Transboundary sediment transfer from source to sink using a mineralogical analysis. Case study
Roseires Reservoir, Blue Nile, Sudan

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Transboundary Sediment transfer from source-to-sink in reservoirs using mineralogical analysis. Case study: Roseires Reservoir, Blue Nile, Sudan

Abstract

Reservoir sedimentation is restricting optimal water resources management of the Roseires Reservoir across the Blue Nile River, in Sudan. About 30% of its storage capacity has been lost by sedimentation before dam heightening (2012), despite regular sediment sluicing and flushing. At the same time, increasing soil erosion in the upper river basin in Ethiopia is significantly reducing land productivity.

This paper shows the results of combining mineralogical X-Ray Powder Diffraction (XRPD) and cluster statistical analyses to identify the source areas of the sediments deposited inside Roseires Reservoir. The XRPD was used to determine the mineral content in the soil and rocks from the reservoir and from the upper basin in Ethiopia. The cluster analysis was used to determine the degree of similarity between sediments in the reservoir (sink) and the ones in the upstream sub-basins (source areas). The results show that the sub-basins of Jemma, Didessa and South Gojam are the main sediment source areas. This is also supported by a sediment balance study at sub-basin level showing that most of the sediment originates from these areas. The high sediment production in these two sub-basins could be related to the land use changes that occurred during the last 40 years, when natural forest soil cover decreased from more than 70% to less than 25% and agricultural crops increased from 30% to more than 70%. The results from the study are relevant for water resources planning and watershed management at transboundary level.

1. BACKGROUND

The Blue Nile River Basin (Fig.1) is increasingly under pressure because of rapidly growing population, both in Sudan and Ethiopia (Balthazar et al., 2013). The basin is experiencing fast development pace with regard to building new hydraulic structures. This has already resulted in a number of environmental problems caused by the extensive exploitation of territory and resources (Garzanti et al., 2006, J. Nyssen et al., 2004). The land-use changes from natural forest to agricultural land has increased soil erosion from the run-off generated catchments. Slope failures of the deep gorges and rugged valley walls, causing land sliding and rock falling, is another factor leading to soil erosion in the basin (Ayalew and Yamagishi, 2004).

The increased soil erosion in the highlands of the upper Blue Nile Basin has resulted in increased reservoirs sedimentation further downstream, Roseires and Sennar (Ali et al., 2014b, Gebremicael et al., 2013) and will negatively affect the new reservoirs, as the Grand Ethiopian Renaissance Dam which is under construction near the border with Sudan (Fig.1) (Ali, 2014). Therefore, better understanding of sediment source and its sinks is important for water resources planning and management at all scales, at the local level as well as at the transboundary level (Ali, 2014). High soil erosion rates are apparent from the agricultural lands in the Upper Blue Nile, especially those of Gojam area (BCEOM, 1999). Therefore, new agricultural development in the basin, e.g., in Didessa, Jemma and Illubabor may promote similar soil erosion rates, although this depends on farming practices and adopted soil conservation techniques (BCEOM, 1999).

This paper presents the results of the experiments conducted to link the sediment deposited inside Roseires Reservoir in Sudan (sink) with those eroded from the soil in the upper Blue Nile Basin. Sediment samples were analyzed using X Ray Powder Diffraction (XRPD) to identify their mineral content and then a cluster analysis was applied, using the Minitab software package, to identify groups of samples that share a high degree of "similarity", in terms of mineralogical composition. The results were then cross-checked with findings from the literature.

1.1 SEDIMENT FINGERPRINTING

Sediment fingerprinting links the mineralogical or geochemical properties of sediment to its source material (Walling et al., 2003) and quantifies the relative contributions of sediment from different sources (Collins et al., 2010, Collins and Walling, 2002). Two famous methods are used for semi qualitative finger-printing sediment: isotopes and minerals. The isotopes method was used in many sediment source applications; see for examples Owen et al. (2012), who used Cesium (^{137}CS) and Lead (^{210}Pb), and Taylor et al. (2012), who used Beryllium(^{7}Be) as sediment tracer.

The mineralogical approach using XRPD (Xie et al., 2013, Al-Jaroudi et al., 2007), has also proven effective in the identification of the sediment sources (Ruan and Ward, 2002, Ottner et al., 2000). Two main informations can be derived from the XRPD method, in the resulting diffractogram: (1) the suite of minerals in a sample, (2) the relative amount of each mineral in a sample, expressed by the peak intensity of the reflected XRay for each mineralogical species (Cullity and Stock, 1956).

1.2 CLUSTER ANALYSIS

Clusters are collections of (data) objects that are similar to one another within the same cluster and dissimilar to the (data) objects in another cluster. Cluster analysis is a powerful statistical method that can be used in finding similarities between clusters of data according to any characteristics found in the original data (Aldenderfer and Blashfield, 1984, Everitt et al., 2001). The output of cluster analysis is graphically comparable to a family tree where groups of similar (data) objects are united under the same branch and groups of dissimilar objects are far away in the tree branching (Aldenderfer and Blashfield, 1984).

Many different disciplines, such as engineering, zoology, medicine, linguistics, anthropology, psychology, marketing, and indeed geology have contributed to the development of clustering techniques and to their application (de Meijer et al., 2001, Cortés et al., 2007, Mamuse et al., 2009). In mineralogical analysis, cluster analysis is used to find similarities (in terms of presence and abundance of mineralogical species) between different samples containing suites of minerals, and collected in different locations: samples that share a high degree of mineralogical species and of their abundance are grouped under the same branch.

2. DESCRIPTION OF THE STUDY AREA

2.1 BLUE NILE RIVER

The Blue Nile River (Fig. 1) is the tributary providing most of the waters to the Main Nile: 60-65 % of its total annual flow, with a clear bimodal seasonal pattern (Waterbury, 1979, Yates and Strzepek, 1998 b). It also transports between 72 to -90 % of total Nile sediment (Williams and Talbot, 2009, Goudie, 2005). The Blue Nile - called Abay in Ethiopia, originates on the western side of the Main Rift Valley flanks, from Lake Tana as (Shahin, 1985, Ali et al., 2014a). The river flows for nearly 1,635 km to Khartoum, where it meets the White Nile to form the main Nile River. The basin (Fig. 2) is divided into 17 major sub basins namely, Blue Nile Sudan, Dinder, Rahad, Tana, Jemma, Beles, Dabus, Didessa, Jemma, Muger, Guder, Fincha, Anger, Wonbera, South Gojam, North Gojam and Welaka (Ali et al., 2014b).

2.2 ROSEIRES RESERVOIR

Roseires Dam, constructed in 1966, is located nearby Alddamazeen City, about 550 km southeast of Khartoum, as shown in Fig.1. The reservoir is a multi-purpose scheme providing high economic benefits to Sudan (GIB, 1968). The stored water is mainly used for irrigation and hydropower generation. The first purpose of Roseires Reservoir is to store water for irrigation; in particular for Gezira Scheme, covering an area of 882,000 hectares (Ali et al., 2014a, Awulachew et al., 2008). The hydropower generation varies through the year due to the seasonal flow changes and variable sediment concentration especially during the flood season (July to September). The design storage capacity is 3 billion m^3 for the level of 480 m above sea level (Irrigation Datum)(Omer et al., 2015, GIB, 1968). The dam was recently heightened by 10 m (490 m above sea level, Irrigation Datum), increasing the storage capacity of the reservoir to 7.4 billion m^3 (SMEC, 2012).

The sediment types brought in by the Blue Nile are sand, silt and clay (Ali et al., 2014b). Silt and clay originate mostly from the enormous soil erosion in the upper catchment area in Ethiopia (Ahmed and Ismail, 2008). The flushing during the flood season, from July to September, when the water in the reservoir is kept at the minimum operation level, is the only measure used to reduce reservoir sedimentation (Goodwill et al., 1995). In addition, more than 100,000 m^3 of sediment is dredged annually from the area in front of the hydropower station to ensure water flow to the intakes of the turbines. The cost of sediment dredging may reach up to two US$ per m^3 of removed sediment (Loman as cited by (Siyam et al., 2005)). Even though, Roseires Reservoir has lost one third of the design capacity before heightening because of sedimentation. The variations of reservoir storage capacity with time from as given by the bathymetric surveys of the years 1976, 1981, 1985, 1992, 2005 and 2007 are summarized in Table 1. The total capacity of the reservoir (at 480 m) reduced to 1,704 million cubic meters in 41 years time. As shown in Table 1, the rate of sedimentation has decreased from 55 Mm^3/year during the first 10 years of operation to 15 Mm^3/year during last 15 years.

2.3 BLUE NILE BASIN GEOLOGY

Three main geological units have been distinguished in the upper Blue Nile in Ethiopia (Fig. 3) (BCEOM, 1999):

(i) Precambrian metamorphic rocks represent the oldest complex; they form the crystalline basement underlying the volcanics and are exposed over about 32 % of the basin in the western lowlands;

(ii) Mesozoic sedimentary formations represent about 10-11 % of the basin, being mainly visible in the deep valleys of major southern tributaries of the Upper Blue Nile and,

(iii) Thick Tertiary and Quaternary volcanic formations cover 55-56 % of the basin, in the north, centre and east of the basin (Wolela, 2007, Wolela, 2008, MWR, 1999).

The main part of the Sudan Lowlands (Fig. 3) is underlain by deep unconsolidated colluvial sediments of tertiary and quaternary age. Older Basement Complex rocks and the Nubian Sandstones are located to the north. The Nubian Sandstones are located in the northwest corner and overly uncomfortably the Basement Complex rocks and comprise mainly sandstones, siltstones and conglomerates (ENTRO, 2007).

2.4 BLUE NILE BASIN MINERALOGY

The basin soil (Fig. 4 and Fig. 5) consists of Vertisol, Nitisol and Leptosol among others. Nitisols (24%) dominate the western Highlands, whilst shallower and more infertile Leptosols (19%) occupy the eastern Highlands. Vertisols (29%) dominate the unconsolidated sediments of the Sudan Plains (Hydrosult et al., 2007, FAO, 1998) and the flat plateaus in the Ethiopian Highlands.

