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Draft technical report

Machar Marshes Eco-Hydrology Assessment Project

Contract No. ENTRO-02-CS-QCBS

Nile Basin Initiative/Easter Nile Technical Regional Office (ENTRO)

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1. Introduction

The "Machar Marshes Eco-Hydrology Assessment Project" is carried out by the Eastern Nile Regional Technical Office (ENTRO) with support from the German International Cooperation (GIZ) and with technical assistance from HYDROC GmbH. The project is implemented in parallel to the "Nile Basin wetlands of transboundary significance: Inventory, Baseline Study and Framework Management Plan with a nested case study on the Sudd" project, utilizing synergies with this overarching basin wide study, and making use of its approaches and results regarding data collection, remote sensing data analysis, wetland modelling, biodiversity assessment, ecosystem services analysis and environmental flow assessment work. The Machar works will specifically benefit from the lessons learned with regards to wetland modelling and will make use of the collected datasets with regards to biodiversity and ecosystem aspects.

The Machar Marshes are part of the Baro-Akobo-Sobat (BAS) system (Figure 1), which is a vast and complex river- and wetland network, including a wide expanse of plains. The area drains into the White Nile through the Sobat river. The Machar Marshes are fed by torrential stream inflow from the Ethiopian escarpments as well as from spill from the Baro river before the confluence with the Pibor. The Machar Marshes are a seasonal wetland, located in South Sudan, while the runoff-generating catchments extend into Sudan and Ethiopia. The marshes are important grazing land and fish resource for the Nilotic tribes of South Sudan. Further, the marshes have been recognized as an important bird area in Africa by Bird Life International (Water Watch, 2006). The entire wetland of the Machar Marshes depends on the hydrology of the Baro Akobo Sobat (BAS) sub-basin. The sizes of the wetland vary with floods and the rainy seasons. There is a substantial untapped potential for hydropower development in the overall basin, as well as opportunities for developing irrigation and improving rainfed agriculture.

This study aims at conducting an in-depth investigation of the water balance dynamics of the Machar Marshes, making use of all available data obtained from both ground and remote sensing measurements and assessing the interaction of water resource with the ecosystem. The output provides additional information to support the larger endeavour of water resources development in the basin and implication on the wetland.

The objective of the study is:

- To conduct the baseline assessment for an improved understanding of the hydrology of the Machar Marshes, extent and seasonal variability of wetland coverage; and
- To conduct a detail water resources analysis to evaluate various options of development in the BAS sub-basin to assess its implication on supporting the resilience of the ecosystem of wetland.

The study includes the following phases:
Phase 1: Desk study
Phase 2: Baseline assessment
Phase 3: Water resource analysis
Phase 4: Workshops and capacity building training

The works and interim results described in this report are part of Phase 3, the baseline assessment.

Figure 1: The Mashar Marshes location

2. Baseline assessment of water balance dynamics summary

2.1 Data collection

The consultant has collected a broad array of available datasets including spatial data (e.g. stream networks, elevations, vegetation), time-series data (e.g. meteorological and hydrological datasets), narrative information (e.g. description of hydrology and ecology), and data from previous modelling efforts of the Machar system (e.g. the Baro-Akobo-Sobat Multipurpose Water Resources Development Project Study, BAS-MWRDP). Further, historic analysis and reports have been collected. An evaluation of the available data has been conducted with regards to assessing water balances and is included in Section 2.2 of this report.

Spatial datasets available for the assessment and covering the Machar Marshes at the current moment include:

- **Soils from SoilGrids[1], 250m resolution**
  The Soil Grids dataset is the most recent, most detailed global soil dataset available. It is based on 230 000 soil profile observations against which prediction models were fitted using over 400 spatial global covariates.

- **Vegetation cover from CCI Landcover[2] 20m, as well as from current Nile Wetlands study[3], 10m resolution**
  The two datasets are available at HYDROC and provide the most detailed and most recent classified land cover datasets available for the Machar Marshes.

- **Detailed stream network, digitized[4]**
  All available sources of streams were found inadequate in covering the streams in the Machar Marshes. The digitized streams are based on the most recent satellite images and cover the Machar Marshes in over 1000 individual river reaches.

- **Discharge data available from previous studies[3,] 10daily temporal averages, details shown in the Annex**
  No other sources of discharge data are available

- **Actual evapotranspiration (AET): MODIS (2000-2013), 250m resolution and FAO WaPOR (2009-2018) 250m**
  Both datasets of the actual evapotranspiration of the Nile Basin were obtained from Nile Secretariat. WaPOR data were generated for the Nile Basin countries through a project called "Generation of Operational Evapotranspiration Datasets for Nile Basin Countries Using Remotely Sensed Inputs". According to the comparisons made by the project, "WaPOR was selected as the best-performing ETa product for the Nile Basin Countries after an evaluation based on the water balance approach".

- **Potential evapotranspiration (PET): calculated from Princeton climate data[5] based on the Hargreaves method**
  The NileDSS utilizes PET data from the Princeton dataset and to enable seamless integration into the NileDSS, the data was acquired from the Princeton FTP servers.

- **Rainfall: CHIRPS[6] (1981-near real-time), 5km resolution; Princeton[5], 25km resolution**

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[1] https://soilgrids.org/

[2] http://2016africalandcover20m.esrin.esa.int/

[3] GIZ, NBI. 2020. Nile Basin wetlands of transboundary significance: Inventory, Baseline Study and Framework Management Plan with a nested case study on the Sudd

[4] GoogleEarth Digital Globe Satellite images

[5] http://hydrology.princeton.edu/data/pgf/v3/0.25deg/daily/

[6] https://www.chc.ucsb.edu/data/chirps

CHIRPS rainfall data is the highest spatio-temporal resolution global dataset with near-real-time coverage that is freely available. The dataset was compared to the state-of-the-art global precipitation datasets and found highly suitable[7]. The NileDSS utilizes PET data from the Princeton dataset and to enable seamless integration into the NileDSS, the data was acquired from the Princeton FTP servers. In addition, Worldclim v2 precipitation data was also collected and screened to derive the long-term rainfall pattern over the Machar Marshes.

- **Soil moisture: ESA CCI[8] (1978-2018), 25km resolution and TerraClimate (1958-2019)[9]**
  The two products cover both the region and temporal period of interest.
- **Inundation: ENTRO flood monitoring website[10]**
  Was screened but is not suitable since no significant inundation is shown for the Machar Marshes.
- **Digital Elevation Model (DEM) MERIT[11], 90m and Airbus WorldDEM topographic data:**
  The DEM is of vital importance for the hydraulic modelling of the Machar Marshes. The 90m resolution MERIT DEM is a vegetation- and noise-corrected version of the SRTM and the ALOS DEM. Since no commercial Digital Terrain Model (DTM) can be procured for the vast area of the Machar Marshes within this project (costs would exceed 50.000 US$), the MERIT DEM is chosen and based on the experience of the consultant in the Sudd, it should be of sufficient resolution and quality to depict the flow processes. Especially in flat regions, the removal of absolute bias, stripe noise, speckle noise, and tree height bias increase the accuracy and suitability for hydraulic modelling significantly[12]. However, more detailed digital elevation data is required to depict the spilling region of the Baro. Therefore, a commercial DTM dataset was acquired for the 400km² large spilling region. The WorldDEM from Airbus based on the TerraSAR-TanDEMX Radar providing a 12m global DEM with vegetation correction. Compared to other commercially available DEMs, the AIRBUS DTM has a superior depiction of ground elevation based on radar.

As per the contract No. ENTRO-02-CS-QCBS, a field visit with survey will not be conducted. HYDROC has already conducted a survey in the BAS basin and the Baro and Sobat rivers.

2.2 Water balance assessment

The Machar Marshes are mainly associated with the Khor Machar watercourse that receives water from three key sources: a) rainfall, b) spills from Baro river, and c) streams flowing from Ethiopian highlands eastwards. Discharge of the Machar Marshes water occurs to the White Nile through the Khor Adal as well as through water losses due to evapotranspiration and infiltration to shallow groundwater. Thus, the water balance equation of the Machar Marshes may be expressed as follows:

$$Q_{rain} + Q_{Baro} + Q_{East} = ET + Q_{gw} + Q_{outflow}$$

where Q_{rain} – rainfall amount; Q_{Baro} – spill water from Baro river with floods; Q_{East} – inflow from rivers Yabus, Daga and other streams draining Ethiopian highlands; ET – evapotranspiration; Q_{gw} – groundwater flow; $Q_{outflow}$ – outflow to White Nile.

El-Hemry and Eagleson (1980) in their water balance modelling, also mention that part of the water leaves the Machar Marches by ungauged flow to the Wadudu swamps that lie to the north. In this work, based on flow measurements on stations at the rivers Baro, Yabus and Daga, they estimate inputs to the

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[7] Mazzoleni, Brandimarte, Amaranto, 2019. Evaluating precipitation datasets for large-scale distributed hydrological modelling. Journal of Hydrology 578.

[8] https://esa-soilmoisture-cci.org/

[9] http://www.climatologylab.org/terraclimate.html

[10] https://entro-flood-monitoring.cloudtostreet.info/recent-data

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

[12] Yamazaki D, et al. 2017. A high-accuracy map of global terrain elevations. Geophysical Research Letters 44, 5844-5853.

Machar lowlands separately for the eastern catchments, plains and swamps (El-Hemry & Eagleson, 1980). An overview is provided in Figure 2.

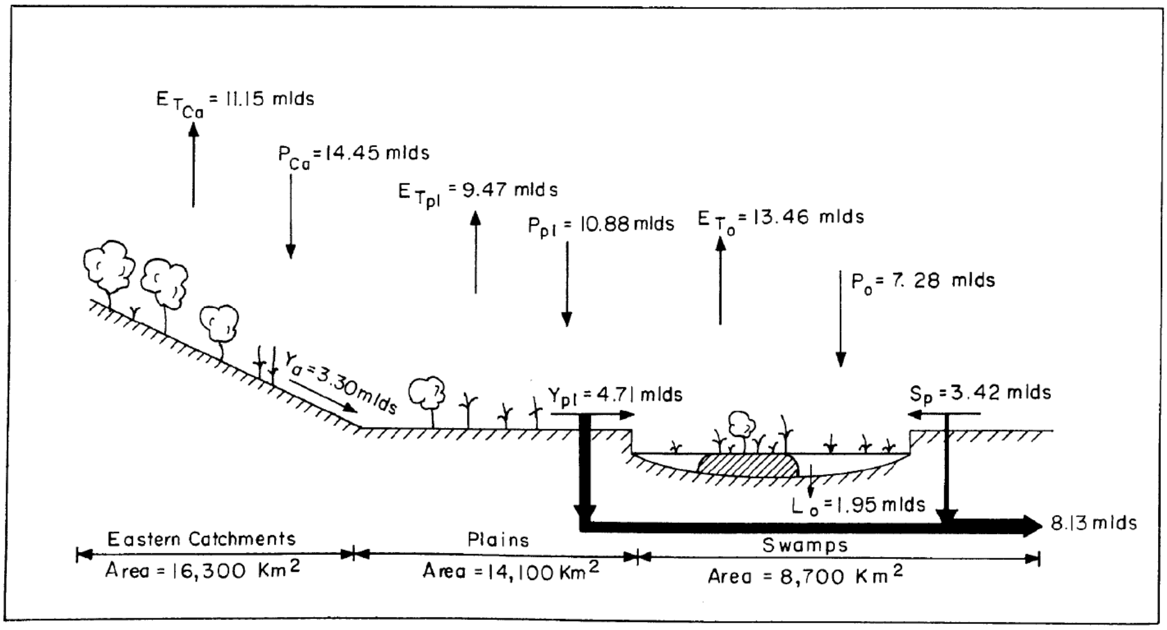

Figure 2: Mean annual water balance of the Machar region (El-Hemry & Eagleson, 1980) P – precipitation, ET – evapotranspiration, S – spill water, L – groundwater flow and ungauged flow northwards

Return flow to the White Nile from the Machar Marshes can hardly be estimated since there is little direct evidence of that. The average outflow via the Khor Adar and the Khor Wol was estimated at about 0.10–0.12 km^3 in early reports, while in BAS study (ENTRO, 2017) under baseline scenario annual outflow is defined up to 0.523 km^3 (Table 1).

Table 1: Estimations of the Machar Marshes water balance elements in literature

Study	Rainfall, mm/year	ET, mm/year	ET, km^3 / year	Spill from Baro river, km^3/year	Inflow from East, km^3/year	Outflow to White Nile, km^3/year	Percolation, km^3/year	Wetland area, km^2	Notes	Approach
Hurst et al, 1950	900	1460	9.5	2.5–3.0				6500		Ref from El-Hemry, 1980 p. 25-26: Hurst calculated difference between mean values of the streamflow at the head and tail of the Adura,
JIT, 1954	800			2.8	1.74	0.1 – 1.0		20 000	Area included plains and swamps	Ref from 2011 ENTRO: measurements, water balance, areal surveys, site visits
El-Hemry & Eagleson, 1980	837	1547	13.5	3.42	4.2	0.12		8700		Measurements, dimensionless analytical model of the annual (seasonal) water balance
Shahin, 1985	900	1515	10.1	4.0	1.4	0		6700	All water totally evapotranspirated	
Sutcliffe and Parks, 1999	933	2150	7.2	2.3	1.7	0.1		3350		
ENTRO, 2012		2202	12.7-14.1	5	4	5		5786-6434		Delineation: satellite imagery processing (HAND and NDVI methods)
	55 km^3/year	2202	58	5 (total spill)	2 (Yabus) + 2 (Daga)	3 (Khor Adar) + 2 (Khor Wol)	2 (percolation) + 1 (soil water)			Water balance: SWAT modelling
ENTRO, 2017*	897	1732	7.59	3.956		0.526		2371-5303		Flow measurements, validation by MIKE HYDRO Basin model

* Baro-Akobo-Sobat Multipurpose Water Resources Development Study Project. Strategic Social and Environmental Assessment, 2017. 382 p.

The spill from the Baro river into the marshes is estimated from 2.3 to 5.0 km^3/year what is relatively comparable with inflow from the eastern rivers and streams, which is about 1.4 – 4.2 km^3/year. Evapotranspiration is assessed from 7.2 to 14.1 km^3/year depending on the marshland area considered. All authors show that evapotranspiration is the main process of water leaving the Machar Marshes taking up to 80 % of total water discharge.

Based on evidence from different authors, water balances for the Machar Marshes are estimated as shown in Table 2

.

Table 2: Estimations of the Machar Marshes water balance based on available information

Parameter	Range	Min km^3/year	Max km^3/year	Average km^3/year
Area *	3350-8700 km^2			
Inflow escarpments	1.4- 4.2 km^3/year	1.4	4.2	3.5
Inflow from Baro spill	2.3- 5.0 km^3/year	2.3	5.0	4.8
Rainfall	2.7- 8.1 km^3/year	2.7	8.1	6.8
Total in		6.4	17.3	15.1
Evapotranspiration	4.9-19.2 km^3/year	4.9	19.2	14.5
Infiltration **	unknown	*1.5*	*-1.9*	0.6
Outflow to White Nile	0.0- 5.0 km^3/year	0.0	5.0	2.5
Total out		6.4	17.3	15.1

** The ranges are calculated disregarding the area estimate of JIT (1954) of 20,000 km^2*

*** Infiltration is unknown and calculated as delta*

3. Watershed schematization

A region of interest has to be defined for masking the remote sensing and modelling analysis. This is required to exclude neighboring areas that may inadequately be assigned as wetlands while not being connected to the Machar Marshes. To delineate this mask, an integrated approach was followed involving digital elevation models as well as results from previous studies and satellite images.
First, the Baro-Akobo-Sobat (BAS) sub-catchments boundaries were delineated using the hydrologically conditioned USGS HydroSHEDS DEM to identify the catchment area of the wetland.

Within the Baro-Akobo-Sobat Multipurpose Water Resources Development Study, the maximum flood extent of the marshes was delineated using satellite images. This extent was superimposed on the DEM. However, this extent didn’t follow the elevation contour lines and may cause an underestimation of the actual extent.

Therefore, to avoid exclusion of part of the wetland area, Google Earth images were additionally used for visual inspection. The elevation of 465 mASL was selected iteratively to generate a contour line that delineates the wetland catchment on the eastern and north-eastern part. The resulting delineated area is shown in Figure 3.

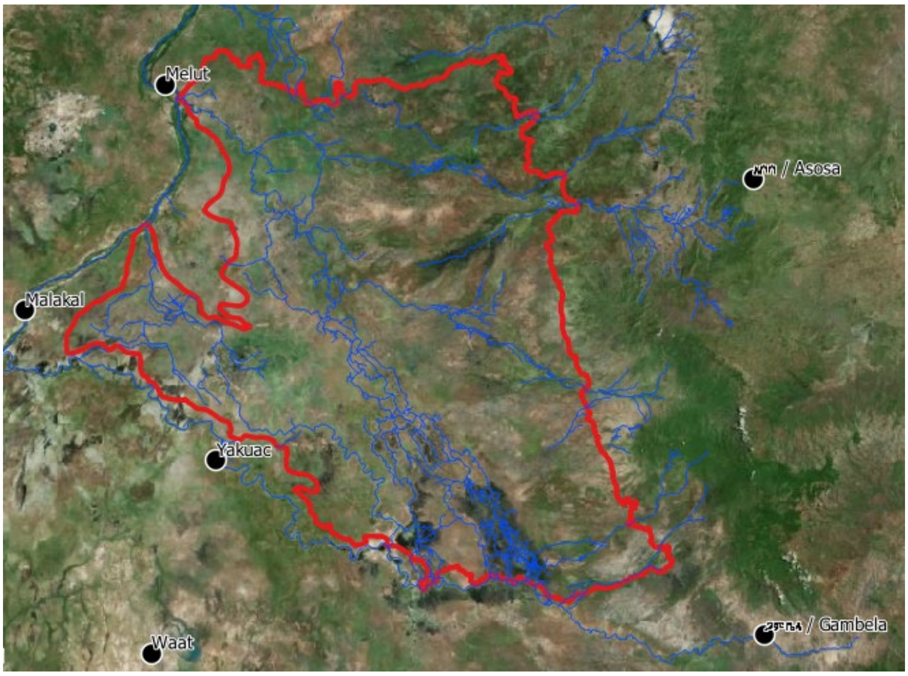

Figure 3: Delineated Machar Marshes mask to be used for further analysis (Background: Bing Satellite Images)

4. Remote Sensing to delineate wetland extent

The delineation of wetland extent involves the screening and assessment of a wide range of remote sensing data. Based on the data sources described in Chapter 2, Python models were established to assess the different data sources and to estimate the spatio-temporal wetland extent. These models follow the characteristics that in a wetland, soil moisture and evapotranspiration are higher than in the surrounding area and that ratios of water balances such as precipitation to evapotranspiration are significantly different to neighboring areas. Therefore, the following models were built, involving the datasets described in Section 2.1:

a. Difference between precipitation, actual evapotranspiration (AET) and soil moisture
b. Actual evapotranspiration to precipitation ratios
c. Soil moisture to precipitation ratios
d. Normalized evapotranspiration
e. Normalized rainfall from multiple sources
f. Normalized soil moisture
g. Difference between normalized rain and normalized evapotranspiration
h. Difference between normalized rain and normalized soil moisture
i. Difference between normalized precipitation, normalized actual evapotranspiration and normalized soil moisture
j. Relationship between AET and PET

The result of the models was quality- and plausibility checked using long-term average seasonal and average annual plots. The results of the models a. to i. were not satisfactory and the established patterns did not enable a delineation of the wetland extent (for example see Figure 4) over the whole year. Despite major efforts invested in resampling techniques and data normalization, no satisfactory delineation of the Machar Marshes extent could be achieved.

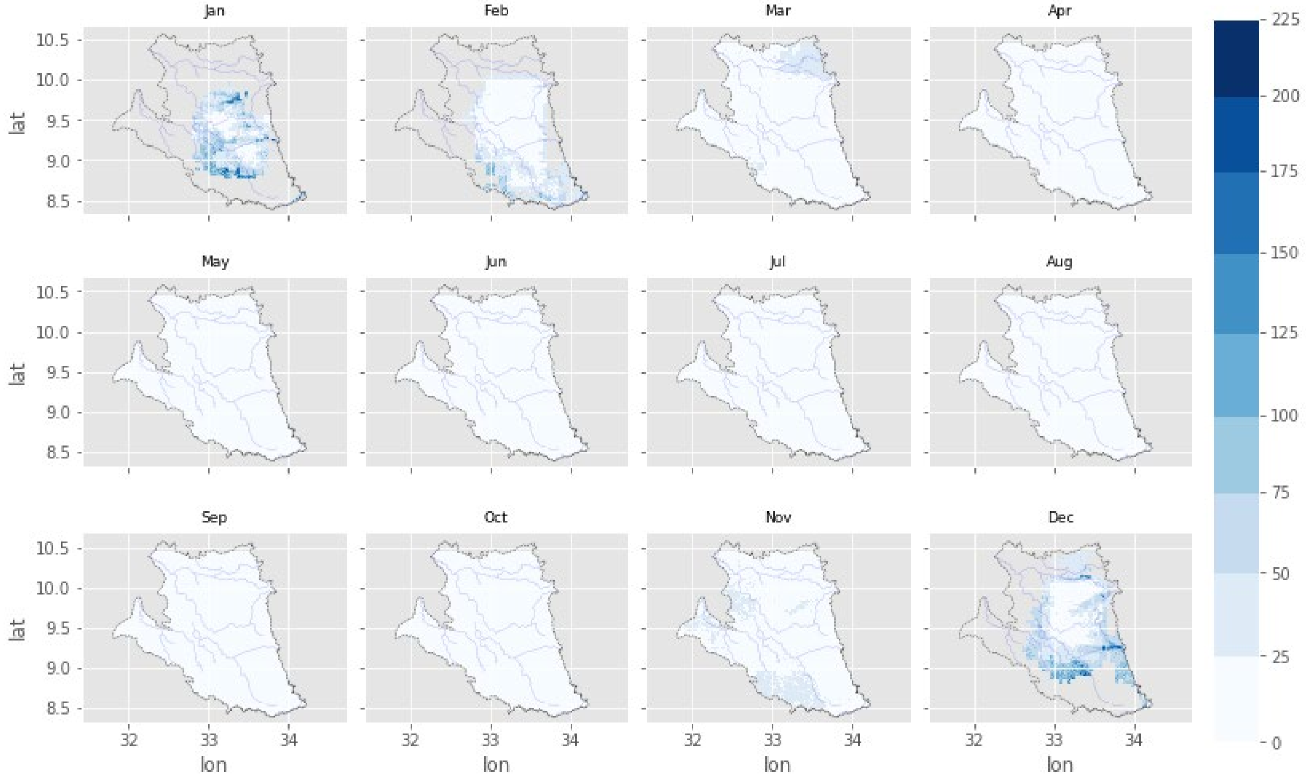

Figure 4: Actual evapotranspiration (MODIS and FAO WaPOR ET) to precipitation (CHIRPS) ratio where darker blue colors reveal locations of higher evapotranspiration than precipitation

MODIS ET (from 2000 to 2008) and FAO WaPOR ET (from 2009 to 2018), both 250m resolution, were analysed in more detail. This analysis revealed that MODIS and FAO WaPOR ET data do not produce similar results, while the results from FAO WaPOR ET are more plausible and are also the dataset adopted by NBI and ENTRO. While we bias-corrected MODIS data, the results were still not meaningful and therefore, the subsequent analyses are based on the data from 2009-2014 using the FAO WaPOR ET data.

The FAO WaPOR ET data shows a more meaningful pattern of wetland area across different seasons/months (Figure 5). As can be seen, especially during the months from January to May, the inflows from the Ethiopian escarpment, as well as the spills from the Baro and the resulting higher AET in the southern central part of the region of interest, is visible.

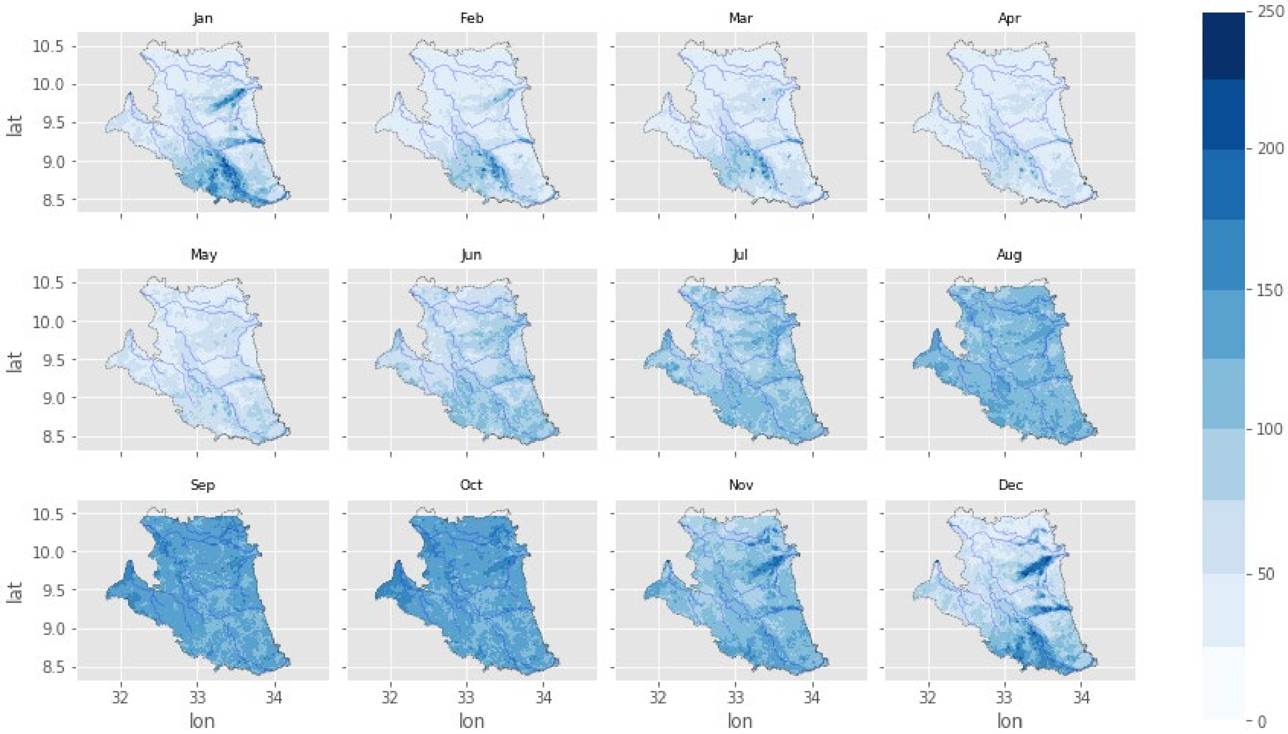

Figure 5: Long-term monthly actual evapotranspiration 2009-2014 (FAO WaPOR ET)

To delineate seasonal wetland areas based on AET, a reasonable threshold for AET has to be defined above which an area is classified as a wetland. Following Petersen and Fohrer (2007)[13] who carried out field studies in the Sudd wetland of South Sudan, and found that the permanent wetland areas evaporate about 80% of PET. This relationship was applied on the gridded PET and AET data for the Machar Marshes, and all areas where annual AET ≥ 0.8 PET where selected. These areas were statistically analysed over the long-term monthly averages (Table 3). The month of May (peak of the dry season) shows the lowest median AET value (111mm/month) that satisfies the 0.8*PET constraint and hence represents the threshold marking the permanent wetland extent and is therefore selected as the threshold to be applied for all months. The long-term seasonal averages for the wetland extent over the years 2009-2014 is shown in Figure 6 and summarized in Table 4.

