Earth Surf. Dynam. Discuss., 2, 153–179, 2014
www.earth-surf-dynam-discuss.net/2/153/2014/
doi:10.5194/esurfd-2-153-2014

Earth Surface Dynamics
Discussions
Open Access

Modelling of sedimentation processes inside Roseires Reservoir (Sudan)

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Received: 27 September 2013 – Accepted: 31 October 2013 – Published: 18 March 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Roseires Reservoir, located on the Blue Nile River, in Sudan, is the first trap to the sediments coming from the upper catchment in Ethiopia, which suffers from high erosion and desertification problems. The reservoir lost already more than one third of its storage capacity due to sedimentation in the last four decades. Appropriate management of the eroded area in the upper basin could mitigate this problem. In order to do that, the areas providing the highest sediment volumes to the river have to be identified, since they should have priority with respect to the application of erosion control practices. This requires studying the sedimentation record inside Roseires Reservoir, with the aim of identifying when and how much sediment from a certain area is deposited. The identification of deposition time is derived from soil stratification inside the reservoir. This requires expensive coring campaigns that need to be optimized. The most promising sampling coring areas were therefore selected beforehand by combining bathymetric data and the results of a depth-averaged morphodynamic model able to record vertical stratification in sediment deposits. The model allowed recognising the areas that are potentially neither subject to net erosion nor to bar migration during the life span of the reservoir. Verification of these results was carried out by analysing sediment stratification from the data collected in subsequent field campaign.

1 Background information

1.1 Blue Nile River

The Blue Nile is the main tributary of the Nile River. The river originates at the outlet of Lake Tana and flows for nearly 900 km through Ethiopia, before reaching the Sudanese border. In Ethiopia, the Blue Nile has 14 major tributaries (Fig. 1a), which represent the majority of the estimated annual flow of the river that is 46.2 billion $m^3\,yr^{-1}$. Here, the river falls from 1800 m a.s.l. at Tana to about 490 m a.s.l. at the Sudan border, which

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gives an averaged longitudinal slope of 1.5 m km^{-1} (Fig. 1b). The upper basin suffers from high erosion problems due to intensive land use and upper catchment desertification and delivers huge quantities of sediment to the river system. After leaving Ethiopia, the Blue Nile runs through Sudan for about 735 km to Khartoum, where it joins the White Nile to form the Nile River. Presently, the Blue Nile waters encounter two dams: the Roseires Dam and the Sennar Dam (Fig. 1a), both in Sudan, but a new dam is currently under construction in Ethiopia and other dams are planned.

The Dindir and Rahad join the river downstream of Sennar Dam in Sudan, adding an average annual flow of 4 billion m^3 yr^{-1}.

The slope from the Ethiopian border to Khartoum is one order of magnitude milder than in the Ethiopian side, only 15 cm km^{-1} (Abdelsalam and Ismail, 2008).

The flow of the Blue Nile reflects the seasonality of rainfall over the Ethiopian highlands, which can be distinguished in wet season, from July to October, with maximum flow in August–September and dry season, from November to June. Consequently, the annual Blue Nile hydrograph at the Ethiopian Sudanese border has a bell-shape pattern. The daily flow of the river fluctuates between 10 million m^3 in April to 500 million m^3 in August with a ratio of 1 : 50 (Awulachew et al., 2008).

1.2 Roseires Reservoir

Roseires Reservoir is located in Sudan 550 km southeast of Khartoum, near the border with Ethiopia (Fig. 1a). It is one of the oldest reservoirs in the basin, since the dam was finalised in 1966. This reservoir plays an important role for the economy of Sudan, since it provides hydropower, water for irrigation and flood control. The length of the reservoir is about 80 km and the wet area surface is up to 290 km^2. The total storage capacity was 3 billion m^3 in the feasibility study of 1955, but in the mean time the reservoir lost 40 % of this storage capacity due to sedimentation. To limit sedimentation, the gates are kept to the minimum level (open) during the wet season and are raised to the maximum level one month before the end of the high flow season and kept so during

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the dry season (Hussein et al., 2005). Dredging is executed every year in front of the power intake. Dredged sediment is dumped it in front of the deep sluice gates to be flushed during the flood season when all the dam gates are opened. The process is generally carried out before the flood season (Bashar and Eltayeb, 2010).

To increase the storage capacity of the reservoir, the dam has been recently heightened by 10 m (in 2013). Before heightening, the full supply level was 481 m a.s.l. (Irrigation Datum) and the minimum supply level of the power generation during flood season was 467.6 m a.s.l. (Irrigation Datum) (Hussein et al., 2005). The reservoir bed morphology is not homogeneous but there is a main channel that is approximately 10 deeper than the surrounding plains and that during the flashing period the water drop by approximately 13 m leaving the plains dry.

2 Reservoir sedimentation from bathymetric data

Rough flow and sediment data were filtered, treated and analyzed in order to be useful for the study proposes. The reservoir was surveyed in 1976, 1981 (DEMAS, 1985), 1992 (Gismalla, 1993), 2007 (Abd Alla and Elnoor, 2007) and 2009 (Omer, 2011). Bathymetric surveys prior to 2009 do not cover the upstream river reach up to ElDeim station (at the border between Sudan and Ethiopia), as well as the left and right wings of the reservoir.

The morphological trends, in terms of cumulative bed level changes, were obtained by comparing the bathymetric data of 20 sections surveyed in 1985, 1992 and 2007. Temporal variations in storage capacity of Roseires reservoir are given in Table 1. The total volume of sediment deposited at the reservoir in the two periods 1985–1992 and 1992–2007 is 146 and 238 million m^3, respectively.

