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new developments in suspended sediment research
theme 2: river sedimentation and dredging

P. J. M. Kerssens

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NEW DEVELOPMENTS IN SUSPENDED SEDIMENT RESEARCH

1. Introduction

During the sixties the basic research on sediment transport at the Delft Hydraulics Laboratory was mainly focussed on situations with bed load transport. Starting from a relationship between local sediment transport and local hydraulic conditions, physical and mathematical model techniques were developed to describe and simulate morphological processes [6,7].
In the early seventies, more being involved with problems related to the transport and deposition of fine sediments, research on the fundamentals of suspended sediment transport increased. Two mathematical models were developed to describe the morphological processes in situations with suspended sediments. Both models are based on the two-dimensional diffusion-convection equation for the suspended sediment and the sediment continuity equation to obtain the bed-level changes.
The first model (SUSED) has been developed for application on river reaches without tidal influence. The model is used to predict bed-level changes as a result of human interference with the natural condition of a river, viz.:

- the effect of regime changes due to reservoir operation;
- degradation of the riverbed downstream of dams and/or weirs;
- the effect of water withdrawal;
- the effect of bed regulation, etc.

The second model (SUTRENCH) has been mainly focussed on tidal conditions and is provided with special procedures to describe the flow field and sedimentation in dredged trenches.
A short description of the basic equations, boundary conditions and solution techniques of both models is presented in Section 2.

The possibilities for application of the described models are demonstrated by two computational examples in Section 3. Firstly an investigation of the morphological behaviour of a canal that diverts the greater part of the discharge of a big river with high suspended sediment concentrations directly to the sea is described. Secondly an example of computations to predict the sedimentation in a trench in a tidal estuary is presented. Computed sedimentation rates were compared to prototype measurements to verify the mathematical model.

In Section 4 a research program on suspended sediment transport which has recently been started at the Delft Hydraulics Laboratory and will be continued for the forthcoming years is described.

Finally in Section 5 some attention has been paid to two new devices to measure suspended sediment concentrations, which were developed at the Delft Hydraulics Laboratory in recent years. Both instruments, an acoustic Doppler meter and a pump filter sampler, are briefly described, together with some of the characteristics of the instruments.

2. Description of the mathematical models

The mathematical models SUSED and SUTRENCH simulate the morphological processes and the transport of suspended sediment transport under quasi-steady flow conditions. The one-dimensional motion of the water is expressed by the equations of motion and continuity (see Figure 1):

$$\bar{u} \frac{\partial \bar{u}}{\partial x} + g \frac{\partial h}{\partial x} + g \frac{\partial z_b}{\partial x} = - g \frac{\bar{u}|\bar{u}|}{C^2 R} \tag{1}$$

$$q = q\ (t) \tag{2}$$

The one-dimensional motion of sediment in situations with predominant bed load is in general described by a direct relationship between local sediment transport and local hydraulic conditions [6,7]. For suspended sediments the vertical motion of the particles by diffusion and gravity influences the sediment concentrations and the local sediment transport. In such cases the motion of the sediment is expressed by the two-dimensional diffusion-convection equation. In both models a simplified diffusion equation is used [2]:

$$u \frac{\partial c}{\partial x} = w_s \frac{\partial c}{\partial z} + \frac{\partial}{\partial z} (\varepsilon_z \frac{\partial c}{\partial z}) \tag{3}$$

Using the sediment concentrations which result from this equation, the local sediment transport in flow direction can be derived by means of vertical integration over the total depth:

$$s = \int_0^h uc\ dz \tag{4}$$

The local velocities are usually computed from the logarithmic distribution:

$$u(z) = \frac{u_*}{\kappa} \ln \frac{30z}{k_n} \tag{5}$$

For non-uniform flow conditions the local velocities can be derived from prototype measurements, or a semi-empirical velocity distribution can be applied.

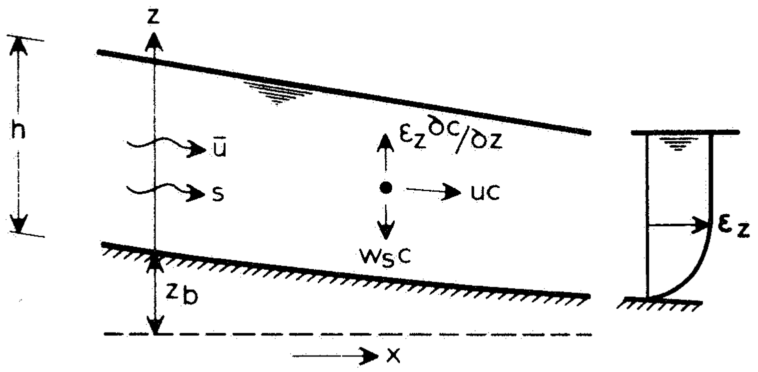


Figure 1 Definition sketch

Assuming that the unsteady depth and concentration terms can be neglected, the bed-level changes are computed from the sediment continuity equation:

$$\frac{\partial z_b}{\partial t} + \frac{\partial s}{\partial x} = 0 \qquad (6)$$

For the diffusion coefficient ε_z in Eq.(3) an empirical expression as developed by Kerssens [2] is applied:

$$\left.\begin{aligned} \varepsilon_z &= \varepsilon_{max} = \{\alpha_1 + \alpha_2 \left(\frac{w_s}{u_*}\right)^{\alpha_3}\} u_* h & \text{for } z/h \geq 0.5 \\ \varepsilon_z &= 4(z/h)\ (1 - z/h)\ \varepsilon_{max} & \text{for } z/h < 0.5 \end{aligned}\right\} \qquad (7)$$

This expression represents a parabolic-constant (PARC) distribution (see Figure 1).

To solve the described differential equations a set of boundary conditions is needed. Eq.'s (1) and (2) together form the familiar backwaterequation, which requires the following conditions (see Figure 2):

1 initial condition : bed-level $z_b(x)$ must be given,
2 upstream boundary : discharge q(t) given,
3 downstream boundary: waterlevel h(t) or h(q) given.

