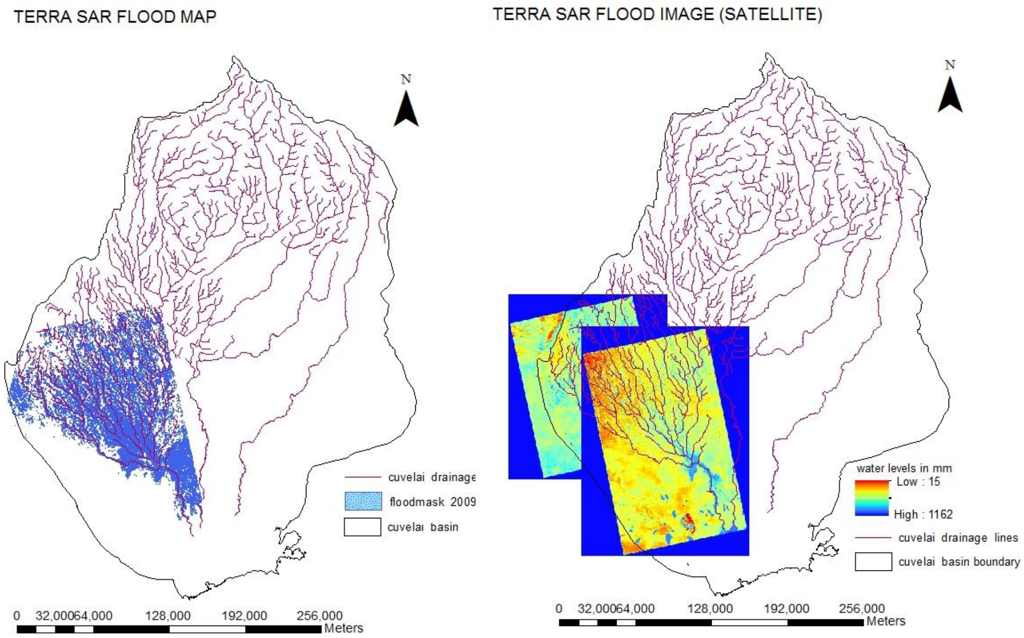


Figure .?: Cuvelai drainage network overlain by Terra Sat flood maps**.**

4 Modelling Results

Outputs by LISFLOOD are generated as PCRaster maps of as time series. The table below describes the output time series that are reported by default. Other outputs can be produced by activating the 'options' in –listoptions in the settings file. In the LISFLOOD model version applied for this study the flood inundation mapping was inactive and focus only was on large scale stream flow modelling. Moreover, the course grid element scale adapted in this study (5 km × 5 km) did not allow for flood inundation simulation since inundation is scales much smaller than the grid scale. We note that stream flow results from the course scale model could serve as input when setting up a model at fine scale (<100 m^2 resolution).

Table 4 shows model outputs in this study.

Table 4: LISFLOOD default output time series (source van der Knijff and de Roo, 2008)

RATE VARIABLES AT GAUGES		
Description	**Unit**	**File name**
channel discharge	m^3/s	dis.tss
Numerical checks		
cumulative mass balance error	m^3	mbError.tss
cumulative mass balance error (mm water slice over area)	mm	mbErrorMm.tss
number of sub-steps for gravity-based soil moisture routine	-	steps.tss

Source: van der Knijff and de Roo, 2008

In this study we simulate the stream flow that caused the the flood situation of February-March 2009. Detailed filed measurements onflow discharges ar not availble. This patly because each ochann cannot enequepped with a gauges. We estimated stream flow by considering all wetted cross-section on areas of the ochannas that constributed to the conveyance of the water. Since the Cuvelai area inNamibia is very flat much runoff water is stored and very small hydrualic gradients drive the flow of water. As such the stream flow estimates must beconsidred very unertain.

The model was initialised using a period of 1000 days. Since data only ws availbel for the wet season period in2009 we repeated simulations where output of all state variables served as iput for the next simulation run. Bij the sequence of simualtion runs we assume that the model is initialised. The model initialisation run is shown in figure 10. The actual simulation period during which foods occurred stretches from 21st January to 28th February.

