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publication no. 238

October 1980

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presented at the UNESCO / IAHR seminar on hydraulic research and river basin development, September 1980 Nairobi, Kenya

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HYDRAULIC AND MORPHOLOGICAL IMPACTS OF DAM CONSTRUCTION

by

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Synopsis

In this paper attention will be paid to the hydraulic and morphological impacts of dam construction in a river. Also the interrelated aspects regarding the over-all ecology of the riverbasin, water quality, fisheries, communication, vegetation, wildlife, etc. will be indicated. Methodologies to study the hydraulic and morphological consequences of dam construction are given. Moreover, examples of some relevant projects on irrigation, power and flood control etc., are presented for which studies were executed by the Delft Hydraulics Laboratory.

Resumé

Cet article décrit les conséquences hydrauliques et morphologiques de la construction d'un barrage dans un fleuve. Les aspects reliés à l'écologie totale du bassin du fleuve, la qualité de l'eau, la pêche, la communication, la végétation, le cheptel gibier, etc. sont indiqués aussi. Des méthodologies pour rechercher les conséquences hydrauliques et morphologiques de la construction du barrage sont données. En outre on a présenté des exemples de quelques projets importants relatifs à l'irrigation, l'hydro-électricité et l'évacuation des crues, pour lesquels le Laboratoire d'Hydraulique de Delft à effectué des études.

Hydraulic and morphological impacts of dam construction

1. Introduction

The construction of a dam and the creation of a reservoir upstream means an important intervention in the natural conditions of a river. In general in the downstream river part both extreme low and extreme high discharges will occur less frequent, with regard to the previous situation, by the regulating effect of dam and reservoir. Also upstream of the dam-location a huge area may be effected. Depending on the dam height a large area may more or less permanently be covered by a man-made lake. Moreover, large water level variations will presumably lead to extensive swampy areas along the borders of the reservoir.
As in general the sediment supply will be blocked by the presence of a reservoir, downstream of the dam/reservoir erosion can be expected. The rate of erosion and the final degradation of the river bed depend on several factors outlined later on.

It will be clear that the function of a dam is one of the main factors governing the type of impact. A single purpose project, viz. a low level dam to set up the water level for irrigation-water intake, will lead to other consequences than a multi purpose project for power, flood control etc. with in general a large reservoir. In particular for the water quality the volume of the reservoir, or actually the retention time of the water, is an important aspect.

In the following section the several types of impact of dam construction, concerning hydraulics and morphology, are identified. Also interrelated aspects regarding the over-all ecology of the riverbasin are indicated. In the final section some practical examples are given to demonstrate the research methods used at the Delft Hydraulics Laboratory to study the impact of dam construction.

2. Impact analysis

To study the feasibility of dam construction, be it for power, flood control, irrigation or else, an early identification of the impacts is required. On base of this a preliminary evaluation of the importance of the possible impacts can be made while additional studies and/or remedial measures can be indicated. An inventory of possible hydraulic and morphological impacts is given below.

2.1 Flood control and water levels in the lower river

During normal operation of a dam/reservoir the discharge regime downstream will be more regular than in the original situation. The influence of the discharge regulation on the waterlevels in the lower river can be assessed using a mathematical model for one dimensional flow [1]. Such model can also serve to study the influence of dam construction on extreme flood conditions and related management options, beneficial flood releases for agricultural purposes on the flood plains of the lower river, etc. If substantial degradation of the bed of the lower river is to be expected the hydraulic computations should be repeated for several phases within the lifetime of the project.

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1. Grijsen, J.G. and Meijer, Th.J.G.P.,
   On the modelling of flood flow in large river systems with flood plains,
   Contribution on IAHR Congress Cagliary, Italy, September 1979,
   Delft Hydraulics Laboratory, Publication no. 227, March 1980.

For water quality studies evenso the hydraulic conditions in the lower river should be determined.

Finally for multi purpose projects a combination of a simulation program of reservoir operation with a hydraulic model of the lower river will enable studies on optimization of dam and reservoir management, taking into account aspects of power production, flood control, water quality, salt intrusion, river degradation, agriculture, fisheries, recreation, etc.

2.2 Ground water levels along the lower river

It can be expected that on short term dam construction itself will not lead to changes of the mean groundwater level in the lower river basin since in general the mean annual discharge will not change in relation to the original conditions. Only if high losses of water by excessive evaporation in the reservoir will occur and/or if water withdrawal for agricultural or domestical use will be applied a decrease of mean annual discharge and consequently lowering of average groundwaterlevels is to be expected.
Furthermore, by the regulating effect of a dam/reservoir annual variations of the groundwaterlevel may be dampened.
On the long term a lowering of average groundwater levels may occur if degradation of the river bed will happen (see 2.3).

Changes of groundwaterlevel in the lower river may have an impact on vegetation, agriculture, wildlife, etc. Therefore the response of the groundwater level to changes of water levels in the river should be assessed. This can be investigated by means of field studies, borings, permeability tests etc., and by the application of a mathematical model for groundwater flow [2].

