

# On the modelling of biological effects on morphology in estuaries and seas

M.A.F. Knaapen \*, H. Holzhauser, S.J.M.H. Hulscher

University of Twente

M.J. Baptist, M.B. de Vries

WL|Delft Hydraulics

M. van Ledden

Delft University of Technology

## Abstract

Morphological modelling aims to explain and predict the changes in rivers, seas and estuaries due to these interaction. In recent history, a lot of progress has been made, especially with stability analysis approaches. However, so far only the physical interactions have been taken into account. It is known however, that biological factors are important to the dynamics of the water systems. In this paper a first step is made in the inclusion of biology into the morphodynamic models. This inclusion is based on the effect that benthic organisms have on the erodibility of the bed. This can easily be included by a change of the critical bed shear stress. These changes in the critical bed shear stress then influence the morphology. This idea has been applied to two cases. The results of the first case indicate that this approach can reproduce the influence of benthic organisms on the mud content of the bed in estuaries. The second case shows that even low numbers of organisms can influence the characteristics of large bed forms.

## 1 Introduction

The aim of geomorphology in aquatic systems is to understand the changes of the planform and bed forms as a result of the interactions between the erodible bed and banks and the water flowing over it. These morphodynamic changes are difficult to model due to the nonlinearity of the processes and positive feedback within the system De Vriend (2001).

Biogeomorphology is the interaction between biology and morphology. Biological activity affects the sediment structure and the sediment dynamics and may influence the hydrodynamics. Well known is the effect of sea grass on flow velocities and waves. The energy in the water is reduced enormously, resulting in a very stable bed. Less known is the effect that organisms have on the bed, especially in areas that are inundated for long periods. In this paper we will focus on the effect of benthic organisms in such areas on the stability of the bed. The term 'benthos' refers to all organisms living on, in, or near the bottom of water bodies. One distinguishes

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\*Water Engineering & Management, Fac. of Engineering Technology, University of Twente. P.O.Box 217, 7500 AE Enschede, The Netherlands. E-mail: M.A.F.Knaapen@utwente.nl. Fax: +31-534895377

phytobenthos, i.e. the primary producers like algae, and zoobenthos i.e. all consumers, like clams and worms.

All benthic organisms affect their environment to some degree. Lee and Swartz (1980) explain that these effects can be divided in four. Biosuspension is the suspension of sediment due to movement of fauna. The second effect is biodeposition, the filtering of small particles out of the water column by worms or clams for example. Bioturbation is the effect that zoobenthos redistributes the sediment within the bed. This may be caused burrowing or by sediment filtering by worms and results in a less consolidated water bottom. Finally, biostabilisation is the effect that the bed is stabilised by benthos, for example by the binding effects of roots, cover by mussel beds or due to the sticky effect of algae mucus.

In this paper we will focus on the opposing effects of bioturbation and biostabilisation. Benthic diatoms excrete EPS mucus, which is a sticky substance, made of polysaccharides that glues the sediment together and therefore protects the sediment against erosion. It has been observed that biopolymers formed by microphytobenthos (diatoms) increase the sediment stability and increase erosion thresholds (Widdows, 2000b), especially when these diatoms form extensive mats. Bioturbation by zoobenthos has two components (see figure 1 for a visualisation). Due

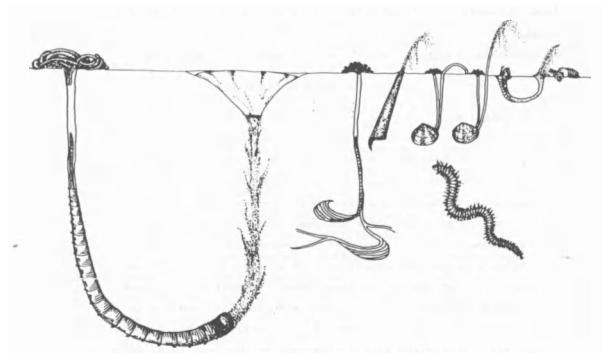


Figure 1: Bioturbation due to burrowing and deposit feeding visualised.

to burrowing, the sediment is moved around in the top layer of the bed. Consequently, the top layer is less compact as without burrowing. More important is the effect of the deposit feeding. Some feed from the top and dispose in the deeper parts, others eat from the deep bed and deposit at the surface. After removal of the organic matter, the sediment is then deposited lower in the sediment column. Consequently, the top layer is well mixed continuously. One of these deposit feeders is the *Macoma balthica*, a bivalve that is found abundantly in the estuaries of Northern Europe.

