COMBINING LABORATORY, FIELD AND MATHEMATICAL MODELLING RESEARCH FOR BED FORMS, HYDRAULIC ROUGHNESS AND SEDIMENT TRANSPORT DURING FLOODS

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INTRODUCTION
Simulation and prediction of the behaviour of alluvial rivers at a certain level of accuracy require the use of mathematical models representing the basic hydrodynamic and sediment transport processes. Essentially, the models are the reflection of our knowledge of the processes.
In recent years a range of useful mathematical model concepts has been developed, which can be classified into two broad categories: process-related and behaviour-related models.
Generally, the process-related models are based on a detailed description of all relevant processes by implementation of a series of submodels representing the fluid dynamics, the sediment transport rates and bed-level changes combined in a loop system to effectuate the dynamic interaction of the processes involved. Examples of process-related models are: 1D-morphological models, 2DH-river bed models and 2DV-suspended sediment models.
Behaviour-related models describe the behaviour of morphological features or systems using relatively simple expressions formulated to represent the phenomena at the larger scales of interest. Hence, the basic phenomenological behaviour of the system is described neglecting unnecessary details. All process-related information and additional empirical information is represented by coefficients, parameterized functional relationships or by stripped process-based submodels. Long-term datasets are indispensable for calibration of the model coefficients and functional relationships. In this way behaviour-related models can integrate the process-related information representing the basic driving forces and the long-term phenomenological behaviour based on field observations. Examples are: River meandering models and bar behaviour models.

In this presentation the attention is primarily focussed on the physics of the process-related models, being sediment transport, bed form migration and hydraulic roughness which are strongly coupled through non-linear interactions. These processes are the key issues in the behaviour of alluvial rivers, especially during floods.
Field research so far has been mainly concerned with measuring bulk parameters like discharge of water and sediment, energy gradients and cross-sectional areas, which has resulted in a set of useful sediment transport formulae. The validity of these formulae for large-scale rivers and upper regimes is not yet clear. Furthermore, many details of the physical processes of bed-load and suspended load motion, bed form migration and associated hydraulic roughness in field conditions are still missing. Most of the available process-related knowledge has been obtained from laboratory studies in the ripple and dune regimes. It is not always clear whether the results of these studies are valid for large-scale rivers (scale effects). Field research is required to validate and extend the available process-related information.

Mathematical models representing the vertical distribution of flow velocity and sediment concentration offer the most promising description of sediment transport processes and can be extended to the upper regime and non-uniform conditions. Basic formulations will be discussed. Some examples related to local problems will be given.

Details of sediment transport processes over dunes will be discussed on the basis of mathematical model computations because it basically is a non-uniform flow and transport phenomenon. The dune-associated hydraulic roughness will be discussed based on result of laboratory studies. The shape of the dunes appears to be an important parameter with respect to hydraulic roughness. The transition from dunes to sand waves and associated roughness will also be discussed, which is of vital importance for river flood predictions. The sediment transport prediction in the upper regime with high sediment concentrations and its effect (hindered settling, turbulence damping) on the flow characteristics needs further attention; mathematical models can represent these types of processes. Some examples of measurements in Chinese rivers and laboratory flumes with fine sediment will be given.

Finally, suggestions for field, laboratory and modelling research in the future are proposed.

**GENERAL ASPECTS OF FIELD, LABORATORY AND MATHEMATICAL MODELLING RESEARCH**

One of the objectives of this paper is to show that the knowledge of alluvial river processes can be greatly improved by a proper combination of field, laboratory and mathematical modelling research. Each of these research methods has its own strong and weak points. Combining the strong points, an optimum research strategy is obtained.