2.3 Morphology of the lower river

In many cases the construction of a dam in a river will lead to a more or less total blockade of sediment supply into the lower river. Only very small amounts of fine silts and clays may pass the dam in the flood season, while in some cases special structures are made to flush the coarser sediments through the dam also. However, compared with natural conditions, in general a substantial decrease of sediment supply will occur. If the lower river is composed of alluvial deposits this may consequently lead to erosion and degradation of the riverbed downstream of the dam. This degradation will propagate in downstream direction and will finally result in lowering of water levels along the whole riverstretch. Secondary effects will be backward erosion in the tributaries, gully erosion and excessive drainage of the floodplains, problems with agriculture and gravity irrigation, lowering of the groundwater level and many related aspects. Moreover the fertility of the floodplains will be affected in a negative way by the decreasing supply of silts and clays trapped by the reservoir.

The rate of erosion and the final degradation of the riverbed are governed by a number of factors, being:
- operation of the dam, regarding mean discharges and flood releases;
- composition of the river bed sediments (mean particle size, grain size distribution);
- natural conditions of the river (geometry, slope, roughness);
- presence of non-erodible layers and/or rock outcrops in the riverbed.

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2. GROMULA, Groundwaterflow in a multi-layered system of aquifers, description of mathematical model, S 135, Delft Hydraulics Laboratory, January 1979.

It will be clear that a thorough study of the morphological behaviour of the lower river will be required to derive an insight into the consequences of dam construction. In that respect computations with a mathematical model for one-dimensional sediment transport may serve in case dominant bed load takes place [3]. If suspended sediment transport is dominant and if local effects should be regarded a two-dimensional model can be considered [4].

2.4 Erosion of the riverbanks

Apart from river bed erosion, the flow may also erode the riverbanks downstream of a dam directly as a result of the blockade of the sediment supply. Indirectly, as a secondary effect of the degradation of the riverbed, steepening of the riverbanks will occur which eventually may lead to bankslides.
Finally the occurrence of (negative) translatory waves on the lower river, which may develop by a sudden stop of flow through the turbines of a dam, may also lead to riverbank instability by over-pressure of the groundwater. Steep riverbanks will pose large problems for both man and animals using the river and may consequently have a negative impact on communications, fisheries, wildlife, etc. Riverbank erosion may have harmful effects with regard to settlements, water intakes, etc. For these reasons the effect of riverbed degradation and waterlevel lowering on the riverbanks should be studied, making use of data on composition, permeability, etc. of the riverbank material.

2.5 Morphology of estuary and delta

As a result of changing discharge conditions salinity intrusion and sediment transport in an estuary will be affected directly after construction of a dam in the river.

On a longer term the erosion, caused by the stop of sediment supply to the lower river, will reach the estuary which may lead to a change of sediment transport conditions and geometry also. However, this process is relatively slow.
By the presence of a reservoir and its sediment trapping effect the supply of fine sediments (silts and clays) to the estuary will decrease. This may have a negative impact on the ecology of the estuary regarding fisheries etc.

With regard to the delta it can be expected that the anticipated decrease of sediment supply from the lower river on a long term may lead to a change of longshore transport and possibly to coastal erosion. It will therefore be clear that certainly sufficient attention should be paid to studies on the impact of dam construction on the morphology and related aspects of estuary and delta.

2.6 Sedimentation in the reservoir

A very well-known feature of the construction of a dam and creation of a reservoir is the trapping of sediments supplied by the contributing rivers. The total sedimentation is important in relation to the effective volume of the reservoir and the economical lifetime of the project. In some cases delta formation may occur in the reservoir.

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3. de Vries, M. and Zwaard, J.J. van der,
   Movable-bed river-models,
   Paper presented at ASCE symposium Modeling '75, San Francisco,
   Delft Hydraulics Laboratory, publication no. 156, Dec. 1975.

4. Kerssens, P.J.M., Prins, A and Rijn, L.C. van,
   Model for suspended sediment transport,
   Journal of the Hydraulics Division, ASCE, Vol. 105, HY5, May 1979,
   Delft Hydraulics Laboratory, publication no. 221, Nov. 1979.

A study on these aspects is recommended in all cases, being one of the factors determining the economical benefit of the project.

2.7 Consequences for the reservoir area

Of course the area of a reservoir itself and the areas bordering a reservoir will be affected strongly by a dam/reservoir project. Studies should be made regarding the water level variations of the reservoir and the response of groundwaterlevels. The possible development of swampy areas along the reservoir borders, the occurrence of backwater effects on the contributing rivers and their impacts on vegetation, water use, agriculture, wildlife, etc., should be investigated evenso.

