CHAPTER ONE HUNDRED THIRTY NINE

DEVELOPMENT OF A SEDIMENT TRANSPORT MEASURING SYSTEM

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ABSTRACT

A new method for continuously recording sediment concentrations with high accuracy has been developed. It is proposed to apply the method for in-situ measurements in connection with investigations of tidal control and sediment transport induced by shipping traffic.

The operating principle is as follows: at the measurement location, sediment laden water is continuously sucked-in by means of a pump and is forced under pressure into a hydrocyclone (solid bowl centrifuge) through a delivery pipe of varying length. Here the extracted sediment flux (particle size $\geq$ 5 µm) is delivered by the shortest route to a settling tank and continuously weighed under water (wet-weighing). Following calculation and appropriate adjustment to the sample discharge (Q) the weight increase for selected time intervals ($\Delta G\ (\Delta t)$) yields the mean concentration for the time interval ($\bar{c}\ (\Delta t)$) in weight / unit volume (mg/l) (direct measurement, calibration not required).

Details and experiences of the 3 major development stages will be described. A fully-automatic instrument for continuously measuring nonsteady sediment movement is now available. The instrument may be installed above as well as below water as desired.

1. INTRODUCTION AND PROBLEM DEFINITION

In connection with investigations of tidal control to reduce sedimentation and of sediment transport induced by shipping traffic in the inner German Bight / North Sea, it is necessary to continuously record instationary sediment transport over long periods at different measuring stations. Owing to a lack of information concerning the spatial distribution and temporal variation of sediment

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movement in the investigation areas, it was necessary to develop an overall concept which was realised in practice according to the following stages:

1. Selection and partial development of a suitable method of continuously recording sediment concentrations and the specification of a minimum performance

2. Preliminary experiments concerning the measurement of the instationary nature of sediment movements at a single point of measurement. This was necessary in order to estimate the most appropriate measurement frequency and measurement duration.

3. Simultaneous test recordings at various depths in the same cross-section in order to access the importance of vertical variations in the transport (number of instruments !)

4. Simultaneous test recordings at various measuring points in a horizontal plane at the same cross-section in order to access the importance of horizontal variations in the transport (number of instruments !)

5. Further development of the measuring technique in order to obtain optimal conformity with the overall objective with due consideration of the above-mentioned experimental tests

Since each stage of the investigation depended to a large extent upon the results of the experiments, it was necessary at the outset to ensure a high degree of flexibility in research planning and conduct. In accordance with the latter, the following basic principles were specified:

a) Adoption of uncomplicated and readily available instrument components as building blocks

b) On-the-spot evaluation of test results in order to ensure an optimal progress of the experiments

c) Well-conceived stage planning in order to ensure overall optimisation of the investigation aim and solution possibilities

In this paper, attention will be mainly confined to the development stages of the measuring technique.

2. SELECTION CRITERIA FOR THE MEASURING TECHNIQUE

In order to prescribe the measuring technique , a study of existing investigations was first carried out (1),(2),(3). The following basic information led to constraints regarding the technical problems of measurement concerned with here:

1) Existing data concerning grain-size distributions for suspended sediment and bed samples reveal mean frequency maxima ranging between about 5o and 1oo µm.

2) At the present time, existing indirect recording techniques require extensive calibration by means of sampling and laboratory analyses (weighing), especially under consideration of particle dependence.

3) The determination of sediment balances (residual transport) depends predominantly upon the number of instruments used.

For these reasons, the continuous partial flux analysis with sediment weighing was selected as the most suitable method of investigation ((4), and Fig.1).
With the aid of a pump and a suitable extraction and feed system, a sample discharge is continuously forced under pressure through a hydrocyclone (solid bowl centrifuge). The separated particle stream falls within seconds by gravity into a settling tank and is continuously weighed. Following calculation and appropriate adjustment to the sample discharge (Q), the weight increase for selected time intervals ($\Delta G\ (\Delta t)$), directly yields the mean sediment concentration for the time interval ($\bar{c}\ (\Delta t)$) in weight / unit volume (mg/l).
The development of the measuring technique and the corresponding instrumentation took about 2 years. This essentially involved 3 major stages of development (see Fig.3).