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[13] Petersen G and Fohrer N 2010. Water balances of the Vertisol floodplains of southern Sudan. Hydrol. Sci. J. 55(1)

Table 3: Long-term (2009-2014) monthly statistics of the FAO WaPOR AET values of the cells above the 0.8 PET threshold. The month of May (peak of the dry season) shows the lowest median AET value (111mm/month)

Month	**mean**	**std**	**min**	**25%**	**50%**	**75%**	**max**	**median**
Jan	206	23	121	189	206	222	293	206
Feb	169	28	80	150	168	188	272	168
Mar	154	35	55	128	154	181	263	154
Apr	115	31	39	92	115	135	230	115
May	113	29	35	94	111	135	190	111
Jun	126	24	41	109	126	150	175	126
Jul	132	16	56	122	133	145	172	133
Aug	136	14	80	126	140	147	169	140
Sep	141	13	78	132	142	152	179	142
Oct	158	16	100	149	162	170	194	162
Nov	177	20	122	161	175	194	233	175
Dec	191	30	42	178	197	211	258	197

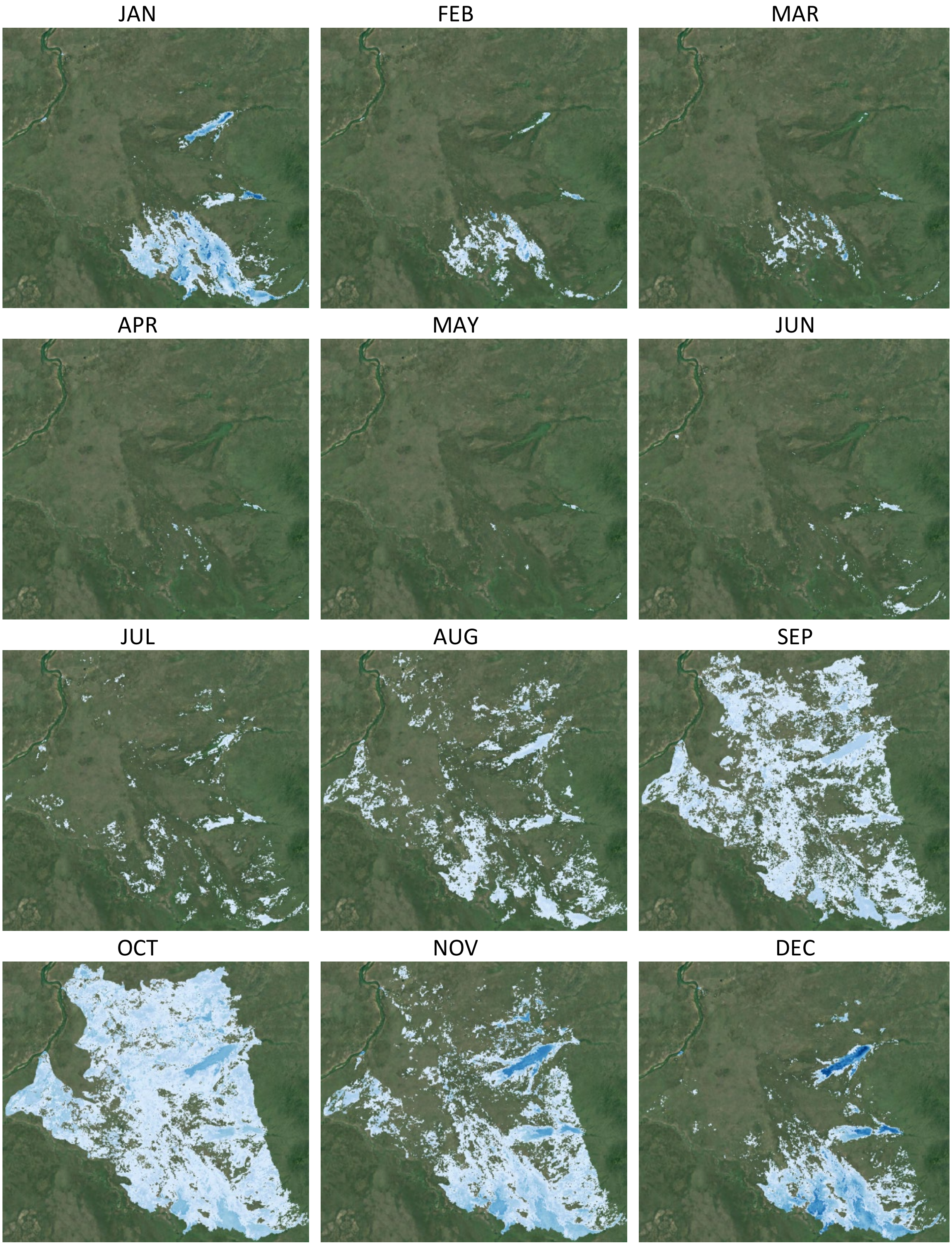

Figure 6: Actual Evapotranspiration (AET) of the Machar Marshes area for an AET threshold of 111mm/mon (which equals to 80% potential evapotranspiration), averaged over the years 2009-2014, FAO WaPOR dataset

Table 4: Tabulated seasonal wetland areas of the Machar Marshes for the AET threshold of 111mm/month

Month	**Area [km²]**		**Month**
January	5 570	July	2 378
February	1 985	August	7 516
March	891	September	19 355
April	133	October	28 448
May	56	November	15 373
June	458	December	8 038

The results show that the intra-annual wetland extent from 2009-2014 ranges between approximately 56km² in the dry and 28,448km² in the wet season. This leads to an average extent of 6947km², which is in line with results from previous studies (see Table 2). Also, the wetland extent of below 100km² during the dry season is in line with wetland classifications under the Nile Wetlands project, where only small and isolated papyrus patches in the same order of magnitude where found in the Machar Marshes region.

These results, in addition to specific monthly extents that were produced for all years, will be used to calibrate the 2D hydraulic model.

5. Development of the water balance model and incorporate into the NileDSS

5.1 Using the BAS-MWRD mode

In order to define the boundary conditions for the coupled MIKE SHE and MIKE 11 model, as described below, an existing MIKE HYDRO BASIN model provided by ENTRO was analysed. This MIKE HYDRO BASIN model covers the full Baro-Akobo-Sobat sub-basin (Figure 7). MIKE HYDRO BASIN is a river basin management and planning modelling tool, but it lacks the level of detail required to understand the water balance and flow dynamics in the Machar Marshes. Therefore, the BAS-MWRD model has the purpose of undertaking an accurate representation of the hydrology upstream of the Machar Marshes which serves as an input to the hydraulic model developed for the Machar Marshes.

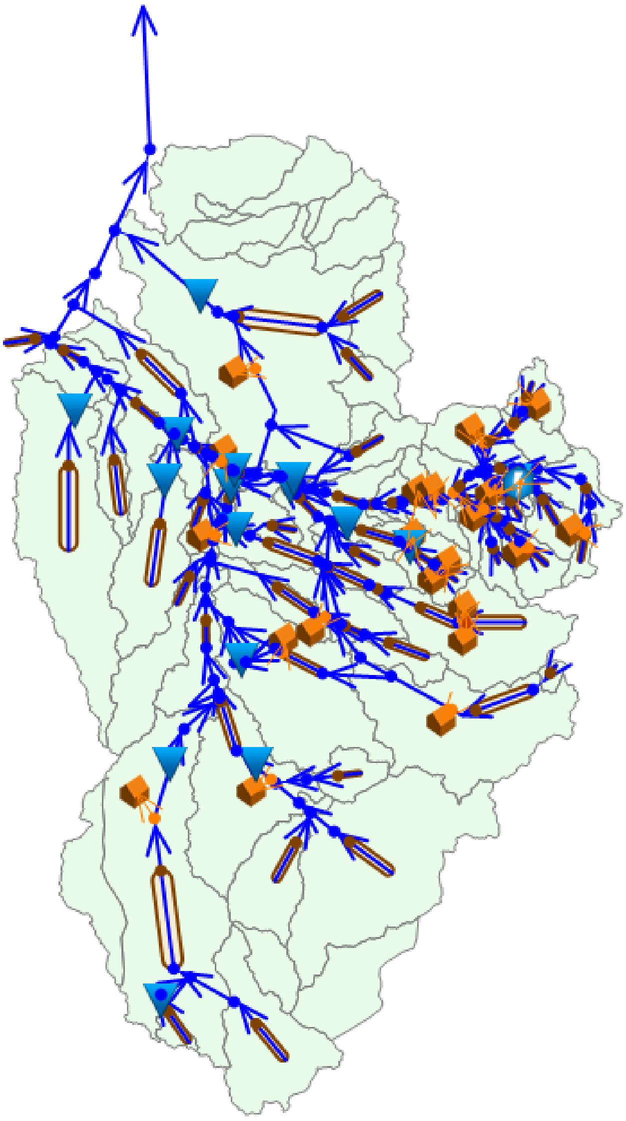

Figure 7: Screenshot of the model schematic

Based on the information provided by the different reports associated with this modelling implementation, the MIKE HYDRO BASIN model for the Baro-Akobo-Sobat sub-basin has the following elements:

- A model network of the Baro-Akobo-Sobat sub-basin
- A different MIKE HYDRO RIVER model (using MIKE NAM hydrological model) was implemented in two different stations in the sub-basin, namely in Gambella, Yagus, Daga and Alwero stations, in

order to calibrate the sub-catchments draining into the location of those stations. The parameters from this calibration were transferred to nearby catchments in order to provide flow conditions for the whole sub-basin.

The modelling network in MIKE HYDRO BASIN has several additional elements, with the main purpose of trying to represent all the processes occurring in the area of study, including dams, water spills, flood walls and irrigation channels.

The MIKE HYDRO BASIN model was assessed and analysed in detail, in order to have a better understanding of the modelling implementation. It should be noted that within the provided data there are other scenario options modelled and also a baseline scenario (Option 0). The latter has been used for the initial implementation of the MIKE SHE model for the Machar Marshes.

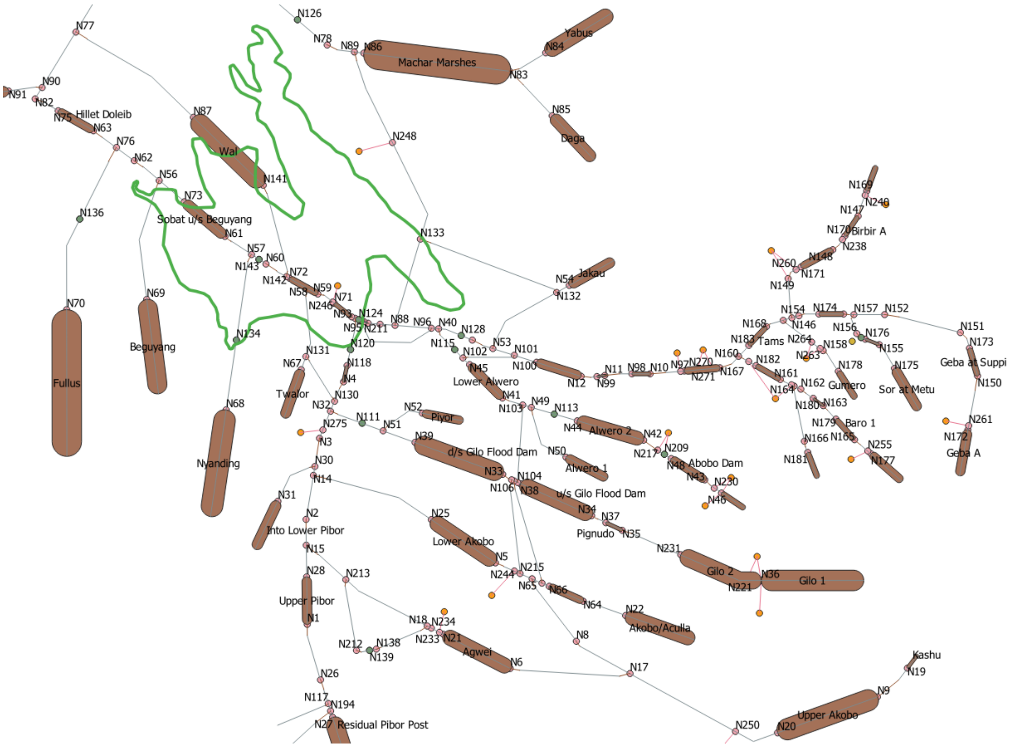

Figure 8: Screenshot of the detailed model schematic (rough Machar Marshes outline are represented by the green polygon)

Figure 8 shows the area close to the Machar Marshes which has been analysed in more detail in order to properly defined the inflows to the MIKE SHE model. The network nodes, sub-catchments, modelling links and all the elements depicted have been carefully assessed. It should be noted that the simulation period has been extended in order to cover the period of the satellite data for the calibration and validation of the model (Chapter 4). Therefore, the simulation of the MIKE HYDRO BASIN model has been extended using available data within the BAS-MWRD model until 2014, in order to have 5 years of coincidence of satellite data and modelling data.

5.2 Inflows defined

After a careful analysis of the MIKE HYDRO BASIN Model, the following inflows have been defined (Figure 9).

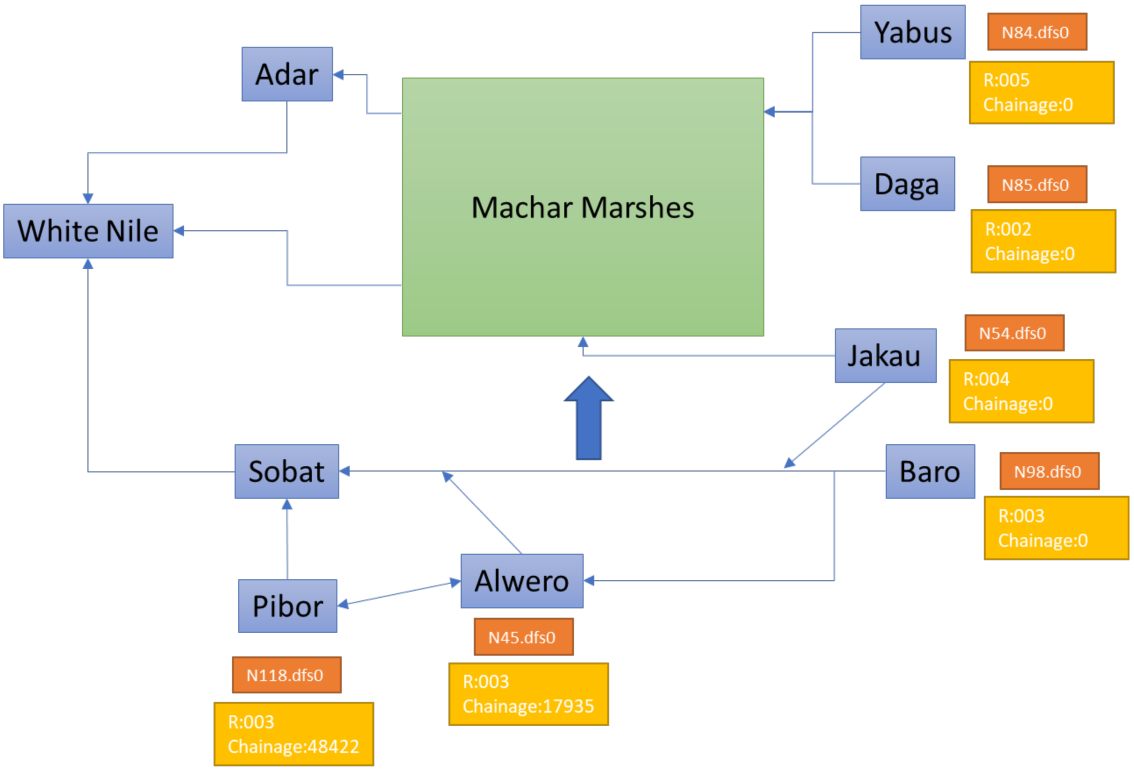

Figure 9: Inflows from the Baro-Akobo-Sobat sub-basin MIKE HYDRO BASIN model to the Machar Marshes MIKE SHE model

These flows have been defined in order to provide upstream boundary conditions for all the watercourses included in the MIKE SHE model. It should be noted that the modelling nodes in MIKE HYDRO BASIN have been carefully chosen in order to provide a better depiction of the hydrological processes in the catchment. Also, it should be added that the main rationale behind this modelling implementation is that the MIKE SHE model implemented will simulate all the processes in the Machar Marshes and downstream (of the modelling domain), while the MIKE HYDRO BASIN model will provide the necessary boundary conditions to represent the processes upstream of the Machar Marshes. The spilling volumes from the Baro to the Machar Marshes (thick blue arrow in Figure 9) are depicted by a separate and more detailed modelling approach (Chapter 6.3).

5.3 Scenarios to be depicted

In addition to the baseline scenario (Option 0 in the information provided) which will be used to calibrate the Machar Marshes hydraulic model, the following scenarios will be used:

- OPTION 1: “Precautionary Principle” scenario, with reduced but significant irrigation areas (small-scale and large-scale) and with no encroachment into environmentally sensitive areas.
- OPTION 2: as per the Option 1 scenario above, but in this case, the Tams dam and Birbir dam are included.
- OPTION 3a: This is an intermediate case, similar to Scenario 2, but with environmental water releases imposed on all dams in order to conserve natural flow patterns.
- OPTION 3b: This is an intermediate case, similar to Scenario 4a, but with environmental water releases imposed on all dams in order to conserve natural flow patterns
- OPTION 4a: This is a Full-development case, with Tams dam operated to maximise hydropower production.
- OPTION 4b: This is a Full-development case, with Tams dam operated to optimise irrigation and flood control

Inflows from each of these scenarios listed above, from the implemented MIKE BASIN HYDRO model, will be used in the calibrated hydraulic model.

6. Development of the 2D Hydraulic model and incorporate into NileDSS

6.1 Approach

As noted above and also as noted in the inception report, the main modelling approach is as follows:

- A MIKE SHE model has been implemented for the Machar Marshes. MIKE SHE is a fully integrated hydrological modelling system that included overland water processes (in 2D), and that can link a river model (in 1D) to a gridded topographical domain (in 2D). The 2D domain also features hydrological processes and interaction with the groundwater.
- A MIKE 11 (1D) model has been implemented in order to represent the flow dynamics in the main watercourses in the area, including the spill from the Baro River into the marshes.
- While the MIKE 11 model will provide water input into the MIKE SHE domain when the water in the channels spills out of the banks, the gridded domain in MIKE SHE will provide overland water input into the defined channels.
- The MIKE SHE-MIKE 11 coupled model (MIKE SHE model from now on) will be calibrated against satellite data and against observed discharge values in several stations in the study area.

6.2 Data sources used

The implementation of a MIKE SHE model is very demanding from a data input point of view. In the sections below, the data requirements and the data sources for implementing the model are described:

6.2.1 Model Domain

The modelling domain for the MIKE SHE implementation was defined considering the information from several sources, including the wetland classification undertaken within the framework of the Nile Wetlands Project, the information from the satellite-derived soil moisture, the river branches to be included in the modelling domain, the information from the MIKE BASIN HYDRO model for the Baro-Akobo-Sobat sub-basin and the objectives of this study.

It should be noted that the model domain in MIKE SHE has been defined using GIS resources in order to properly define the boundary following the MIKE SHE requirements, i.e. a boundary with a value of “2” in a domain with a value of “1”. The modelling domain is shown in Figure 10.

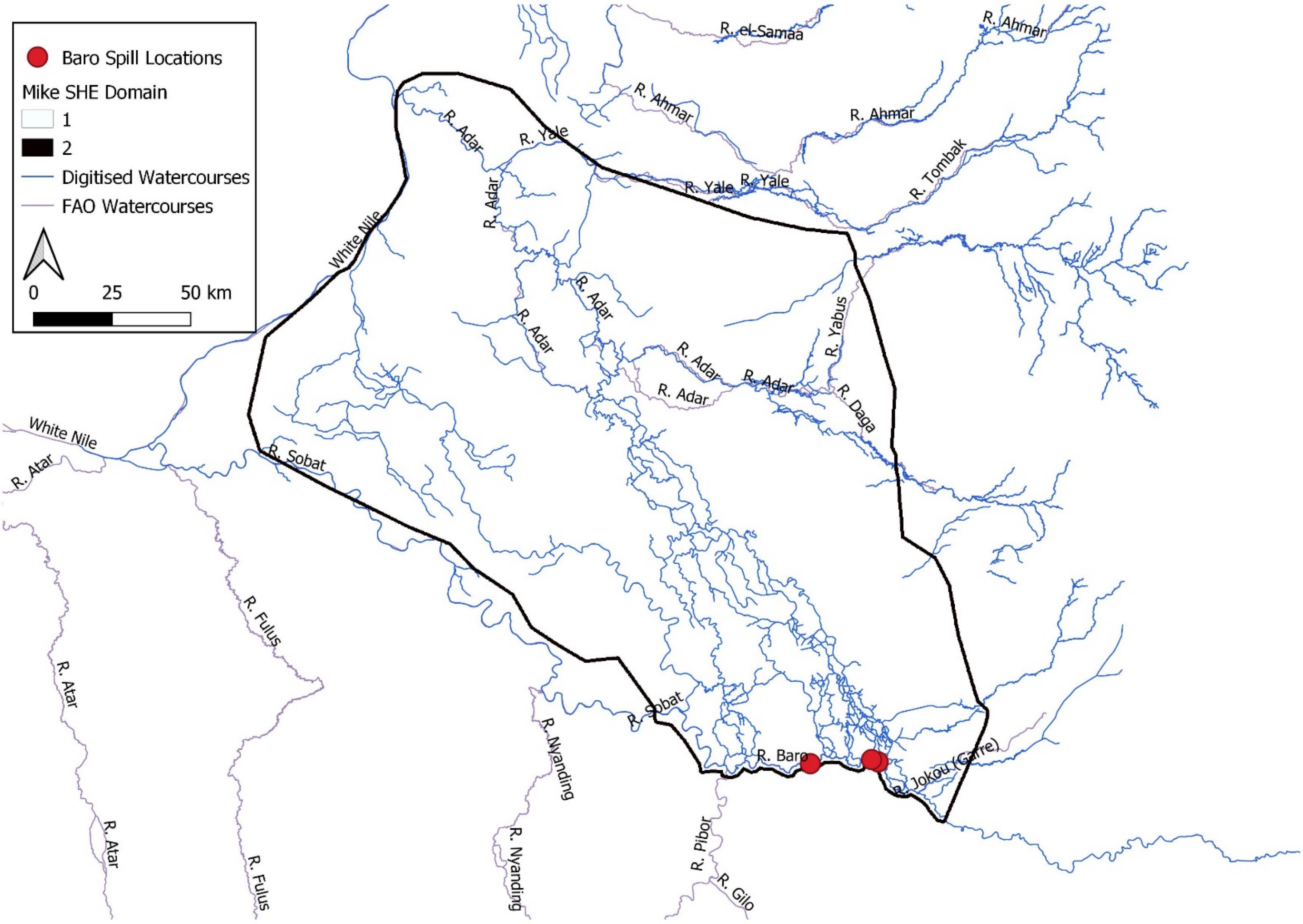

Figure 10: Modelling Domain (outline boundary)

6.2.2 Topography

The topography for the MIKE SHE model of the Machar Marshes have been defined using several sources, as follows:

- MERIT DEM: the MERIT DEM (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/) was developed by removing multiple error components (absolute bias, stripe noise, speckle noise, and tree height bias) from the existing spaceborne DEMs (SRTM3 v2.1 and AW3D-30m v1). It represents the terrain elevations at a 3sec resolution (approximately 90m at the equator), and covers land areas between 90N-60S, referenced to EGM96 geoid. The DEM is publicly available under the "Open Database License (ODbL 1.0)", which means that results from the study have to be publicly available.
- WorldDEM: the WorldDEM from Airbus is a 12m DEM with a vertical accuracy of 4m. This DEM was ordered in order to more accurately represent in the spilling region of the Baro river.

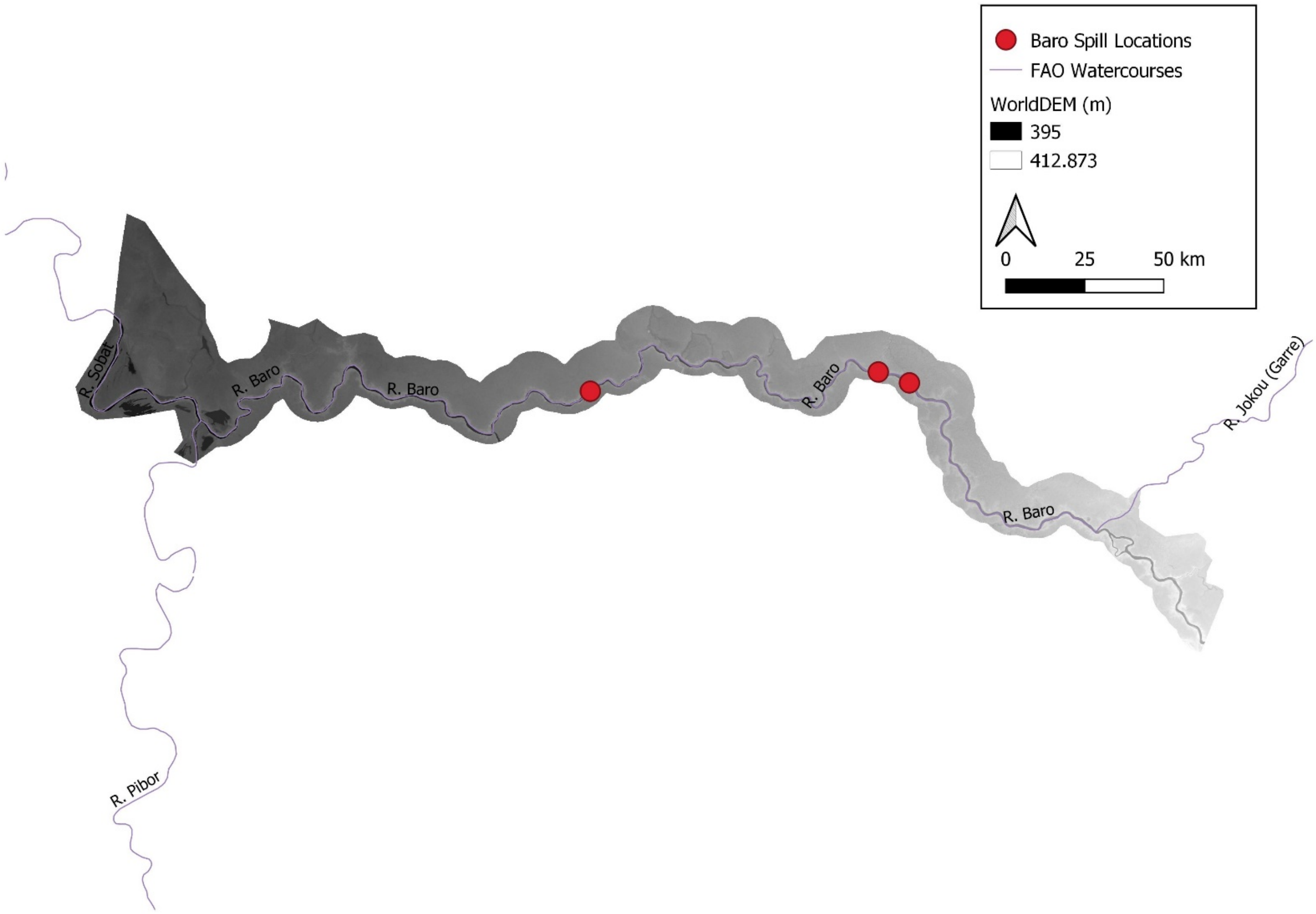

Figure 11: WorldDEM DEM for the Baro river spilling region

The two DEMs have been merged in a single topography file for MIKE SHE (Figure 12). The initial grid horizontal resolution used in the initial runs, as depicted below in Section 6.5, is 540m. This is due to the computational resources required for simulating several years with this model.