In the past quite some research has been done on this subject (Eckman et al., 1981; Widdows et al., 2000; Herman et al., 2001). However, most research has focussed on the effect of biotic factors on the short term sediment transport. Due to the complexity of the morphodynamics described by De Vriend (2001), these are difficult to extrapolate to long-term morphological changes. Here we discuss the possibility to introduce the biological effects directly into the longterm morphodynamic models that model the bathymetry of water system (Hulscher, 1996; Schuttelaars and De Swart, 1999; Calvete et al., 2001), the changes in bed composition Van Ledden (2002) or even the combination of both (Van Ledden and Wang, 2001). In these morphodynamic models, the flow dynamics and the bed changes are coupled and analysed using stability analyses.

In the next section, the concept of the coupling of biology with the morphodynamic models is explained. After that, this concept is tested for two example cases. In section 3 the effect on the

bed compositions in the Western Scheldt estuary is evaluated and in section 4 the possible effects on the bathymetry of large bed waves. We will end with some conclusions and a discussion in section 5

## 2 Concept

In this paper we present a simple concept to include biological effects in morphodynamic modelling. This concept is based on the knowledge that benthic organisms influence the erodibility of the seabed.

Both bioturbation and biostabilisation can be introduced in the morphodynamic models as a change in the critical bed shear stress (Figure 2). Bioturbation will reduce the critical bed shear stress, while biostabilisation increases the critical bed shear stress. This can be modelled using the following equation:

$$\tau_c = \tau_c^0 \cdot f_p(C_m) \cdot f_s(C_p) \quad (1)$$

in which  $\tau_c^0$  and  $\tau_c$  are the critical bed shear stress without and with biological influence. The stabilisation function  $f_s$  will increase with an increase in the concentration of phytobenthos  $C_p$ , resulting in an higher critical bed shear stress. The perturbation function  $f_p$  will decrease with an increase in the concentration of *Macoma balthica*  $C_m$ , resulting in a lower critical bed shear stress.

If this critical bed shear stress with biological influence is included in the morphodynamic model, a high concentration of algae will result in a stable bed, whereas a high number of bivalves will result in a more unstable bed. Due to the changing stability or erodibility, the morphology is influenced. Using stability models the effects on bed topography and bed composition can be analysed, which will be done in section 3 and section 4, respectively.

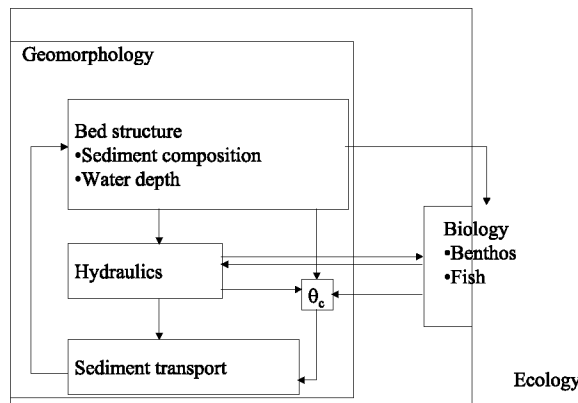


Figure 2: Flow chart of the biogeomorphological approach. Note the double feedback loop. In this paper we focus on the effects related to the critical bed shear stress  $\theta_c$  only.

## 3 Case 1: Western Scheldt

The approach proposed in section 2 is applied on the opposing effects of biuperturbation by the bivalves (*Macoma balthica*, see figure 3) and biostabilisation by phytobenthos on the Molen-



Figure 3: The bivalve *Macoma balthica*. Courtesy Dr W.J. Langston, Marine Biological Association of the UK. The bivalve is about 2 cm in diameter.

plaat. On this shoal in the Western Scheldt, extensive measurements are taken on the bed composition as well as the present benthic organisms Thoolen et al. (1997); Herman et al. (2001).