The soil physical and chemical soil properties have been investigated in the upper basin in many projects, as reported by Ermias (2015). Generally, the bulk density varies from 0.99 to 1.29 g/cm-3 (Getachew et al., 2012, Demessie, 2015). Organic Carbon content varies from 3.92 to 4.94%, while the pH is neutral to slightly alkine 5.6 (Demessie, 2015).

The Vertisols in the lower basin in Sudan is described to form an active layer, swelling and shrinking with changes in soil moisture, in which the organic carbon content is generally less than 2% and the pH is neutral to slightly alkine (Ahmad, 1996, Weg, 1987).

3. MATERIAL AND METHODS

In order to select the location of sediment sampling within the reservoir we first simulated the sediment processes inside Roseires Reservoir using a model based on the open-source Delft 3D software (www.deltares.nl) to investigate sedimentation process and soil stratification in the reservoir (Omer et al., 2015). From the model output it was possible to identify the locations inside the reservoir where no erosion occurred since 1985. Four locations were then selected as coring spots for the study of soil stratification and sediment sample collection. Coring of sediment samples was taken when the reservoir was at the minimum operation level of 370 m (Alexandria Datum = Irrigation Datum +3 m) in the month of July. This is the best time of the year to carry out soil sampling in locations that are normally underwater.

Soil samples were collected from two zones in the Blue Nile River Basin: (1) from the source areas in the upper basin where erosion takes place and (2) from the sink area, (Roseires Reservoir) where a significant amount of the sediment coming from the upper basin is deposited. The samples were analysed using XRPD to identify the mineral content. After that a cluster analysis was carried out to identify groups of samples that share a high degree of mineralogical "similarity". Cluster analyses were performed on the XRPD data using Minitab software package.

3.1 COLLECTION OF SEDIMENT SAMPLES

In the source area, 28 soil samples were collected in June-July 2013 at the locations shown in Fig. 2, with spatial distribution covering most of the (accessible) eroded area in the upper basin. The samples were collected from gullies, eroded rock and from the river banks and bed. In the sink area, coring was carried out at four locations. A total of 35 soil samples were collected, as given in Table 2. At each of the four locations inside Roseires Reservoir (Fig. 2), trenches were dag up to depths of 2.5 m to 4 m, according to the occurrence of water table. Soil samples were collected every 50 cm. Only in one trench the samples were collected every 25 cm to check the vertical variation of the deposited material in more details. Photos showing samples collection from various locations in the two zones are shown in Fig. 6.

3.2 X-RAY POWDER DIFFRACTION (XRPD)

Each sample was dried in an oven at 100°C for 24 hours, followed by manual crushing of soil and rock at the chemical laboratory of UNESCO-IHE in Delft, the Netherlands. The crushed samples

were further sieved to recover the smaller than 100 μ meter fraction prior to the analysis by XRPD at the laboratory of the Technical University of Delft, in the Netherlands.
The X-Ray Powder Diffraction is based on the interaction between a strong source of energy (X-Ray) and the ordered crystalline structure of atoms in minerals or other crystalline materials. Each mineral has a unique crystalline structure, or lattice, where atoms are arranged in a periodic array in fixed positions. When electromagnetic energy hits a mineral lattice then it is scattered by its atoms and the intensity of energy scattered is proportional to the number of electrons orbiting around each atom. The X-Rays are ideal for mineral diffractometry, because they have a wavelength that is similar to the distance between atoms in the lattice and therefore they allow atoms to become point scatterers. Each periodic array of atoms produces a unique diffraction pattern and thus it allows for the identification of mineral species. The scatterogram is digitally compared with a database of pure minerals for identification of the mineral species. A more detailed treatment of the XRPD is available at http://www.iucr.org/education/pamphlets and at http://pubs.usgs.gov/of/2001/of01-041/index.htm

XRPD patterns were recorded in a Bragg-Brentano geometry using a Bruker D5005 diffractometer equipped with Huber incident-beam monochromator and Braun PSD detector. Data collection was carried out at room temperature using monochromatic Cu radiation (Kα1 $\lambda = 0.154056$ nm) in the 2θ region between 10° and 90°, step size 0.038 degrees 2θ.

All samples were measured under identical conditions. The samples, of about 20 milligrams each, were deposited on a Si (510) wafer and were rotated during measurement. Data evaluation was done with the Bruker program EVA. The measured XRPD patterns are in the 2θ range 10-60 degrees. The outputs are shown in graphs where on the X-axis are plotted 2θ of the rotating sample and on the Y-axis are plotted the amount of counted reflected X-Ray signal. Different samples have different colours; an example is shown in Fig.7. The colour bars give the peak positions and intensities of the identified minerals, such as found using the ICDD pdf4 database (http://www.icdd.com). All patterns are background-subtracted, meaning that the contribution of air scatter and possible fluorescence radiation is subtracted.

The XRPD method like all analytical techniques has some shortcomings. The diffraction pattern is ‘‘unique’’, in practice there are sufficient similarities between patterns as to cause confusion (Cortés et al., 2007). There are probably in excess of two million possible unique ‘‘phases’’, of which only around 120,000 on the reference database in the International Centre for Diffraction Data (ICDD file) as single-phase patterns exist.

Moreover, the diffraction method is not comparable in sensitivity to the other X-ray-based techniques. Whereas in X-ray spectrometry one can obtain detection limits in the low parts per million regions, the powder method has difficulty in identifying several tenths of one percent. To this extent it is less sensitive than the fluorescence method by about three orders of magnitude (Ascaso and Blasco, 2012, Jenkins, 2000).

Notwithstanding these possible shortcomings, the method appears the most promising one to study the mineral content of the sediment from the Blue Nile Basin.

3.3 CLUSTER ANALYSIS

Cluster analysis is a statistical technique that applied here to identify clusters of mineralogically similar samples, between the source and the sink areas(de Meijer et al., 2001). This technique was applied to the 63 samples, to analyse six major mineral species and thus quantifying how "similar" two samples are.

In order to define similarity in cluster analysis, a linking method between clusters and a distance measure need to be specified. For the present analyses, linkage was taken as the average of the distances in mineral contents between all pairs in the two groups (known as average linkage) and distance was taken to be Euclidean distance after measurements in each fraction were standardized to have common variation (de Meijer et al., 2001). The average clustering was found to perform the same as simple linkage and complete linkage (Cortés et al., 2007). Cluster analysis can be readily carried out in most of the standard statistical packages. The analysis for this study was carried out using MINITAB software package (Minitab, Inc., 1998).

4. RESULTS AND DISCUSSION

Here we present the XRPD results from the sink and source areas. Six major minerals were found to be constituent parts of all the samples.

4.1 MINERAL CONTENT

The XRPD pattern of the random powder analysis for seven samples in the left bank of Roseires Reservoir is shown in Fig. 7 as an example.

The XRPD results indicate that all sediment samples, from the four trenches inside Roseires Reservoir and the eroded soils and rocks samples in the source areas consist of the following five major minerals, namely:

- Quartz [SiO_2],
- Albite [$Na_{0.685}Ca_{0.347}Al_{1.46}Si_{2.54}O_8$],
- Muscovite 2M1, [$K_{0.86}Na_{0.10}(H_3O)_{0.01}Mg_{0.06}Ti_{0.01}Fe_{0.07}Al_{2.88}Si_{3.02}O_{10}(OH)_2$],
- Microcline [$KAlSi_3O_8$].
- Calcite [$CaCO_3$],

However, one sample (sample 49 from the upstream catchment) contains also Augite [Ca(Mg,Fe,Al)(Si,Al)$_2$O$_6$]. And only two samples have Rutile mineral.

The minerals content percentages in the four trenches inside Roseires Reservoir are shown in Fig. 8, Fig. 9, Fig. 10 and Fig.11, respectively and detailed in Table A 1 in the Annex.

The mineral content percentages of the upstream samples are shown in Fig. 12 and detailed in Table A 2 in the Annex.

4.2 CLUSTER ANALYSIS

First, cluster analysis was performed to check if all sediment deposited in the reservoir are similar in their mineral content. Then the analysis was performed on the entire set of 63 samples to get a grouping between source and sink samples, in terms of their mineralogical content.

The results shows that the samples collected from Roseires Reservoir (samples no. 1 to 35) have different similarities varied from (30-95) % as shown in Fig. 13. This figure uses Sample no 1 as reference for comparison and shows that the mineral content in Sample no 17 has similar mineralogical characteristics and have similarity of more 95%. Samples no 24 and 33 have the best similarity but when compared with the reference sample (Sample no 1) they have a similarity of 70 %. Moreover, the characteristics of Samples 1 are different from those of Sample 2 even if these two samples were collected from the same trench where their depths were 50 cm apart.

All samples from Roseires Reservoir and upper catchments were then used in the analyses to determine the overall patterns of similarity between samples from different parts of the catchment. The dendrogram shown in Fig.14 illustrates the combined five mineral fractions Quartz, Albite, Muscovite, Microcline and Calcite. The dendrogram visualizes on the X-axis, from left to right, the order in which samples, or groups of samples, combine to form clusters with similar mineral content and on the Y-axis, the similarity levels at which the combinations of minerals occur. Thus the samples are closer on the X-axis if they have similar mineralogical content, and are linked by a small horizontal bar whose position on the Y-axis defines the degree of similarity: the lower the horizontal bar the higher the degree of similarity.

Cluster similarity is a measure of distance between clusters relative to the largest distance between any two individual samples. One hundred percent similarity means the clusters were zero distance apart in their composition.

We observed seven major groupings from A to G based on the similarity occurred between samples (see Fig.14). Group A contains all samples with similarity equal or greater of 85%. Group B contains samples that have similarity of 80% with group A. Group C represents all samples that have similarity of 75% with subgroup A and B, and so on.

