Hydrodynamic, water quality and habitat modelling in the Inner Niger Delta

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CONTENTS

1 Introduction 4

2 Hydrodynamic modelling in the Inner Niger Delta 5

2.1 Preparation of the topographical input data 5

2.1.1 Evaluation of existing topographical datasets 6

2.1.2 Building up a new DTM from the available data 8

2.1.3 Recommendations for improving the DTM 10

2.2 Development of the new hydrodynamic model for the Inner Niger Delta 11

2.2.1 Recommendations for improving the model 14

3 Habitat modelling in the IND 16

3.1 Calculation of depth maps 16

3.2 Validation of depth maps 18

3.3 Key habitat types 20

3.4 Key species 21

3.5 Habitat assessment 24

3.5.1 Area with bourgoutiere and rice 25

3.5.2 Distribution of depth zones over flood period 26

3.5.3 Habitat type and depth 26

3.6 Recommendation for improvement 27

4 Water quality modelling in the IND 29

4.1 Model description 29

4.1.1 The baseline equation 29

4.1.2 Calculation of coliform sources and sinks 29

4.2 Application of the model in the IND 31

4.3 Results 33

4.4 Recommendations 36

List of references 38

Attachment 40

1 Introduction

Inner Niger Delta (IND) is a huge wetland in Mali formed by the braiding channel system of the Niger River and its tributaries (Figure 1). Hydrological regimes of these rivers have fundamental influences on most of the ecosystems and ecosystem services of the IND. Floods supply water and nutrients to the rice fields, which are essential sources of food for local people. Floods also inundate the huge, uncultivated floodplains of the Delta for the benefit of fish and waterfowls. Fisheries depend highly on floods, as it is proven by the strong correlation between annual maximum inundation areas and annual fish catches (Zwarts et al., 2005). Water bodies of the IND are recipients of various organic and inorganic pollutions coming from the settlements and from the agricultural areas. These pollutants are transported in the river channels and cause serious water-borne disease and eutrophication problems in other parts of the wetland.

Figure 1. Location of the Inner Niger Delta (IND) in the Niger River Basin

It can thus be concluded that a proper knowledge about hydrological, water quality and habitat conditions in the IND, and also about the consequences of potential changes in these conditions, is essential for the management of this wetland. The mean for gaining such knowledge is modelling. This report introduces the hydrodynamic, water quality and habitat models that have been developed for the IND within the frame of the WETwin project, with the aim of supporting the management of the wetland. It is important to emphasize that due to poor data availability, the accuracy of the hereby presented models is weak. This means that they cannot be applied for management purposes in their present forms. Raising their accuracy to the desired level requires more data, which have to be either purchased from data sources, or generated by means of monitoring. The report gives recommendations for how to acquire and process auxiliary data for developing the models to the desired level in the most efficient way.

2 Hydrodynamic modelling in the Inner Niger Delta

The hydrodynamic modelling tool applied in this study is the River2D (Steffler & Blackburn, 2002), which is a freeware software downloadable from the internet (www.river2d.ualberta.ca). Before this study, an initial River2D model was already available for the IND. It was developed by the ANTEA Group within the frame of the WETwin project (de Boeck & Cools, 2010). The spatial extend of this model is restricted to the main channels of the Niger and Bani rivers near the town of Mopti (Figure 2). Due to this restriction, this model was capable to simulate low flow situations only. The present study aims at developing further this model by expanding the model boundaries both to lateral and longitudinal directions. The objective is to simulate the water regime at mean and high waters too, when floodplains, lakes and lateral channels get connected to the main channel and store/convey significant shares of the total flow.

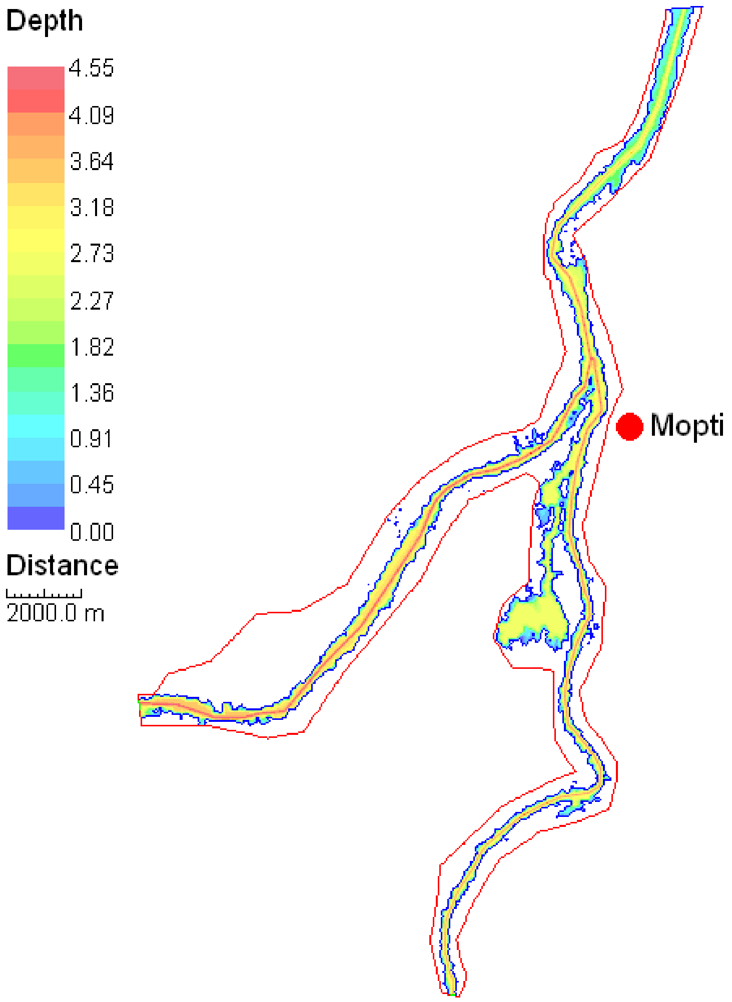


Figure 2. Water depths in the Niger and Bani rivers at the city of Mopti at a total flow of 470 m^3/s: results of steady-state River2D modelling (de Boeck & Cools, 2010)

2.1 *Preparation of the topographical input data*

The Inner Niger Delta, like other natural river-floodplain systems, has a rather complex topography formed by various hydro-morphological structures, such as: river channels, dead branches, lakes, natural levees, point bars and islands (Figure 3). Increasing the domain of 2D modelling beyond the banks of the main channels necessitates a high-resolution Digital Terrain Model (DTM), which includes and clearly represents all these hydro-morphological structures.

Figure 3. The Inner Niger Delta at the bifurcation of the River Niger 21 km-s downstream of Mopti - Google Earth image

2.1.1 Evaluation of existing topographical datasets

The only available DTM about the IND is the one generated by the Shuttle Radar Topography Mission (SRTM). The resolution of this DTM is 90 m; its vertical error can be as high as 16 m (CGIAR CSI, 2011). As Figure 4 indicates, only the main channel of the River Niger is visible on this DTM. Other hydro-morphological structures are simply not represented, due to the low resolution and accuracy. This means that the SRTM DTM is not applicable for the envisaged 2D hydrodynamic modelling.

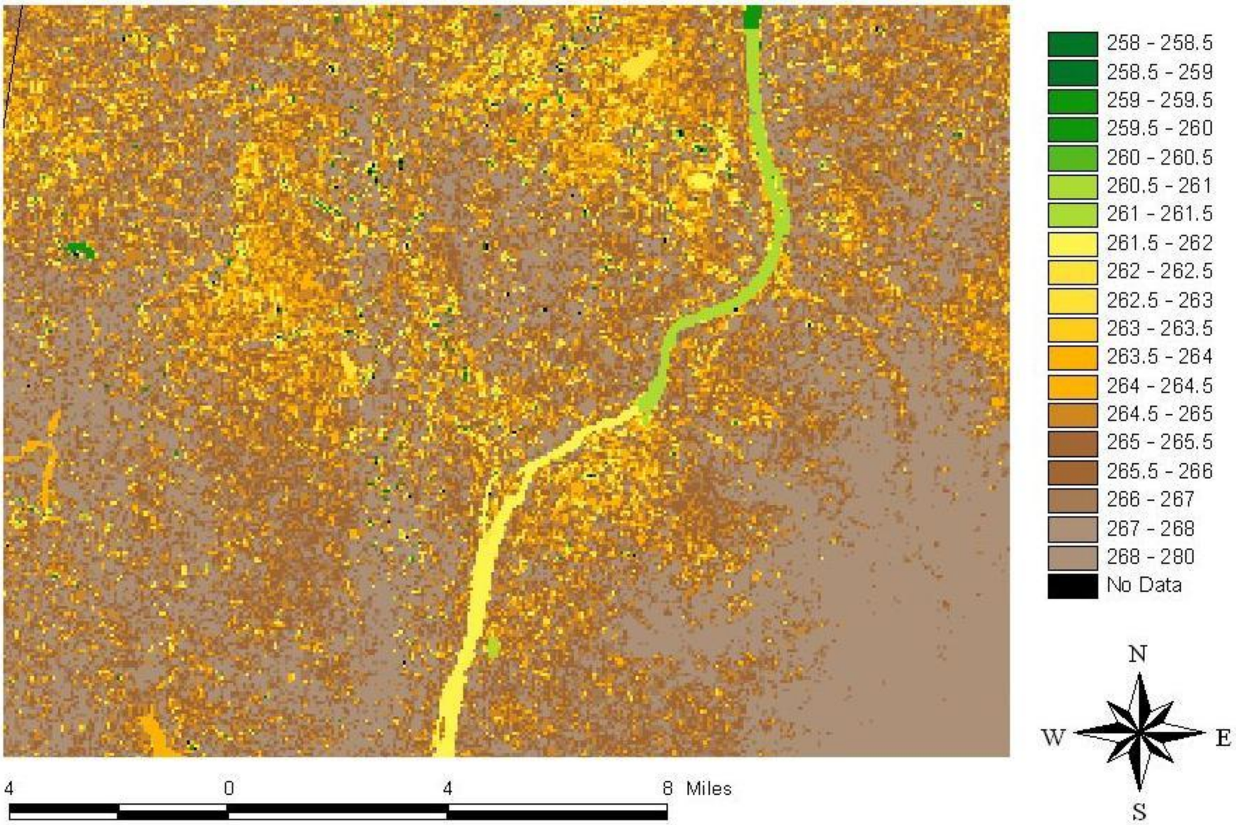


Figure 4. The IND at the bifurcation of the River Niger 21 km-s downstream of Mopti, as represented by the SRTM DTM

Besides the SRTM DTM, there is also the ‘water map’ (see Figure 5) generated by the Niger Lifeline project (Zwarts et al., 2005). This map was built up from a series of Landsat satellite images. Each of these images shows the areas covered by water at a certain stage of the annual floods. By comparing Figure 5 to Figure 4 and Figure 3, we can conclude that:

- the resolution of the water map is much better than that of the SRTM DTM;
- the water map clearly represents the topography of the Delta with all its major hydro-morphological structures.

There are however certain problems with this water map:

- The area formed by those pixels, whose attribute values are equal or less than a given number, is identical to the water surface area captured by one of the Landsat images. (The given number equals the water stage recorded on the Akka gauge on the day when the image was taken.) This means that the pixel values cannot be interpreted as elevation data since they do not take into consideration the sloping water surface.
- There are sudden, step-like transitions between the different value zones. The so-formed ‘terraced’ surface is a false representation of the true topography of the IND.

Thus, the water map is not a DTM and it cannot be applied as topographical input for 2D hydrodynamic modelling. On the other hand, it can be utilized for generating the desired high resolution DTM. In the next section we describe how the new DTM was developed from this water map and from other auxiliary data.

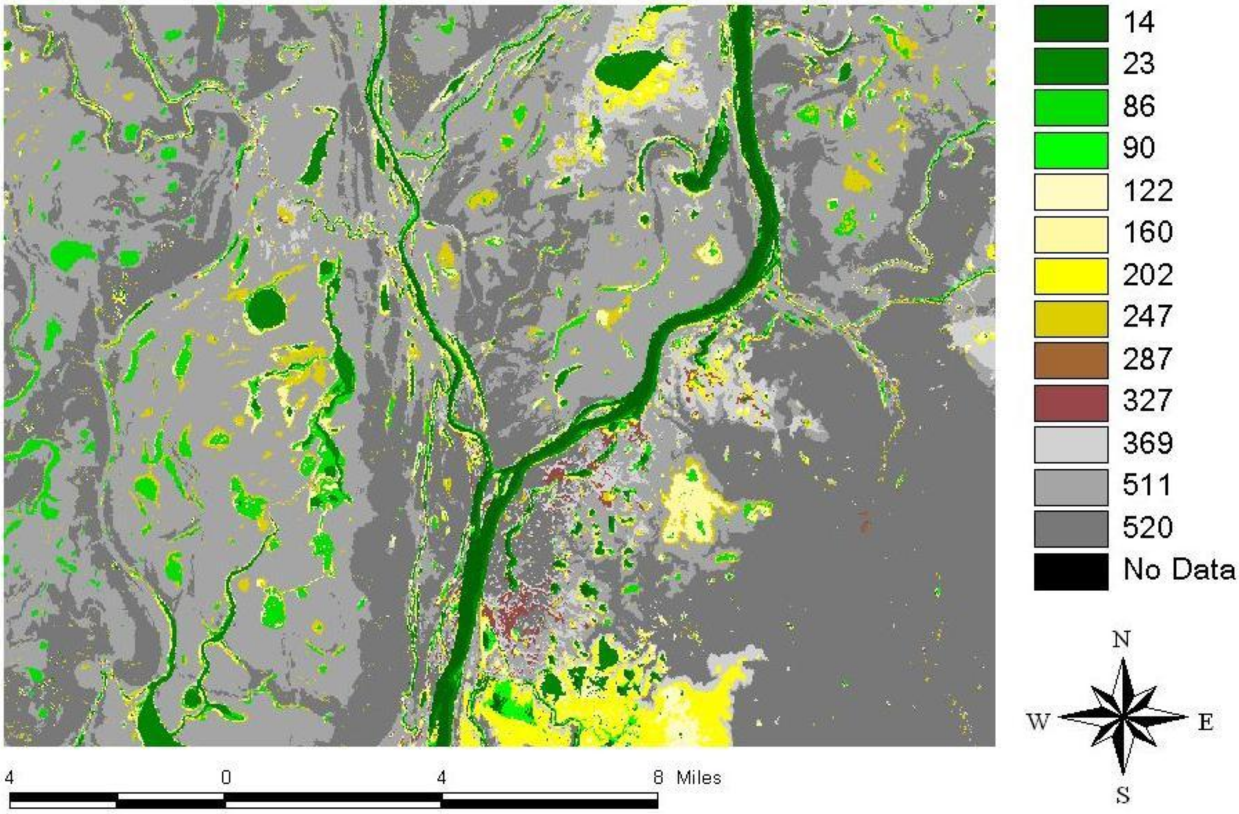


Figure 5. The IND at the bifurcation of the River Niger 21 km-s downstream of Mopti, as represented by the 'water map' (raster layer created by the Niger Lifeline project (Zwarts et al., 2005))

2.1.2 Building up a new DTM from the available data

It follows from the foregoing that a certain contour layer, derived from the water map, shows the edges of water at the time when the related Landsat image was taken. The uniform attribute value of the contours equals the water stage recorded on the Akka gauge on the day when the image was taken.[1] Fortunately the water surface was captured on the Mopti gauge as well (Zwarts et al., 2005). This means that the elevation of the water table is known at two locations: at Akka and at Mopti. Further points of the water table were identified within and around the Delta, along the lines of the contour layer. Elevation data for these additional points were taken from the SRTM DTM. A TIN (Triangular Irregular Network) was stretched over all these points, thus creating a good estimate of the water table. By mapping the 2D contour layer onto this TIN, we get the 3D layer of the water edges, where the Z coordinates of the line-points give good estimates of the terrain elevations (Figure 6).