The areas with net deposition or erosion could be identified by subtracting the bed topography 2007 from the bed topography 1992 and the bed topography 1992 from the bed topography 1985.

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3 Available hydrodynamic and sediment data

Most data were provided by the Ministry of Irrigation and Water Resources (MoIWR) and Dams Implementation Unit of the Ministry of Dams and Electricity, Sudan.

ElDeim gauging station for measuring water level, discharge and sediment concentration is located near the Sudan–Ethiopia border. It was established in 1962 during the construction of the dam; 110 km upstream along the river and 85.5 km air distance (Fig. 2). The station is situated in a deep rock gorge, which is supposed to provide a very stable control, reliable and accurate flows. However, in the last three decades ElDeim station has deteriorated to an extent it is not working properly (Ahmed and Ismail, 2008). Water level, discharge and sediment concentration are also available at other three measuring stations namely; Famaka at the reservoir inlet, Wad Almahi inside the reservoir and Wad Alies, just downstream of the dam.

The concentration of suspended solids was measured during the flood season at ElDeim on a daily basis during the last four decades. The data show a high variability in suspended solids concentrations from year to year and substantial differences between the rising limb and the falling limb of the flood curve (Hussein et al., 2005; Ahmed and Ismail, 2008; Billi and el Badri Ali, 2010; Ahmed et al., 2010). Considering the long-term character of investigation, to represent the historical inputs of suspended solids during the high-flow seasons we derived the averaged values of suspended solids concentrations from the literature data for three periods: the 1970–1980s, the 1990s and the 2000s. For the low-flow seasons, due to lack of historical data, we adopted the averaged sediment concentration of 0.024 $\text{kg}\,\text{m}^{-3}$ that we measured during a field campaign in 2011.

The granulometry of suspended sediment is measured at the end of year and D_{50} is found to be 18.5 µm and 22 µm at Wad Almahi and Wad Alies respectively. This shows that an erosion process happens between these two stations. Silt is the dominant type of sediment in suspension and it represents more than 80 % of the samples. Sand represents about 15 % of the suspended sediment inside the reservoir (at Wad Almahi) and 10 % of the suspended sediment downstream of the dam (at Wad Alies). Based on the analysis of sediment of the bed material (Omer, 2011), at some locations sediment contains up to 30 % of silt and clay. Averaging results in a D_{50} of 1200 µm upstream of Famaka and in a D_{50} of 140 µm just upstream of the dam.

4 Methodology

Environmental conditions and economical issues limit the possibility to perform vast field campaigns in the study site. For this, field campaigns have to be optimized beforehand. With the aim of identifying the most promising coring areas to investigate soil stratification (to derive the time of sedimentation) and origin of the sediment deposited in the reservoir (from the mineralogy of deposited fine material), we combined the analysis of bathymetric data with morphodynamic modelling. Data alone allow identifying areas characterized by net sedimentation, but these areas might experience periods of erosion in which part of the layers are lost.

To study the morphodynamic processes occurring inside Roseires Reservoir (erosion/deposition), we adopted a physics-based model keeping record of the vertical soil development to obtain vertical and horizontal sediment sorting inside the reservoir. The morphodynamic model was constructed using the Delft3D software. The set up of the model required two steps: (1) the development of a 2-D depth-averaged hydrodynamic model; and (2) a morphodynamic model considering two types of sediments: silt (supply-limited) and sand (capacity limited), according to the two types of sediment transported by the Blue Nile River.

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5 Modelling

5.1 Model description

Lesser et al. (2004) extensively describes the open-source Delft3D code which is applied in the current study. The extensive description of the software and of its mathematical background can be found in: http://oss.deltares.nl/web/delft3d.

The hydrodynamic part of the model is based on the 3-D Reynolds-Averaged Navier–Stokes (RANS) equations for incompressible fluid and water (Boussinesq approximation: Boussinesq, 1903). The equations are formulated in orthogonal curvilinear coordinates. The set of partial differential equations in combination with the set of initial and boundary conditions is solved on a finite-difference grid.

We used a 2-D depth-averaged version of the model with an appropriate parameterization of two relevant 3-D effects of the spiral motion that arises in curved flow (Blanckaert et al., 2003). First, the model corrects the direction of sediment transport through a modification in the direction of the bed shear stress, which would otherwise coincide with the direction of the depth-averaged flow velocity vector. Second, the model includes the transverse redistribution of main flow velocity due to secondary-flow convection, through a correction in the bed friction term. Taking into account these 3-D effects becomes important not only in curved channels, but also in straight channels with bars.

The closure scheme for turbulence is a k–ε model, in which k is the turbulent kinetic energy and ε is the turbulent dissipation.

The evolution of the bed topography is computed from a sediment mass balance, a sediment transport formula for capacity-limited sediment transport, as well as an advection–diffusion formulation of suspended solids concentrations for fine supply–limited sediment transport, coupled to two formulas describing the entrainment and deposition processes.

A number of capacity-limited transport formulas are available, such as Meyer-Peter and Muller's (1947), Engelund and Hansen's (1967) and van Rijn's (1984). The model

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accounts for the effects of gravity along longitudinal and transverse bed slopes on bed load direction (Bagnold, 1966; Ikeda, 1982).