Based on the dendrogram of Fig. 14 for all the 63 samples, the following relationships can be highlighted:

- ✓ All samples in group A are similar within each other with a similarity of 85% or more, 24 samples inside Roseires Reservoir (sink) are similar to Sample 39 from Jemma River and Sample 50 from Didessa River (sources). A similar situation occurs for group B, since four samples inside Roseires Reservoir are similar to Sample 42 from the soil eroded near Wello-Dessie in the Jemma Sub-basin, and to Samples 61 and 62 from the soil eroded near Eyasu Ager and in South Wello-Gully (Welaka Sub-basin). The two subgroups A and B are still similar, since they present more than 80% similarity.
- ✓ All samples of group C are similar, with a similarity of 77% or more, the samples in this group are from the upper basin including Sample 40 (Welaka), as well as Samples 43, 54, 55, 56, 58, 59 and 60 (South Gojam), 57 (Tana), 46 (Birr), 48 (Guder) and 63 (Jemma).The similarity between subgroup C and subgroup A and B is less than 75%.
- ✓ Group D consisting of Sample 4 from Roseires Reservoir, similar to Sample 45 (North Gojam) and Sample 47 (Guder) from the upper basin, has similarity of 65% with group (A+B+C).
- ✓ Group E, consisting of Samples 36, 52 and 53 from the sub-basins of Muger, Dabus and South Gojam, has similarity of 55% with group (A+B+C+D).
- ✓ Group F consisting of Samples 2, 25, 16 from Roseires Reservoir, similar to Sample 37 from the Jemma Sub-basin, has similarity of 50% with group (A+B+C+D+E).

In addition to the analysis of all samples, cluster analysis was performed for different layers of deposited sediment inside Roseires Reservoir. First, two samples were collected from the reservoir at depth of 4 m below the surface and other two at a depth of 3 m from Trench 2 and Trench 3. The results of the Delft3D model used to simulate the sedimentation processes inside Roseires Reservoir showed that the sediment layers at 4 m depth and 3 m depth were deposited approximately in the period 1986 to 1991 and 1993 to 1997, respectively (Omer et al., 2015). Table 3 provides the mineral content for the samples collected at a depth of 4 m (No 1 and 2 up) and 3 m (No 1 and 2 down) inside the reservoir. The mineral content for the upper basin samples are given in Fig. 12.

The cluster analysis shown in Fig.15 (left) idicates that Sample 1 from Roseires Reservoir, collected at depth of 4 m, is 90% or more similar to Sample 6 from the Jemma River and Sample

17 from the Didessa River. Sample 2 from the reservoir, collected at depth of 4 m, is 90% similar to Samples 9, 28 and 29 from South Wello in Jemma Sub-basin. The cluster analysis showed that Sample 1 and Sample 2 from Roseires Reservoir, collected at depth of 3 m (Fig.15 right) are 85% similar to Sample 6 from the Jemma River and Sample 17 from the Didessa River.

Four samples were collected at depth of 2 m below the surface and four samples at a depth of 1 m from Trench 1, -Trench 2, Trench 3 and Trench 4. The numerical model shows that the sediment layers at the depths of 2 m and 1 m depth were deposited approximately in the period 1998 to 2002 and 2003 to 2007, respectively. Table 4 provides the mineral content for the samples collected from 2 m (No 1 to 4 up) and 1 m (No 1 to 4 down) depth inside the reservoir. The mineral content for the upper basin samples are given in Fig. 12.

The results of the cluster analysis for the four samples from Roseires Reservoir collected at depth of 2 m and 28 samples from the upper basin (Fig. 16 left) are explained below:

A. Sample 1 at 2 m depth in the reservoir is similar to sample 14 from Bahridar, North Gojam Sub-basin, having similarity of more than 90%, these two samples are similar to Sample 16 from the Guder Sub-basin, with a similarity of about 80%.
B. Sample 2 is 95% similar to Sample 8 from the Jemma River.
C. Sample 4 is 95% similar to Sample 19 from the Didessa River.
D. Group B is 85% similar to Group C.
E. Group A is 70% similar to Group D.
F. Sample 3 showed similarity of about 55% to most of samples from the upper basin.

The results of the cluster analysis for the four samples from Roseires Reservoir collected at depth of 1 m and 28 samples from the upper basin (Fig.16 right) are explained below:

A. Sample 1 is similar to Sample 3 from Roseires Reservoir, having a similarity of more than 80%.
B. Sample 2 is similar to Sample 8 from the Jemma River, having a similarity of more than 95%.
C. Sample 4 and Sample 19 Didessa River have a similarity of more than 95%
D. Group B and Group C have a similarity of more than 90%.
E. Group D and Group A have a similarity of more than 75%.

5. DISCUSSION

Based on the cluster analysis, we suggest that most of the sediment deposited inside Roseires Reservoir is originated by erosion from 3 sub-basins only out of 14: Jemma, Didessa and South Gojam. The upper Blue Nile Basin is characterized by a large variability in topography, natural vegetation cover, rainfall, temperature, soils, and lithology, which explains a large part of the observed variability in sediment yield. Topography is often indicated as an important factor controlling erosion rates (Tamene et al., 2006). Climatic factors, such as rainfall and air temperature, are regularly cited as important factors controlling the river sediment fluxes (Nyssen et al., 2008). Vegetation cover is reported to be important for the sediment fluxes. Although vegetation density is controlled by anthropogenic activity, it may be assumed that broad regional patterns in vegetation cover are strongly naturally controlled and that dense vegetation can act as a biophysical barrier to soil erosion (Kettner et al., 2010, de Vente et al., 2011). Based on sediment yield data from 11 catchments in northern Ethiopia, Tamene (2006) concluded that no significant relation was found between the sediment yield and the proportion of dense vegetation, cultivated land, bush/shrub cover or bare land.

Annual flow discharge and sediment load balances were obtained by integrating the available and newly measured flow discharges, suspended sediment concentration and numerical modelling by Ali et al (2014), based on the Soil and Water Assessment Tool. They estimated the yearly sediment balances at several locations along the main river and the tributaries(Ali Y.S.A. et al., 2014). The long-term annual average sediment load showed that the sub-basins of Jemma, Didessa and South Gojam have provided most of the sediment transported by the Blue Nile River System, as shown in Fig. 17 (Ali Y.S.A. et al., 2014). It is believed that one reason for the increasing erosion in the upper basin is due to land-use changes/land-cover changes (LULCC) (Gebremicael et al., 2013). The LULCC was detected for a 38 years period to verify the sediment contributions from these sub basins. The analysis of Landsat imageries of 1973, 2000 and 2010 in the sub-basins of Jemma, Didessa and South Gojam showed that important land use changes occurred in these sub basins in the last 40 years, where the soil coverage by natural forest, woodland, wooded grassland and grassland decreased from more than 70% to less than 25%. Instead, the cultivated area increased from 30% to more than 70% of the total surface area (Ali, 2014).

The Leptosols mostly occurring in the Jemma sub-basin are shallow soils with limited profile development and are prone to drought. They occur on steep slopes, they are exposed to a high degree of erosion. The Leptosols in the Jemma sub-basin are lying above deep Cambisols and cultivated at altitudes between 2,300 and 3,500 m above mean sea level for about 130-230 days/year, divided between two rainy seasons (Ali, 2014, BCEOM, 1999).

In upper Didessa, the Alisols are deeply leached soils with only moderate to low fertility. Fertility tends to be highest in the top soils, meaning that erosion has deep and permanent impact on these soils. Nitisols and Acrisols are similar in general respects to Alisols. However, Nitisols are in principle better soils, while Acrisols are the most leached with the lowest pH. More detailed survey work would assist in separating such soils, and directing development away from the Acrisols (Ali, 2014, BCEOM, 1999).

6. Conclusions

We can use the results of this study for a semi-quantitative fingerprinting of the sediments depositing in Roseires Reservoir, formed by the Blue Nile River in Sudan, near the border with Ethiopia. At present, this is the first trap for the sediment carried out by the river. In the future, large amounts of this sediment are expected to settle behind the Grand Ethiopian Renaissance Dam, which is currently under construction near the border with Sudan.

The outputs of this study highlight that most sediment originates from the three sub-basins of Jemma, Didessa and South Gojam. The results of previous studies, based on different approaches (SWAT modelling of soil erosion at the sub-basin scale, and change detection using satellite images) support this hypothesis, since these sub-basins showed the largest soil erosion rates when compared to the other sub-basins of the Blue Nile, as well as the largest LULC changes. This result will prove useful to support informed water resources planning and watershed management in the Blue Nile Basin.

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List of Figure:

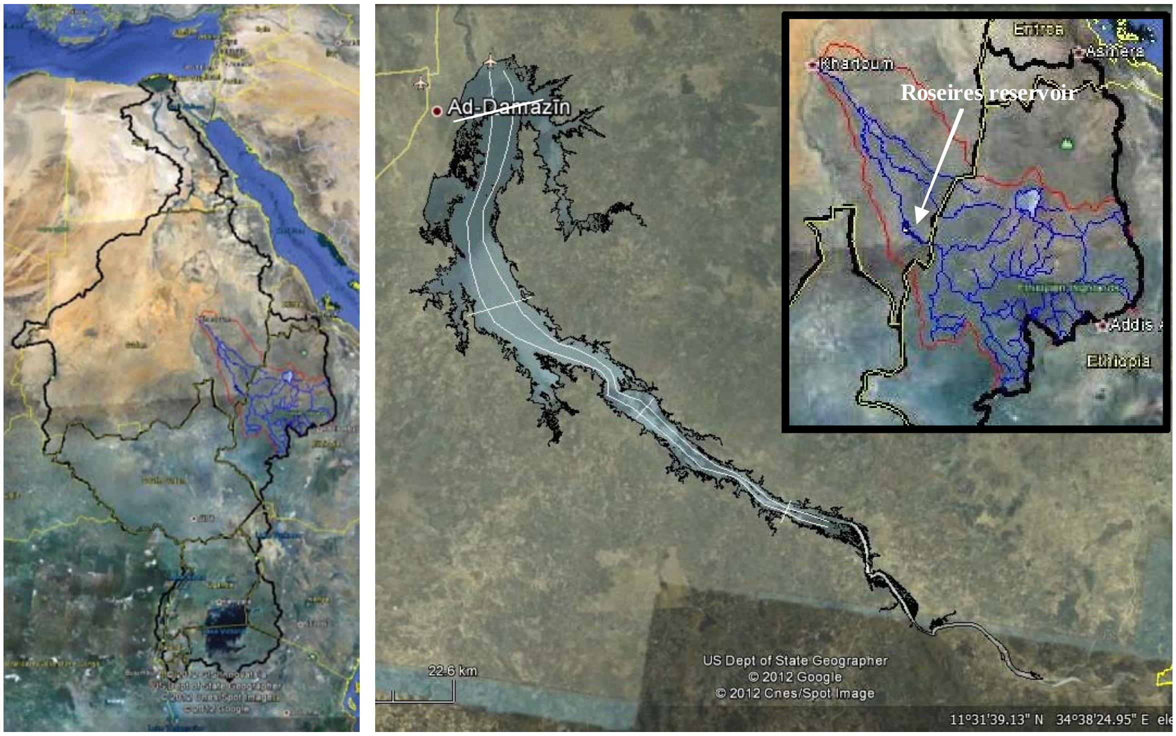

Fig. 1: Location of Roseires Reservoir. a) Entire Nile River basin (left) b) Blue Nile basin, with location of Roseires Dam (right).