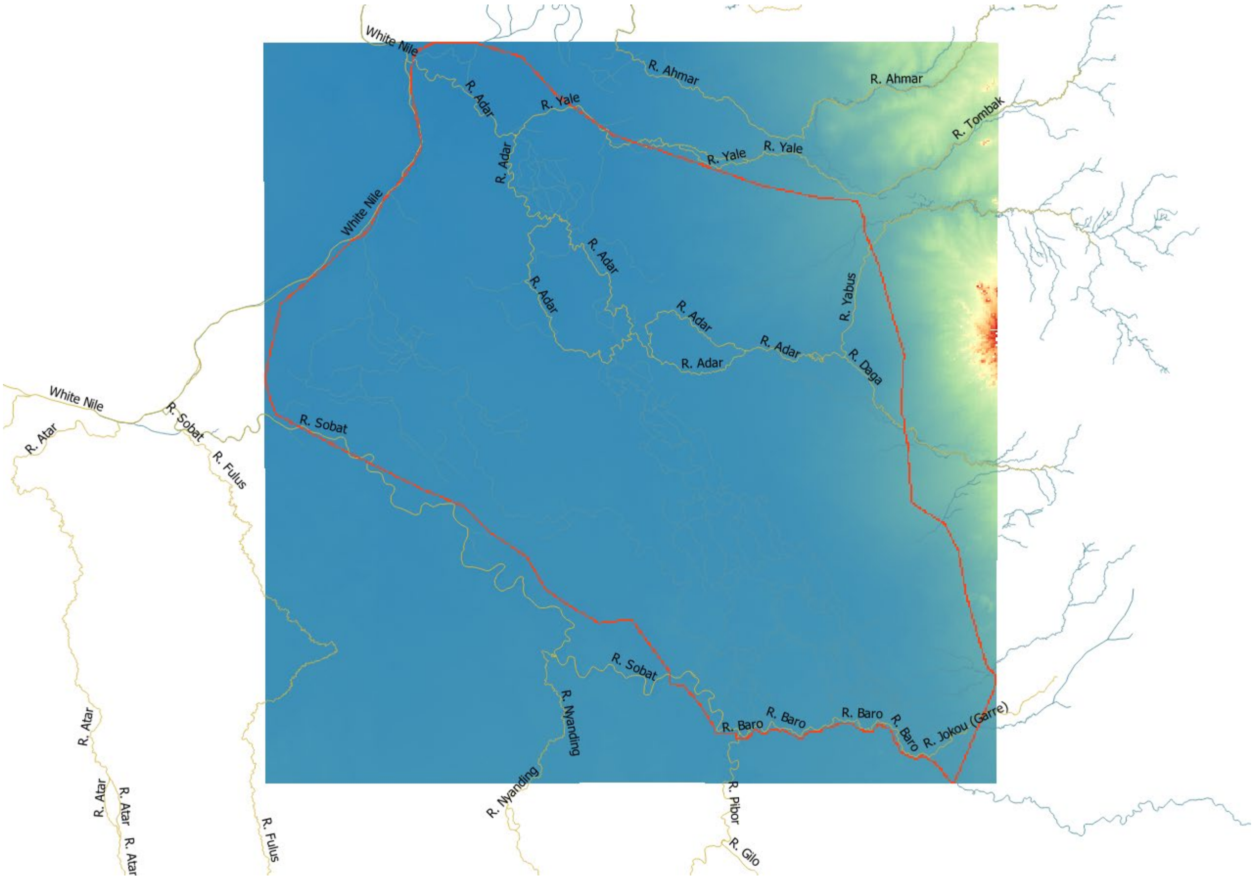

Figure 12: Topography file for MIKE SHE

6.2.3 Climate

As noted, MIKE SHE is an integrated hydrological model, and therefore it does require information about both precipitation and potential evapotranspiration. Climate data were obtained from the Princeton database[14], the same database that is used for the NileDSS to allow a seamless integration into the NileDSS. A NetCDF file for the whole period (1948-2019) was extracted from the Princeton database and imported into MIKE SHE (Figure 13).

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[14] http://hydrology.princeton.edu/data.pgf.php

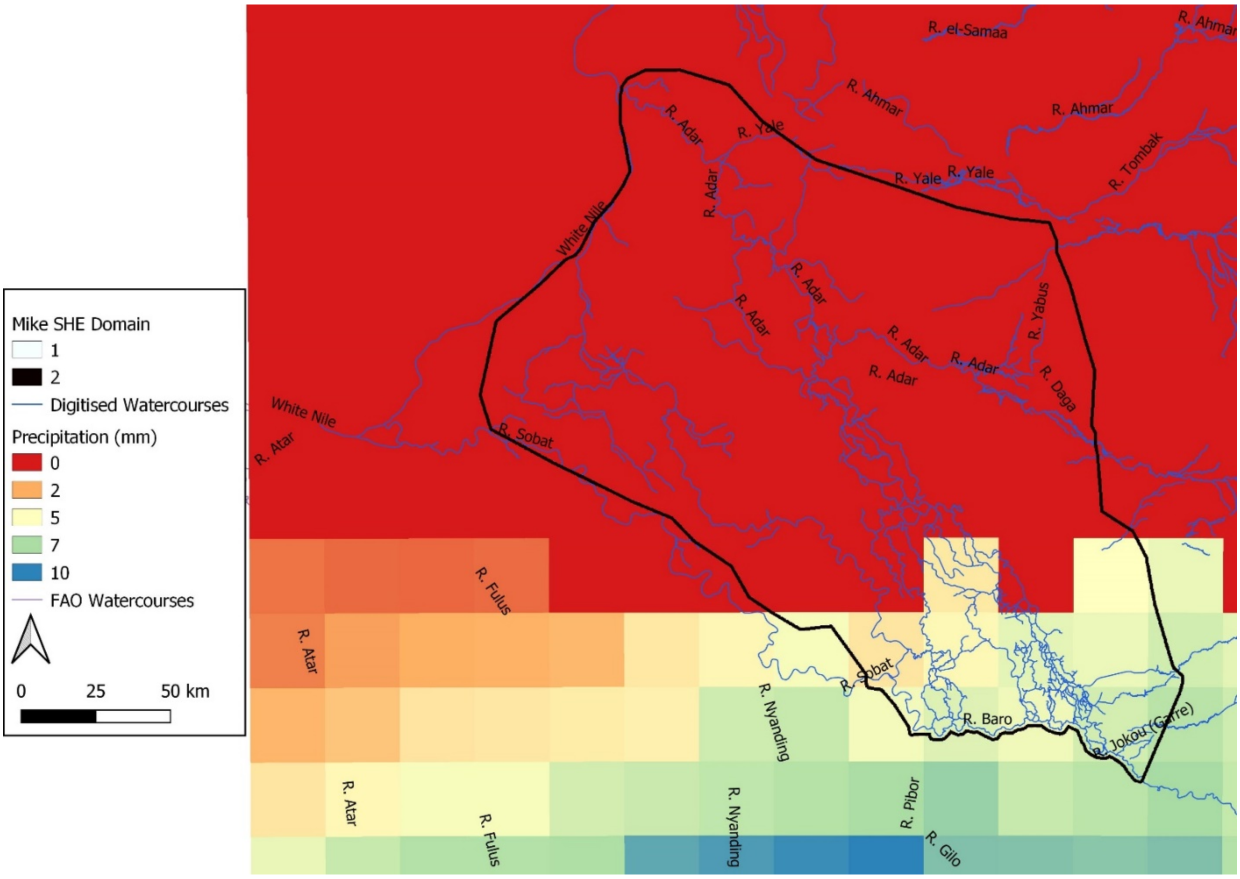

Figure 13: Precipitation for the Machar Marshes Modelling Domain

The potential evapotranspiration was calculated using the Hargreaves method from the Princeton climate data.

6.2.4 Land use – Vegetation

The land-use and vegetation in the modelling domain have to be defined also in MIKE SHE. Information obtained within the Nile Wetlands Project was utilized and imported into MIKE SHE in the modelling domain. The following classes and their respective code were identified (Table 5 and Figure 14).

Table 5: Land-use/Vegetation classes

Class	Code
Trees	1
Shrubs cover areas	2
Grassland	3
Cropland	4
Vegetation aquatic or regularly flooded	5
Bare areas	7
Built-up areas	8
Open water	10

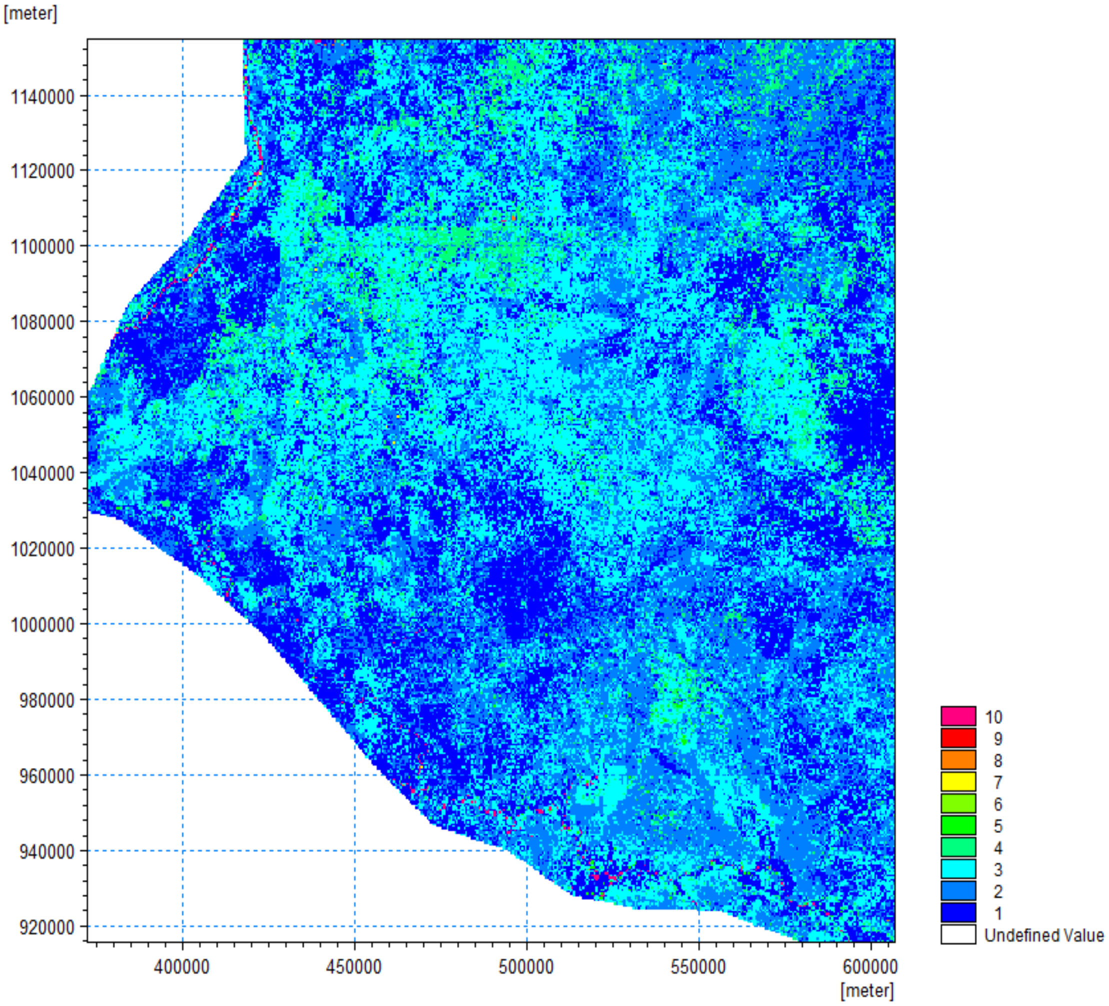

Figure 14: Land-use/vegetation for MIKE SHE model of the Machar Marshes (please note that values 6 and 9 do not exist on the grid and in Table 5, but only in the legend)

6.2.5 Rivers

A MIKE 11 (1D) model has been defined in order to represent the main watercourses of the Machar Marshes. Rivers have been digitized from satellite imagery

6.2.6 Manning Number

The resistance of the floodplains and marshes in the 2D grid domain of MIKE SHE has been defined using the manning approach. This manning number has been derived using the information from the land-use/vegetation outlined above and assigning values from the literature to each of the different classes. It should be noted that in MIKE SHE the manning number has to be defined using the M approach (1/n) instead of the most common n approach (Figure 15).

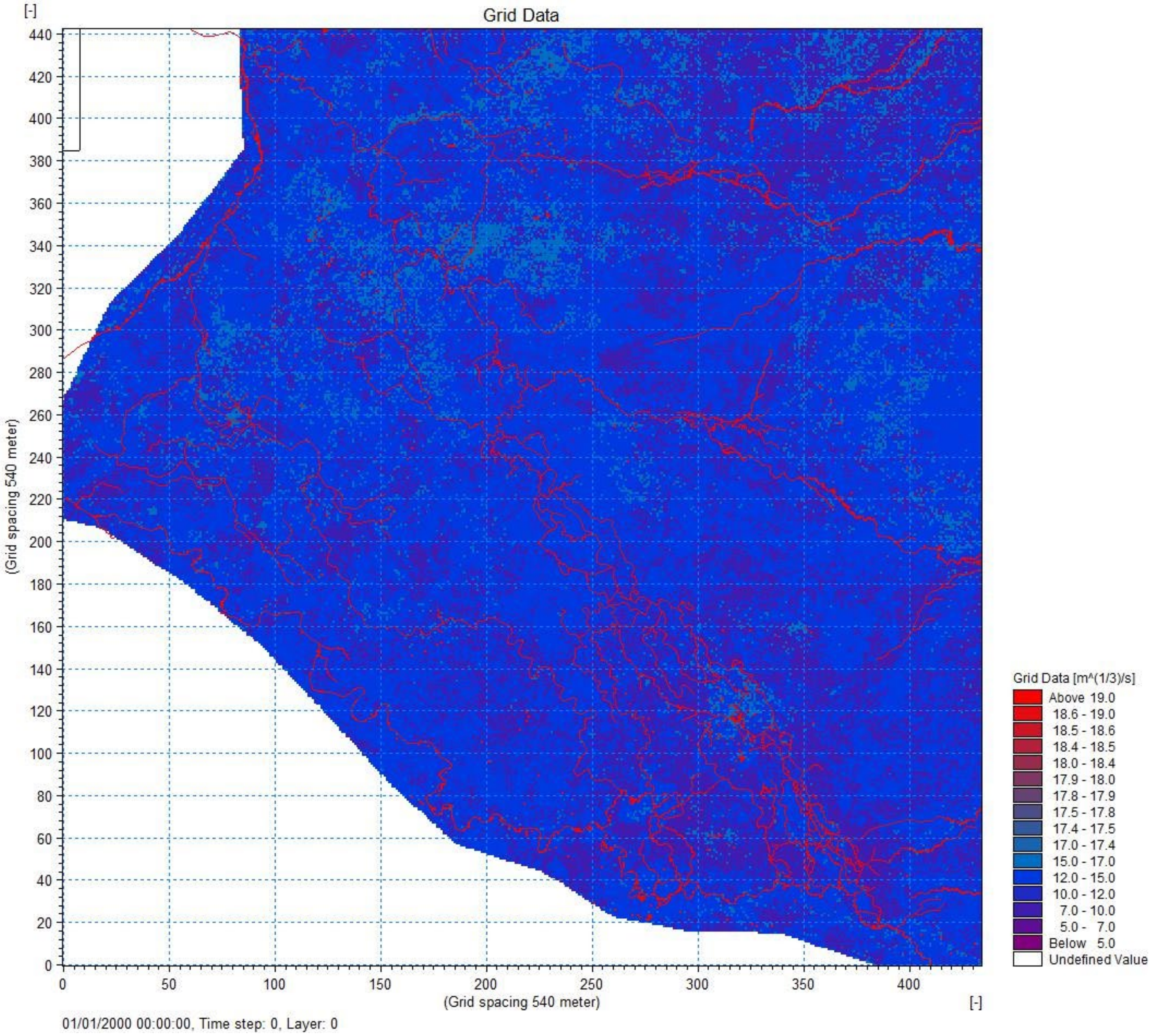

Figure 15: Manning for the MIKE SHE model for the Machar Marshes

6.2.7 Soil

The soil information was extracted from the soil-grid database[15] and processed to derive the texture information for MIKE - SHE. Three different soil profiles have been identified and defined in the study area (Figure 16). As noted, these soil profiles and their characterization have been undertaken using the information from the soil-grid database, but also combining this information with possible infiltration patterns. Thus, these three different soil profiles correspond to three different infiltration values, both from the surface to the unsaturated zone, and subsequently from the unsaturated zone to the saturated one.

In addition to that, for each soil profile, three different layers have been defined, namely from 0.0 to 0.3m (1), from 0.3m to 1.0m (2) and from 1.0 to 3.0m (3). The discretization of the vertical levels has been defined in Table 6.

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[15] https://soilgrids.org

Table 6. Soil vertical discretization

Layer	From depth	To depth	Cell height (m)	No. of cells
1	0.00	0.30	0.10	3.00
2	0.30	1.00	0.23	3.00
3	1.00	3.00	0.25	8.00

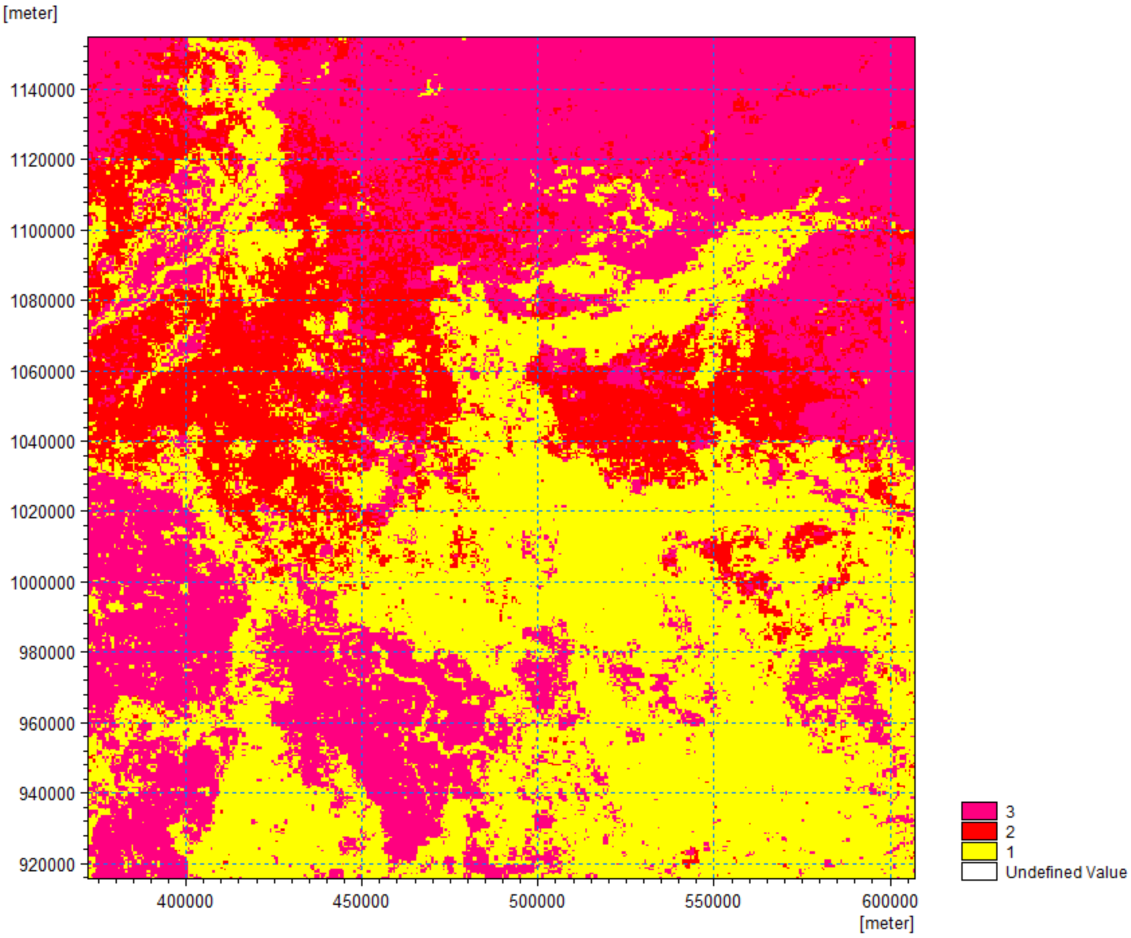


Figure 16: Soil data for the MIKE SHE Machar Marshes model

6.3 Mike11 model of the Baro (extent, schematic, depicted processes)

As noted above, the main rivers in the Machar Marshes MIKE SHE model have been implemented in MIKE 11. The MIKE 11 model has subsequently been dynamically linked to the MIKE SHE Model. The MIKE 11 model implementation has been undertaken in the following manner.

6.3.1 Model domain and network

In order to properly represent the inflow coming into and going out of the Machar Marshes, five watercourses (channels) have been initially defined (Figure 17). These five branches have been defined as regular in MIKE 11, with a maximum calculation (cross-section) spacing of 500m (Table 7)

Table 7. Branch definition

Branch name	Upstream chainage	Downstream chainage	Flow direction	Maximum dx (m)	Branch type
R:001	0	303121.72	Positive	500	Regular
R:002	0	334359.299	Positive	500	Regular
R:004	0	41784.5647	Positive	500	Regular
R:005	0	48608.558	Positive	500	Regular
R:003	0	124822.868	Positive	500	Regular

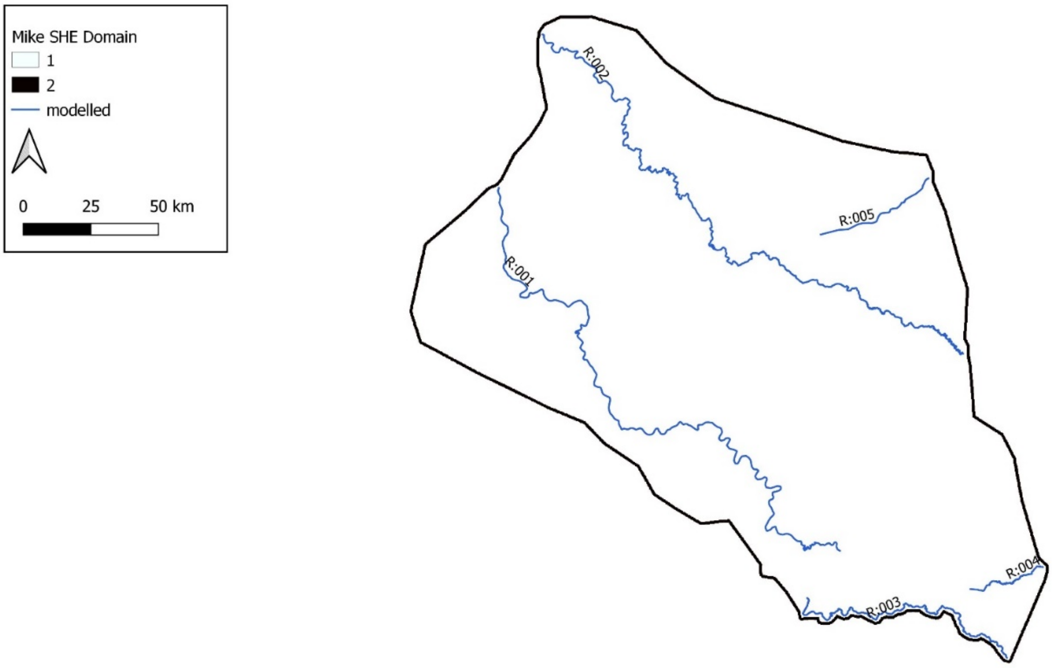


Figure 17: River network

6.3.2 Cross-sections

The cross-section information, as required by the MIKE 11 model implementation, has been extracted from DEM sources. It should be noted that a total of 746 cross-sections have been defined (Figure 18).

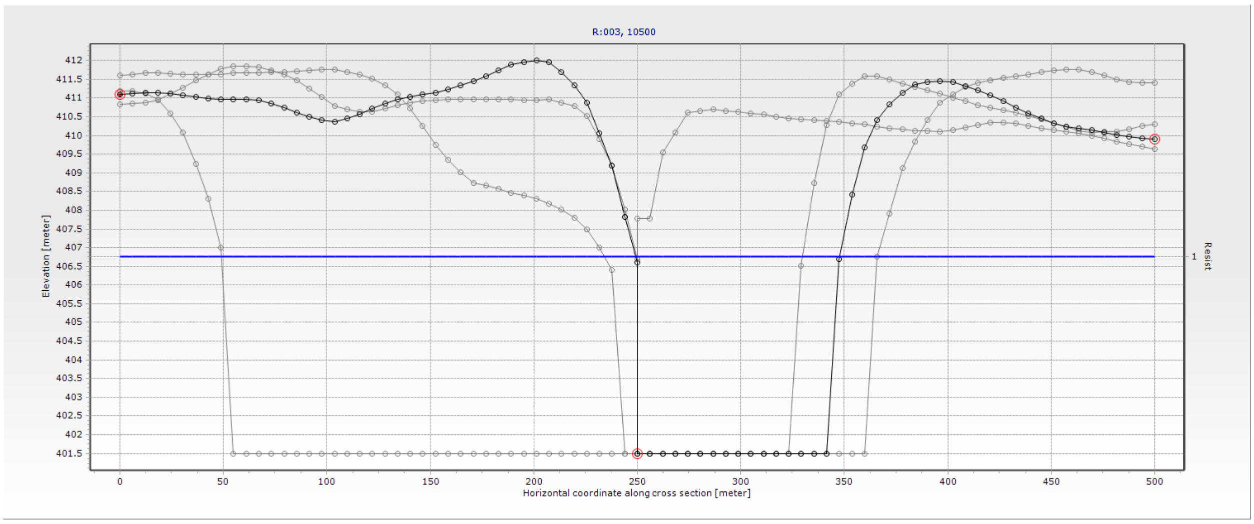


Figure 18: Cross-section in the Baro River

The cross-sections have been defined differently depending on the source of the DEM, as follows:

- For the area not covered by the WorldDEM, but covered by the MERIT DEM, the cross-sections have been defined along the digitized watercourse and initially considering that the channel is 2.0m deep.
- In the area covered by the WorldDEM along the Baro river (branch R:003) the approach has been different. There is topographical information in the Baro river, upstream of the spilling region in the Gambella station. A small section of the WorldDEM was also requested for this area (Figure 19).

