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Sudd Wetland Monograph -Volume 2: Detailed eco-hydrological planning model for the Sudd

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1. INTRODUCTION

1.1 Overview

The main objective of this report is to showcase the development of a detailed eco-hydrological planning model for the Sudd. The resulting model should have the capabilities to assess interventions in terms of wetland status (e.g. extent and flooding using simple 2d hydraulic modelling) and the water balance. This model should be a more detailed version of the Sudd module developed for generally depicting the Nile basin wetlands, to be integrated into the basin-wide planning model under WP 2.

According to these requirements and as requested by NBI, HYDROC has developed a model of the Sudd wetland (Figure 1) that uses DHI software available to the NBI and that can be linked to the NileDSS. A coupled MIKE11 – MIKE-SHE (henceforth designated as “M11-MSHE”) model has therefore been used as the model framework. The feasibility of this model framework was previously assessed by NBI on a small section of the Sudd in the upstream region between Mongalla and Bor and evaluated as being suitable[1].

MIKE 11 (M11) is a 1D hydraulic model that simulates channels and river networks using cross sections depicting the river geometry and branches that define the interlinkage between the cross sections. The model simulates hydraulic variables such as flow velocity and water depth, both depth- and width-averaged, at each cross section. MIKE SHE (MSHE) is a gridded groundwater-surface water model that calculates evaporation, infiltration, surface runoff and groundwater flows for each grid cell.

M11 and MSHE can be dynamically linked and therefor, M11 can provide water input into the MIKE SHE domain in case the water in the channels spill over the banks, while also the gridded domain in MIKE SHE can provide overland water inflow into the defined channels.

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[1] Wetland-River System Interaction Model – Pilot Upper Sudd wetland, NBI

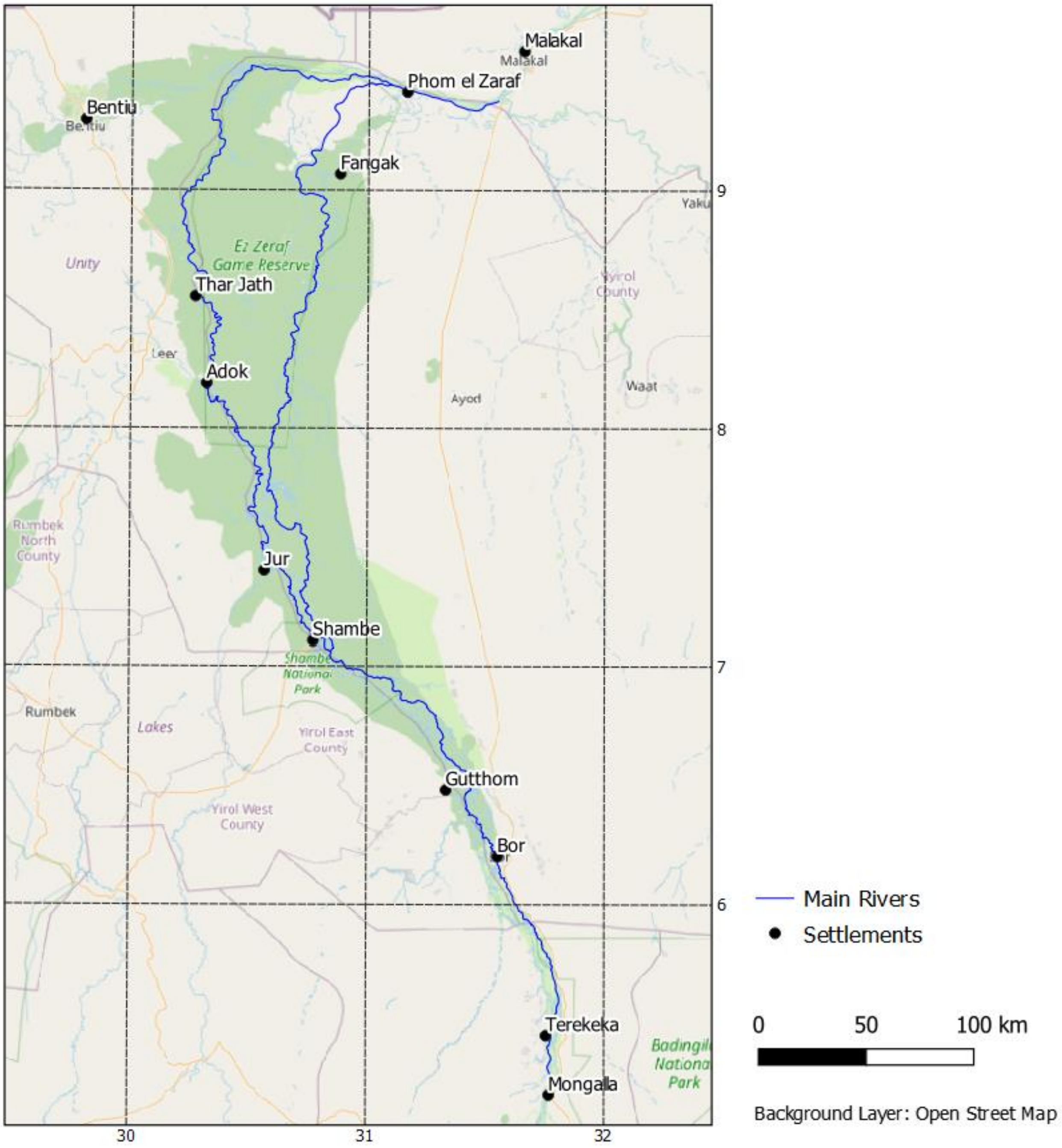

Figure 1. Location of the Sudd in South Sudan, major settlements and rivers

1.2 Purpose and Development

This “Volume 2 – Detailed eco-hydrological planning model for the Sudd” is the 3rd of a 4-part series and a supplementary volume to the Sudd Monograph, a key output of the NBI’s Wetlands Programme support to South Sudan through the South Sudan's Wetlands Working Group, which aims to develop a comprehensive information and knowledge base on the existing conditions of the Sudd that can be used as an aid by decision makers to help guide future planning and development initiatives. Supplementary volumes follow with specific focus on detail aspects such as hydrological modelling, TEEB and environmental flows. These documents will be important sources from which to reference critical information that is required to ensure sound management of the Sudd.

Volume 1 – Sudd Wetlands Monograph

Volume 2 – Sudd Eco-Hydrological Planning Model

Volume 3 – The Sudd Economics of Ecosystems and Biodiversity

Volume 4 – The Sudd Environmental Flows Assessment

The development of the Sudd Monograph has been based on active and sustained stakeholder engagement by consulting with local government officials, NGOs and local communities. Additional consultative meetings and discussions were held with officials from national and regional agencies. This approach enabled the use of significant local expertise and knowledge to understand local issues, challenges, and solution opportunities. The development of the Sudd Monograph can thus be seen as a collaborative effort among NBI and the Sudd stakeholders at regional, national, and local levels.

1.3 Outline of the Report

This report consists of the following chapters:

Chapter 1 gives a brief overview, outlining the purpose of the document and how it has been developed.

Chapter 2 provides the data and information used to setup the model, which includes spatial data such as topography, soil, land use/ land cover and river channels as well as spatio-temporal data such as precipitation, evapotranspiration and river discharge.

Chapter 3 discusses how the datasets described in chapter 2 have been used to develop the model configuration and scenario setup.

Chapter 4 shows the results of the baseline which includes the annual wetting and drying processes, spatial inundation distribution, discharge ratios and water balance, as well as the synthetic scenario results.

Chapter 5 ends the report with a conclusion

2. DATA SUMMARY

2.1 Spatial data

The following static (not variable over time) spatial datasets were collected for the definition of the physical model boundaries:

2.1.1 Topography

The topographic data is the most important input data for the hydraulic model since it mainly governs the flow of water. Therefore, an assessment of the soil data was carried out by comparing the publicly available DEM datasets. Figure 2 shows a close-up of the Sudd for the three globally available DEMs SRTM2, ALOS3 and MERIT4. As can be seen, the SRTM contains implausible surface patterns and in the ALOS, the original optical images used to derive the DEM are still visible in the DEM. The pattern borders show a height difference in the range of 1-3m, a significant difference in a flat region like the Sudd. The MERIT-DEM is an improved and carefully processed version of the SRTM and the ALOS[5], resulting in a higher accuracy and a removal of artificial patterns and noise. Therefore, the MERIT-DEM is chosen as the dataset to use within this project. In case the MERIT-DEM is used for commercial purposes, the results derived from the DEM have to be made publicly available according to the Open Database License (ODbL 1.0).

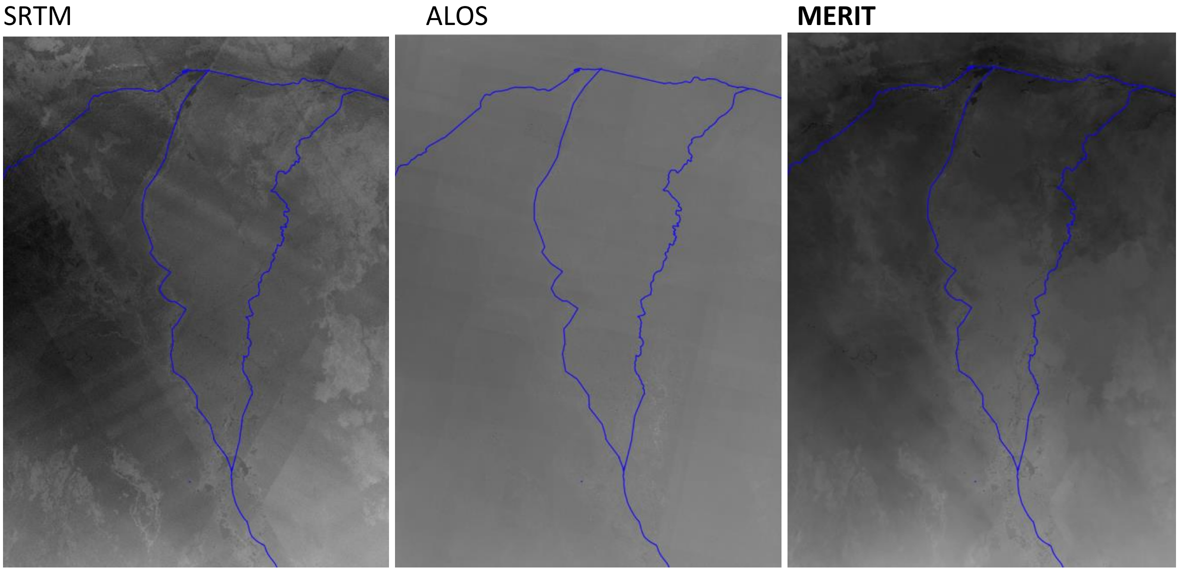

Figure 2. Comparison of SRTM, ALOS and MERIT DEMs in the Sudd (note the patterns in the SRTM and the ALOS, which are >2m along the pattern borders)