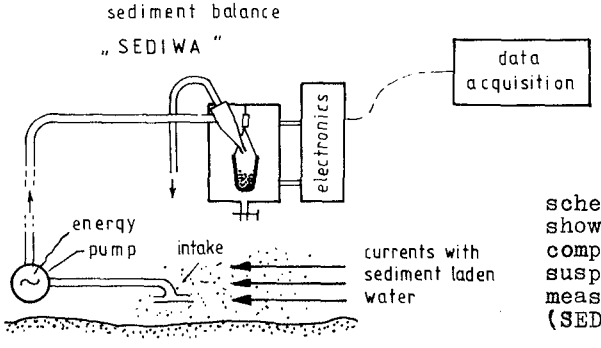


Fig. 1 : schematic drawing showing mean components of suspended sediment measuring device (SEDIWA, submersible)

3. HYDROCYCLONES AS SOLID BOWL CENTRIFUGES

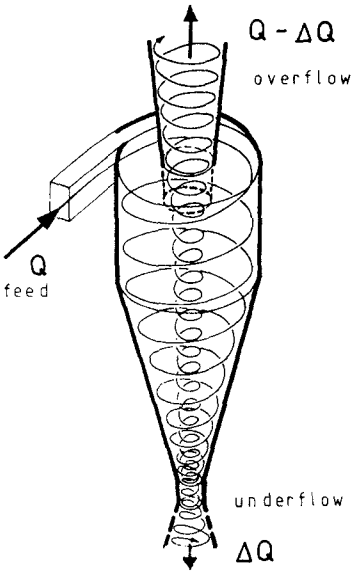


Fig. 2 :
Hydrocyclone flow diagram

As described by TRAWINSKI in (5) the hydrocyclone can be regarded as operating as a solid bowl centrifuge in which the casing is not rotated, but rotation of the suspension is produced by its being fed into the cyclone tangentially under pressure. Depending on the degree of solids recovery to the underflow, the cyclone can act either as clarifier or as classifier. The rejects are thickened in any case.

Fig.2 demonstrates schematically the working of a hydrocyclone. The suspension fed into it forms a primary vortex along the inside surface of the cylindrical and conical wall, aiming to leave the cone apex. As this is throttled, only part of the stream is discharged as underflow, carrying the coarse particles or even all of the solids with it. The bulk of the liquid - being cleaned by the residual fine particles with it - is forced to leave the cyclone through the overflow nozzle by forming an upward-spinning secondary vortex surrounding the core of the casing. Inside the core, a low pressure is generated, collecting all the air that has been carried in as bubbles or dissolved in the feed water. Even vapor will enter this visible air core. Because of the increase in cicumferential speed in the secondary vortex, higher centrifugal forces are generated, resulting in a highly efficient secondary separation. The rejected fine particles settle radially and join the primary vortex, from which most of them are discharged finally through the spigot formed by the cone apex. The separation inside a hydrocyclone therefore takes place as a result of two process stages, the final cut point being determined mainly by the acceleration of the inner secondary vortex.

4. SELECTION OF MEASUREMENT CYCLONES

The separation efficiency of hydrocyclones is mainly determined by the cyclone geometry (diameter, length) and the discharge. The normal measurement specifications for standard cyclones require information regarding concentrations,

particle distribution as well as discharge for the feed. These three design parameters must be estimated by theoretical or empirical methods before instrument construction and specified for the selection of the cyclone. In respect of this, following relationships must be considered:

1. The natural particle distribution of between 0 and approximately 500 µm, with a mean maximum of between 50 and 100 µm, lies within the optimum working range of hydrocyclones. The smaller number of large particles occur very seldom and may therefore be legitimately excluded by means of a prefilter so as to protect the equipment from blockage. Parts of the equipment susceptible to blockage include the slot-shaped inlet nozzle (max d < slot-width) and the circular underflow nozzle (d ≤ 1/5 nozzle diameter). Other than this, no strict requirements are necessary for optimal performance of the equipment.