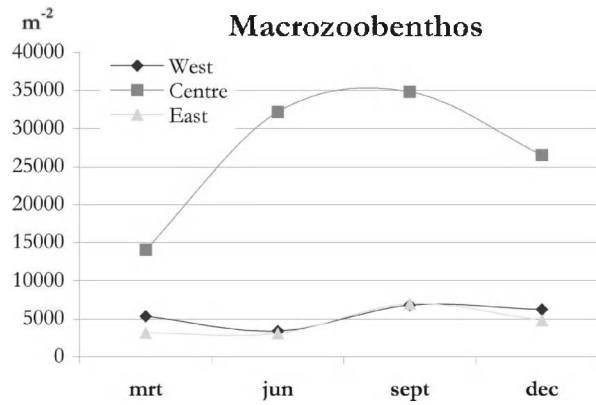


Figure 4: The seasonal variation of the density of macrozoobenthos on the Molenplaat in 1995.

Figures 4, 5, 6 show the seasonal variations in Macro-zoobenthos, mainly consisting of *Macoma balthica*, Chlorophyll a as an indication for phyto-benthos and silt, respectively. From these figures, one can see that there is a correlation between the benthic organisms and the silt percentages. The preference of the zoobenthos for high silt concentrations shows itself in the high density on the centre of the shoal. However, the silt percentage within each of the areas shows correlation with the benthic organisms as well. These variations cannot be explained by physical effects alone. Here we will try to explain some elements in the observation by the biogeomorphological interaction.

According to Van Ledden (2002), the bed composition in estuaries can be modelled using the concentration laws for the water column:

$$\frac{\partial hc_s}{\partial t} = E_s - D_s \quad (2)$$

$$\frac{\partial hc_m}{\partial t} = E_m - D_m + k_m (c_{out} - c_m) \quad (3)$$

in which  $h$  is the water depth, and  $c_s, D_s$  and  $E_s$  are the sediment concentration, deposition volume and erosion volume of grain fraction  $s$ , respectively. Subscript  $m$  denotes the mud fractions, that has slightly different behaviour, that includes the transport of the concentration difference of the column and the neighbourhood ( $c_m - c_{out}$ ), with transport coefficient  $k_m$ . In non-cohesive conditions, the exchange between the column and the bed is given by:

$$E_s - D_s = \gamma w_s (c_{e,s} - c_s) \quad (4)$$

$$E_m - D_m = p_{m,0} M \left[ \frac{\tau_b}{\tau_c} - 1 \right] H \left( \frac{\tau_b}{\tau_c} - 1 \right) - w_m c_m \left[ \frac{\tau_b}{\tau_d} - 1 \right] H \left( \frac{\tau_b}{\tau_d} - 1 \right) \quad (5)$$

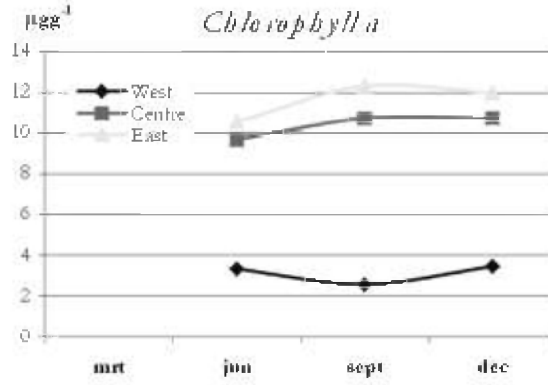


Figure 5: The seasonal variation of the concentration of chlorophyll a, as an indicator of phyto-benthos on the Molenplaat in 1995.

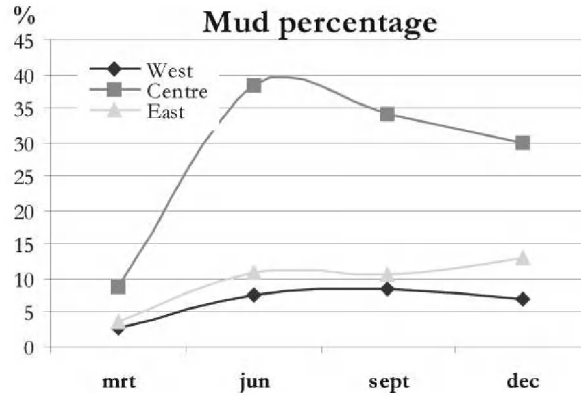


Figure 6: The seasonal variation of the silt percentage in the bed composition of the Molenplaat in 1995.