2.8 Consequences for structures

Both the change of waterlevels and morphological changes, being degradation of the riverbed downstream of a dam, sedimentation in the river reaches upstream of a reservoir and erosion of riverbanks, may threaten the stability and efficiency of structures in and along the river. In this respect intake structures, pumping stations, bridge piers or abutments, landing sites of ferries etc. can be mentioned. Clearly the impact of dam construction on these subjects and required remedial measures should be studied thoroughly.

3. Practical applications

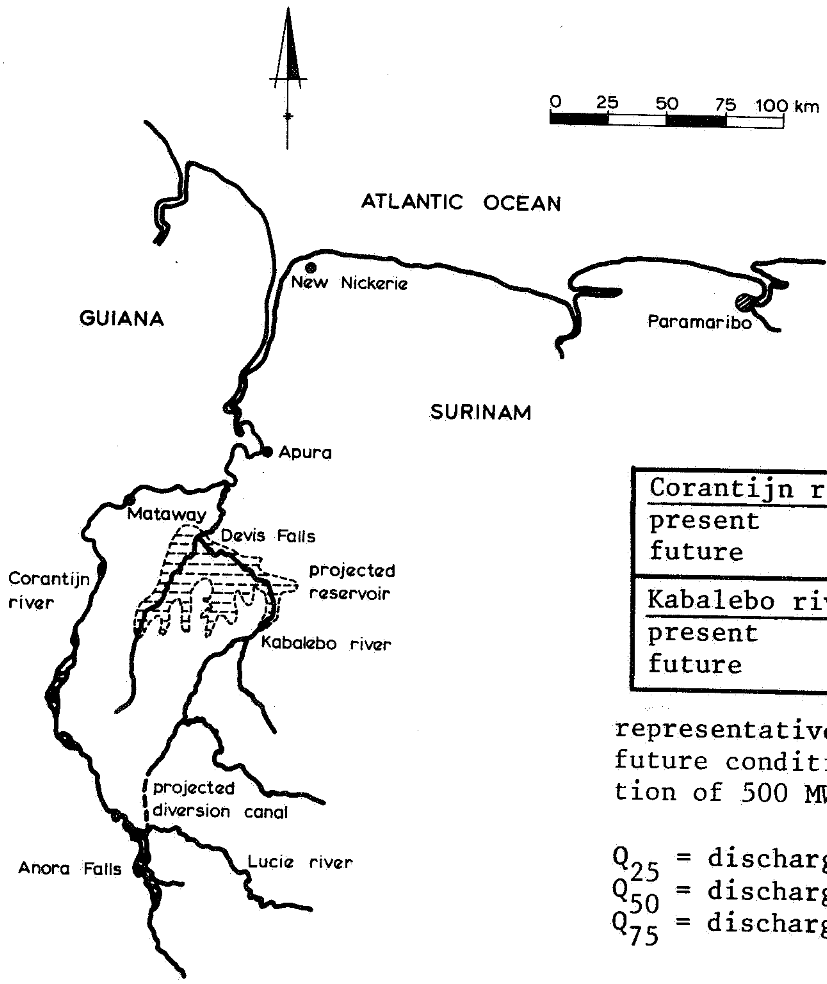
3.1 Ecological impacts of the Kabalebo power project, Surinam

Some years ago a feasibility study of hydro-electric development in Western Surinam has been carried out. As a result of this study a dam and power plant at Devis Falls in the Kabalebo river have been designed (see Figure 1). It was also decided to construct diversion works in the Lucie river and the Corantijn river, at Anora Falls, and a diversion canal from this location to the Kabalebo river. The increased discharges through the Kabalebo river will enable a huge increase of power production since the greater part of the Corantijn discharges (80% up to 2000 m^3/s) will be diverted. An overview of present and future representative discharges in the Middle-Corantijn river (Mataway) and the lower Kabalebo river (Devis Falls) is given in Figure 1.
It will be clear that the substantial change of discharge conditions will have a large impact on the total ecology of the area. Therefore an ecological study has been executed in 1979/80, divided into 3 parts:
1 hydraulic and morphological effects of the project,
2 effects of the project on river-water use, riverbanks and fisheries,
3 analysis of forest clearing in the reservoir area.
The Delft Hydraulics Laboratory executed the first part of the study and was, together with Ilaco Surinam, involved in the greater part of the second study on water use, water-quality, stratification of the reservoir etc.
The study on hydraulic and morphological effects included the following items:
- changes of discharges and waterlevels in the Middle Corantijn downstream of the diversion point and the effects on groundwaterlevels, flotation of logs, areas falling dry, stagnant pools, etc.;
- flooding of the Kabalebo area;
- erosion of the Lower Kabalebo and the effects of the increased sediment supply on the Lower Corantijn;
- river bank erosion and planform changes of the Lower Kabalebo;
- changes of flow pattern at the Corantijn/Kabalebo confluence and its effect on riverbank erosion;
- changes of salinity, tidal motion and morphology in the Corantijn estuary.