2. The natural concentration of the sample discharge (Q) of between about 0 and 10 g/l maximum, with a predominant peak between 50 and 500 mg/l, results in an optimum degree of selectivity in the separation process. The absolute magnitude of the latter, as related to the frequency of occurence, is a decisivly important factor for the dimensioning of the sediment scale. For optimal performance, the accuracy of weighing, measurement frequency, size of the settling tank and flushing frequency must be counterbalanced.

3. The discharge (Q) is essentially proportional to the diameter of the hydrocyclone. Since the size of the separated material also increases with the diameter of the hydrocyclone the sediment stream to be weighed becomes less representative owing to the restricted range of particle size. The fine-grained fraction ($< d_T$) of the residual turbidity in the hydrocyclone overflow increases, and since this cannot be measured at the present time, it must be treated as an error in instrument measurement. Consequently, the optimisation demands a minimization of the discharge (Q).

It should be noted that the sub-optimization of the hydrocyclone and the magnitude of the sample discharge (Q) as a function of the sediment scale both play a predominant role. Owing to the unknown sediment fluxes, further development of the method in the hydraulics laboratory was not undertaken. By adopting readily available instrument components, initial tests and measurements in the field were immediately carried out. By this means, first impressions of actual sediment movements, as referred to in section 1, could be obtained simultaneously.

5. OVERALL OPTIMISATION OF THE MEASURING SYSTEM

5.1 Components of the measuring technique

The in-situ measuring instrument with on-line facilities is comprised of the following sub-units (compare with Fig.1 , Fig.3 and Table 1):

a) Extraction and feed equipment with intake arrangement, delivery pump, feed pipe, support, power supply, positioning facility

b) Hydrocyclone and disposal unit with discharge measurement, overflow pipe, inlet regulation, pressure controls

c) Settling tank and sediment scale with tank adjustment, filling equipment, flushing device, constraining fix - tures

d) Instrument control and data recording with underflow regulation, tank flushing, operation monitor, data acquisition, data storage, concentration computations, in-situ data logging

As indicated in Table 1 , the three development stages involve different dimensions of the sample discharge (Q) and weighing apparatus. Accordingly, the instrument components listed under a) to d) are differently dimensioned. A detailed technical description will be avoided here.

5.2 Determination of sediment concentrations

As described in Sections 3 to 5 , only the sediment stream in the hydrocyclone underflow is continuously weighed at present. All fine particles (smaller than the separation grain diameter d_T) as well as organic material enter the hydrocyclone overflow and are only occasionally monitored by manual sampling (discontinuously) followed by labora - tory analysis.

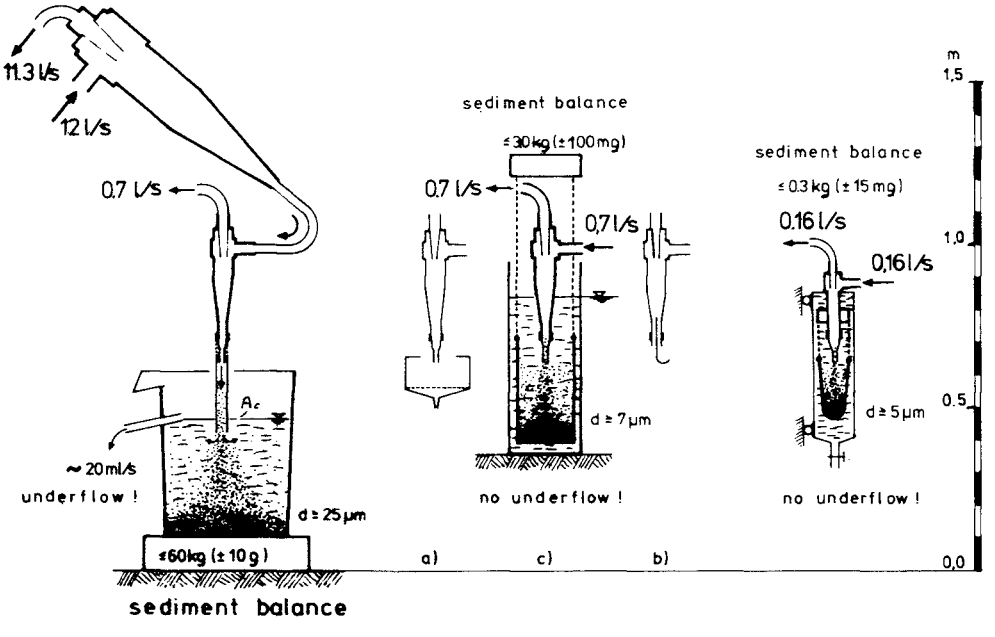
The sediment concentration for particles larger than (d_T) is calculated as follows:

$$\bar{c}\ (>d_T) = \frac{\Delta G}{\Delta t \cdot Q} \quad (\text{mg/l}) \qquad (1)$$

where: $\bar{c}\ (>d_T)$ = mean sediment concentration for particles ($>d_T$) in the time interval (Δt)

ΔG = weight increase in the time interval (Δt)

Δt = time interval for computing mean sediment concentrations ($\bar{c}$) (held constant during a sequence of measure-



STAGE I **STAGE II** **STAGE III**

Fig. 3 : most significant stages (I to III) of the development of the sediment transport measuring system

	COMPONENTS OF OPTIMIZATION	TENDENCY min.	TENDENCY max.	dim.	STAGES OF DEVELOPMENT stage I	stage II	stage III
instrument	1.1 geometry (length, diometer)	x		[m]	1.0 / 0.2	0.6 / 0.1	0.3 / 0.05
	1.2 weight	x		[kg]	200	60	10
operation	2.1 energy	x		[KW]	≈ 10.0	≈ 1.0	≈ 0.5
	2.2 discharge (feed)	x		[l/s]	12.0	0.70	0.16
	2.3 pressure	x		[bar]	5.0	3.5	2.5
	2.4 reliobility		x				OPTIMUM
	2.5 maintenance costs	x					
	2.6 degree of automation		x				
separation	3.1 separation mesh (cut point)	x		[µm]	25	7	5
	3.2 volume split ratio [$\alpha = Q_F / Q_z$]		x	—	≈ 1: 500	≈ 1.0	= 1.0
	3.3 moss recovery [$\Theta = M_G / M_z$]	x		—			
accuracy	4.1 time steps of meosurement	x		[min]	5	0.5	0.5
	4.2 weight increose		x		min.		max.
	4.3 occurocy of meosurement		x	[g]	±10.0	±0.1	±0.02
	4.4 flushing intervals		x	[h]	≤ 5	≤ 2	≤ 2
	4.5 flushing duration	x		[min]	~ 5	~ 2-5	~ 1

Table 1 : Optimization of the sediment transport measuring system S E D I W A

ments, however may be arbitrarily chosen up to the maximum filling - time of the settling tank)

Q = magnitude of the sample discharge

According to the particular stage of development I to III, these measurement parameters vary. Beyond stage II, wet weighing must take account of buoyancy forces (compare with Table 1).The different combinations of hydrocyclone and weighing apparatus are shown to scale in Fig.3 .

5.3 Stage I - Trial tests with a large-scale equipment

In order to become acquainted with the handling and per - formance of hydrocyclones and the measuring technique as well as the variance of the particle discharges, a full - scale instrument was installed for trial tests (compare with Fig.3,I). Owing to the present inability to control the underflow discharge of about 2o ml/s, a through-flow settling tank with a free surface was selected. With a realisable settling area (A_S) of about 12 dm^2 together with the corresponding volumetric capacity ($V \approx 4o$ l) , a separation grain-size of about 25 μm was specified. All finer particles were already eliminated from the measure- ments by means of an exterior large cyclone. The large sample discharge (Q) of about 12 l/s ensured a relatively large sediment delivery to the settling tank. Despite hy- draulic related disturbances of the scale, measuring inter- vals of 5 minutes were possible. The test results yielded detailed information concerning the particle flux ($d > d_T$, d_T = 25 μm). Data was recorded by means of a simple printer.

