CHAPTER 109

TIME-LAG OF DUNES FOR UNSTEADY FLOW CONDITIONS

by

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1. Introduction

Many publications based on theoretical considerations or model tests, give utterance to the demand that there should be unequivocal relations between hydraulic conditions and bed form characteristics which should be generally applicable. These relationships determined for steady conditions and limited water depths should be handled with care when being applied to natural rivers. The bed configurations do not immediately fit themselves to the varying flow conditions. The bed forms need a certain reconstruction time in case of a changing discharge. The time-lag of dunes was observed on numerous rivers, in the past. A general review of investigations made in this field is given by ALLEN (1976 b).

In the following contribution, an attempt is made to describe the magnitude of the time lag of bed forms for unsteady flow conditions.

2. Bed forms and flow conditions

The formation and migration of the different bed forms which may occur, were investigated in many basic theoretical studies and laboratory tests for stationary conditions and restricted water depths. The terms for different bed configurations are explained by the graph in Fig. 1 (ENGELUND and HANSEN, 1967). For the relation between bed shear stress and flow velocity it shows the bed forms which occur for an increasing velocity of flow.

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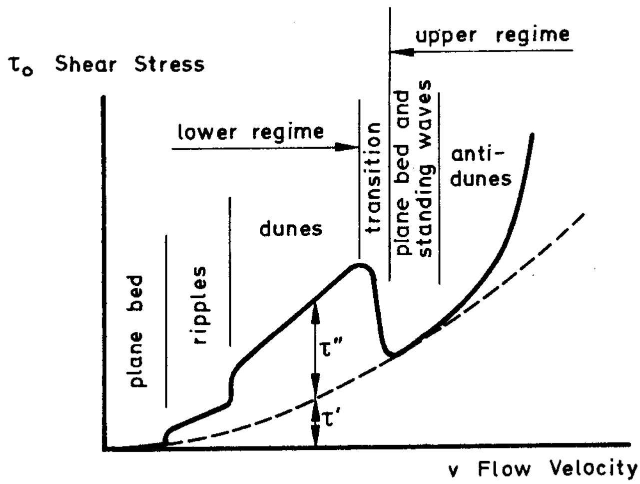

Fig. 1 Bed Shear Stress, Flow Velocity and Bed Forms

(ENGELUND and HANSEN, 1967)

In the lower regime, with streaming flow, ripples or dunes are formed when a certain velocity is exceeded. For a further increase of the flow velocity in the transition zone, the dunes are drawn out.

In the upper regime, standing waves or antidunes may be observed which move against the direction of flow. The upper regime is apparent for Froude numbers Fr $>$ 1 (shooting flow).

Deep water rivers and tidal channels are characterized by low Froude numbers. Following the preceding example, large dunes should be formed with increasing flow velocities.

For unsteady conditions, the maximum dune dimensions should appear with a time-lag, after the maximum flow.

3. Change of bed forms with tidal motion

3.1. Shifting during the tide

From model tests with tidal currents it is known, that the shape of the current ripples adapts itself to the prevailing flood - or ebb-current direction - within a short time (DILLO, 1960).

TERWINDT analyzed on 923 dune fields in tidal channels of the Netherlands (1970) up to what height the tidal dunes change their general shape with the alternating currents.

These observations led to the following result: "The asymmetry of the ripples (H = 30 - 100 cm) may change with the turn of the tidal currents, but this is not always the case. The asymmetry of the ripples (H = 100 - 200 cm) most times does not change with the turn of the tides." From this result it may be concluded that the adaption time or time-lag of the smaller forms is less than one flood - or ebb current phase - which are shorter than 6 hours as the tides at the North Sea coast are semidiurnal. The general shape of the larger dunes (H > 1 m) is not affected by tidal motion, that means the time-lag exceeds 6 hours. There are only local redistributions in the crest area due to the tidal currents (NASNER, 1974 a).

3.2. Fresh-water flow and dune height

In the upper part of a tidal river, the mean current velocities are influenced by the fresh-water discharge. Analyses of many years on four significant dune fields in the navigation channel of the River Weser between Bremen und Bremerhaven (Fig. 2), proved that the height and migration of the ebb predominant sand waves are influenced significantly by the long-term change of the mean ebb-current velocities as a consequence of the change of the fresh-water discharge Q_o (NASNER, 1974 a, 1974 b). The characteristics of the bed forms are not influenced by the tidal motion. The mean wave length is in the order of 50 m, the mean height reaches values of more than 2,5 m in mean water depths of about 10 m. The semidiurnal tides are quite regular with a tidal range of approximately 3,5 m.