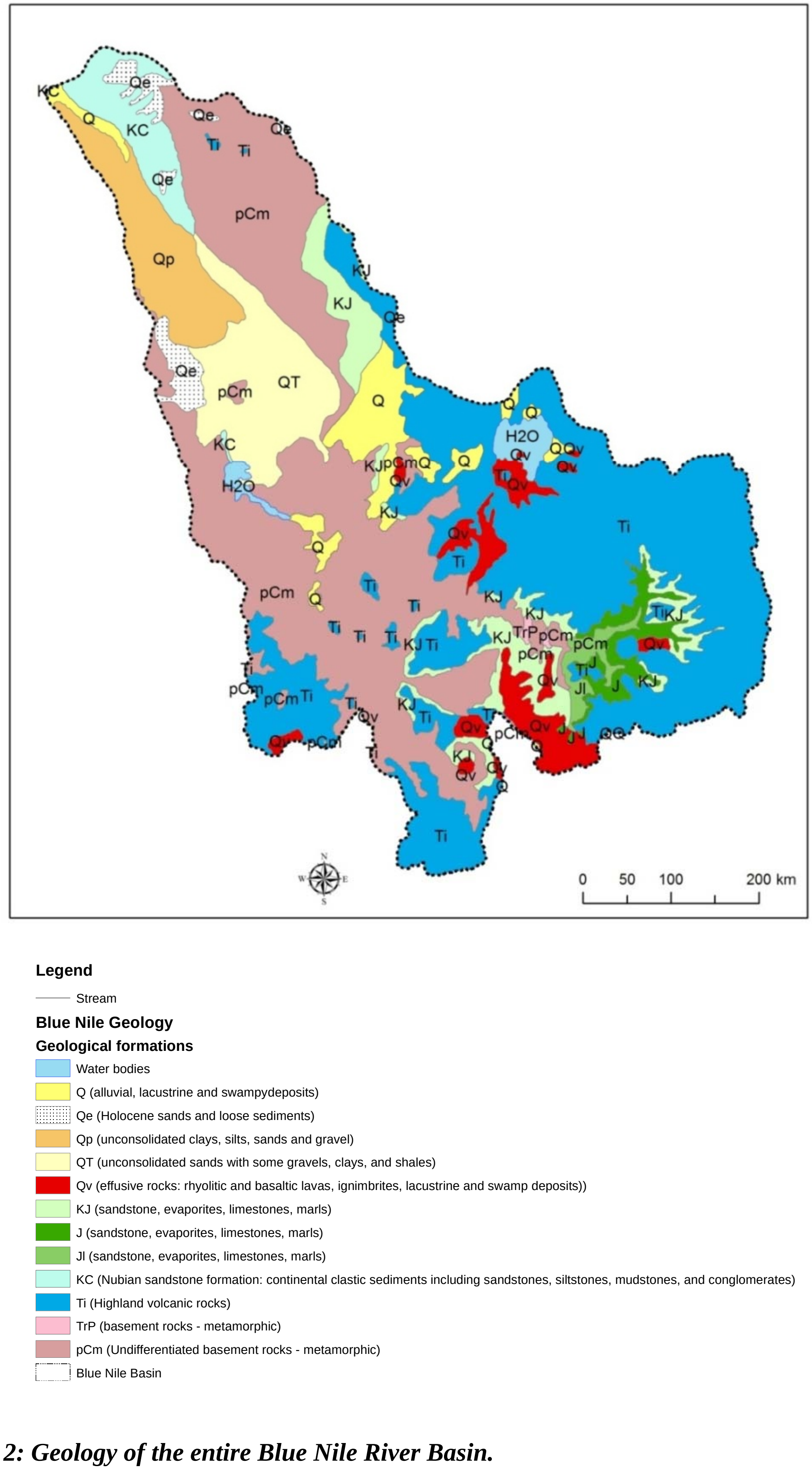

Fig. 2: Geology of the entire Blue Nile River Basin.

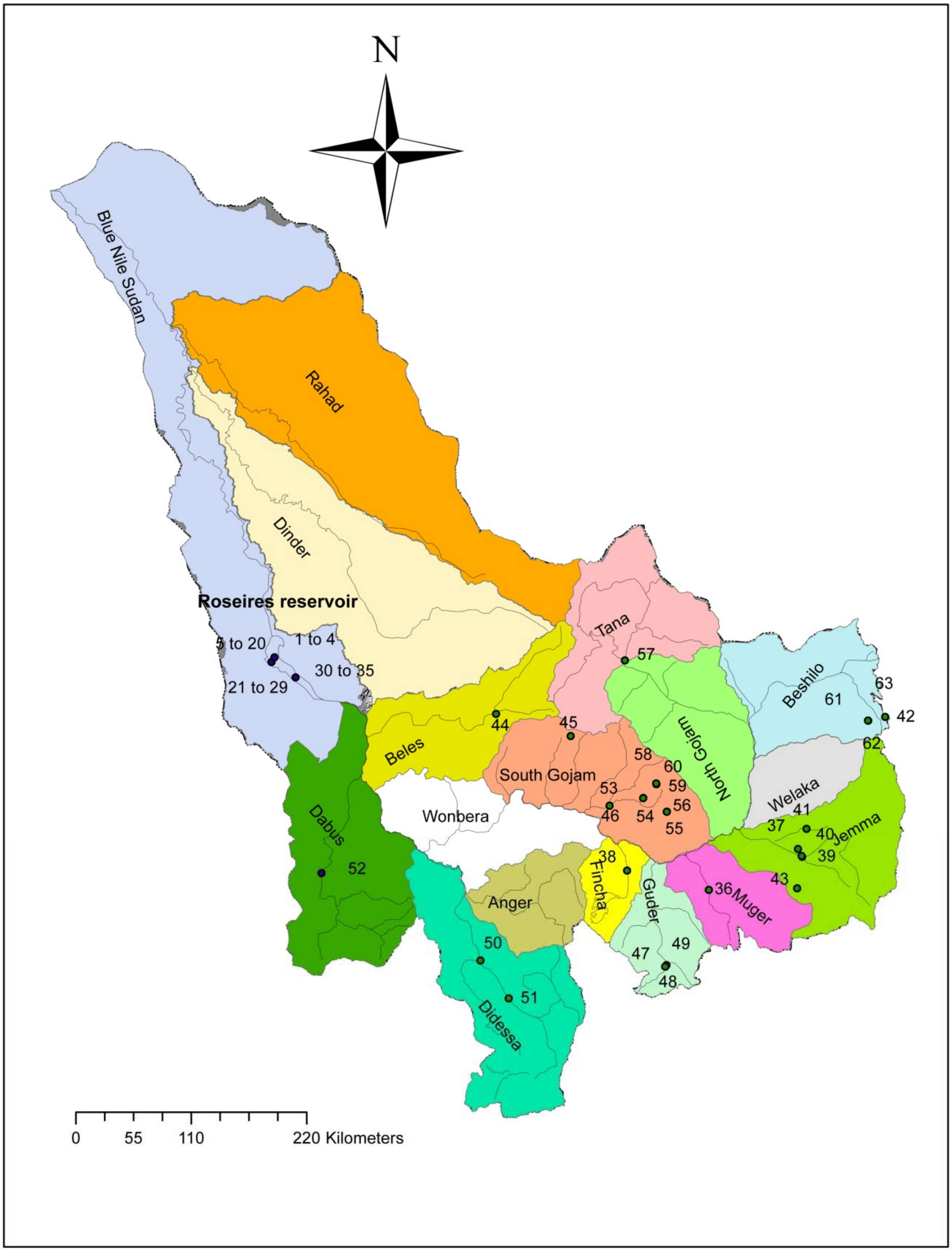

Fig.3: Location of collected soil samples, the number as described in detail in Table 2 and Table 3, and sub-basins of the whole Blue Nile watershed. The sub-basins upstream Roseires Reservoir are 14 in total.