Many interesting field studies have been performed in the period between 1950 and 1970, especially by the researchers of the Geological Survey of the USA. Using relatively simple sampling techniques, bulk parameters like surface slope, discharges of fluid and sediment, water depths and soil characteristics have been collected and analyzed. Many details of the physical processes involved are, however, still missing.
Since then, field research has declined considerably, because of the increase of cost related to more sophisticated survey facilities and instruments. Furthermore, long-duration surveys are required to increase the space and time resolution of the data; sampling techniques yielding synoptic data are still poorly developed. Complicating factors are the three-dimensionality and non-uniformity and the space- and time-dependent variability of the fluid and sediment characteristics. Many phenomena do occur simultaneously in nature preventing a systematic study of the parameters involved. Furthermore, the extreme forces of nature during flood events in combination with the limitations of the sampling instruments often frustrate the collection of adequate data sets and thereby the understanding of the processes involved.

To deal with these problems, the field researchers should have considerable experience of basic river behaviour understanding the details of the most relevant physical processes as well as the strong and weak points of the available high-tech instruments.

Laboratory research of river phenomena is a specialized field of research concerning large-scale movable bed facilities operated by experts, who understand fluid and sediment mechanics as well as the geomorphological behaviour of rivers in general.

Usually, the physical laboratory models are classified into:

- engineering or design models: model simulation to obtain an engineering solution (design of groynes, spurdikes, vanes, intakes, bend cut-off).
- process models: models used to study the detailed behaviour of physical processes (flow and sand transport over dunes and in river bends).

The major advantages of laboratory models are:

- availability of immediate qualitative information (pilot experiments)
- availability of validation data for mathematical models
- systematic study of processes in steady-state conditions; tests can be repeated; boundary and input data can be varied.

A basic element of the operation of physical models in the laboratory is the understanding of scale effects, the latter being the discrepancies between the behaviour of the morphological system in the model and in nature. Scale effects are primarily related to the incorrect representation of sediment mobility, transport rates and bed form behaviour. Discrepancies may also be related to space limitations of the model or to simplified boundary conditions of the model; these discrepancies are often called laboratory effects rather than scale effects.

The basic parameters of the solid phase to be represented, are: the grain Reynolds' number, the grain mobility number (Shields' parameter), the relative density, the relative depth and the suspension number. Ideally, all these parameters must be the same in nature and in the model. However, it is physically
impossible to satisfy all requirements. Hence, scale errors are inevitably introduced. Some parameters are more important than others; the grain mobility number and the suspension number should always be scaled correctly to obtain a correct description of both the bed-load and suspended load transport processes. Often, the sediment size cannot be scaled down sufficiently to obtain the correct suspended load transport. An associated problem is the scaling of the bed forms. The use of fine sediments in the model usually results in the generation of small-scale ripples, whereas large-scale sand dunes may be present in nature.

A possible alternative is the use of light weight materials (bakelite, polystyrene). Using these materials, the ratio of the bed-load and suspended may be somewhat better described, but the representation of the bed forms and associated roughness is far from correct.

Although the errors related to scale effects and laboratory effects of physical models are causing difficult interpretation problems, there are several areas in which the laboratory models continue to be valuable tools (large-scale normalization works in coarse-bed rivers). In most three-dimensional problems the laboratory models still are the only available tools (intake structures, scour near structures), despite the scale effects.

Mathematical models are often presented as an attractive alternative to physical laboratory models because the former are less expensive and devoid of scale effects. Operation of mathematical models, however, also requires experts who understand not only the strongly non-linear fluid and sediment dynamics but also the errors related to mathematical modelling which result from incomplete or simplified formulations, from schematization errors related to memory size and from inaccurate numerical solution methods.

For the present, therefore, it is unlikely that mathematical models will quickly replace the laboratory models. However, the rapid development of mathematical models related to the increased computer power has greatly enhanced the use of detailed process-related laboratory models to obtain verification and validation data.

**BED FORMS, HYDRAULIC ROUGHNESS AND SEDIMENT TRANSPORT DURING FLOODS**

The prediction of water levels during floods depends primarily on hydraulic roughness caused by the dimensions and shape of the bed forms such as ripples, dunes and sand waves. In turn, the dimensions of the bed forms are considered as a complex function of hydraulic and sediment parameters pertaining to sediment motion.