2.1.2 Soil

Soil data is needed for MSHE to calculate the grid-based water balance in terms of infiltration and evaporation from the soil. The representation of the soils is derived from the globally available soil grids dataset[6]. SoilGrids is a machine learning implementation for global digital soil mapping to map the spatial distribution of soil properties. The prediction models are fitted to over 230 000 soil profile observations and extrapolate their results on 250m global resolution. The model uses over 400 environmental layers from Earth observation and other environmental information including climate, land cover and terrain morphology. The outputs of SoilGrids are the following soil property parameters at six standard depth intervals: pH, soil organic carbon content, bulk density, coarse fragments content, sand content, silt content,

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[2] https://www2.jpl.nasa.gov/srtm/

[3] https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm

[4] http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/

[5] Yamazaki et al. 2017. A high accuracy map of global terrain elevations. Geophysical Research Letters 44(11)

[6] https://soilgrids.org/

clay content, cation exchange capacity (CEC), total nitrogen as well as soil organic carbon density and soil organic carbon stock.

This soil data was downloaded, and processed with SoilGridR[7], an R package that utilizes k-means clustering to aggregate the data to soil types that distinguish the Sudd (Figure 3).

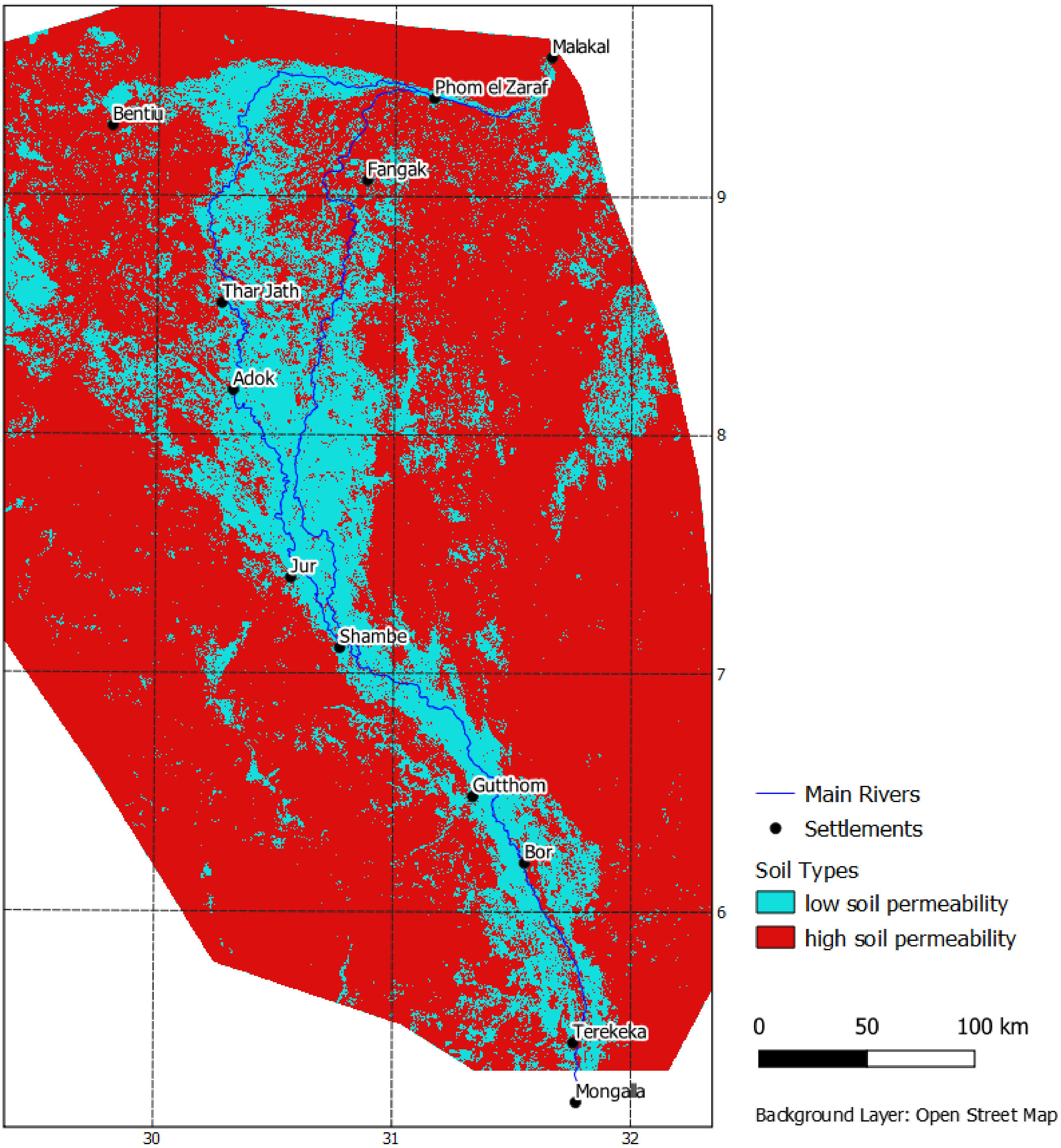

Figure 3. Soils in the Sudd grouped according to lower and higher soil permeability derived from the SoilGrids dataset

2.1.3 Land use / Land cover

Land cover information, more specifically, the vegetation types present in the Sudd are required for the models in order to depict the resistance of the surface to flowing water. The used land use dataset is the classified vegetation based on Sentinel data for the year 2015 (Figure 4).

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[7] https://github.com/chrisschuerz/soilgridr

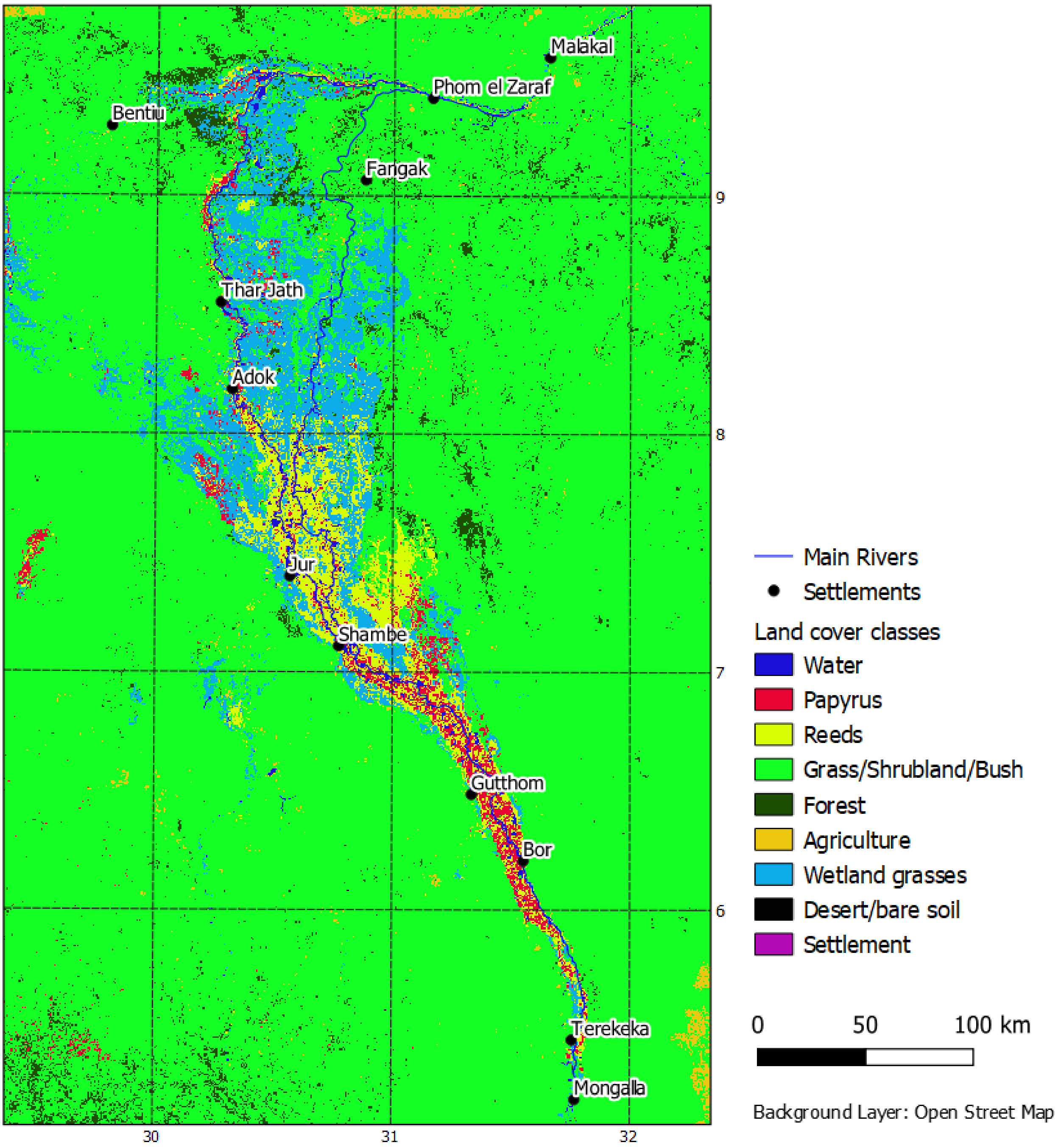

Figure 4. Classified land cover classes for the Sudd from WP1 for the year 2015

This dataset is also used to assess the plausibility of the M11-MSHE model in terms of depicting the inundation. Wetland grasses, reeds and papyrus require frequent flooding and the spatial distribution of these vegetation classes act as a benchmark of where the model should reproduce frequent inundation of the surface.

