

# Temporal and Spatial Sediment Modelling in Masinga Reservoir, Kenya

W. W. Saenyi

## Modellierung der räumlichen und zeitlichen Sedimentierung im Masinga Speicherbecken, Kenia

### 1. Introduction

Masinga dam was built during 1980–1981 to create a storage reservoir upstream of the Seven Forks Development Scheme. Its main function was to regulate the flow of the Tana River into the other four reservoirs (Fig. 1). Benefits in the river regulation are readily translated into an increased output of hydroelectric power through higher flexibility of reservoir operation and increased life spans of the reservoirs below Masinga dam. However, Masinga reservoir is threatened with serious siltation resulting from accelerated ero-

sion in Masinga catchment. The storage capacity of the reservoir is fast declining due to high rates of sedimentation (SAENYI, 2002). Masinga Dam was designed for a siltation rate of 3 million metric tonnes per year, but by 1988, 8 years after operation began, the siltation rate had more than tripled to 10 million tonnes per year and the reservoir capacity reduced by 6 % (BOBOTTI, 1998). At this rate, the lifespan of the dam will be drastically reduced. Therefore, sediment management strategies are required to mitigate the problem of siltation in Masinga reservoir and hence prolong its useful life. However, the remedial measures, which should

### Zusammenfassung

Die Sedimentation im Masinga-Becken wird ein ernstes Problem für die Kenianische Stromerzeugergesellschaft. Deswegen wurde zwischen 1999 und 2002 eine Studie im Masinga Staubecken durchgeführt. Ihr Ziel war es, den Sedimentationsprozess im Staubecken sowohl in zeitlicher als auch in räumlicher Hinsicht zu modellieren. Die Modellierung wurde unter Verwendung des numerischen Modells GSTARS 2.1 ausgeführt. Die Berechnung und Visualisierung der durch Messung und durch Simulation ermittelten Ergebnisse erfolgte gestützt auf ein zweidimensionales BOSS SMS computerbasiertes Modell, um 2 D Tiefenkonturenkarten zu erzeugen. Es war festzustellen, dass die meisten Ablagerungen entlang des Thalweges, entlang des Hauptkanales, an der Mündung des Speicherbeckens, am Zusammenfluss der beiden Arme und in der Nähe der Staumauer auftraten. Das Modell berechnet geringe Ablagerungen an den Staubeckenterrassen voraus.

**Schlagnworte:** Modellierung, Sedimentationsprozess, räumliche Sedimentverteilung, GSTARS 2.1, Masinga Staubecken.

### Summary

Sedimentation in Masinga reservoir is becoming a serious problem faced by Kenya electricity generating company. A study was therefore carried out on Masinga reservoir between 1999 and 2002. The objective was to model the sedimentation process in the reservoir in both temporal and spatial spectrum. Modelling was accomplished using GSTARS 2.1 numerical model. Processing and visualisation of measured and simulated results was done using a two-dimensional BOSS SMS computer-based model to generate 2-D depth contour maps. It was found that most deposition occurred along the thalweg, along the main channel, at the mouth of the reservoir, at the confluence of the two arms, and near the dam wall. The model predicted little deposition on the reservoir terraces.

**Key words:** Modelling, sedimentation process, spatial sediment distribution, GSTARS 2.1, Masinga reservoir, simulations.

be devised to curb siltation, in turn rely on the knowledge of the amount of sediment input into the reservoir and its spatial distribution. In this paper, an attempt was made to model the distribution of deposited sediments in Masinga reservoir using a numerical modelling approach. GSTARS 2.1 was used to model the sedimentation process while BOSS SMS was employed to analyse the results for visual presentation in two-dimensions.

The reservoir is narrow and dendritic in shape. The mean depth is only 13.8 m for a maximum of 47 m indicating that extended shallow areas are likely to dry out as water fluctuates in the reservoir. The bathymetric map of Masinga reservoir (Fig. 2) was traced by linear projection of 86 echo-sounding transects conducted in 1988 (BOBOTTI, 1998). A large part of the reservoir is characterized by lower depths, particularly in the upper sections. It is here that higher water level fluctuations are expected to occur. Of the two arms that compose the western part of Masinga reservoir, the Tana arm carries a large amount of the flows. During the flood period, water circulates from the Tana arm towards Thika river.