The concentrations of fine sediment in suspension are calculated by solving the following 3-D advection–diffusion equation (mass balance):

$$\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial (w - w_s)c}{\partial z} = \frac{\partial}{\partial x}\left(\varepsilon_{s,x}\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_{s,y}\frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(\varepsilon_{s,z}\frac{\partial c}{\partial z}\right) \quad (1)$$

where c is the mass concentration of the fine sediment fraction (kg m^{-3}) and u, v and w are the flow velocity components (m s^{-1}). The velocity and eddy diffusivity ($\varepsilon_{s,x,y \text{ or } z}$) are gained from the hydrodynamic computations (continuity and momentum conservation equation of water). In computing the settling velocity of the sediment particles, w_s, the hindered effect is taken into account. The adjusted settling velocity is given by the following formula:

$$w_s = \left(1 - \frac{c_s}{c_{soil}}\right)^5 w_{s,0} \quad (2)$$

in which c_{soil} is the reference density for hindering settling (kg m^{-3}) and c_s is the total mass concentration of the fine sediment fractions (kg m^{-3}).

The following general formula (Ariathurai and Arulanandan, 1978; Partheniades, 1964) describes the entrainment of fine sediment from the bed:

$$E = M\left(\frac{\tau - \tau_c}{\tau_c}\right) \quad (3)$$

where E is the erosion flux (kg m^{-2} s^{-1}) and M is a coefficient quantifying the quantity of entrained sediment (kg m^{-2} s^{-1}). The following formula describes the deposition rate:

$$D = C_a \cdot w_s \quad (4)$$

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in which D is the deposition rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$) and C_a is the sediment concentration near the bed.

In this study the model is simplified into 2-D horizontal (depth-averaged) formulations. The implications for fine sediment concentrations are described in Montes et al. (2010).

For the description of soil processes, the adopted morphodynamic model includes an adapted version of Hirano's (1971) bed layer model, as described in Blom (2008). The bed is subdivided in numerical layers. These layers allow for different specifications of bed composition and sediment characteristics and record the changes of bed composition in the vertical during the morphodynamic simulations.

5.2 Setup, calibration and validation of the hydrodynamic model

The 2-D depth-averaged model was built to cover the Reservoir area to ElDeim (about 110 km from the dam and 30 km upstream the end of the reservoir). The reservoir shape is rather complex, as shown in Fig. 2. Consequently, the computational curvilinear grid size is variable, ranging between 25 to 280 m (Fig. 3). The upstream boundary condition was represented by the daily discharge time series measured at ElDeim. The downstream boundary condition was represented by the corresponding water levels measured at Wad Almahi and by the dam outflow discharges.

The hydrodynamic model was calibrated on the 2009 water levels measured at Famaka, located inside the reservoir, about 80 km upstream of the dam (Fig. 2). Inaccuracies due to the large size of the computational grid cells were compensated by manual adjustments of topographic levels, ensuring that thalweg elevation in the model is close to the measured one. Finally, the bed roughness, used as calibration parameter, resulted in a Chézy coefficient of $80\,\mathrm{m^{1/2}\,s^{-1}}$. Figure 4a shows the results of model calibration.

The hydrodynamic model was validated using the daily time series of hydrodynamic data measured in 2010. These data include the discharges measured at ElDeim, as

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upstream open boundary condition, dam outflow and the water levels measured at Wad Almahi (inside the reservoir). Figure 4b shows the rather satisfactory results.

5.3 Setup, calibration and validation of the morphodynamic model

The hydrodynamic model was then used to set up the morphodynamic model, with the aim to simulate sediment deposition and erosion inside the reservoir during two periods: 1985–1992, and 1992–2007. The model was calibrated and validated on the measured bed level changes derived from the bathymetric data in these two periods. There were no data available on soil stratification.

The model was speeded up using the morphological factor introduced by Roelvink (2006), taking care of respecting the water balance, by adding and subtracting water. The hydrodynamic boundary conditions were the time series of monthly inflow and outflow discharges and averaged water levels inside the reservoir (pool water levels). Dredging was implemented as yearly operation.

Given the large variation of sediment settling in the reservoir and the necessity to consider only two components (sand and silt), the transport formula for sand having an averaged diameter of 700 µm, fall velocity, critical shear stress for erosion and erosion speed of silt were used as calibration parameters, considering a density of deposited silt equal to 1200 $\mathrm{kg\,m^{-3}}$. The upstream input of suspended sediment concentrations during high flows was the corresponding averaged values derived from the measured data. Suspended sediment input during the low flow season was kept constant and equal to the measured one.

The model was calibrated on the period 1985–1992. The transport formula that gave the best results for the sand component was Van Rijn's (1984). The optimized fall velocity resulted 0.005 $\mathrm{mm\,s^{-1}}$ and the critical shear stress for erosion 1 $\mathrm{N\,m^{-2}}$, whereas the erosion speed of silt resulted 2 $\mathrm{mg\,m^{-2}\,s^{-1}}$. Figure 5 shows the measured and simulated cross-sections 18 and 19B (10.8 km and 15.4 km upstream of the dam). The model does not provide accurate results at this level of detail. Computed section 18 shows that the model fails to simulate the main channel shift (compare measured and

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simulated 1992 topography). The same applies to section 19B. This might be due to the relatively large grid size and the distance of the measured cross-sections (2–5 km) which does not allow for proper reproduction of curved flow effects inside the main channel.

The total computed cumulative deposited volume of sediment in the period 1985–1992, is 188 million m^3, which is 29 % larger than the measured volume (146 million m^3, from Table 1).