2.1.4 River channels

The location of channels, their interlinkage as well as channel widths are required for M11. This data was digitized in full detail for the whole Sudd (Figure 5) including the visible channel width (Figure 6) from satellite imagery. This resulted in 622 individual channel reaches.

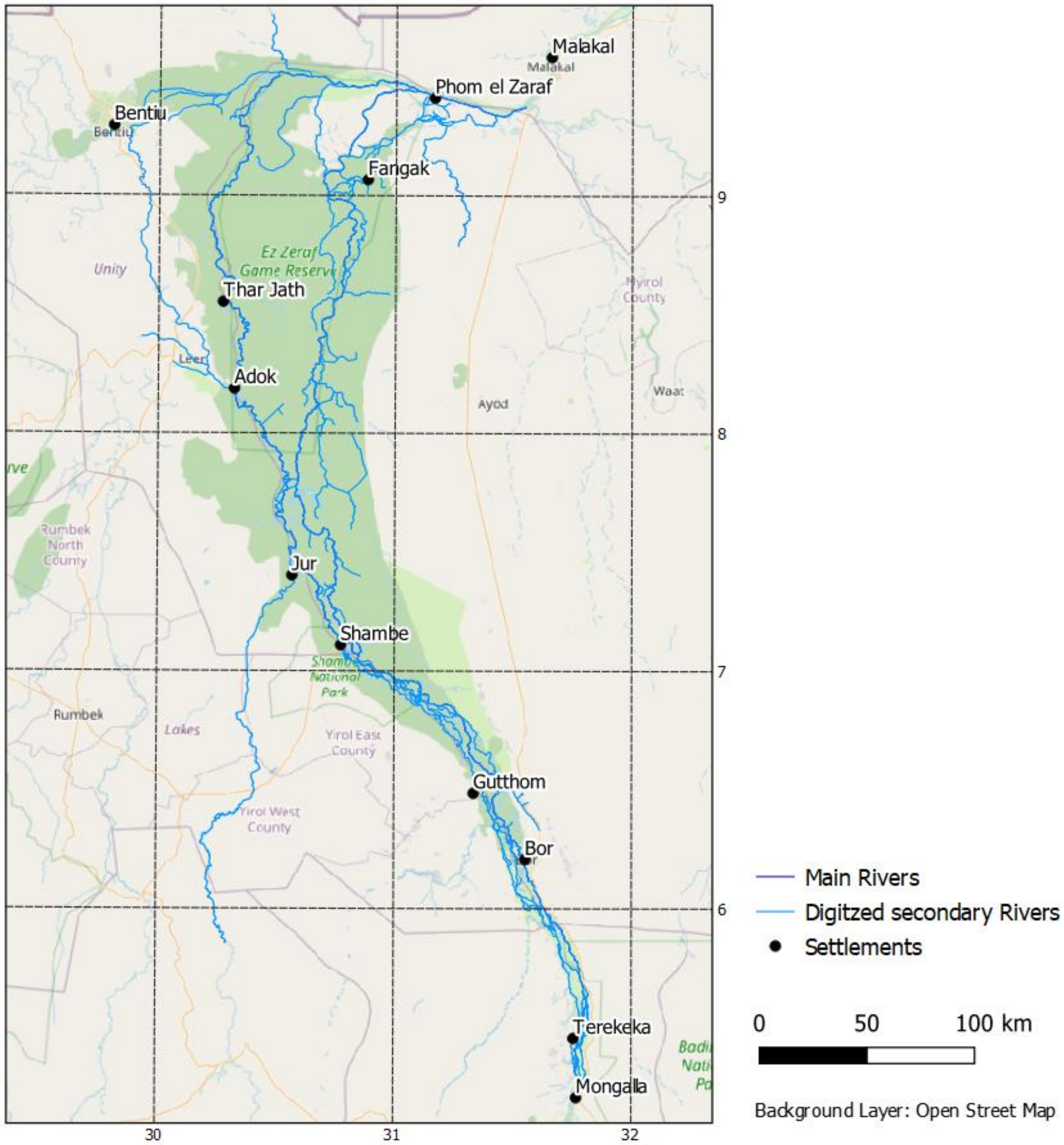

Figure 5. Digitized stream network distinguishing primary and secondary rivers

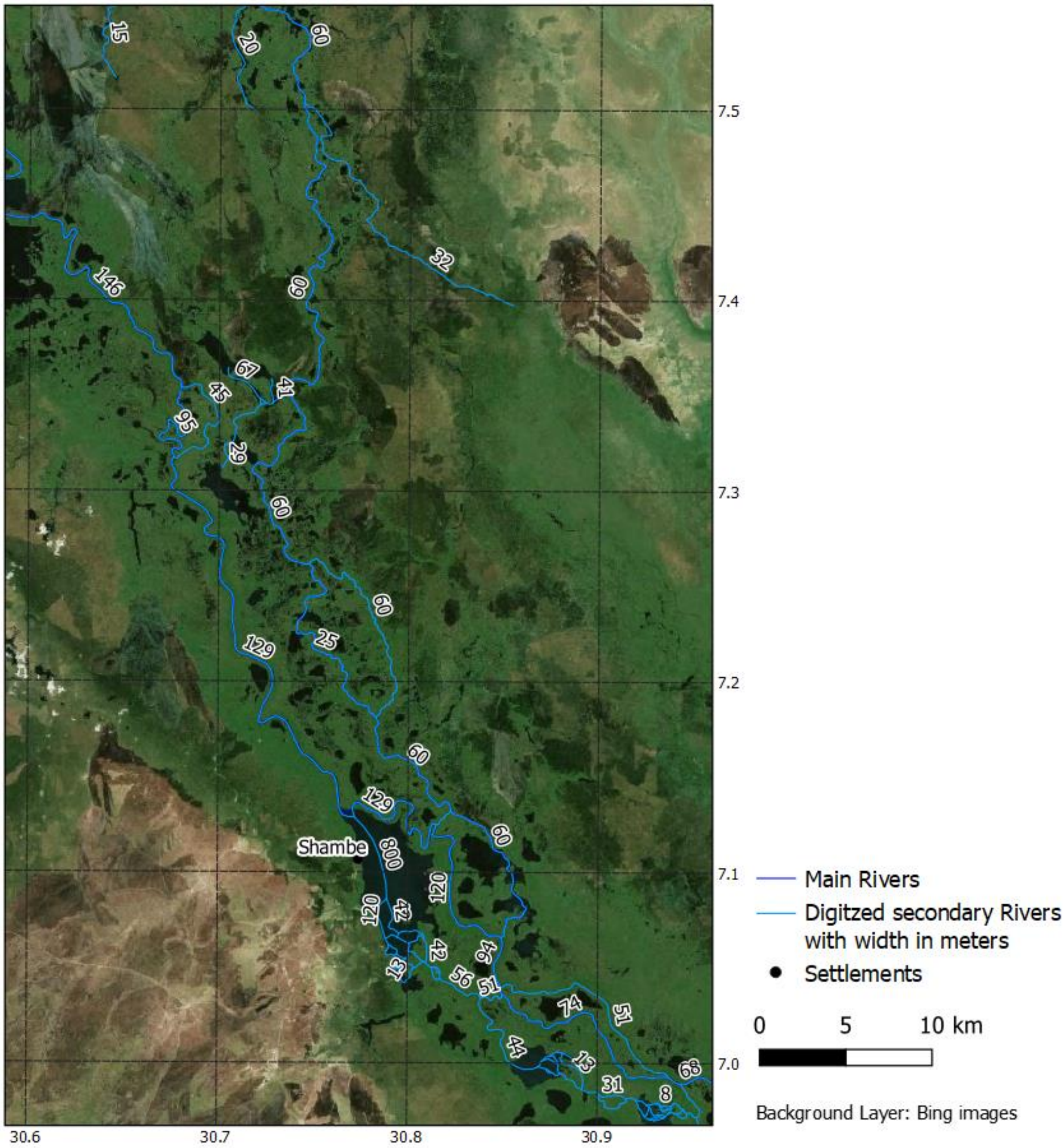

Figure 6. Close-up of digitized rivers with channel width in meters

2.2 Spatio- temporal data

2.2.1 Precipitation

Precipitation data is required for MSHE and one of the most important input datasets since in the wet season, inundation processes in the Sudd are also precipitation-driven. The NileDSS utilizes the Princeton Climate datasets, which are available on a 0.25° grid. For the M11-MSHE model to be compatible to the NileDSS, precipitation data was obtained for the full time period (1948-2016) on a daily time step from the Princeton servers[8], clipped and processed for MSHE.

2.2.2 Potential Evapotranspiration

Potential evapotranspiration is required by MSHE to calculate losses from the gridded model domain in terms of actual evapotranspiration from the soil, plants and open water. Again, to be consistent with the NileDSS,

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[8] http://hydrology.princeton.edu/data/pgf/v3/

potential evapotranspiration is calculated from the Princeton datasets8, where the Hargreaves potential evapotranspiration model was implemented in Python to produce the potential evapotranspiration for each daily time step from 1948 – 2015 in NetCDF format.

2.2.3 River discharge

Since the M11-MSHE model implementation cannot include the full upstream watershed of the Sudd, an inflow boundary condition is required for the model that represents the flow of the Bahr el Jebel at Mongalla. This discharge time series was obtained from the baseline simulation of the NileDSS, where interpolated daily flows from the monthly simulation for the river node “N333 outflow to RiverNode 570” were extracted from the NileDSS.

In addition, observed river discharges are required for calibration of the model, since flow splits and losses within the Sudd should be depicted as realistically as possible. Historical flow data was supplied by NBI and was processed for the locations and time period shown in Table 1.