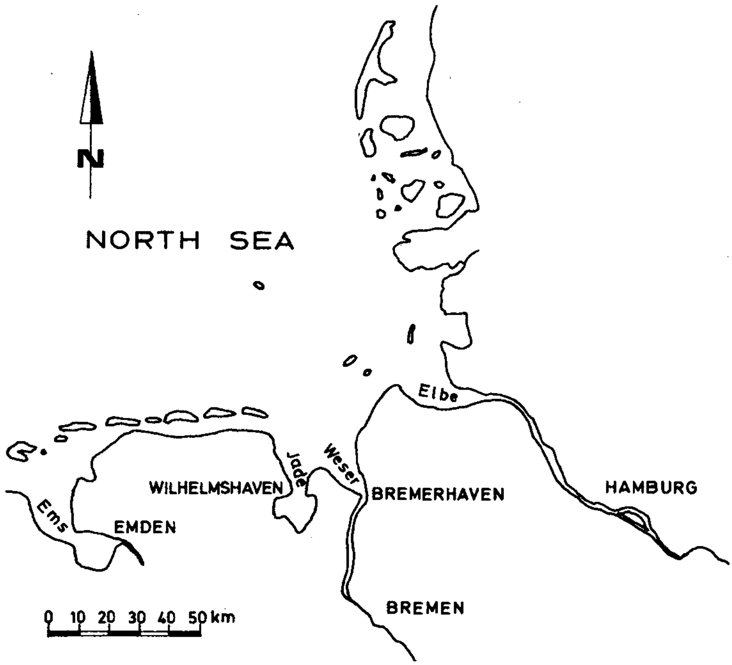

Fig. 2 German North Sea Coast

4. Phase diagrams

4.1. Preliminary remark

A possibility to determine the time-lag between the change of the flow parameters and the adaption of bed form characteristics is given by phase diagrams (ALLEN, 1973; 1976 a; 1976 b; JACKSON II 1976). This can be done by plotting, for example dune height against fresh-water discharge, where both parameters are also functions of the time. Such graphs are loops which ideally are closed, whereas the time may run clockwise or anticlockwise.

4.2. Dune height discharge diagram for the River Weser

By way of example the mean dune height $\bar{H}$ (about 40 dunes are analysed) was plotted as a function of the fresh-water discharge in a phase diagram for the River Weser, from September, 1966 till October, 1967 (Fig. 3). The time-lag between maximum discharge and maximum dune height is extremely large for the River Weser with values up to 7 - 9 months (ALLEN, 1976 b). However, this result is not relevant to the behaviour of dune characteristics and discharge, as the following explanations will show.

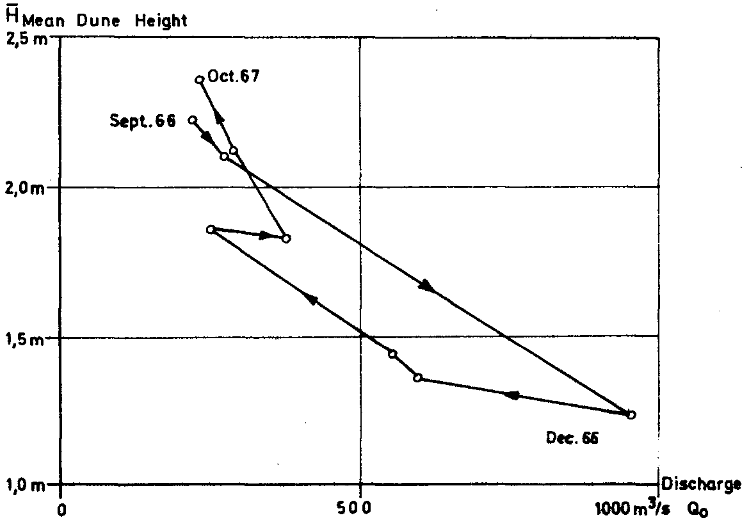

Fig. 3 Mean Dune-Height Discharge Curve for River Weser

According to the preceding description of possible bed forms (Fig. 1), the river bottom of the Weser is far-off the transition zone, as the Froude number compares with Fr = 0,1. For the water depth of approximately 10 m the Froude number obviously is no longer the determinative factor. The dune height H is governed by the mean ebb-current velocity over the dune crest. A state of equilibrium is given, when the flow velocity over the crest reaches a limiting value, which is a function of the sediment characteristics. For the dunes in the River Weser, the limiting velocity is about 1,0 m/sec (NASNER, 1974 a; 1974 b).

