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Effects of temperature and salinity on the suspended sand transport

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Abstract

Purpose – The paper aims to present a study on the effects of temperature and salinity on the vertical distribution of suspended sand concentration and transport rate on the basis of 1DV model.

Design/methodology/approach – The finite difference method based on the implicit scheme of Crank-Nicolson with an irregular grid was used for the fluid flow equation and the implicit upwind scheme with a staggered grid for the equation of concentration diffusion. The model was applied to five tests of the data sets from the Delta Flume with three different cases of temperature and salinity on the basis of parameterisation of the kinematic viscosity, the turbulence-related sediment mixing coefficient and the concentration at the reference level.

Findings – The computed results showed that the vertical distributions of suspended sand concentration depend on salinity and specially, on temperature. When temperature increases or salinity decreases, the settling process of particles occurs considerably faster. For fine sand, the discrepancy on suspended sand transport rates due to temperature or salinity decreases with wave height. For coarse sand, the effect of temperature and salinity is not much affected by the wave height.

Originality/value – The quantitative evaluation of the roles of salinity, especially temperature once again confirmed their importance for the sediment transport and the process of coastal morphology. The further sense from this research may suggest some new ideas on the tendency of evolution of sea bed due to the warming of the earth in the future.

Keywords Kinematics, Viscosity, Temperature, Modelling, Suspensions (chemical), Sedimentation

Paper type Research paper

Introduction

So far it is clear that the knowledge on the mechanism of the vertical suspended sediment as well the exchange between suspended and bed load sediment at the reference level is still limited, especially in the surf zones. This became a problem of great interest for many scientists around the world. The methods of research that are based on the mathematical and physical models are still sensible and preferable, because the advantages of numerical solution and measurement are combined.

The accuracy of evaluation of the suspended sediment transport rate and then coastal morphodynamics process considerably depends on the vertical distribution of suspended sediment concentration. In fact, the profile of suspended sediment is based on many different factors, such as the current, the wave amplitude and the bed form, etc.

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The aim of this paper is to consider the effects of temperature and salinity on the vertical distribution of suspended sand concentration and then the time-averaged suspended sand transport rate under irregular waves.

In the surf zone, the suspended sand transport rate comprises two major components, namely the current-related transport component and the wave-related transport component.

The current-related transport over rippled beds has been studied in considerable detail (Van Rijn *et al.*, 1993; Van Rijn and Havinga, 1995), but the wave-related transport is less well known. The wave-related transport over a flat bed has been studied in more detail based on numerous experiments in wave flumes (Ribberink, 1998). Recently, the effect of ripple-related sediment mixing has been studied comprehensively on the basis of the 1DV turbulent fluid flow model for irregular waves (Dang Huu and Van Rijn, 2003). The model was calibrated carefully through the comparison with the measured data in the Delta Flume of Delft Hydraulics. Therefore, this paper is a continuation of the earlier work.

Experimental design and mathematical model

In order to understand the origin of the data, a short description on the Delta Flume is given. This is a large-scale flume with a total length of 233 m, a depth of 7 m and a width of 5 m. On the bed a sand layer of 0.5 m was placed over a length of about 40 m. Regular and irregular waves were generated by a piston activated wave board on one side of the flume. The instruments for measurement were mounted in a tripod, which was placed on the sand bed in the centre at location $x = 125$ m to measure instantaneous concentration and velocity components at five different positions in the vertical direction between the lowest $z = 0.075$ m and the highest measurement point $z = 1.075$ m. It should be noted that the water temperature for the experiment is 10°C. For each test the instruments were operated for about 15 min to sample over a representative wave record. The experimental conditions include different sand sizes, wave type, wave height and the orientation of ASTM and they are divided into five groups (Dang Huu and Grasmeijer, 1999).