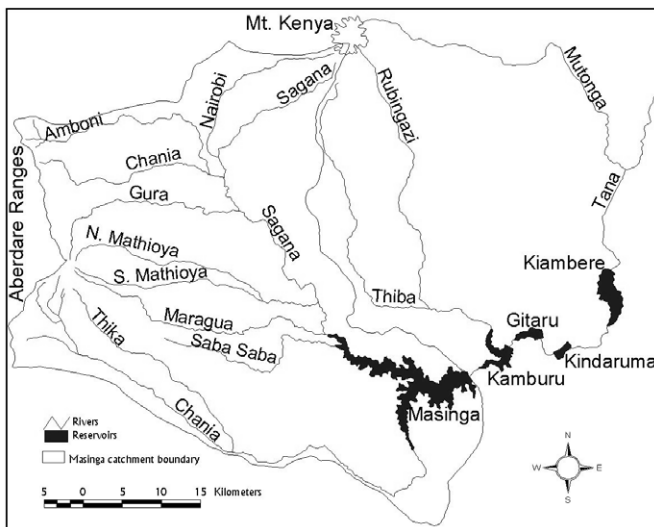


Figure 1: Location of Masinga catchment and reservoir  
Abbildung 1: Lage des Masinga Einzugsgebietes und des Staubeckens

## 2. Methodology

### 2.1 Database for Masinga Reservoir

Data used to run the numerical model, GSTARS 2.1, for simulating the sedimentation process in the reservoir are comprised of the bathymetric data, discharge into the reservoir, for both Tana and Thika arms, dam levels, water tem-

peratures, and sediment data. As is often true in many water and sediment transport modelling, it is not always possible to have all the required data, and so, one must manage with what is available. In this study, discharge data, water levels and temperatures were readily available. However, very little information was available on sediment load in rivers discharging into the reservoir. In this case, a suspended sediment generator was developed to compute the sediment load in the rivers discharging into the reservoir (SAENYI, 2002). Some information on sediments was obtained from literature for similar studies while in some cases, it was entirely assumed.

Bathymetric data corresponded to the stretch between Tana bridge and Masinga dam as well as the Thika arm as shown in Figure 2. These consisted of two sets: the 1981 survey data, measured before the reservoir was filled up and the 1988 echo-sounding survey conducted when the reservoir was full. For both sets of data, measurements were done for a total of 86 cross sections representing the main reach of approximately 45 km in length and a tributary (Thika arm) of about 15.1 km.

Hydrological data consisted of daily flows and water temperatures at the upstream end of the reach, and of daily reservoir levels at the downstream end. The input of these data into the model was done by use of the stage-discharge table at control station. Head loss due to friction on the channel bed was computed by the average slope method while Manning's equation was chosen for roughness calculations. The reservoir channel was divided into 3 stream

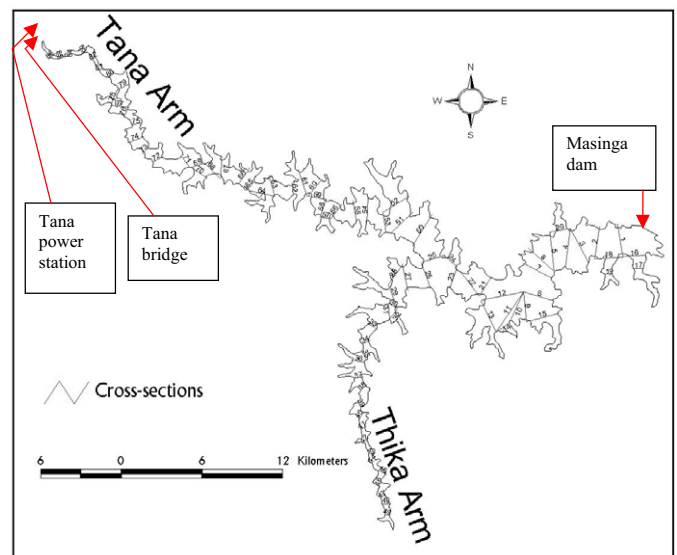


Figure 2: Plan view of Masinga reservoir showing cross sections  
Abbildung 2: Plandarstellung des Masinga Staubeckens mit Veranschaulichung der Querschnitte

tubes to represent the main channel, left, and right flood plains.