Various methods are available to predict the bed form dimensions in alluvial rivers. Some doubt has recently arisen regarding the applicability of these methods at high bed-shear stresses as expected during floods.
BED FORM DEVELOPMENT
It is a well-known phenomenon that the bed forms generated at low velocities are washed out at high velocities. It is not clear, however, whether the disappearance of the bed forms is accomplished by a decrease of the bed form height, by an increase of the bed form length or both.
Many attempts have been made to explain the transitional regime with washed out dunes by use of instability analysis. The basics and merits of this approach will be explained in a paper by Fredsøe (1995).

Laboratory
Flume experiments (Termes, 1986) with sediment material of about 450 μm show that the transition from the lower to the upper regime is effected by an increase of the bed form length and a simultaneous decrease of the bed form height, as shown in Figures 1 and 2. Ultimately, relatively long and smooth sand waves with a roughness equal to the grain roughness were generated (see Figure 2).

In the transition regime the sediment particles will be transported mainly in suspension \((u_*/w_s) \geq 5\), \(u_* = \text{bed-shear velocity and } w_s = \text{fall velocity}\). This will have a strong effect on the bed form shape. The bed forms will become more symmetrical with relatively gentle lee-side slopes. Flow separation will occur less frequently and the effective bed roughness will approach to that of a plane bed. Based on Van Rijn (1984, 1993), the transition regime will occur for \(T \geq 15\) with \(T = (\tau_b - \tau_{b,cr})/\tau_{b,cr}\). \(\tau_b\) = effective bed-shear stress and \(\tau_{b,cr}\) = critical bed-shear stress for initiation of motion according to Shields. Plane bed conditions (fully washed out dunes) during floods will occur for a \(T\)-value of about 25, which is approximately equal to a Shields' mobility parameter \((\Theta) = \tau_b / \left((\rho_s - \rho) g d_{50}\right)\) in the range of 0.8 to 1.0.

The laboratory results of Termes (1986) confirm the establishment of transition conditions for \(T\)-values larger than 15 (see Figures 1 and 2) but plane bed conditions are not fully established at \(T = 25\).

Van den Berg and Van Gelder (1993) studied the behaviour of bed forms of fine sand and silt during floods as present in the Yellow river in China. Experiments in a flume with a fine silt bed \((d_{50} = 33 \mu m, d_{90} = 52 \mu m)\) were carried out. A special run with a flow velocity of 0.75 m/s \((\Theta' = 1.5)\) was performed in order to observe the large number of succeeding cycles of depositional climbing ripples followed by erosional scouring. The sequence of bed morphologies resulting from the experiment is shown in Figure 3. Due to the high flow velocity, the ripple amplitude was low. Sometimes ripples were completely flattened and a transition to the upper plane bed phase occurred (Figure 3, 42 min. after start).
Erosion and sedimentation occurred separately in patches of a few metres length. Taking the technical limitations into account, a good resemblance was found between the scour-and-fill structures seen in the field and those produced under controlled conditions. Possibly the scour-and-fill cycles are related to local
differences in the hydraulic roughness and initial consolidation of the bed. In patches of accumulation the bed is relatively smooth and little turbulence is created so that the sediment transport remains slightly above the equilibrium capacity. In places with erosional scour holes much turbulence is produced. This stimulates erosion and a higher capacity of the flow to transport suspended sediment. Thus, small deviations in the overall equilibrium conditions lead to

Figure 1. Bed form development in a laboratory flume ($T = 9.3$ to $24.9$; $d_{50} = 450 \mu m$, maximum bed form height $= 0.15 \text{ m}$; water depth $= 0.3$ to $0.35 \text{ m}$; Termes, 1986)
Figure 2. Bed form dimensions and hydraulic roughness in the transition regime

Figure 3. Scour and fill cycles in subcritical upper regime (θ' = 1.5, Fr = 0.4); Van den Berg and Van Gelder (1993)
accumulation in rippled areas whereas at the same time erosion continues in patches with erosional scours. The presence of the depositional humps created by this process results in a local increase of the vertical flow velocity gradient or shear stress and a reduction of the deposition rate. Ultimately, erosional processes will start and, because of the initial consolidation, scours will be formed, which enhance further erosion. An opposite reasoning holds for the moment that erosional patches change into smooth areas of deposition.

