FOURTH PART

SEDIMENT TRANSPORTATION

and

CHEMICAL ANALYSIS OF WATER
CHAPTER X

SURVEY OF SEDIMENT TRANSPORTATION

The sediment transportation of a river is either a suspended load or a bed load, depending on how sediments are transported. The suspended load presents finer particles such as fine sand, silt and clay, whereas the bed load presents coarser particles such as coarse sand, gravel and pebbles. Both types of material contribute to sedimentation of reservoirs. The total sediment transportation is mainly represented by suspended load.

The erosion factors of the basin conditioning the amount of material transported by rivers are the rainfall conditions, the climate, the physical features of the basin (geology, pedology, relief) and the density of the vegetative cover.

10.1. MEASUREMENT CONTRIVANCE

Water was sampled at various stations on the WABI-SHEBELLE and on the FAFEN in order to determine the turbidity of water. These stations were selected mainly with respect to the development project of the basin. In this end, measurements were made at the following stations:

- WABI SHEBELLE at MALKA-WAKANA -

This station controls the inflows at the site of the electric dam project -

- WABI-SHEBELLE and DAKETA at HAMERO-HEPAD -

These two stations control most of the project site at the entrance of the lower valley -

- WABI-SHEBELLE at GODE -

This station controls the sediment discharge in the lower valley. The results are useful for irrigation development plans -

- WABI SHEBELLE at BURKUR -

This station enables determining the sediment discharge at the border after the decantation of the WABI SHEBELLE water in the flood plains located between KELAFO and MUSTAHIL -
This station controls the sediment transportation of the FAFEN before it flows into the water-spreading plains.

In order to be accurate turbidity measurements must be made in the stream-flow from the surface to the bottom. But this requires heavy equipment which may not be easily used especially in rivers presenting a swift current. Turbidity may be estimated approximately, though easily, by sampling at the surface. This has been done for the WABI SHEBELLE and FAFEN.

Some complete measurements were carried out at the beginning in order to know the distribution of suspended load in the reach, then measurements were made at reference points near the surface (generally from 1 to 3 samples for each measurement). The 10 litres samples were flocculated with hydrochloric acid then decanted. The resulting solution was then analysed by the Project Laboratory at ADDIS-ABABA.

10.2. RESULTS OF MEASUREMENTS AND INTERPRETATION

Annexe III presents in tables 10.1 to 10.6 all the results of the measurements made at the six stations of the WABI SHEBELLE and of the FAFEN.

The data for water discharges given in these tables correspond to the depth of flow at the time of sampling but are not always equal to the mean daily discharges.

When several samples are used for a same measurement, the turbidity in g/m³ is the arithmetic mean of the turbidities of each sample. The sediment discharge in kg/s is obtained by multiplying the mean turbidity by the discharge.

10.2.1. Turbidity of the WABI SHEBELLE at Malka-Wakana

Sixty-one measurements of sediment transportation were made from the 27th of September 1968 to the 28th of September 1969 for discharges ranging from 5.9 to 130 m³/s. The results of these measurements are presented in table 10.1 of the annexe. It may be noted that turbidity varies from 20 to 305 g/m³.

Graph X.1 gives the values of sediment transportation in kg/s related to the water discharge in m³/s. The relation between water discharge and sediment transportation is suitable. This relation is due to the fact that the floods issuing from the high volcanic mountains are considerably reduced in the GUEDEB plain.

The load of transported sediments has been computed for each month of the observation period using the curve of the graph.
Relation between water discharges and sediment discharges

High flow
*Hautes eaux*

Discharge $m^3/s$

Sediment discharge $kg/s$

Low flow
*Basses eaux*
The results are as follows, i.e.:

<table>
<thead>
<tr>
<th>Year</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>J</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
<th>Yearly Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968-69</td>
<td>2 050</td>
<td>3 530</td>
<td>34 830</td>
<td>7 700</td>
<td>2 950</td>
<td>11 550</td>
<td>32 300</td>
<td>8 950</td>
<td>3 840</td>
<td>1 030</td>
<td>550</td>
<td>980</td>
</tr>
<tr>
<td>1969-70</td>
<td>2 530</td>
<td>8 170</td>
<td>2 580</td>
<td>3 750</td>
<td>920</td>
<td>16 000</td>
<td>50 300</td>
<td>15 940</td>
<td>1 690</td>
<td>590</td>
<td>440</td>
<td>820</td>
</tr>
<tr>
<td>1970-71</td>
<td>400</td>
<td>6 190</td>
<td>5 140</td>
<td>2 090</td>
<td>550</td>
<td>4 580</td>
<td>68 900</td>
<td>29 200</td>
<td>5 880</td>
<td>1 160</td>
<td>380</td>
<td>450</td>
</tr>
<tr>
<td>1971-72</td>
<td>370</td>
<td>450</td>
<td>1 610</td>
<td>3 630</td>
<td>4 150</td>
<td>1 720</td>
<td>53 900</td>
<td>16 180</td>
<td>20 100</td>
<td>1 400</td>
<td>690</td>
<td>400</td>
</tr>
</tbody>
</table>

The suspended load scarcely varies from one year to the next. The mean annual load computed for four years is 110 000 tons. This will be considered as valid for an average year, hence, the mean annual erosion corresponds to 21 tons per km².

Considering that the mean density of earth is 1.6 tons/m³, the annual volume of transported sediment is 68 800 m³.

10.2.2. Turbidity of the WABI SHEBELLE at HAMERO-HEDAD

One hundred and seventeen measurements of sediment transportation were made from the 20th of July 1968 to the 28th of September 1971 for discharges (water) ranging from 19.8 to 606 m³/s. Most of these measurements were carried out during the high-flow gauging campaigns. The results of these measurements are presented in table 10.2 (annex). It may be noted that turbidities vary considerably: the minimum being 14.3 g/m³ and the maximum 38 kg/m³.

These results show that there is no well determined relation between sediment transportation and water discharge. For a same discharge the amount of sediments is usually greater during the flood rising than during the recession period. Besides, the amount of sediments also depends on the period of the year and on the origin of floods. The floods of the first rainy season are generally more turbid than the floods of the second season. The floods coming from the high basalt plateaus transport a smaller amount of sediment than floods formed on limestone series.

From these measurements different series of stage discharge relations were established according to the period of the year, to the origin of the floods and to the moment of sampling (flood-rising or recession). These relations allowed estimating the suspended load transported during the months for which measurements are available. The results are given below:
Graph X. 2 gives the values of monthly suspended load related to the mean monthly discharge. Two different relations are observed: a relation corresponding to the months of the first rainy season which produces the most turbid floods, and another for the second season.

These relations are relatively loose but allow estimating the suspended load for the months lacking measurements of sediment transportation but with a known average rate of flow.

The values of annual suspended load obtained through these relations are as follows:

- Year 1968 - 1969: 20,600,000 tons or 320 tons/year/km²
- Year 1969 - 1970: 12,600,000 tons or 196 tons/year/km²
- Year 1970 - 1971: 12,600,000 tons or 196 tons/year/km²
- Year 1971 - 1972: 5,900,000 tons or 92 tons/year/km²

If these values are related to the mean annual discharge, a linear relation may be observed.

The mean annual discharge being 86 m³/s, the mean annual suspended load is then approximately 8 million tons or 124 tons per km². Supposing the density is 1,6 ton per m³, the annual volume of sediment discharge corresponds to 5 million m³.

10.2.3. Turbidity of the DAKETA at HAMERO-HEDAD

Thirty one measurements of sediment transportation were carried out from the 25th of September 1971 to the 11th of May 1971 for rates of flow ranging from 0,5 to 430 m³/s. The results of these measurements are given in table 10.3 in the annex and show that turbidity is always considerable except for very low rates of flow (less than 1 m³/s) which usually correspond to the subsurface flow resulting from the drying-up of soils after flooding. The maximum turbidity observed is 61,3 kg/m³ for an instantaneous discharge of 210 m³/s. When flash floods occur, turbidity certainly exceeds 100 kg/m³.