Figure 19: Gambella station DEM

Therefore, the WorldDEM and the existing topographical information in the Gambella station were compared in order to identify a depth pattern that could be applied to the remaining DEM (in the spilling region). It was identified that a bias of 4.5m could be applied, and therefore, the cross-section in the Baro river spilling region was extracted from the DEM and applied in the channel using a -4.5m correction.

6.3.3 Boundary conditions

The following boundary conditions have been defined for the MIKE 11 model.

Upstream boundary conditions

Upstream boundary conditions have been defined for the five branches included in the model. It should be noted that this information, as previously stated, has been extracted from the existing MIKE BASIN HYDRO model for the Baro-Akobo-Sobat sub-basin. Time-series of discharge (Figure 20) were extracted from the model. It should be added that for branch R:001 no time-series data were used, as the MIKE SHE model will provide the necessary inflow into this branch coming out of the marshes.

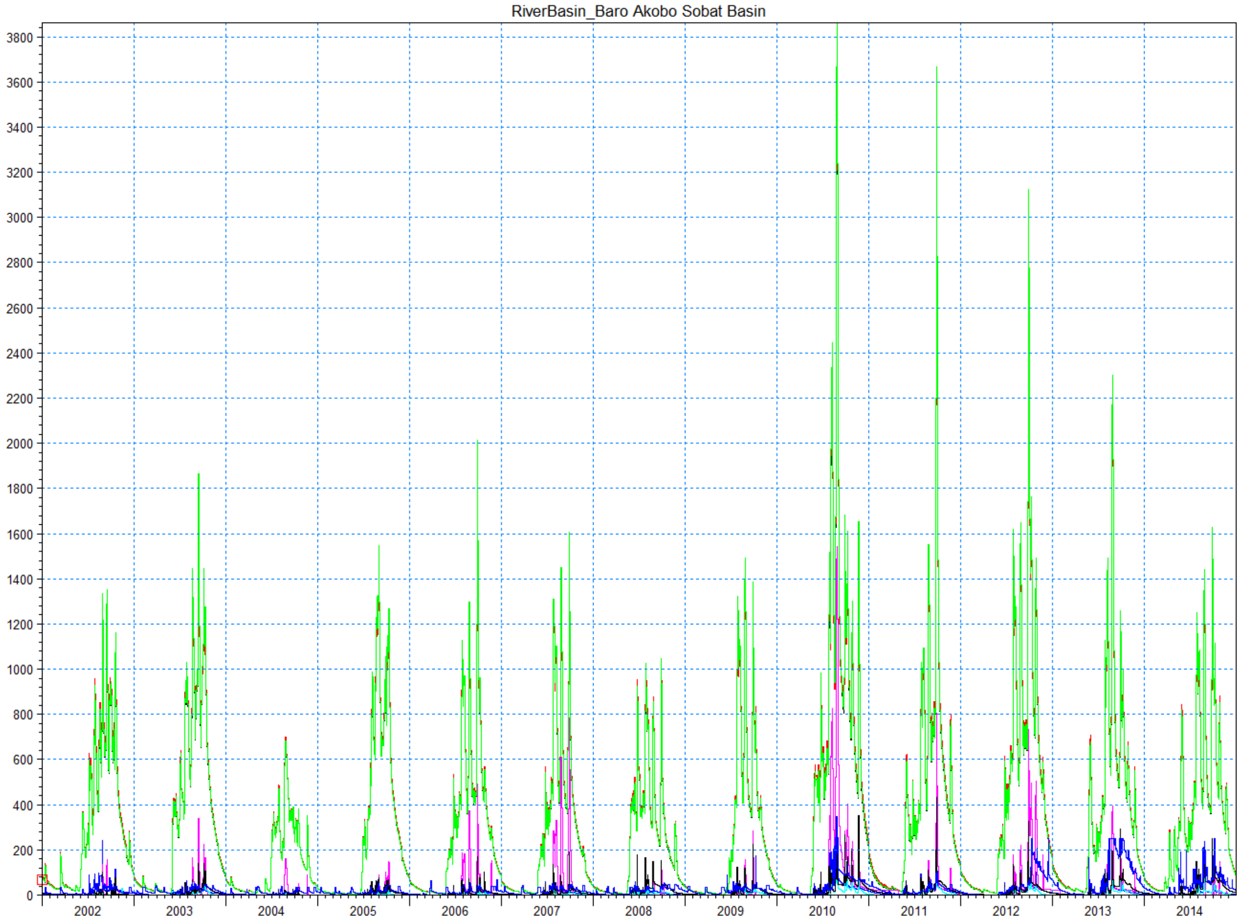


Figure 20: Discharge time-series

Downstream boundary conditions

At the downstream end of all branches, Q/h (Discharge-depth) relationships have been established. These relationships have been derived for each branch at the downstream end using the information from the cross-section topography.

6.3.4 Hydro-dynamic parameters

The hydro-dynamic parameters for the MIKE 11 implementation have been defined in Table 8.

Table 8: Hydro-dynamic parameterization

Parameter	Value	Unit
Initial water depth	1	m
Initial discharge	2	m^3/s
delta	0.95	dimensionless
delhs	0.01	m
delh	0.1	m
alpha	1	dimensionless
theta	1	dimensionless
eps	0.0001	dimensionless
dh_node	0.01	m
zeta_min	0.1	dimensionless
struc_fac	0	dimensionless
Wave approximation	High order fully dynamic	

6.4 MIKE SHE-MIKE 11 Linking Process

The MIKE 11 and the MIKE SHE models have been linked through the branches. As noted, and as depicted in Figure 21, the river channel has been modelled in MIKE 11, while the overland flow (through the floodplains and the marshes), the groundwater and all other hydrological processes have been modelled in MIKE SHE. Whenever the water depth is above the defined bank levels, water will spill from the MIKE 11 model to the MIKE SHE overland grid. This process is based on the weir equation, with movement of water is initiated whenever there is 0.1m of water above the crest level of the bank. It should be noted that no interaction between the channel and the groundwater has been established at this stage.

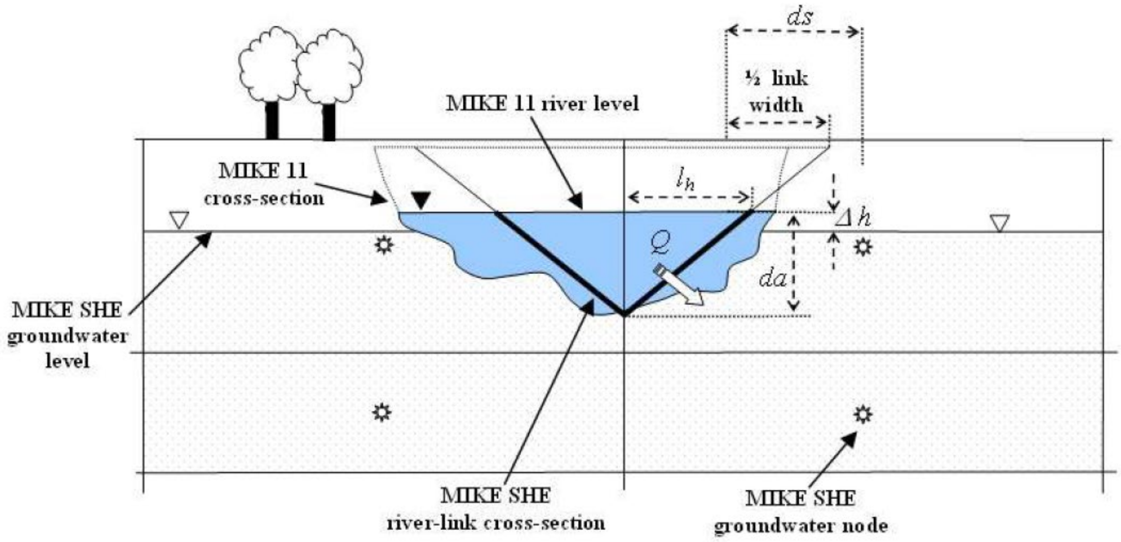


Figure 21: MIKE SHE-MIKE 11 links (from MIKE SHE Volume 2: Reference Guide, DHI 2019)

6.5 Final simulation results

6.5.1 Baseline scenario (Option 0)

The results from the implemented MIKE SHE modelling framework has been calibrated against all the data available, both the discharge in the Baro river and the spatial results from the remote sensing delineation of the wetlands. There are several things to consider for this calibration:

- The spatial results from the wetland delineation are a representation of the existence of evapotranspiration, and therefore of the existence of water content, either at surface level or at sub-surface level. These results do not provide information about the water depth. Also, these results are conditioned by the temporal and the spatial resolution.
- There is no information in the Baro river during the simulation period. As noted above, the simulation period is from January 2009 until January 2014 (five years, with a warm-up period at the beginning of the simulation). The existence of discharge data in the Baro river dates back to several years back, but during the 1940s and 1950s the data is more abundant. However, as it has previously detailed, the flow in this river is highly affected by spills to the Machar Marshes, where a threshold has been observed in previous years. Considering this and the existence of a marked rainy season, the comparison of the flow has been undertaken for different periods (in the observed and simulated data) in order to observe the flow patterns. Therefore, the exact values of the discharge should not be considered in detail when comparing the simulation results.

The simulation period for the baseline scenario (option 0), as well as for all the option simulations, has been from the 1st of September 2008 until the 1st of January 2014. The results have been analysed and processed from the 1st of January 2009 until the 1st of January 2014. The four months of simulation in 2008 have been used to warm-up the model. It should be noted that initially a hot-start file has been used in MIKE SHE but due to instabilities in the results, it has been found preferable to use this approach for warming-up the model. These four months correspond to a period with some precipitation and with significant flow in all the branches in the area. Therefore, these four months are sufficient to bring the model to proper initial conditions by the 1st of January 2009.

MIKE 11 results

The flow and water levels in the five pre-defined watercourses in MIKE 11 were analysed and, when possible, calibrated. After the first initial results, it was apparent that the MIKE 11 model was predicting more discharge in the lower (downstream) Baro and Sobat than what was expected after analysing the data from the observational campaigns. This was also deduced by the lower than expected spills from the Baro to the Machar Marshes, based on the spatial analysis comparison that will be described further below. In order to reduce the flow in the downstream end of the Baro the following was undertaken to improve the calibration:

- The Manning number in the Baro was increased to 0.045 from 0.033. This value was increased after an inspection of the channel and floodplain characteristics using remote sensing sources and photographs taken during previous HYDROC fieldwork in the basin. This value predicted discharges and water levels more realistic than the initial ones. It should be added, for clarification purposes, that a higher Manning number results in lower velocities and higher water level due to the higher resistance of the surface to the water flow.
- The main spill locations, as shown in Figure 10 and Figure 11, were assessed in detail. In the first place, more cross sections were included in these areas in order to ensure that the model has all the required topographic information to assess spills properly. The information in the MIKE SHE 2D grid should have been sufficient in order to ensure that the spill region was properly represented, but the initial results indicated that more information was required. In a second step, the topographic information in the 2D domain was manually adjusted in very specific locations. The justification for this manual adjustment was based on aerial and satellite images of the area. It was observed that while in remote sensing images there was a direct

connection between the main Baro channel and secondary channels draining into the Machar Marshes, in the DEM, this direct connection was prevented by elevation values higher than the values immediately downstream in these secondary channels. The elevation values were adjusted considering the bank levels in the Baro.

During the calibration process some other improvements were attempted. For instance, the bed level in the Baro was adjusted. In the initial simulations, a constant four and a half metres depth was assumed for the whole Baro. These channel depths were revised and a 3.5m channel depth was finally adapted. It should be noted that some other depth values were tested, but that the impact that the channel depth had on the results was secondary to the impact that the roughness (Manning) and manual alteration of the 2D grid had on the results.

While Figure 22 shows the discharge in the Baro river for the simulation period, Figure 23 shows the comparison between the simulation discharge results and the observations. As explained above, it should be noted that the periods are not coinciding, and therefore:

- The information in the 'x' axis should not be considered
- The discharge peak information should not be taken into account.

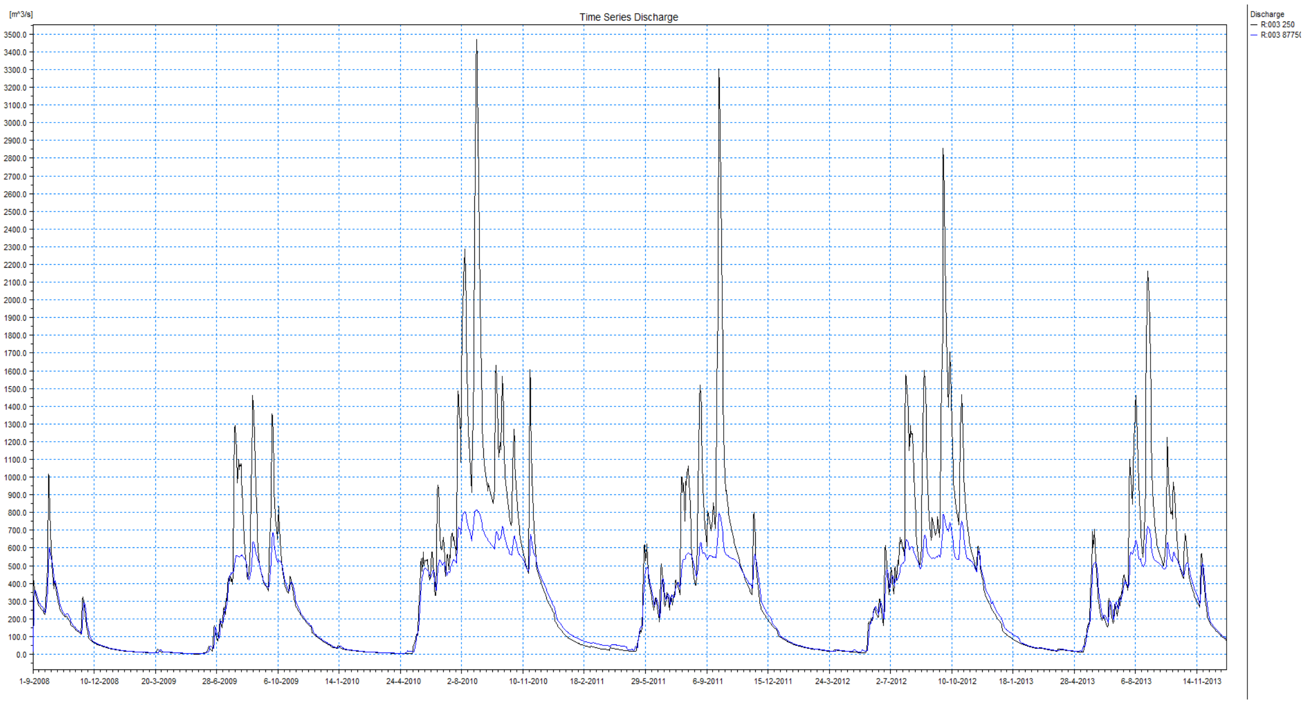


Figure 22: Discharge in the Baro river for the simulation period

The main objective was to ensure that the Baro River spills were occurring at roughly a similar discharge threshold as the one that could be estimated based on the observed data. As it can be deducted from Figure 23, the discharge spill threshold is around 600-650 cumecs, and therefore the discharge at the downstream end of the Baro from the observations and from the simulation results are very similar. The discharge values in the Baro are slightly higher, but this is because these results are based on daily values and because the initial inflow at the Baro upstream end are higher for all the simulated years as compared to the observation values.

Therefore, it can be concluded that the model produces a correct depiction of the spills and flow processed in the Baro. Subsequently, it should be noted, that the roughness values (Manning) in the other four watercourses modelled were also raised to the same values for consistency purposes.

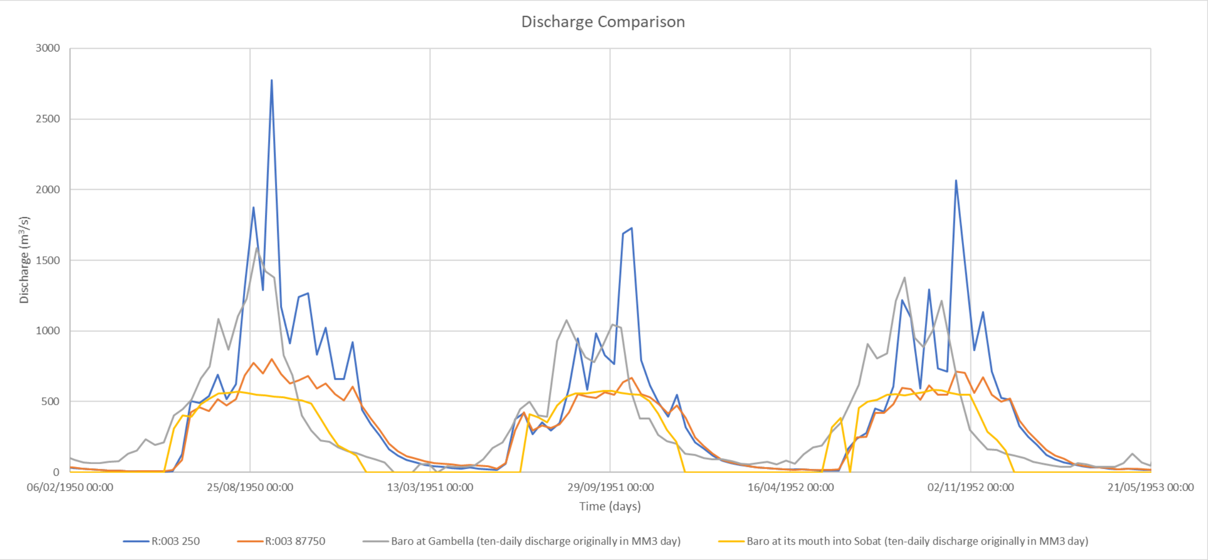


Figure 23: Comparison of the simulation discharge results against observations

The Figure 24 below shows the maximum spills (outflow) from the Baro to the 2D grid in MIKE SHE. As it can be observed, there are three major spill locations, the two locations further downstream are the ones associated with the spill locations previously noted. The first one is associated with low elevation values at the upstream end of the model and it is flow that mostly is coming back to the Baro river.

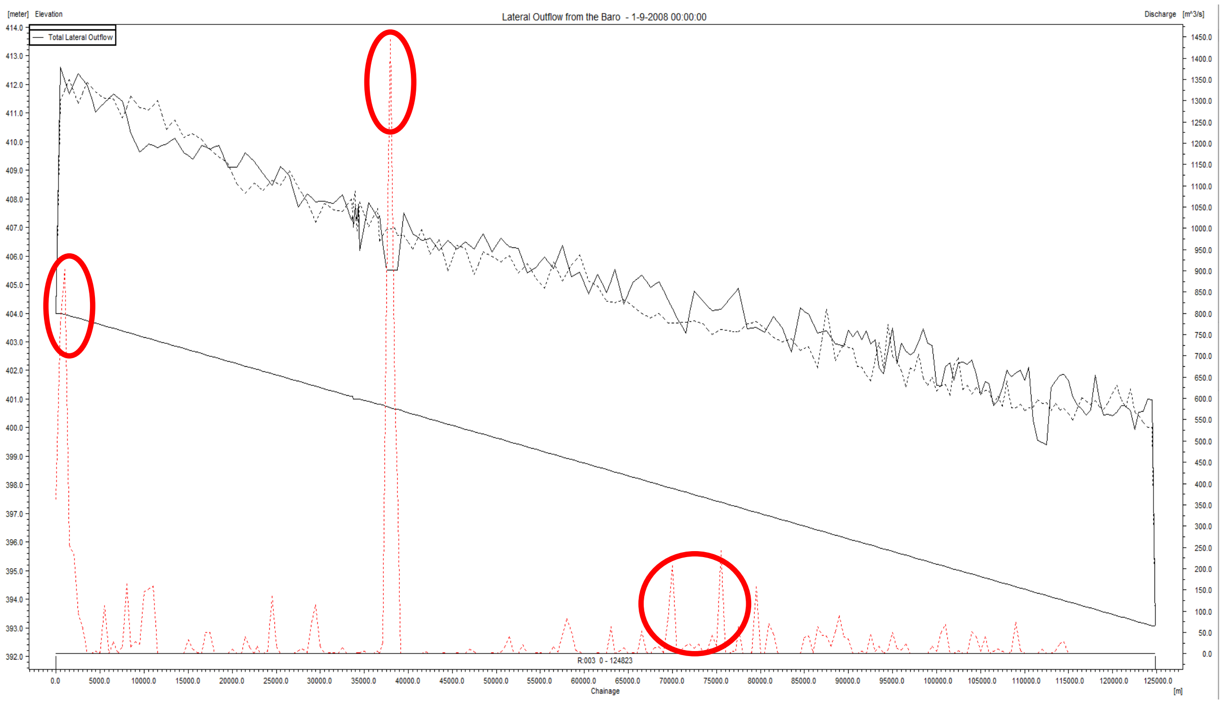


Figure 24: Spills from the Baro River to the Machar Marshes

In addition to the 1D (MIKE 11) results in the Baro, the results and dynamics in all the other watercourses were analysed too. As noted above, the inclusion of the watercourses was limited in the MIKE SHE-MIKE 11 coupled model to ensure that most of the processes were covered within the 2D engine, because there were many unknowns regarding the channels and the dynamics from a 1D point of view. Nonetheless, there were three branches (watercourses) that were fully included in the model, the Baro River, the Daga-Adar river and the branch R:001 (unknown name), that begins in the Machar Marshes and drains directly to the White Nile.

Figure 25 shows the longitudinal profile of the Daga-Adar River, as it flows through the Machar Marshes. The red line in the figure below shows the maximum water level as predicted by the model. As it can be observed, there are several locations where spills from this river into the Machar Marshes is predicted. Also, there are locations where inflow from the Machar Marshes into the river are predicted.

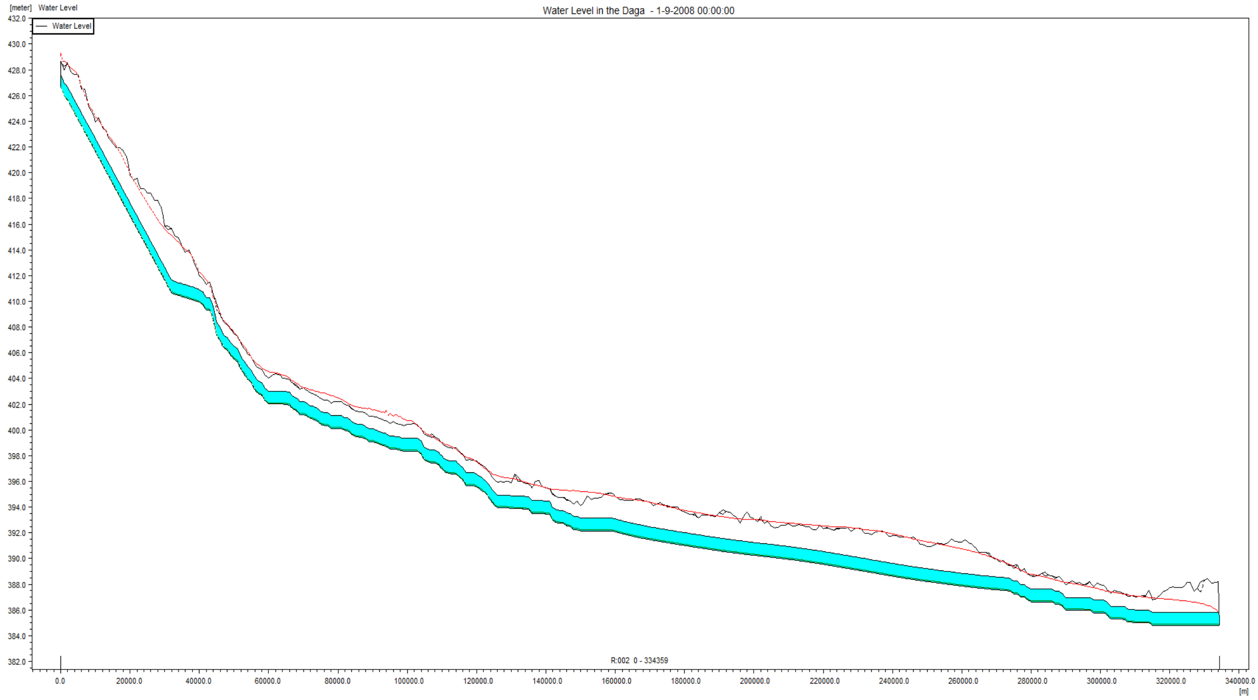


Figure 25: Daga-Adar river longitudinal profile

The Figure 26 shows the longitudinal profile of the branch R:001. As noted, this branch begins directly in the Machar Marshes and it has no direct inflow in the MIKE 11 model. All the flow in that branch comes from direct inflow from the MIKE SHE grid overland flow. As it can be observed, the maximum water level (red line) is over the banks at several locations and therefore spills from this branch back to the Machar Marshes is predicted in several locations.

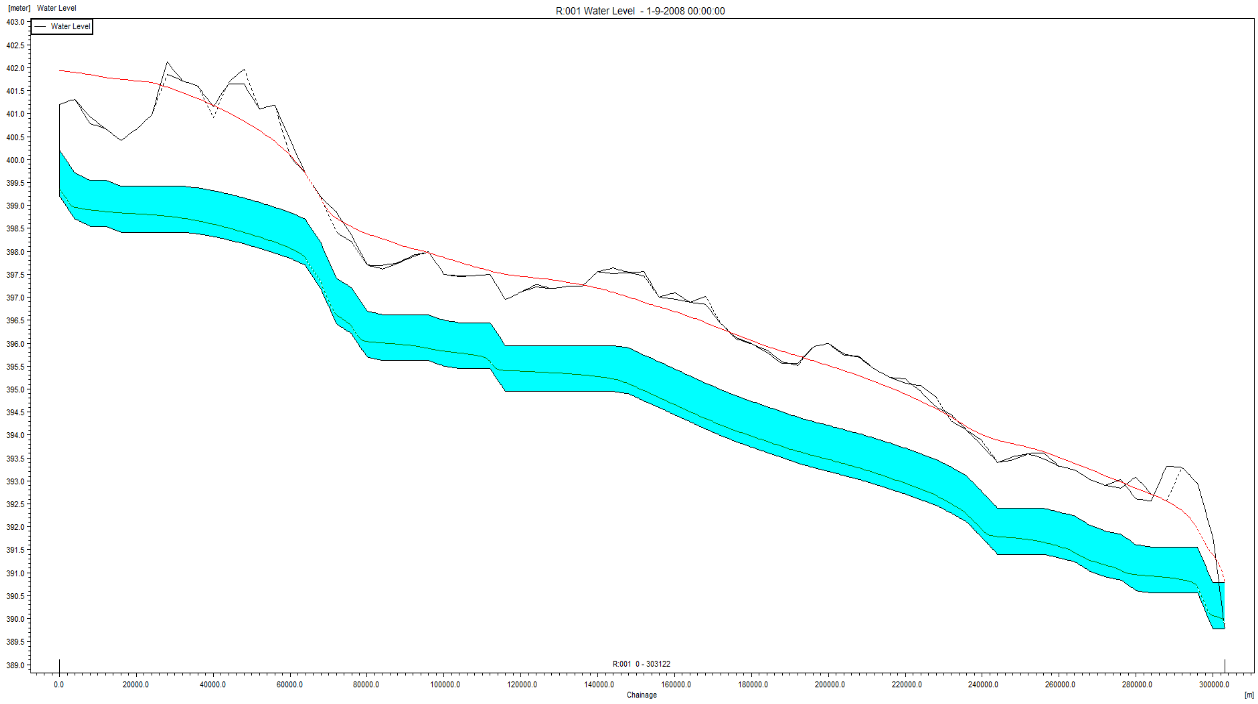


Figure 26: R:001 longitudinal profile

MIKE SHE results

The results of the MIKE SHE grid overland flow results have been compared to the spatial results yielded by the remote sensing analysis described in Section 4. From Figure 27 to Figure 36, a comparison between the simulated results (left) and the remote sensing results (right) for the April and September months can be analysed. These two months have been selected because they correspond to the extremes (lowest and highest values respectively) in the Machar Marshes. The results of both methods depend highly on the thresholds used for representation, but as can be observed, the modelling results can be easily compared to the remote sensing results, and therefore the results of the modelling exercise are considered satisfactory and plausible.