The sediment diffusion-convection equation (3) requires the following conditions:

4 surface boundary : no vertical transport of sediment, thus at z = h:

$$w_s c + \varepsilon_{max} \frac{\partial c}{\partial z} = 0 \qquad (8)$$

5 bed boundary : at a certain reference level z_a a concentration c_a or a concentration gradient $(\frac{\partial c}{\partial z})_a$ must be given,

6 upstream concentration condition: at the upstream boundary the vertical sediment concentration distribution $c_o(z)$ as a function of time must be given.

For the solution of the sediment continuity equation (6) no additional conditions are required. The same initial condition 1 as given above is used for the initial bed levels along the computational reach. At the upstream boundary the sediment supply in time, which can be derived from condition 6 and the local flow velocities, or the bed level $z_b(0,t)$ as a function of time must be provided.

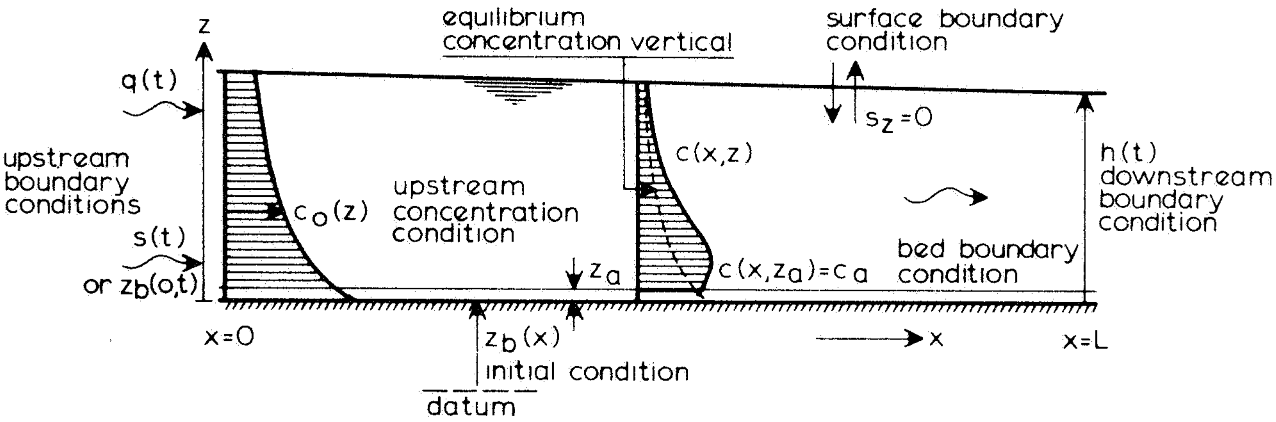


Figure 2 Boundary conditions

No unanimity yet exists about the most appropriate bed boundary condition 5. In the initial versions of the mathematical model the author assumed, as for bed-load transport, that the reference concentration c_a adapts instantaneously to the local flow conditions. Its value can be derived by relating the sediment concentration vertical for equilibrium conditions to one of the existing transport formulae (see Figure 2). In many cases, however, from a theoretical point of view it seems more relevant to set a concentration gradient at the bed boundary. Its value can also be computed from the equilibrium concentration vertical, assuming an immediate adaption of the concentration gradient to local flow conditions. It would be better to derive the value of $\partial c/\partial z$ from an "entrainment function" , taking into account the local shear velocity, sediment characteristics, etc. As no methods are yet available for this, in the recent versions of the SUSED and SUTRENCH models only one of the following bed boundary conditions can optionally be used:

a concentration $c(x,z_a) = c_a$, according to local flow conditions,

b concentration gradient $\left(\frac{\partial c}{\partial z}\right)_{x,z_a} = \left(\frac{\partial c}{\partial z}\right)_a$ according to local flow conditions,

c concentration gradient $\left(\frac{\partial c}{\partial z}\right)_{x,z_a} = 0$.

The latter condition can f.i. be used if no re-entrainment of sediment in a sedimentation reach is to be expected.

The differential equations are solved by means of finite difference methods. For the backwater-equation a simple explicit method is used. The diffusion-convection equation is solved by means of a six-point implicit scheme, making use of a favourable transformation of the basic equation. For the sediment continuity equation a four-point explicit Lax-scheme and a Fromm method have been succesfully applied.

A more detailed description of the basic equations, the solution method and the numerical aspects have been given in other references [2]. Investigations of the sensitivity of the computational method to the sediment diffusion coefficient ε_z, the reference level z_a etc. can also be found elsewhere [3].

3. Practical examples

The mathematical model SUSED has been applied to simulate the morphological behaviour of a diversion canal in Indonesia (see Figure 3). To improve the flood protection the greater part of the discharge of the Serang river, with high suspended sediment concentrations, will be diverted from Godong to the sea. The new canal will reduce the distance to about 50% of the length of the lower Serang river. As the canal will run through a densely populated area, the flood protection and consequently the canal capacity to transport both the high floods and the sediments are of great importance. For this reason