[1] This water stage can be transformed into absolute water level on the basis of the '0' point elevation of the water gauge.

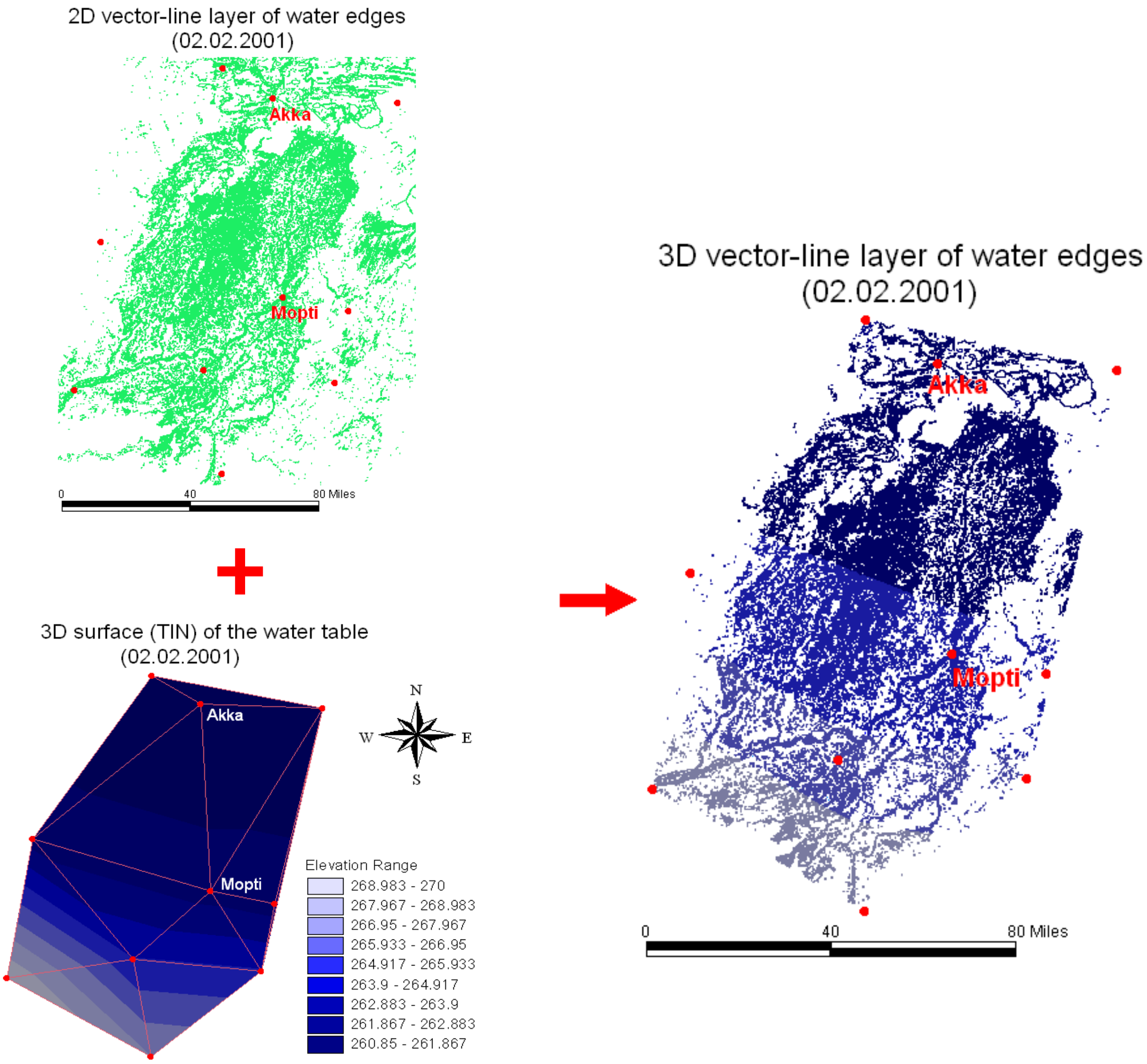


Figure 6. Generation of the 3D vector-line layer of water edges that occurred on the 2nd of February 2001. The water level on this day was 247 cm on the Akka gauge.

Such 3D layers of water edges were generated for each contour layer of the water map. Each of these 3D layers represents a particular stage of the annual flood. These water edge layers were than directly used for building up the new digital terrain model for the IND in the form of a TIN. The TIN was than transformed into a grid with a cell size of 20 m (Figure 7).

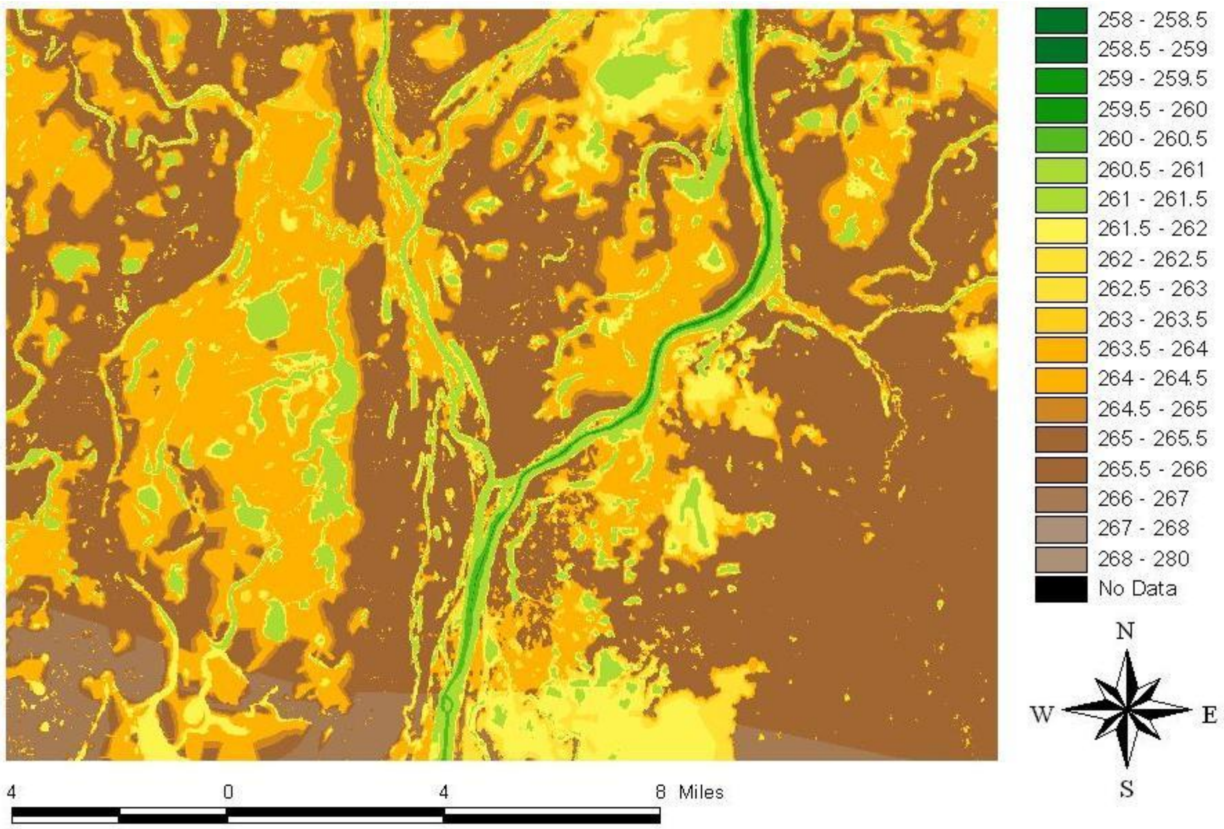


Figure 7. The IND at the bifurcation of the River Niger 21 km-s downstream of Mopti, as represented by the new DTM

As Figure 7 indicates, the new DTM represents all the major hydro-morphological structures of the IND, thanks to its high resolution. Such a DTM is already applicable for 2D hydrodynamic modelling on wetland scale. Also the accuracy of this DTM is better than that of the SRTM DTM, especially near and in-between Akka and Mopti. On the other hand, the accuracy in those regions, where elevation data were taken from the SRTM DTM, is probably still quite low. In addition, the potential differences between water levels in the river channels and water levels in the neighbouring isolated lakes were not taken into consideration at the generation of the water map, and thus also at the creation of the new DTM. These differences can be quite high, especially after long isolation periods. Thus the new DTM – in spite that it is much better than the SRTM - requires further improvements.

2.1.3 Recommendations for improving the DTM

In order to capture the water tables within the Delta in a more accurate way, it is recommended to install auxiliary gauges along the river channels and also in the major lakes. It is also recommended to acquire fresh satellite images, capturing the full range of flood and dry situations in the Delta. The latest Landsat images are accessible in the web-based database of the USGS (glovis.usgs.gov). It is important that the time of gauge readings must be in synch with that of the satellite images. Based on the new sets of images and gauge readings, a new and more accurate DTM can be built up for the IND.

In the near future it will also be possible to monitor the elevation of the water table in a remote sensed way. This will be made possible by the SWOT (Surface Water Ocean Topography) satellite mission. The aim of SWOT is to cover the world's oceans and freshwater bodies with repeated elevation measurements using the wide-swath altimetry technology. Thus, SWOT can be used as a substitute or complement to the proposed auxiliary gauges. For further info about SWOT the reader is referred to Rodríguez (2009) and to swot.jpl.nasa.gov.

Certain parts of the IND do not fall within the elevation interval of water level fluctuation. These are the bottoms of lakes and river channels and also the flood-free high-grounds. Proper representation of these sites in the DTM requires topographical data generated by onsite land surveys. Adequate representation of channel bottoms is especially important from the point of view of hydrodynamic modelling, since channel geometries have significant impacts on the flow regime.[2]

2.2 Development of the new hydrodynamic model for the Inner Niger Delta

As mentioned in the Introduction, the software applied for 2D hydrodynamic modelling is the River2D Steffler & Blackburn, 2002). This modelling tool is based on the numerical solution of the two-dimensional equations of mass and momentum conservation:

Conservation of mass:

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0$$

Conservation of momentum in the x direction:

$$\frac{\partial q_x}{\partial t}+\frac{\partial}{\partial x}(U\cdot q_x)+\frac{\partial}{\partial y}(V\cdot q_x)+\frac{g}{2}\cdot\frac{\partial}{\partial x}h^2 = g\cdot h\cdot\left(S_{0x}-S_{fx}\right)+\frac{1}{\rho}\cdot\left(\frac{\partial}{\partial x}(h\cdot\tau_{xx})\right)+\frac{1}{\rho}\cdot\left(\frac{\partial}{\partial y}(h\cdot\tau_{xy})\right)$$

Conservation of momentum in the y direction:

$$\frac{\partial q_y}{\partial t}+\frac{\partial}{\partial y}(V\cdot q_y)+\frac{\partial}{\partial x}(U\cdot q_y)+\frac{g}{2}\cdot\frac{\partial}{\partial y}h^2 = g\cdot h\cdot\left(S_{0y}-S_{fy}\right)+\frac{1}{\rho}\cdot\left(\frac{\partial}{\partial y}(h\cdot\tau_{yy})\right)+\frac{1}{\rho}\cdot\left(\frac{\partial}{\partial x}(h\cdot\tau_{xy})\right)$$

Where:

h : water depth

$q_x=h\cdot U$, $q_y=h\cdot V$: discharge intensities in the *x* and *y* directions

U, V : depth-average flow velocities in the *x* and *y* directions

S_{0x}, S_{0y} : bed slopes in the *x* and *y* direction

S_{fx}, S_{fy} : friction slopes in the *x* and *y* direction

τ_{xx}, τ_{yy} : normal shear stresses due to turbulence

τ_{xy} : transverse shear stresses due to turbulence

River2D solves these equations numerically using the finite element method. In this method the unknown hydrological variables (h, U, V, q_x, q_y) are calculated at the nodes of a Triangular Irregular Network that covers the computational domain. The adaptive resolution of the TIN enables to decrease the node density in flat floodplain areas with low flow rates and low flow variabilities, and

[2] For the time being, the bottoms of the main river channels are represented by arbitrary 3D vector-lines created on the basis of expert judgements. These lines were added to the 3D vector-line layers of water edges when the DTM was generated.

increase it over channels, reefs, narrows and steep banks, where flow rate and flow variability are high (Figure 8). This makes River2D very efficient in terms of computational efforts. Thanks to this efficiency, River2D is capable to model large hydrological systems - such as the IND.