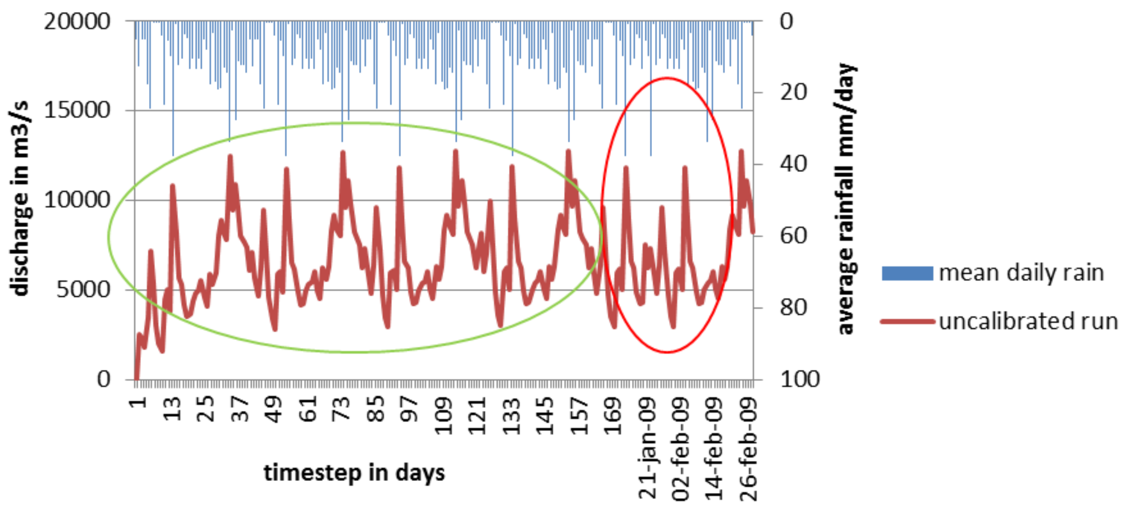


Figure 10 : Plot of model simulated discharge against rainfall received

It .is shown that timing of the peaks of the discharge from the period of interest marked in the red circle not directly correspond to the rainfall received. Thus calibration of the model was carried out to improve timing of the peak flows with the maximum average daily rainfall received. Calibration was based on a sensitivity analyses for five parameters suggested by (van der Knijff and de Roo, 2008). These parameters are: two infiltration parameters *b_Xinanjiang* (b) and *PowerPrefFlow* (c_{pref}) as well as *UpperZoneTimeConstant* (T_{uz}), time constant for the upper groundwater zone [days]; *LowerZoneTimeConstant* (T_{lz}), time constant for the lower zone in days and *GwPercValues* (GW_{perc}), the maximum rate of percolation going from the upper to lower groundwater zone (mm/day). Prior parameter ranges are indicated in Table 5.

Table 5: Prior ranges of model parameters (upper and lower bounds).

	Parameters				
	UZTC	LZTC	GPV	bX	PPF
Range[1]	1 – 50	50 – 5000	0 – 1.5	0.1 - 1	1 – 6
Range[2]	1 – 10	10 – 5000	0 - 0.5	0.05-0.5	5-15
Default	5	1756	0.11	0.993	4.9043
Optimum	15	2500	1.2	0.8	5

Source : range[1]and default values: (van der Knijff and de Roo, 2008) range[2] : (Feyen , 2005)

Sensitivity of the LZTC

The lower zone time constant the residence time in the lower ground water zone. It controls the amount and timing of outflow from the ground water resevoir which reflects in the river bank as discharge. Figure 11 shows the sensitivity of the LZTC