Table 1. Flow data of the Sudd including location (Lon, Lat), the temporal coverage (Yrs) and the calculated flow percentiles (from 0 to 100)

Station	Yrs	Lon	Lat	Percentile flow [m^3/s]												
				0	1	2	5	10	25	50	75	90	95	98	99	100
BeJ Mongalla	1903 - 84	31.77	5.20	207	333	372	439	520	598	722	856	1130	1380	1657	1827	2700
BeJ Gemeiza	1931 - 84	31.78	5.68	332	377	421	458	491	554	663	1053	1480	1595	1809	1965	2310
BeJ DS Lake Nyong	1937 - 83	30.60	7.45	336	379	404	450	472	510	557	625	742	773	791	805	909
BeJ Hillet Nuer	1936 - 83	30.30	8.15	259	280	292	313	326	342	357	375	430	446	457	466	481
BeJ Buffalo Cape	1936 - 83	30.38	9.22	256	272	286	301	310	321	330	343	397	411	423	430	454
WN US Zeraf	1923 - 83	31.12	9.43	202	227	241	264	276	294	311	330	350	365	400	445	578
BeJ Gigging	1931 - 67	31.75	5.65	62	91	97	110	125	156	190	222	254	286	310	322	382
BeZ Meshra Kwatch	1940 - 73	30.70	8.32	88	95	100	106	110	123	141	152	169	212	227	237	244
BeZ Mouth	1900 - 82	31.13	9.42	32	65	71	91	104	118	136	155	216	291	348	383	450

3. MODEL SETUP

The datasets described in chapter **Error! Reference source not found.** have been further pre-processed using QGIS, Excel, Python and read into M11-MSHE using the MikeZero shell. The development of custom-tailored scripts to automatically derive the model domains and input files for M11 and MSHE was needed for being able to flexibly setup the models and change the configuration in such a complex wetland as the Sudd. The programmed tool to enable this automatic setup includes the following steps:

- Derive cross sections in the respective width and user defined spacing for each digitized reach
- Convert the connections, junctions and branches from the digitized stream network into the M11 format
- Read bank elevations from the DEM
- Enable different options to set channel depth (e.g. Savitzky Golay filter of the Thalweg, restrict up-downstream elevation changes, linear interpolation of elevation changes, set constant elevation, minimize elevation changes within junctions, set channel depths based on river width)
- Write the M11 network and M11 cross section file

Mostly using these scripts, HYDROC has gone through 108 different model configurations of which about a third were run with different parameterizations, leading to more than 200 different model setups. Each of these setups required between 1-7 days computational time (computation in parallel), hours of data preparation, model setup and results analysis. A major hindrance in using a physically plausible model setting was, that about a third of these model setups were unstable and led to crashes in the 1D domain of the model framework, mostly during times of highest flows and maximum precipitation. In addition to own investigations, and discussing with the NBI modelling team, HYDROC has contacted DHI for possible solutions. In total, the major characteristics that were tested in these configurations are:

- different number of channels in MIKE 11 (ranging from 243 to 2)
- multiple channel depths
- different channel widths
- different channel depths distributions from south to north
- multiple cross section spacings
- reducing the noise (up- and down fluctuations) in the channel thalweg through smoothing
- constraining channel thalweg increases when going downstream
- testing physically plausible range (and beyond) of roughness values in channel and floodplain
- different DEM grid resolutions in MIKE SHE
- correcting for vegetation effects through burn in of papyrus and reeds into the DEM
- different approaches for the evapotranspiration
- different approaches for the calculation of the infiltration to and from the saturated zone
- multiple parameter settings for the saturated and unsaturated zone
- separate soil parameterizations for the major Sudd wetland and outer riparian areas
- splitting the model domain in three sub-domains and linking those
- running the models with different time steps, accuracy thresholds and stability settings
- using different initial conditions for the model, both from remote sensing or from hot-start files
- using different thresholds for water movement initiation within the 2D grid
- selecting different approaches for the modelling of the overland flow in the 2D domain
- different elevation correction approaches

The last point in the list was crucial and also influences model results most significantly, since we needed to change the underlying topography of the Sudd. Changing topographic data for hydraulic modelling is unusual and therefore requires a clear justification and plausibility assessment. The reason for the elevation correction is the inland delta structure of the Sudd. This inland delta is shown in Figure 7 where the higher elevation (up to 4m for the example cross section) of the Sudd wetland compared to the surrounding plains is clearly visible.

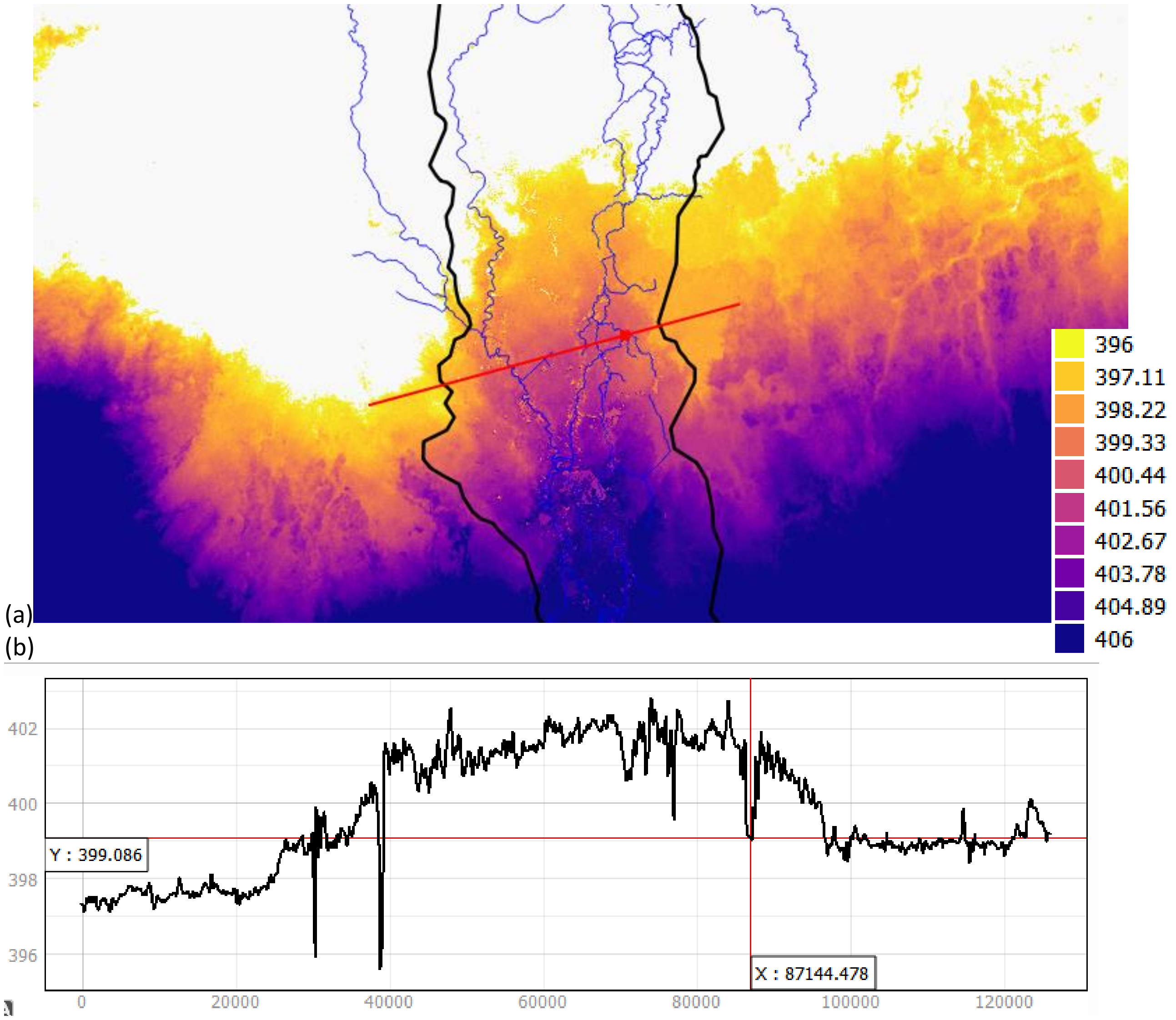

Figure 7. (a) digital elevation model (MERIT 90m DEM) of a section of the Sudd with the outline of the inner delta structure (black line) and a cross section location (red line); (b) the elevation distribution of the cross section, red dot and crosshair mark the location of the Bahr el Zeraf channel

These unique characteristics of the Sudd exist due to sedimentation of the White Nile's sediments in the papyrus fields and on the plains after leaving the southern-mountainous area and the abundant organic matter production and die-off. Therefore, compared to the surrounding plains, the Bahr el Jebel and Bahr el Zeraf rivers flow on an elevated surface that is constrained by dense papyrus and reed vegetation. Flood waters do not significantly spill on the plains due to the dense vegetation and the strong evapotranspiration, removing the slow-flowing floodwaters before they are able to reach the plains (Figure 8).

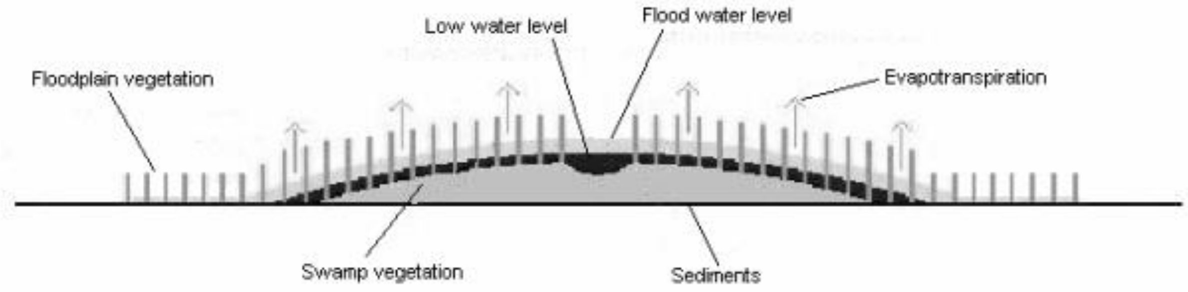

Figure 8. Schematic cross section of the Sudd swamps (Petesen & Fohrer, 2019)

One model approach to depict these characteristics is to extensively increase roughness values of the vegetation to reduce lateral flows. This approach has worked with MIKE21 [9], however, this software is not available to NBI. All attempts to depict these characteristics in the coupled M11-MSHE framework have been unsuccessful, mainly due to the fact that the model became unstable for high roughness values and plausible channel depths. Based on this assessment, in agreement with NBI, the decision was made to change the topography of the Sudd, as described in chapter **Error! Reference source not found.**.