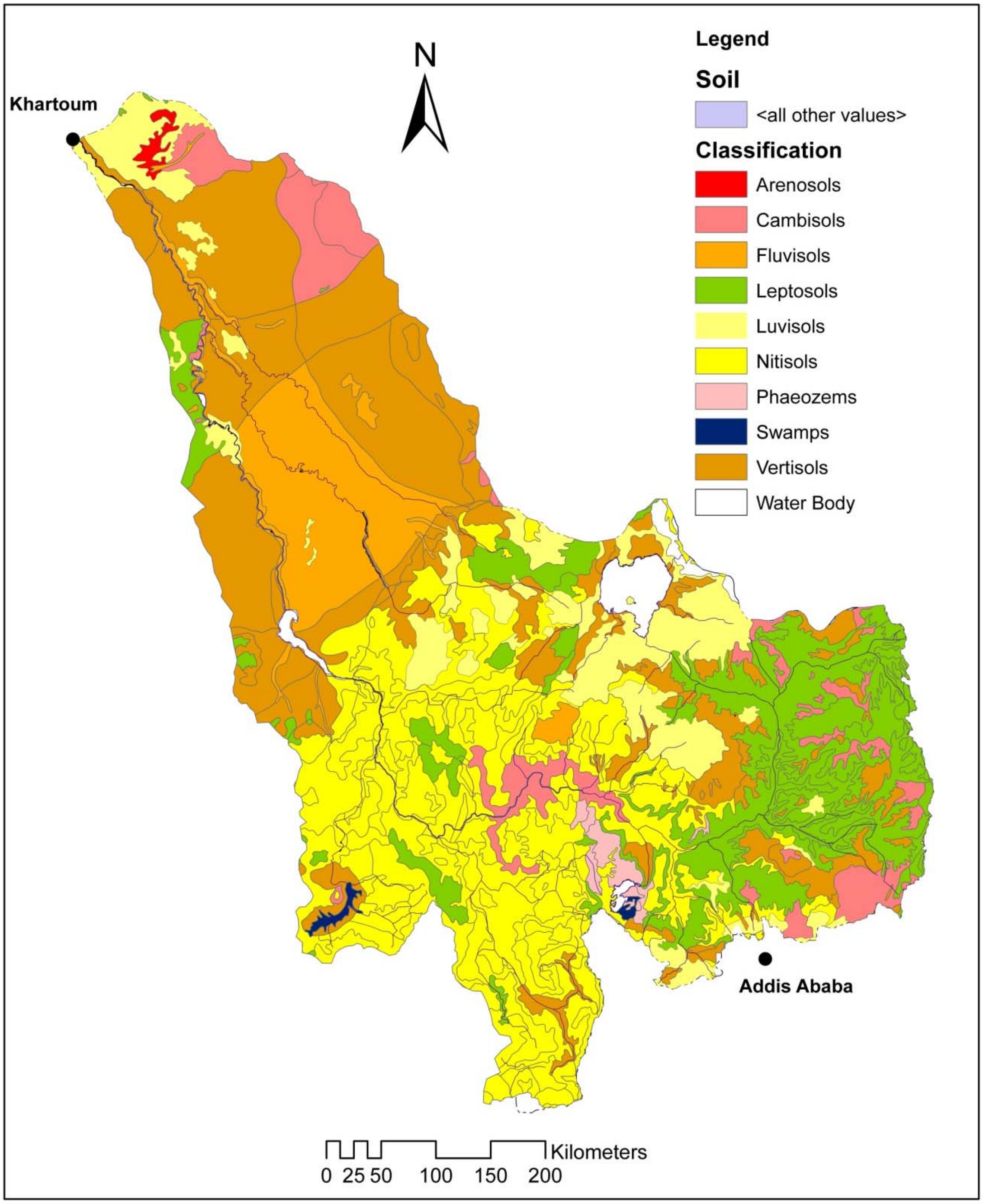

Fig.4: Blue Nile Basin- soil map according to FAO (1998).

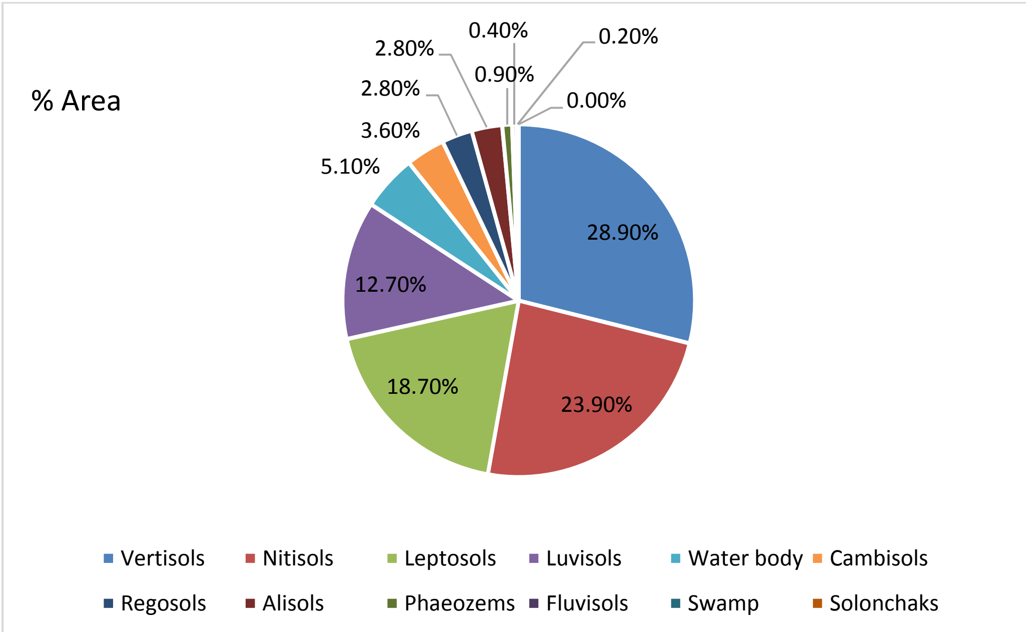

Fig. 5: Abbay-Blue Nile Sub-basin: Dominant soil types - % of Area (Source: FAO, 1998 Soil and Terrain Database for Northeast Africa)'.

Fig.6: photos showing samples collection from Jemma basin (upper left), Didessa Basin (upper right), trench 3 inside Roseires Reservoir (lower left) and trench 4 inside Roseires Reservoir (lower right)

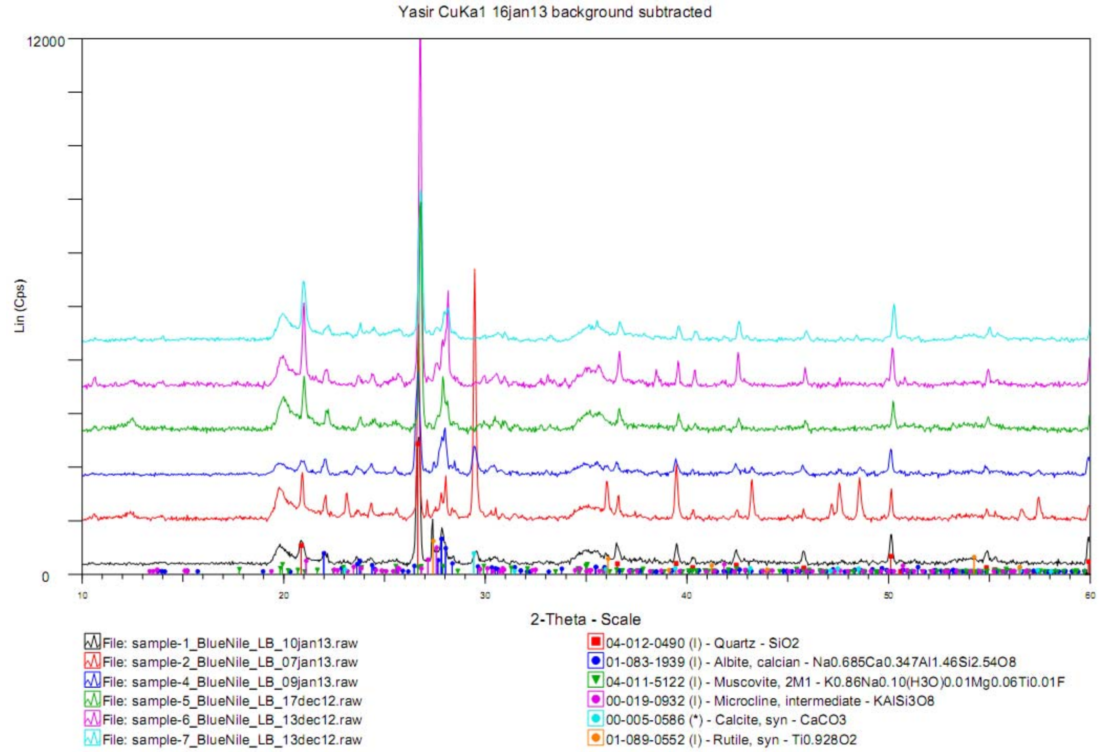

Fig.7: XRPD results from Roseires Reservoir left bank (samples 1-7)

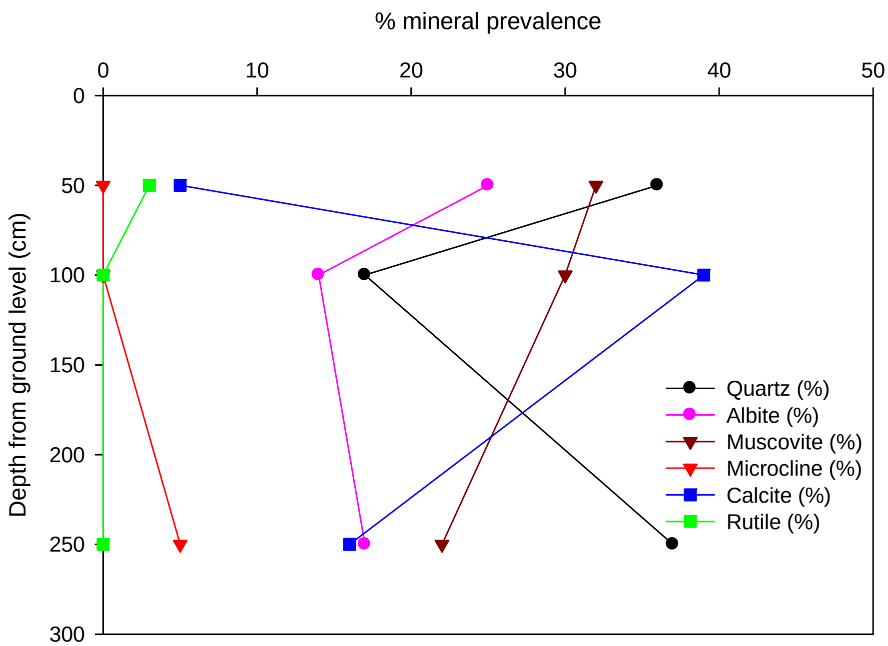

Fig.8: Mineral content percentages for samples collected from Trench 1 in Roseires Reservoir (L.B.)