For the hydraulic studies use was made of both flood routing methods and of a mathematical model of the river system [1]. To investigate the morphological changes the one-dimensional model for sediment transport was applied [3]. In Figure 2 the results of a morphological computation are presented. Similar computations were made for several scenarios, resulting in several sets of discharge time series. The scenarios were selected on base of variations in the future power demand and on three different assumptions regarding hydrological conditions (10% dry, average, 10% wet).

The flow patterns at the confluence were studied with a mathematical model for two-dimensional flow field computations [5]. The result of such computation for future discharge conditions is given in Figure 3. The increased flow velocities along the left river bank of the Corantijn will result in accelerated erosion of the banks. Remedial measures were recommended since this riverbank forms the international border between Surinam and Guiana.

The study on salinity intrusion was executed in cooperation with the Hydraulic Research Department Surinam, which used a one-dimensional mathematical model for this purpose.



	Q_{25}	Q_{50}	Q_{75}	Q_{mean}
Corantijn river				
present	380	800	1875	1265
future	115	220	520	655
Kabalebo river				
present	25	85	230	155
future	525	620	1070	770

representative discharges in m^3/s;
future conditions for maximum power production of 500 MW

Q_{25} = discharge not exceeded in 25% of time
Q_{50} = discharge not exceeded in 50% of time
Q_{75} = discharge not exceeded in 75% of time

Figure 1 Overview Kabalebo power project

5. Kuipers, J. and Vreugdenhil, C.B., Calculations of two-dimensional horizontal flow, Report on basic research S 163-I, Delft Hydraulics Laboratory, October 1973.