The setup and model characteristic described below are based on the final model setup that led to stable model runs, reasonable run times and a model that is able to depict the seasonal wetland processes.

3.1 Model domain and schematization

The model domain and schematization that led to the most suitable model is shown in Figure 9. It includes the main channels of the Bahr el Jebel, the Bahr el Zeraf and the White Nile. The domain has a cell size of 540m and covers the channels and major floodplains, as well as the total extent of the Sudd inland delta.

In M11, this leads to two branches with 1766 and 841 cross sections for the Bahr el Jebel and Bahr el Zeraf respectively. In MSHE, the grid contains 1041 cells in x and 933 cells in y-direction with a cell size of 540m.

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[9] Petersen and Fohrer. 2010. Two-dimensional numerical assessment of the hydrodynamics of the Nile swamps in southern Sudan. Hydrological Sciences Journal 55(1): 17.26.

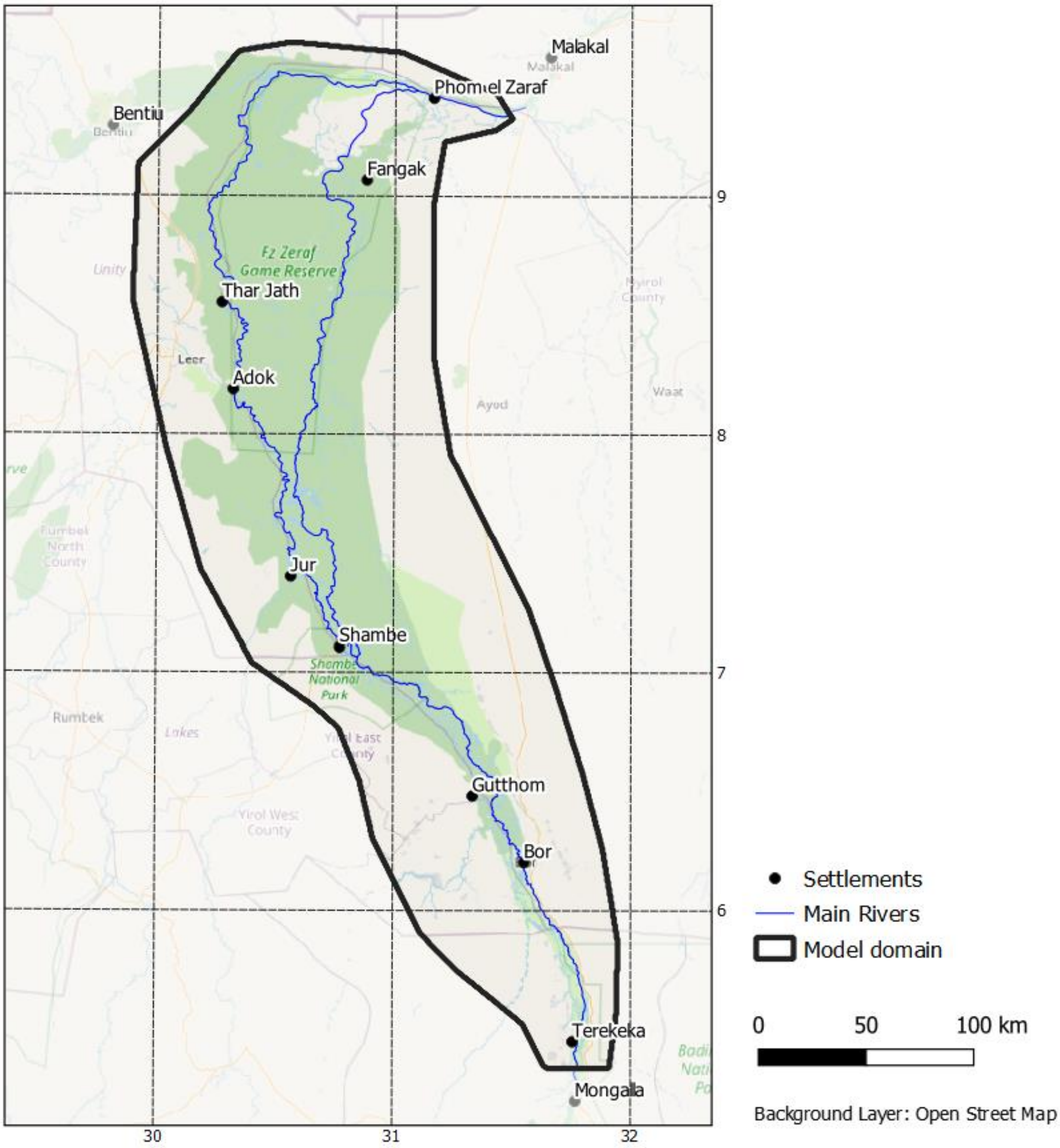

Figure 9. Sudd model schematization with the model domain and depicted channels

3.2 Model calibration

The model period for calibration was chosen as the March 1960- March 1962 time series (including three months warm-up), henceforth designated as ‘baseline’. This period was subject to both a rather dry- (1960-1961) and wet scenario (1961-1962). Even though the period does not correspond to the remote-sensing based classification of the wetland extent, the period is ideal because it covers a wide range of flow percentiles and wetting- and drying conditions.

The model was calibrated towards different objectives. For the further application of the model also within and beyond the Nile Wetlands project, the model should be able to depict:

- the annual wetting- and drying cycle of the Sudd,
- match the approximate inundation extent to the remote-sensing-based classification of papyrus and reeds (Figure 4)
- depict the in-channel spatial distribution of observed discharge percentiles (Table 1)

To reach these objectives, the model parameters were calibrated within distinct ranges and to the final values as shown in Table 2. The calibrated model parameters can be considered plausible given the uncertainty of the available input data sources. The most important calibration process that improved model results most significantly across both high- and low flows was the 'inversion of the Sudd inland delta elevation'. Therefore, this calibration step is explained in further detail below.

Table 2. Model calibration parameters, parameter range and final value

Model parameter	Unit	Range min	Range max	Calibrated value
Channel (cross section) depth	m	0-3.5 (distributed)	3-10 (distributed)	5 (for all branches)
Potential evapotranspiration	%	50	100	85
Roughness values (Manning M)	-	Channel: 30 Papyrus: 40 Reed: 45 Natural vegetation: 50 Forest: 50	Channel: 15 Papyrus: 5 Reed: 10 Natural vegetation: 15 Forest: 15	Channel: 20 Papyrus: 20 Reed: 25 Natural vegetation: 30 Forest: 30
Land cover burn-in into the raw MERIT-DEM	m	No burn-in	Papyrus&1st streams: -3 Reed&2nd streams: -1.5 WetlandGrasses: -1 Lagoons: -4	Papyrus&1st streams: -1.75 Reed&2nd streams: -0.75 WetlandGrasses: -0.25 Lagoons: -1.5
Sat. hydraulic conductivity of soils within/outside main Sudd (see Figure 3)	m/s	Main: 5e-15 Outside: 5e-12	Main: 1e-05 Outside: 1e-05	Main: 5e-13 Outside: 5e-10
Inversion of Sudd inland delta elevation	%	No correction	100	35
Detention storage	mm	0	0.1	0.001
Leaf Area Index	-	Papyrus: 4 Reed: 2 Natural vegetation: 2 Forest: 2	Papyrus: 16 Reed: 8 Natural vegetation: 8 Forest: 8	Papyrus: 8 Reed: 4 Natural vegetation: 4 Forest: 4
Root Depth	mm	Papyrus: 400 Reed: 200 Natural vegetation: 500 Forest: 1000	Papyrus: 1600 Reed: 800 Natural vegetation: 2500 Forest:3000	Papyrus: 800 Reed: 400 Natural vegetation: 1200 Forest: 2500
Initial Water Depth	mm	0	Grid File from Remote Sensing Classification	Grid File from Remote Sensing Classification

The elevation correction "Inversion of Sudd inland delta elevation" is accomplished by carrying out the following steps:

- Manual delineation of the inland delta based on elevation contours (black outline in Figure 10)
- Iterate through each cross section covering the inland delta extent from east to west
- Read the elevation distribution into an array
- use a Savitzky Golai filter on the stored elevation values in multiple filter strengths to extract different elevation 'noise' distributions – this results in a partitioning of the elevation values into 'noisy' and 'smooth' elevation distributions
- calculate the elevation difference between different Savitzky-Golay-filtered elevation distributions and the raw data
- subtract the elevation difference of the strongest smoothing (without noise) from the raw DEM to inverse the general elevation
- add the elevation difference of the weakest smoothing (the noise) to the previous step

- Set constraints to reduce jumps in elevation and interpolation artefacts (consider multiple neighbouring cells for reading elevation, set maximum elevation threshold from one step to the next)
- re-write the new elevation to the DEM

These steps were carried out multiple times with different settings. The result at one cross section is shown in Figure 10. The obtained DEMs were assessed visually and within M11-MSHE until the calibration results were satisfactory. The overall elevation difference of the inland delta for the final model is shown in Figure 11.