5.4 Stage II - Trial tests with a mobile instrument

In order to quickly obtain information regarding the spa- tial distribution of sediment movements over a cross-sec- tion, the simultaneous operation of three mobile sediment measuring instruments was necessary (types due to stage II, see Fig.3). Corresponding considerations concerning a minimization of instruments led to a drastic reduction of the required sample discharge (Q) from 12 to o.7 l/s. This was achieved by regulating the hydrocyclone underflow. Following preliminary tests with filters (stage IIa) and special valves (stage IIb), hydraulic regulation of the underflow by means of pressure control was eventually adopted. By immersing the lower part of the hydrocyclone beneath the free surface of the settling tank, the under- flow (water) was completely choked. The sediment ($> d_T$) escaped with negligible delay due to density currents alone. By this means, the free surface-area of the set - tling tank could be reduced by a factor of 1o to 3 dm^2.

The improved selectivity (separation grain-size d_T=7µm) obtained with the smaller sample discharge of o,7 l/s considerably increased the measurement range in the direction of fine sediments. Owing to the reduced sample discharge, however, the sediment flux in the underflow decreased by about one-tenth. In order to maintain the same accuracy of measurements (resolution, measurement frequency), it was necessary to reduce the weighing range by the same factor (one-tenth).

By taking advantage of the above-mentioned instrument reductions, a completely submerged suspension of the weighing container was possible. As a result, hydrodynamic disturbances during weighing were eliminated. In addition, the accuracy of measurement could be increased by a further order of magnitude (see Table 1) by taking advantage of buoyancy forces during weighing. The weighing was carried out with high precision laboratory scales and a hand-held-computer was used for data acquisition.

With this instrument configuration, which may be termed semi-automatic, several dozen tides were monitored (see Fig.4). The measurements revealed large spatial and temporal variations in sediment concentrations. Correspondingly, the filling times of the settling tank to maximum capacity also differed (from about o.5 to 5 hrs in the EIDER Estuary / North Sea). Changing of the settling-tank, followed by underflow stabilization for the next period of measurement, lasted on average between about 2 to 5 minutes.

5.5 Stage III – Fully-automatic sediment concentration measuring instrument SEDIWA

The valuable experiences gained in instrument handling, precision and measured results during the development stages I and II led to a further optimisation of the equipment (Fig.3, Stage III and Table 1). The long-term installation of several instruments, especially on poorly accessible and submerged mountings, necessitated a further minimisation of instruments, improved operating stability and full automation (compare with Fig's 3 and 5).

The selection of a mini-cyclone with a discharge capacity of o.16 l/s reduced the separation grain-size (d_T) to 5 µm. Due to the new reduction in the sample discharge of about one-fifth, a corresponding increase in the weighing accuracy of around ± 2o mg will be necessary. This can only be justified, however, provided the hydraulic disturbances for the instrument and environment are relatively small. Owing to the fact that underflow pressure was several tenths of a bar, the hydraulic regulation of the underflow had to be abandoned. The corresponding effects of oper-