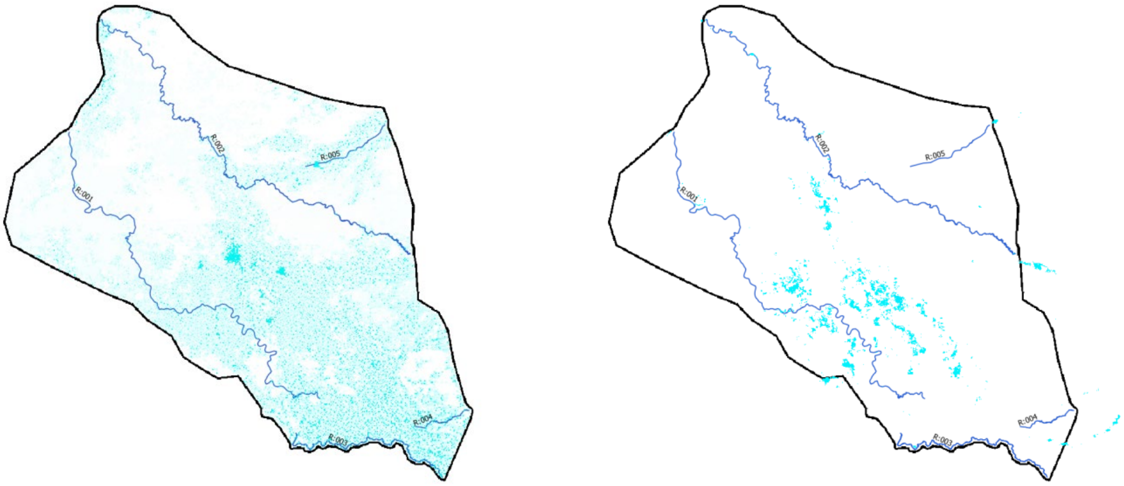


Figure 27: April 2009 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

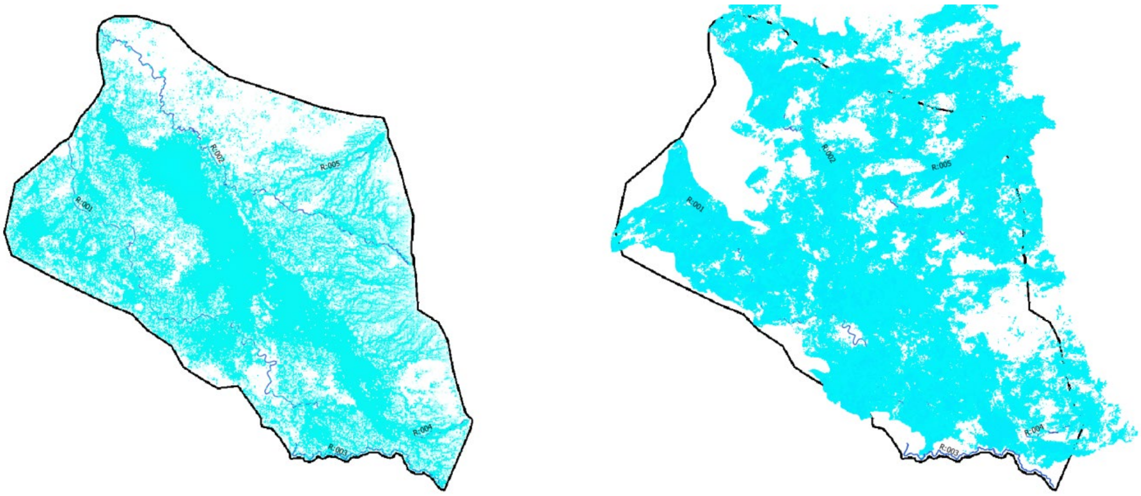


Figure 28: September 2009 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

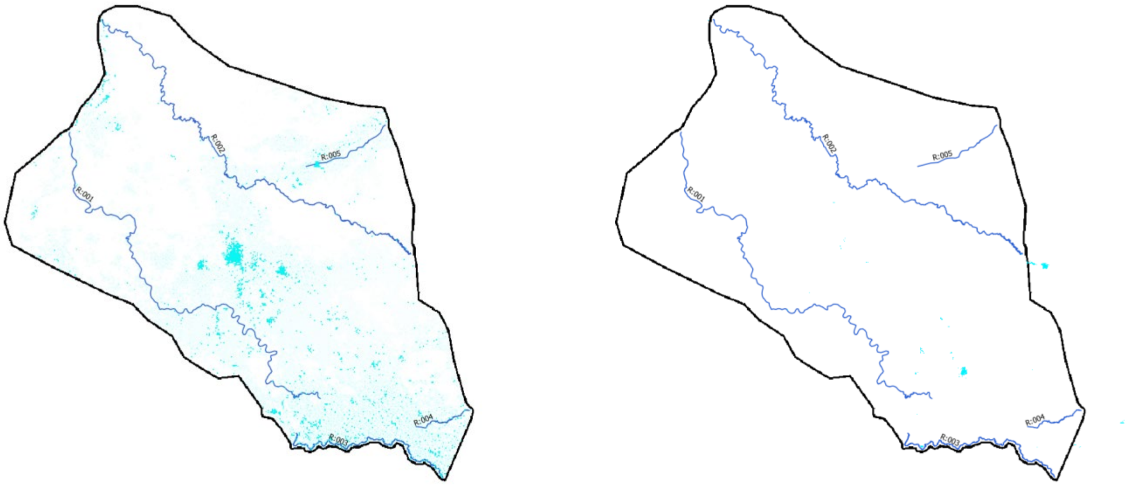


Figure 29: April 2010 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

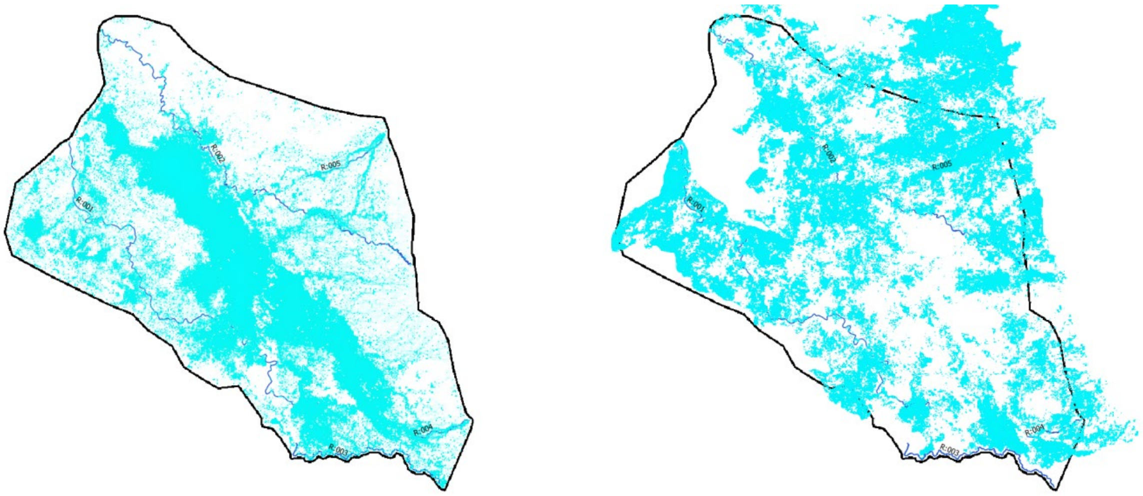


Figure 30: September 2010 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

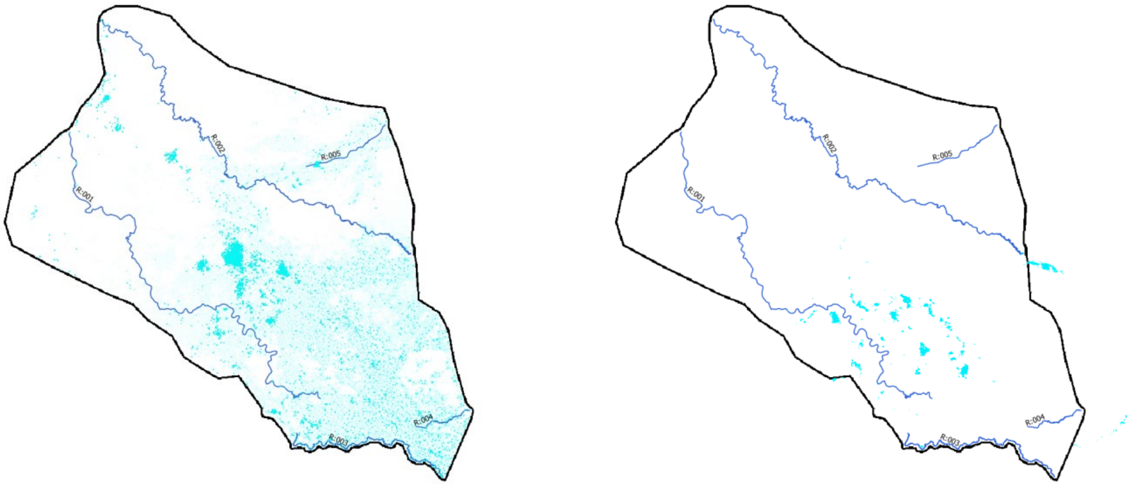


Figure 31: April 2011 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

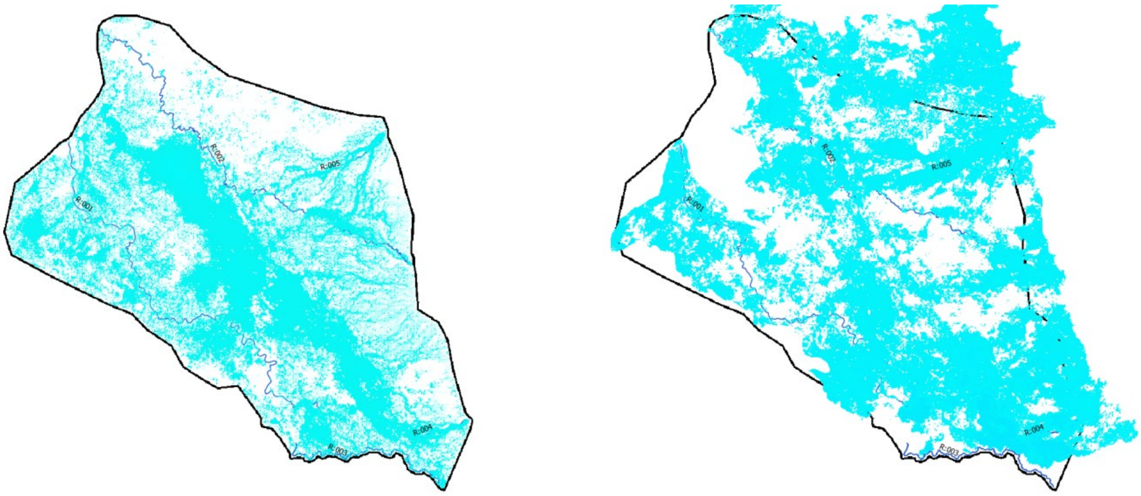


Figure 32: September 2011 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

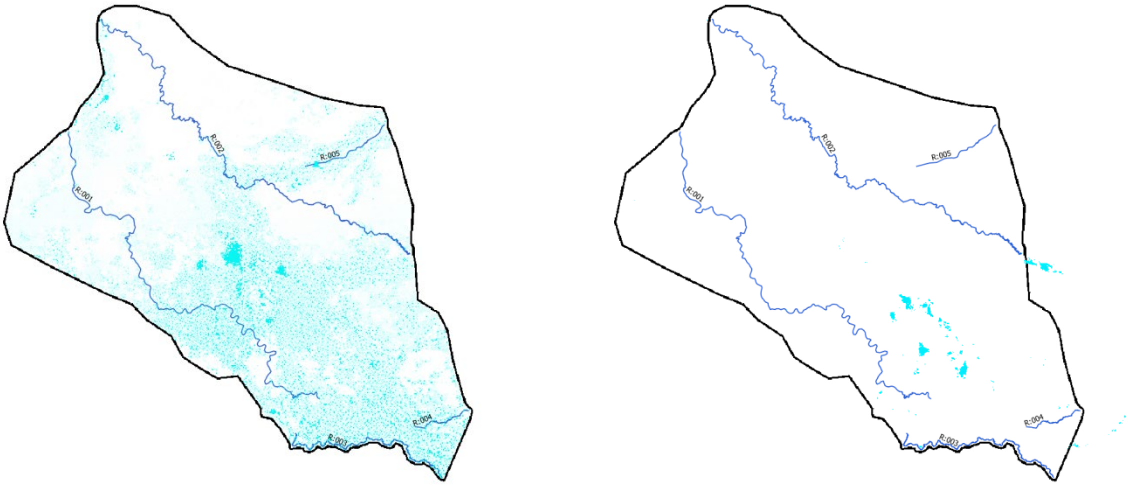


Figure 33: April 2012 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

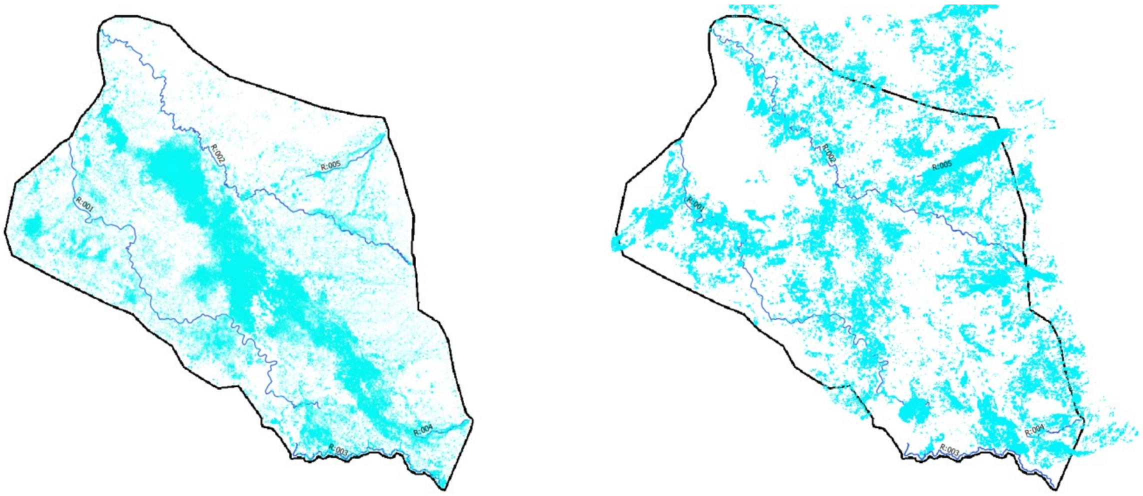


Figure 34: September 2012 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

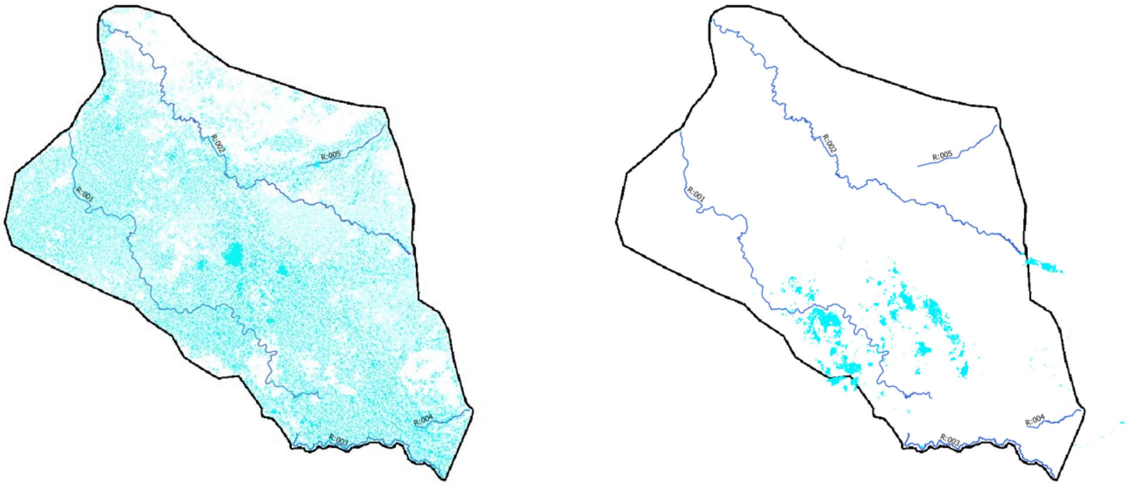


Figure 35: April 2013 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

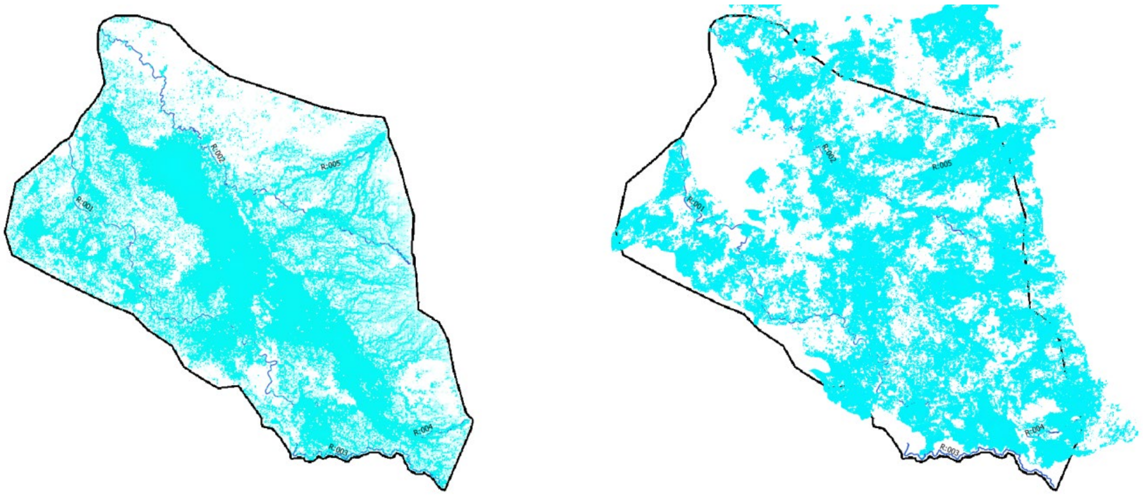


Figure 36: September 2013 simulated (left) and remote sensing (right) results for the inundation in the Machar Marshes

The results for all the simulated months are available. It should be noted that the simulated results in all the cases show a greater extent than the remote sensing results, but this is believed to be because the simulated results are the monthly maximum values while the remote sensing results depend on the time of the data acquisition. It should be added that there are two major areas where the results are not entirely similar. The first area would be in the centre of the Marshes, where there is in most cases a significant amount of flooding predicted by the model, while the remote sensing results do not always show this. This is supposed to be related to the topographic information, because in this area a depression in the DEM is observed. The second location is located to the north-east of the modelling domain, and this corresponds to the flow coming from higher elevations to the Machar Marshes. In this case, the remote sensing results in most cases show a wider representation of the flood extent, and this is believed to be caused because the flow from that area was not accurately represented in the MIKE HYDRO BASIN model.

In order to undertake the calibration for the MIKE SHE grid overland flow results, the following was attempted:

- The soil infiltration modelling processes were revised, including a change from the Richards Equation to the 2 Layers Equation. The saturated hydraulic conductivity was reviewed and adjusted based on calibration results.
- The influence of the different spills from the Baro was properly assessed.
- The roughness coefficient in the Machar Marshes was revised.

6.5.2 Optioneering

As noted above, simulations have been undertaken for options 1, 2, 3a, 3b, 4a and 4b. The model parametrisation for these options is the same as the one for the baseline scenario, the only difference among these models being the inflow used within MIKE 11. These flows have been obtained from the MIKE HYDRO BASIN model for each of the options. Because the simulation period for the implemented MIKE HYDRO BASIN model did not initially cover the period of interest, the simulation period was extended. Otherwise, the models provided are exactly the same as the ones used to produce this inflow information for comparison purposes. The discharge from these models was extracted at the same locations and input into the MIKE 11-MIKE SHE models for each of the options.

A simple water balance calculation was undertaken for the different scenarios. The results below shows the total values for the 5 years simulation, and it describes the total inflows from all the different watercourses: The lateral inflows in the MIKE SHE grid due to the overland run-off, infiltration and evapotranspiration, the overland flow leaving the Machar Marshes, and the flow from the three main rivers leaving the domain (namely the Baro-Sobat, the Daga-Adar and the R:001 (Table 9).

Table 9: Water balance for the different options (m^3)

	Option0	Option1	Option2	Option3a	Option3b	Option4a	Option4b
A: Initial volume in model area	**80053946.46**	**80053946.46**	**80053946.46**	**80053946.46**	**80053946.46**	**80053946.46**	**80053946.46**
B: Final volume in model area	**54451350.46**	**28483436.26**	**44825612.28**	**70438847.14**	**70414238.97**	**35639200.46**	**37880678.61**
MIKE SHE overland inflow	52907845206	1.99237E+11	3.42116E+11	1.76609E+12	1.85114E+12	2.82818E+11	1.24541E+12
Lateral sources inflow	13165902358	12169646386	12169646386	12011166034	7913034227	8495360527	8495360527
Rivers inflow							
Baro (m3)	*65828085264*	*53080448256*	*42404363050*	*47562799190*	*47276143776*	*46958593190*	*40039246512*
Jakau (m3)	*2857971341*	*2858408179*	*2858508230*	*2858313658*	*2858222592*	*2858546419*	*2858432026*
Yabus (m3)	*3455357702*	*3456297734*	*3459402259*	*3456309398*	*3456021514*	*3455635046*	*3455699242*
Daga (m^3)	*1421715715*	*1421742067*	*1421971546*	*1421731267*	*1421730922*	*1421726774*	*1421732218*
Total river inflow	73563130022	60816896237	50144245085	55299153514	55012118803	54694501430	47775109997
C: Total inflow	**1.39637E+11**	**2.72224E+11**	**4.04429E+11**	**1.8334E+12**	**1.91407E+12**	**3.46008E+11**	**1.30168E+12**
MIKE SHE overland outflow	77628399553	2.21496E+11	3.59768E+11	1.8155E+12	1.89917E+12	2.98133E+11	1.28021E+12
Rivers outflow							
R:001 (m3)	*4578774221*	*4523022202*	*4451489741*	*4414169174*	*4246355318*	*4370471510*	*4352386435*
Daga-Adar (m3)	*1367435693*	*1371866371*	*1371742906*	*1857461674*	*1857613046*	*1372921229*	*1591655443*
Sobat (m3)	*52321626432*	*43958923776*	*41818851504*	*49127185238*	*47913421536*	*44007350371*	*39516865891*
Total rivers outflow	58267836346	49853812349	47642084150	55398816086	54017389901	49750743110	45460907770
D: Total outflow	**1.35896E+11**	**2.7135E+11**	**4.0741E+11**	**1.8709E+12**	**1.95319E+12**	**3.47884E+11**	**1.32567E+12**
E: Continuity balance = B-A-C+D =	**-3766244283**	**-925458474**	**2945786984**	**37487246594**	**39114846702**	**1831476092**	**23940616133**
Relative deficit E/max (A, B, C, D) =	**0**	**0**	**0**	**0**	**0**	**0**	**0**

6.6 Plan for DSS integration

Integration procedure (guidelines to proof-of-concept spreadsheet)

6.6.1 General

One of the objectives of this assignment is to integrate the resulting modelling framework into the existing DSS of the NBI as well as integrate an ecological rule set into the DSS in order to assess flows and responses to flows. This has been set out as a proof-of-concept to show how it would be done. The proof-of-concept is to be read with the accompanying spreadsheet which relates to the following text. The integration procedure consists of 6 steps (Table 10).

Table 10: Integration procedure steps

Step 1:	**Integrate the MIKE 11 - Mike SHE model into the NileDSS**
Step 2:	**Obtain direct output from DSS - daily / monthly timeseries for baseline and scenario flows**
Step 3:	**Conduct seasonality check**
Step 4:	**Use timeseries flow data to generate depth duration data**
Step 5:	**Integrate duration data with ecological matrix of rules to produce a vegetation response**
Step 6:	**Calculation of wetland integrity & optional land use scenario facility**

Step 1: Integrate the MIKE 11 - MIKE SHE model into the Nile DSS

One of the objectives of this assignment is to integrate the resulting modelling framework into the existing DSS of the NBI. The following shall be considered while undertaking this integration:

- The implemented MIKE SHE modelling framework is the result of a couple MIKE 11 model with a MIKE SHE modelling domain. The MIKE SHE domain resolves the following hydrological processes:
    - Run-off from rainfall in the whole modelling domain
    - Spill overland flow coming from the Baro and from any other watercourse in the domain
    - Infiltration and saturation processes
    - Flow coming in and coming out of the Machar Marshes.
- The implemented MIKE SHE modelling framework shall be integrated with the existing White Nile Equatorial Mike HYDRO DSS model. A schematic representation of this model can be observed in the figure below (Figure 37).