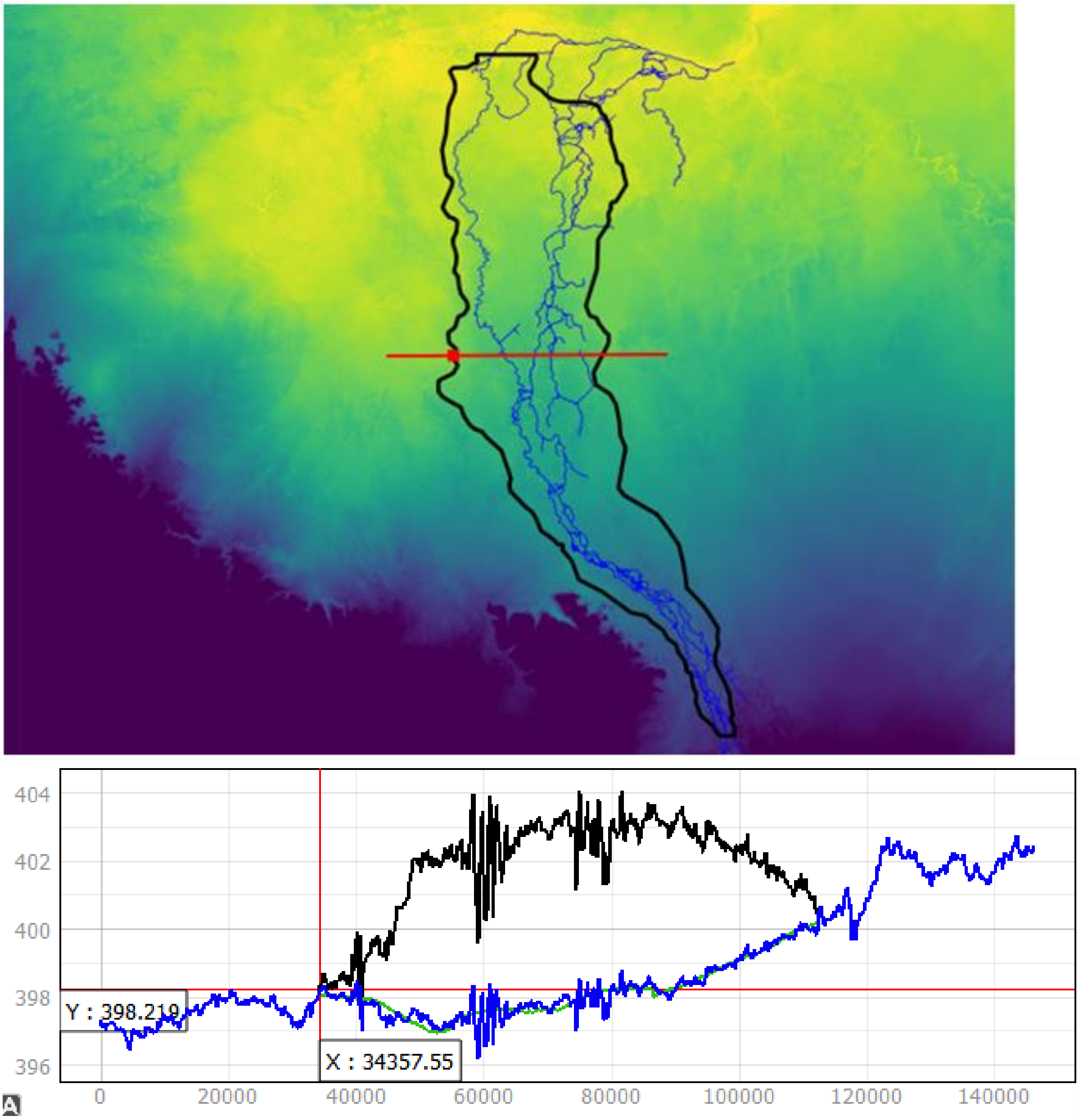

Figure 10. Exemplary cross section showing the Sudd inland delta based on the MERIT-DEM (black line) and the option with the removed inland delta (green and blue lines)

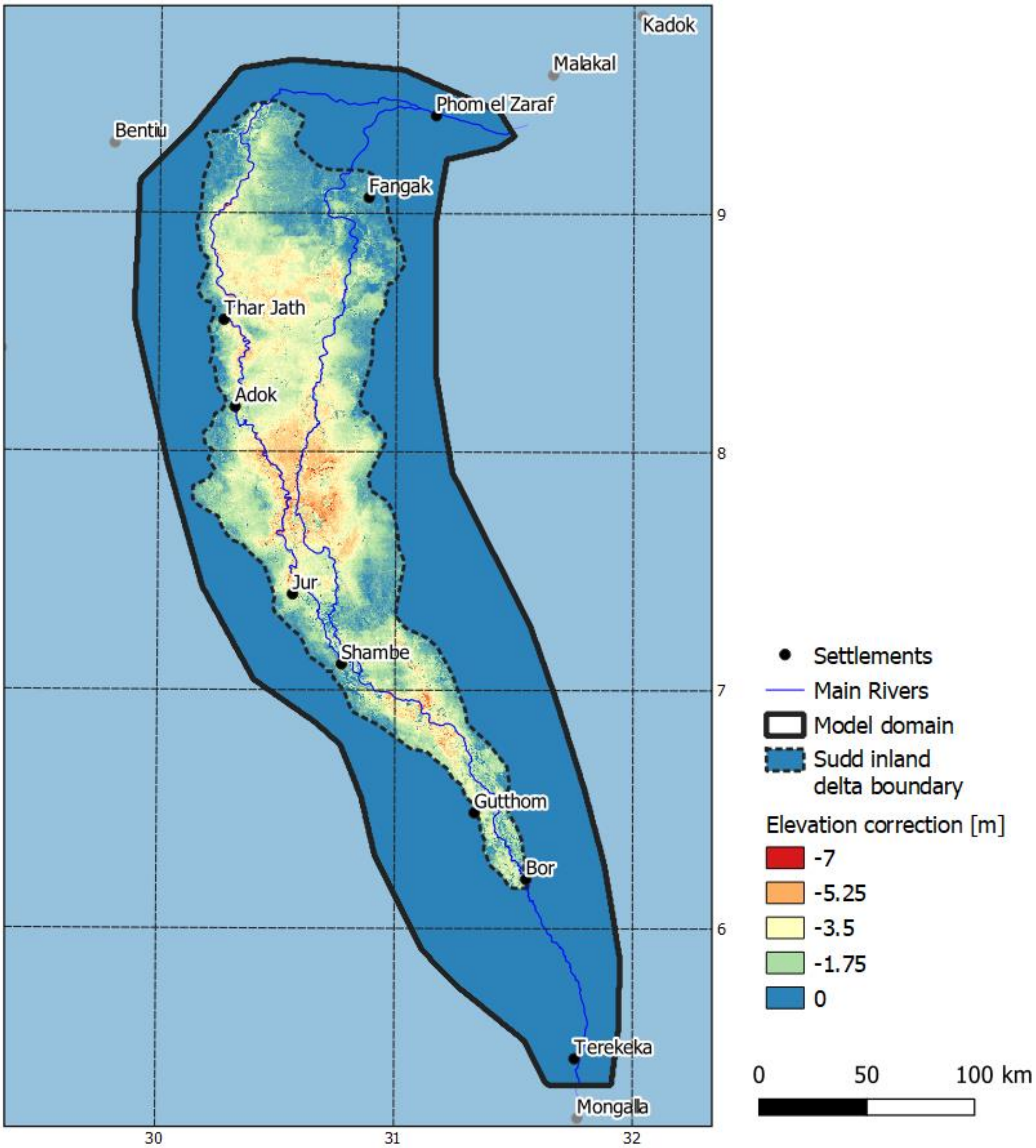

Figure 11. Sudd inland delta elevation correction

3.3 Synthetic scenario setup

The further implementation of a simplified Sudd model into the NileDSS require an exceptionally wide range of hydrological and hydraulic conditions for being able to depict all possible climate change and development scenarios. Therefore, the baseline inflows at Mongalla and precipitation values were scaled in seven individual scenarios with factors ranging from 0.3 (70% drier than baseline) to 1.5 (150% wetter than baseline) to represent a wide range of flow percentiles (Table 3). These scenarios do not represent a certain 'real-world' situation but have to be seen as 'synthetic scenarios' that are used as 'pre-computed lookup' events.

Table 3. Synthetic scenarios with average flows and the respective percentiles of the full discharge time series at Mongalla

Option	WaterYear	Average Percentile [%]	Average annual flow [m³/s]
Option1	Year1	1	235
Option1	Year2	1	367
Option2	Year1	1	471
Option2	Year2	6	735
Option0	Year1	10	785
Option5	Year1	19	824
Option6	Year1	33	902
Option7	Year1	46	1044
Option3	Year1	63	1177
Option0	Year2	71	1225
Option5	Year2	78	1286
Option6	Year2	89	1408
Option4	Year1	95	1570
Option7	Year2	95	1629
Option3	Year2	96	1837
Option4	Year2	100	2450

4. MODEL RESULTS

4.1 Baseline results

4.1.1 Annual wetting and drying processes

A good reproduction of the annual wetting and drying processes is important to assess general model plausibility. Figure 12a shows the inundation in a typical dry season month (May 1961), with inundation occurring between Mongalla and Shambe and further downstream mainly along the Bahr el Jebel and Lake No. Figure 12b shows the inundation in a typical wet season month (October 1961) with inundation covering almost the full model domain and with inundation depths exceeding 1.5m in many parts of the Sudd.

(a) (b)