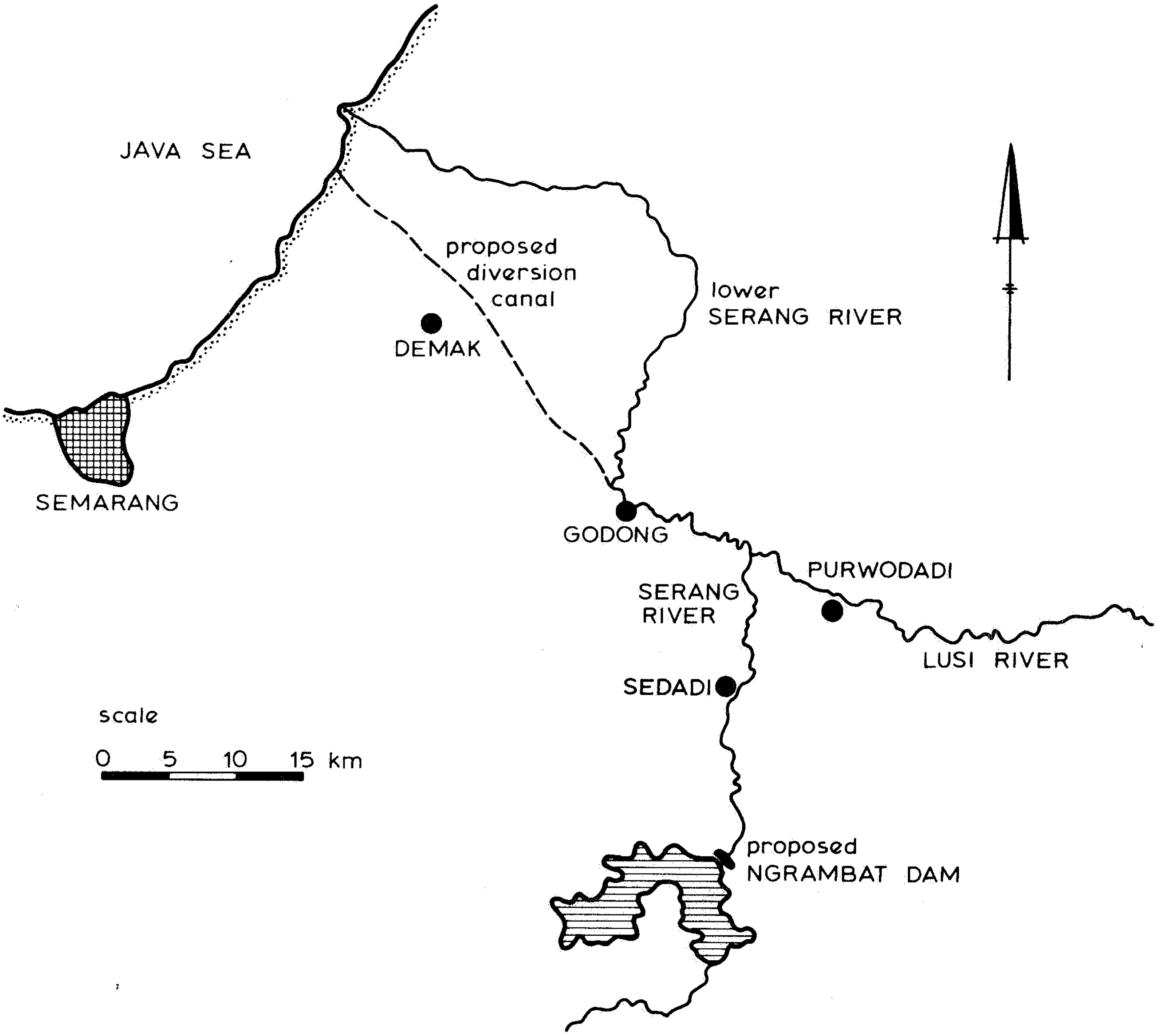


Figure 3 Situation sketch Serang river

in the frame work of the feasibility study of the Serang diversion canal, an investigation has been executed concerning the long-term morphological behaviour of the canal and its relation to flood protection [4].

Data on discharges, sediment transports, topography etc. were collected to derive a good insight into the hydraulic and morphological behaviour of the contributing rivers. For the transported sediments a representative diameter $D_{50} \approx 50\ \mu m$ was found, with a particle fall velocity $w_s \approx 0.003$ m/s. As it appeared that the Engelund-Hansen formula gave the best correlation with the measured data, it was assumed that the sediment transport in the proposed diversion canal could be described by the same formula.

In the initial design (see Version 1, Figure 4) the canal was composed of a main channel and flood plains which both follow the original slope of the terrain, except the main channel bed-slope in the lower two branches. The embankments are constructed from soils excavated from the main channel.

	Branch 5	Branch 4	Branch 3	Branch 2	Branch 1	
length	10	7	5	5	5	km
terrain slope	0.10	0.18	0.24	0.50	0.60	‰
slope main channel	0.24	0.24	0.24	0.50	0.60	‰

version 2 : slope main channel 0.24 ‰ all branches

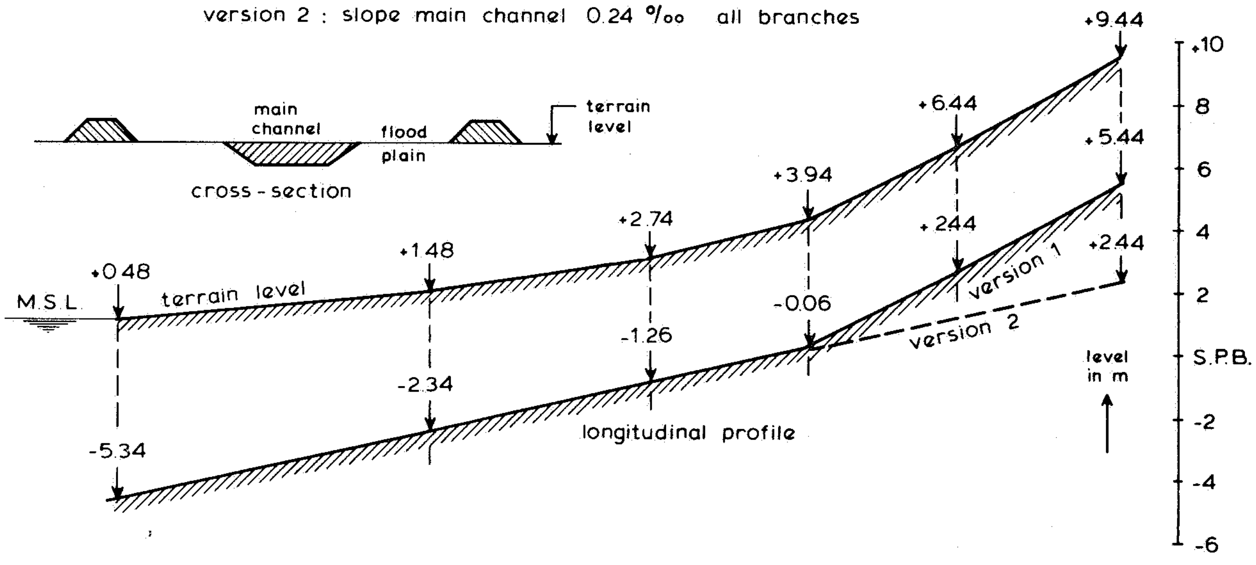


Figure 4 Canal design

With the mathematical model SUSED the morphological changes of the diversion canal were computed. This was executed for cases with and without a proposed dam in the upper Serang river at Ngrambat (see Figure 3), enabling an optimization of the canal profile for both alternatives.

Computations took place for a number of representative discharges. For each discharge interval Q_i the frequency of occurrence $f(Q_i)$, which acted as a weight-factor in the sediment transport computations, was determined.