The model was then run for a period fifteen years, from the end of 1992 to the end of 2007. The results were compared to the measured bed levels in 2007. The simulated morphological changes inside Roseires Reservoir show higher deposition rates than the measured ones. The computed total cumulative sediment deposit in this period is 567 million m^3, which is more than the double of the measured 238 million m^3 (Table 1). To analyze the implications of this overestimation at the cross-sectional scale, we compare the measured and simulated sections 18 and 19B in Fig. 6. The simulated section 18 in 2007 shows a deposition of 2–2.5 m with respect to section 18 in 1992, which is larger than the measured one. The model does not correctly reproduce the main channel shift inside the reservoir at section 19B.

We believe that the unavailability of good field data reflects on the model accuracy and output reliability. In this study, data were not available in sufficient detail, and were limited in terms of quality and extent. For instance, the cross-sections measured during the bathymetric surveys of 2009 are 2 to 5 km far from each-other and the surveys do not cover the entire length of the reservoir. This creates inaccuracy to prepare the reservoir bed topography considering the length of Roseires Reservoir (80 km) and its meandering shape.

The discrepancies between model and measurements could also be caused by an overestimation of the sediment inputs. In particular, the suspended solids concentrations for the years 2000's seem to be overestimated by the adopted averaged value. For this reason, suspended solids concentrations should be carefully measured in the

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future. In particular, more measurements are required during the low-water season, at least for modeling purposes.

6 Identification of promising coring areas

Coring areas to study soil stratification and mineralogy must fulfil the conditions: (1) easy accessibility; (2) absence of net bed erosion; (3) absence of bar movement, destroying soil stratification; (4) recognizable soil stratification.

Two areas were selected for the coring, as shown in Fig. 7. The selection of these two areas is based on the tendency of sediment to always deposit there and to the apparent absence of bar migration, based on both measured data analysis and model results.

Area 1. Figure 8 shows the vertical profiles of deposition at Area 1. In Fig. 8a, the solid lines represent the final bed levels of 1985, 1988 and 1991. In Fig. 8b, the solid lines represent the final bed levels of 1992, 1995, 1998, 2001, 2004 and 2007. In areas characterized by the absence of bed erosion, the lowest solid line represents the first year, whereas the top line represents the final year of the computation. In Area 1, according to the model, deposition always occurs at the right side of the reservoir, from 0 m to 250 m from the right bank. Erosion occurs due to channel shift in the middle of the reservoir. The last 200 m at left side of the reservoir, from 1500 m to 1700 m, are again characterized by deposition only. The dominant deposited sediment in 1986 (dry year) is sand. Sand content is higher in the period 1985–1992 (Fig. 8a) than in the following 15 yr (Fig. 8b). The general trend in the years 1989, 1990, 1991 and 1992 is deposition of coarser sediment in the deepest area (main channel). Deposition and stratification occur at the sides of the reservoir. These areas become dry at the end of the dry season, are always characterized by deposition and are therefore promising coring areas.

Area 2. According to the model, the left side of this section appears to have been subject to deposition only, for approximately 3 km. In this area, the reservoir is relatively

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wide. Most of sediment deposited in this section is silt with only a minor percentage of sand. Stratification is less visible or absent and for this Area 2 seems less suitable than Area 1 for coring.

7 Model verification based on soil stratification data

A subsequent field campaign was carried out in the summer 2012 in the coring areas identified by the model. This allowed studying the characteristics of the deposited sediment and validating the model results in terms of soil statification. Three trenches were excavated in Area 2, about 25 km upstream the dam, and a forth trench was excavated in Area 1, 45 km upstream of the dam. The characteristics of the four trenches are summarized in Table 2. The analysis of the sediment showed that indeed, at least in the selected areas, the reservoir soil is stratified. However, the layers are not distinguishable from alternations of sand and silt, but from alternations of coarse and fine sand. These are visible from the vertical profile of the D_{90} of the sediment (Fig. 9). No signs of soil erosion could be detected from the analysis of the cores.

8 Conclusions

The most promising coring areas inside Roseires Reservoir were selected by combining bathymetric data analysis with the results of a quasi 3-D morphodynamic modelling including horizontal and vertical sorting. The model allowed studying the contribution of two sediment types, sand and silt, both transported by the Blue Nile into the reservoir. The model set up was based on the idea that sand is deposited during high flows, whereas fine material, mainly originating from upper catchment erosion, is deposited during low flow periods. This creates soil stratification inside the reservoir, which allows the recognition of specific wet or dry years. The model, with recorded bed level changes and soil composition in vertical direction, shows vertical stratification in the

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reservoir soil at several cross-sections. Two of them were selected as the best areas for analysing the sedimentation process in the reservoir.

The results of the subsequent field campaign carried out in the summer 2012, show clear layers at the four trenches excavated in the selected areas, but layers are mainly distinguishable from the presence of coarse and fine sand rather than from alternations of sand and silt. Coarse sand was mainly deposited there during distinguishable wet years, which allowed recognising the progression of sediment deposition in the reservoir. Although the model did not allow distinguishing the fate of different sand sizes, but only of sand and silt, yet the model results allowed selecting two appropriated coring areas.