The bed material distribution over the simulated reach was known at specific locations and was interpolated for sections lying between those locations. Sediment discharge into the reservoir was specified as a function of water discharge. The functions were derived from the results of the WEPP model watershed simulations and were obtained using the least squares method (SAENYI, 2002). From the WEPP watershed model output, sediment-rating curves were developed for both Tana and Thika rivers. First, sediment concentration in the flow ( $\text{kg}/\text{m}^3$ ) was computed from runoff volume ( $\text{m}^3$ ) and sediment yield ( $\text{kg}$ ) results of WEPP Model. Sediment discharge ( $\text{kg}/\text{s}$ ) was then computed by multiplying sediment concentration with water discharge ( $\text{m}^3/\text{s}$ ). Plotting the logarithm of sediment discharge (metric tonnes per day) versus logarithm of water discharge ( $\text{m}^3/\text{s}$ ) gave the following relationships: for Tana;

$$Q_s = 0.421Q^{0.822}, R^2 = 0.917, n = 616 \quad (1)$$

and for Thika;

$$Q_s = 1.062Q^{0.714}, R^2 = 0.946, n = 204 \quad (2)$$

where  $Q_s$  is the sediment discharge in metric tonnes per day,  $Q$  is the water discharge in  $\text{m}^3/\text{s}$ ,  $R^2$  is the coefficient of determination, and  $n$  is the number of sediment yield events.

The above two functions were used as input into GSTARS 2.1 sedimentation model. It is the use of these two functions derived from WEPP model results that marks the connection point between the erosion prediction model (WEPP) and sedimentation model (GSTARS 2.1).

Reservoir sedimentation processes are essentially non-equilibrium, hence there was need to specify the non-equilibrium parameters. Since modelling was done for a reach with mixed characteristics (river-like upstream and reservoir-like downstream), different values for the recovery factors were defined. The recovery factor for deposition varied between 0.25 and 0.001. Recovery factor for scour was, however, taken to be 1. Since most of the sediments entering the reservoir are fine-grained silt and clay, the cohesive sediment part of GSTARS 2.1 was used. Yang's 1996 modified formula was selected for computing sediment transport capacity while some of the cohesive sediment transport parameters were obtained from literature for a similar case (YANG and SIMOES, 2000).

## 2.2 Modelling of Reservoir Sedimentation Process

The generalized Stream Tube model for Alluvial River Simulation (GSTARS) was first released by the US Bureau of Reclamation in 1986 (MOLINAS and YANG, 1986) for CYBER mainframe computer application. A revised and enhanced model GSTARS version 2.0 (GSTARS 2.0) was released by YANG et al. (1998). The most recent version, GSTARS 2.1, released by YANG and SIMOES (2000) was used in this study.

With proper selection of sediment transport functions, GSTARS 2.1 was applied to a wide range of sediment conditions with particle size ranging from clay, silt, sand and gravel. GSTARS 2.1 also has the ability to consider the effects of wash load on sediment transport rate by using the modified unit stream power formula proposed by YANG et al. (1996). Since there is high concentration of wash load in the flow entering Masinga reservoir (BOBOTTI, 1998), its effect on particle fall velocity, flow viscosity, and relative specific weight of sediment is significant. Hence, a modified sediment transport function for sediment-laden flow with high concentration of wash load (YANG, et al., 1996) was used for sediment transport computations in the reservoir as:

$$\log C_{ts} = 5.165 - 0.153 \log \frac{\omega_m d}{\nu_m} - 0.297 \log \frac{U^*}{\omega_m} + \left( 1.780 - 0.360 \log \frac{\omega_m d}{\nu_m} - 0.480 \log \frac{U^*}{\omega_m} \right) \log \left( \frac{\rho_m}{\rho_s - \rho_m} \frac{VS}{\omega_m} \right) \quad (3)$$

- $C_{ts}$  = total sediment concentration in parts per million by weight;  
 $\omega_m$  = particle fall velocity in sediment-laden flow;  
 $\nu_m$  = kinematic viscosity of sediment-laden flow;  
 $d$  = sediment particle diameter;  
 $U^*$  = shear velocity;  
 $VS$  = unit stream power;  
 $V$  = average flow velocity;  
 $S$  = water surface or energy slope;  
 $\rho_s, \rho_m$  = specific weights of sediment and sediment-laden flow, respectively.