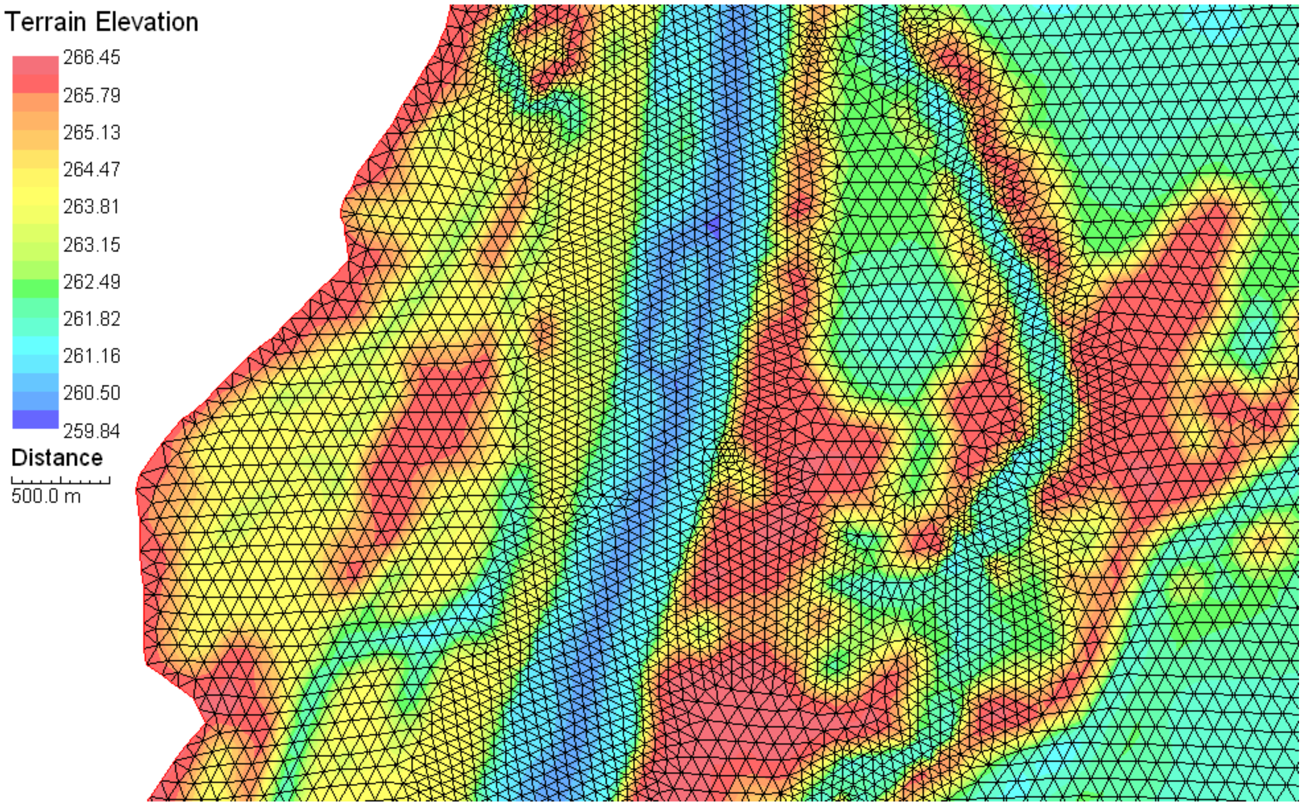


Figure 8. Adaptive computational mesh of River2D (detail of the model set up for the IND)

Based on the new DTM, a mezzo-scale River2D model has been set up for the IND, as a first step (Figure 9). Unlike the previous River2D model (see Figure 2), this model includes the reach of the River Niger between Mopti and the bifurcation point (see also Figure 7), together with all the riparian floodplains and water bodies up to the flood-free high-grounds.

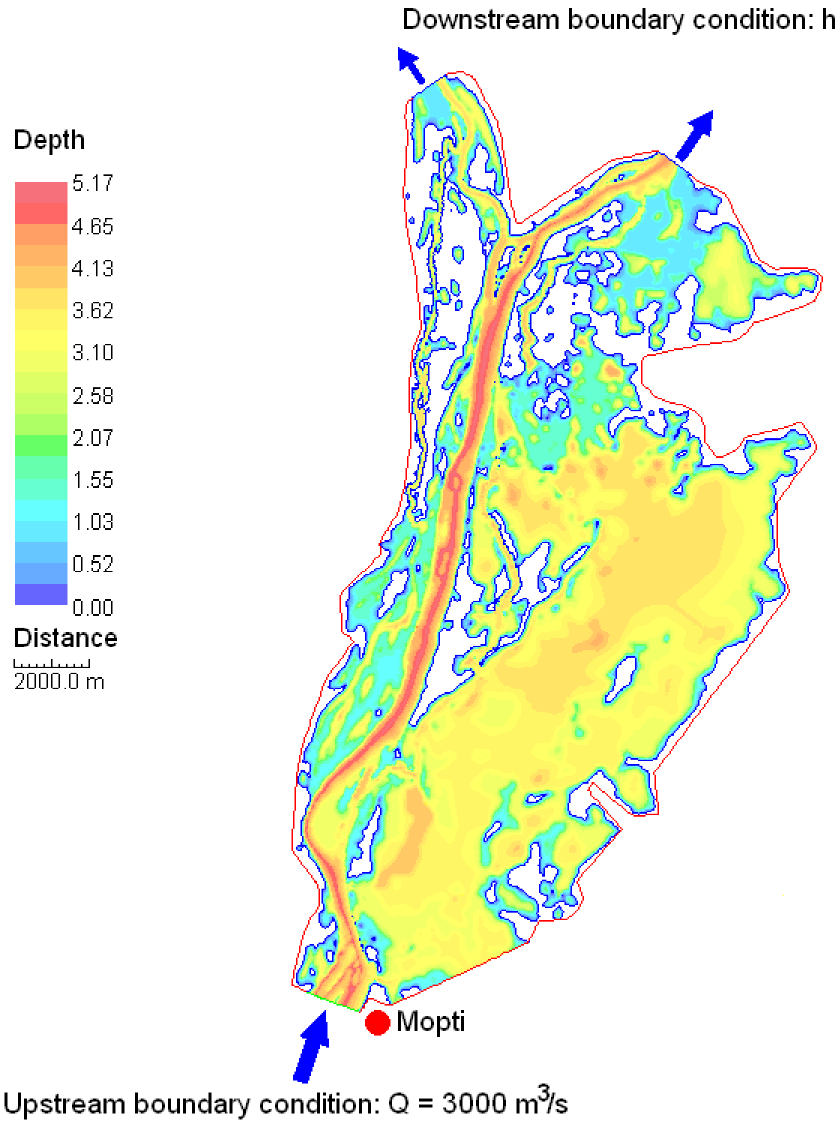


Figure 9. Water depths in the model area at a total flow of 3000 m^3/s: results of steady-state River2D modelling

As Figure 9 indicates, this model is already capable to simulate the water regime at floods, when the water leaves the main channel and inundates the riparian floodplains and water bodies. The primary outputs of the model are distributions of water depths and depth-averaged water velocities over the computational domain (Figure 10).

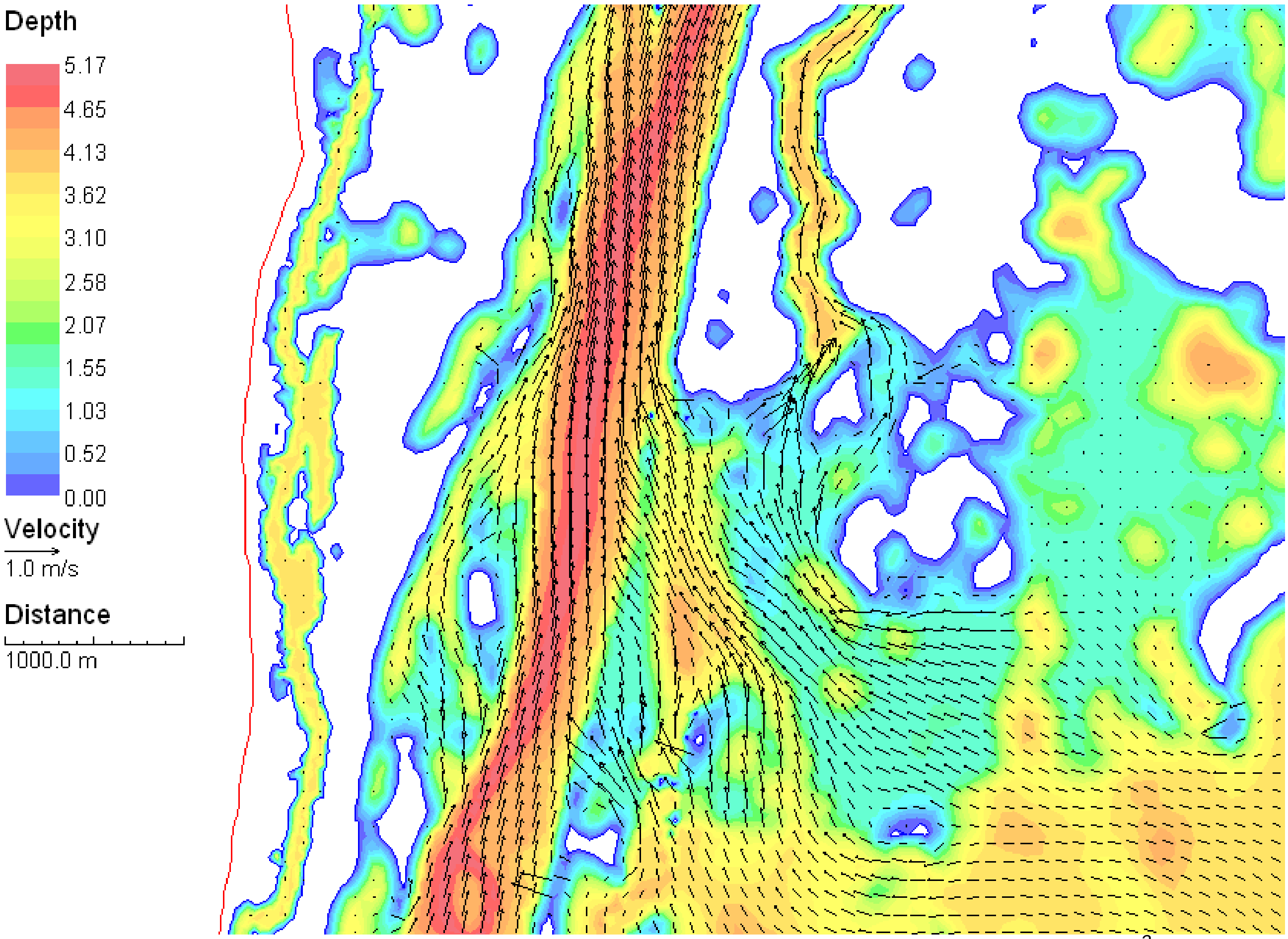


Figure 10. Water depths and velocities in the Inner Niger Delta at a total flow of 3000 m^3/s: results of steady-state River2D modelling (detail of Figure 9)

It is important to state that due to the lack of land cover data and measured water levels, this model hasn't been calibrated yet.

2.2.1 Recommendations for improving the model

First and foremost the model needs to be calibrated and validated. Calibration of a River2D model means the adjustment of 'roughness height' parameters, until the differences between computed and measured water levels get minimized. Thus, calibration necessitates measured water levels from the modelling domain. These water levels can be obtained with the help of the auxiliary gauges and/or with that of the SWOT remote sensing mission (see also Section 2.1.3). For calibration, it is also important to know the total discharge entering the modelling domain at the time of water level monitoring. This is not a simple issue since discharge data are available only from Ké-Macina (River Niger) and Douna (River Bani), which are both far upstream of the model domain. A large share (about 55%) of the Niger's flow leaves the main channel right downstream of Ké-Macina and flows into the Diaka and Moya-Kotia regions of the IND (Zwarts et al., 2005). In addition, there are considerable evaporation losses both from the Niger and Bani rivers. So, only a certain fraction of the flows measured at Ké-Macina and Douna enters the model domain at Mopti. More accurate information about these flows can be derived either by measuring discharges at Mopti, or with the help of large scale hydrological models, which account for evaporation losses and are capable to calculate the distribution of flow among the sub-systems of the IND. Such hydrological models are already available for the IND. The MIDIN reservoir model developed by Kuper et al. (2003) and the RIBASIM water balance model developed by the Niger Lifeline project (Zwarts et al., 2005) are both applicable, even though they need to be updated on the basis of new hydrological and topographical data.

Proper calibration also requires some preliminary information about the spatial distribution of roughness. Roughness can be linked to land cover categories. In general, the surface of the IND is quite open and smooth. There are however areas, such as settlements and forests, where roughness is higher than in the open fields. There are also the floating rice and bourgou fields, which likely raise considerable resistance against the flow. A GIS layer, which shows all these land cover types within the Delta, would thus help to initiate the distribution of roughness values over the modelling domain.

It is also important to improve model accuracy at those micro-topographical structures, which influence flow conditions over large parts of the model domain. These are typically those natural/artificial weirs and channels, through which the river inundates the huge lateral floodplains and lakes. The adaptive, finite element approach of River2D makes it possible to improve model resolution at these locations, without significantly increasing the total number of computational nodes (see Figure 8). Such improvements of the model however necessitate detailed information about the geometry of these structures with special regard to the elevations of their flow thresholds. This information needs to be acquired either from the owners of these structures, or by means of land surveys.

Evaporation needs to be considered as well, since it has a significant impact on hydrological processes within the Delta.[3]

Finally, 2D hydrodynamic modelling needs to be expanded over the total area of the IND. This will likely necessitate multiple models covering the different sub-systems of the Delta, since a single model for the whole IND would exceed the computational capacity of a PC. It is recommended to embed these sub-system models into a large scale hydrological model (e.g. MIDIN or RIBASIM), which would provide them with the required boundary conditions.