The canal was divided in a number of branches as shown in Figure 4. The discharge distribution between the main channel and flood plains for all the representative discharges in all the branches was determined by means of backwater computations. Next the main channel and flood plain were separated to execute simultaneous sediment transport computations with the numerical model. In the transition points between the various branches a concentrated exchange of flow between main channel and flood plains has been taken into account. In a similar way an exchange of suspended sediments could also be simulated in the grid-points of the network, as is presented schematically in Figure 5.

By comparison of the upstream sediment supply and the sediment discharge at the downstream boundary of each branch an insight could be obtained into the total sedimentation or erosion in that particular branch. As for each representative discharge computations were executed for a unit time step of one day, the total yearly sediment balance per branch could be determined by multiplying the specific sedimentation/erosion rates by the frequency of occurrence $f(Q_i)$ expressed in days per year. From these accumulated values the mean bed level changes per year could be derived.

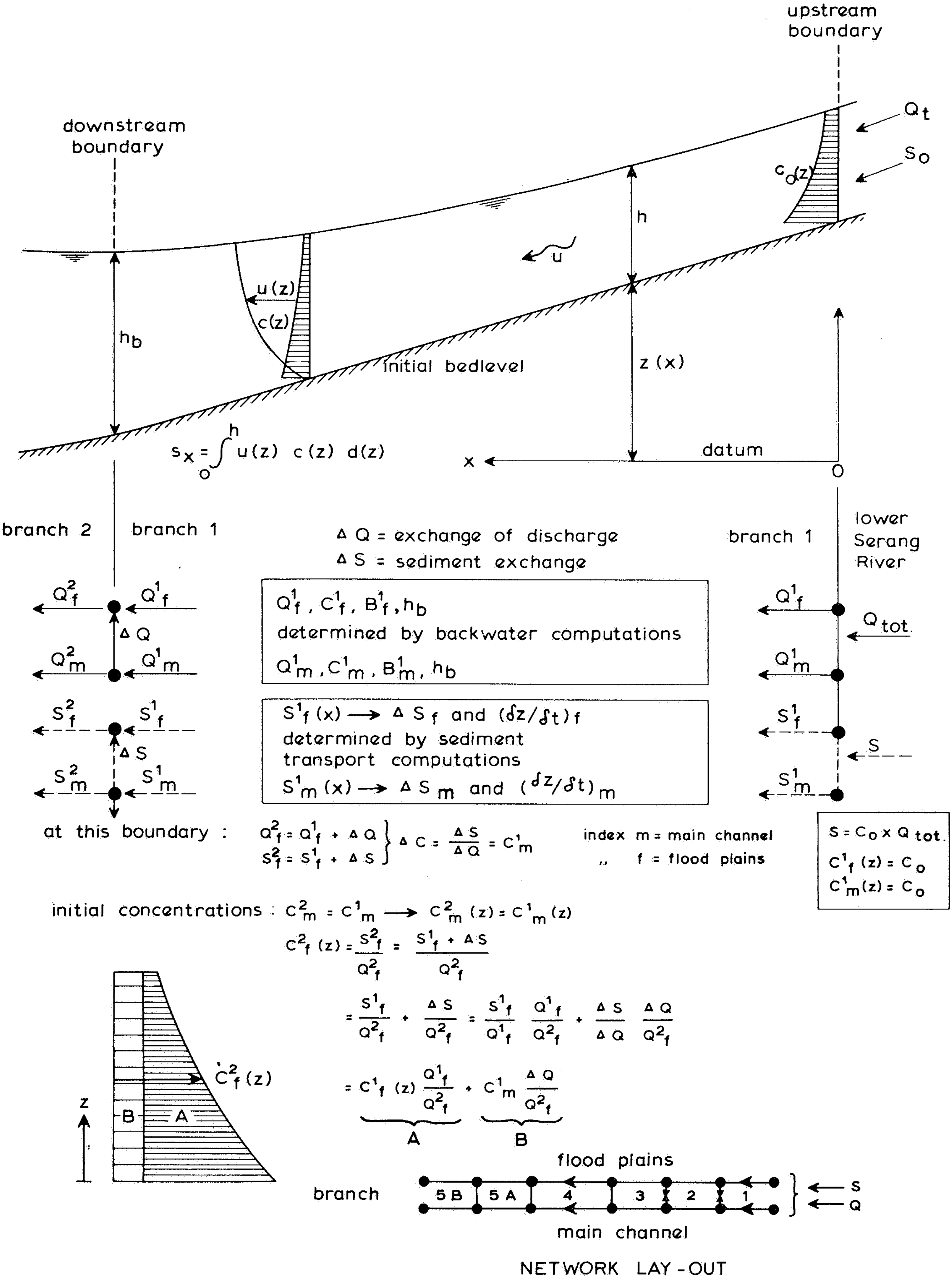


Figure 5 Principles of the sediment transport computations

In Figure 6 an example is given of the specific yearly sedimentation and the cumulative sedimentation on the floodplains of Branch 3. The latter computations started from the initial bed-levels as given for Version 2 (see Figure 4), as it appeared from earlier computations that a canal design according to Version 1 would have resulted in most unfavourable conditions with regard to sedimentation and flood protection.

Computations as described above are very laborious, particularly as the sediment exchange at the transition points had to be calculated separately, since the SUSED model had not been adapted to compute sediment transports in a network. However, the results of such computations can be very useful to obtain a first insight into the morphological behaviour of such an artificial, although alluvial, canal.