The too small number of measurements does not allow estimating with enough accuracy the annual suspended load since the relations between sediment transportation and water discharge vary and depend on the shape and origin of floods. For three flood periods the average relations between sediment transportation and water discharge were calculated from the results of measurements, and thus the load of transported sediments during these floods were obtained. The results achieved for these three floods are as follows, i.e.:
WABI SHEBELLE AT HAMERO-HEJAD

Relations between mean monthly discharges and suspended load

Weight, $10^6$ ton-

First rainy season
Second rainy season

Première saison des pluies
Deuxième saison des pluies

Mean monthly discharge m$^3$/s

Poids en tonnes

Débit moyen mensuel m$^3$/s

Gr. X 2

O.R.S.T.O.M. Service Hydrologique
RELATION BETWEEN MEAN ANNUAL DISCHARGES AND SUSPENDED LOAD

WABI SHEBELLE AT GODE

Mean annual discharge in m³/s

WABI SHEBELLE AT HAMERO-HEADAD

Mean annual discharge in m³/s

ors trom service hydrologique date des 273 0  etr 291819
- Flood of 25th to 27th of September 1970 (simple flood)
  Volume of runoff : 11 millions m³
  Suspended load : 375 000 tons

- Flood of 17th to 23rd of October 1970 (compound flood)
  Volume of runoff : 33 millions m³
  Suspended load : 1 600 000 tons

- Flood of 3rd to 8th of May 1971 (compound flood)
  Volume of runoff : 33 millions m³
  Suspended load : 1 600 000 tons

- Flood of 3rd to 8th of May 1971 (compound flood)
  Volume of runoff : 45 millions m³
  Suspended load : 1 000 000 tons

The amount of transported sediments largely varies for a same volume of runoff. The average relation corresponds to a suspended load of 35 000 tons per million m³ of runoff. This relation applied to the annual runoff volume gives the following results.

Year 1970 - 1971 : 6,7 million tons or 472 ton/km²
Year 1971 - 1972 : 3,4 million tons or 239 ton/km²

These figures are relative and only give an approximate value of the amount of sediments transported by the DAKETA.

The mean annual suspended load should be approximately 5 million tons or 350 ton/km², that is to say practically the same as the suspended load of the WABI SHEBELLE upstream from HAMERO-HEDAD.

10.2.4. Turbidity of the WABI SHEBELLE at GODI

Two hundred and twenty one measurements of sediment transportation were made from the 6th of September 1968 to the 4th of June 1971 for discharges ranging from 4 to 598 m³/s. The results of these measurements are given in table 10.4. (annexe). The minimum turbidity measured is 10 mg/l and the maximum turbidity is 71 kg/m³.

For the same reasons as at the HAMERO-HEDAD station, turbidity is very variable and no relation exists between sediment transportation and water discharge.

The measurements allowed establishing a whole series of sediment transportation / water-discharge relations depending on the periods. These relations enabled (as for HAMERO-HEDAD) evaluating the suspended load during the months when these measurements were carried out. The results are given below:
<table>
<thead>
<tr>
<th>Year</th>
<th>Suspended load (in thousands of tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968-1969</td>
<td></td>
</tr>
<tr>
<td>1969-1970</td>
<td>282</td>
</tr>
<tr>
<td>1970-1971</td>
<td>510</td>
</tr>
<tr>
<td>1971-1972</td>
<td>2</td>
</tr>
</tbody>
</table>

On graph X. 4 the data for monthly suspended load are given in relation to the mean monthly water discharge. The points represent two relations, the first corresponding to the months of the first rainy season (from February to June) and to the late floods of OGADEEN (October and November). These months produce the most turbid floods. The second relation corresponds to the months of the second rainy season on the high plateaus (July, August and September). During these three months, the amount of suspended load is far less for equal discharges.

These two curves allow estimating the suspended load for all the monthly discharges observed. The values in annual weights of transported sediments are as follows, i.e.:

1968 - 1969 : 29 000 000 tons or 228 ton/km².
1969 - 1970 : 10 700 000 tons or 84 ton/km².
1970 - 1971 : 19 900 000 tons or 156 ton/km².
1971 - 1972 : 10 500 000 tons or 82 ton/km².