Field
Field measurements of bed form dimensions in large rivers, such as the Rhine river branches in The Netherlands, the Mississippi river in the USA and the Jamuna river in Bangladesh show a different behaviour of the bed form development in the transition regime (Raslan, 1991 and Julien, 1992). The large river data (Raslan, 1991) show quite clear that the dune height does not vanish at $T = 25$ but rather remains relatively high at values of $T$ as high as 50, see Figure 4. The method of Van Rijn for predicting the bed form height largely underestimates the observed values.

![Figure 4](image)

It has been discussed and argued that the gradual disappearance of the bed forms in the transition regime is related to the suspension mechanism. The sediments accumulated in the bed forms are eroded layer after layer to go into suspension at large values of the $T$-parameter ($\geq 15$). The bed forms in large rivers do not seem to behave like this. One of the reasons for this deviating behaviour may be the composition of the bed material. In field conditions the composition of the bed material may vary considerably along the river, but also in lateral direction along the cross-section. This may have a damping effect on the erosion of the bed material particles. Most of the laboratory experiments are related to uniform
sediment materials. Some evidence for the influence of the sediment composition is given by Chiew (1991), who studied the influence of the geometric standard deviation of the bed material \( \sigma_g = d_{94}/d_{50} \) on the type of bed forms in the upper regime. For uniform sediment material the dunes were fully washed out at \( Fr = 0.8 \); for non-uniform sediments dune-type bed forms were present up to \( Fr = 1 \).

An important parameter, not discussed so far, which may be of influence in the behaviour of the bed forms during floods is the Froude number \( Fr = \frac{\bar{u}}{(gh)^{0.5}} \).

Analysis of field data shows that large bed forms can be observed in large rivers at values of \( T \) larger than 25 in combination with low Froude numbers (Julien, 1992). For laboratory data, \( T \) will be about 25 as the Froude number approaches unity. In large rivers, the flow remains subcritical as \( T \) approaches 25.

Based on all available empirical information, two subregimes seem to be present in the upper transport regime (van Rijn, 1993):

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<th>Subcritical upper regime</th>
<th>( T \geq 25 ) and ( Fr &lt; 0.8 )</th>
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In the subcritical upper regime as present in large rivers, rather large bed forms remain present for \( T \)-values up to 50, as observed in the Mississippi river. The shape of these bed forms are herein characterized as smooth symmetrical sand waves because their effect on hydraulic roughness is negligible, as will be shown later in this paper.

In the supercritical regime, the bed form types will be plane bed and/or antidunes.

**Mathematical modelling**

Mathematical models describing the detailed behaviour of large bed forms like dunes and sand waves are rather scarce.

Models describing the development and migration of sand dunes have been presented by Fredsøe (1980, 1982), Allen (1976) and by De Ruiter (see Termes, 1988).