in which  $\gamma$  accounts for the vertical velocity and concentration profile,  $w_s$  and  $w_m$  are the settling velocities of sand and mud, respectively, and  $c_{e,s}$  is the depth-averaged equilibrium concentration of sand according to Engelund-Hansen. Furthermore,  $p_{m,0}$  is the mud content in the exchange layer,  $M$  is the erosion rate,  $\tau_b$  is the shear stress and  $\tau_c$  its critical value, and  $\tau_d$  the critical deposition shear stress. In cohesive conditions, the exchange of sand between the column and the bed changes to:

$$E_s - D_s = p_{s,0} M \left[ \frac{\tau_b}{\tau_{c,c}} - 1 \right] H \left( \left[ \frac{\tau_b}{\tau_{c,c}} - 1 \right] \right) - w_s c_s \quad (6)$$

In which  $\tau_{c,c}$  is the critical bed shear stress for erosion of cohesive sediment, with  $\tau_{c,c} > \tau_c$ . Parameter  $p_{s,0}$  is the sediment content, with grain size  $s$  within the exchange layer of the bed.

Following section 2, the biological effects are included into this sand-mud model as variation of the critical bed shear stress following equation 1. The stabilisation effect  $f_s$  is derived from the biostabilisation relation of Widdows et al. (2000):

$$\tau_c(C) = 0.2 + 0.014C \quad (7)$$

in which  $C$  is the chlorophyll a concentration within the sediment. This relation gives a correlation factor  $R^2 \approx 0.60$  with field measurements.

The perturbation effect  $f_p$  is derived from the relation between bed stability and the density of *Macoma balthica* in the Humber estuary reported by Widdows et al. (2000). However, in this relation the effect of algae is still included in part of the data. Assuming that with higher densities of the *Macoma balthica* (over 500 organisms per square metre), the biostabilisation effect can be neglected, we find the following trend <sup>1</sup>:

$$U_c(M) = 0.17 - 0.0063 \ln(M) \quad (8)$$

in which  $U_c$  is the critical flow velocity for erosion. Based on the log boundary layer velocity profiles Dyer (1986), the velocities can be used to estimate the bed shear stress (Widdows et al., 1998):

$$\tau_b = 8u^2 - 0.06u + 0.0052 \quad (9)$$

resulting in the following critical bed shear stresses:

$$\tau_c(M) = 0.2 - 0.017 \ln(M) + 0.00032 \ln(M^2) \quad (10)$$

These relations are combined to find the following bio effect function:

$$\tau_c = \tau_c^0 \cdot f_p \cdot f_s = \tau_c^0 \cdot (1 - 8.5 * 10^{-2} \ln(M) + 1.6 * 10^{-3} \ln(M^2)) \cdot (1 + 0.08C) \quad (11)$$

Now the concept presented in this paper can be tested. The dynamics of the shoal are comprised to one set of parameter values for the sand-mud model: water depth  $3m$ , flow velocity  $0.8ms^{-1}$ , initial bed consists of 80 % sand. The critical deposition shear stress without biology are for mud  $\tau_d^0 = 0.15Nm^{-2}$  and for sand  $\tau_c^0 = 0.18Nm^{-2}$ . The bed becomes cohesive with a mud content of 30 % and then has a critical shear stress  $\tau_{c,c} = 1.6\tau_c^0$ . The erosion rate  $M$  is about  $1 * 10^{-8}ms^{-1}$ , the bed roughness modelled using Manning coefficient  $n = 0.03$ , relative sediment density of 2.65 and the turbulent viscosity  $\nu = 1 * 10^{-6}m^2s^{-1}$ . Note that these parameter choices are not realistic as they assume the same conditions on top of the tidal flat as on the sides near the channels and constant in time. However, in this way, the results of the modelling concept are shown as clearly as possible.

Figure 7 shows the promising model results with and without biological activity for three areas on the shoal. In agreement with the observations in figure 6, the mud content is slightly higher in the east than in the west. The concentration in the centre are strongly underestimated. The main cause is probably the choice of the physical conditions. Especially the flow velocity is quite high for the centre area which is on top of the tidal flat. A lower flow velocity will surely result in more mud. Next to these obvious results some marginally seasonal effects are visible.