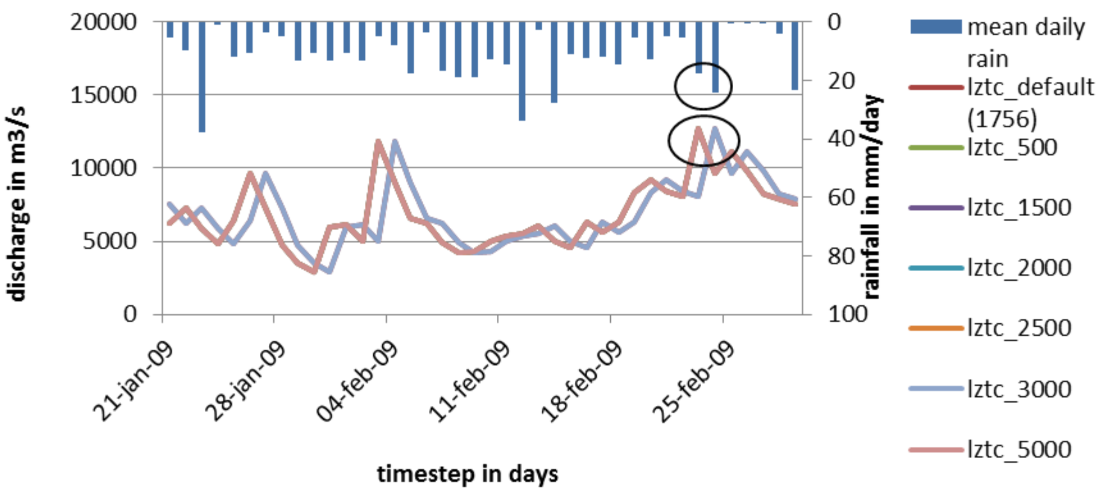


Figure11: Sensitivity analysis of LZTC

The increase in LZTC values shifts the peak flows to coincide more with the average daily rainfall, as can be seen with the change on 23 to 25 February marked with a black circle. Changes inLZTC do not notibly affects the stream flow discharges.

Sensitivity of b_X parameter

Increasing the value of b_X affects simulation of infiltration. The b_X parameter controls the fraction of saturated area within a grid cell that is contributing to runoff, thus it is inversely related to saturation and infiltration. It is expected that high b_X values would decrease the infiltration, and ultimately increase surface runoff (quick-flow) causing high peak lfows..

The general observation is that the model is very sensitive to the changes in the b_X parameter values. The role of b_X as a shape parameter is indicated in figure 12 below where the ascending and descending limbs are visibly different for b_X values of 0.1 and 0.2 which develop gentle receeding limbs for the periods (7 to 13 February; 19 to 21 February and 24 to 28 February). The higher b_X parameter values of 0.8 and 1 trigger high flows with relatively steep hydrolgrapph limbs. High b_X also result in lowest flows in beteeen the high flow periods.