A detailed theoretical analysis of dune development and migration based on the equations of kinematics and sediment continuity has been given by Fredsøe (1980, 1982). The migration velocity was expressed in terms of the dune height, and the maximum transport rate at the dune crest. The transport rate was expressed as a function of depth-averaged velocity and depth. Based on this, Fredsøe derived an expression of the equilibrium dune height as a function of the transport rate at the crest and gradients of the transport rate with depth and velocity. The dune shape remains constant (invariant). Graphs were presented to find the equilibrium dune height and length. For sediment sizes smaller than 1 mm, the dune height decreases for mobility parameters larger than 0.3 \( (\theta_{cre} > 0.3) \).
Figure 5. Definition sketch of dune migration model (De Ruiter, see Termes, 1988)

Figure 6. Computed and measured velocity profiles along sand dune (Van der Knaap et al, 1990)
Allen (1976) developed a stochastic model describing the creation and destruction of the dunes based on empirical information. After a dune has travelled a certain assigned distance it is destroyed and a new dune is created. At the moment of creation the dune dimensions correspond to the prevailing flow conditions assuming steady flow. During the lifetime of the dunes, the dune height can adjust to changes in the flow conditions, but the dune length remains constant.

The dune migration model of De Ruijter (see Termes, 1988) consists of three submodels for the flow velocities and associated bed-shear stresses, the sediment pick-up and deposition and the bed-level changes from the mass balance equation. A definition sketch is given in Figure 5. The most sophisticated model to describe the flow and turbulence field above sand dunes is the K-Epsilon model (Rodi, 1980). This latter model was used by Van der Knaap et al (1990), see Figure 6. De Ruijter used a simplified model based on depth-integrated variables to describe the flow field. The sediment pick-up along the dune face was modelled by a stochastic function based on the mean value and the standard deviation of the grain-related bed-shear stress.

HYDRAULIC ROUGHNESS

In an alluvial river the hydraulic roughness mainly consists of grain roughness related to skin friction forces and of form roughness related to the fluid pressure distribution along the bed forms.

Field

The fundamental problem of bed roughness prediction in an alluvial river is that the bed form characteristics and hence the bed roughness depend on the main flow variables (like depth, velocity) and sediment variables (like size, composition). These variables are, however, in turn strongly dependent on the bed configuration and its effective roughness.

The effective roughness is herein expressed by the Nikuradse roughness parameter $k_s$. This parameter for a given bed material size is not constant, but depends strongly on the flow conditions, as shown in Figure 7.

The $k_s$-values were derived from measured surface slopes, water depths and discharges using the Chézy-equation. As can be observed, the $k_s$-values strongly decrease for increasing velocities. For example, the $k_s$-value is about 1 mm (of the order of the grain size) at a velocity of 2.3 m/s, which is an indication of the disappearance of form roughness. As the data of Raslan (1991) show the presence of rather large bed forms at high velocities (Figure 4), it is most logic to assume that the effective form roughness is negligible small. This type of behaviour suggests the presence of smooth symmetrical sand waves which act as topography to the river flow. It seems that the asymmetrical sand dunes are transformed into symmetrical sand waves during flood conditions.
Effective bed roughness of Mississippi river (Van Rijn, 1993)

Laboratory
The effect of the shape of the sand dunes on the hydraulic roughness was studied in a laboratory flume of Delft Hydraulics (Kormman, 1994). Artificial dunes of plywood with four different shapes were used (see Figure 8). Sand with a median diameter of 250 μm was glued on the dunes in the measuring section. In these experiments the attention was focussed on the shape of the dunes in the crest region. The crest is defined as the highest point of the dune. The point of flow separation is defined as the brink point. For natural sand dunes, the dune surface between the crest and the brink point usually has a gentle downward slope, depending on the strength of the flow. In the upper regime the dune may become almost fully symmetric. Laser Doppler equipment was used to measure the flow and turbulence field above the dunes. Water surface slopes were measured at various discharges and water depths to determine the effective hydraulic roughness of the dunes.