Acknowledgements. The study was carried out as a project within a larger research program called "In search of sustainable catchments and basin-wide solidarities in the Blue Nile River Basin", funded by the Foundation for the Advancement of Tropical Research (WOTRO) of the Netherlands Organization for Scientific Research (NWO) and UNESCO-IHE. The authors are grateful to the Ministry of Water Resources and Electricity, Hydraulic Research Station, Wad Madani, and the Dam Implementation Unit, Khartoum, Sudan, for providing data free of charge. The authors wish to thank Mick van der Wegen, Kees Sloff for their helpful advices in the modelling phase.

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Table 1. Storage capacity of Roseires Reservoir in million m^3 at different years as a function of level, derived from measured bed topographies.

level m a.s.l. (ID)	origin (1966) volume (Mm^3)	1985 volume (Mm^3)	1992 volume (Mm^3)	2007 volume (Mm^3)	2009 volume (Mm^3)
465	452	17.13	11.9	9.05	10.88
467	638	60.13	38.97	25.9	26
470	991	259.2	179.8	113	106.6
475	1821	992.8	859	660.5	682.8
480	3024	2082	1937	1701.4	1734.7
481	3329	2337.6	2191.6	1953.8	1984.7

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Table 2. Summary of the characteristics of the four trenches.

E	N	Depth (m)	Area
650 539	1 280 023	2.5	Area 2 (trench 1)
650 539	1 280 023	4.0	Area 2 (trench 2)
653 332	1 284 514	4.0	Area 2 (trench 3)
673 117	1 286 508	2.5	Area 1 (trench 4)

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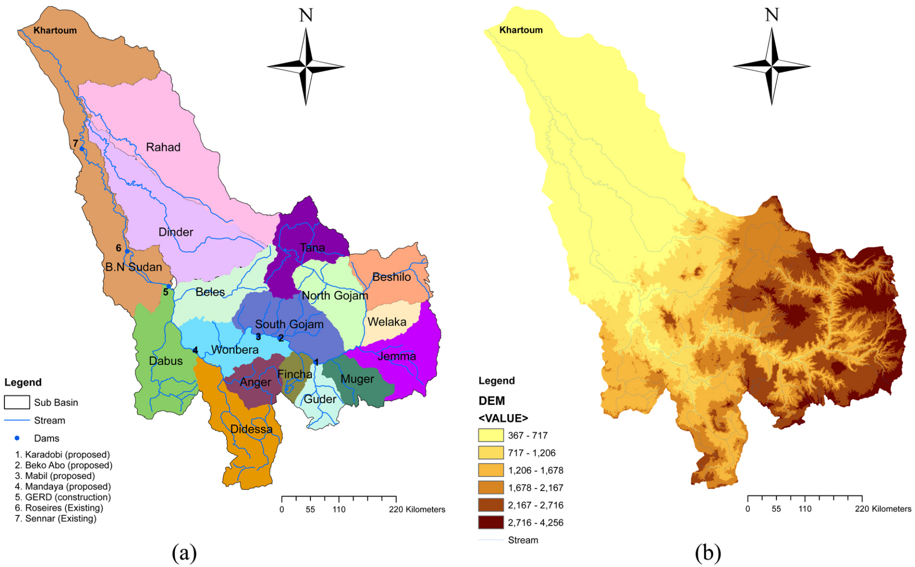

Fig. 1. Blue Nile Basin and Roseires Dam. The elevation map was derived from STRM (90 m) and is in m a.s.l. (WGS84 Datum).

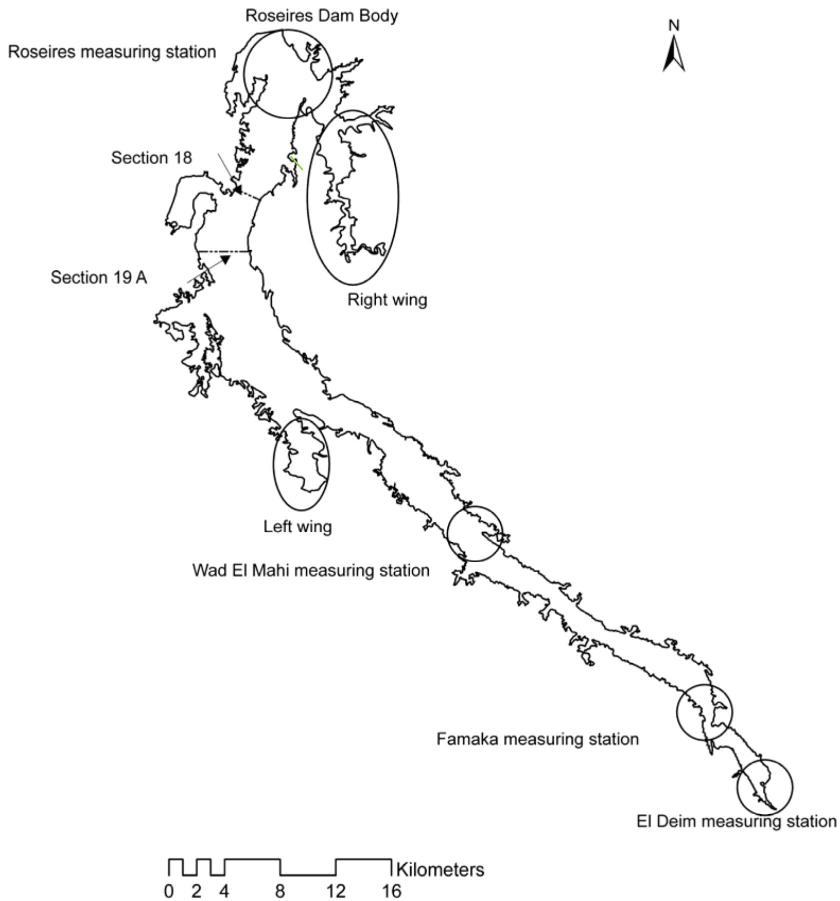

Fig. 2. Measurement stations and the areas (circled) that are not covered by the surveys of 1985 and 1992. The thick black line represents the contour of the reservoir at an elevation of 481 m a.s.l. (Irrigation Datum).