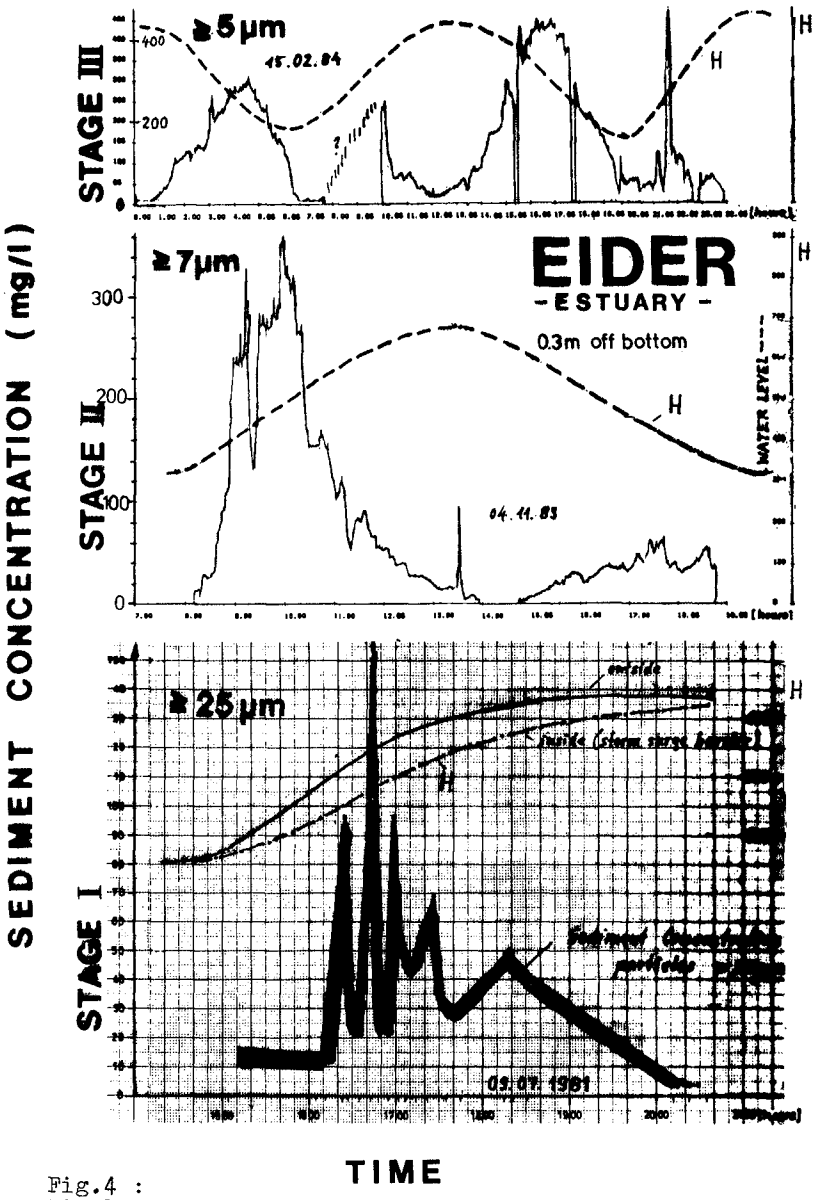


Fig.4 :
Simultaneous records of suspended sediment concentration and water level (tidal curve)

ating pressure fluctuations upon the several meters high water column of a free-surface buoyancy tank would adversly affect the separation process.

The necessity of including a submerged scale in a pressure-stabilized instrument configuration required a transition to a closed excess-pressure chamber in the hydrocyclone underflow. By this means, a highly sensitive underwater weighing cell (± 15 mg) could be developed and installed. The weighing container, which is about the size of a beaker, has a maximum filling capacity of approximately 2oo g of sediment (>5 µm). Depending on the rate of sediment accumulation, the filling time is of the order of several hours.

Emptying of the container (compare with Fig. 5 c) is achieved by simply opening the flushing valve located at the base of the chamber. By choking the overflow, the excess pressure of about 1 bar in the chamber falls drastically. This leads to a strong flushing jet in the cyclone underflow which re-empties the full settling tank within about 1 minute. Following the flushing phase, the valve is closed again. The chamber pressure and the underflow discharge immediately stabilize and the measuring procedure resumes without delay.

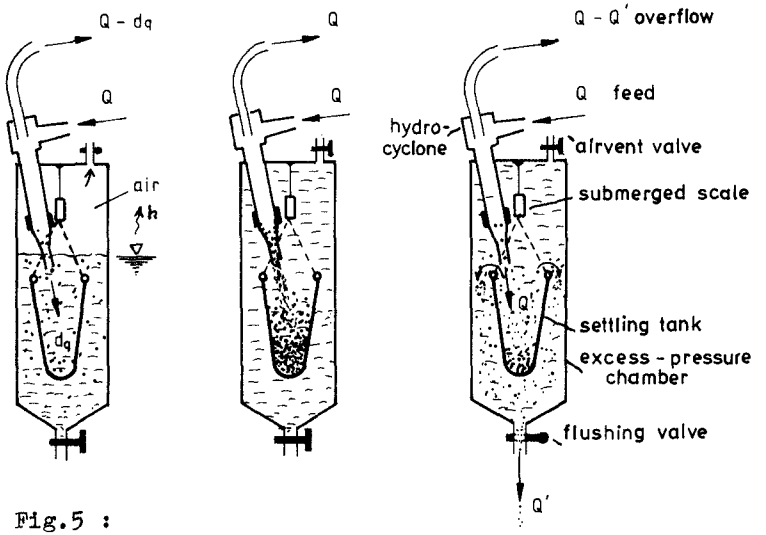


Fig.5 :
a) filling ··· b) operation ··· c) flushing ·· of SEDIWA
– submersible sediment measuring system –