## 2.3 Calibration Process and Difficulties Encountered

The first step in the application of GSTARS 2.1 on Masinga reservoir was to calibrate the model. The following parameters were adjusted to fit the simulated cross-sections (1988) to the measured cross-sectional data (1988):

- Shear threshold for deposition of clay and silt which was

- used to determine the initial condition for deposition,
- Shear threshold for particle erosion of clay and silt,
- Slope of the erosion rate curve for mass erosion, and
- Size gradation distribution of the incoming sediment

To calibrate GSTARS 2.1, first, the size gradation distribution of incoming sediment was varied and predicted reservoir cross-sections obtained. The predicted cross-sections and thalweg were then compared with measured ones to establish whether the two sets match. The reason for varying size gradation distribution of incoming sediment was to distribute sediment deposits longitudinally in such a way that predicted and measured cross-sections and thalweg approximately match. Normally, the bed load and coarser fraction of the suspended load are deposited at the mouth of the reservoir, while fine sediments with lower settling velocities are transported and deposited further into the reservoir or near the dam wall.

There were some problems encountered while calibrating the model. Indeed, it was difficult to adjust the model parameters so that the simulated and observed cross-sections match for all the stations. For instance, there was a greater deviation between the measured and observed cross-sections for the sections around the confluence. This could be attributed to the formation of eddy and/or secondary currents at the confluence of the two arms (Thika and Tana). Since GSTARS 2.1 is based on a stream tube concept, the presence of secondary and eddy currents phenomena makes the model to fail. It was also seen that there was a great deviation between model-estimated and observed data for cross sections near the dam wall. This could be attributed to the backwater flow and formation of eddy currents making the program to fail. Otherwise, for other cross-sections, the observed and simulated bed elevation changes were in good agreement.

### 3. Simulated Results and Discussion

The focus of the sedimentation modelling was to see how the reservoir bed elevations change after 20 years of reservoir operation. In this paper, a quasi-1D numerical model, GSTARS 2.1 was applied to model spatial sediment accumulation in Masinga reservoir. After calibration of the model using measured data, predictive computations were carried out over a period of 20 years to assess possible changes in reservoir bed elevations during the two decades. The simulated changes on some selected cross sections due

to deposition are given in Figures 3 and 4. From the plotted cross sections, it was found that most deposition occurred along the thalweg with deposition depths typically in the range of 0.5 m to 3 m. The trend of sedimentation during predictive computations was similar to that observed during calibration simulations.

Model-estimated cross sections do not correspond favourably with observed cross sections for deeper parts of the channels (SAENYI, 2002). In such cases, GSTARS 2.1 seems to underestimate the amount of deposited sediments within these deeper parts. It does not show the accumulation of sediments in these narrow deeper parts as observed in the field. The reason for this discrepancy could be the failure of GSTARS 2.1 to model local flow conditions existing in these areas. The program however, seems to simulate deposition on flood plains quite well as evidenced in the coincidence of observed and model-estimated data points on flood plains for most cross-sections (SAENYI, 2002).

A survey conducted on all plotted cross sections revealed that GSTARS 2.1 model poorly approximated measured data for complex cross sections (SAENYI, 2002). The reason for this could be the failure of GSTARS 2.1 to split such complex cross-sections into stream-tubes of equal conveyance. It performed satisfactorily for simple cross sections whose geometrical shapes are well defined as illustrated in SAENYI (2002).