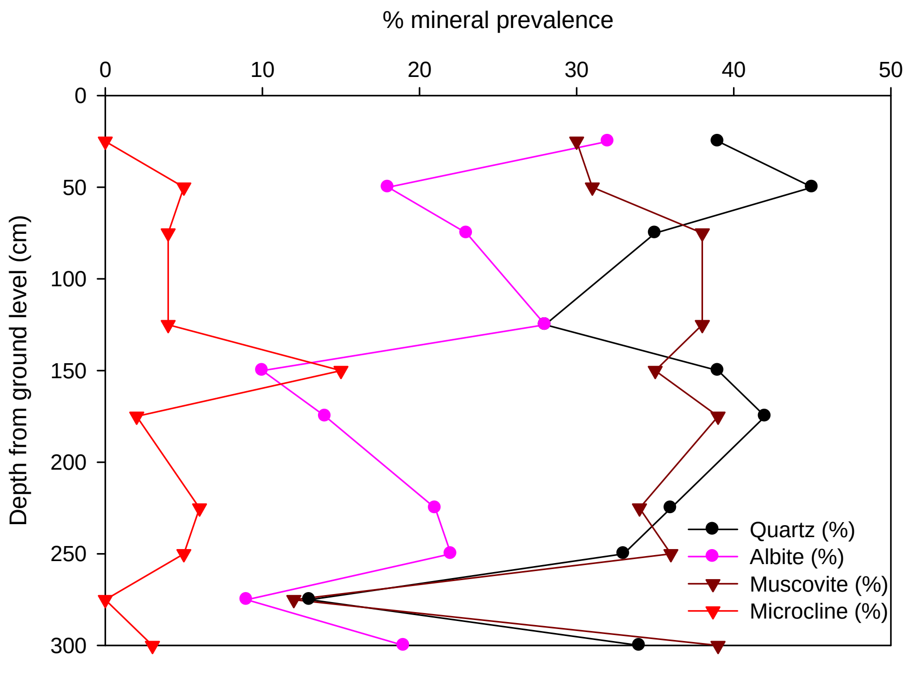

Fig.9: Mineral content percentages for samples collected from Trench 2 in Roseires Reservoir (L.B.)

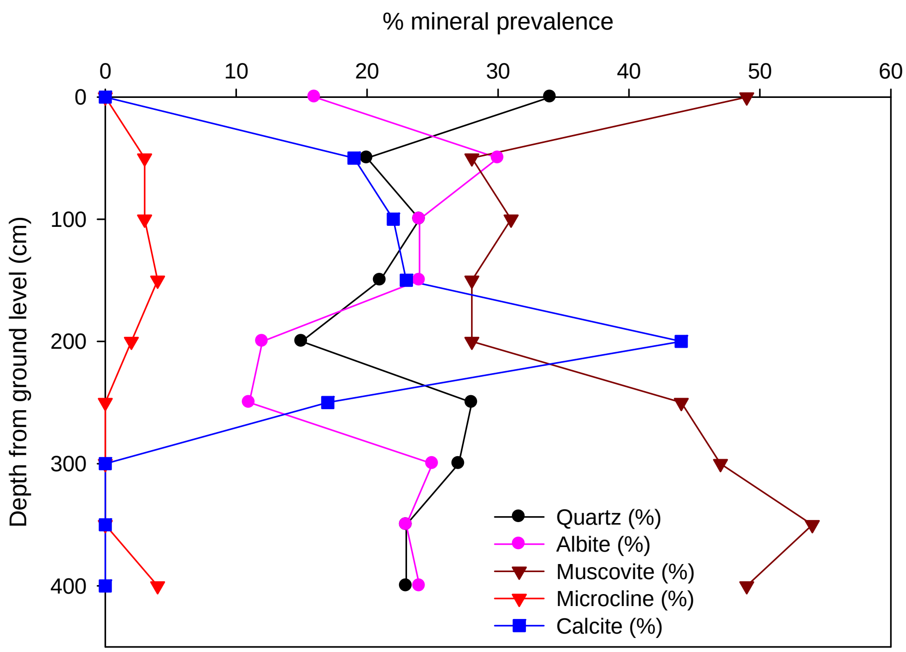

Fig.10: Mineral content percentages for samples collected from Trench 3 in Roseires Reservoir (R.B.)

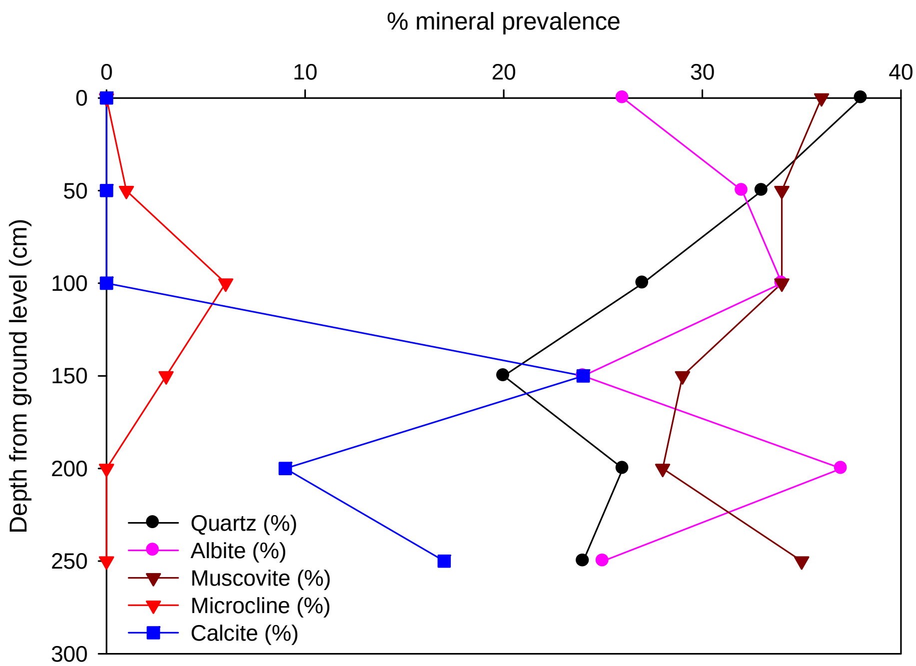

Fig.11: Mineral content percentages for samples collected from Trench 4 in Roseires Reservoir (L.B.)

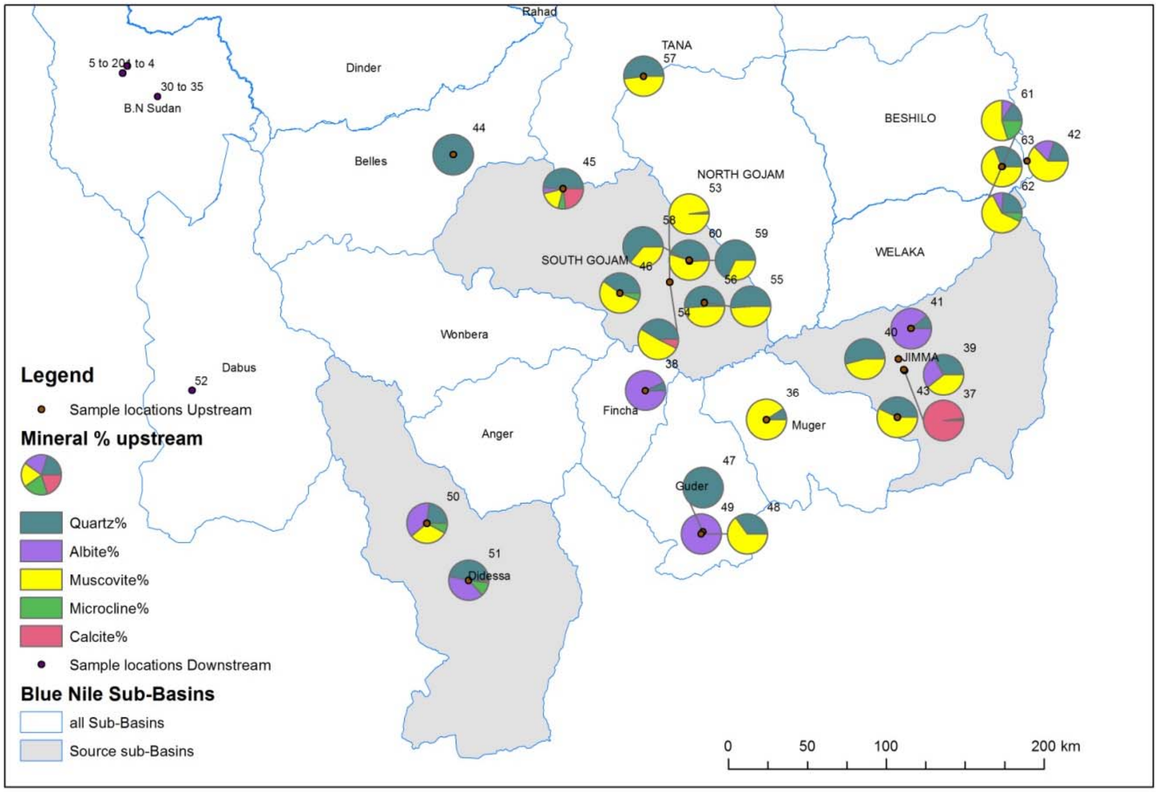

Fig.12: Mineral content percentages for samples collected from Upper Blue Nile Basin.