If these values are related to the mean annual discharge, a certain link may be observed (graph X. 3), but unlike HAMERO-HEDAD, the link is not linear. The gradient of sediment transportation increases together with the mean annual discharge. This is due to the very considerable sediment transportation observed in the intermediate basin between HAMERO-HEDAD and CODE and especially for the DAKETA. Consequently, the mean suspended load is certainly greater than the suspended load corresponding to the mean annual discharge; the latter being approximately 10 million tons, an average load of 15 million tons or 118 ton/km² is very likely and the annual volume of transported soil is probably about 9.4 million m³.

10.2.5. Turbidity of the WABI SHEBELLE at BURKUR

Eight measurements of sediment discharges were made during the rising of the flood of August-September 1970 for discharges ranging from 18.6 to 243 m³/s.
Relations between mean monthly discharges and suspended load

From February to June

July-August-September

October-November

Relations entre débits moyens mensuels et poids de sédiments transportés en suspension

From February to June

July-August-September

October-November

Mean monthly discharge m³/s
Relation between water discharges and sediment discharges

Relation entre débits liquides et débits solides
The results of these measurements are given in table 10.5 (annexe). Though these measurements do not allow estimating the mean annual sediment transportation, they give an idea of the role played by the flood plains located between KELAFO and MUSTAHIL as regards the decantation of water. The maximum measured turbidity is 400 g/m³ at the beginning of the flood rising. It then falls very quickly and is only 40 g/m³ for the flood maximum.

During the same period at GODE, turbidity is 3 to 5 kg/m³. It is therefore obvious that over 95 per cent of the sediments transported by the WABI SHEBELLE at GODE are deposited in the flood plains. The travel-time of runoff between GODE and BURKUR during the flood period averages 13 days which represents a very small velocity of 18 cm/s; the velocity in the flood plains from KELAFO to MUSTAHIL is still less.

Only the local floods formed between MUSTAHIL and BURKUR bring a considerable amount of turbidities because of the weakness of inflows, they contribute in a small proportion only to the total annual quantity of sediment transportation.

These observations being taken into account, the suspended load should not exceed 750 000 tons for an average year.

10.2.6. Turbidity of the FAPEN at KEBRI-DAHAR

Thirty-two turbidity measurements were carried out in October 1970 and May 1971. The results are given in table 10.6 (annex). Turbidity is always considerable and exceeds 40 kg/m³ for discharges greater than 1 m³/s and the maximum measured turbidity is 170 kg/m³.

Graph K. 5 gives the values of sediment transportation in kg/s in relation to the water discharge in m³/s, and a curve has been plotted.

This graph enabled computing the suspended load for each month of the observation period. The results are given below:

<table>
<thead>
<tr>
<th>Year</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>J</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
<th>J</th>
<th>n. tot.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969-1970</td>
<td>0</td>
<td>28</td>
<td>1</td>
<td>224</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>56</td>
<td>284</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1970-1971</td>
<td>0</td>
<td>474</td>
<td>1</td>
<td>240</td>
<td>1067</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>76</td>
<td>516</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1971-1972</td>
<td>0</td>
<td>280</td>
<td>998</td>
<td>168</td>
<td>9</td>
<td>0</td>
<td>62</td>
<td>496</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2 040</td>
</tr>
</tbody>
</table>

Taking these results into account, the mean annual sediment load is approximately 2 500 000 tons which corresponds to a mean annual erosion of 98 ton/km². The annual volume of transported sediments is 1 600 000 m³.
10.3 ESTIMATE OF SEDIMENT DISCHARGE AT THE ENTRANCE OF THE LOWER VALLEY.

10.3.1. Suspended load for an average year

The sediments transported to the dam site at the entrance of the lower valley may be estimated from the results achieved for the WABI SHEBELLE and for the DAKETA at HAMERO - HEDAD.

We have already seen that the suspended load of the WABI SHEBELLE and of the DAKETA is respectively 8 million tons yearly and 5 million tons yearly.