The computed thalweg were compared with the observed ones as shown in Figures 5 and 6, for Thika and Upper Tana arms, respectively. An error analysis performed on Thika arm thalweg data indicated that the observed and predicted data were not significantly different for many stations (SAENYI, 2002). For Tana arm, predicted and observed thalweg deviate slightly from each other near the mouth of the

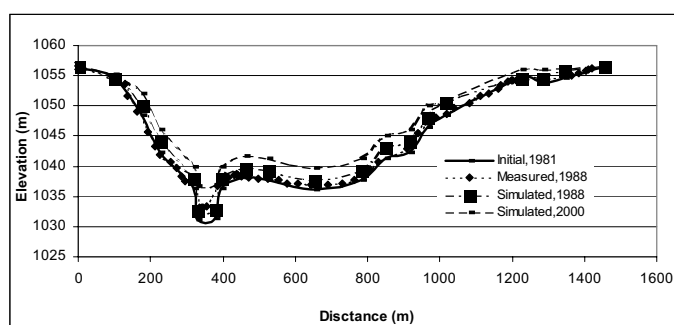


Figure 3: Predicted channel development compared with measured cross section for a station 5 km upstream of Masinga dam  
Abbildung 3: Vergleich zwischen vorausberechneter Kanalentwicklung und gemessenem Querschnitt für eine Station 5 km oberhalb des Masinga Dammes

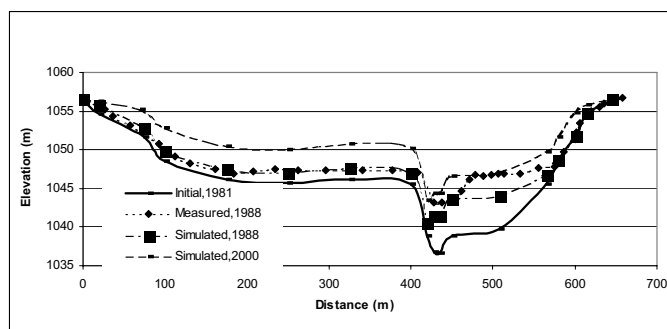


Figure 4: Predicted channel development compared with measured cross section for a station 10 km upstream of Masinga dam  
 Abbildung 4: Vergleich zwischen vorausberechneter Kanalentwicklung und gemessenem Querschnitt für eine Station 10 km oberhalb des Masinga Dammes

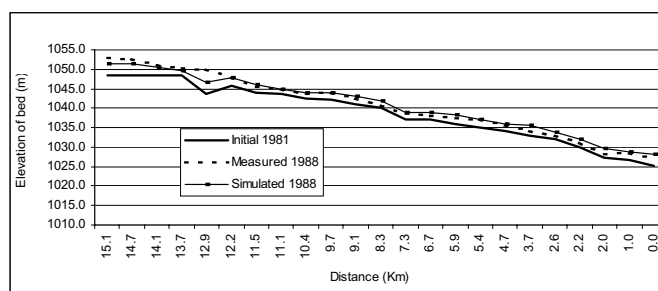


Figure 5: Thalweg for Thika arm of Masinga reservoir  
 Abbildung 5: Thalweg für den Thika-Arm des Masinga Staubeckens

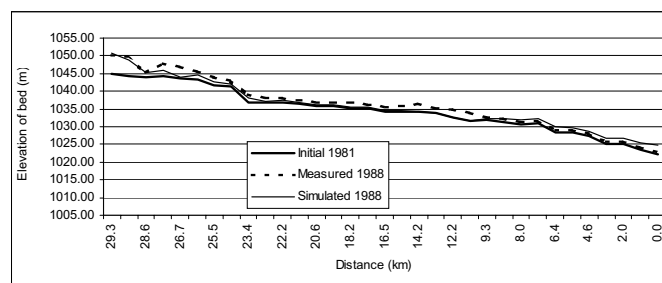


Figure 6: Thalweg from the mouth of reservoir to station 29.9 km upstream of Masinga dam  
 Abbildung 6: Thalweg vom Zufluss des Speicherbeckens bis zur Station 29 km oberhalb des Masinga Dammes