Analysis of the measured velocity profiles shows that flow separation occurs downstream of the brink point for all dune shapes. The separation length ($L_s$), defined as the distance between the brink point and the reattachment point, was measured, yielding dimensionless values of $L_s/\Delta_h = 3.5$ to 5 with $\Delta_h$ = height of brink point above the rough level. The $k_s$-values derived from the Chézy-equation, are given in the following Table 1.
Table 1. $k_s$-values of artificial dunes

The $k_s$-value of dune shape 4 (triangular form) is approximately equal to half the dune height ($k_s = 0.5 \Delta_b$).
The other $k_s$-values are approx. 0.3 $\Delta_b$ for dune shape 3 and 0.15 $\Delta_b$ for dune shape 2. The form roughness of dune shape 1 is approximately zero, which is caused by the more rounded form of dune shape 1. Therefore, the form roughness related to rounded symmetrical sand waves can be neglected and the effective hydraulic roughness can be fully attributed to grain roughness.
Based on the analysis of flume data, Van Rijn (1984) proposed the following empirical expression to represent the effective form roughness of dunes:

$$ k_s = 1.1 \Delta \left[ 1 - e^{-2.5 \Delta / \lambda} \right] $$

(1)

in which: $\Delta = $ dune height, $\lambda = $ dune length. At that stage the influence of the dune shape was neglected. Application of Eq. (1) to field data resulted in a considerable overestimation of the hydraulic roughness. Analysis of the field data showed that the lee-side slopes of natural sand dunes in rivers were less steep than those of dunes in laboratory flumes (Ogink, 1988). This effect was taken into account by introducing a shape factor $\gamma$ as a multiplication to the right-hand side of Eq. (1). The $\gamma$-factors of natural dunes were found to be about 0.7.

The flume data of Table 1 (Kormman, 1994) have also been used to determine the $\gamma$-factors based on Eq. (1). Figure 9 shows the $\gamma$-factor as a function of the angle $\alpha_s$.

![Figure 9, Dune shape factor $\gamma$ (Kormman, 1994)](image)

**Mathematical modelling**

Computed values of the hydraulic roughness related to dunes can be obtained from a mathematical model describing the detailed flow velocity and turbulence field above dunes. The shear stress and fluid pressure computed along the bed can be integrated, yielding the overall mean bed-shear stress:

$$ \tau_b = \frac{1}{\lambda} \left[ \frac{1}{\lambda} \int_0^\lambda \tau_f \, dx + \int_0^\lambda p \, dx \right] $$

(2)
in which: $\tau_f = \text{skin friction stress}$ and $p = \text{fluid pressure at bed surface}$, $\lambda = \text{dune length}$.

The K-epsilon model offers the most promising results. Figure 10 shows an example of the skin friction stress along a dune computed by the K-epsilon model of Delft Hydraulics (Van der Knaap et al., 1990). A basic requirement for accurate modelling of the acceleration and deceleration phenomena along the dune is a refined schematization of the computational domain in the vertical plane. About 6000 grid points were used by Van der Knaap et al. (1990) to obtain good agreement between measured and computed results (Figure 10).

![Figure 10, Computed and measured skin friction stress (Van der Knaap et al., 1990)](image)

SEDIMENT TRANSPORT
To be able to estimate the sediment transport rates and morphological changes during floods, it is of extreme importance to have a reliable and accurate sediment transport predictor. Depth-averaged velocities during floods may be as large as 3 m/s and the question is which sediment transport formula can be used with confidence in such extreme conditions. Very few field data are available for verification of the available formulae.

Large-scale flume experiments at Delft Hydraulics have been performed to study the sediment transport processes at high velocities. A two-dimensional vertical mathematical model for suspended sediment transport was applied to analyse the results of the flume experiments and to compute the equilibrium transport rates (Voogt et al., 1992).

Laboratory
The objective of the experiments was to determine the equilibrium sediment transport rate at high velocities in the range of 1.5 to 2.5 m/s. To obtain realistic results comparable to those in nature, a water depth of about 1 m was taken assuming that scale errors would then be minimum. The experiments were carried out in a flume with a total length of about 100 m and a width of 1.55 m. Given these large dimensions, the establishment of equilibrium conditions by a sand feeding system was not feasible. For example, the Engelund-Hansen for-
mula predicts a transport rate of about 30,000 kg/hour for sediment material of 200 μm at a velocity of 2 m/s.