[3] Unfortunately, the current version of River2D doesn't make it possible

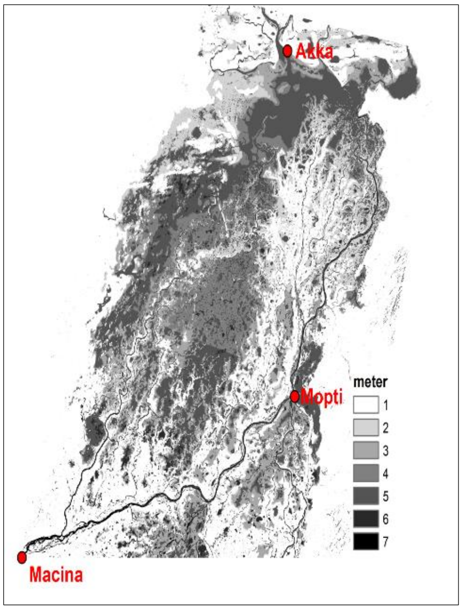
3 Habitat modelling in the IND

The primary purpose of hydrodynamic modelling is to provide hydrological boundary conditions for ecological and water quality models, which can be used for assessing the impacts of different management options on the ecosystem services of the wetland. For example, nature conservation and fisheries in the IND can be supported by aquatic habitat models, which help to estimate the diversity and abundance of aquatic species under different hydrological conditions.

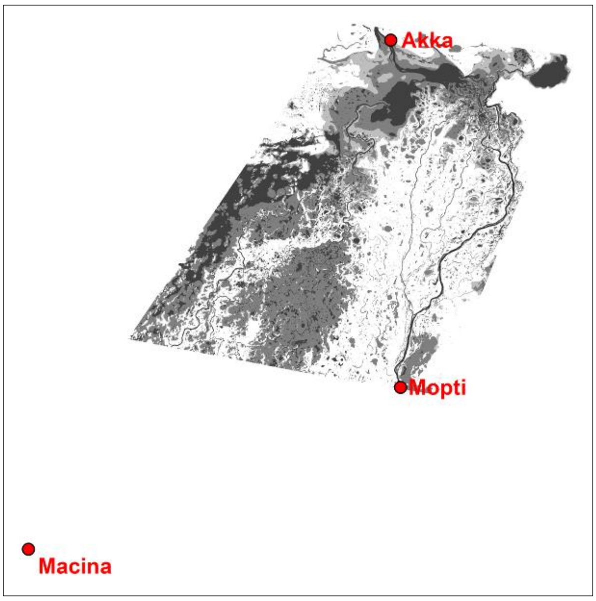
The hereby presented habitat model is considered to be the first step towards setting up more complex habitat models that are ready to be used for supporting management.

3.1 Calculation of depth maps

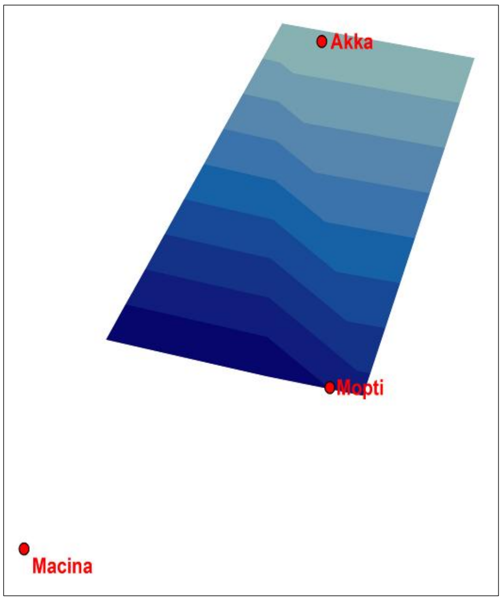
Since the hydrodynamic model (Chapter 2) only covers a small area north of Mopti, which is of relative low importance for wildlife, a simple approach is used to calculate depth maps required for habitat models, assuming that the water levels in the plains can be projected from the water levels in the main river channel. In the area of the IND, data from three gauge stations are available (provided by the Regional Direction of Hydrology in Mopti) where water levels/discharge is recorded regularly: Akka, Mopti and Macina. Based on this data, an approximation of the sloping water tables in the different stages of the flood can be calculated based on a TIN layer using ArcGIS. Based on the water table layer and the DTM (see Chapter 2) a depth map can be calculated for each date where gauge data were recorded (Figure 11). A sequence of depth maps calculated for a hydrological year can be used to calculate the maximal water depth and duration of flooding, both important input variables for habitat modelling, or it can be directly used to calculate usable areas of aquatic habitat in the different zones of the Delta during different stages of the flood. Only the area north of Mopti was further used for analysis, since the accuracy of the DTM was of acceptable quality (see Section 2.1.2) for further analyses of habitat availability.



Raster of relative depth of terrain (DTM)



Depth map for the specific date. (Flooded areas are shown in grey scale)



TIN of water table for specific date

Figure 11. Calculation of water depth maps for the area from Mopti (south-east) to the central lakes around Akka based on the DTM and TINs of water tables calculated from data of three gauging stations.

3.2 Validation of depth maps

Satellite images (True Colour Composite) are used to calibrate and test the prediction of water coverage based on the above-described approach. Therefore, the area covered with water (aquatic vegetation and open water) is defined as the absence of red colour in the area using the red colour band in ArcGIS (see Figure 12).

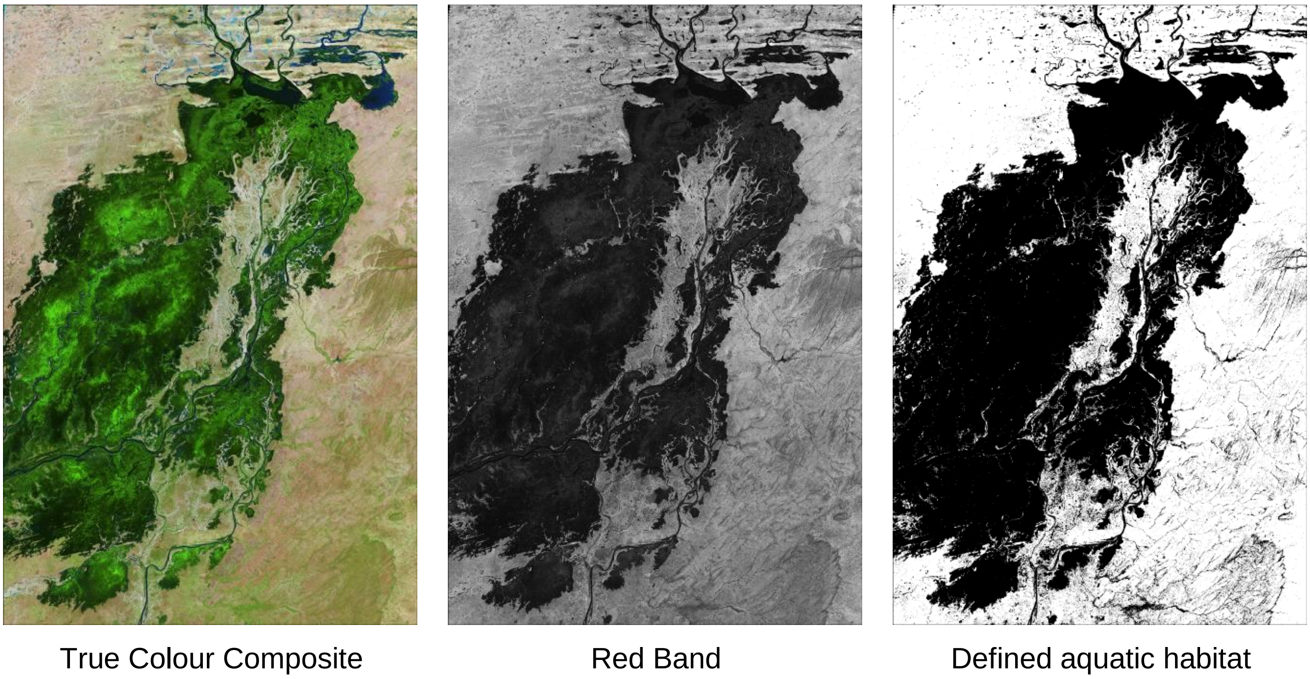


Figure 12. Definition of the aquatic habitat (right) at a given date (16.10.2003) based on the Red band (middle) of the True Colour Satellite image (left)

In a second step the aquatic habitat defined from the satellite images can be compared with the predicted flooded area based on the DTM and the water table TIN. For the available satellite images classification characteristics can be calculated and receiver operating characteristics (ROC) graphs were used to calculate and visualize the predictive performance (see e.g. Fawcett, 2006). Therefore areas of four classifiers are calculated: **true negative**: area with correct prediction with non-aquatic habitat, **true positive**: area with correct prediction for aquatic habitat, **false negative**: area with incorrect prediction of non-aquatic habitat and **false positive**: area with incorrect prediction for aquatic habitat (see Figure 13).

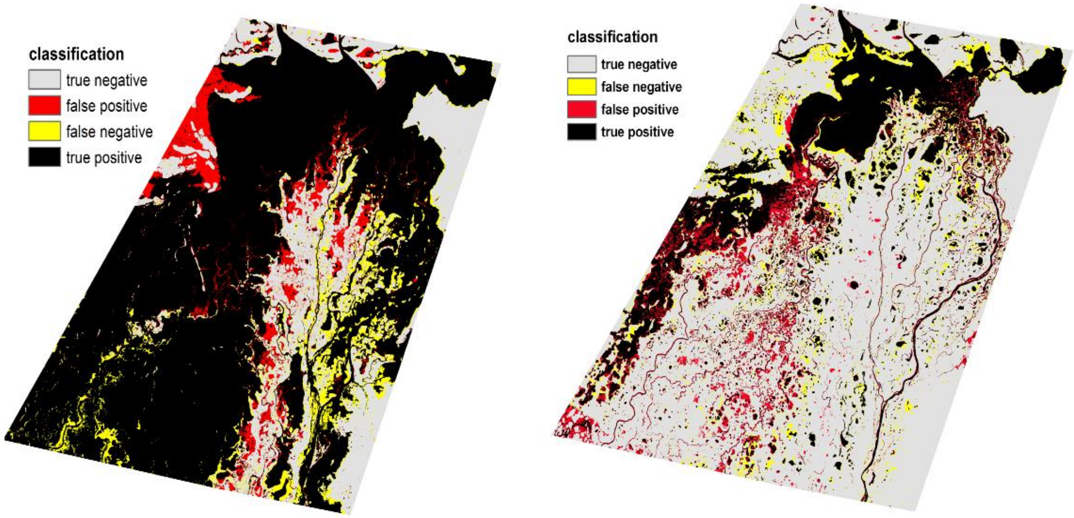


Figure 13. Correlation between the aquatic habitat defined based on satellite images and predicted based on the DTM and water table TIN for a date with high water levels (left, 16.10.2003) and low water tables (right, 08.02.2003): grey: correct prediction with non-aquatic habitat, black: correct prediction with aquatic habitat, red: false prediction with non-aquatic habitat and yellow: false prediction with aquatic habitat.

Based on the four classifiers the two input variables required for ROC analysis can be calculated the **true positive rate** as:

$$tp\ rate \approx \frac{\text{Positives correctly classified}}{\text{Total positives}}$$

And the **false positive rate** as:

$$fp\ rate \approx \frac{\text{Negatives incorrectly classified}}{\text{Total negatives}}$$

Both values are plotted in a receiver operating characteristics (ROC) graph (Figure 14.a), which compares true positive and false positive rate for each classifier. One point in the ROC space is the better the more it is situated in the upper left of the graph since a true positive rate of 1 and a false positive rate of 0 means perfect discrimination. On the other side the diagonal line (dashed line in Figure 14.a) marks the threshold for random classification, i.e. if a classifier is close to the diagonal line the predictive power of a model is not better than by chance. The lower left corner marks predictions that are worse than by chance.

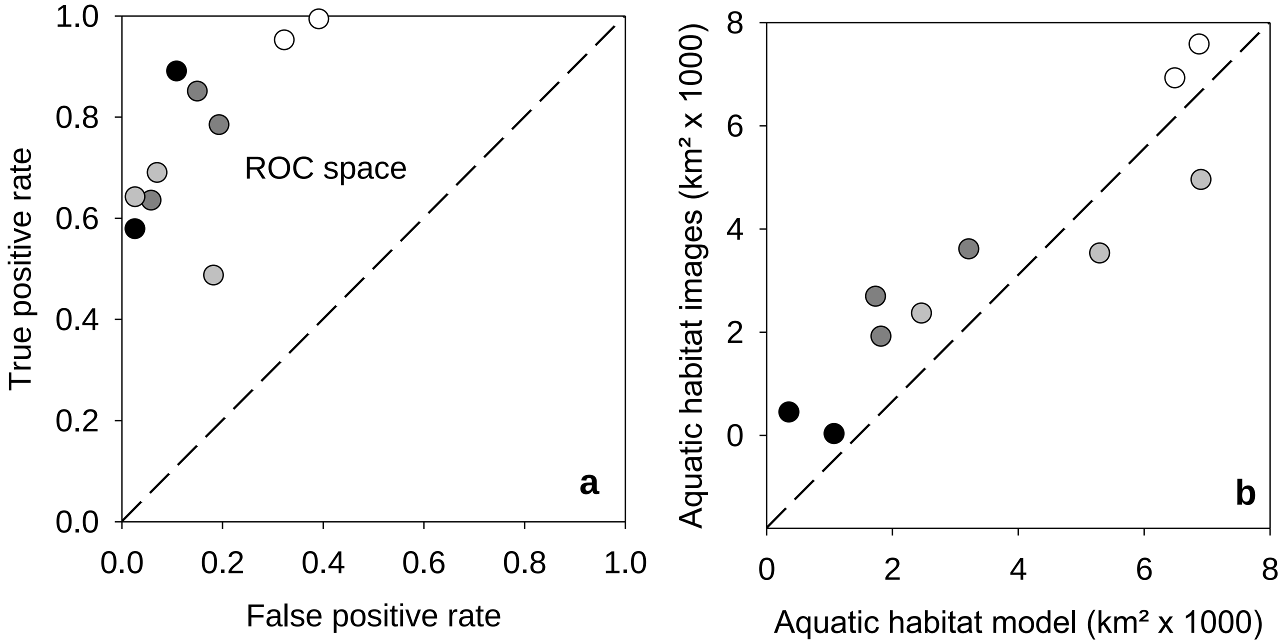


Figure 14. Valuation of predictive power of the prediction for aquatic habitat via a) ROC graph and b) comparison of predicted (model) and "real"(sat images) total aquatic habitat based on nine available satellite images for the IND showing different stages of flooding: black: dry period, white: peak levels, light grey: increasing water levels (crue) and dark grey: decreasing water levels (decrue).