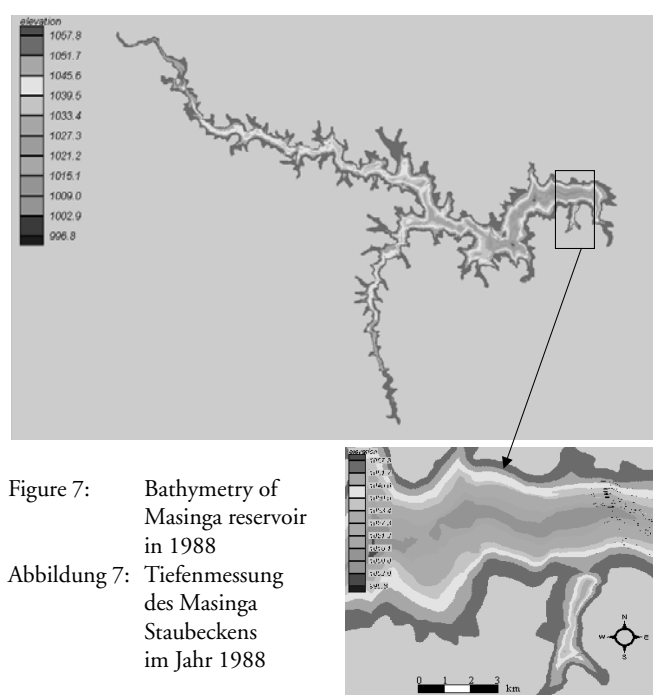


Figure 7: Bathymetry of Masinga reservoir in 1988  
 Abbildung 7: Tiefenmessung des Masinga Staubeckens im Jahr 1988

reservoir but the deviations become small for downstream stations.

The processing and visualisation of these depth data sets (1988 observed and 2000 simulated values) were performed using a two-dimensional BOSS SMS computer-based model (1996) to generate 2-D depth contour maps. This program produces a topographic surface through unbiased interpolation of elevation (depth) between randomly or regularly spaced data points.

The resulting 2-D pictures are compared to establish the trend and pattern of sedimentation between 1988 and 2000. Changes in the spatial bathymetric pattern indicate the specific locations where sediment had been deposited. From the graphical presentation (Figures 7 and 8), it could be seen that the reservoir bathymetry had been altered drastically between 1988 and 2000 due to siltation. The changes were clearly discerned by zooming in at specific areas of the reservoir as shown in Figures 7 and 8.

Generally, simulations showed that sedimentation occurred

at the mouths of the reservoir, at the confluence of the two arms and near the dam wall. There was little sedimentation for the rest of the other stations. Simulations also showed that most of the material was deposited in the old river channel and little on the reservoir terraces (flood plains). However, field observations conducted on the reservoir bed in August 2000 revealed that there was no deposition on the terraces as opposed to simulated results, which showed that little deposition occurred. The reason for this discrepancy could be attributed to the inability of GSTARS 2.1 to simulate the phenomena of secondary currents, eddy currents, and diffusion, which play crucial roles for the siltation process on terraces.

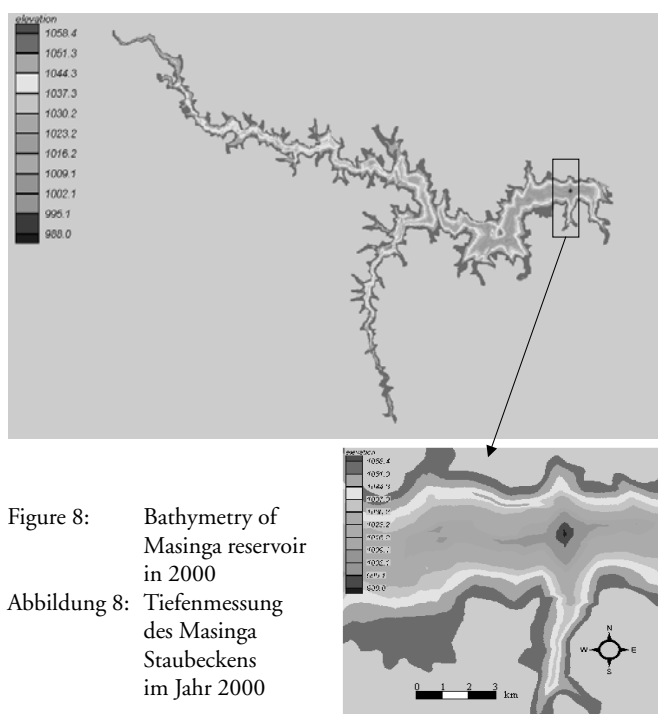


Figure 8: Bathymetry of Masinga reservoir in 2000

Abbildung 8: Tiefenmessung des Masinga Staubeckens im Jahr 2000

#### 4. Conclusion and

#### Recommendations

From the simulated results, it was found that most deposition occurred along the thalweg with deposition depths in the range of 0.5 m to 3 m. Most of the sediment delivered to the reservoir was deposited along the main channel and little on the reservoir terraces. The model predicted more sedimentation at the mouth of the reservoir, at the confluence of the two arms (Tana and Thika), and near the dam wall.