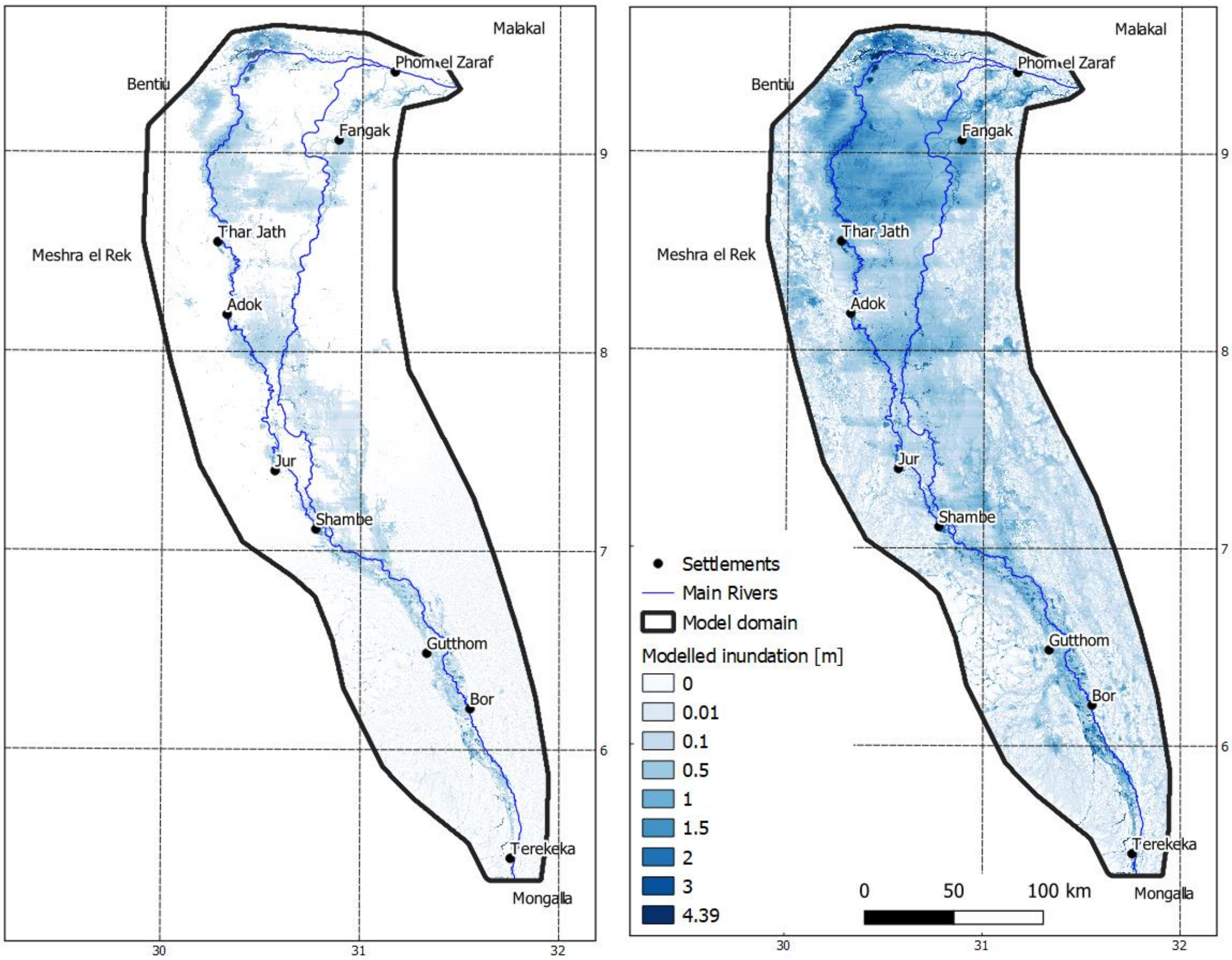

Figure 12. Modelled inundation during (a) the dry season month of May and (b) wet season month of October for the year 1961

4.1.2 Spatial inundation distribution

To assess the spatial model plausibility, modelled dry season inundation was compared to classified wetland vegetation that requires multiple years of flooding. Figure 13 shows the comparison between the classification of wetland vegetation of water, papyrus and reeds based on the Sentinel images and simulated dry season inundation >0.2m. The agreement upstream of Shambe is very good. In the locations further downstream, the simulation quality declines due to the uncertain elevation data. However, overall area that is marked as inundated corresponds to the classified wetland vegetation area, even though locations do not always match perfectly.

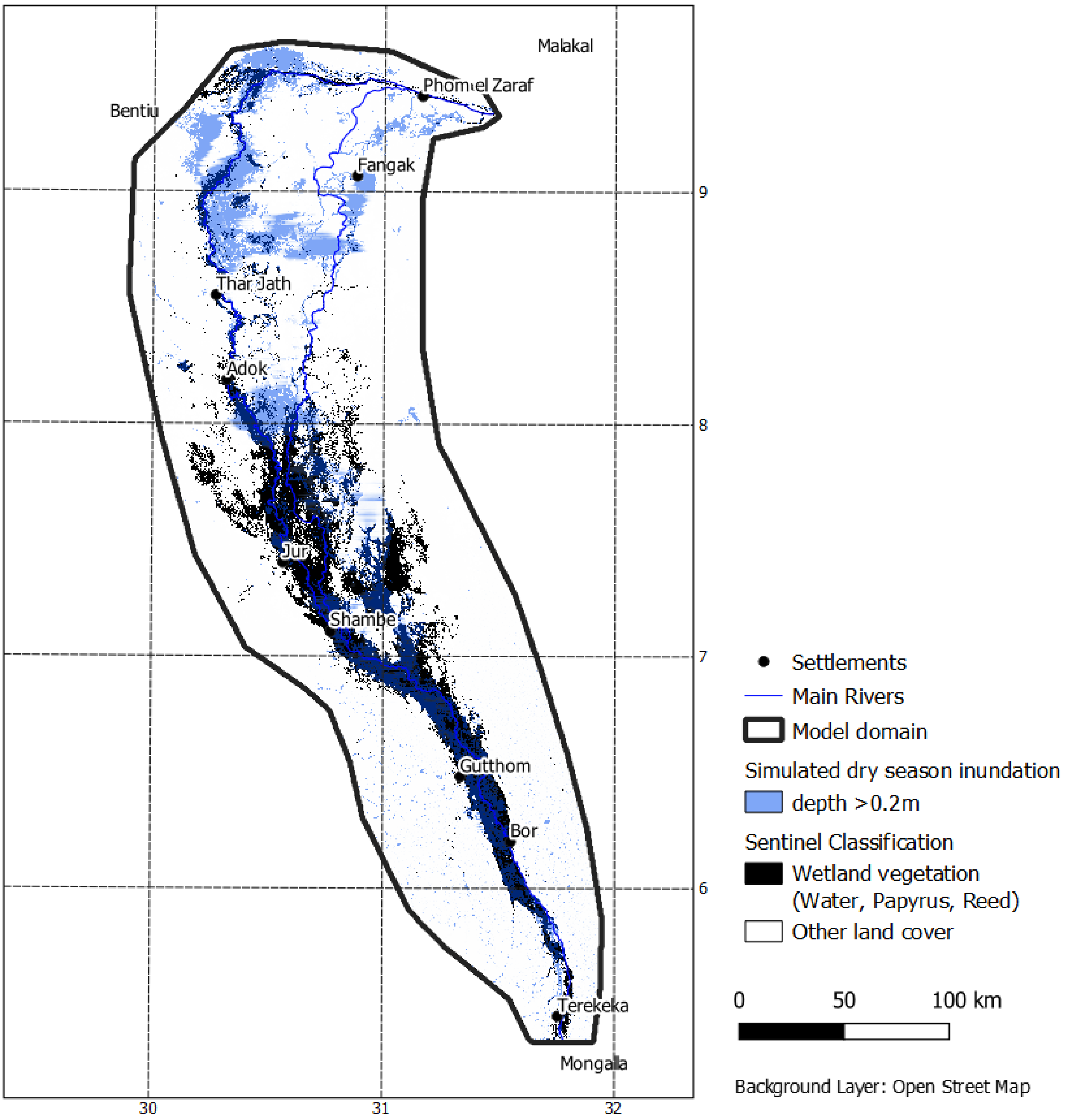

Figure 13. Comparison of dry season inundation (May) to Sentinel classification of wetland vegetation

4.1.3 Discharge ratios

The discharge results from the M11 model were compared to the historical observations (see Table 1) in the Sudd Wetland. Since this comparison was undertaken for the 1960-1962 event used during the calibration. Two different percentiles (75 and 100) are shown in Table 4. As can be seen, the model underestimates channel flows in the upstream regions (Gemeiza, and DS LakeNyong, while further downstream, the flow distribution matches well with the observations.

Table 4. Discharge ratios comparison for flow percentile 75 and 100

Station	75th percentile OBS [m³/s]	75th percentile Flow Ratio to Mongalla OBS	Sim	Diff	100th percentile OBS [m³/s]	100th percentile Flow Ratio to Mongalla OBS	Sim	Diff
BeJ Mongalla	856	1.0	1.0	0.00	2700	1.0	1.0	0.00
BeJ Gemeiza	1053	1.2	0.6	-0.58	2310	0.9	0.3	-0.53
BeJ DS LakeNyong	625	0.7	0.2	-0.51	909	0.3	0.1	-0.25
BeJ HilletNuer	375	0.4	0.2	-0.24	481	0.2	0.1	-0.10
BeJ BuffaloCape	343	0.4	0.3	-0.15	454	0.2	0.1	-0.05
WN US Zeraf	330	0.4	0.3	-0.07	578	0.2	0.1	-0.08
BeJ Gigging	222	0.3	0.1	-0.12	382	0.1	0.1	-0.08
BeZ MeshraKwatch	152	0.2	0.2	0.01	244	0.1	0.1	-0.02
BeZ Mouth	155	0.2	0.1	-0.03	450	0.2	0.1	-0.10
Downstream End	485	0.6	0.5	-0.05	1028	0.4	0.2	-0.15

4.1.3 Water balance

The calculated water balance for the baseline scenario is summarized in Table 5. About 63% of the inputs from precipitation and inflow at Mongalla are lost to evapotranspiration and 32% leave the Sudd as outflow. Infiltration is minor with about 5%. While the water balance is generally plausible, outflows mostly occur across the domain boundary, which should rather be directed to the White Nile. This could however not be accomplished with the current setup.

Table 5. Water balance components extracted from the modelled baseline scenario, "+" indicates gains, "-" indicates losses

Water balance component	Value [mm/yr]	Value [%]
Precipitation	+740	+100
Inflow at Mongalla	+554	
Infiltration	-63	-5
Actual Evapotranspiration	-813	-63
Outflow at downstream end	-79	-32
Outflow across boundary	-339	

4.2 Synthetic scenario results

4.2.1 Inundation

An example of the inundation range of the synthetic scenarios are provided in Figure 14. All dry season results are provided for the scaled flow and precipitation of May 1961, all wet season results for October 1961. The synthetic options shown include option 1 and 2, which are drier than the baseline and option 5 and 7 which are wetter than the baseline (see Table 3).

As can be seen, the dry season results range from the domain being almost completely dry with minor inundation occurring only near Lake No. This indicates that the flows are completely contained in the channels. This subsequently increases up to option 7 where dry season inundation reaches significant inundation, but completely without inundation from precipitation since no inundation exists near the model domain boundaries. Wet season for the different synthetic options also shows a wide range of inundation. As opposed to the dry season results, inundation is also driven by precipitation, which can be seen in the inundation further away from the main channels.