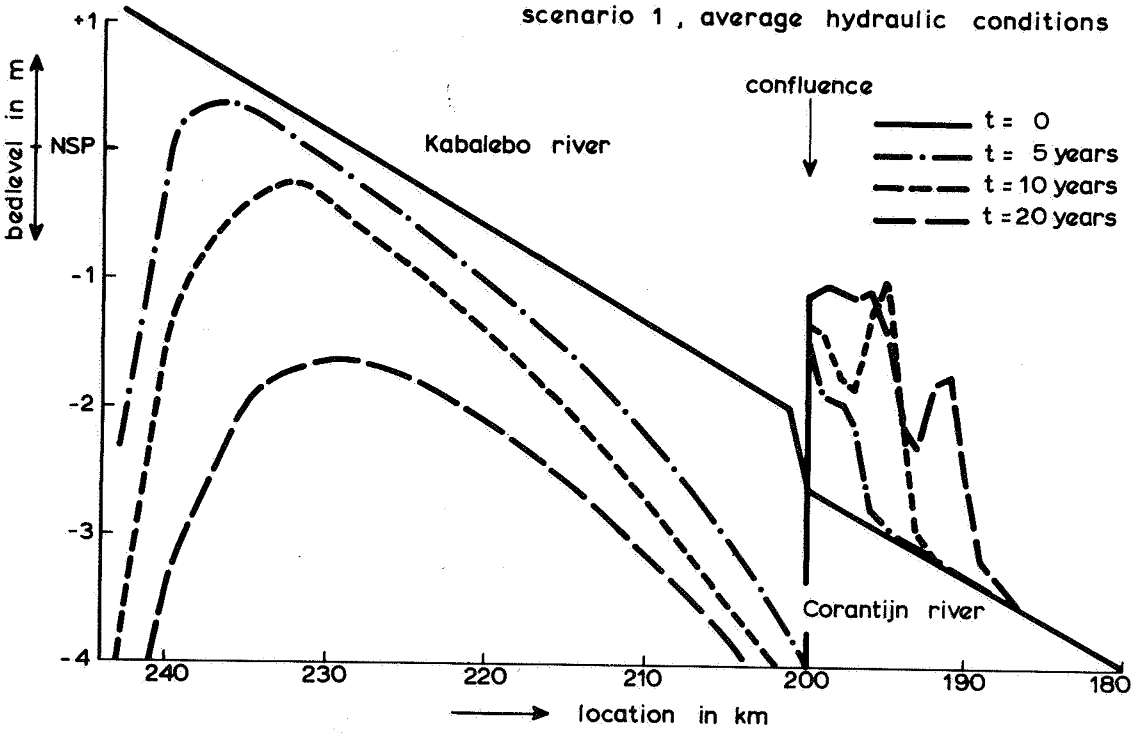


Figure 2 Morphological changes, Kabalebo power project

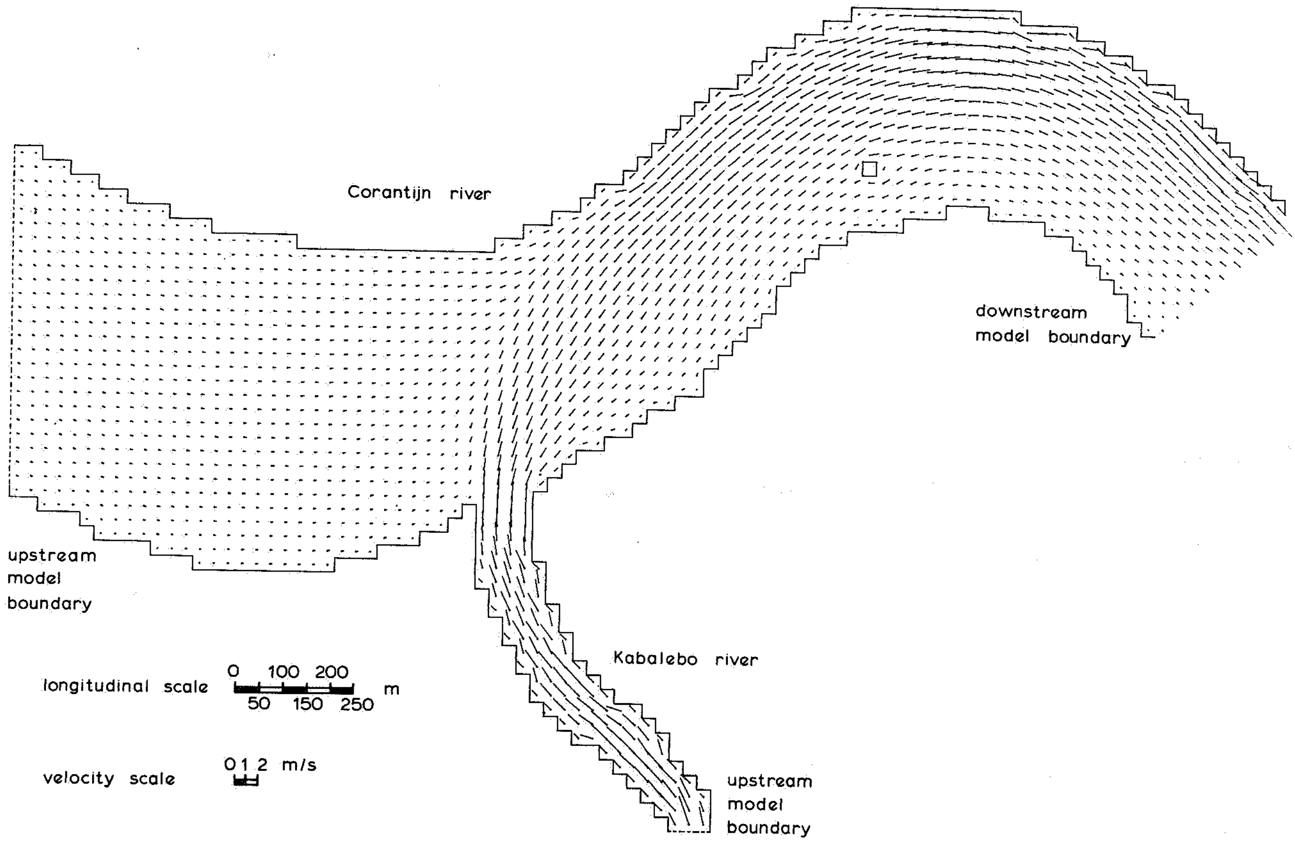


Figure 3 Flow field pattern, Q_{75} future conditions, Kabalebo-Corantijn confluence

3.2 Bura irrigation project, Kenya

In 1974/75 the Delft Hydraulics Laboratory investigated the morphological consequences of a weir and water intake structure in the Tana river, Kenya (see Figure 4). Water will be withdrawn for the Bura irrigation project and the weir will be constructed to set up the waterlevels, facilitating the water intake. By means of a sandtrap the sediment, together with the water withdrawn from the river, will be caught to prevent sedimentation in the irrigation system. These sediments will be transported back to the river downstream of the weir. Consequently the original amount of sediment will enter the lower river but by the withdrawal of irrigation water in future this has to be transported by less discharge.

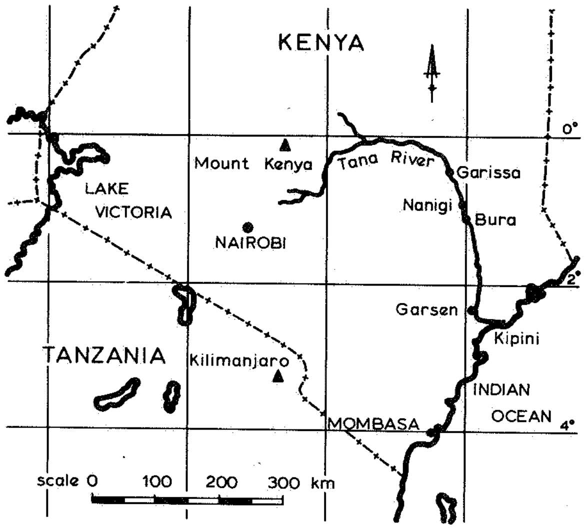


Figure 4 River basin of Tana river

To predict the morphological effects of the project a one-dimensional model for bed-load transport was used [3]. On base of field observations some assumptions could be made:

- the river is alluvial;
- the river is in equilibrium;
- for the sediment transport the Engelund/Hansen formula can be applied.