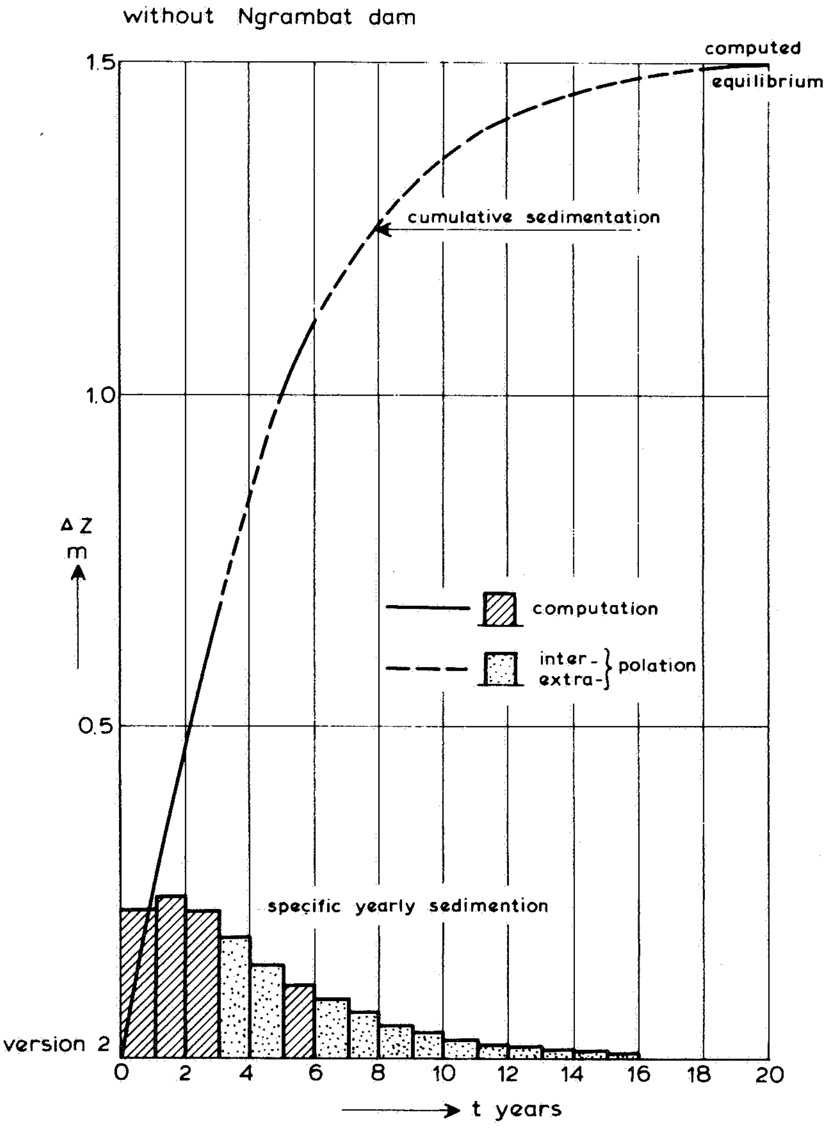


Figure 6 Sedimentation on the floodplains of branch 3

As a second example a verification of the model SUTRENCH is demonstrated. This model has been set up in particular to predict the sedimentation rate in dredged trenches, and is provided with an optional routine for use in tidal conditions. To verify the model the sedimentation in a trench for a gas pipeline in the Western Scheldt, a wide tidal estuary in the Netherlands, was predicted and compared with measured sedimentation rates derived from regular soundings [3].

The representative tide was schematized to four quasi-steady flow conditions of 2 hours each (see Figure 7).

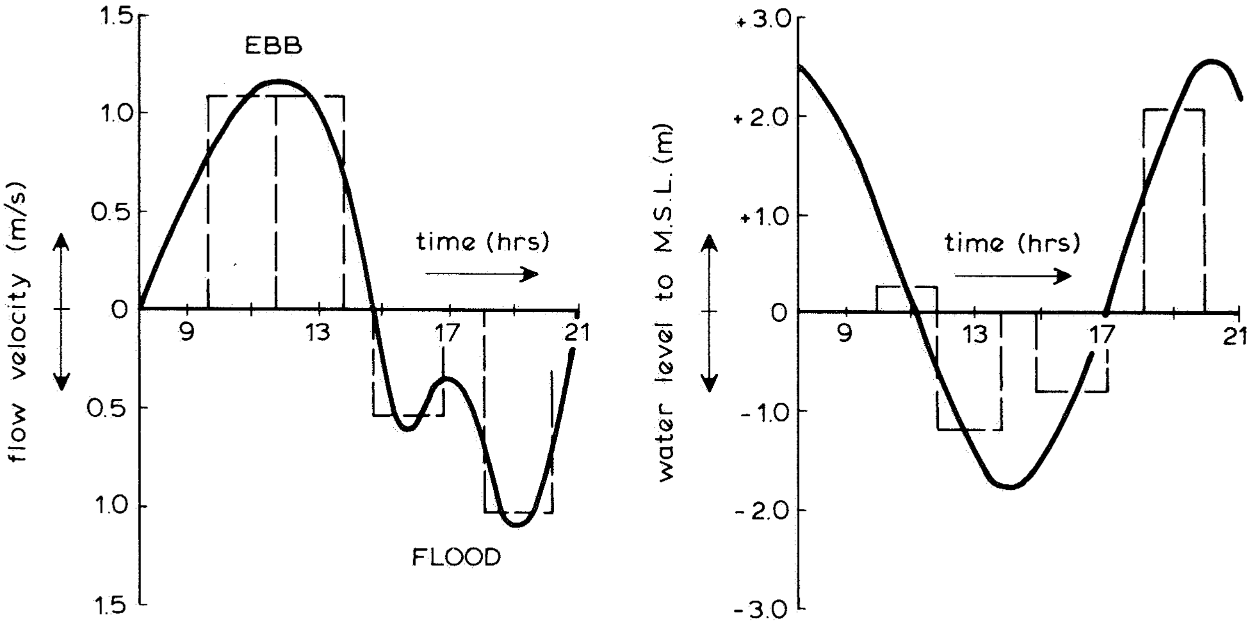


Figure 7 Representative tide

From field measurements the suspended sediment transport could be correlated with the mean flow velocity (see Figure 8). The derived transport formula was used to determine the local transport capacity under equilibrium conditions and the reference concentration c_a for the bed boundary condition.