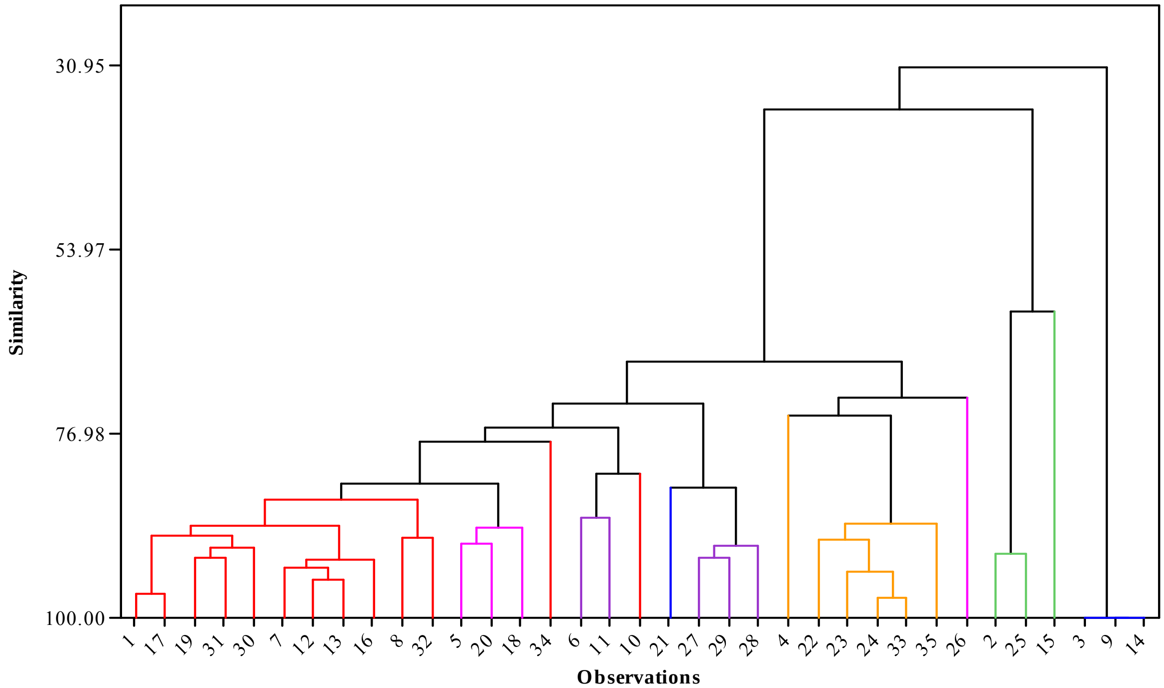

Fig.13: Dendrogram for the mineral content with Average Linkage and Euclidean Distance (Source samples collected from Roseires Reservoir only).

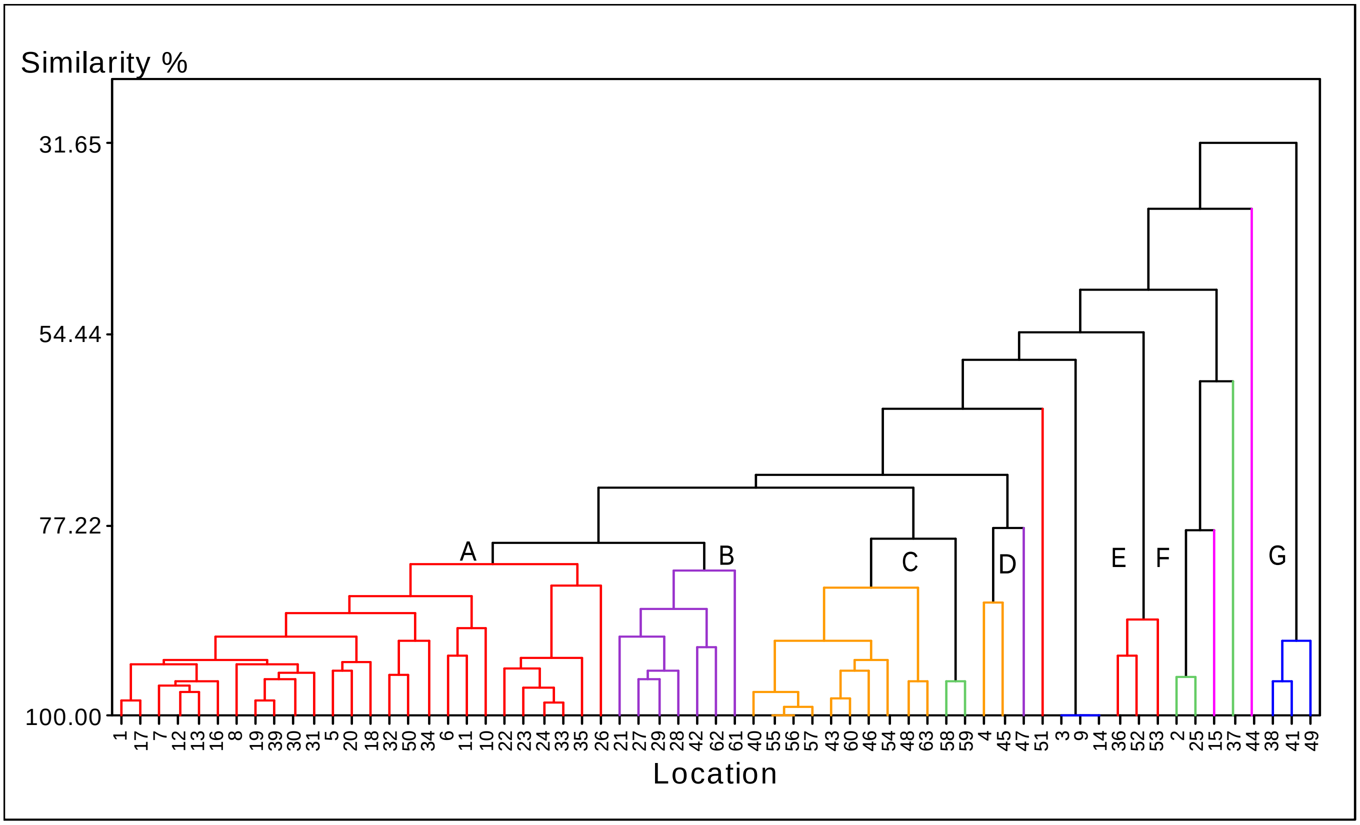

Fig.14: Dendrogram for the mineral content with Average Linkage and Euclidean Distance (all samples). X-axis numbers are sample numbers (see Table 3 and 4 for reference)

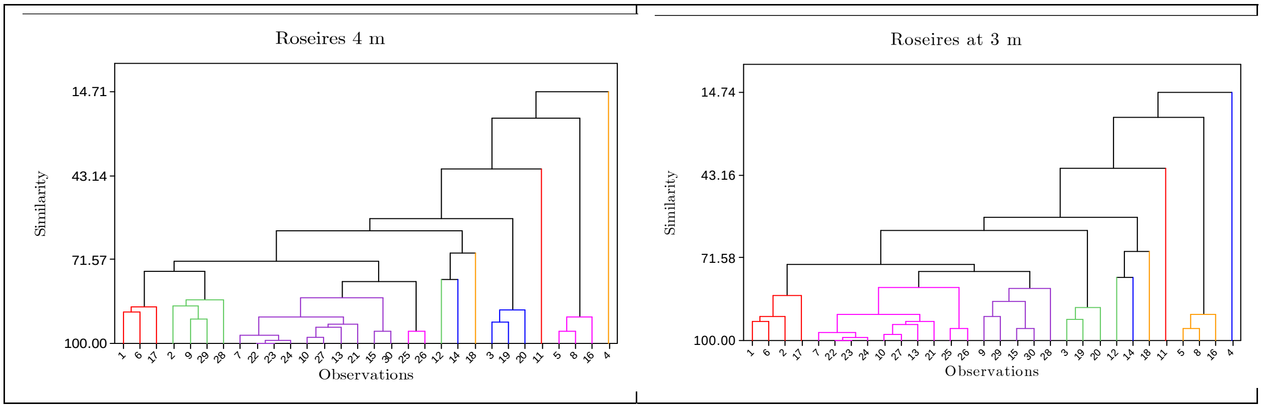

Fig. 15: Cluster analysis for samples collected from the upper basin and inside Roseires reservoir at depth of 4 m (left) and 3 m (right).

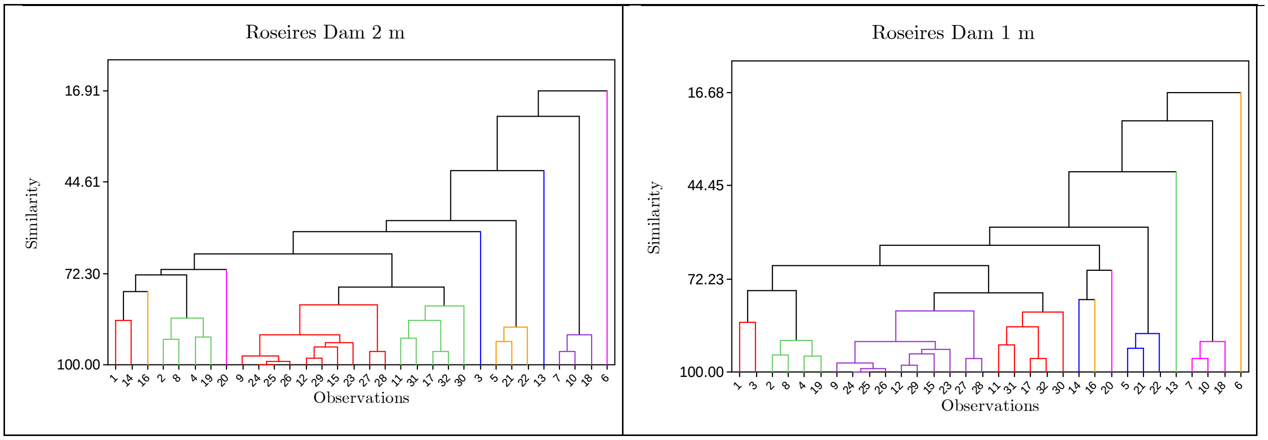

Fig.16: Cluster analysis for samples collected from the upper basin and inside Roseires reservoir at depth of 2 m (left) and 1 m (right)