Figure 14.a shows the results of ROC analysis, while Figure 14.b shows the comparison of predicted and actual (based on satellite images) total area of aquatic habitat for ten satellite images showing different stages of the flood. In general the position of the values shows reasonable predictive performance in the ROC space, except for early crue (27.8.2001) showing reduced values. Comparison of predicted and actual total flooded area shows that values for increasing water levels are slightly overestimated whereas values for decreasing water levels are underestimated, what can mainly be explained due to the fact that depressions get filled in a later stage of the flood and remain flooded when the flood level in the surrounding area has already decreased. This problem can basically only be solved with true hydrodynamic modelling (see Chapter 2). For an overview of the impact of different flood pattern on the habitat availability at large scale, estimations can be based on the selected approach.

3.3 Key habitat types

Flood levels in the Inner Niger Delta show drastic differences between the investigated years and are altered due to construction of dams in the upstream region. Additionally the IND has a high vulnerability to drought, due to the temporal and spatial variability in rainfall, as well as to the uncertainty of climatic conditions. The seasonal aquatic/semi-aquatic vegetation of the Inner Niger Delta is dominated by floating grasses. The occurrence of the different vegetation associations is determined by the flood pattern during wet season based on flooding duration and water depth at a given point at the flood peak (Zwarts et al. 2005).

Bourgoutiere is mainly dominated by the floating grasses *Echinocloa stagnina* (the local name is Bourgou) and *Vossia cuspidata* (the local name is Dideré) and is of dominance in long lasting inundation zones with a maximal depth of 2-5 meters and a flood duration of 5-7 months. The deeper zones are dominated by bourgou, whereas the shallower areas are dominated by Dideré; in between mixed plots can be found (Kone, Wymenga, Diallo, 2002, Zwarts et al 2005). Planted bourgou can grow up to a depth of 6 meters with a flood duration of approx. 8 month (Zwarts et al. 2005). A large proportion of the bourgou fields is planted by the local communities and used for grazing of sheep, goat and cattle.

Floating rice (Oryzaie): wild rice grows at a water level between 1-2 meters depth and requires an inundation period of at least 3 months (Quensiere 1994). Plots of floating wild rice are dominated by *Oryza longistaminata,* which is an important food source for local population. In the suitable areas sometimes other varieties of rice like *Orya sativa* and *Oryza glaberrima* are planted by local communities.

Water lily (Nenuphar) grows under the same conditions as bourgoutiere and floating rice and forms plots within this two vegetation types. The main taxa of this vegetation type are *Nymphaea* and *Utricularia* (Zwarts et al. 2005).

Vetiveraie: This vegetation type is dominated by the grass *Vetivera nigritiana* and occurs on the highest elevated parts of the flooded area, showing lowest water depth and low flood duration (Hievernaux, 1982).

Flooded forests constitute of *Acacia kirkii* (an endemic species) and *Zyzhyphus mauriciana*. The water level in the forest stands can even exceed 3 meters of water depth depending on flood water levels in different years. Under natural conditions large areas of the IND were covered by flood forests. Due to human activities only few plots remained having and important ecological function.

Open water can be defined as area without floating vegetation. If the water bodies are not suitable for growth of vegetation (flood duration >8 month and water depth >6 meters) it is open water. If these water bodies dry up they become a **mudflat**.

3.4 Key species

Because of availability of literature records and data required for habitat assessment, birds and fish can be selected to describe ecosystem health in the IND. 111 species of water birds (Zwarts et al. 2005) and 138 species of fish (RAMSAR sheet IND) are recorded for the IND with approx. 60% and 10% are analysed for their habitat preferences in the IND respectively.

Table 1 shows the habitat parameters for 10 important **bird** guilds. Many of them are either listed as vulnerable or threatened according to IUCN red lists or are threatened or vulnerable in Europe or locally in the IND. Mainly dependent on the foraging strategy of the species groups different habitat types are preferred for feeding. For example species that catch their food, while they are wading (waders, herons), require shallow water. Whereas species that have swimming/diving foraging strategy (e.g. pelican, geese and ducks) require deeper water and species with areal foraging strategy (e.g bird of prey) are independent from water depth. There are also specific preferences for the different habitat types, whereas diving species (e.g cormorant) prefers open water e.g. moorhen and jacarna are dependent on vegetation types and cover. The main breeding habitats are the flooded forest stands, and floating vegetation (flooded or dried up). The breeding success in flooded forest colonies depends on the reached water level If it is lower than 2 meters at the peak level, the forest is accessible for people and eggs are taken as food source. Flood levels in the flooded forest stands are sufficient, if the flood level at Akka reaches a value of 450cm (Mori Diallo, personal communication).

Different **fish** species are known to require bourgoutiere as spawning ground and for the larval development (13 rare or threathened species e.g. *Citharinus citharus, Distichodus bevipinus, Gymnarchus niloticus, Malapterus electricus, Tetraodon;* Henne Ticheler, Fish diversity workshop in IND 1999-2000) The optimal maximal water depth is >2 meter, if the water level is lower or flood duration is shortened, reproductive success is reduced (Kersten, Kodjo & Diallo 2006).

Table 1: Habitat parameters for 10 bird species guilds of the Inner Niger Delta. C: source: [1] Bird Life International (2010), [2] Zwarts & Diallo (2001), [3] Van der Kamp, Diallo, Fofana (2001), [4] Van der Kamp, Zwarts, Diallo (2001), [5] Diallo, Fofana, Van der Kamp (2002), [6] Diallo, Fofana (2009); Status: IUCNv: vulnerable according to IUCN red list, IUCNnt: near threatened according to IUCN red list, EC: vulnerable in Europe (criterion 2-3, Heath & Evans 2000), v: vulnerable in the IND (Van der Kamp, Diallo & Fofana, 2002), t: threatened in the IND (Van der Kamp, Diallo & Fofana, 2002); underlines mark Afro-tropical species others are Palearctic.

Species	Common name	Status	Feeding ground	Nesting ground	C
Hen/Jacana					
Gallinula chloropus	Lesser Moorhen				4
Porphyrio porphyrio	Purple Swamphen	v	Bourgoutiere + rice, deep (>1 meter)	Bourgoutiere + rice, deep (>1 meter)	4
Micropara capensi	Lesser Jacana				4
Actophilornis africana	African Jacana				4
Herons					
Ardea cinera	Grey Heron				2
Ardea purperea	Purple Heron				2
Agretta Alba	Great Egret		bourgoutiere + rice, shallow (0-1 meter)	flooded forest (deep >2m)	2
Egretta ardesiaca	Black Heron	v			2
Egretta intermedia	Intermediate Egret				2
Egretta gularis	Western Reef-Egret	v			2
Egretta garzetta	Little Egret				2
Bubilcus ibis	Cattle Egret				2
Ardeolla ralloides	Squacco Heron				2
Bautorus striatus	Striated Heron				2
Bautorus stellaris	Great Bittern	EC			2
Nycticorax nycticorax	Black-crowned Night-heron				2
Gees/Ducks					
Dendrocygna bicolor	Fulvous Whistling-Duck				3
Dendrocygna viduata	White-faced Whistling-Duck				4
Plectroptrus gambensis	Spur-winged Goose		bourgoutiere + rice and water lily, deep (>1 meter)	bourgoutiere + rice, dry (0 meter)	4
sarkidionis melanotos	Comb Duck				4
Alopochen aegyptius	Egyptian Goose	v			4
Nettapus auritus	African Pygmy-Goose	v			4
Anas acuta	Northern Pintail				4
Ans querquedula	Garganey				4
Species	**Common name**	**Status**	**Feeding ground**	**Nesting ground**	**C**
Bird of prey					
Asio capensis	African marsh owl		bourgoutiere + rice	bourgoutiere + rice	6

Milvus migran	Black Kite		bourgoutiere + rice	flooded forest (deep >2m)	6
Pandion haliaetus	Osprey				6
Haliaetus vocifer	African Fish-Eagle				6
Circus aeroginesus	Western Marsh Harrier				6
Passerines					
Riparia riparia	Sand martin		bourgoutiere + rice		6
Motacylla flava	Yellow wagtail				6
Acrocephalus paludicola	Aquatic warbler	IUCNv			7
Crane					
Baleorica pavonina	Black Crowned Crane	IUCNv	mudflat, shallow (0-1 meter)	bourgoutiere + rice, shallow (0-1 meter)	*5*
Waders					
Rostratula bengalensis	Greater Painted Snipe		mudflat, shallow (0-1 meter)	mudflat + bourgoutiere + rice, dry (0 meter)	5
Pluvianus aegyptius	Egyptian Plover				6
Glareola pratincola	Collared Pratincole				6
Burhinus senegalensis	Senegal Thick-knee				6
Vanellus spinosus	Spur-winged Plover				6
Vanellus tectus	Black-headed Lapwing				6
Charadrius pecuarius	Kittlitz's Plover				6
Himantopus himantopus	Black-winged Stilt				6
Limos limosa	Black-tailed Godwit				6
Numenius arquata	Eurasian Curlew				6
Tringa erythropus	Spotted Redshank				6
tringa stagnatilis	Marsh Sandpiper				6
Tringa nebularia	Common Greenshank				6
Tringa glareola	Wood Sandpiper				6
Tringa hypoleucos	Common Sandpiper				6
Gallinago media	Great Snipe	IUCNnt			6
calidris minuta	Little Stint				6
Calidris ferrigenea	Curlew Sandpiper				6
Philomachus pugnax	Ruff				6
Species	**Common name**	**Status**	**Feeding ground**	**Nesting ground**	**C**
Waders (long-legged)					
Mycteria Ibis	Yellow-billed Stork		mudflat, bourgoutiere + rice, shallow (0-1 meter)	flooded forest (deep >2m)	3
Leptoptilos crumenuferus	Marabou Stork				3

Threskiornis aoegypticus	Sacred Ibis	v			3
Plegadis falcinellus	Glossy Ibis				3
Platalea alba	African Spoonbill	v			3
Cicinia ciconia	White Stork	EC			3
Platalea leucorodia	Eurasian Spoonbill	EC			3
Divers/Pelican					
Phalacrocorax africanus	Long-tailed Cormorant		open water, deep (>2 meter)	flooded forest (deep >2m)	1
Anhinga rufa	African Darter	v			1
Pelecanus onocrotalus	Great White Pelican	t			1
Terns/Gulls					
Chkydonias hybridus	Whiskered Tern	EC, t	open water, deep (>1 meter)	bourgoutiere + water lily (>2 meter for the 2 first species , dry (0 meter) for the little tern)	6
Chlydonias leucopterus	White-winged Tern				6
Sterna albifrons	Little Tern				6
Larus fuscus	Lesser Black-backed Gull				6
Gelochelidon nilotica	Gull-billed Tern				6
Sterna caspia	Caspian Tern				6

3.5 Habitat assessment

An important factor is that the availability of described habitats can change dramatically during the flood period. Zwarts et al (2005) could show that a bird density estimation assuming constant bird densities during the flood period led to underestimations at low water levels compared to actual counts leading to the conclusion that birds aggregate at the remaining small habitat areas. Therefore, it is important to analyse temporal changes in habitat availability during the flooding season. For example we showed changes in habitat availability in monthly steps during decrue for four selected years differing in flood level and flood duration (see Figure 15): 1987 a year with low water level and flood duration; 1974 a year with high water level and flood duration and 1972 and 1973 years with similar flood level and high and low flood duration, respectively. The years 1973 and 1987 have similar flood duration, but are different in flood level. We concentrated on the vegetated habitat areas since for the largest areas with open water (central lake systems, see black area in Figure 16 and Figure 17) no information on depth levels was available.

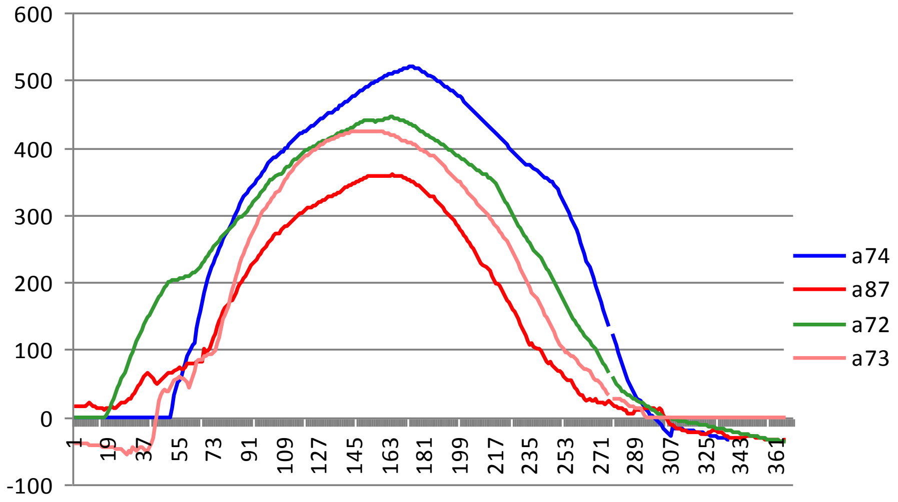


Figure 15. Water levels at Akka for four selected years.

3.5.1 Area with bourgoutiere and rice

Potential area suitable for growth of bourgoutiere and floating rice defined by depth range (1-6 meter) and flood duration (3-8 month) is presented in Figure 16. In the upper IND region total area was similar for all selected years, whereas in the lower region it was found to be largest in 1974, followed by 1972 and 1973, while smallest in 1984.