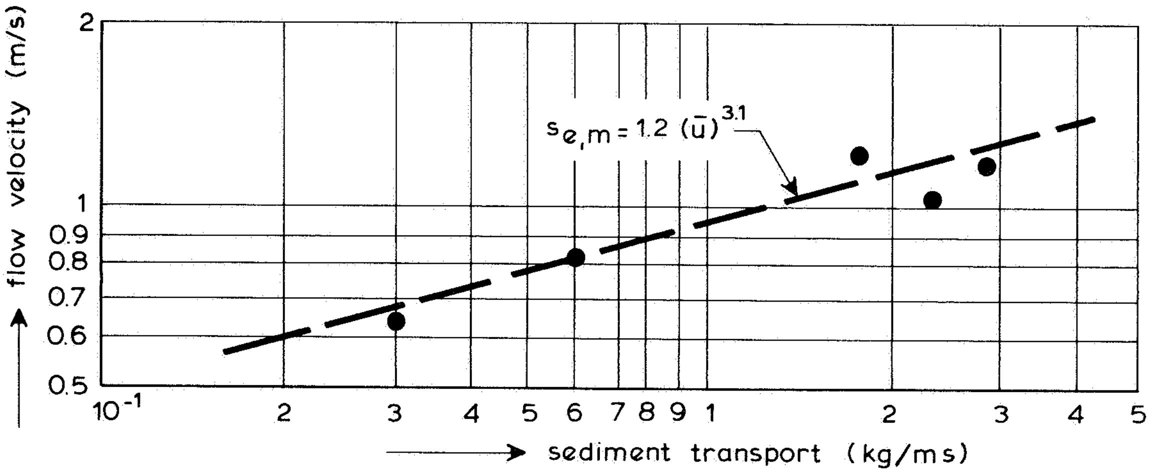
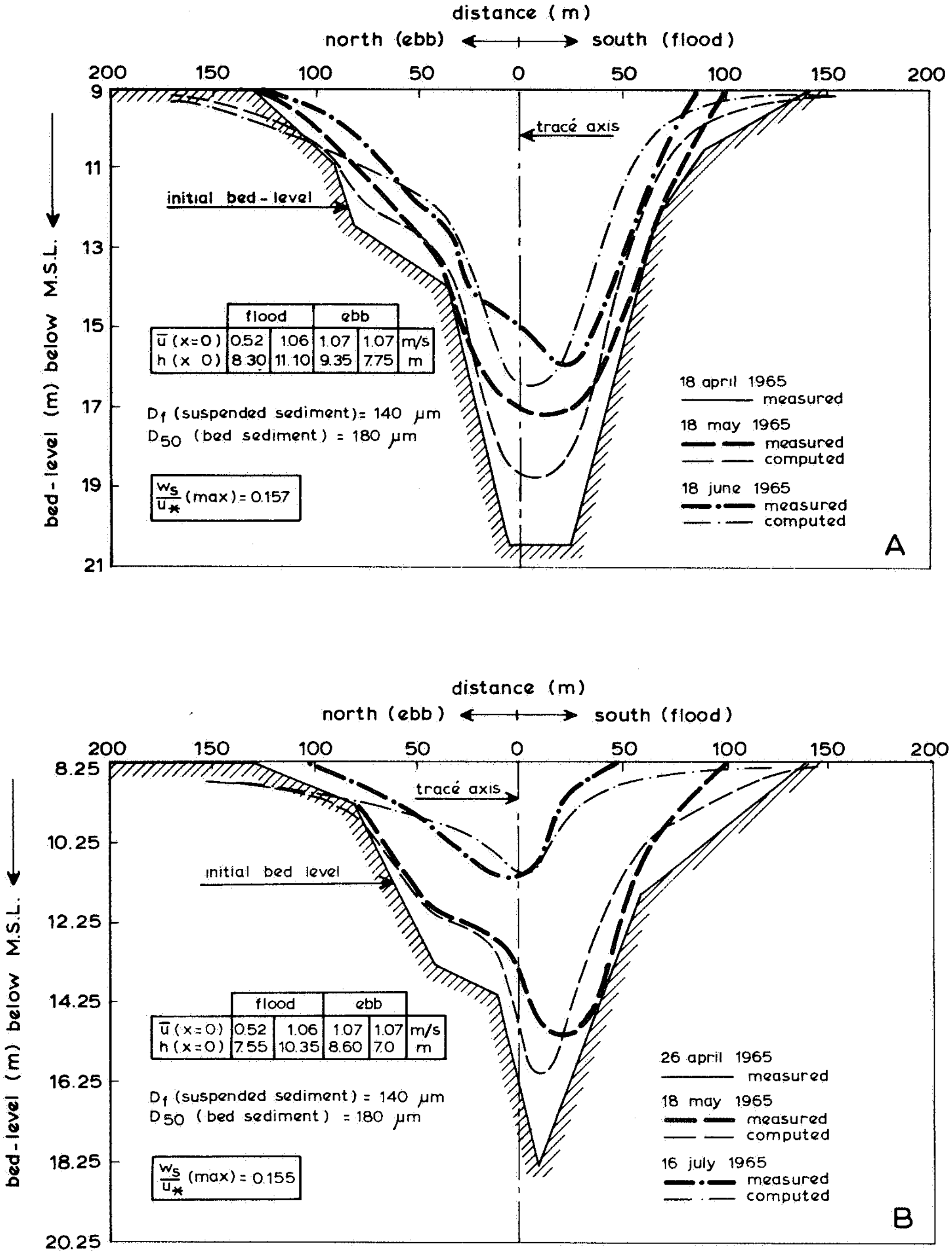


Figure 8 Relation sediment transport - flow velocity

At the upstream boundary of the trench the concentration verticals were assumed to be in a quasi-steady state. The representative diameter D_{50} of the bed sediment is 180 μm, whilst for the suspended sediment a particle fall diameter of 140 μm with a fall velocity of 0.011 m/s (temperature 15°C) was used.