The conditions for the River Weser are represented ideally in Fig. 4. Due to the unsteady situation, there are no unique relationships between dune height and fresh-water flow. One value of discharge ($Q_{a'b}$) corresponds to two values of dune height (H_a; H_b) and inversely.

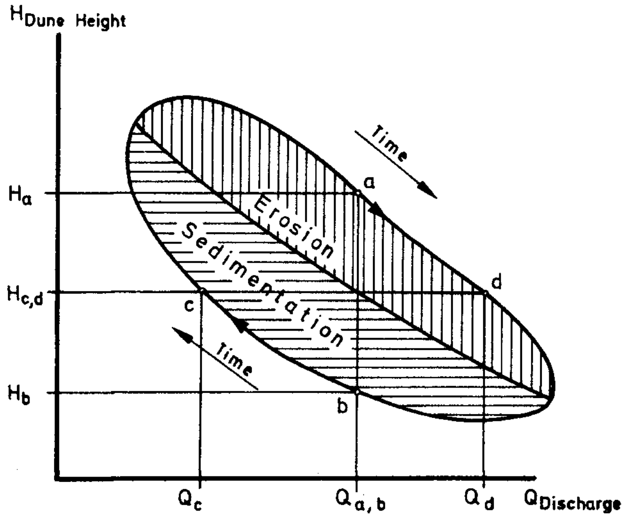

Fig. 4 Schematic Dune-Height Discharge Curve for River Weser

With increasing fresh-water discharge, the limiting ebb-current velocity is exceeded and erosion is caused. The dunes are higher than they should be (lag of erosion). With decreasing discharge, dunes are smaller than they should be (lag of sedimentation). It is mentioned elsewhere that a state of equilibrium is reached in the River Weser, when there is a quasi steady fresh-water discharge for about 30 days.

As a result, the tidal dunes of the River Weser are to be assigned to the transition zone in Fig. 1. This may be seen from the shape and time sequence of the diagram in Fig. 4. The smaller dunes thus are related to the higher discharge. The assumption that higher bed forms are built up with a higher discharge, is refuted by the preceding descriptions.

The adapting of the dunes to the fresh-water discharge in the River Weser ist clearly given in the time-series in Fig. 5. For the hydrological years 1966 to 1972, the daily fresh-water discharges Q_o of the River Weser are compared with the mean dune heights $\bar{H}$. The example shows the continuous creation-destruction process to which the bed forms are subjected.

The model tests carried out by Simons and Richardson (1960) are quite interesting in this connection. Fig. 6 shows the flow velocities, water depths and different bed forms as functions of the Froude number. Even for water depths of only 0,3 m the beginning of transition was measured for a flow velocity of about 1,0 m/sec. Similar results were found by model tests in a circuit flume with water depths of approximately 1 m and sand from the River Weser (ZANKE, 1976). As the prototype investigations have shown, the limiting value for the flow velocity may be extrapolated to greater water depths.