The mathematical model is a modified version of the model presented by Ribberink and Al-Salem (1995) by including the effects of irregular waves and vortex-related mixing. The turbulent fluid movement for uniform horizontal flow in the vertical plane is considered assuming that the vertical velocity is relatively small compared to the horizontal velocity. Furthermore, it is assumed that the region of flow can be divided into an upper and a lower layer, in which the upper layer has no vertical velocity gradient. Hence, by using the term of pressure gradient from the equation for the upper layer, the movement in the lower layer is described by the Reynolds' equation as follows (Dang Huu and Van Rijn, 2003):

$$\frac{\partial u}{\partial t} = \frac{\partial u_0}{\partial t} + \frac{\partial}{\partial z}\left(\nu_{\mathrm{t}} \frac{\partial u}{\partial z}\right), \quad z_0 \leq z \leq h \tag{1}$$

in which $u(z,t) =$ horizontal velocity in the oscillatory lower layer, $h =$ depth, $u_0 =$ horizontal velocity at elevation $z = h =$ transition from lower to upper layer, $t =$ time, $z =$ elevation above bed, $v_{\mathrm{t}} =$ turbulent viscosity and $z_0 =$ position of zero velocity.

The initial and boundary conditions used in the model are given in the following:

$$u(z,t)|_{z=h} = f_1(t) \tag{2}$$

$$u(z,t)|_{z=z_0} = 0 \tag{3}$$

in which $f_1(t)$ is a time series data of irregular wave orbital velocities.

Using the same assumptions as for flow equation (1), the vertical distribution of sediment concentration is described by the 1DV diffusion equation as follows:

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial z}(w - w_s)c = \frac{\partial}{\partial z}\left(\varepsilon_s \frac{\partial c}{\partial z}\right), \quad z_a \leq z \leq h \tag{4}$$

in which: $w =$ vertical flow velocity, $w_s =$ the settling velocity of sediment particle determined by Soulsby (1997), $c =$ volume concentration, $z_a =$ reference level, and $\varepsilon_s =$ diffusion coefficient for sediment. The reference level is assumed to be equal to the effective bed roughness k_s, which is assumed to be equal to the ripple height.

The overall sediment mixing coefficient was modelled as the sum of two components, being the bottom-induced turbulence and the effective vortex-induced mixing:

$$\varepsilon_s = \sqrt{\varepsilon_{st}^2 + \varepsilon_{sw}^2} \tag{5}$$

in which ε_{st}, ε_{sw} are the mixing coefficients for sediment due to turbulence and due to vortex motions, respectively. The turbulence-related sediment mixing coefficient is related to the eddy viscosity v_t and the vortex-induced mixing coefficient is due to waves. For details their formulas can be found in Dang Huu and Van Rijn (2003) and the latter is proposed by these authors as follows:

$$\varepsilon_{sw} = \frac{1}{n}\hat{U}z\left(1 - \frac{z}{h}\right) \tag{6}$$

in which n is the coefficient most likely dependant on grain size and ripple dimensions, $\hat{U}$ is the peak orbital velocity.

The initial condition for the sediment diffusion equation is:

$$c(z,t)|_{t=0} = f_2(z), \quad z_a \leq z \leq h \tag{7}$$

in which $f_2(z)$ is a function derived from measured data.

The boundary condition at $z = h$:

$$\varepsilon_s \frac{\partial c}{\partial z} = -w_s c, \quad z = h \tag{8}$$

The boundary condition at $z = z_a$:

$$c(z,t)|_{z=z_a} = c_a(t), \text{ at } z = z_a \tag{9}$$

or:

$$\varepsilon_s \frac{\partial c}{\partial z} = -w_s c_a, \text{ at } z = z_a \tag{10}$$

in which $c_a =$ suspended sand concentration at the reference level and is given from the following formula:

$$c_a = m\rho_s \frac{\left(\theta' - \theta'_{cr}\right)^{1.5}}{D^*}, \tag{11}$$

in which $\theta' =$ instantaneous dimensionless bed shear stress related to the grains, $\theta'_{cr} =$ critical dimensionless bed shear stress known as Shields parameter, $\rho_s =$ density of sediment, $D^* =$ dimensionless particle diameter and $m =$ empirical coefficient related to ripple characteristics and is determined by Dang Huu and Van Rijn (2003) on the basis of the least square method:

$$m = 8.4\left(\frac{r}{\lambda}\right)^2 - 0.7\frac{r}{\lambda} + 0.06 \tag{12}$$

with r, $\lambda =$ ripple height and length, respectively.