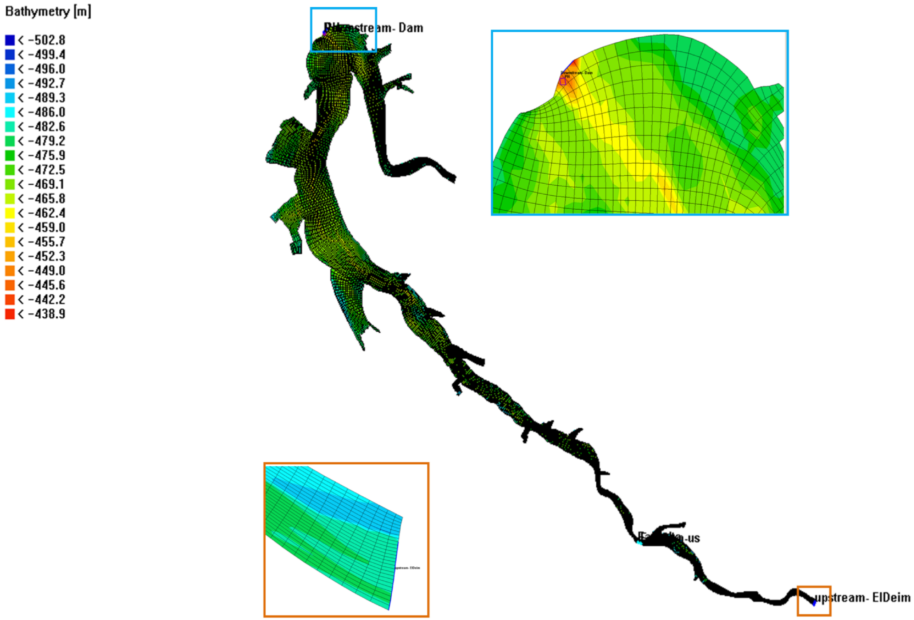

Fig. 3. Upstream and downstream boundaries, computational grid and bed elevations in 2009, in m a.s.l. (Irrigation Datum).

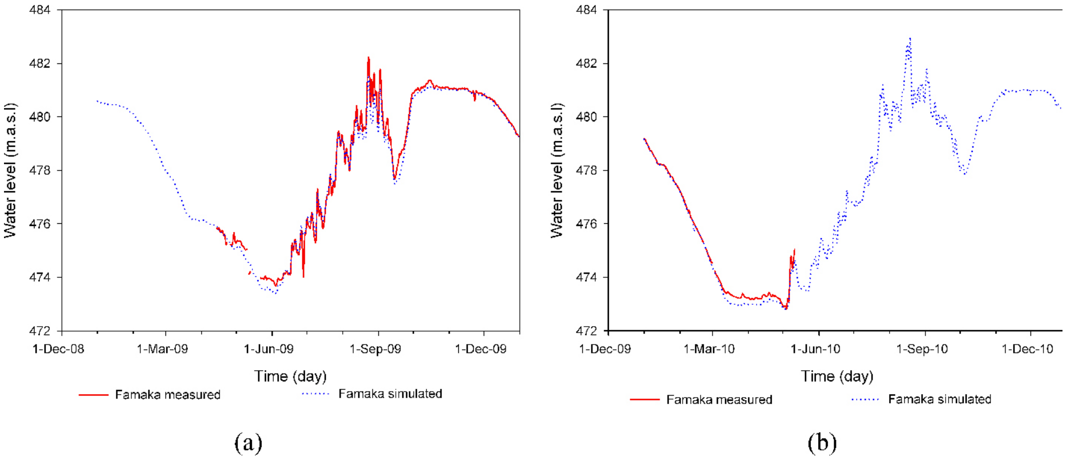

Fig. 4. Results of hydraulic model calibration **(a)** and validation **(b)**: computed vs. measured water levels at Famaka (Irrigation Datum).

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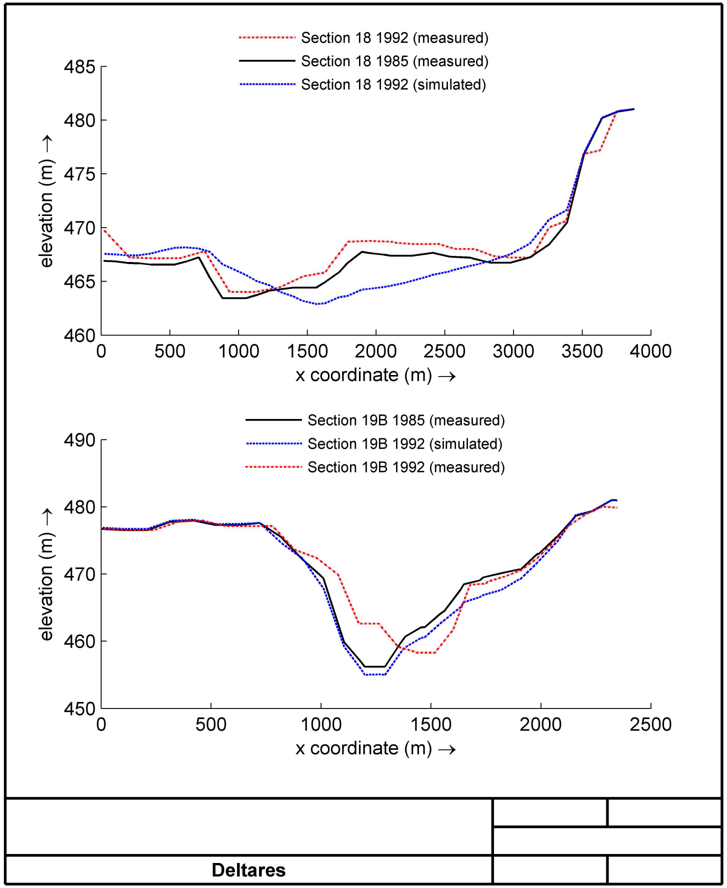