For fully-automatic operation, a control unit with data acquisition is provided. Together with time and weight measurements, the magnitude of the sample discharge (in general constant) is continuously monitored by means of a discharge meter in the return-flow line behind the cyclone overflow. The calculation of sediment concentrations (according to Equation (1), section 5.2), inclu - ding processing of the measured data, is achieved by means of simple software.

With this type of instrument, several series of measure - ments lasting a number of days have already been successfully carried out in the absence of personnel (compare with Fig.4). The continuous recording over several tides provided valuable information for the subsequent analysis of the wide-ranging data relating to instationary sediment movement.

6. MERITS OF SEDIWA AND CONCLUSIONS

1. Flow sampling, i.e. delivery of the total material to be investigated (water with contents) for further detailed examination
2. Continuous extraction, i.e. the possibility of detecting special events (eg. detection of transient peaks)
3. Sediment sample collector, i.e. availability for subsequent (eg.) sediment-petrographical analysis
4. Accumulative weight method, i.e. especially for temporally dependent analysis and evaluation (integration, balances), the relative influence of errors becomes increasingly less
5. Minimum time discretization, i.e. optimum suitability to highly instationary sediment movement
6. Absolute measurement technique, i.e. recordings in weight / unit volume (avoids calibration)
7. Larger range of material, i.e. weighing of all particles greater than d_T = 5 µm (separation grain-size of the hydrocyclone = cut point)
8. High precision, i.e. by minimising the sample discharge (Q) and with pressure-stable isolation of the hydrocyclone underflow, including weighing unit as well as weighing under buoyancy, a highly sensitive weighing cell may be employed
9. Immersed installation, i.e. minimisation of support and serving facilities
10. On-line measurement technique, i.e. as a consequence of cyclonisation followed by immediate submerged weighing of sediment, complete availability of the com -

puted concentration values only a few seconds after sampling (also later, as desired)

11. Full automation, i.e. hydraulic delivery technique, reduction of mechanical parts to only a flushing valve, waterproof electrics and electronics, presence of personnel not required

7. ACKNOWLEDGEMENTS

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REFERENCES

(1) Christiansen, Hermann , 1974 - Über den Transport Suspendierter Feststoffe in Ästuarien am Beispiel der Elbmündung bei Neuwerk. Hamburger Küstenforschung Heft 28

(2) Göhren, Harald , 1973 - Ein automatisches Schwebstoff-Dauermeßgerät für den Einsatz im Wattenmeer und in Brandungszonen. Die Küste, Heft 24, S.8-19

(3) Renger, Eberhard ,and Partenscky, H.-W., 1980 - Sedimentation processes in tidal channels and tidal basins caused by artificial constructions. 17th Int. Conf. on Coastal Engineering, Proc.Vol. II, pp 2481 - 94

(4) Renger, Eberhard , 1982 - Dauermessungen des suspendierten Feststoffgehaltes im Tidegebiet mit Hilfe von Durchlaufzentrifugen. Int. conf. on marine research, ship technology and ocean engineering, IMT 82-418, Hamburg

(5) Trawinski, Helmut , 1976 - Theory, applications and practical operation of hydrocyclones. Engineering and Mining Journal (E/M), pp 115-127

(6) Trawinski, Helmut , 1981 - Sind die Anwendungsgrenzen des Hydrozyklons konstruktiv zu erweitern ? - Sonderdruck aus MM - Maschinenmarkt, 87.Jahrgang, Heft 34 und 52 (S. 684-87, 1069-72)