A second cause may be an overestimation of the bioturbation. A slightly weaker relation would mainly increase the critical shear stress in the centre, where the density of *Macoma balthica* is relatively high. Figure 8 shows the biological correction of the critical shear stress. A reduction of the stabilization factor would move the stabilisation area (above the line) to the right, and flatten the line of no biological effect.

## 4 Case 2: North Sea sand wave field

Sand waves are rhythmic bed level variations in sandy beds of shallow seas. These patterns can be several metres high and having a wavelength of 200 to 800 metres. They are supposed

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<sup>1</sup>Note that this relation is incorrect regarding the units. This is caused by the dimensional trend analysis by Widdows et al. (2000) and cannot be easily corrected. Here we assume that the densities are no-dimensionalised without changes in the values.

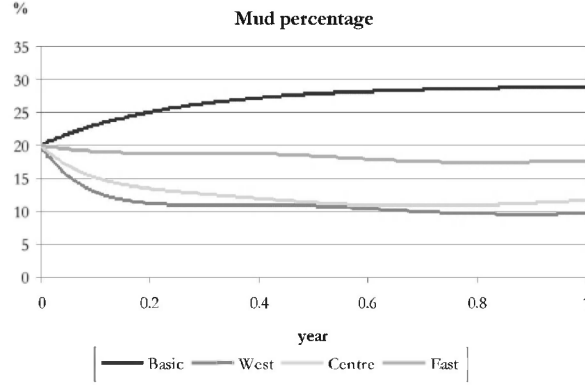


Figure 7: The mud concentrations in the bed according to the sand-mud model without biological activity (Basic) and for three areas with biological activity.

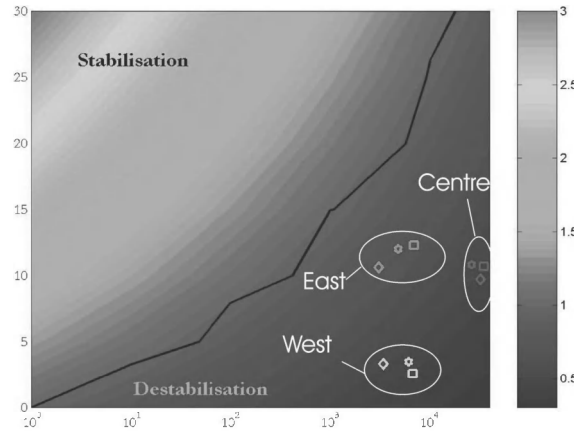


Figure 8: The biological correction of the critical bed shear stress. The circles enclose the values in the three areas for three different seasons. The black line denotes the line of no biological effect.

to be a free instability of the sandy bed due to the tidal flow over it Hulscher (1996). Due to the character of this instability mechanism, the sand waves might be sensitive to changes in the critical bed shear stress. In this section, it is investigated, if the biological factors in the bed shear stress could be large enough to influence the occurrence of sand waves.

The density of the benthos in the offshore sand wave areas of the North Sea are much smaller than those in an estuary (Holtmann, 1996). Due to the depth of 20 to 40 metres, phytobenthos is almost absent. The macrozoobenthos is dominated by tube-building polychaete, with densities in the order of 500 per square metre, which is considerably less than the zoobenthos densities in the Western Scheldt. However, even with these low densities the bioturbation might affect the bed topography. To explain this influence, we will introduce the reduction of the critical bed shear stress due to bioturbation into the sand wave model of Hulscher (1996). This model is based on the shallow water equations in 2 dimensions with one horizontal direction. The bed load sediment transport  $S_b$  at position  $x$  is modelled as (Komarova and Hulscher, 2000):

$$S_b(x) = \alpha \sqrt{|\tau_b|} \left( \tau_b - \lambda(\tau_b) \frac{dz_b}{dx} \right) \quad (12)$$

in which the  $\alpha$  is a proportionality parameter, whereas  $\lambda$  parameterises the bed slope effect. The

bed level is denoted by  $z_b$ , whereas  $\tau_b$  denotes the bed shear stress.