Experimental expression for kinematic viscosity

The vertical distribution of sand concentration presented by equation (4) depends on temperature and salinity through the settling velocity of sediment particle, the diffusion coefficient for sediment and the suspended sand concentration at the reference level. Therefore, it is necessary to use the general formulas of temperature and salinity for the mathematical model.

From the experimental data presented by Soulsby (1997), it is shown that the water density depends very much on temperature and salinity, while the kinematic viscosity nearly does not change according to the salinity. Also from the experimental data, the analytic curves for the water density (Figure 1) and viscosity (Figure 2) were established previously. However, in this paper a new function for the kinematic viscosity is proposed for a better approximation based on the least square method for the hyperbolic behaviour, namely:

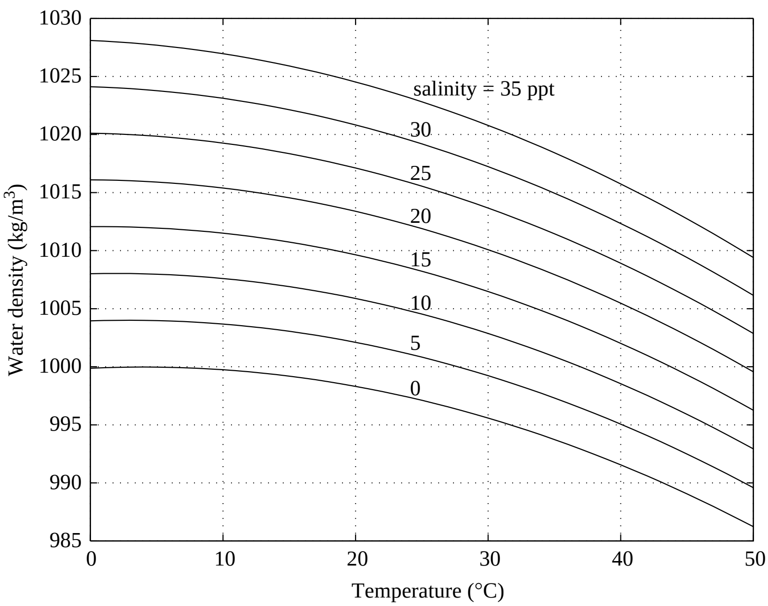

Figure 1.
Water density versus temperature for some values of salinity

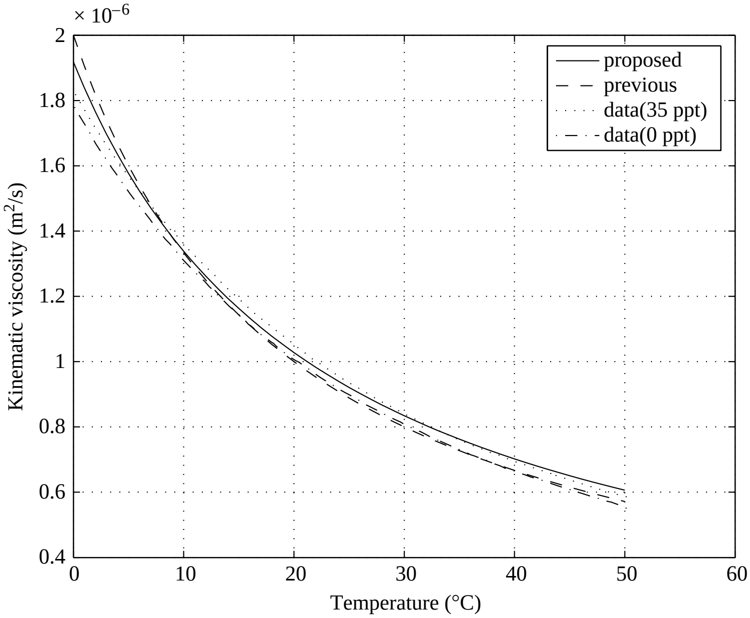

Figure 2.
Kinematic viscosity versus temperature for two values of salinity

$$\nu = \frac{4.43 \times 10^{-5}}{23.1 + T_e}, \tag{13}$$

where T_e is the Celsius temperature. In fact, the formula (13) is only different from the previous one by the values of the coefficients, $(4.43 \times 10^{-5}, 23.1)$ instead of $(4 \times 10^{-5}, 20)$.