Therefore, another approach was followed, using a self-eroding flow without initial sediment load in the flume. The basic principle of this type of flow is shown in Figure 11. However, the flume was not long enough (length of test section = 60 m) to ensure full equilibrium transport at the end of the flume.

![Figure 11. Development of sediment transport in a self-eroding flow (Voogt et al., 1992)](image)

Therefore, sediment-concentration and flow-velocity profiles measured at various locations in the flume were used to calibrate a two-dimensional vertical mathematical suspended-sediment model. The calibrated model was then used to compute (by extrapolation) the equilibrium sediment transport. The bed material was sand ($d_{50} = 200 \mu m$, $d_{90} = 260 \mu m$).

Some results of test T6 are given: mean flow velocity = 2.3 to 2.5 m/s, water depth = 1 to 1.5 m, bed roughness $k_s = 0.001 m$. The measured sand concentrations were about 50,000 mg/l near the bed. The sand concentrations near the water surface varied from about zero in the beginning of the flume to about 300 mg/l at the end of the flume, showing the horizontal adjustment of the concentrations.

**Mathematical modelling**

Since the flume was too short to ensure full equilibrium conditions at the end of the flume, a two-dimensional vertical mathematical model for suspended-sediment transport was used to extrapolate the measured transport rates to equilibrium transport rates. The basic equation is the convection-diffusion equation for steady flow, written

$$\frac{\partial}{\partial x} (uc) + \frac{\partial}{\partial z} [(w - w_s)c] - \frac{\partial}{\partial z} \left( \epsilon_s \frac{\partial c}{\partial z} \right) = 0$$

(3)
in which \( c \) = local sediment concentration; \( u \) = local horizontal flow velocity; \( w \) = local vertical flow velocity; \( w_p \) = particle fall velocity; \( \epsilon_x \) = sediment mixing coefficient; \( x \) = horizontal coordinate; \( z \) = vertical coordinate.

The horizontal flow velocities \( u \) are described by logarithmic profiles. The vertical velocity \( w \) is computed from the fluid-continuity equation. The sediment mixing coefficient \( \epsilon_x \) is described by a parabolic distribution in the lower half of the depth and a constant value in the upper half of the depth. The boundary conditions are a zero concentration profile at the beginning of the sand bed and a zero vertical transport at the water surface. At the boundary of the bed the equilibrium bed concentration \( c_{de} \) is specified as a function of local flow and sediment parameters.

The model was calibrated by adjusting the coefficient of the bed boundary condition equation in order to obtain a depth-integrated transport rate in the last measurement section (section 90) equal to the measured transport rate in that section. After calibration, the model was used to compute the equilibrium transport rate, which was assumed to be reached at coordinate \( x/h_0 = 200 \) (see Figure 12). The procedure is illustrated in Figure 12, which shows measured and computed transport rates for test T6. The input data are based on measured parameters (see Figure 12).

Figure 12. Computed and measured sediment transport along flume (Voogt et al., 1992)
The computed equilibrium sediment transport rate for test T6 is about 25 kg/s/m, which is about 1.5q_{t,90}; q_{t,90} measured transport rate in section 90. Similar calibration runs have been made for the other experiments. All runs show that the longitudinal adjustment of the suspended sediment transport in eroding flows with velocities up to 2.5 m/s can be simulated quite well by a mathematical model based on the convection-diffusion equation. The computed equilibrium transport rates for all tests are shown in Figure 13. Data of some other experiments are also shown, as well as the results of three transport formulae. All three formulae yield reasonable results up to velocities of 3 m/s. Basic phenomena such as hindered settling and damping of turbulence (reduction of mixing) were, however, not taken into account. These processes should be studied in more detail.