Fig. 5. Cross-sections 18 and 19B seen from downstream. Measured 1985 and 1992 bed elevations and simulated 1992 bed elevation. Cross-section 18 and 19B are located 10.8 km and 15.4 km upstream of the dam, respectively.

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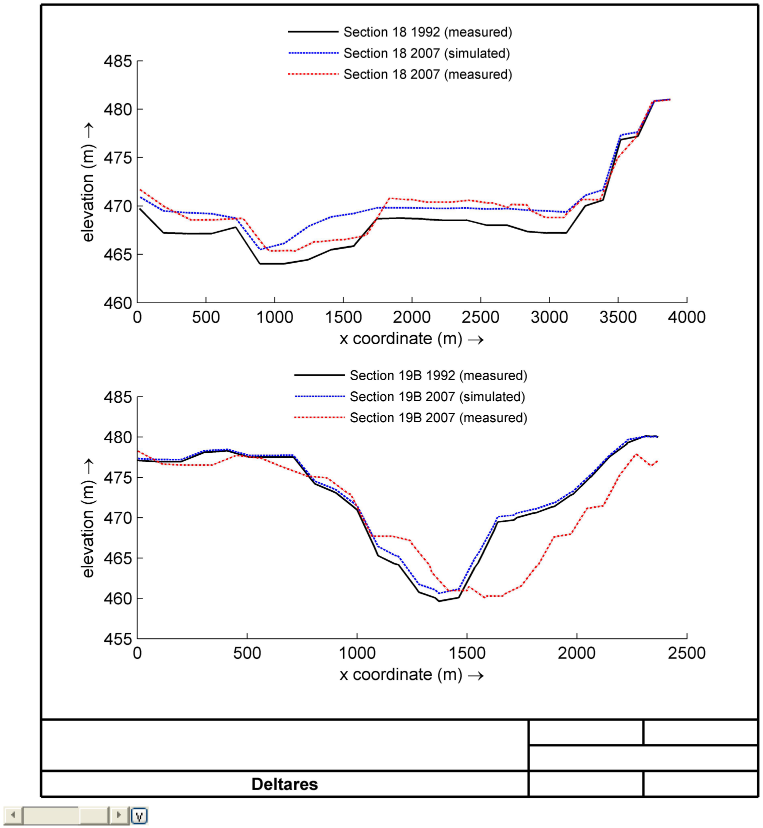

Fig. 6. Cross-sections 18 and 19B seen from downstream. Measured 1992 and 2007 bed elevations and simulated 2007 bed elevation. Cross-section 18 and 19B are located 10.8 km and 15.4 km upstream of the dam, respectively.

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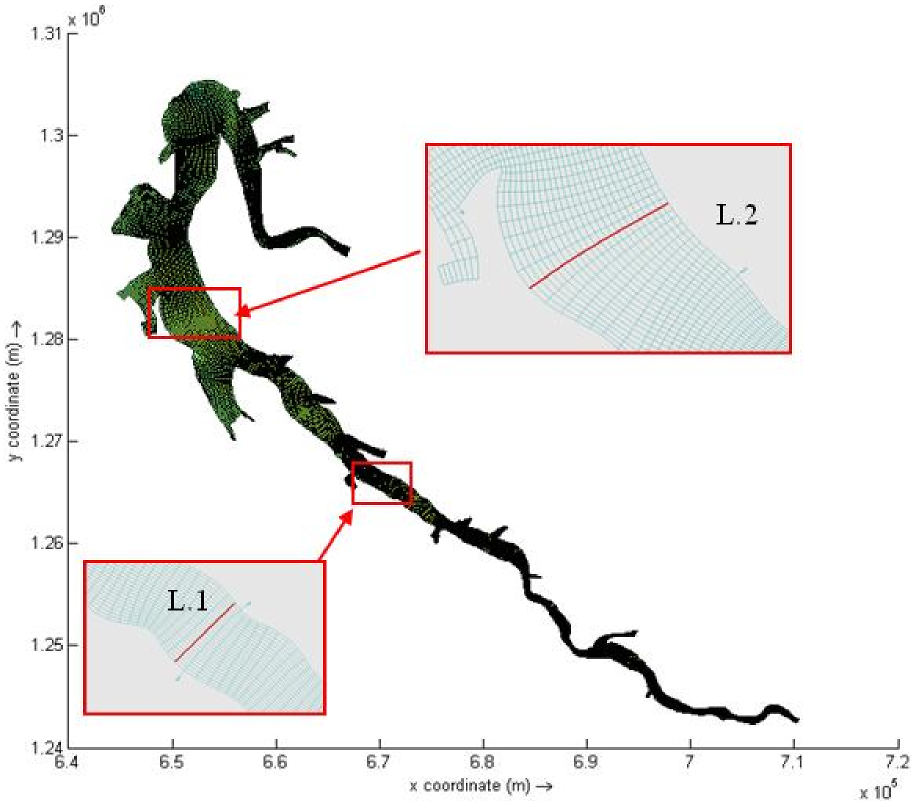

Fig. 7. Selected coring areas (L1 and L2).