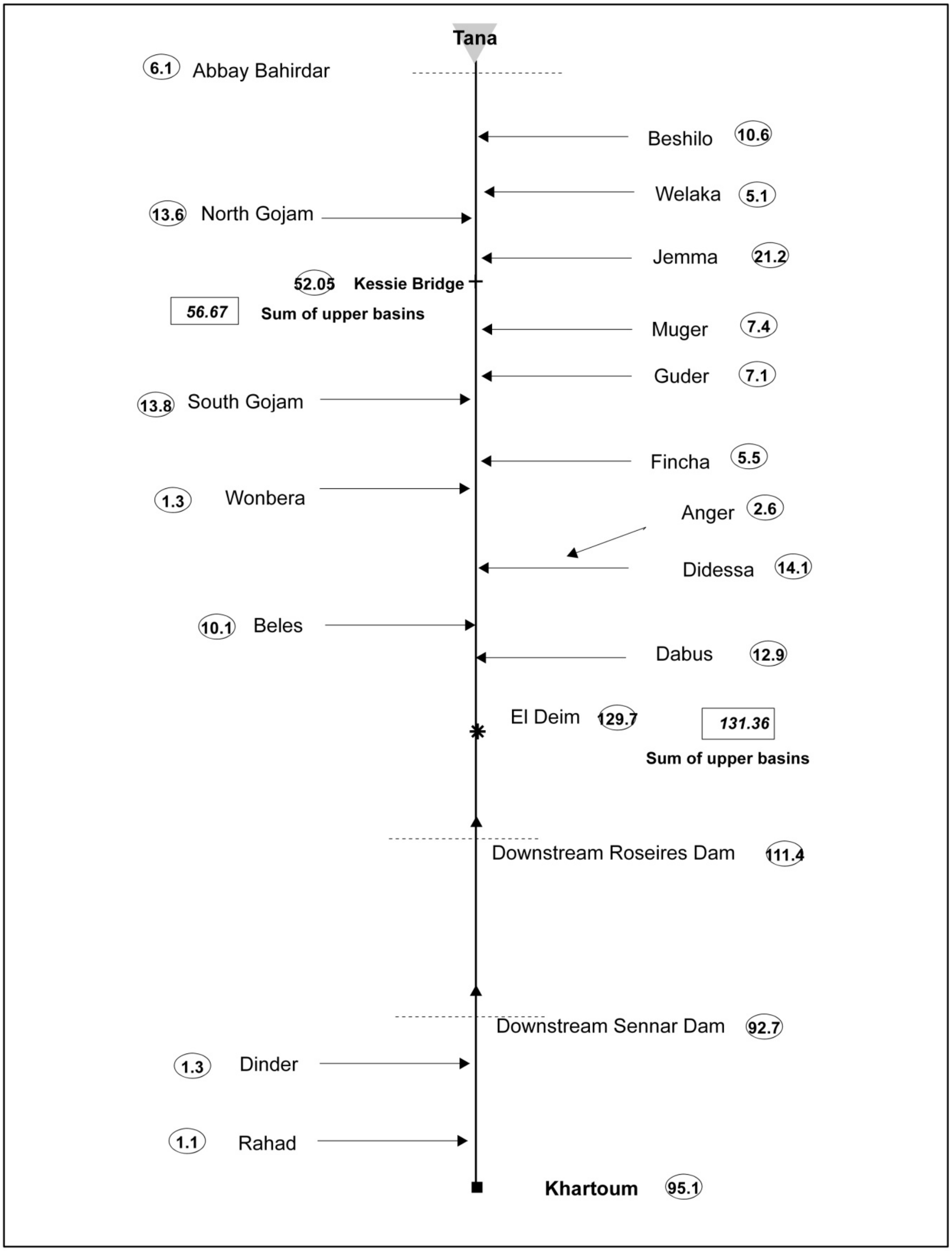

Fig. 17: Long-term average (1980-2004) sediment loads along Blue Nile River Basin network in million tonne/year estimated from the nonlinear regression rating curves (Ali et al. 2014).

List of Tables:

Table 1: Roseires Reservoir historical surveys including storage capacity (Irrigation Datum).

Reduced level (m)	**Storage capacity (million m³)**					
	1966	**1976**	**1981**	**1985**	**1992**	**2007**
465	454	68	36	17.13	11.9	9.05
467	638	152	91	60.13	38.97	25.9
470	992	444	350	259.2	179.8	113
475	1821	1271	1156	992.8	859	660.5
480	3024			2082	1937	1701.4
481	3329	2779		2337.6	2191.6	1953.8

Table2: Characteristics of trenches inside Roseires Reservoir

E	**N**	**Depth (m)**	**Samples interval (m)**	**No. samples**	**Name**	**Remarks**
650539	1280023	2.5	0.50	4	Trench 1	Left bank
650537	1280055	4.0	0.25	16	Trench 2	Left bank
653332	1284514	4.0	0.50	9	Trench 3	Right bank
673117	1265608	2.5	0.50	6	Trench 4	Right bank

Table 3: minerals percentage for the samples collected from 4 and 3 m depth inside Roseires reservoir

No	Location	Basin	Quartz	Albite	Muscovite	Microcline	Calcite
1	Roseires Dam	Trench 2(4 m)	36	31	26	5	2
2	Roseires Dam	Trench 3(4 m)	23	24	49	4	0
1	Roseires Dam	Trench 2(3 m)	34	19	39	3	4
2	Roseires Dam	Trench 3(3 m)	27	25	47	0	0

Table4: minerals percentage for the samples collected from 2 and 1 m depth inside Roseires Reservoir.

No	Location	Basin	Quartz	Albite	Muscovite	Microcline	Calcite
1	Roseires Dam	Trench 1(2 m)	37	17	22	5	16
2	Roseires Dam	Trench 2(2 m)	36	21	34	6	3
3	Roseires Dam	Trench 3(2 m)	15	12	28	2	44
4	Roseires Dam	Trench 4(2 m)	26	37	28	0	9
1	Roseires Dam	Trench 1(1 m)	17	14	30	0	39
2	Roseires Dam	Trench 2(1 m)	28	28	38	4	3
3	Roseires Dam	Trench 3(1 m)	24	24	31	3	22
4	Roseires Dam	Trench 4(1 m)	27	34	34	6	0

__Table A 1: minerals percentage for the samples collected from four trenches inside Roseires Reservoir__

No	Location	Depth*(cm)	Quartz (%)	Albite (%)	Muscovite (%)	Microcline (%)	Calcite (%)
1	L.B (trench 1)	50	36	25	32	0	5
2	L.B (trench 1)	100	17	14	30	0	39
4	L.B (trench 1)	250	37	17	22	5	16
5	L.B (trench 2)	25	39	32	30	0	0
6	L.B (trench 2)	50	45	18	31	5	0
7	L.B (trench 2)	75	35	23	38	4	0
9	L.B (trench 2)	125	28	28	38	4	3
10	L.B (trench 2)	150	39	10	35	15	0
11	L.B (trench 2)	175	42	14	39	2	2
13	L.B (trench 2)	225	36	21	34	6	3
14	L.B (trench 2)	250	33	22	36	5	3
15	L.B (trench 2)	275	13	9	12	0	67
16	L.B (trench 2)	300	34	19	39	3	4
17	L.B (trench 2)	325	35	25	33	0	7
18	L.B (trench 2)	350	43	27	26	0	4
19	L.B (trench 2)	375	33	28	38	0	2
20	L.B (trench 2)	400	36	31	26	5	2
21	R.B (trench 3)	0	34	16	49	0	0
22	R.B (trench 3)	50	20	30	28	3	19
23	R.B (trench 3)	100	24	24	31	3	22
24	R.B (trench 3)	150	21	24	28	4	23
25	R.B (trench 3)	200	15	12	28	2	44
26	R.B (trench 3)	250	28	11	44	0	17
27	R.B (trench 3)	300	27	25	47	0	0
28	R.B (trench 3)	350	23	23	54	0	0
29	R.B (trench 3)	400	23	24	49	4	0
30	R.B (trench 4)	0	38	26	36	0	0
31	R.B (trench 4)	50	33	32	34	1	0
32	R.B (trench 4)	100	27	34	34	6	0
33	R.B (trench 4)	150	20	24	29	3	24
34	R.B (trench 4)	200	26	37	28	0	9
35	R.B (trench 4)	250	24	25	35	0	17

* Depth is measured from the ground surface

L.B: Left bank of Blue Nile River

R.B: Right bank of Blue Nile River

Table A 2: minerals percentage for the samples collected from the upper basin

Sample	Location	Basin	Quartz (%)	Albite (%)	Muscovite (%)	Microcline (%)	Calcite (%)
36	Muger	Muger	9	0	89	0	0
37	Jemma R (L.B)	Jemma	2	0	0	0	98
38	Fincha R	Fincha	7	93	0	0	0
39	Jemma R (R.B)	Jemma	33	27	39	0	0
40	Welaka	Welaka	54	0	46	0	0
41	Welaka R	Welaka	11	89	0	0	0
42	Wallo-Dessie	Jemma	20	17	63	0	0
43	DebreBirhan	S. Gojam	43	0	57	0	0
44	Beles	Beles	100	0	0	0	0
45	Bahridar	N. Gojam	49	5	17	6	23
46	Birr	Birr	40	0	54	6	0
47	Guder basin	Guder	42	0	0	0	0
48	Guder R	Guder	35	0	65	0	0
49	Guder Rock	Guder	0	100	0	0	0
50	Didessa R	Didessa	23	38	31	8	1
51	Didessa R	Didessa	47	40	0	11	2
52	Dabus R	Dabus	17	0	83	0	0
53	Jedeb Rock	S. Gojam	2	0	98	0	0
54	Jedeb soil	S. Gojam	41	0	51	0	7
55	Chamoga Rock	S. Gojam	51	0	49	0	0
56	Chamoga soil	S. Gojam	51	0	49	0	0
57	Abbay	Tana	52	0	48	0	0
58	TamamaiGuly	S. Gojam	64	0	36	0	0
59	Tamamai Rock	S. Gojam	68	0	32	0	0
60	Tamamai Guly	S. Gojam	45	0	55	0	0
61	South Wello	Jemma	16	9	55	20	0
62	South Wello	Jemma	24	9	61	7	0
63	South Wello	Jemma	31	0	69	0	0