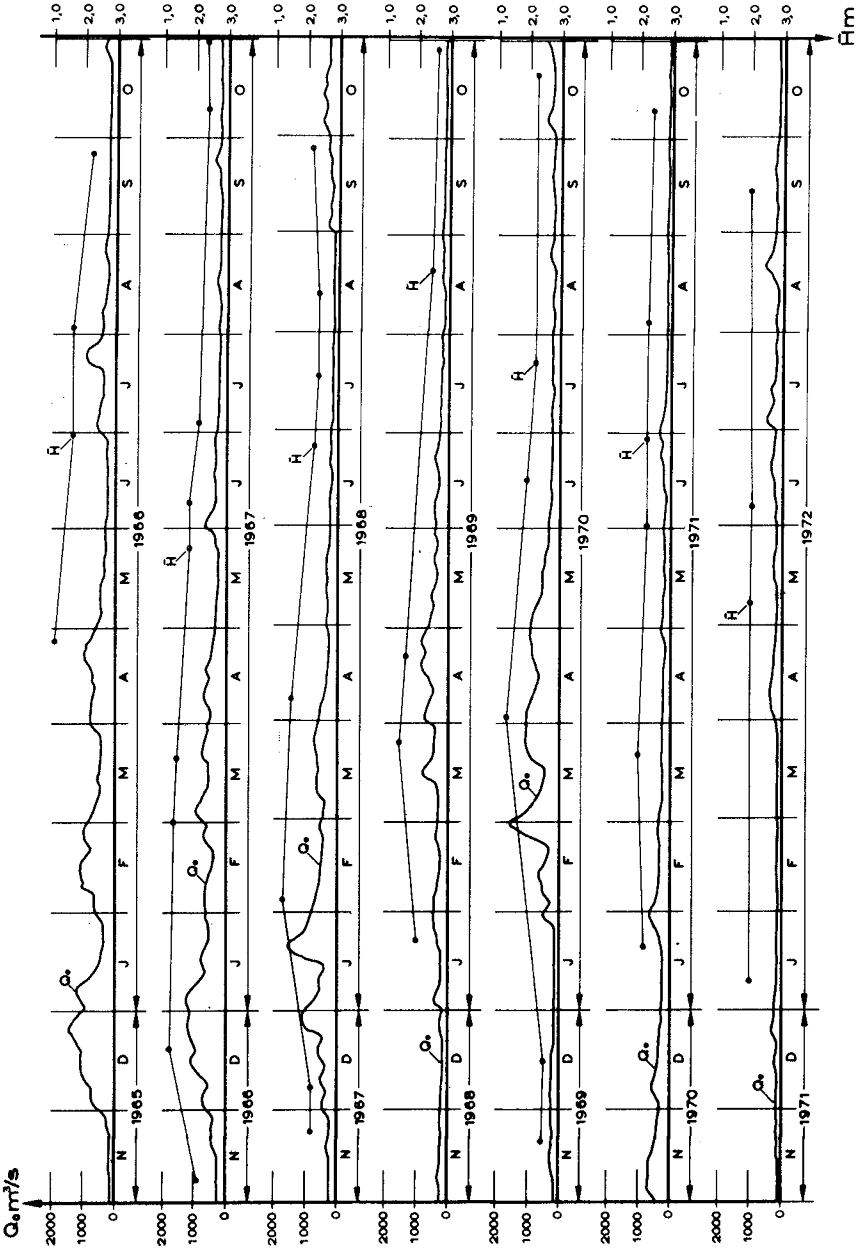

Fig. 5 Progress Line of Discharge Q_O and Mean Dune Height $\bar{H}$ for River Weser

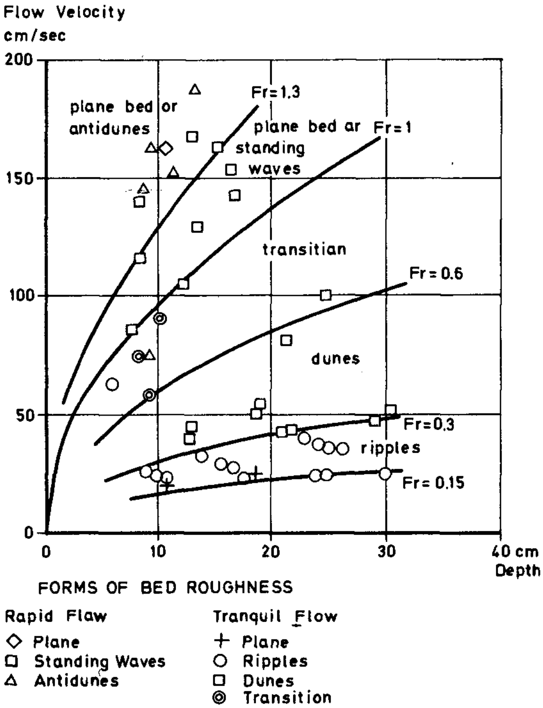

Fig. 6 Flow Velocity, Water Depth and Bed Form (SIMONS and RICHARDSON, 1960)

5. Comparison with other rivers

The results found for the River Weser, can be generalized as they also apply to other rivers, where with raising water levels due to the increasing flow velocities, there occur smaller dunes (phase of erosion) than with falling water levels (phase of sedimentation). Examples are given for rivers without tidal motion by the investigations of NEDECO (1959) on the River Niger and of STÜCKRATH (1969) on the Rio Paraná (Fig. 7 and 8).