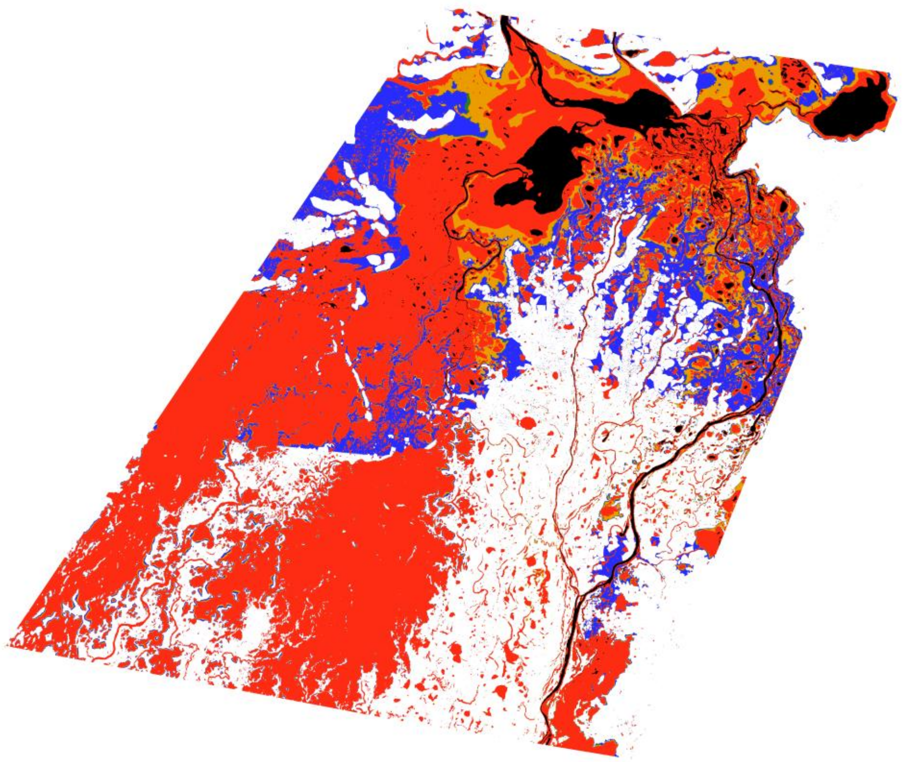


Figure 16. Predicted area suitable for growth of bourgoutiere and floating rice defined by depth range (1-6 meter) and range of flood duration (3-8 month). red: 1987, blue: 1974, orange: 1972 and 1973.

3.5.2 Distribution of depth zones over flood period

Figure 17 shows availability of preferred feeding habitats for wading birds (water level 0-1m) in a monthly interval during decreasing water levels in a wet year (1974, left) and dry year (1987, right). Overall it can be seen that in the dry year large parts of the delta reach the optimal depth range between November and April whereas in the dry year it ranges mainly from December to February. Additionally, there was a difference between the upstream and downstream region, in the upstream region (close to Mopti) habitat availability was highest between December and February, whereas it was highest between January and March in the downstream region (close to Akka) and north-west.

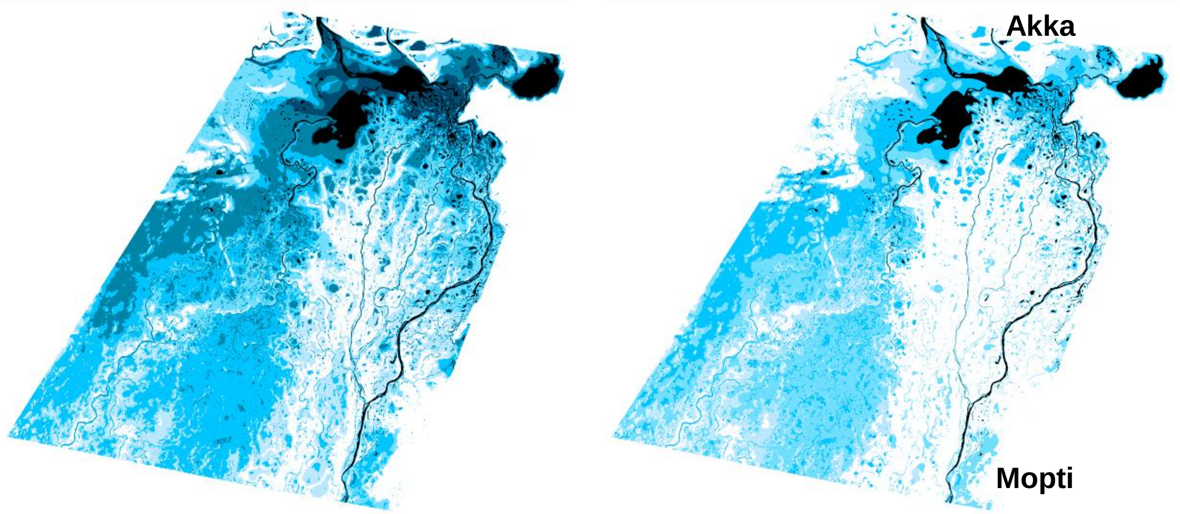


Figure 17. Monthly availability of preferred feeding habitat for wading birds (water level 0-1m) during decreasing water levels in a wet year (1974, left) and a dry year (1987, right). Colour ranges from light blue: available at flood peak between November and December and dark blue: available at late decrue between March and April. The permanent/semi-permanent water bodies where no depth profile is available are marked in black.

3.5.3 Habitat type and depth

Combining both, depth and habitat type, trends in availability of habitat for different species groups were analysed. Figure 18 shows change in availability of habitat most relevant e.g. for herons and long-legged waders (bourgoutiere and floating rice with shallow water 0-1 meter). Generally during flood peaking (Nov-Dec) the availability of this habitat type was low, the flood level in the vegetation zones exceeded one meter. When comparing the different years, it was evident that habitat availability was shorter and in sum much lower in the dry year (1987) than in the wet year (1974). For the years differing only in flood duration (1972 and 1973) also the duration of availability was shorter for the year with short flood duration, but the overall area was similar. Comparison of the two years (1987 and 1973) only differing in flood level showed mainly a difference in sum and low difference in duration.

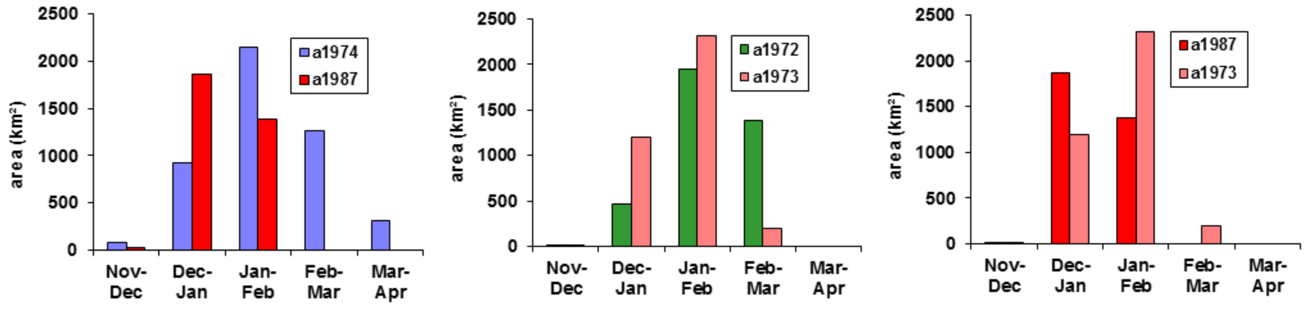


Figure 18. Monthly availability of preferred feeding habitat for herons and long-legged waders(water level 0-1m, bourgoutiere and floating rice) during decreasing water levels in left: a wet year and dry year, middle: years differing in flood duration and not in flood depth and right: years differing in flood level and not in flood duration.

The trend in availability of preferred habitat for e.g. geese, ducks, hen and jacana (water level >1m, bourgoutiere and floating rice) was different. Habitat availability was highest at the flood peak. Between the dry and wet year (1987 and 1974) duration as well as total available area were largely different, but also between the years only different in flood duration (1972 and 1973) both (duration and total area) were different. For the years differing only in flood level (1987 and 1973) mainly the total area was different and the duration differed slightly.

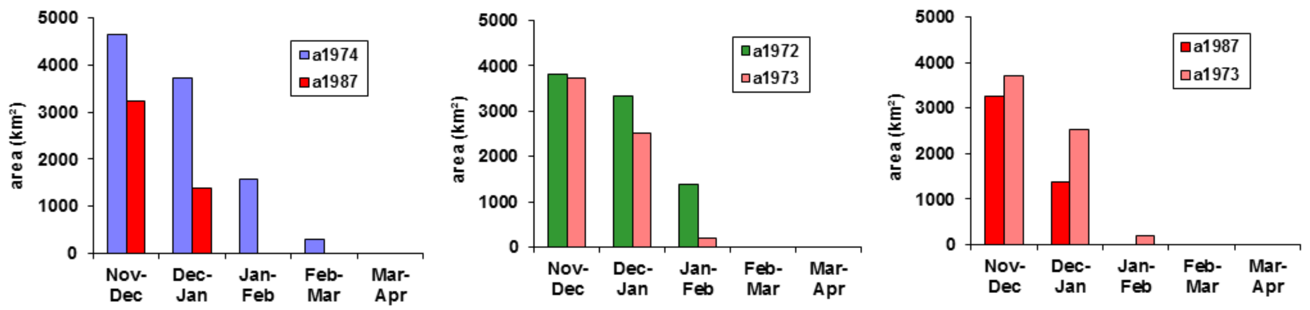


Figure 19. Monthly availability of preferred feeding habitat for gees, ducks, hen and jacana (water level >1m, bourgoutiere and floating rice) during decreasing water levels in left: a wet year and dry year, middle: years differing in flood duration and not in flood depth and right: years differing in flood level and not in flood duration.

Based on the results presented, it can be concluded that the used habitat model approach has a high potential to predict impacts of different aspects of the flood regime (duration, water level) due to damming/reservoir management or climate change impacting both, the duration and peak level of the flooding season. The prediction power can be increased significantly by using an accurate hydrological model.

3.6 Recommendation for improvement

Besides the recommended improvements regarding the DTM (Section 2.1.3), including a depth profile for the permanent/semi-permanent areas, and hydrodynamic modelling (Section 2.2), further recommendations can be made regarding the analysis of habitat requirements:

- Further field work would be an important step to enhance knowledge about requirements of single bird and fish species. For some bird species Zwarts et al. (2005) could show differences in bird densities in different habitat types, also within guilds.

- These differences in bird densities for different habitat types may be explained to some extend by habitat preferences themselves and to some extend by an aggregation effect due to change in availability of total habitat area during flooding season, thus, an important question for further research.
- To link feeding and breeding habitats for birds it would be essential to gain more knowledge on feasible flight distances between these habitats, especially for the birds breeding in the flooded forest stands, which form only few and small patches in the Delta.
- In general one of the most important factors determining fish distribution (adult and juvenile) is distribution of flow velocity. As hydrodynamic modelling can show these patterns in the Delta, the knowledge on velocity requirements for various fish species (and age classes) would be a necessary requisite. Thus, a more integrated and targeted sampling will be required.
- Different fish species spawn in bourgou fields. For those species it would be important to know the time span that is needed for egg and larval development to make a more precise prediction of required flood duration.
- A further important factor for (lateral) migrating fish is the hydrological connectivity of the different parts of the plain (duration and timing) to the main channel. Flooded areas can only be relevant for reproduction, if they are accessible for spawning and for migration of the juvenile fish to the main river before the dry period. Therefore also detailed knowledge on the reproductive cycle of the species would be an important factor to be investigated.

4 Water quality modelling in the IND

People living in the Inner Niger Delta are often threatened by waterborne diseases such as diarrhea and cholera. The pathogens of these diseases are coliform bacteria, which enters the environment with human waste waters. Since none of the settlements of the IND is equipped with wastewater treatment plants, the produced wastewaters are either desiccated locally or discharged into the waters of the Niger. In case of floods the proportion of wastewaters discharged into the water increases considerably. In addition, the flood helps to spread the bacteria over large areas of the IND. It is thus not by chance that diarrhea and cholera epidemics in the Delta usually coincide with the floods of the river.

To simulate the transport of coli bacteria in the water system of the IND, a water quality model has been set up and applied.

4.1 Model description

Calculation of the temporal and spatial distribution of coli bacteria in the selected subsystem of the IND was carried out with the help of a two-dimensional non-conservative transport model. This model was developed by VITUKI specifically for this task. Formulas from previous modelling studies (Szél & Józsa 1990; Aizawa et al., 2005) dealing with the transport of suspended materials and coli bacteria were adapted. The model calculates the concentrations of bacteria within the modelled area by solving the baseline differential equation with the help of the finite differences numerical method.

4.1.1 The baseline equation

The propagation of coli bacteria in a water system like the Inner Niger Delta is adequately described by the two-dimensional equation of transport of dissolved and suspended matter in shallow waters:

$$\frac{\partial C}{\partial t}+U\cdot\frac{\partial C}{\partial x}+V\cdot\frac{\partial C}{\partial y}-\frac{1}{h}\cdot\frac{\partial}{\partial x}\left(h\cdot D_{xx}\cdot\frac{\partial C}{\partial x}\right)-\frac{1}{h}\cdot\frac{\partial}{\partial x}\left(h\cdot D_{xy}\cdot\frac{\partial C}{\partial y}\right)-\frac{1}{h}\cdot\frac{\partial}{\partial y}\left(h\cdot D_{xy}\cdot\frac{\partial C}{\partial x}\right)-\frac{1}{h}\cdot\frac{\partial}{\partial y}\left(h\cdot D_{yy}\cdot\frac{\partial C}{\partial y}\right)=S$$

Where:

h : water depth (m)

C : concentration of bacteria (CFU/m^3) (CFU: coliform unit)

U, V : depth-average flow velocities in the *x* and *y* directions (m/s)

D : dispersion tensor (m^2/s)

S : source/sink of bacteria (CFU/m^3/s)

Water depth (*h*) and depth-averaged flow velocities (*U*, *V*) are the hydrological boundary conditions, which are derived either by monitoring or by hydrodynamic modelling.

4.1.2 Calculation of coliform sources and sinks

The sources of bacteria in the waters of the IND are the settlements that discharge their communal wastewaters into the river without treatment. In the model, these settlements appear as point-sources of bacteria, where the actual loads are calculated as a function of population size:

$$L=n\cdot l\cdot\left(1-\frac{s}{100}\right)\cdot\eta$$ for non-inundated settlements with sewer systems

$$L = n \cdot l$$ for inundated settlements

Where:

L : Load of bacteria (CFU/day)

n : population size of the settlement (head)

l : Number of coliform bacteria emitted by a single individual in one day (CFU/head/day)

s : rate of waste water purification in the settlement (%) - this is practically 0 in the IND

η : rate of collected and total emitted waste waters in case of a settlement with sewer systems (-)

In case of settlements without any sewer systems, no coliform load is accounted for if the settlement is not inundated. It is assumed that all the bacteria get killed while the waste water is desiccated locally.