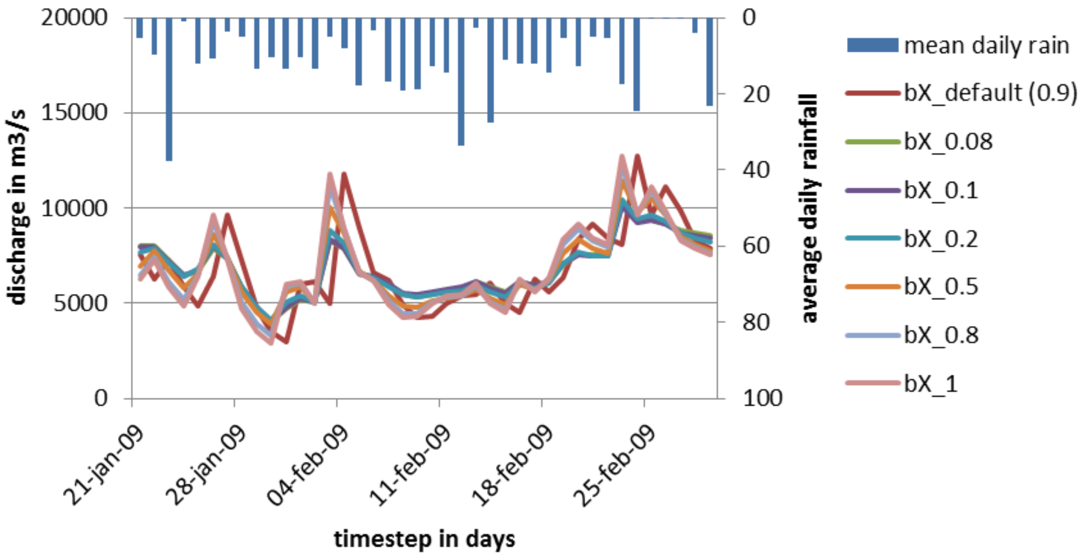


Figure 12: Sensitivity analysis on the b_X parameter

Optimized parameters are shown in Table 5.

Figure Below shows the behaviour of the three different discharge simulations resulting from the study. Graphs indicate that discharge estimations inferred from the flood maps are reasonably simulated by the model. This applies for the simulations that apply optimised model parameters but also default parameters. Both simulation results,however, generate flower flows over the simulation period suggeting that the estimated flow discharges are too high. With respect to timing of peak flows, results hen using calibrated parameters shows a better match. Performance indicaters only suggest fair modleperformance withrelatively low NS values and high RMSE values.Overall it can be stated that the modelshows potential to be applied too the Cuvelai with satllite products that serve for meterological model forcing.

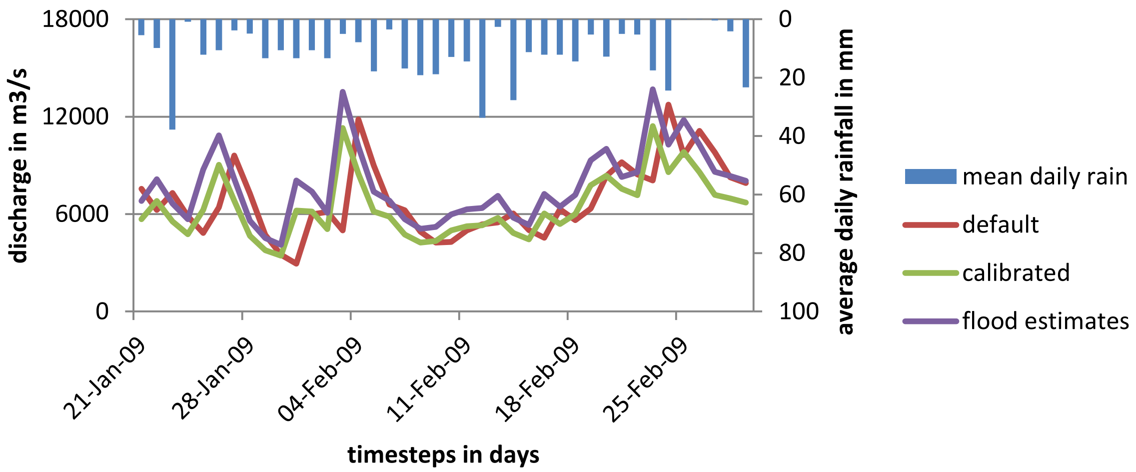


Figure 13: Comparison of simulated stream flow hydrographs versus inversely estimated stream flow .

Table 5: Results of the sensitivity analysis carried out on LISFLOOD calibration parameters. Bold values indicate optimal runs