In a 40 km river stretch of the River Niger, soundings were performed by NEDECO. In Fig. 7 the frequencies of dune heights at low water and at high water are plotted. The dunes are smaller at the raising stage (A) than at the falling stage (B).

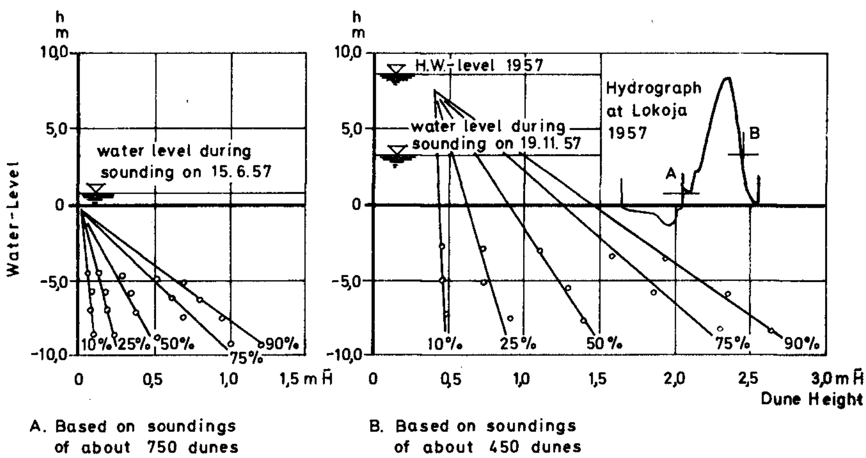

Fig. 7 Dune Heights on the Niger at Low Water and at High Water (NEDECO, 1959)

STÜCKRATH analyzed soundings on the Rio Paraná from May, 1967 up to December, 1968 (Fig. 8). The time progress is indicated by the arrows in Fig. 8. In general, there is a decrease in dune height with an increase of the water level and flow velocities. The Froude number is smaller than Fr = 0,1. The range of the mean flow velocities, which is between 0,9 and 1,1 m/sec comparable with those in the River Weser, is of special interest. It can be stated from Fig. 8 that the dunes on the bottom of the Rio Paraná are in transition.

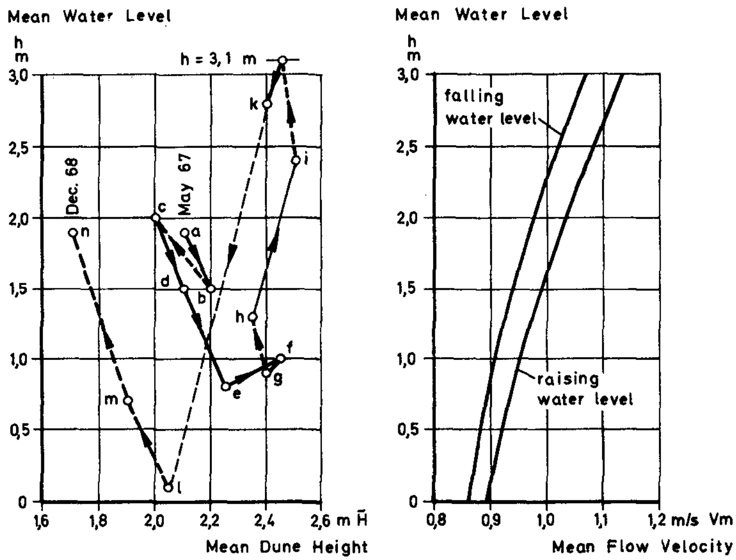

Fig. 8 Mean Dune Height, Flow Velocity and Water Levels in the Rio Paraná (STÜCKRATH, 1969)

Mean water level and dune height

In Fig. 9, besides the progress line of the daily fresh-water discharge and the measured dune heights, the monthly mean tide levels are plotted. Again the continuous adaption of the dunes to the changeable discharges is shown as well as the fact that the time-lag is a short-term event.

A remarkable result is the circumstance that the fixed boundary (dune height) reacts to changed flow conditions in a more sensitive way than the free surface. The fluctuation of the mean tide is significantly smaller than the variation of the dune heigt. The height variation is caused mainly by erosion and sedimentation in the crest area with a nearly constant through level (NASNER, 1976 a). The significant parameter is the flow velocity to which the river bottom adjusts itself. It is of interest, in this connection, that in many formulas on sediment transport, the bed-form contribution is considered by an additional friction factor.