The intermediate basin of 2 600 km$^2$ is not controlled by these two stations since the dam is located downstream from the DAKETA tributary, in the hemmed-in area above IMI. This basin belongs to the same type as the basin of the DAKETA and presents a similar annual erosion of 350 ton/km$^2$. This figure represents an annual suspended load of 900 000 tons for this basin.

Finally, the suspended load at the dam-site for an average year is probably approximately 14 million tons yearly or about 9 million m$^3$/yearly, if we consider that the sediment density is 1.6.

10.3.2. Estimate of total sediment transportation at the dam-site

To the suspended load must also be added the bed-load which increases upstream from the dam and will largely contribute to the silting-up of the reservoir.

No well-defined methodology exists for a direct measuring of this type of sediment supply to large basins. Only a subsequent study of the filling in of reservoirs located at the outlet of drainage basins presenting similar relief, geological and climatic conditions, allow estimating the bed-load transport.

In his work "Silting up of reservoirs" published in 1953, KHO SLA studies the sediment supply measured in 146 dams throughout the world. This study shows that the quantity of material deposited in the reservoirs largely varies according to the types of basins but that for arid basins, it is always approximately the same and averages 360 m$^3$/km$^2$ yearly. This figure was determined through the survey of 10 basins of variable sizes and generally located in the U.S.A. or Africa.

This figure applied to the basin of the WABI SHEBELLE leads to a total annual sediment transportation at the dam site of 29 million m$^3$. This value seems very high if one considers that the high volcanic plateaus of the upper basin which cover approximately 20 per cent of the basin upstream from this site do not present a torrential flow of subarid type. In fact, it has already been seen that the suspended load at MALKA-WAKANA is very moderate. This value nevertheless gives an idea of the total annual volume of sediment transportation (suspended load and bed load).

A sediment volume of approximately 20 million m$^3$ yearly is a very likely figure.
CHAPTER XI

CHEMICAL ANALYSIS OF THE WABI SHEBELLE WATER

Water samples analysed at the Project laboratory at ADDIS-ABABA and at O.R.S.T.O.M. in PARIS enabled determining the chemical composition of the WABI SHEBELLE water for several stations of the basin.

The results of these analyses are given in table 11.1 (annex). The largest number of samples were made at the stations of MALKA-WAKANA, HAMERO-HEDAD CODE and KELAFO. Some samples were taken during the low flow period at the IMI and BURKUR stations.

A first examination of this table shows an essential difference in the chemical composition between water at MALKA-WAKANA and water in the middle and lower valley from HAMERO to BURKUR, since water flowing over volcanic soils is far less saline than water flowing on limestone and gypsum soils.

11.1 CHEMICAL ANALYSIS OF THE WABI SHEBELLE WATER AT MALKA-WAKANA

The ten samples taken for discharges ranging from 123 to 4,62 m3/s show the evolution of the chemical composition of water with the flow period.

a) Global salinity

The global salinity is termed in conductivity in millimhos/cm -1.

During the rainy season the water of the WABI SHEBELLE mostly consists of overland flow. Conductivity is then very low and regular and corresponds approximately to 0,075 millimhos/cm -1 or an average salinity of water of 50 mg/l.

During the minimum flow period for discharges less than 20 m3/s, the water of the WABI SHEBELLE is mainly due to the emptying of ground water tables, and since the contact of water with the soil of the basin lasts longer, this water is more mineralized. The conductivity increases in proportion as the discharge decreases. The maximum conductivity observed for a discharge of 4,6 m3/s is approximately 0,23 mmhos/cm -1 which corresponds to a global salinity of 170 mg/l.

b) Ionic content

Water presents a calcic bicarbonated chemical facies. The content of Cl and SO4 is less than 0,1 milliequivalent/l, hence it is very weak. The relative contents of cations are distributed as follows:

Ca > Na > Mg > K with Ca + Mg > Na + K.
11.2 CHEMICAL ANALYSIS OF THE LOWER VALLEY

The samples taken at the stations of HAMERO-HEDAD, IMI, GODE, KELAFO and BURKUR show the evolution of the salt content and distribution in the middle and lower valley. Chemical analysis reveals the preponderating influence on the ionic composition of water of the very soluble limestone and gypsum soils.

a) Global salinity

The conductivities observed are far greater than the conductivities of the MALKA-WAKANA water and increase noticeably from the upstream part to the downstream part.