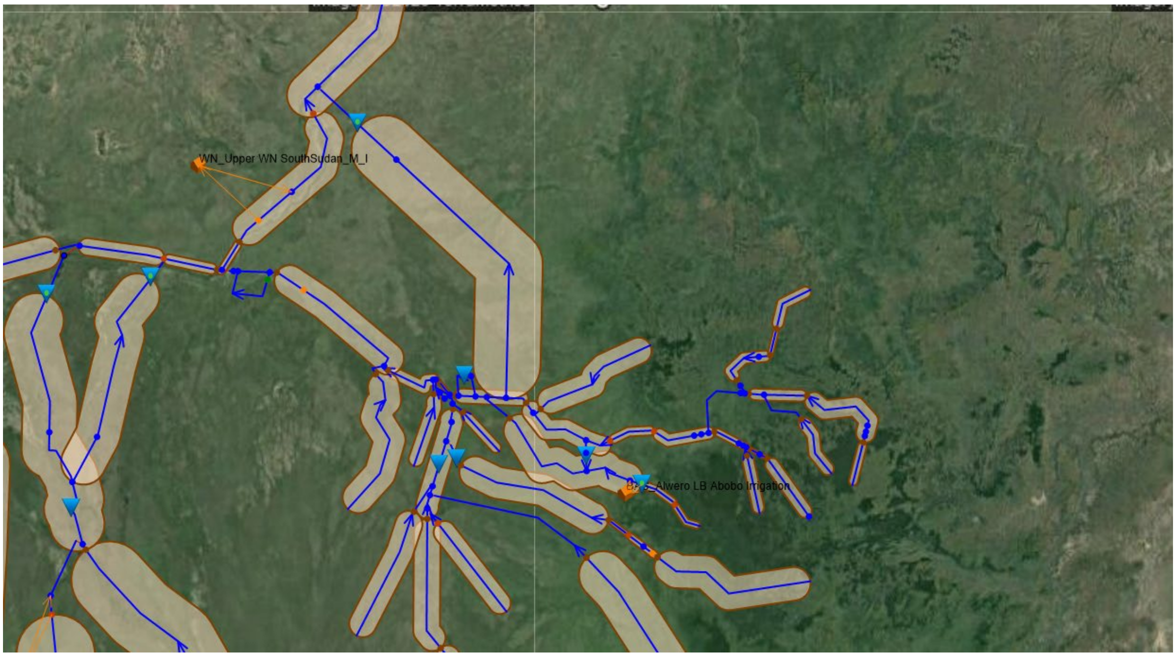


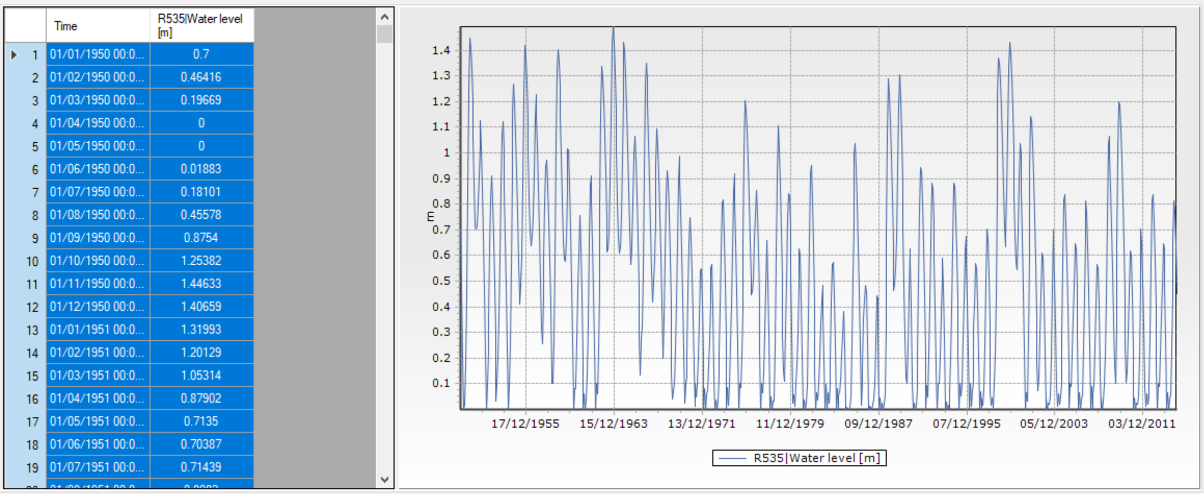
Figure 37: White Nile Equatorial MIKE HYDRO Model

- Due to the data used, modelling effort and considering the calibration results, the hydrological processes occurring in the Machar Marshes are supposed to be better depicted within the MIKE SHE modelling framework.
- There are several sub-catchments defined in the MIKE HYDRO model that correspond to the modelling domain. The MIKE HYDRO Model is a rainfall-runoff and a basin model, while the MIKE SHE model is a full rainfall-runoff and run-off overland model coupled with a 1D hydrodynamic model, considering all the relevant hydrological processes.
- Thus, during the integration of the MIKE SHE in the White Nile Equatorial MIKE HYDRO DSS model, the information yielded by the MIKE SHE model should be used to replace the information provided by the MIKE HYDRO model in those relevant sub-catchments and links. This is especially important with the spills from the Baro and with the rainfall-runoff processes.
- It should be considered that processes should be implemented in order to allow for the outflows from the Baro River (R:003, as a result of the MIKE SHE simulation) to be included in the MIKE HYDRO model.
- Also, the discharge information resulting from R:001 (the branch coming out of the Machar Marshes) should be used to replace the information of the correspondent sub-catchment in the MIKE HYDRO model. Actually, in the MIKE HYDRO model, there is just one sub-catchment representing both the outflow from the Baro and the associated Machar Marshes outflow.
- All the sub-catchment associations will be thoroughly explored and rules would be implemented in order to integrate the MIKE SHE results into the MIKE HYDRO DSS model.

Step 2: Obtain direct output from the DSS

Obtain direct output from the DSS – either daily or monthly time series of maximum depth (m), for present day (PD-baseline) and all scenarios (examples show monthly data).

Running the DSS on monthly (or daily interpolated) time step and extract the “water level” data from the respective wetland – this shows the maximum water level in the wetland over time (see Figure 38 for example). Note, a minimum of 1 year of data is required, a minimum of 5 years is recommended to capture the longer-term dynamics of vegetation response:



	Time	R535|Water level [m]
1	01/01/1950 00:0...	0.7
2	01/02/1950 00:0...	0.46416
3	01/03/1950 00:0...	0.19669
4	01/04/1950 00:0...	0
5	01/05/1950 00:0...	0
6	01/06/1950 00:0...	0.01883
7	01/07/1950 00:0...	0.18101
8	01/08/1950 00:0...	0.45578
9	01/09/1950 00:0...	0.8754
10	01/10/1950 00:0...	1.25382
11	01/11/1950 00:0...	1.44633
12	01/12/1950 00:0...	1.40659
13	01/01/1951 00:0...	1.31993
14	01/02/1951 00:0...	1.20129
15	01/03/1951 00:0...	1.05314
16	01/04/1951 00:0...	0.87902
17	01/05/1951 00:0...	0.7135
18	01/06/1951 00:0...	0.70387
19	01/07/1951 00:0...	0.71439

Figure 38: Example of DSS interface to access the wetland water level data

Note: Scenario “drier” and “wetter” in the excel table are two hypothetical scenarios (employed for the proof-of-concept) which can serve as an example for climate change scenarios.

Step 2 serves as input data for step 3 and step 4.

Step 3: Conduct seasonality check

Before an assessment of scenarios can proceed, baseline data are used to conduct a seasonality check to make sure flooding occurs in the wet season and not the dry season, as this is not discernable from the depth duration data alone. A change in seasonality focusses on floods or high base flows in the natural dry season i.e. flooding or inundation at the wrong time of the year which does not elicit the normal biological response. If this occurs, the biota should respond detrimentally as applicable to the severity of the perturbation.

Indicators such as aquatic vegetation (AQ), fringe vegetation (FR) and papyrus (PA) which are already adapted to permanent flooding will not likely be significantly affected by flooding in a different season. Reeds (RE) are adapted to permanent shallow flooding but prefer seasonal fluctuation, hence flooding during the dry season is likely to favour reeds where they interface with floodplain grassland (GR) i.e. the drier edge, while they will likely persist where they interface with papyrus (PA) i.e. endure wetter periodicity in the dry season.

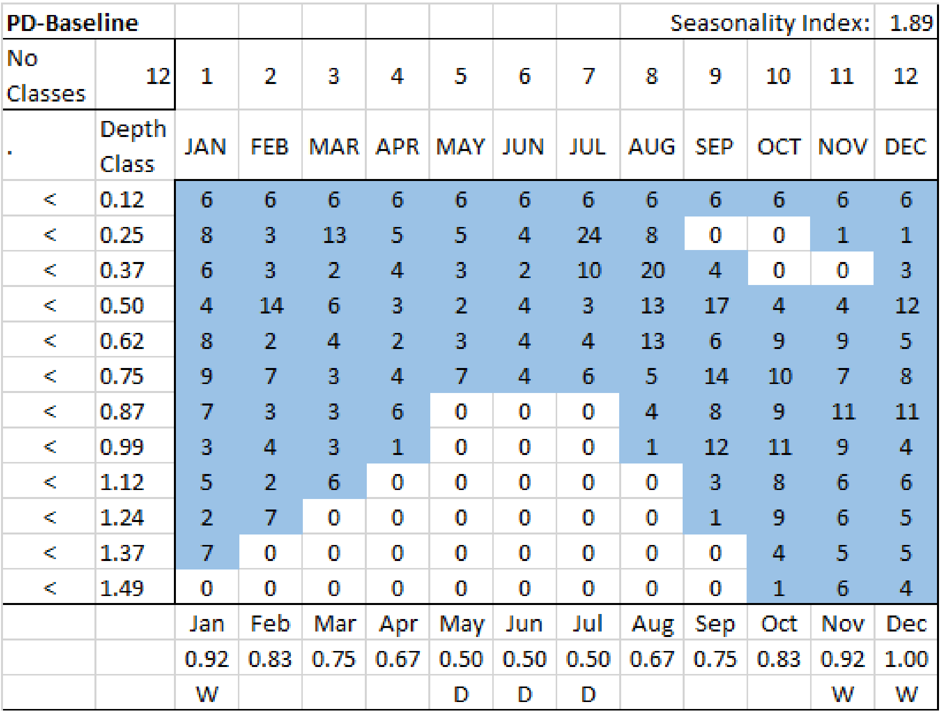
Flooding during the dry season will therefore favour reed expansion at the expense of floodplain grassland which is distinctly seasonal and can also become dormant during the dry season. The degree of change should be proportional to the severity of loss of seasonality. In order to empirically measure the degree of seasonality a “seasonality index” was calculated (method outlined below) in order to compare the seasonality of scenarios to that of the baseline data.

6.6.2 Calculation of the wet & dry season and the seasonality index

The baseline timeseries data (monthly or daily) are used to calculate which months are typically wet season months, which are typically dry season months, and the seasonality index (refer to Figure 39). The timeseries is divided into 12 depth classes, each an equal 12th of the maximum depth of the full dataset. Each depth class is then counted for occurrence (or absence) for each month of the year. The deepest class should only occur in the wettest months.

An average count of occurrence (a proportion of 12) is then expressed for each month, for example in Figure 39 the count for December is 1 since all depth classes occur while the count for July is 0.5 since only half the depth classes occur. These depth count proportions are used to assign months to wet and dry season: If the depth count proportion is >= the 75th percentile of all the months then it becomes a wet season month, similarly if the depth count proportion is <= the 25th percentile of all the months, the month becomes a dry season month. Hence in Figure 39, November, December and January are assigned as typical wet season months while May, June and July are typical dry season months.

It is important to note that these seasonality months are derived from the baseline (PD) data and once set are enforced upon the scenario data i.e. wet and dry season months remain such irrespective of the time series data of scenarios. The seasonality index is simply the ratio of the depth count proportions of wet season months and the dry season months. For example, the seasonality index in Figure 39 is 1.89 (depth count proportions of Nov, Dec, Jan divided by depth count proportions of May, Jun, Jul) i.e. wet season months are essentially 1.9 times wetter than dry season months by this measure, which can now be compared to scenario seasonality indexes. The seasonality index for each scenario is calculated in the same way i.e. 12 depth classes as defined by the scenario time series maximum, however the wet and dry season months are already set by the baseline data.



PD-Baseline												Seasonality Index:	1.89
No Classes	12	1	2	3	4	5	6	7	8	9	10	11	12
.	Depth Class	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
<	0.12	6	6	6	6	6	6	6	6	6	6	6	6
<	0.25	8	3	13	5	5	4	24	8	0	0	1	1
<	0.37	6	3	2	4	3	2	10	20	4	0	0	3
<	0.50	4	14	6	3	2	4	3	13	17	4	4	12
<	0.62	8	2	4	2	3	4	4	13	6	9	9	5
<	0.75	9	7	3	4	7	4	6	5	14	10	7	8
<	0.87	7	3	3	6	0	0	0	4	8	9	11	11
<	0.99	3	4	3	1	0	0	0	1	12	11	9	4
<	1.12	5	2	6	0	0	0	0	0	3	8	6	6
<	1.24	2	7	0	0	0	0	0	0	1	9	6	5
<	1.37	7	0	0	0	0	0	0	0	0	4	5	5
<	1.49	0	0	0	0	0	0	0	0	0	1	6	4
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
		0.92	0.83	0.75	0.67	0.50	0.50	0.50	0.67	0.75	0.83	0.92	1.00
		W				D	D	D				W	W

Figure 39. Screenshot from seasonality check of baseline data for the Machar Marshes

6.6.3 Response as a result of the seasonality index

If the seasonality Index of a scenario is equal to the baseline then the rule matrix (see Step 5) determines 100% of the vegetation response. If the scenario seasonality Index is between the baseline and 1.35 then the depth duration rule matrix should produce a realistic response and determines 100% of the vegetation response. If the scenario seasonality index <=1.35 then expansion of reeds at the expense of floodplain grasslands is expected, by x% of scenario output value for floodplain grassland. The value can be altered by the user, but the default is set to 25% i.e. 25% of existing floodplain grasslands will become colonised by reeds. Similarly, if the scenario seasonality index <=1.00 then reeds expand at the expense of floodplain grasslands by x% of scenario output value for floodplain grassland. The value can be altered by the user, but the default is set to 50% i.e. 50% of existing floodplain grasslands will become colonised by reeds. Response changes resulting from seasonality alteration are to be superimposed on the response output to depth / duration matrix i.e. are overriding to other expected responses.

	Scenario: Drier									Seasonality Index:	1.29
	1	2	3	4	5	6	7	8	9	10	11	12
Depth Class	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.06	0	0	0	0	0	0	0	0	0	0	0	0
0.11	1	0	4	5	16	5	5	4	24	8	0	0
0.17	0	1	4	4	5	4	3	2	10	20	4	0
0.23	4	3	10	3	20	3	2	4	3	13	17	4
0.28	9	3	3	7	6	2	3	4	4	13	6	9
0.34	7	1	9	7	10	4	7	4	6	5	14	10
0.40	11	2	10	6	6	6	0	0	0	4	8	9
0.45	9	0	5	2	7	1	0	0	0	1	12	11
0.51	6	2	5	4	8	0	0	0	0	0	3	8
0.57	6	1	4	2	7	0	0	0	0	0	1	9
0.62	5	1	7	4	0	0	0	0	0	0	0	4
0.68	6	2	2	0	0	0	0	0	0	0	0	1
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	0.83	0.75	0.92	0.83	0.75	0.58	0.42	0.42	0.42	0.58	0.67	0.75
	W				D	D	D				W	W

Figure 40. Snapshot example of a drier scenario with a seasonality index of 1.29

	Scenario: Drier									Seasonality Index:	0.77
	1	2	3	4	5	6	7	8	9	10	11	12
Depth Class	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.06	0	0	0	0	0	0	0	0	0	0	0	0
0.11	0	0	1	1	8	1	15	5	5	4	24	8
0.17	4	0	0	3	6	1	4	4	3	2	10	20
0.23	17	4	4	12	4	2	18	3	2	4	3	13
0.28	6	9	9	5	8	0	6	2	3	4	4	13
0.34	14	10	7	8	9	1	9	4	7	4	6	5
0.40	8	9	11	11	7	1	5	6	0	0	0	4
0.45	12	11	9	4	3	1	6	1	0	0	0	1
0.51	3	8	6	6	5	0	8	0	0	0	0	0
0.57	1	9	6	5	2	3	4	0	0	0	0	0
0.62	0	4	5	5	7	0	0	0	0	0	0	0
0.68	0	1	6	4	0	0	0	0	0	0	0	0
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	0.67	0.75	0.83	0.92	0.83	0.58	0.75	0.58	0.42	0.42	0.42	0.58
	W				D	D	D				W	W

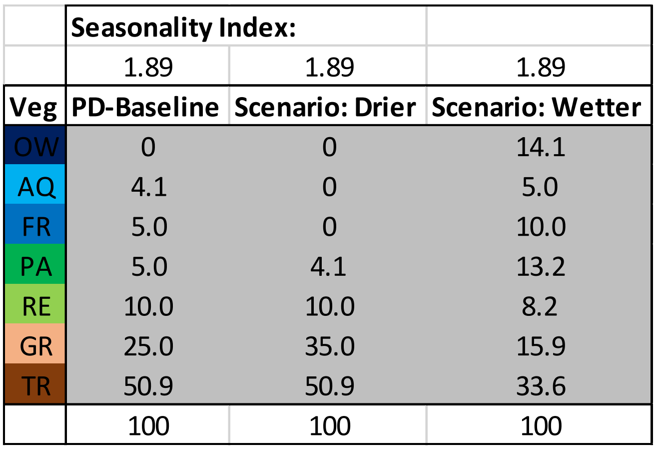
Figure 41. Snapshot example of a drier scenario with a seasonality index of 0.77

Step 4: Generation of depth duration data from daily/monthly depth time series

Create a depth-duration curve by sorting the depths from "Step 2" from minimum to maximum, and then calculate for each depth value, the percentage of times that water depth is below the current value. Carry out this calculation for each scenario.

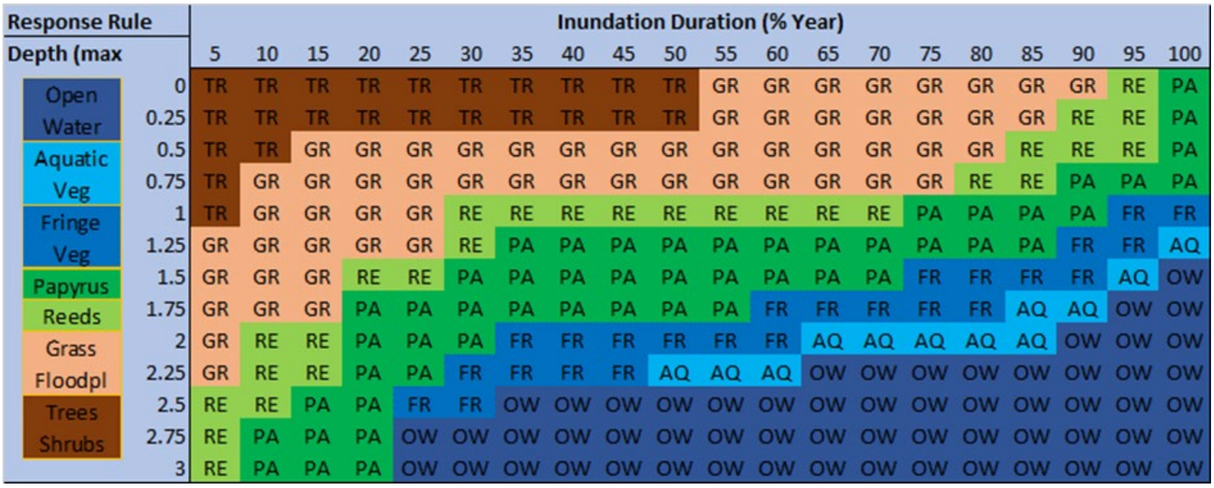
Step 5: Vegetation response from ecological matrix of rules

The niche preferences of vegetation types are represented here by a matrix of occurrence rules according to combinations of water depth and duration (Figure 42). These ecological rules (the response rule matrix) integrate with depth duration data to produce a proportional response automatically (Figure 6).



	Seasonality Index:		
	1.89	1.89	1.89
Veg	PD-Baseline	Scenario: Drier	Scenario: Wetter
OW	0	0	14.1
AQ	4.1	0	5.0
FR	5.0	0	10.0
PA	5.0	4.1	13.2
RE	10.0	10.0	8.2
GR	25.0	35.0	15.9
TR	50.9	50.9	33.6
	100	100	100

Essentially the calculation assigns the applicable vegetation unit to each datum point using the depth-duration data and the response rule matrix, and then calculates a proportion using all points in the dataset. If new scenario data have been entered at step 1, make sure calculations in columns AM to AP point to the correct data extent. The outputs from the interaction of the ecological rules and the hydrology are shown as proportions of vegetation types within the wetland, for example to the left with no seasonality changes but with 2 scenarios, 1 drier and 1 wetter.



Response Rule		Inundation Duration (% Year)																			
Depth (max		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Open Water	0	TR	TR	TR	TR	TR	TR	TR	TR	TR	TR	GR	GR	GR	GR	GR	GR	GR	GR	RE	PA
	0.25	TR	TR	TR	TR	TR	TR	TR	TR	TR	TR	GR	GR	GR	GR	GR	GR	GR	RE	RE	PA
Aquatic Veg	0.5	TR	TR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	RE	RE	RE	PA
	0.75	TR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	RE	RE	PA	PA	PA
Fringe Veg	1	TR	GR	GR	GR	GR	RE	RE	RE	RE	RE	RE	RE	RE	RE	PA	PA	PA	PA	FR	FR
	1.25	GR	GR	GR	GR	GR	RE	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	FR	FR	AQ
Papyrus	1.5	GR	GR	GR	RE	RE	PA	PA	PA	PA	PA	PA	PA	PA	PA	FR	FR	FR	FR	AQ	OW
Reeds	1.75	GR	GR	GR	PA	PA	PA	PA	PA	PA	PA	PA	FR	FR	FR	FR	FR	AQ	AQ	OW	OW
Grass	2	GR	RE	RE	PA	PA	PA	FR	FR	FR	FR	FR	FR	AQ	AQ	AQ	AQ	AQ	OW	OW	OW
Floodpl	2.25	GR	RE	RE	PA	PA	FR	FR	FR	FR	AQ	AQ	AQ	OW	OW	OW	OW	OW	OW	OW	OW
Trees	2.5	RE	RE	PA	PA	FR	FR	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW
Shrubs	2.75	RE	PA	PA	PA	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW
	3	RE	PA	PA	PA	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW

Figure 42. Screenshot of the ecological rule matrix for the Machar Marshes

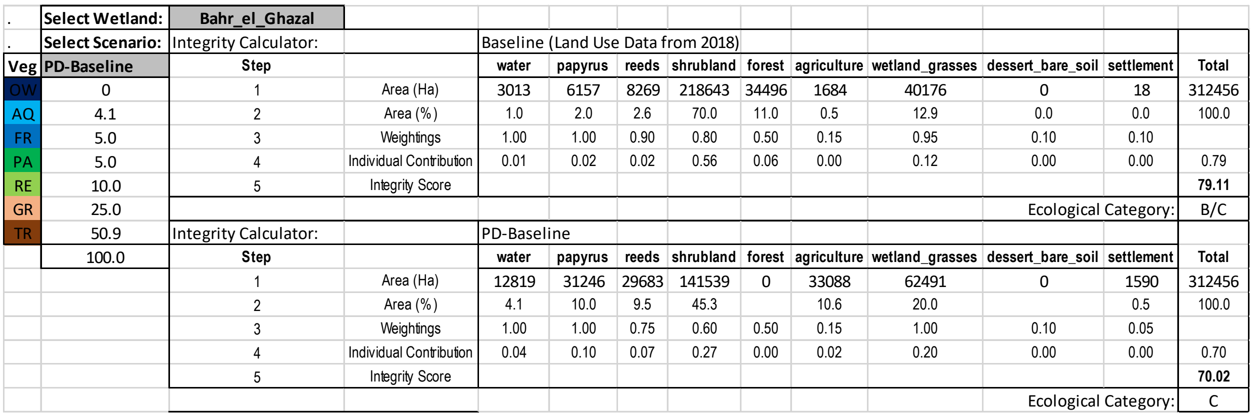
Depending on the result of the seasonality check, any changes resulting from seasonality alteration are superimposed on the response output to depth/duration matrix i.e. are overriding. The user has the ability to change the severity of the seasonality override, if it triggers, but defaults should suffice. Essentially this allows the user to change the proportion by which reeds will encroach floodplain grasslands, given a specific seasonality index change.

Step 6: Calculation of wetland integrity & land use scenario facility

The example below has been done for the Bahr El Ghazal and is shown here as the same that is being prepared for the Machar Marshes, with data at a finer scale:

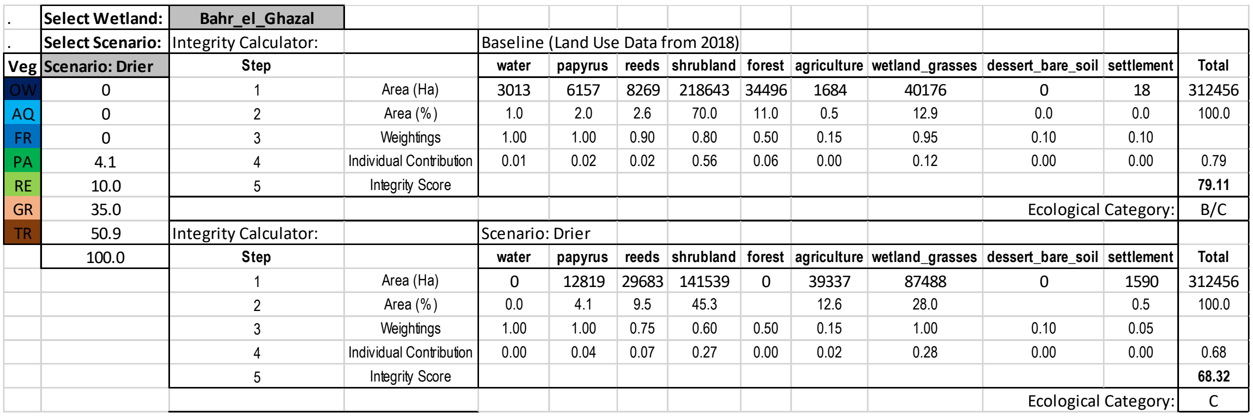
The outputs of the vegetation response are related to the land use categories and used to calculate a resultant internal wetland integrity score of the scenario being evaluated. The evaluation is for one scenario only so the scenario to evaluate must be selected from a dropdown list. Calculation of the integrity score and ecological category is automatic thereafter.

The integrity score is that calculated for the baseline using 2018 land use data from WP4 of the Nile Transboundary Wetlands Project (shown for comparison only). The integrity score is that calculated for the scenario being evaluated within the rule matrix, one of which will also be the baseline. The ecological category is calculated automatically and represents the overall wetland health (see Figures 43 and 44 for example outputs).