Mean monthly discharges derived from discharge/waterlevel recordings at Garissa, were used in the computations. After 20 years of operation the discharges will change as a result of regulation upstream. For the water withdrawal ΔQ a constant value was used, also changing after 20 years.

With regard to the bed level changes two effects can be recognized [6]:

- on short term the construction of the weir and the set up of the waterlevels will lead to sedimentation upstream and consequently to a temporary degradation downstream of the weir;
- on long term downstream of the weir sedimentation will take place as the original amount of sediments passing the weir cannot be transported by the decreased discharges in the lower river.

The computed bed level changes in time, just upstream and just downstream of the weir, are presented in Figure 5. Also the sedimentation at Garissa, where a bridge has been planned, is given.
Initially a rapid erosion occurs downstream of the weir, while upstream a relatively rapid increase of the bed level takes place. After about 1 to 2 years the final bed level rise upstream of the weir is reached and the sediment transport is re-established again. From this moment on the sedimentation of the river reach downstream will proceed. The effect of the annual discharge variations on the annual bed level changes just up- and downstream of the weir can clearly be recognized in Figure 5.

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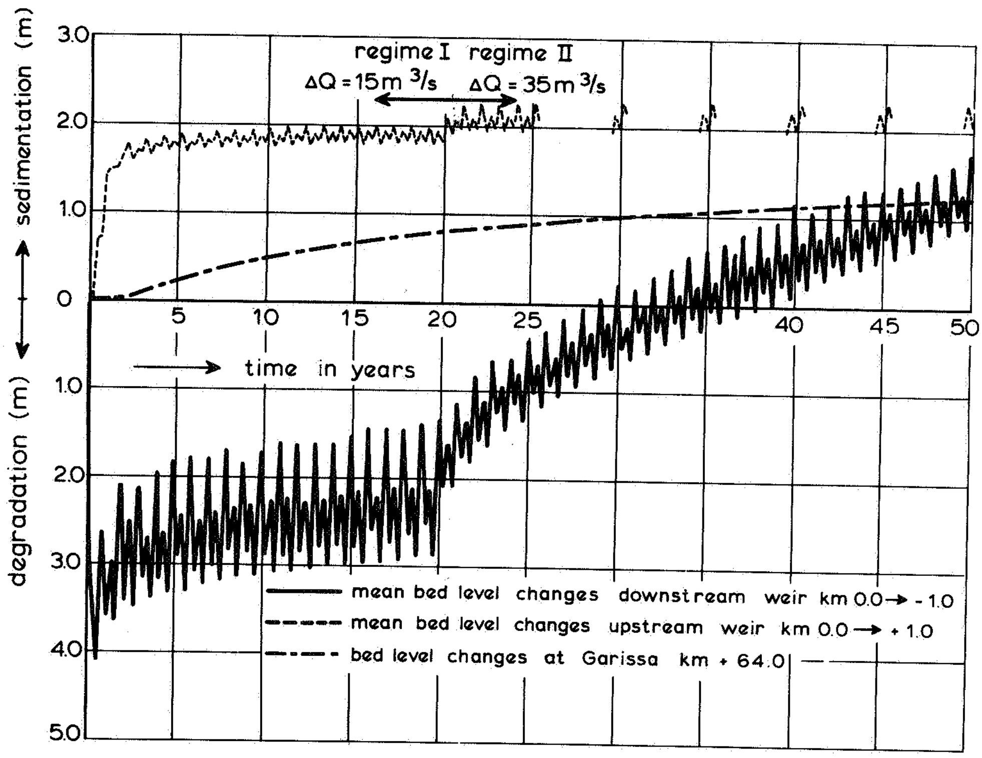
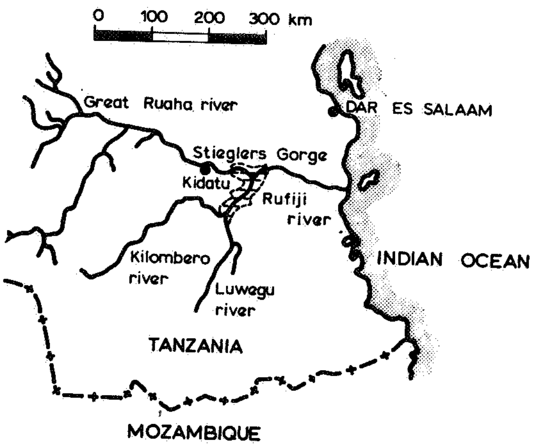
6. Jansen, P.Ph. (Editor),
   Principles of river engineering,
   The non-tidal alluvial river,
   Pitman Publishing Limited, London, 1979.