During the high flow period the mean conductivities are as follows,

- at HAMERO-HEDAD: 0.38 mmhos/cm -1 or a salinity of 280 mg/l.
- at GODE: 0.45 mmhos/cm -1 or a salinity of 320 mg/l.
- at KELAFO: 0.45 mmhos/cm -1 or a salinity of 320 mg/l.

Downstream from IMI, local floods spreading on gypsum soils may produce an average salinity of 1,420 mg/l, while the conductivity of October 1970 is 1.98 mmhos/cm -1 or an average salinity of 320 mg/l; this global figure signifies that the salt load of the local flood periods and for discharges less than 30 m3/s, the salinity progressively increases together with the decreasing discharge.

For minimum flow periods and for discharges less than 30 m3/s, the salinity progressively increases together with the decreasing discharge.

The maximum conductivities observed at the stations during the same period are as follows, i.e.:

- at IMI: 0.72 mmhos/cm -1 or a salinity of 520 mg/l.
- at GODE: 0.73 mmhos/cm -1 or a salinity of 560 mg/l.
- at KELAFO: 0.73 mmhos/cm -1 or a salinity of 560 mg/l.
- at BURKUR: 0.91 mmhos/cm -1 or a salinity of 650 mg/l.

It may be noted that during the minimum flow period, salinity increases very noticeably from the upstream part to the downstream part. This may be linked to the reduction of the local water discharge through evapotranspiration. The interaction with the alluvial groundwater table also play a role. The latter presents a global salinity varying from 1.5 to 3.8 g/l between GODE and MUSTAHIL, which is three to six times more than the salinity of the river.

* Information provided by OGADEN*.

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* Another Project report: "Hydrogeological survey of
b) Ionic contents

Water presents different chemical facies in relation to the period of the year.

During the months of high flow when runoff mainly occurs on the upper basin, water is calcic bicarbonated. The sulphate and chlorine contents are nevertheless relatively high (approximately 2 meq/l for SO\textsubscript{4}-- and 0,40 meq/l for Cl\textsuperscript{−}). The relative contents in anions and cations are distributed as follows:

\[ \text{CO}_3^> > \text{SO}_4^> > \text{Cl}^> > \text{Ca}^> > \text{Mg}^> > \text{Na}^> > \text{K}^> \].

During the flood periods in OGADEN and the minimum flow periods (for discharges less than 30 m\textsuperscript{3}/s), water becomes calcic sulphated. The sulphate and chlorine contents are far greater (from 3 to 5 meq/l for SO\textsubscript{4}-- and from 0,70 to 1,65 meq/l for Cl\textsuperscript{−}). The relative contents in anions and cations are distributed as follows:

\[ \text{SO}_4^> > \text{CO}_3^> > \text{Cl}^> > \text{Ca}^> > \text{Mg}^> > \text{Na}^> > \text{K}^> \]. The Na and Mg contents also increase (from 1 to 2 meq/l for Na and from 2 to 3 meq/l for Mg).

These considerably high contents of sulphate and chlorine reveal the influence of gypsum soils on the chemical quality of water.

The water of the alluvial ground water table of the lower valley is also a sodic sulphated water with the following distribution:

\[ \text{SO}_4^> > \text{Cl}^> > \text{CO}_3^> > \text{Na}^> > \text{Ca}^> > \text{Mg}^> \]. The influence of the local ground water table is therefore apparent in the process of the rising of contents mainly for sulphates and chlorides. One must remind that the alluvial water table is contaminated by the water table of the subjacent main gypsum formation (salinity : 40 g/l at the GODE well).**

** The content in milliequivalent/litre : meq/l - is equal to the content in milligrams per litre divided by the quotient of the atomic mass of the element by its valency.