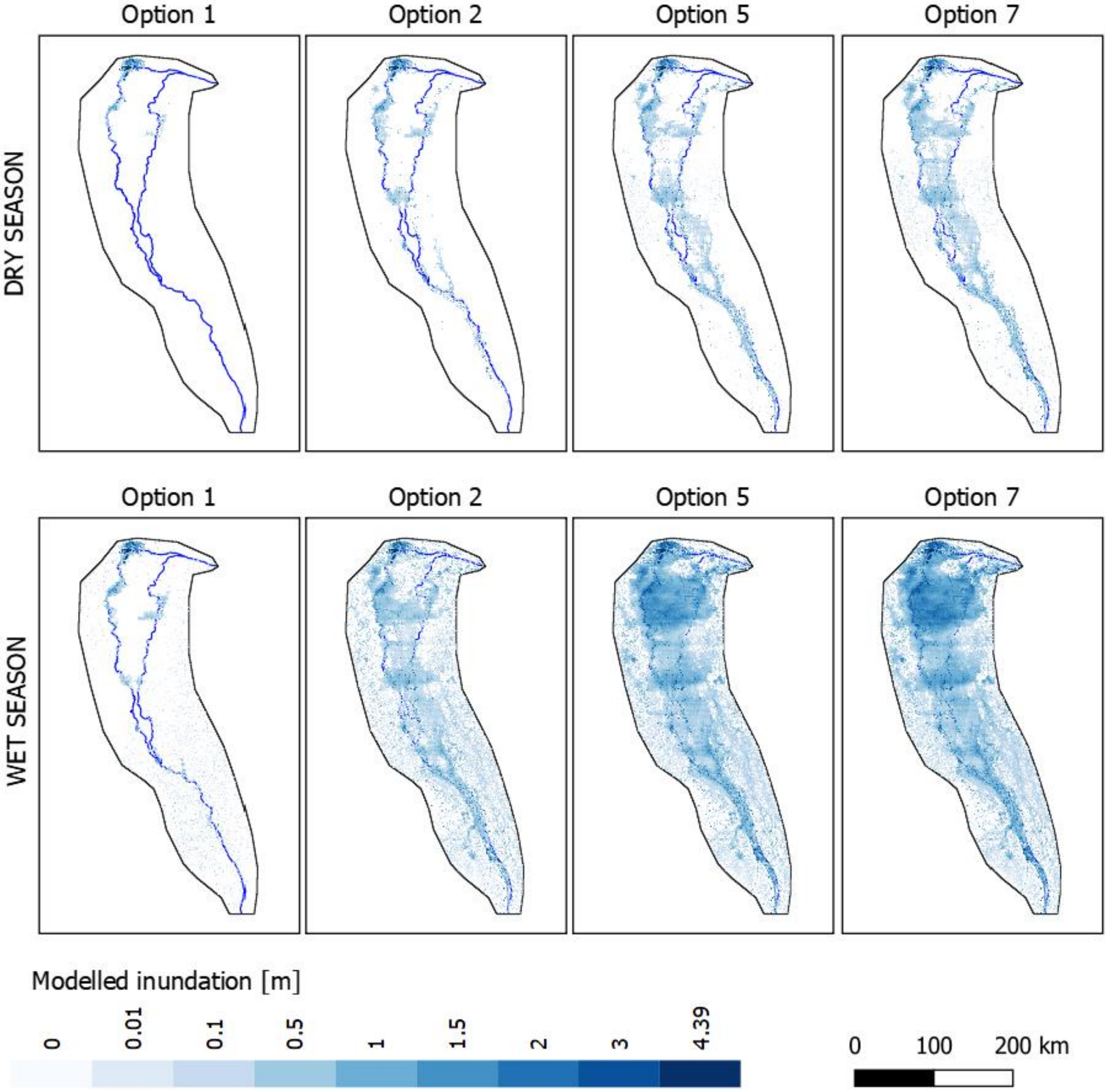

Figure 14. Comparison of inundation results for different synthetic scenario options

4.2.2 Data processing and handover

For the e-flows assessment and for providing simplified models to be linked to the NileDSS, the model domain had to be split into three zones as shown in Figure 15. For each zone and each of the seven scenario options, inundation areas within 14 depth-classes and inflows and outflows were calculated as a post-processing step based on the M11-MSHE results files.

For each zone, spill curves, water level – area – volume curves and bifurcation rules were also derived which are needed to define the simplified Sudd model implementation in the NileDSS.

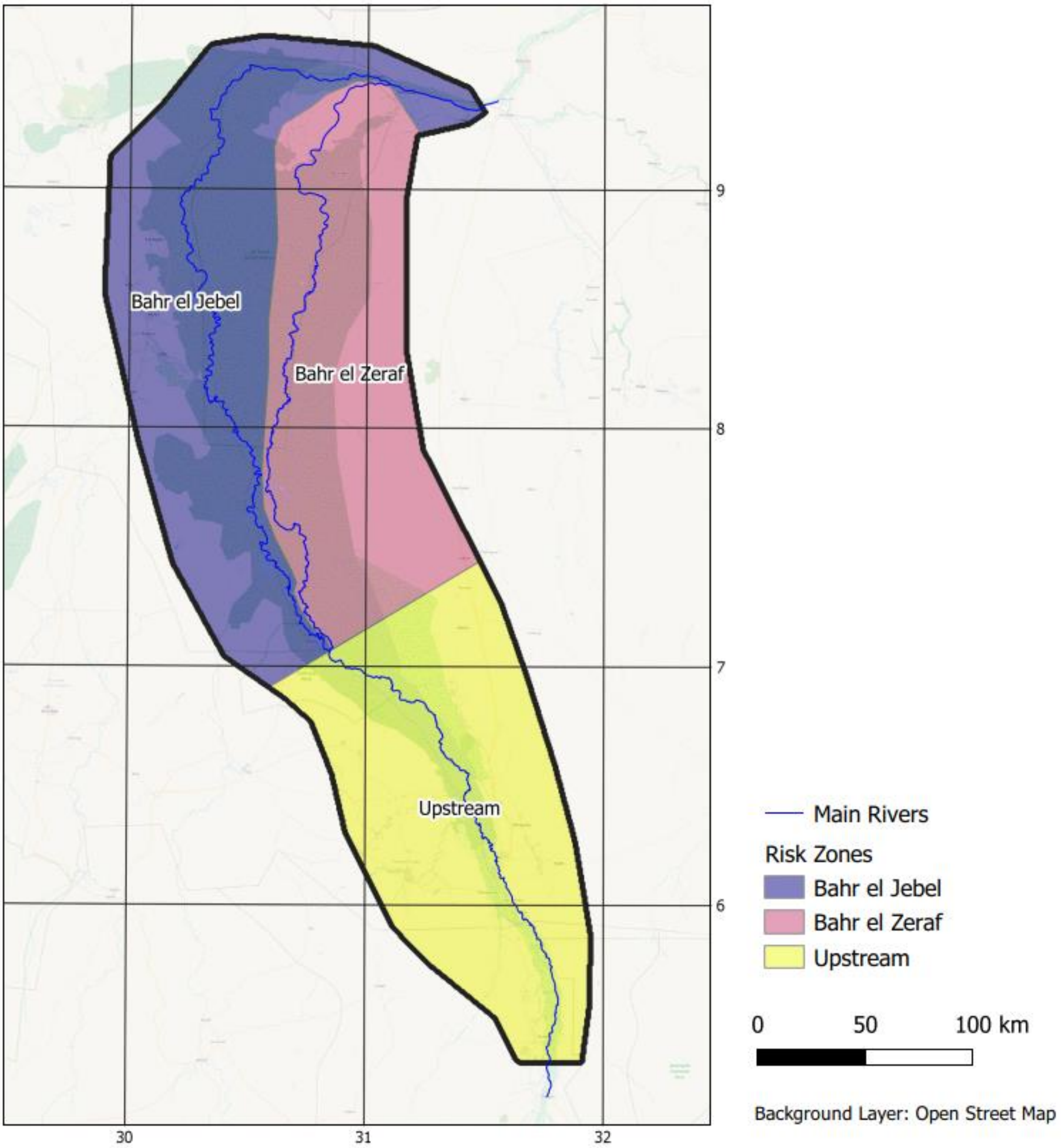

Figure 15. Splitting of the Model domain in three zones

5. CONCLUSION

A M11-MSHE model was successfully implemented to depict hydrological and hydraulic processes occurring in the Sudd. Major efforts were needed to implement the models and to obtain plausible results. In particular, complex data interfaces had to be programmed to setup and run more than 200 different model configurations. Topographic data was heavily modified to enable plausible wetting-drying and for matching spatial inundation.

Despite encouraging results that advance previous modelling efforts of the Sudd, the model still shows weaknesses in the exact spatial representation of inundation in the region downstream of Shambe and in the location of the outflows. Model results were obtained for a wide range of scenarios and processed for further use in subsequent workpackages for biodiversity and eflows assessments.

For future implementations and possible improvements of the Sudd hydraulic models, it is suggested to use a full 2D hydrodynamic model that enables the consideration of losses and gains on the model domain. Possible models that should be screened for this application are Mike Flood (DHI), HEC-RAS (USACE, the next release version), TELEMAC (Open Source Consortia) or the Adaptive Hydraulics Model (ADH, from USACE). While computational efforts will increase when using these models, they will probably not require an elevation correction of the topographic data.

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Nile Basin Initiative Secretariat
P.O. Box 192
Entebbe – Uganda
Tel: +256 414 321 424
+256 414 321 329
+256 417 705 000
Fax: +256 414 320 971
Email: nbisec@nilebasin.org
Website: http://www.nilebasin.org

Eastern Nile Technical Regional Office
Dessie Road
P.O. Box 27173-1000
Addis Ababa – Ethiopia
Tel: +251 116 461 130/32
Fax: +251 116 459 407
Email: entro@nilebasin.org
Website: http://ensap.nilebasin.org

Nile Equatorial Lakes Subsidiary
Action Program Coordination Unit
Kigali City Tower
KCT, KN 2 St, Kigali
P.O. Box 6759, Kigali Rwanda
Tel: +250 788 307 334
Fax: +250 252 580 100
Email: nelsapcu@nilebasin.org
Website: http://nelsap.nilebasin.org

/Nile Basin Initiative
@nbiweb
ENTRO
NELSAP-CU