.	**Select Wetland:**	**Bahr_el_Ghazal**											
.	**Select Scenario:**	Integrity Calculator:		Baseline (Land Use Data from 2018)									
Veg	**PD-Baseline**	**Step**		**water**	**papyrus**	**reeds**	**shrubland**	**forest**	**agriculture**	**wetland_grasses**	**dessert_bare_soil**	**settlement**	**Total**
OW	0	1	Area (Ha)	3013	6157	8269	218643	34496	1684	40176	0	18	312456
AQ	4.1	2	Area (%)	1.0	2.0	2.6	70.0	11.0	0.5	12.9	0.0	0.0	100.0
FR	5.0	3	Weightings	1.00	1.00	0.90	0.80	0.50	0.15	0.95	0.10	0.10	
PA	5.0	4	Individual Contribution	0.01	0.02	0.02	0.56	0.06	0.00	0.12	0.00	0.00	0.79
RE	10.0	5	Integrity Score										**79.11**
GR	25.0										Ecological Category:		B/C
TR	50.9	Integrity Calculator:		PD-Baseline									
	100.0	**Step**		**water**	**papyrus**	**reeds**	**shrubland**	**forest**	**agriculture**	**wetland_grasses**	**dessert_bare_soil**	**settlement**	**Total**
		1	Area (Ha)	12819	31246	29683	141539	0	33088	62491	0	1590	312456
		2	Area (%)	4.1	10.0	9.5	45.3		10.6	20.0		0.5	100.0
		3	Weightings	1.00	1.00	0.75	0.60	0.50	0.15	1.00	0.10	0.05	
		4	Individual Contribution	0.04	0.10	0.07	0.27	0.00	0.02	0.20	0.00	0.00	0.70
		5	Integrity Score										**70.02**
											Ecological Category:		C

Figure 43. Wetland integrity score and ecological category for baseline scenario data



.	**Select Wetland:**	**Bahr_el_Ghazal**											
.	**Select Scenario:**	Integrity Calculator:		Baseline (Land Use Data from 2018)									
Veg	**Scenario: Drier**	**Step**		**water**	**papyrus**	**reeds**	**shrubland**	**forest**	**agriculture**	**wetland_grasses**	**dessert_bare_soil**	**settlement**	**Total**
OW	0	1	Area (Ha)	3013	6157	8269	218643	34496	1684	40176	0	18	312456
AQ	0	2	Area (%)	1.0	2.0	2.6	70.0	11.0	0.5	12.9	0.0	0.0	100.0
FR	0	3	Weightings	1.00	1.00	0.90	0.80	0.50	0.15	0.95	0.10	0.10	
PA	4.1	4	Individual Contribution	0.01	0.02	0.02	0.56	0.06	0.00	0.12	0.00	0.00	0.79
RE	10.0	5	Integrity Score										**79.11**
GR	35.0										Ecological Category:		B/C
TR	50.9	Integrity Calculator:		Scenario: Drier									
	100.0	**Step**		**water**	**papyrus**	**reeds**	**shrubland**	**forest**	**agriculture**	**wetland_grasses**	**dessert_bare_soil**	**settlement**	**Total**
		1	Area (Ha)	0	12819	29683	141539	0	39337	87488	0	1590	312456
		2	Area (%)	0.0	4.1	9.5	45.3		12.6	28.0		0.5	100.0
		3	Weightings	1.00	1.00	0.75	0.60	0.50	0.15	1.00	0.10	0.05	
		4	Individual Contribution	0.00	0.04	0.07	0.27	0.00	0.02	0.28	0.00	0.00	0.68
		5	Integrity Score										**68.32**
											Ecological Category:		C

Figure 44. Example of how the outputs change for a drier scenario

A land use scenario of non-flow related impacts (in this case agriculture) is also applied to the response outputs before calculation of the integrity score. The defaults of the land use scenario tool are changeable by the user to enable manual exploration of different intensities of agriculture on resultant vegetation. The table below shows the default proportions of reeds, shrubland and floodplain grasslands that are assigned to agriculture. The proportions from Table 11 (5, 10 and 20%), may be adjusted by the user to determine the effect of changing agriculture on the wetland integrity and ecological category.

Table 11: Default proportions

Land use scenario	
Prop of reeds to be used for agriculture	5
Prop of shrubland to be used for agriculture	10
Prop of floodplain grassland to be used for agriculture	20

6.7 Initial simulation results

The modelling implantation, as described above, has been used for initial runs. These initial simulations have been undertaken for the 2009-2011 period (2 full years). These initial results have been analysed and the model is being improved and calibrated at this stage in order to enhance the results.

In Figure 45 below water depth results for the MIKE SHE grid can be observed. These results show the maximum water depth during the first five months, simulated in every grid in the model domain. As it can be observed, the overland flow resulting from the spills coming out from the four different branches coming to the vicinity of the Marshes (the Yagus, the Daga, the Jakau and the Baro rivers) can be observed.

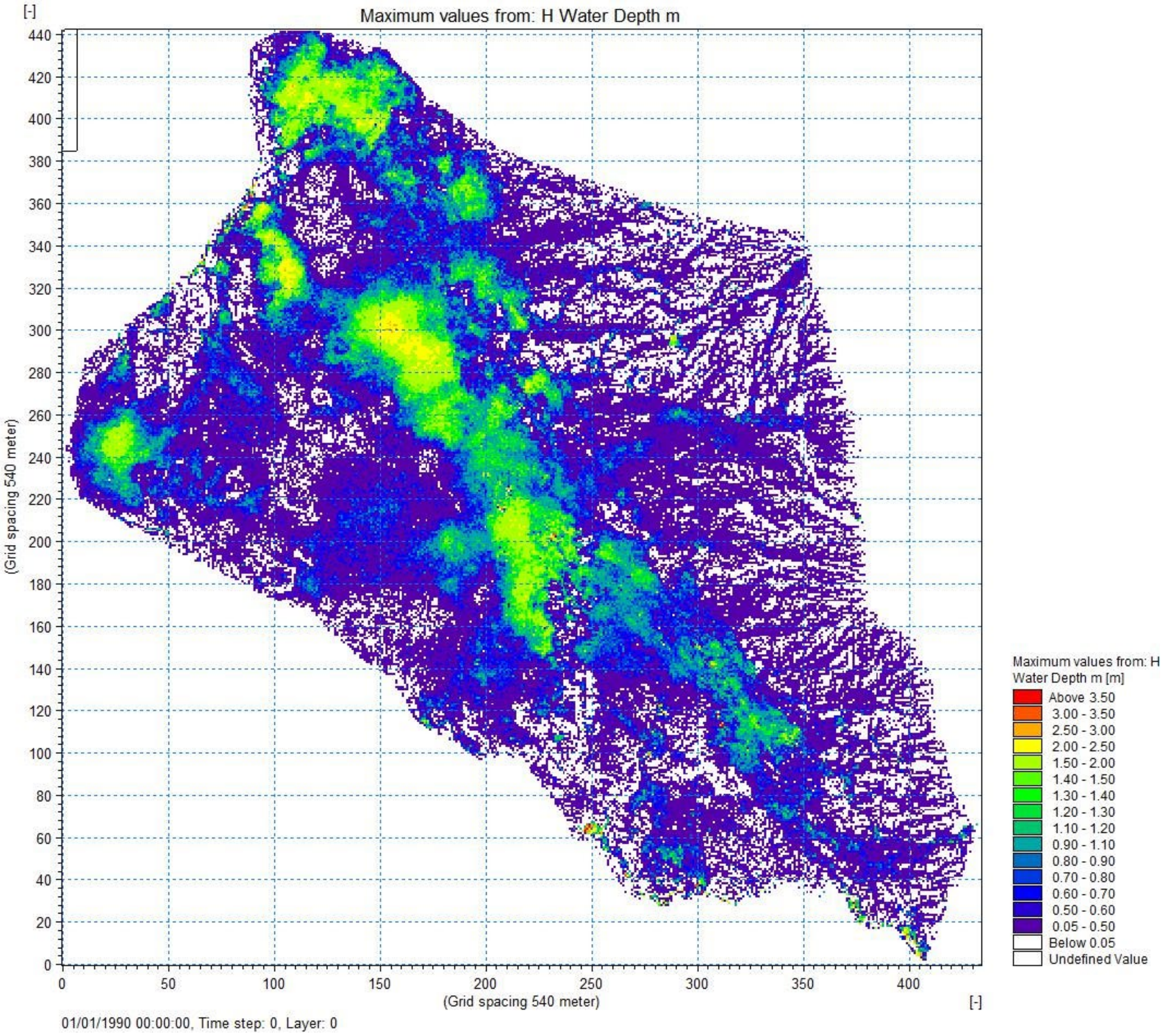


Figure 45: Water depth in the Machar Marshes after five months of simulation

One of the key aspects to investigate during the modelling implementation is the spills from the Baro River to the Marshes. Figure 46 below shows the longitudinal profile of the Baro river and the outflow from the MIKE 11 model to the MIKE SHE model. As it can be observed, at this stage the model is predicting that most of the spill discharge occurs in one single location, with some other spills of lesser severity distributed along a wider area. This will be explored further during the modelling implementation and especially during the calibration of the models.

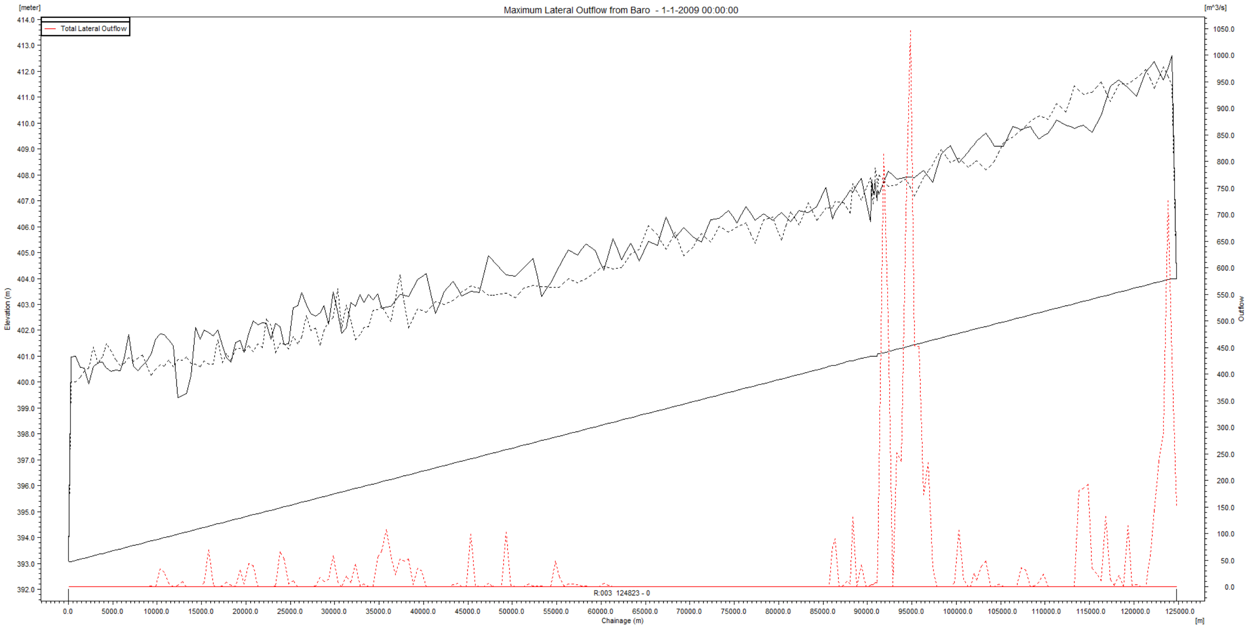


Figure 46: Water spill from the Baro 1D model to the Machar Marshes 2D grid

Also, the discharge values in the branch R:001 are being thoroughly investigated. It should be noted that this branch has no direct inflow set-up in the model (Figure 17 and Figure 9), and any flow in this branch is coming from the overland flow through the marshes. In Figure 47, the longitudinal profile of this branch and the maximum water depth can be observed. During model calibration, a wide range of discharges will be tested.

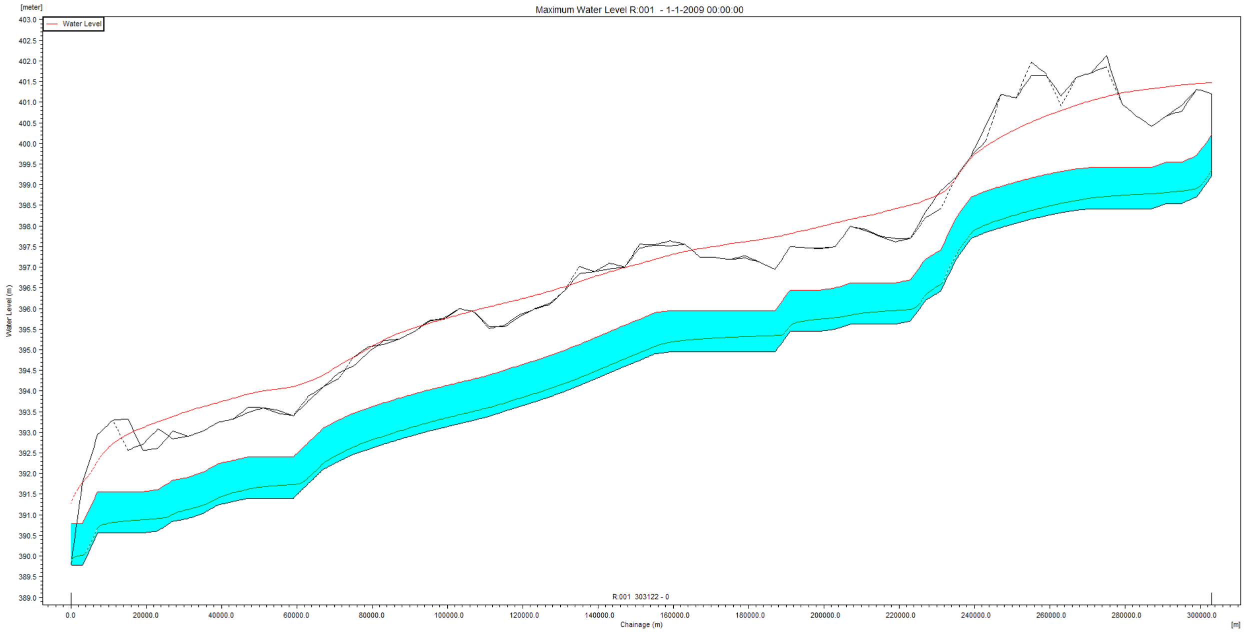


Figure 47: Longitudinal profile of branch R:001

6.8 Way forward and results to be expected

Based on the results above, the following tasks will be undertaken:

- If required, the topographical model grid horizontal resolution will be enhanced (to 180m). This will be undertaken in order to enhance the simulated results in the marshes.
- Once the results show patterns and results that are reasonable, the calibration of the model will be undertaken. The following will be considered for the calibration.
  - Resistance in the channels and the floodplains/marshes
  - The spills from the Baro river

    - All the other hydrological parameters (infiltration, evapotranspiration, outflows to the Nile) will also be considered
- As noted above, the model is being initially run for the 1st January 2009 to 31st December 2010 period (2 full years). The calibration will be undertaken in periods of 5 years, from 2009 to 2014, in order to be able to coincide with the data from the remote sensing exercise
- The calibrated model will be run for all the scenarios depicted above in order to get a greater understanding of the dynamics in the Machar Marshes for these scenarios and to provide the information for the subsequent depiction of the environmental flow requirements and subsequent depiction of wetland vegetation.

7. Ecosystem aspects

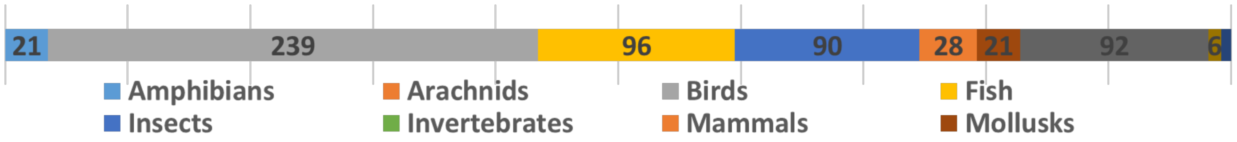
The Machar Marshes are a seasonal wetland, dependent on flows from the Ethiopian highlands and overbank spills from the Baro river. The system is hence directly dependent on these inflows, but also on inputs from precipitation. Should any water from this system be stored or extracted upstream of the inflow/overflow, the area of seasonally flooded marshes may be altered with potentially serious impacts on vegetation, wildlife and ecosystem services (Rebelo & McCartney, 2012; Sutcliffe, 2009).

The Machar Marshes have three mainland covers namely permanent wetlands with deep water bodies; seasonal floodplains inundated by river spills and rainfall and dry fringes, which include seepage wetlands. The permanent swamps are dominated by *Cyprus papyrus*, *Phragmites* and *Typha* and grassland on the floodplains. *Acacia spp* and scattered shrubs occur in the dry areas of the fringes (Mahomed, 2016; Rebelo & McCartney, 2012). Invasive weeds found in the wetlands are *Mimosa pigra* and *Eichhornia crassipes*. *Mimosa pigra* forms impenetrable thickets thus hindering movement and destroying natural biodiversity. *Eichhornia crassipes* increase siltation and evapotranspiration, reduces fish stock and reduces water quality (Bezabih & Mosissa, 2017).

Some of the mammals occurring in the wetlands include *Hippopotamus amphibious* (hippopottamus), *Tagelaphus spekei* (Sitatunga), endemic *Kobus megaceros* (Nile Lechwe), *Kobus kob leucotis* (White-eared Kob), *Damaliscus lunatus* (Tiang) and *Ourebia ourebi* (Oribi). The Baro river has a high ratio of fish species to diversity and contains a mixture of Nilo-Sudanic, East African and endemic species. Some of these fish species include *Lates niloticus* (Nile Perch); *Clarotes laticeps; Bagrus bajad; Citharinus; Barbus; Sarothrodon; Oreochromis niloticus* (Nile Tilapia); *Protopterus aethiopicus* (Lung Fish). Some of the main commercial species are *Labeo hori*, *Clarias gariepinus*, *Barbus spp*. and *Lates niloticus* (Kebede *et al*, 2017). Flagship bird species for the Baro-Akobo wetland system include *Balaeniceps rex* (Shoebill); *Pelecanus onocrotalus* (Great White Pelican); *Anastomus lamelligerus* (African Openbill); *Scotopelia peli* (Pel's fishing owl); *Aythya nyroca* (Ferruginous Pochard).

The Machar Marshes floodplains are used for livestock grazing during the dry season. Hunting and fishing occur within the wetland throughout the year but especially in the wet season. The Baro wetlands provide a source of water, fish, grazing, an area for cultivation, construction material and medicinal plants. The increased population around the wetlands has resulted in increased loss of wetland due to agriculture and the resultant degradation (Rebelo & McCartney, 2012). The headwater wetlands of the Baro Akobo provide important flow regulation in the Baro Akobo River which plays an important role in maintaining the downstream dry-season river flows. The Machar Marshes play an important hydrological function in the White Nile and its tributaries through reducing flood peaks and supporting dry-season river flows thus reducing the seasonal variation in the flow of the White Nile (Rebelo & McCartney, 2012).

According to available information and data, the Machar Marshes support to greater or lesser degrees 598 taxa / species, which represents 19% of all taxa within the Nile river basin (refer to Nile Basin Transboundary Wetlands Project). Of these, 15 are endemic to the area, 31 are flagship species, 11 are umbrella species and 43 are threatened to some degree, with 4 notable alien species (Figure 48). The following line scheme shows the breakdown of all 598 taxa into taxonomic groups. Knowledge gaps are clearly evident from the low numbers of invertebrates, including mollusks and shrimps.



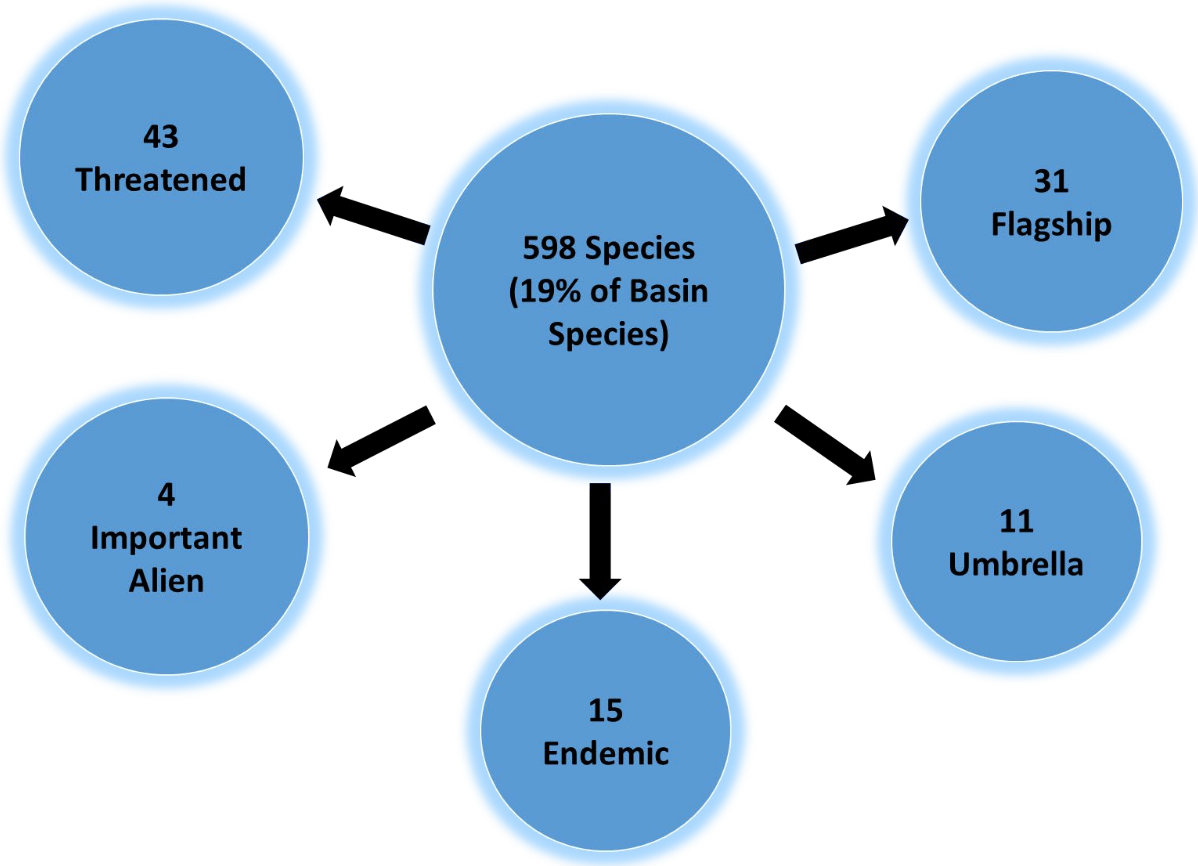


Figure 48: Summary overview of biodiversity aspects of the Machar Marshes

The flagship species are shown in Table 12: Common names of the flagship species of the Machar Marshes while the keystone / umbrella species include buffalo, elephant, cattail (*Typha*), Common reed (*Phragmites*), hippo, Nile perch, tigerfish and wild rice (*Oryza*). Threatened taxa are shown as proportions within taxonomic groups for the wetland according to IUCN spatial data (Figure 49). Large proportions of reptile and mammal populations are threatened to some extent.

Table 12: Common names of the flagship species of the Machar Marshes

African Clawless Otter	Garganey	Northern Pochard
African Elephant	Great Snipe	Northern Shoveler
African Openbill	Great White Pelica	Nubian Flapshell Turtle
African Pygmy Goose	Hippopotamus	Pel's fishing owl
African Skimmer	Hottentol Teal	Pink-backed Pelican
Basra Reed Warbler	Marsh Mongoose	Sahelian Flapshell Turtle
Black Crowned Crane	Nile crocodile	Shoebill
Black-tailed Godwit	Nile Lechwe	Tigerfish
Black-winged Pratincole	Nile Softshell Turtl	Vundu Catfish
Ferruginous Pochard	Northern Pintail	White-eared kob

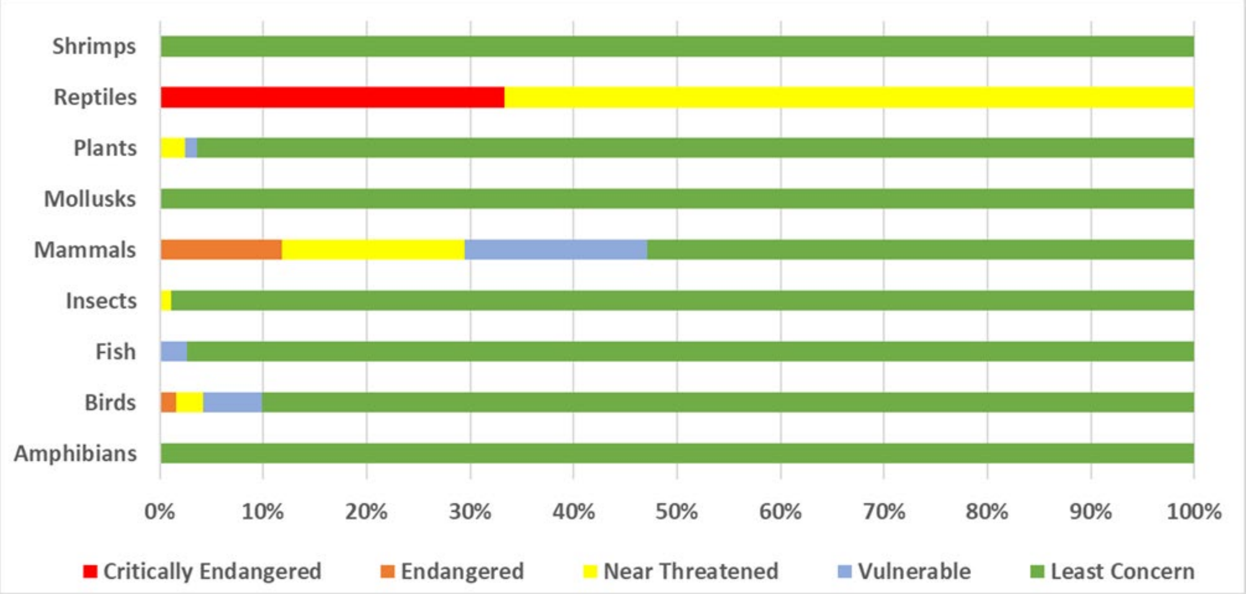
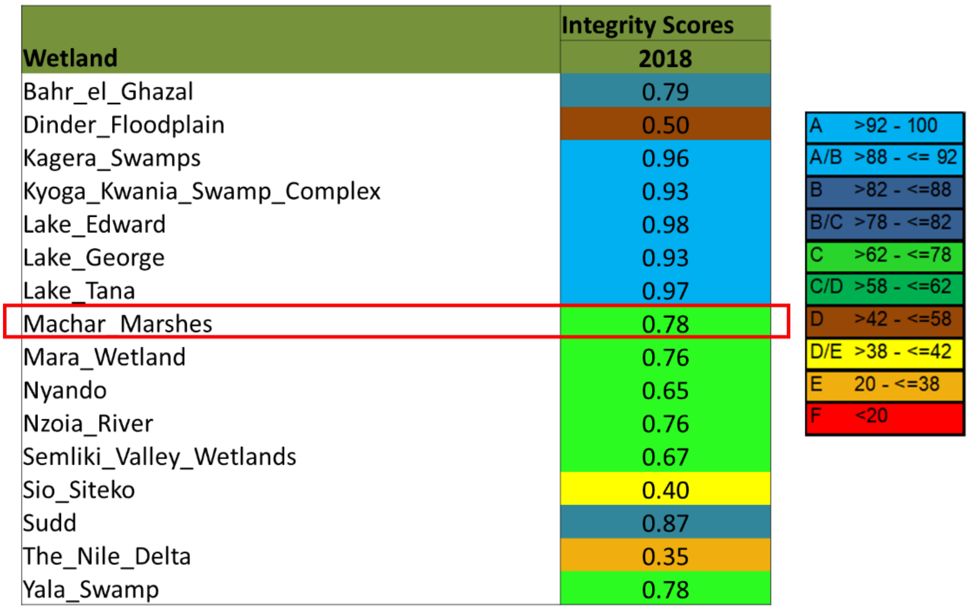


Figure 49: Threat status of taxa within taxanomical groups for the Machar Marshes

Species diversity and habitat diversity are the two major components of biodiversity. Habitat diversity can be assessed in terms of both habitat types (structure and proportion) and the “condition” or integrity of habitats. In our case, these are wetland specific habitats that together comprise the full extent of the wetland. Several tools have been designed to calculate wetland integrity (MacFarlane et al., 2007; SANBI & DWS, 2014a; DWS, 2014b) but the method employed is largely determined by the availability and quality of relevant data. The within-wetland integrity scores calculated for select wetlands in the Nile Basin Transboundary Wetlands study are shown in Figure 50, for 2018 representing the current state. For ease of view, they have been colour-coded according to each assigned ecological category. The Machar Marshes (highlighted) has an integrity score of 0.78 which equates to an ecological category of a C. The ecological relevance of this category is taken to mean that the system is moderately modified. Loss and change of natural habitat and biota have occurred in terms of frequencies of occurrence and abundance. Basic ecosystem functions are still predominantly unchanged. The resilience of the system to recover from human impacts has not been lost and its ability to recover to a moderately modified condition following disturbance has been maintained.