In this equation the critical bed shear stress is absent as it is assumed that the sediment transport is dominated during the maximum flow velocities which are far above criticality. However, the effect of the critical bed shear stress are taken into account in the parameters  $\alpha$  and  $\lambda$  (Komarova and Hulscher, 2000):

$$\lambda = \frac{3\theta_c g(s-1)d_{50}}{2\tilde{\gamma} \tan \phi_s} + \frac{\tau_b}{\tan \phi_s} \quad (13)$$

$$\alpha = \frac{4\tilde{\gamma}\tau_b^{\frac{3}{2}}}{g(s-1)\nu} \quad (14)$$

with

$$\tilde{\gamma} = \frac{|\tau_b| - \frac{3}{2}\theta_c g(s-1)d_{50}}{\tau_b} H \left( |\tau_b| - \frac{3}{2}\theta_c g(s-1)d_{50} \right) \quad (15)$$

in which  $\theta_c$  is the critical Shields number,  $s$  is the relative density of the sediment, that has median grain diameter  $d_{50}$ . Furthermore,  $\phi_s$  denotes the angle of repose of the sediment in water and  $\nu$  denotes the turbulent viscosity.

From equations 14 and 15 one can see that a decrease of the critical bed shear stress due to bioturbation will lead to an increase in the sediment transport. According to the sand wave model this will decrease timescale of the growth and migration rates of the sand waves. The sand waves will grow a bit faster, and migrate faster as well.

More important however is the effects visible in the combination of equations 13 and 15. A lower critical bed shear stress will decrease the bed slope parameter. This parameter is critical to the growth rate of the sand waves. If the slope parameter is below a critical value, the patterns will have a positive growth rate and sand waves will occur. When the bed slope parameter is above its critical value, the growth rate will be negative and the bed will remain flat (see figure 9). Consequently, when the conditions are such that the bed slope effect of the sediment transport is just above the critical value, bioturbation may force it below the critical value. This would mean that sand waves could occur in areas where they would be absent without biological activity. Note that a bioturbation factor of 0.975 (a 2.5% change) results in a 2% change in the bed slope parameter.

Another effect of the changing bed slope parameter is that the most probable sand wave length, that corresponds to the wave number with the maximum growth rate, will increase if the bed slope parameter decreases (see figure 9). This implies that bioturbation will lead to slightly shorter sand waves.

## 5 Discussion and conclusions

In this paper a new concept has been proposed to include biological effects like bioturbation and biostabilisation directly into the models. In the cases given as an example, a lot of assumptions are made, some of which cannot be justified scientifically yet. Therefore, the results have to be used carefully. The goal of these exercises is to show the opportunities of this biogeomorphological approach and the geomorphological consequences. Only part of the interactions between benthic organisms and their environment have been taken into account. For example, the effect of organisms on the flow or the redistribution of sediment by organisms are not accounted for. Further analysis is necessary to get accurate descriptions of the relations between biology and geomorphology, and eventually, a complete ecological loop will be necessary as it is well known



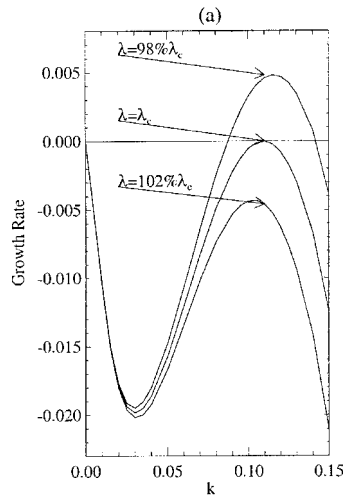


Figure 9: The growth rates of bed patterns as function of the wave number  $k$  for different values of the bed slope parameters  $\lambda$ . For the critical value, the sand waves (wavenumber  $k \approx 0.1$ ) is exactly 0. For a slightly lower  $\lambda$  sand waves will start to grow.

that the bed topography is an important factor in the abundance of the organisms. To model the double feedback system that results from this coupling will be a big challenge.

Nevertheless, some conclusions can be drawn. The approach to make the critical bed shear stress biologically dependent give promising results. The inclusion of perturbation and stabilisation into the geomorphological models enables us to explain some morphological variation, that is difficult to explain otherwise. And even with very low densities of organisms there might be biological influence on the bed topography. Furthermore, the approach is very easy to implement into the geomorphological models.

## Acknowledgement

This research has been financially supported by the Delft Cluster Programme of the Dutch government.

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