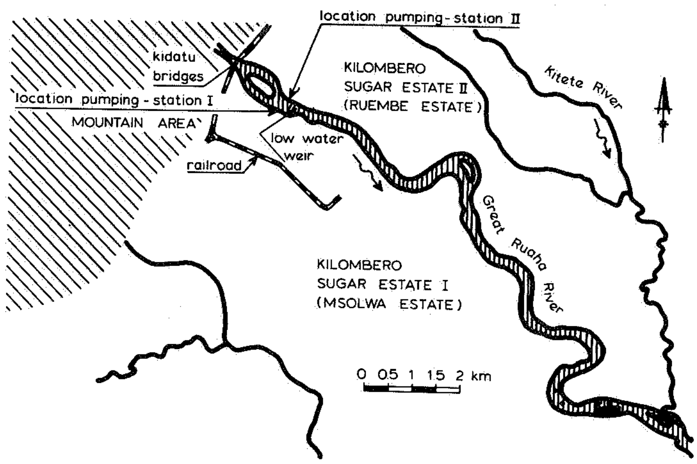
<u>Figure 5</u> Computational results morphological model Tana river

3.3 Hydraulic and morphological impact of the Kidatu dam, Tanzania

In 1974 the H.V.A., a company which was involved in consultancy and management for the Kilombero Sugar Estate, commissioned the Delft Hydraulics Laboratory to investigate the possible effects of degradation in the Great Ruaha River near the Estate, which might take place after the construction of the Kidatu Dam. The Kidatu Dam is situated in the mountainous area just upstream of the river stretch mentioned (see Figures 6 and 7). The main conclusion of the 1974 investigation was that after the Kidatu Dam would be operational, the river bottom near the Kilombero Sugar Estate would degradate considerably in a short time (some years).



<u>Figure 6</u> Situation sketch Great Ruaha and Rufiji Rivers, Tanzania



<u>Figure 7</u> Situation near Kilombero

This would result in such low water levels during the dry season (low river discharges) that water supply to the pump stations would be endangered. Based on this result, it was recommended to construct a low water weir just downstream of the Kilombero pump stations to maintain the water level in front of these stations at a required minimum level during the dry season. It was also stressed to pay special attention to the stability of the weir in view of excessive local scour.

A provisional weir was constructed in November 1975 under the responsibility of the Kilombero Sugar Estate itself. However, with respect to both the way of execution and the size of the weir itself, it was not possible to fulfill fully the guide-lines and requirements as formulated by the Laboratory and Bish and Partners, consulting engineers. Upto the high water season of 1977, the temporary weir worked quite satisfactorily, but during the mentioned high water the weir-structure was partly washed away, initiating an increasing attack by the flowing water. In May 1978 there were two gaps in the weir, which made it impossible to maintain the required water levels in front of the Kilombero pumping-stations during the low water period.The Laboratory and Bish and Partners were asked to send a reconnaissance mission to Tanzania, to evaluate the situation of the weir and recommend the short-term measures required to ensure a water supply for the crops and the sugar factories during the dry season of 1978.
The mission visited the weir site in May/June, 1978, and carried out a survey of the weir and surrounding river bottom, as well as making water level and current observations (see Figure 8). Besides an evaluation of the situation, the mission made recommendations for the immediate repair and conservation of the weir. The materials to be used and the method of execution were discussed with the authorities concerned, so that the repair works could start immediately. Outlines for a more extensive survey to supply data for the design of the conservation works were given.

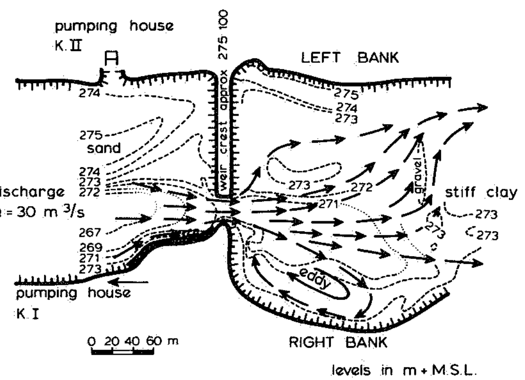


Figure 8 Measured current pattern

3.4 Ecological impacts of Stieglers Gorge Project, Tanzania

At Stieglers Gorge, located in the Rufiji River at a distance of about 200 km from the Indian Ocean, a dam has been planned for power production and flood control (see Figure 6). Euroconsult B.V., Resource Management and Research and Delft Hydraulics Laboratory in 1979/80 carried out an identification study on the ecological consequences of the dam construction, the creation of the reservoir and of the additional works. Many aspects mentioned in Chapter 2 were included: hydraulics and morphology, water quality, fisheries, land resources, salt intrusion, terrestrial ecology, public health etc. An extensive inventory of possible impacts was set-up and required additional studies were identified. With regard to hydraulics and morphology the main conclusions are:
- a strong and rapid erosion downstream of the dam can be expected (see Figure 9);
- this erosion will initiate a number of impacts on water levels, groundwater levels, vegetation, agriculture, wildlife etc.