	RUN	PARAMETERS					OBJECTIVE FUNCTIONS	
		UZTC	LZTC	GPV	bX	PPF	RMSE	NS
Upper Zone	**default**	5	1756	0.11	0.9993	4.9043	89.60	0.57
	2	10	1756	0.11	0.9993	4.9043	91.70	0.55
	3	**15**	**1756**	**0.11**	**0.9993**	**4.9043**	**90.33**	**0.58**
	4	20	1756	0.11	0.9993	4.9043	90.69	0.56
	5	25	1756	0.11	0.9993	4.9043	89.75	0.57
	6	35	1756	0.11	0.9993	4.9043	89.42	0.57
	7	45	1756	0.11	0.9993	4.9043	89.21	0.57
Lower Zone	**default**	5	1756	0.11	0.9993	4.9043	90.57	0.56
	2	5	1500	0.11	0.9993	4.9043	81.75	0.55
	3	5	500	0.11	0.9993	4.9043	91.43	0.53
	4	5	2000	0.11	0.9993	4.9043	88.05	0.58
	5	**5**	**2500**	**0.11**	**0.9993**	**4.9043**	**91.19**	**0.59**
	6	5	3000	0.11	0.9993	4.9043	87.14	0.59
	7	5	5000	0.11	0.9993	4.9043	88.19	0.58
GwPercValue	**default**	5	1756	0.11	0.9993	4.9043	84.01	0.61
	2	5	1756	0	0.9993	4.9043	82.63	0.63
	3	5	1756	0.4	0.9993	4.9043	83.28	0.63
	4	5	1756	0.5	0.9993	4.9043	84.19	0.61
	5	5	1756	0.8	0.9993	4.9043	83.94	0.62
	6	5	1756	1	0.9993	4.9043	82.62	0.63
	7	**5**	**1756**	**1.2**	**0.9993**	**4.9043**	**84.94**	**0.62**
b_Xinanjiang	**default**	5	1756	0.11	0.9993	4.9043	92.63	0.52
	2	5	1756	0.11	0.08	4.9043	91.30	0.55
	3	5	1756	0.11	0.1	4.9043	88.05	0.58
	4	5	1756	0.11	0.2	4.9043	87.19	0.59
	5	5	1756	0.11	0.5	4.9043	89.75	0.57
	6	**5**	**1756**	**0.11**	**0.8**	**4.9043**	**92.43**	**0.60**
	7	5	1756	0.11	1	4.9043	90.76	0.60
PowerPrefFlow	**default**	5	1756	0.11	0.9993	4.9043	94.63	0.52
	2	5	1756	0.11	0.9993	1	82.63	0.63
	3	5	1756	0.11	0.9993	2	83.28	0.63
	4	5	1756	0.11	0.9993	3	91.49	0.55
	5	5	1756	0.11	0.9993	4	83.01	0.63
	6	**5**	**1756**	**0.11**	**0.9993**	**5**	**91.30**	**0.63**
	7	5	1756	0.11	0.9993	6	90.16	0.56

5 Conclusions and discussion

The general conclusion is that it is possible to simulate flood events based on short term extreme rainfall events for catchments using LISFLOOD. The satllitte data selected for this study proved to be usefull in a manner that the model forcing could be performed by satllite data. Also representation of topograpy, land use and leaf area by satllite data seems tobe appropriate although specific (quality) assessments could not be performed.

Model sensitivity analysis indicate that the model is very sensitive to the parameters b_X. Peak flows as well as flows during interstorm periods are affecteed.Volumetric test, howeve, on total dischargeed water value have not been performed. The LZTC both control slow runoff mechanisms and are more sensitive to the 'timing' of the peaks and show a shift towards better coincidence with rainfall events. The UZTC is the least sensitive of the parameters, and generally any values within the suggested range can be used within the context of this study and with the dataset available because from a minimum of 10 to a maximum of 50 the response is almost negligible. The channel bottom width map 'chanbw.map' and the channel bankful maps 'chanbnkf.map' respectively are critical to the accurate simulation of the calculation of water levels through kinematic routing.

Unavailability of in-situ data caused that simulation results are very uncertain. Stream flow estimates from the Cuvelai in Namibia only are invesely estimated. This by considering the accumulated conveance area of the oshanas. We note that estimates on interstorm flows and peak flow cannot be reasoned for when compared to observed flows frorm cachemnt of similar size.
Meaurements by the Namibian Hydrological services suggest much lower flows in the order of 200 to 300 m^3/sec. discharge commonly observed for catchments of maximum regional scale (1500 km^2). We speculate that most runoff water is stored in the oshanas in the very flat Cuvelail area at the Angolan-Namibian border. Since flat areas commonly cause that hydraulic gradients only are small this could explain why flow estimates are of different magnitued. Clearly, hydraulic behaviour should be evaluated and and substantiated by field assessments and verification.