The stability of a dune-covered bed against discharging is subject to the transport mechanism of the bed forms, by which the bed load is considerably reduced in comparison with a flat bed (FÜHRBÖTER, 1967). Investigations in the prototype have proved that the sand transport in a dune field is effected essentially through a local redistribution of the bed material corresponding to about the migration velocity of the dunes (NASNER, 1976 b).

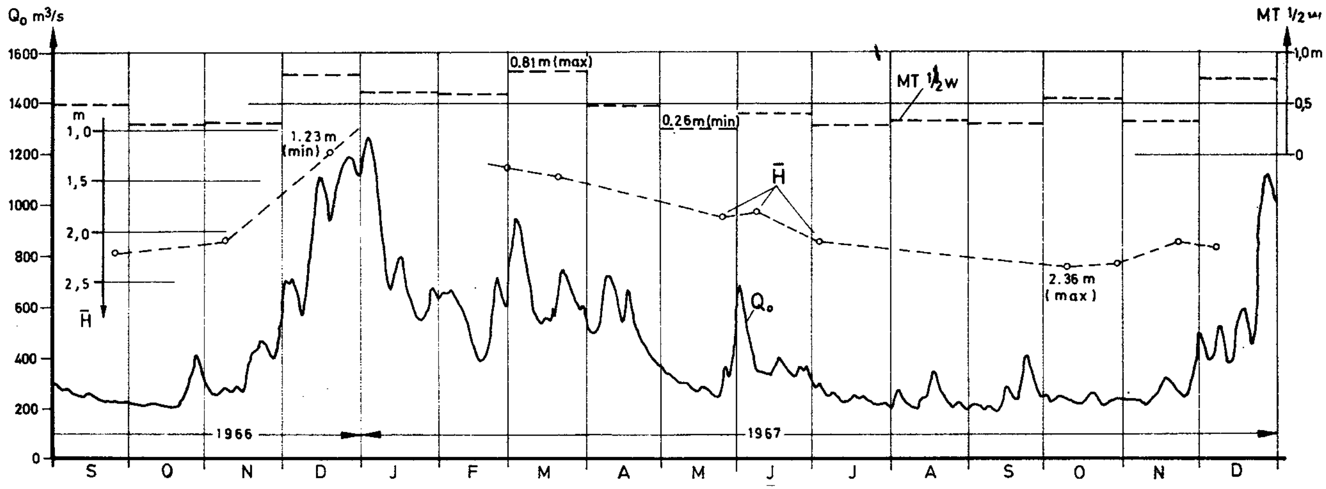

Fig. 9 Progress Line of Discharge Q_o, Mean Dune Height $\bar{H}$ and Mean Tide Level $MT\frac{1}{2}w$ for River Weser (1966-1967)

7. Concluding remarks

In this paper, the time-dependent behaviour of dunes as a function of the governing hydraulic conditions have been described. The results can be summarized as follows:

- It has been proved that it is difficult to apply the results from experiments on models, to natural rivers. A clear-cut relationship between bed form properties and flow conditions may be given for steady circumstances. In nature where unsteady flows prevail, the bed configuration adjusts itself to the changing hydraulic conditions with a time-lag. However, also for significant dunes in deep-water rivers, this is a short-term process.

- The knowledge gathered from laboratory tests, according to which for low Froude numbers and increasing velocities, higher dunes will be established, obviously applies to limited water depths only. The governing parameter for rivers of greater depths is the flow velocity which determines the limiting dune height - depending on the sediment characteristics. In spite of the low Froude numbers, the river bottom may be situated in the transition zone. The dunes become smaller by erosion, for increasing discharges and flow velocities. In case of falling water levels and lower current velocities, the bed forms may be enlarged again by sedimentation.

- The investigations revealed that the river bottom shows a very sensitive reaction to changed discharge and flow conditions. The variations of the dune height are of a remarkably greater order of magnitude than the fluctuations of the mean water level. On principle, the dunes cause a stabilization of the bottom so that the sediment removal is reduced. Compared with a flat bed, the sand transport is considerably reduced by the merely local redistribution of the bed material. In this respect, the dune height is of minor significance, as the height as well as the migration velocity of the bed forms is governed by the mean velocity of the flow and not inversely.

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