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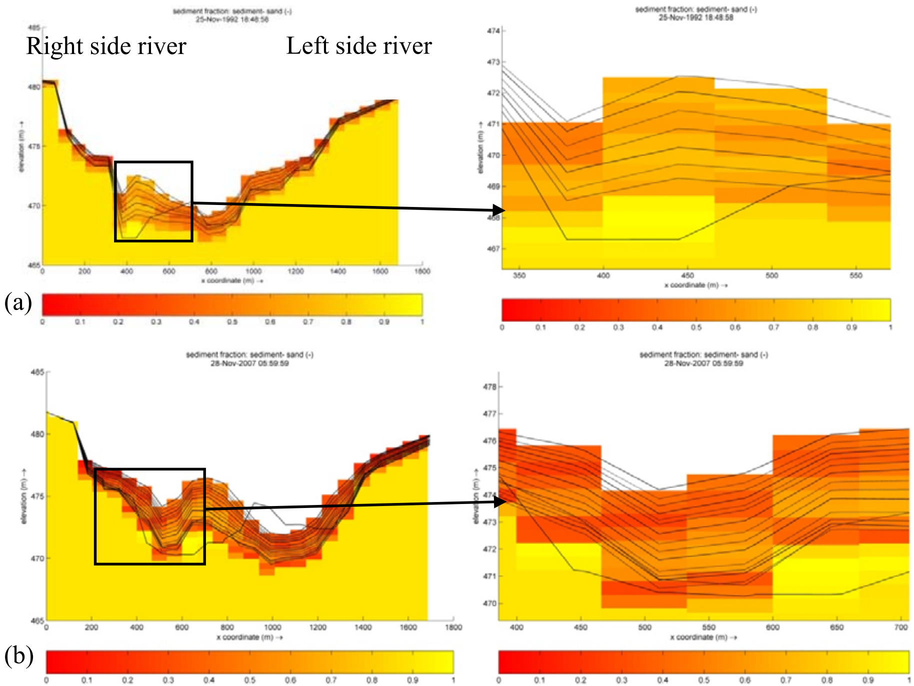

Fig. 8. Vertical profiles of bed composition in Area 1 seen from downstream. Left: entire cross-section. Right: zoomed areas. **(a)** period 1985–1992, **(b)** period 1992–2007. Colour bar: sand content from 0 (red) to 100 % (yellow).

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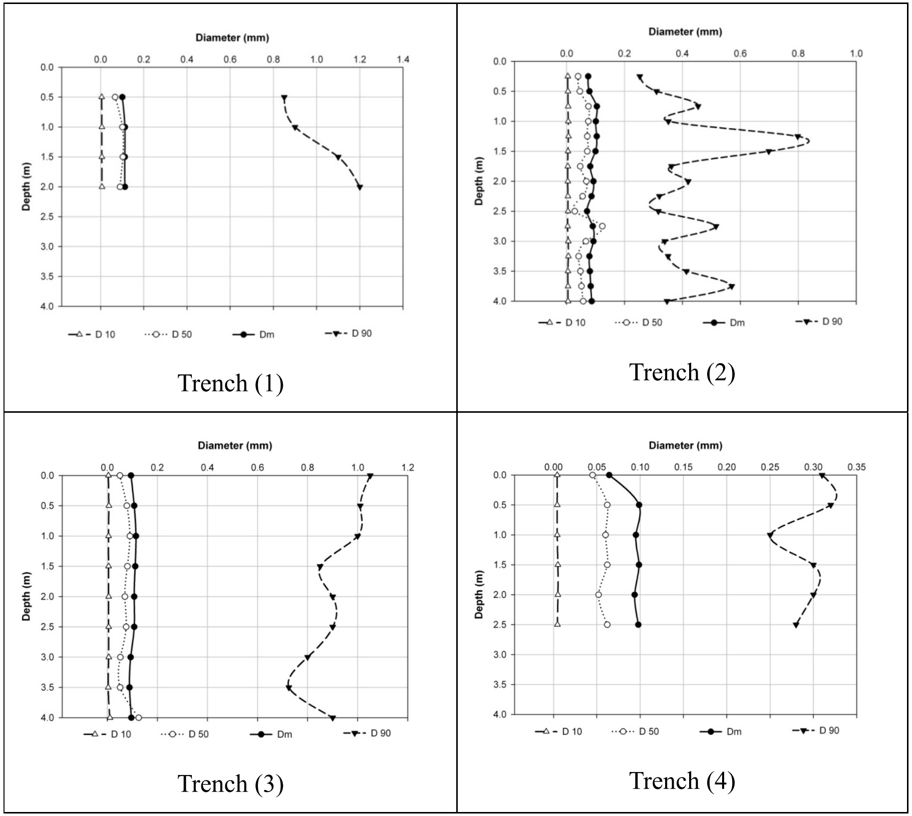

Fig. 9. Soil stratification at the four trenches.

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