The indicated degradation of the riverbed, the consequent lowering of waterlevels and the lack of silt supply may result in very unfavourable and possibly even hazardous conditions with regard to the agriculture, drainage and irrigation of the floodplains in the lower river. Moreover, lowering of river water level and groundwater level may have a very negative impact on the wildlife. Both the projected dam and the reservoir will be located in the Selous Game Reserve, containing a large stock of unique wildlife.

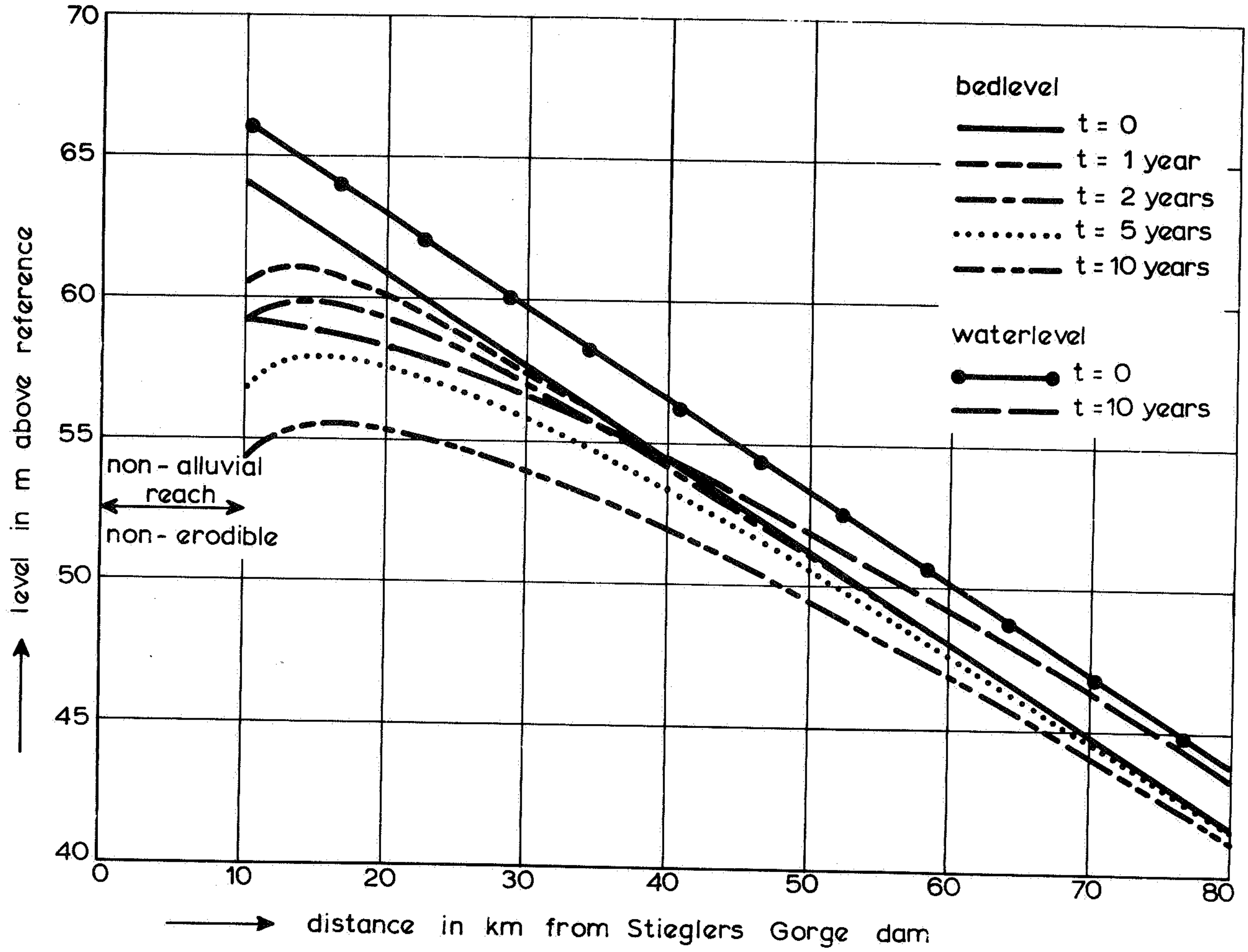


Figure 9 Morphological changes Lower Rufiji River

Because of the high ecological value of the area, regarding both wildlife and agriculture in the floodplains of the lower river, an extensive study on the morphological consequences and the related aspects has been recommended. This study should include the retarding effect of bank erosion, rock outcrops, non-erodible layers, armouring etc. on the riverbed degradation. Also remedial measures to retard the process of degradation should be studied viz. diversion of sediment deposits from the reservoir to the lower river, protection of river bed and/or river banks, artificial armouring of the river bed by addition of well-graded sediments, construction of additional weirs or sills in the Lower Rufiji River, etc.

Acknowledgements

The relevant Governmental Authorities of Kenya, Surinam and Tanzania are gratefully acknowledged for giving their permission to use the results of the studies as described in Chapter 3 of this paper.