Mortality of bacteria in the water (sink) depends on water temperature, transport time, solar radiation and relation with other bacteria. In case of high solar radiation, water temperature may change quickly along depth. Because information from the site is very uncertain, we adopted the formula developed for the Mekong Delta (Aizawa et al., 2005) for calculating bacteria mortality as a function of radiation and depth:

$$m = 117.64 \cdot e^{-0.0033 \cdot R}$$ at *h* = 0.2 m

$$m = 129.97 \cdot e^{-0.0007 \cdot R}$$ at *h* = 1 m

$$m = 113.59 \cdot e^{-0.001 \cdot R}$$ at *h* = 2 m

$$m = 217.33 \cdot e^{-0.0029 \cdot R}$$ at *h* = 3 m

$$m = 204.9 \cdot e^{-0.0021 \cdot R}$$ at *h* = 4 m

Where:

R : the effective solar radiation ($J/cm^2/day$)

m : rate of mortality (%)

For calculating the effective solar radiation, the formula of Aizawa et al., 2005 was used:

$$R = \left(1 - \frac{A}{100}\right) \cdot R_{max}$$

Where:

R_{max} : solar radiation above the water surface ($J/cm^2/day$) (meteorological boundary condition)

A : degree of absorption (%)

The degree of radiation absorption depends on the concentration of suspended solids (Aizawa et al., 2005):

$$A = 0.0809 + 0.0146 \cdot SS$$

Where:

SS : concentration of suspended solids (g/m^3)

4.2 Application of the model in the IND

The coliform bacteria transport model has been set up for the investigated sub-system of the Inner Niger Delta (see Figure 9). The hydrological boundary condition was a characteristic flood wave passing through the sub-system during the flood season of the year. This flood wave was defined as a series of steady hydrological states (Figure 20). At each step of this simplified flood wave, the spatial distributions of hydrodynamic parameters (*h*, *U*, *V*) were calculated with the help of the River2D model (see Section 2.2).

Meteorological boundary conditions for bacteria transport modelling were solar radiations reaching the water surface. Average daily radiations, calculated from measurements from 1960-2001, were used as daytime radiations (Figure 20), while 0 radiation was taken into account during the night-time period of the day.

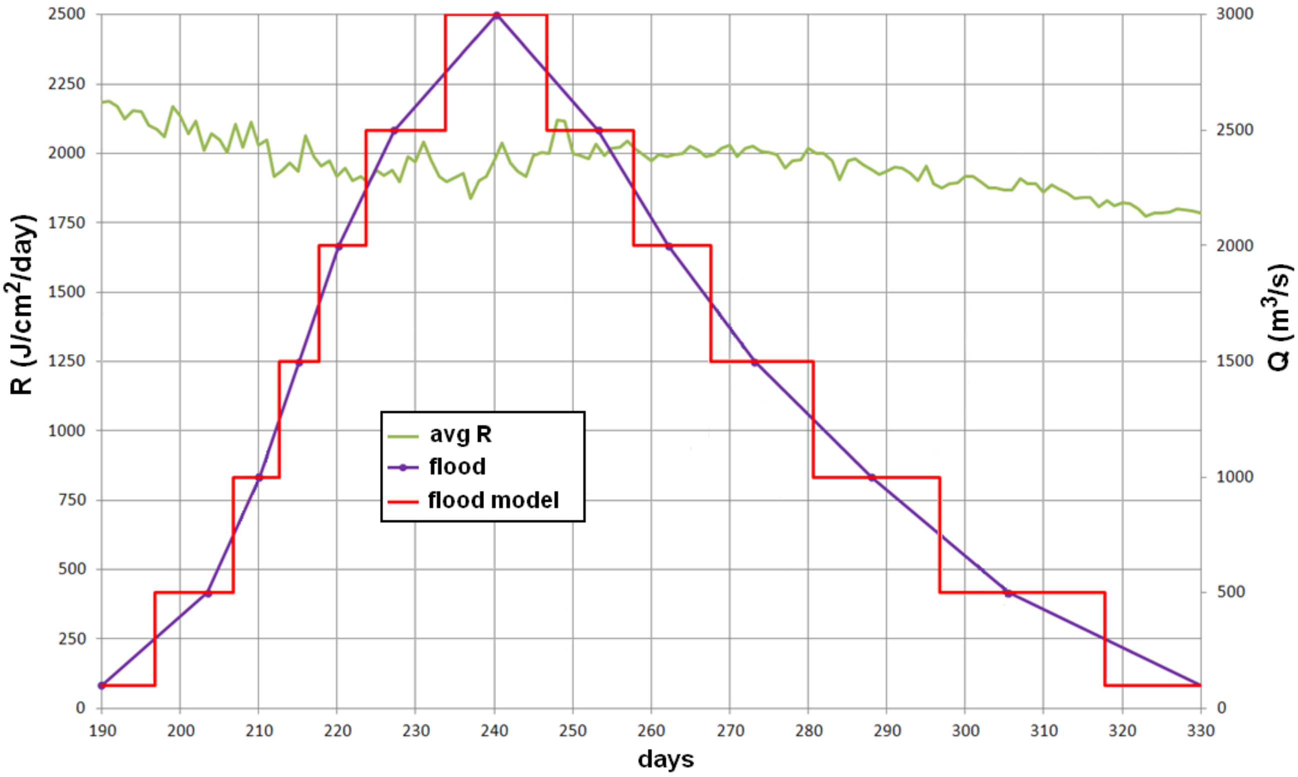


Figure 20. Hydro-meteorological boundary conditions for coliform transport modelling in the IND

Coliform bacteria are loaded into the river system whenever a settlement gets flooded and its communal wastewaters get washed into the system. In case of sewered settlements, wastewaters are kept on being loaded into the system during flood-free periods too. As mentioned before, no coliform load is accounted for if a non-sewered settlement is not inundated; it is assumed that all the bacteria get killed while the waste waters are desiccated locally. Figure 21 shows the locations of those settlements that have been taken into consideration as coli bacteria sources in the model.

Thus, the actual coli bacteria load into the modelled water system depends on: hydrological conditions, advancement of the sewer system and the wastewater production of the settlement. Wastewater production is calculated from the population size using the assumption that one person produces 29.4 l wastewaters a day (Table 2). The actual coli bacteria content of the wastewater is derived from the generic mean bacteria concentration of human wastewaters that is 20,000,000 bacteria/l.

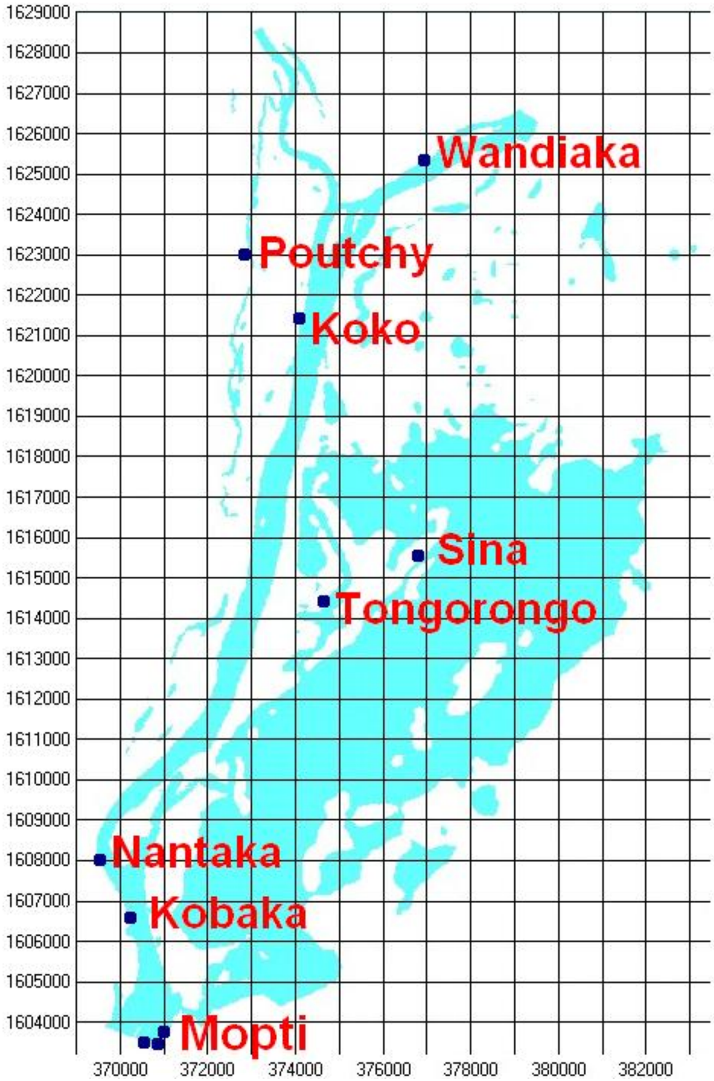


Figure 21. Locations of settlements from where coliform bacteria could enter the water system during the flood season: settlements being inundated by the characteristic flood wave of the river (see also Figure 20)

Table 2: Wastewater productions of the settlements

SETTLEMENT	Population size	Wastewater production (l/d)
Koko	812	23872,80
Wandiaka	1537	45187,80
Mopti - Komoguel	11564	339981,60
Mopti - Nouveau quartier	5953	175018,20
Mopti - Taikiri	3584	105369.6
Sina	525	15435,00
Poutchy	745	21903,00
Kobaka	893	26254,20
Nantaka	1309	38484,60
Tongorongo	1333	39190,20

4.3 Results

The results of model-based simulation of coli bacteria transport in the selected subsystem of the Inner Niger Delta are shown by the **coliformtrans_IND.wmv** animation file, which is an attachment of this report. Frames of this movie are shown on Figure 22, Figure 23 and Figure 24.

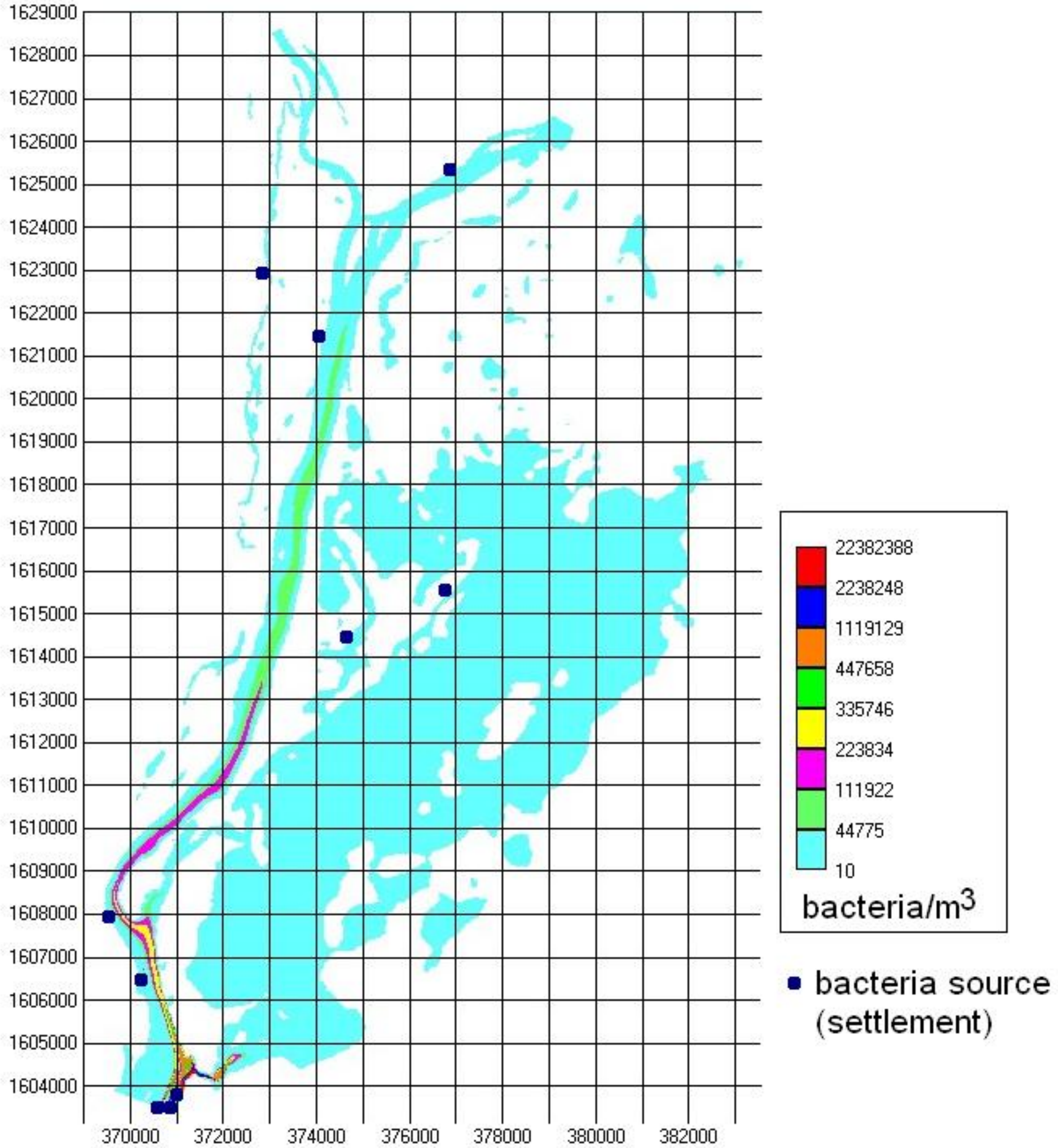


Figure 22. Simulated coli bacteria concentrations in the modelled sub-system of the IND 6.75 days after the start of the simulation, when the total discharge was 100 m^3/s