Using longitudinal steps of 5 m and time-steps of 2 hrs., the bed-level changes in the trench were computed over a period of about 2 months with the numerical model. The computed and the measured bed levels for two cross sections of the trench are presented in Figure 9. It can be seen that the prediction of the total amount of deposited material is reasonably good, whilst the time dependent development of the bed profiles is also satisfactory. It must be remarked, however, that sensitivity computations showed a substantial influence of the sediment transport formula used for the predicted sedimentation rates. This stresses the fact that realistic predictions can be obtained only if detailed and accurate prototype measurements over a long period are carried out.
On the contrary it can be stated that even without extensive measurements the model can be very useful to test the relative influence on the sedimentation process of several parameters, sediment characteristics, boundary conditions etc.



	flood		ebb		
ū (x=0)	0.52	1.06	1.07	1.07	m/s
h (x 0)	8.30	11.10	9.35	7.75	m

D_f (suspended sediment) = 140 μm
D_{50} (bed sediment) = 180 μm

$\frac{w_s}{u_*}$ (max) = 0.157

	flood		ebb		
ū (x=0)	0.52	1.06	1.07	1.07	m/s
h (x=0)	7.55	10.35	8.60	7.0	m

D_f (suspended sediment) = 140 μm
D_{50} (bed sediment) = 180 μm

$\frac{w_s}{u_*}$ (max) = 0.155

Figure 9 Measured and computed bed levels in a trench

4. Future developments on mathematical modelling

Basic research on suspended sediment transport and on advanced mathematical techniques to describe the phenomena is being steadily carried on at the Delft Hydraulics Laboratory.
Recently the mathematical model SUTRENCH has been provided with a procedure to describe the water motion in two dimensionals. In the sediment diffusion-convection equation the vertical flow velocity can be taken into account easily by the addition to the particle fall velocity w_s. This computational procedure is particularly required if the sedimentation rate in a dredged trench with steep side slopes is to be predicted.
At the beginning of 1980 a research programme in which the following subjects will be investigated was started:

- improved numerical techniques to solve the diffusion equation;
- derivation of an expression for the sediment diffusion coefficient by way of mixing-length theories;
- most appropriate choice of the bed boundary condition and derivation of entrainment theories;
- improved description of the two-dimensional flow field by way of boundary layer or turbulence models.

With respect to SUSED it is planned to extend the mathematical model in 1980/1981 to enable simultaneous computations of sediment transport and bed level changes in two parallel channels. In all computational grid points the two channels will be connected laterally, so that a continuous exchange of water and sediments (by diffusion, convection and eventually gravity) can be considered. This may lead to a substantial increase in computational possibilities and hopefully to a decrease in cost in comparison to the laborious hand computations described in Section 3 (see Figure 5). Apart from simultaneous computations in a main channel and its flood plains, it will also be possible to tackle cases where a trench is dredged in the flow direction in a river or estuary. Both the sediment transport and bed level changes in the trench itself and in the original bed can be computed, taking into account any lateral exchange of water and sediments.

Also the coupling of sediment transport to a mathematical model for unsteady one-dimensional flow in networks will be executed on short term.

In the long term the following subjects will be tackled to improve and extend the mathematical model techniques to describe the phenomena of suspended sediment transport:

- possibility of depth-integrated modelling of both convection and diffusive transport of suspended sediments in a two-dimensional (x,y) flow field;
- coupling of sediment transport and bed-level changes to a two-dimensional (x,z) flow model with density differences, to include the combined effect of sediment transport and salt intrusion;
- further development of the SUSED model for use in networks of channels.

5. Measurement procedures

Apart from research on fundamentals and the mathematical description of suspended sediment transport,new methods to measure suspended sediment concentrations in situ have also been investigated. For such measurements a wide range of instruments have been developed throughout the world, from simple bottle samplers, the well-known US depth-integrating samplers, the Delft Bottle and the mouse-trap to sophisticated optical samplers.
In recent years attention has been paid at the Delft Hydraulics Laboratory to the development of two instruments to measure suspended sediment concentrations in unsteady flow conditions. Firstly the acoustic Doppler meter must be mentioned, which is based on the scattering of ultrasound with a frequency of 4.4 MHz [1]. The instrument can take non-contacting, continuous or instantaneous measurements of both velocity and concentration, i.e. the transport, of sand suspensions. The calibration curve of the instrument with regard to measured concentrations depends on the grain size of the sediment particles.

Secondly a pump-filter sampler which enables the sampling of a relatively large volume (about 0.05 m^3) of a water-sediment mixture has been developed. As the sampling time is relatively small the instrument is most suitable for use in tidal conditions [5]. By means of an in-situ filtration unit a direct separation of water and sediment is applied. In contrast to measurements with single bottle samples and their relative low accuracy due to small sediment catches, the large volume of the total sample on the filter will lead to a higher accuracy of the measurements. Moreover an amount of material sufficient to make a sieve analysis of the sample will be collected.

The efficiency of the sampler, which is shown in Figure 10, was checked by laboratory tests with sediments of D_{50} = 95 μm. For field conditions the instrument was checked with local bed material D_{50} = 320 μm, velocities up to 1.5 m/s and depths up to 25 m.

The main conclusions of these tests are [5]:

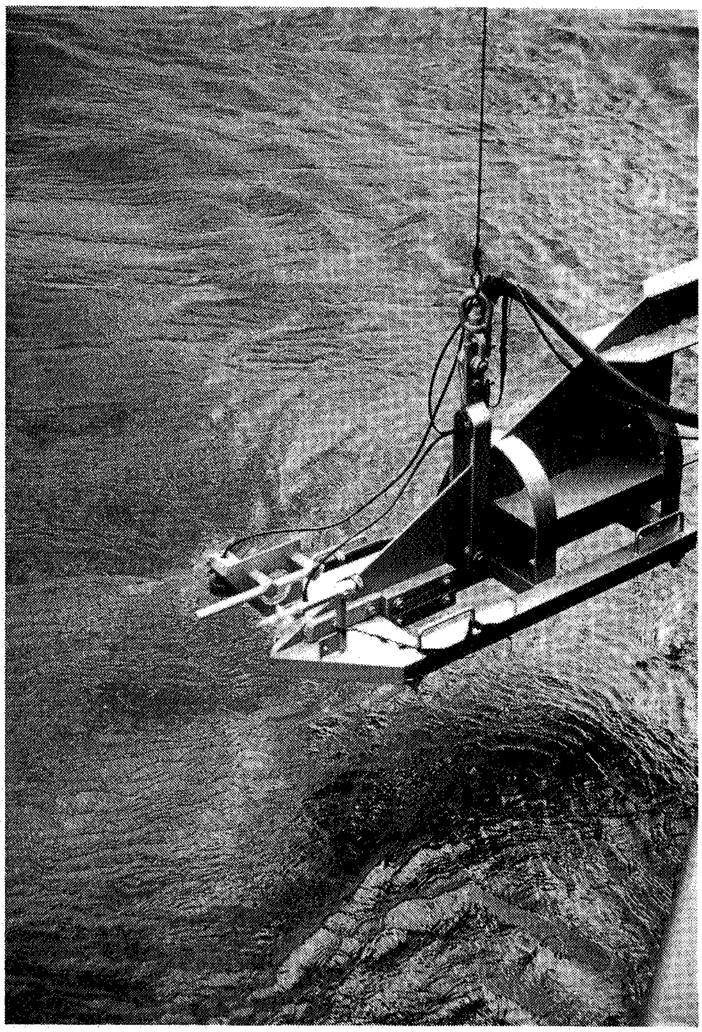


Figure 10 Sampling unit with intake nozzle, current meter and echo sounder

1 A minimum intake velocity of about 1 m/s is required to avoid settlement of the particles in the suction hose;

2 From a practical point of view it is not suitable to equalize the nozzle intake velocity to the local flow velocity;

3 Sampling errors up to only 10% may occur for intake velocities that deviate about 50% from the local flow velocity;

4 Sieve-analysis of samples caught by the pump-filter sampler show representative sampling;

5 Comparison of the pump-filter sampler and the described acoustic Doppler sampler show a good agreement in results (see Figure 11);

6 The pump-filter method is not suitable for operation in a silty or muddy environment due to rapid clogging of the filters.

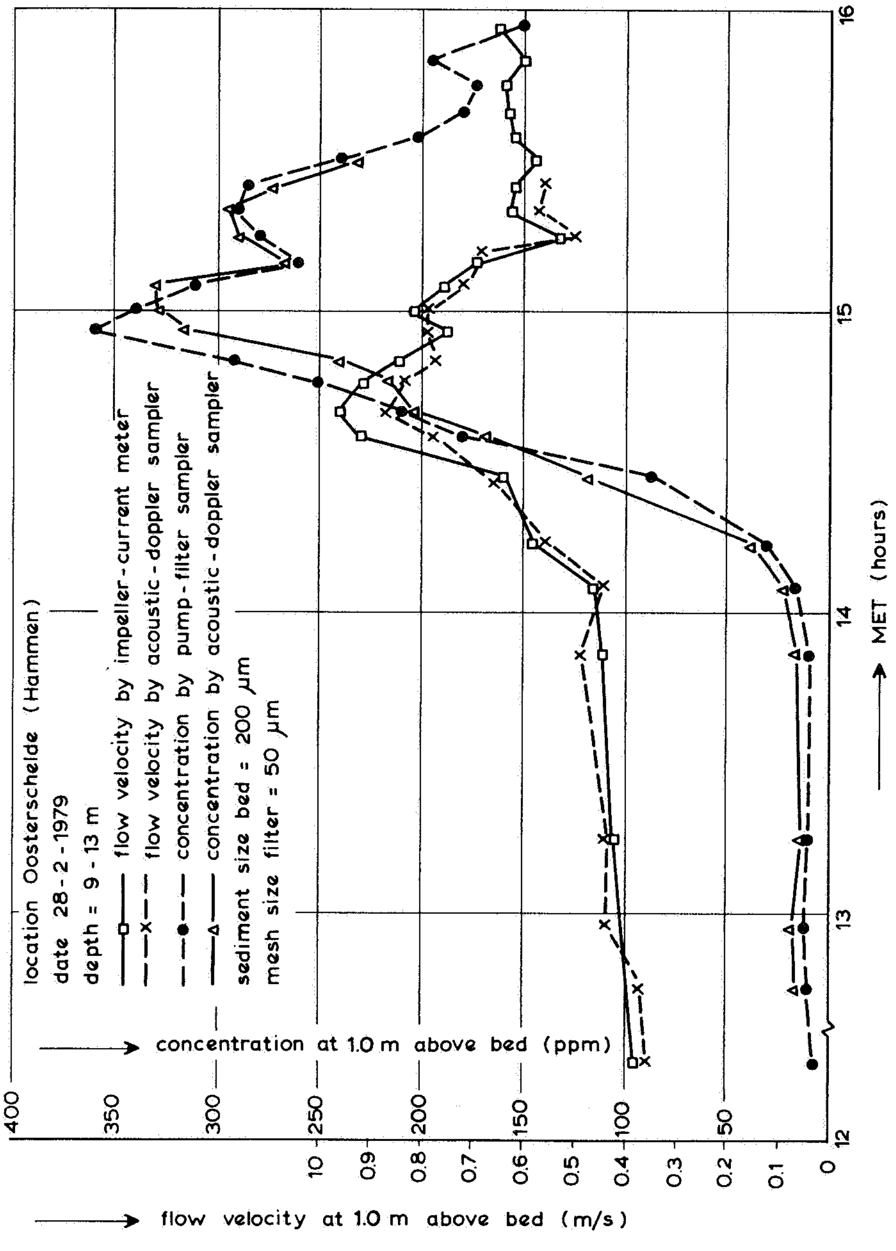


Figure 11 Time concentration lines for pump-filter sampler and acoustic-doppler sampler

SYMBOLS

C	Chézy roughness coefficient	$L^{\frac{1}{2}}T^{-1}$
c	sediment concentration	ppm
c_a	reference sediment concentration	ppm
D_{50}	representative particle diameter	L
g	acceleration of gravity	LT^{-2}
h	flow depth	L
k_n	roughness parameter of Nikuradse	L
Q	total discharge	L^3T^{-1}
$f(Q_i)$	frequency of occurrence for discharge Q_i	-
q	discharge per unit width	L^2T^{-1}
R	hydraulic radius	L
S	total sediment transport (volume)	L^3T^{-1}
s	sediment transport (volume) per unit width	L^2T^{-1}
t	time	T
u	flow velocity in longitudinal direction	LT^{-1}
$\bar{u}$	mean flow velocity	LT^{-1}
u_*	shear velocity	LT^{-1}
w_s	particle fall velocity of suspended sediment	LT^{-1}
x	longitudinal coordinate	L
y	lateral coordinate	L
z	vertical coordinate	L
z_a	reference level above bed	L
z_b	bed level relative to datum	L
$\alpha_1, \alpha_2, \alpha_3$	parameters in diffusion coefficient distribution	-
ε_z	diffusion coefficient in vertical direction	L^2T^{-1}
ε_{max}	maximum value of diffusion coefficient	L^2T^{-1}
κ	von Karman constant	-

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