The following recommendations could help to improve the results of GSTARS 2.1 simulations carried out in this study:

Installation of more river gauging stations and reviving the abandoned ones to improve data on the hydrological regime of the area. Data should be collected on a more regular and uniform basis than before.

Installation of additional sediment monitoring stations and stepping up measurement of sediment transport in rivers. The supply of bed load to a reservoir determines the depositional process close to the mouth of the inflowing river. The proportion of bed load to total load should therefore be estimated, calculated or measured and be included in the reservoir sedimentation simulations.

Continuation of regular sediment surveys on Masinga reservoir. Hydrographic surveys should be undertaken once every 3 to 5 years.

Shear threshold for deposition of clay and silt, shear threshold for particle erosion of clay and silt, and slope of the erosion rate curve for mass erosion parameters should be determined *in situ* or by laboratory tests to improve on the results of GSTARS 2.1 simulations. The parameters are highly dependent on the local conditions and may vary widely from case to case, always requiring field verification.

#### Acknowledgements

This study was partly supported by Austrian Academic Exchange Service (ÖAD), and the Institute of Water management, Hydrology and Hydraulic Engineering of the University of Agricultural Sciences, BOKU, Vienna, Austria. Thanks to Professor Peter Nachtnebel and Andreas Klik for their support and guidance throughout this study.

#### References

- BOBOTTI, O. K. (1998): Masinga Reservoir Capacity and Sedimentation, Kenya. A World Bank Project; Tana and Athi Rivers Development Authority, TARDA Report, Vol. 2: Data Annexes.
- BOSS SMS model (1996): BOSS SMS Computer program user's manual version 4.3. Engineering Computer Laboratory, Brigham Young University.
- MOLINAS, A. and C. T. YANG (1986): Computer program users manual for GSTARS. Technical report, U.S. Department of Interior Bureau of Reclamation Engineering and Research Centre, Denver, Colorado.
- PACINI, N. (1994): Coupling of land and water; phosphorus fluxes in the Upper Tana River catchment, Kenya. Unpublished Thesis submitted for Ph.D., Ecology Unit, Department of Zoology, Leicester University, UK.
- SAENYI, W. W. (2002): Sediment Management in Masinga Reservoir, Kenya. A Ph.D thesis submitted to the University of Agricultural Sciences, BOKU; Institute of Water Management, Hydrology and Hydraulic Engineering Vienna, Austria.
- YANG, C. T., A. MOLINAS and B. WU (1996): Sediment transport in the Yellow River. *J. of Hydr. Engineering*, ASCE, 122 (5).
- YANG, C. T., T. J. RANDLE and S. K. HSU (1998): Surface erosion, sediment transport, and reservoir sedimentation. In: SUMMER, W., E. KLAGHOFER and W. ZHANG (eds.): IAHS Publication, no. 249. Vienna, 3–12.

YANG, C. T., M. A. TREVINO and F. J. M. SIMOES (1998): User's manual for GSTARS 2.0 (Generalized Stream Tube model for Alluvial River Simulation version 2.0). U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado.

YANG, C. T. and F. J. M. SIMOES (2000): User's manual for GSTARS 2.1 (Generalized Stream Tube model for Alluvial River Simulation version 2.1). U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado.

### **Address of author**

**Dr. Wycliffe Wanyonyi Saenyi**, Senior lecturer, Department of Water and Environmental Engineering, Egerton University, P.O. Box 536 Njoro, Kenya; e-mail: saenyiw@yahoo.com

Eingelangt am 6. Mai 2003

Angenommen am 12. Jänner 2004