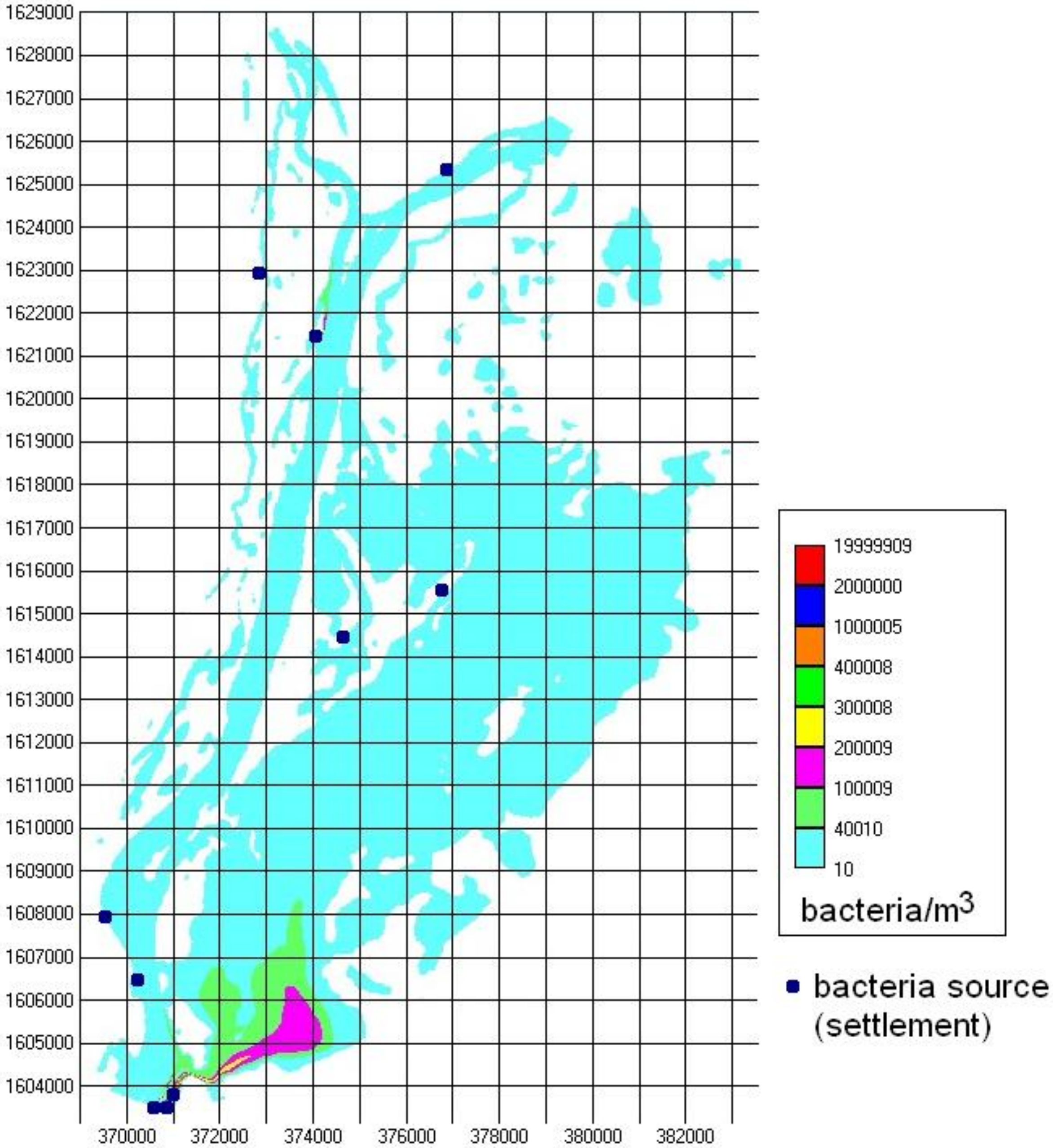


Figure 23. Simulated coli bacteria concentrations in the modelled sub-system of the IND 16.79 days after the start of the simulation, when the total discharge was 500 m^3/s

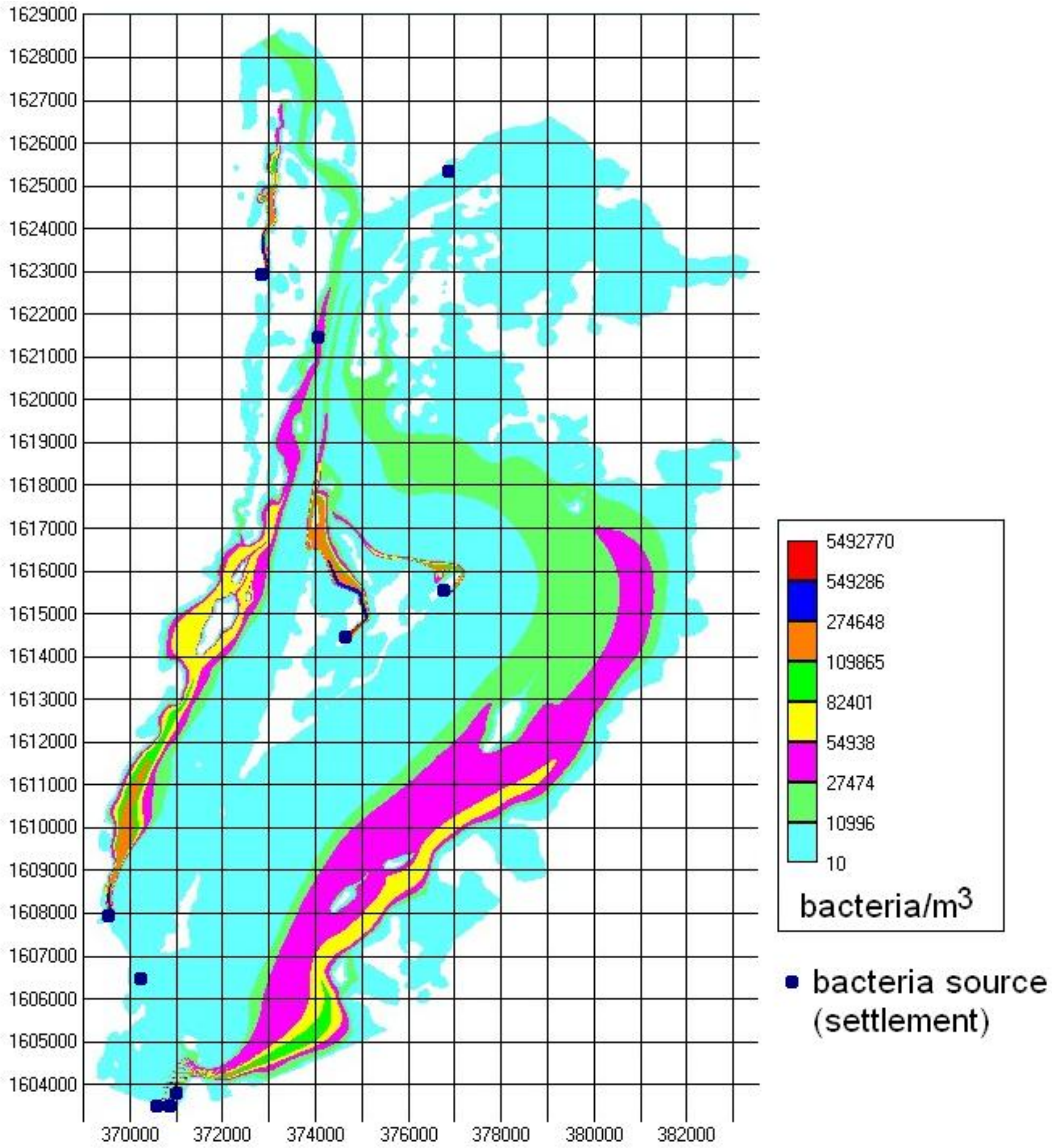


Figure 24. Simulated coli bacteria concentrations in the modelled sub-system of the IND 56.75 days after the start of the simulation, when the total discharge was 3000 m^3/s

According to these results, the relatively huge bacteria loads of Mopti town get fully diverted into the big floodplain on the right side of the main river channel, as soon as larger quantities of water start to flow out of the main channel through the small gap on the natural levee right downstream of the town (Figure 25). The reason is that the wastewaters of Mopti, discharged into the river from the right bank, don't have enough time to mix with the river's water in such a short distance. The wastewater plumes stay along the right bank and get diverted into the floodplain through the gap. This means that the entire bacteria load of Mopti is spread over these floodplain threatening the health of the people living over there.

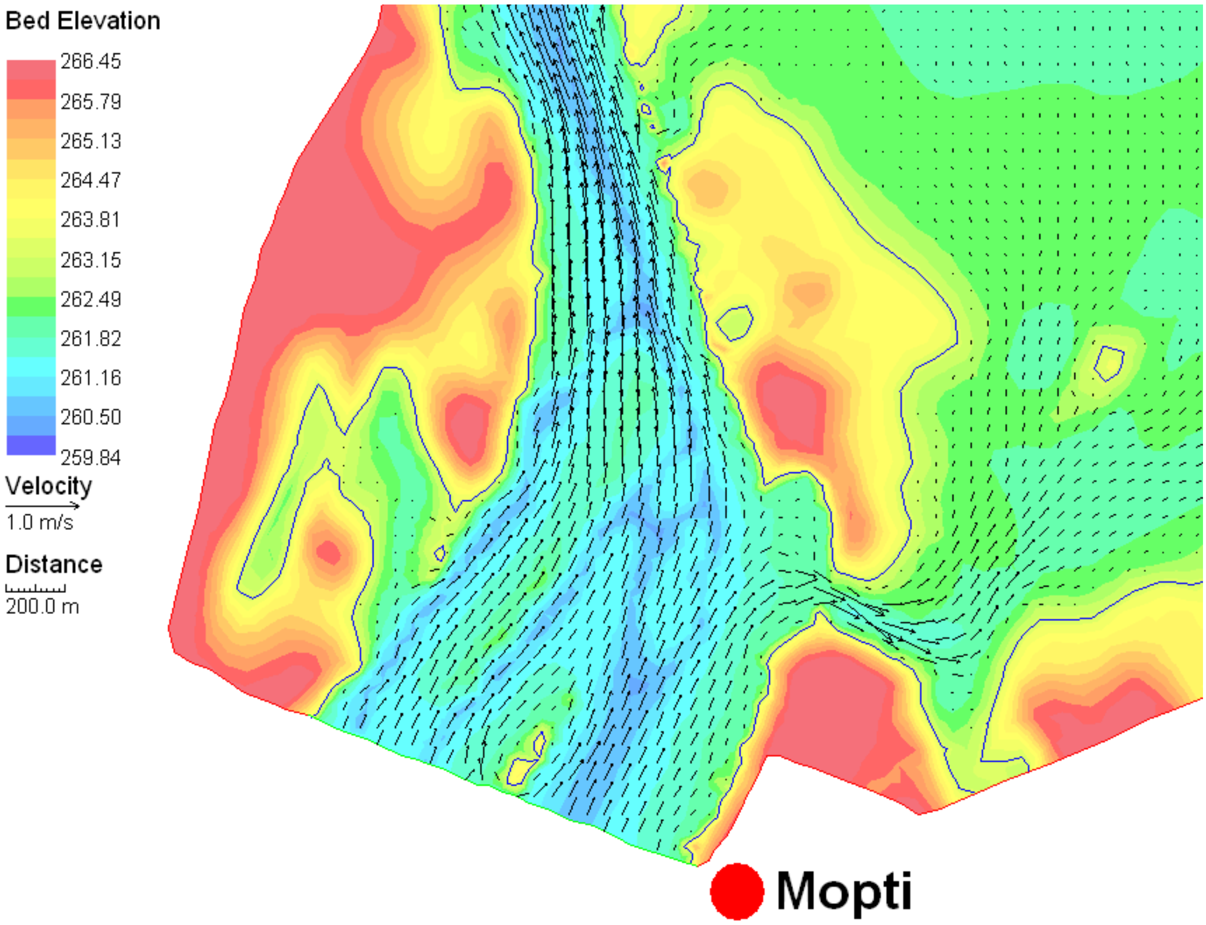


Figure 25. Flow velocities downstream of Mopti at a total discharge of 500 m^3/s: results of steady-state River2D modelling

We can thus conclude that small micro-topographical structures, such as the gap on the levee, have the potential to influence hydrological and water quality conditions over huge areas in the IND. The accurate representation of these structures in the hydrodynamic model is thus essential. At the present state, the River2D-based model doesn't meet this requirement. For example, that lateral gap downstream of Mopti hasn't been validated yet, by means of field measurements. It may even turn out that the gap is actually closed by an artificial levee, in which case the bacteria transport process would take a totally different way in the entire model area.

The model results also verify the observations that waterborne diseases tend to coincide with the floods of the Niger. As Figure 22 shows the bacteria transport stay in the main channel of the Niger at low flow. In case of higher discharges, bacteria are spread over the lateral floodplains and water bodies (Figure 23 and Figure 24), thus increasing the threat of diseases. In addition, the raising water levels involve more settlements into the bacteria loading, which enhance further the threat.

4.4 Recommendations

Accurate hydrodynamic input to the coli transport model is essential. Recommendations for improving the River2D-based model have already been given in Section 2.2.1. Hereby we only emphasize the importance of key micro-topographical and artificial structures, which have the potential to influence the hydrological and transport processes over large areas. Accurate representation of these structures likely requires field measurements. In case of controllable structures (e.g. sluices), it is equally important to acquire information about their operation and incorporate it into the model.

Like the hydrodynamic model, the coli transport model has to be calibrated and validated too. For this purpose, much more measured bacteria concentrations are needed from different locations of the IND and from different stages of the annual floods. Also the bacteria loads of the settlements need to be identified in a more accurate way.

The improved, calibrated and validated hydrodynamic and coli transport model-system has the potential to identify the regions within the IND, where coli bacteria related diseases, such as diarrhoea and cholera, are expected to occur under the different potential hydrological regimes. The model-system can support raising awareness among the communities with regard to the increased threats during floods.

The model-system is also applicable for real-time forecasting of floods and bacteria transport, given that adequate forecasts of incoming discharges are available. Prediction of discharges can be carried out with the help of basin-scale rainfall-runoff models such as the SWIM-based model developed by Liersch et al. (2012) for the Upper Niger Basin within the frame of the WETwin project. Forecasting of floods and bacteria transport will enable authorities and community leaders to warn people living in threatened sites and, if the situation demands, to organize preventive actions such as evacuation.

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Attachment

coliformtrans_IND.wmv : animation showing the spatial distribution of coliform bacteria concentrations over the modelled sub-system of the Inner Niger Delta at the different stages of the annual flood wave