![Figure 13. Equilibrium sand transport rates as a function of depth-averaged velocity (Voogt et al., 1992)](image)

When large bed forms are present, the computation of the suspended sediment transport is much more complicated, because the flow over the bed forms basically is non-uniform. The bed-load particles are transported close to the bed by rolling, sliding and saltating at the upsloping parts of the dunes. Arriving at the top of the dune, the majority of the bed-load particles jumps over the edge and rolls down the leeside slope of the dune towards the dune trough where they are buried waiting for a new (transport) cycle.
The suspended load particles are entrained from the bed-load layer developing at the up-sloping part of the dune. The entrainment rate is maximum at the dune top (large velocities). Above the dune trough the suspended particles are transported further upwards by turbulence mixing produced in the shear layers of the vortex generated in the dune trough.

The variability of the bed-load transport and suspended sediment concentrations along dunes in the lower regime of the Nile river was studied by Gaweesh and Van Rijn (1994) and by Gaweesh (1994). Figure 14 presents sediment concentration profiles along a dune in the Nile river. The near-bed concentrations show rather large variations.

![Figure 14. Suspended sediment concentrations along dune in Nile river, station 1, cross-section El-Korimat, Beni Sweif, (Gaweesh, 1994)](image)

A detailed mathematical representation of the afore-mentioned processes requires the application of a sophisticated hydrodynamic model and a higher order turbulence model such as the K-epsilon model (Rodi, 1980) in combination with a convection-diffusion model for the suspended sediment particles. The horizontal grid size should be much smaller than the dune length ($\Delta x < \lambda$); the reference level should be applied at the upper edge of the bed-load layer ($a < \Delta$). To get a first understanding of the phenomena involved, a relatively simple two-dimensional vertical suspended sediment model was used by Van Rijn (1993) to compute the concentration profiles for the flow over dunes.

Figure 15 shows computed concentration profiles at the dune top and at the dune trough representing two extreme profiles; all other profiles are within the indicated variation range. As can be observed, the near-bed concentrations can vary over a range of nearly a factor 10. In vertical direction the concentration variation is confined to a near-bed region of about 0.3 h ($h = \text{depth}$). The concentrations in the upper layers are not noticeably affected.

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Generally, the application of mathematical models for river problems requires a schematization on a macro-scale (limited computer facilities) applying a horizontal grid size much larger than the bed-form length. Consequently, a detailed representation of the concentration profiles and also the velocity profiles is not feasible. The effect of the dunes on the flow field, usually, is represented by introducing an effective roughness parameters \( (k_u) \), as shown in Figure 15. In that case a schematized concentration profile being an estimate of the spatially-averaged concentration profiles, is proposed to represent the suspended sediments.

**FUTURE RESEARCH**

Future research related to bed form development and migration, hydraulic roughness and sediment transport during floods should be focussed on:

**Field**

- Shape and dimensions of the large-scale bed forms (dunes, sand waves) in relation to flow velocity field, water surface slope and bed material composition (including variations along cross-section);
• Near-bed sediment concentrations and velocities along the surface of the bed forms (development of measuring equipment for high velocities; measuring procedures);
• Bed-load transport along the surface of the bed forms (measuring procedures).

Laboratory
• Effect of flow velocity and bed material composition on the crest shape of the bed forms (movable bed tests);
• Effect of bed material composition on the disappearance of bed forms (movable bed tests);
• Effect of high sediment concentrations on turbulence characteristics (damping of mixing effect);
• Measuring procedure for suspended sediment transport along bed forms (number of stations along bed forms in relation to variability of the processes).

Mathematical modelling
• Computation of flow velocity and turbulence field, bed-shear stress distribution and fluid pressure distribution along the surface of the bed forms using advanced models (K-epsilon models);
• Development and migration of bed forms including non-uniform bed materials (dimensions of bed forms and adjustment in non-steady flow);
• Development of near-bed concentrations and suspended sediment transport along bed forms (including hindered settling and turbulence damping).

Detailed field research should have a high priority in future research programmes.

REFERENCES