	Integrity Scores
Wetland	**2018**
Bahr_el_Ghazal	0.79
Dinder_Floodplain	0.50
Kagera_Swamps	0.96
Kyoga_Kwania_Swamp_Complex	0.93
Lake_Edward	0.98
Lake_George	0.93
Lake_Tana	0.97
Machar_Marshes	0.78
Mara_Wetland	0.76
Nyando	0.65
Nzoia_River	0.76
Semliki_Valley_Wetlands	0.67
Sio_Siteko	0.40
Sudd	0.87
The_Nile_Delta	0.35
Yala_Swamp	0.78

A	>92 - 100
A/B	>88 - <= 92
B	>82 - <=88
B/C	>78 - <=82
C	>62 - <=78
C/D	>58 - <=62
D	>42 - <=58
D/E	>38 - <=42
E	20 - <=38
F	<20

Figure 50: Wetland integrity scores for select wetlands in the Nile basin in 2018, Machar Marshes highlighted for this study

8. Establishment of the environmental flow requirements

This task aims to relate ecological aspects of the Machar Marshes to flow and in particular flow scenarios, so that water resources management options might be considered. This also needs to explicitly consider human use of the wetland, largely packaged as ecosystem services. This requires the definition of flow dependencies of habitats and indicators in terms of their hydraulic and hydrological niche preferences and linkages of these preferences to changes in flow. These linkages, from autecological preferences to management, biodiversity and services in response to flow scenarios need common currency for interactions. It is suggested here, that in this task, land use be such a common currency because not only do the categories adequately represent flow-sensitive habitats (and therefore also their biota and requirements) but they can also be linked to ecosystem services. Land use data are also aerial, so they are easily collected and therefore lend themselves well to management scenarios and monitoring in real-time. Figure 51 attempts to visually represent the proposed causal linkages and feedbacks.

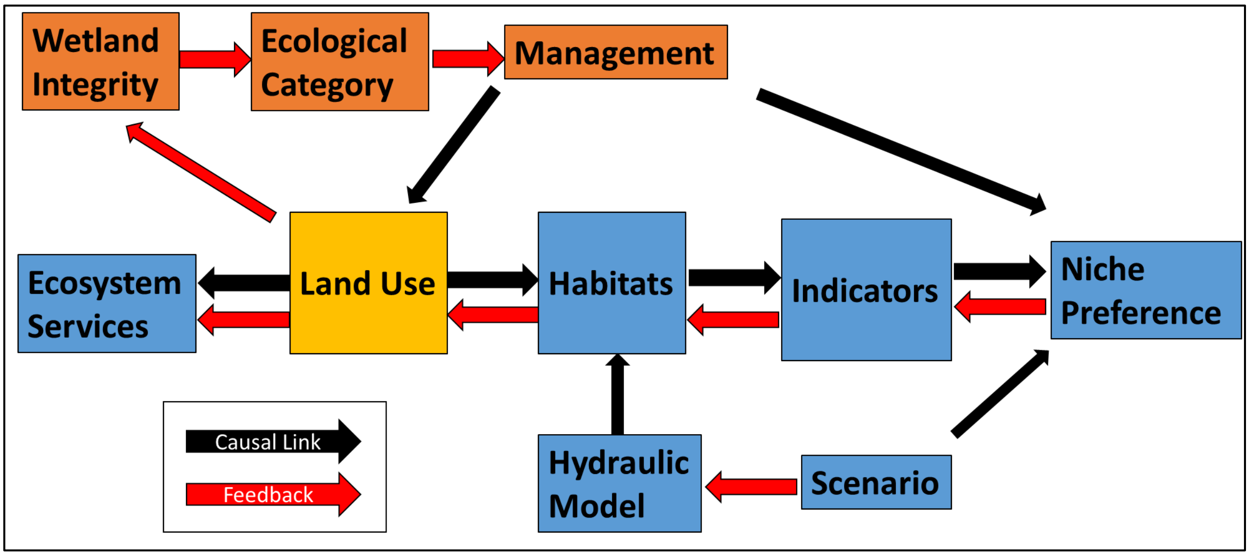


Figure 51: Flow chart of system links and feedbacks

The general task of environmental flow requirement (EFR) determination comprises four main sub-tasks:

1) Defining indicators and endpoints and relate these to habitats, land use and ecosystem services.
2) Parameterizing the hydrological / hydraulic niche preferences of indicators and linking to endpoints. Such parameterization is to form an ecological "rule-set" for use in modelling.
3) Integration of "rule-set" into 2D modelling for EFR and scenario outputs.
4) Proposing a monitoring protocol.

8.1 Indicators and Endpoints

Ecosystem indicators relate to the most vital vegetation (or other) habitats with the aim to maintain habitats and ecosystem processes for critical indicator macrophytes and riparian/wetland vegetation. The following vital habitat/indicator combinations represent ecosystem endpoints for wetlands within the Nile Basin in general, but also for the Machar Marshes specifically (see):

- Open water (this represents non-vegetated ecosystems)
- Aquatic vegetation (rooted, submerged, not discernable for land use data)
- Fringe vegetation (in association with Papyrus, inundated, emergent, mostly hydrophilic grasses)
- Permanently flooded swamp (represented by Papyrus marsh – Cyperus papyrus, not common in the Machar Marshes)
- Reeds / reed beds (dominated by *Phragmites* species)
- Floodplain grassland (both flood and rainfall dependent grasslands but dominated by hydrophilic grasses)

- Woody vegetation (trees and shrubs of different densities, forest at the highest density)

Most of these can be discerned in satellite data and therefore relate directly to the land use data, which is useful for model calibration and subsequent monitoring. Each habitat type, in turn is represented by a dominant indicator or suite of indicators, each with a set of hydraulic and hydrological niche preferences. These links between habitats, land use and indicators (shown in concept in Figure 33) are shown in and the respective niche preferences and responses in Table 13.

Table 13: Links between Habitats, land use and indicators

Habitat type	Land use category	Indicators
Open water	Water	Unvegetated, usually permanently flooded
Aquatic vegetation	Water	Indicators of this habitat include floating vegetation such as water hyacinth (*Eichornia crassipes*), water fern (*Azolla nilotica*) and water lettuce (*Lemna giba*), but these don't make good indicators of flow, so rooted species are preferred. These include water Lily (*Nymphae lotus), Potamogeton, Trapa* and *Ceratophyllum* species.
Fringe vegetation	Papyrus	Fringe Vegetation characterized by bands of *Vossia cuspidata* or *Echinochloa stagnina.*
Papyrus marsh	Papyrus	Notable zones of Papyrus (*Cyperus papyrus*) and *Typha domingensis,* permanently flooded zone.
Reed beds (Phragmites)	Reeds	A zone beyond the Papyrus but be included at times and dominated *by Phragmites karka* (reeds). *Oryza barthii* also present.
Floodplain Grassland	Wetland Grasses	Toich: the tall grasses are dominated by *Phragmites, Sorghum, Hyparrhenia* and *Setaria* species as well as *Oryza* and *Echinochloa*. Two grassland types are recognized. These are wild rice grassland dominated by *Oryza longistaminata* and *Echinochloa* grassland dominated by *Echinochloa pyramidalis*. Also, a social endpoint for ecosystem services
Woody begetation	Trees & shrubs; Forest	Comprises woody trees and shrubs from highly dense areas (Forest) to more open woodland to more sparse shrubland. Also, a social endpoint for ecosystem services.

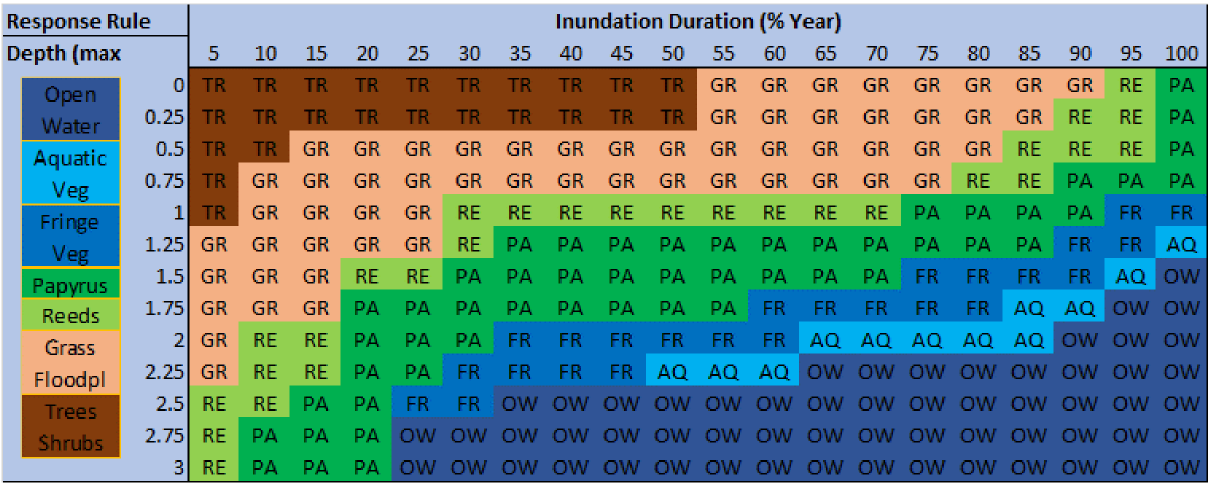
Social endpoints can also be recognized and are based on those components of the biodiversity that are vital to sustaining livelihoods and as such water resource management aims to maintain indigenous vegetation components in order to sustain community livelihoods including natural vegetation production, subsistence agriculture and fisheries. The Machar marshes and surrounding areas are home to hundreds of thousands of people from the Nilotic tribes (the Dinka, Nuer and Shuluk), as well as other tribes (the Morlei and Anjwak). These tribes are predominantly nomadic and migrate with their cattle to and from the grazing lands, locally referred to as "toich," which are predominantly seasonally flooded grasslands and surrounding shrubland (Mohamed, 2016; ENTRO, 2016). Shrubland and forested areas also provide the main source of building materials and energy (fuel) for rural communities, and the livelihoods of tens of thousands of the people living alongside the marshes depend on fish resources as an important source of protein (Mohamed, 2016). As such, the main social endpoints include the seasonally flooded grassland areas which are cultivated and used for grazing, the forested or shrub zones and ecosystems that support fish harvests such as flooded marsh and fringe vegetation and shallow open water.

8.2 Defining the hydraulic / hydrological niche of indicators and endpoints

The ultimate drivers of all ecosystem indicators and social endpoints are the flow regime and rainfall. Vital components of the flow regime include perenniality (wet and dry season base flows), timing (seasonality) of floods, magnitude and duration of flood events and by implication the distribution of depth/area parameters associated with floods. Various biotic indicators show niche preference for combinations of the drivers and can be modelled as such for integration into the 2D hydraulic model. Each vegetation type (endpoint / indicator) has clear niche preferences in terms of flooding depth, duration and timing, as well as timing and severity of flows during the dry season. Each set of such preferences can be defined as an ecological "rule-set" that will respond within the modelled environment and the outcome of which can be measured. This measured response of endpoints / indicators is mainly expressed as proportions and aerial extent of indicators in response to a given flow regime. The flow regime that describes the current situation represents the environmental flow requirements, against which response to scenarios may be measured. Both the endpoints and the "rule-sets" require definition to describe an acceptable ecological quality, deemed to be the environmental flow requirement.

These hydraulic and hydrological niche preferences, which were outlined in detail by Sutcliffe (2009), and modified for use here (see Table 14), and responses provide a direct link to water depth distribution across the floodplain via the hydraulic model outputs and can therefore be used to assess flow scenarios and their influence on wetland habitats and overall biodiversity.

The autecological information outlined in Table 14 was used to develop a rule-based matrix comprising flooding duration and depth. Each indicator is assigned a preference within the matrix as represented in Figure 52. This matrix of preferences forms the basic rule-set which now needs to be integrated with outputs from the hydraulic model in order to predict an ecological response to flow.



Response Rule		Inundation Duration (% Year)																			
Depth (max		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Open	0	TR	TR	TR	TR	TR	TR	TR	TR	TR	TR	GR	GR	GR	GR	GR	GR	GR	GR	RE	PA
Water	0.25	TR	TR	TR	TR	TR	TR	TR	TR	TR	TR	GR	GR	GR	GR	GR	GR	GR	RE	RE	PA
Aquatic	0.5	TR	TR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	RE	RE	RE	PA
Veg	0.75	TR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	GR	RE	RE	PA	PA	PA
Fringe	1	TR	GR	GR	GR	GR	RE	RE	RE	RE	RE	RE	RE	RE	RE	PA	PA	PA	PA	FR	FR
Veg	1.25	GR	GR	GR	GR	GR	RE	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	PA	FR	FR	AQ
Papyrus	1.5	GR	GR	GR	RE	RE	PA	PA	PA	PA	PA	PA	PA	PA	PA	FR	FR	FR	FR	AQ	OW
Reeds	1.75	GR	GR	GR	PA	PA	PA	PA	PA	PA	PA	PA	FR	FR	FR	FR	FR	AQ	AQ	OW	OW
Grass	2	GR	RE	RE	PA	PA	PA	FR	FR	FR	FR	FR	FR	AQ	AQ	AQ	AQ	AQ	OW	OW	OW
Floodpl	2.25	GR	RE	RE	PA	PA	FR	FR	FR	FR	AQ	AQ	AQ	OW	OW	OW	OW	OW	OW	OW	OW
Trees	2.5	RE	RE	PA	PA	FR	FR	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW
Shrubs	2.75	RE	PA	PA	PA	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW
	3	RE	PA	PA	PA	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW	OW

Figure 52: Ecological rule set is given as vegetation alignment to a depth duration matrix

Table 14: Hydrological and hydraulic links between indicators, land use and niche preference

Indicator guild	Land use category	Indicators	Niche preference				Biodiversity link	Response
			Water depth preference (determined at peak flood)	Flow vel preference	Flood duration	Seasonality		
Open water vegetation (Aquatic)	Water	Indicators of this habitat include floating vegetation such as water hyacinth (Eichornia crassipes), water fern (Azolla nilotica) and water lettuce (Lemna giba), but these don't make good indicators of flow, so rooted species are preferred. These include water Lily (Nymphae lotus), Potamogeton, Trapa and Ceratophyllum species.	> 1.3m up to 2.5m for rooted species, not applicable to floating species, these deep-rooted species frequently occur on the deep side of Papyrus	slow (<0.3m/s)	permanent, slow-flowing	Year-round	1) Aquatic vegetation 2) Fish diversity in the Sudd is impressive and appears to be a response to the favorable environmental conditions for recruitment and survival offered by the mosaic of habitat types, but especially limnophylic and potamodromous fish species 3) Aquatic invertebrates 4) Water bird nesting sites (floating) 5) Piscivorous birds	1) If flows are too fast these species become vulnerable to loss of parts or individuals due to scour, flows faster than 0.3m/s over prolonged periods will reduce their occurrence 2) The deeper water gets the more limiting light becomes to rooted aquatic plants. Below 2.5m for prolonged periods will reduce occurrence or result in total loss. If water clarity is compromised the critical depth becomes less than 2.5m

Indicator guild	**Land use category**	**Indicators**	**Niche preference**				**Biodiversity link**	**Response**
			Water depth preference (determined at peak flood)	**Flow vel preference**	**Flood duration**	**Seasonality**		
Papyrus marsh (permanent)	Papyrus	Fringe Vegetation characterized by bands of Vossia cuspidata or Echinochloa stagnina, usually followed by notable zones of Papyrus (Cyperus papyrus) and Typha domingensis.	Can be various but Papyrus generally limited by prolonged flooding below 1.5m, although can withstand much deeper flooding for shorter periods; optimal depth from 1.5m to 1.3m, shallower than 1.3m mixed stands co-occur with reeds	slow (<0.3m/s)	permanent, slow-flowing	Year-round	1) The fish communities in the wetland are comprised of 31 Siluroids, 16 Characoids, 14 Cyprinoids, 11 Momyrids, 8 Cichlids, and 7 Cyprinodonotids. Fish species whose life-cycles start and end in the wetland belong to the following genera: Polypterus, Heterotis, Hyrocymus, Alestes, Distichordus, Citharinus, Labeo, Sarotherodon, Synodontis, Auchenoglaris, Oreochromis, Ctenopoma, Clarias and Protopterus. 2) Marsh dependent birds such as the Shoebill, Basra reed warbler, Yellow Papyrus Warbler, Papyrus Gonolek and	1) The levels of the boundary between the shallow-flooded species and deep-flooded species are related to the maximum depth of flooding. The presence or absence of papyrus indicates that the range of flooding is important. 2) Depths >1.5m and for prolonged periods (near permanent) tend to be faster flowing and the presence of Papyrus becomes limiting. 3) Other fringe vegetation is likely to be lost before Papyrus. 4) If water depths are reduced for prolonged periods, or permanently, fringe vegetations and Papyrus will encroach towards the channel, as will

Indicator guild	Land use category	Indicators	Niche preference				Biodiversity link	Response
			Water depth preference (determined at peak flood)	Flow vel preference	Flood duration	Seasonality		
							Papyrus Canary. 3) The tall plants provide a framework for climbers such as Luffa cylindrical and Vigna luteola. 3) Papyrus-dependent insects such as the Papyrus Wisp (endangered).	reeds which will begin to encroach into existing Papyrus beds.
Reed beds (Phragmites)	Reeds	A zone beyond the Papyrus but be included at times and dominated by Phragmites karka (reeds). Oryza barthii also present.	0.5-1.3m (optimal range for distribution but can withstand deeper flooding for shorter periods)	slow (<0.3m/s)	spans both permanently and seasonally flooded zones	Wet season (June to Oct)	1) Several endangered animal species are found in the Sudd namely, Cheetah, White addax, Grévy's zebra, Nile lechwe, and African wild dog. Other swamp-dwelling mammals include Hippoptamus, Sitatunga, Marsh Mongoose. Elephant makes local movements in the wetlands as the water recedes. Migratory mammals	1) A water depth of 0.5-1.3m is the optimal range for distribution but can withstand deeper flooding for shorter periods. 2) Deeper depths for prolonged periods will cause die-off and encroachment laterally towards higher ground, into existing grassland. 3) Shallower depth for prolonged periods will cause lower densities and

Indicator guild	Land use category	Indicators	Niche preference				Biodiversity link	Response
			Water depth preference (determined at peak flood)	Flow vel preference	Flood duration	Seasonality		
							depend on the wetland for their dry season grazing. The Sudd is one of the most important wintering grounds in Africa for Palaearctic migrants, providing essential habitats for millions of migrating birds such as Pelecanus onocrotalus, Balearica pavonina, Ciconia ciconia and Chlidonias nigra. The Shoebill avoids the main channels of the swamp and very tall vegetation. The Shoebill prefers the smaller channels and pools specifically those surrounded by Typha. It mostly eats air-breathing fish which the Shoebill ambushes when they come up for air.	possibly die-off on the upper side and encroachment towards the channel and into Papyrus on the channel side.

Indicator guild	Land use category	Indicators	Niche preference				Biodiversity link	Response
			Water depth preference (determined at peak flood)	Flow vel preference	Flood duration	Seasonality		
River flooded grassland	Wetland Grasses	The tall grasses are dominated by Phragmites, Sorghum, Hyparrhenia and Setaria species as well as Oryza and Echinochloa. Two grassland types are recognized. These are wild rice grassland dominated by Oryza longistaminata and Echinochloa grassland dominated by Echinochloa pyramidalis.	0 in the dry season, optimally 0.5 - 1.1m during floods, but up to 1.3m, steep decline beyond 1.5m	slow, not flowing	seasonal, about 70-90 days in the wet season; max flood up to 10 days at 1.3m and 1 month at 1.18m	Wet season (June to Oct)	1) Grassland can be divided into seasonally river-flooded grassland and seasonally rain-flooded grassland. 2) Seasonal flooding enables the growth of grasses such as Sorghum sudanica, Echinochloa spp. and Oryza longistaminata, wild rice-grass. This grassland is known as the 'toich'. Where the water is deeper the Oryza longistaminata is dominant, but needs several months (mostly up to 3) of surface water in order to flower. Echinochloa pyramidalis is the dominant grass with Sporobolus pyramidalis, Digitaria debilis and Desmodium hirtum where the flood water is shallower. 4)	1) Loss of annual floods will result in loss of productivity, altered species composition and encroachment by alien and terrestrial species. 2) Flood duration of 70-90 days is important to productivity and reproduction (plants and fish), shorter periods will result in reduced productivity, failure of reproduction and shrinkage of floodplains which are also important to Sitatunga, and Nile lechwe, which migrate between the swamps and 'toich', i.e. follow changing water levels and vegetation. 2) potamodromous fish species that are dependent on flooding seasonality

Indicator guild	Land use category	Indicators	Niche preference				Biodiversity link	Response
			Water depth preference (determined at peak flood)	Flow vel preference	Flood duration	Seasonality		
							Many potamodromous fish species are dependent on wetland habitats for overall population wellbeing and especially for recruitment during flooding. Notable among these groups are the limnophilic species such as the Cyprinids (includes the carps, the true minnows, and their relatives, e.g. the barbs and barbels), Cichlids and Siluriformes (catfish). Fish migration includes both lateral and longitudinal en mass movement, can be extensive and is always flood dependent, highlighting the importance of river / wetland connectivity and interconnectivity	and duration for recruitment and overall population health will be severely hampered if floods are absent, of too short a duration, or in the wrong season.

Indicator guild	Land use category	Indicators	Niche preference				Biodiversity link	Response
			Water depth preference (determined at peak flood)	Flow vel preference	Flood duration	Seasonality		
							as well as the conservation of critical hydrological flow parameters. 5) Nile Lechwe are endemic to the Sudd and their movements are related to the flood cycle. It does not live in the swamp but follows the waterline of the river flooded grasslands. White-eared Kob makes large migrations in the seasonal grasslands, they feed in the grasslands mainly on Hyparrhenia and associated grasses.	

8.3 Integration of “rule-set” into 2D modelling for EFR and scenario outputs

The matrix rule-set, shown in Figure 34 needs to be calibrated against present-day land use to make sure outputs of responses represent current reality. This is the next task. Once calibration is achieved, the hydrological time series from the hydraulic model will be used to integrate depth-duration data with the matrix rule-set to produce an output according to vegetation indicator preferences. This prediction is a proportional response to assign a vegetation unit to each modelled grid. Then, area (extent) and proportion can be calculated and compared to other scenarios. Figure 35 shows an example of proportional outputs for 3 scenarios: the baseline, a drier scenario and a wetter scenario. These are currently unrealistic scenarios but are designed to make sure the ecological response is logical and generally correct before calibration and employment start.

Veg	PD-Baseline	Scenario: Drier	Scenario: Wetter
OW	0.1	0	14.0
AQ	3.9	0	12.0
FR	9.9	0	8.6
PA	10.1	9.2	19.4
RE	10.0	24.8	9.1
GR	45.0	45.0	17.5
TR	21.0	21.0	19.5
	100	100	100

Figure 53: Example of proportion outputs of vegetation indicators in response to 3 hypothetical scenarios

8.4 Generate and run scenarios

The baseline model developed in Phase II and extended with the SSEA will be used to evaluate future development options and scenarios. Six scenarios have been defined in the BAS-MWRD project, which ranges from precautionary to full basin development as detailed in Section 6.5. These scenarios will be analyzed regarding their impact on the Machar Marshes. For scenarios that are relevant to the Machar Marshes, an ecological response will be described and quantified as outlined in Figure 53.

8.5 Monitoring recommendations

Future monitoring recommendations regarding both hydrology and ecosystem services of the Machar Marshes are summarized in Table 15. The bulk of the monitoring should be at the whole wetland scale and make use of satellite data as far as possible. This will be the most cost-effective approach and still provide useful data for monitoring and management decisions.

Table 15. Detail of when and what to measure for monitoring

Sites	Frequency	Variables	Comment
Hydrology			
Monitoring at key locations, e.g.: - Before and after the spill locations - Inlet of Khor Machar - Outflow of Khor Adar - Big water ponds (could be selection of pilot ponds), or in large flood plain areas	constant	Discharge, water level and climate parameters	

Sites	**Frequency**	**Variables**	**Comment**
- Meteorological data in major towns in the area (e.g. Nassir)			
Hydraulics / flooding			
Whole wetland	annual	Flood extent	Satellite-based map showing the peak flood extent
Whole wetland	once every 10 years	The extent of flooding and drying	Satellite based map showing the change over time of both peak flood and also the dry season extent, that should be reviewed every 10 years
Vegetation			
Whole wetland	As often as new satellite data become available	General vegetation distribution	Earth observation of the spatial extent of wetland vegetation (general types as far as discernable e.g. Papyrus, Reeds, Grass, Trees), including open water.
Select sites (where hydraulic cross-sections occur, or discharge is measured)	As often as new satellite data become available	Woody / non-woody extents; extent of permanent swamps	Earth observation of the spatial placement and integrity of the treeline. To be done for a reasonable distance upstream and downstream (~500m) at select sites.
Whole wetland	once every 5 years	Distribution of key species / suites (defined as endpoints above)	A full biodiversity survey is not practical for management; thus, this survey is based on a high-level overview of the vegetation composition and the changes being experienced. Based on change over time at fixed sites located by GPS coordinates. Sites should be as large as possible. Site surveys are best since non-woody vegetation differences are difficult to discern using satellite imagery, but its best to use both as far as possible: satellite for extents and sites for ground-truthing and species. Should include at least extents of generic vegetation types e.g. permanent swamp, Papyrus, Reeds, floodplain grasses, trees and shrubs.
Fish			
Select points in the wetland	3 yearly in the wet and dry season	Survey of fish caught by small fishers	A full biodiversity survey is not practical for management; thus, this survey is based on a survey of small-scale fishers and their catch (species, size, numbers)
Birds			
Select points in the wetland	once every 5 years	Bird sittings	Bird sittings and comparison of presence / absence data