Figure 2 shows that the new formula fits quite well the experimental data in the range of temperature from 7 to 35°C, while the previous function for the kinematic viscosity shows a less good effect in the ranges of temperature under 7°C and from 14 to 35°C and it is nearly the same with the curve of no salinity in the later range of temperature. It means that the previous formula should be used for sweet water and the new one is better for sea water.

Quantitative results from the model

Equations (1)–(3) for horizontal velocity were solved with the finite difference method based on the implicit scheme of Crank-Nicolson and the implicit upwind scheme with a staggered grid was used in equations (4) and (7)–(10) for the vertical distribution of sediment concentration. At the same time the irregular grid was applied to get a better approximation for the changes near bed.

The tests and basic input parameters of the model are given in Table I, in which the typical tests representing five data sets from the different conditions on bed roughness, grain size, wave height and relative steepness of ripples were considered.

The five tests are in turn computed for three different cases of temperature and salinity, as shown in Table II. Case T1S1 is used as a standard to evaluate the effect on temperature created by the case T2S1 and the effect on salinity by the case T1S2.

In general, for all cases under consideration the computed instantaneous velocities outside the layer affected by the ripples (roughly two ripple heights above the mean bed; $z > 0.1 - 0.2\,\mathrm{m}$) behave quite well in comparison with the measured velocities. The vertical distribution of the time-averaged velocity and the instantaneous velocity at the lowest elevation of measurement ($z = 0.075\,\mathrm{m}$) for the test H3 are shown in Figure 3. Model errors mainly occur close to the bed in the vicinity of the ripples ($z < 0.1\,\mathrm{m}$) with an acceptable range.

Figures 4-8 (left) show the computed time-averaged suspended sand concentration profiles with three different cases (T1S1, T2S1 and T1S2) and the comparisons with the measured data.

It is seen that the model results of all the tests fit quite well the measurement except the test D1 due to a very strong relative steepness of ripples ($r/\lambda \approx 0.27$). The discrepancies on suspended sand concentrations between the cases T1S1 and T2S1 as well as between T1S1 and T1S2 are shown in Figures 4-8 on the right. The effect of increasing temperature or reducing salinity is to reduce the predicted suspended concentration for all five tests. The reduction in concentration is larger for a 10° increase in temperature than it is for a reduction in salinity from 35 to 0. This can be explained as follows.

Test	Bed roughness z_a (m)	Grain size d_{50} (mm)	Wave height H_s (m)	Ripple height r (m)	Ripple length λ (m)
D1	0.06	0.33	1.00	0.06	0.22
B2A	0.05	0.33	1.25	0.05	0.23
G2	0.03	0.16	1.00	0.03	0.72
H3	0.03	0.16	1.25	0.03	0.72
M1	0.02	0.16	1.50	0.02	0.72

Table I. Input parameters for computations

Case name	Temperature (°C)	Salinity (ppt)
T1S1	10	35
T2S1	20	35
T1S2	10	0

Table II. Cases for computations

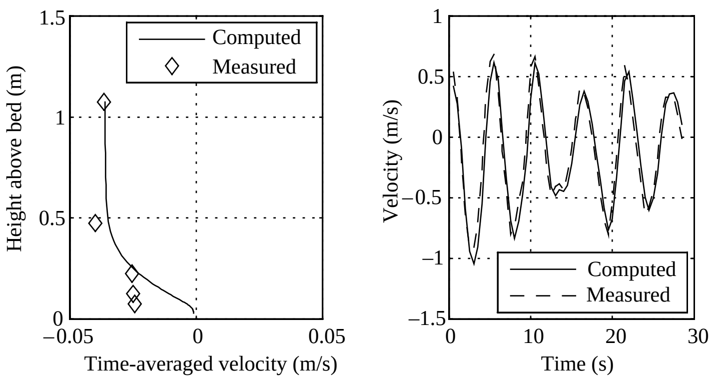

Figure 3. Left: vertical distribution of time-averaged velocity for the test H3; right: instantaneous velocity of the first 30 s at $z = 0.075\,\mathrm{m}$ for the test H3

When the temperature increases or the salinity decreases, the water density and viscosity decrease as well, hence the relative density of the particles increases resulting in an increase of the settling velocity of the particles. Moreover, from Figure 2 it is seen that viscosity hardly changes with salinity variations and this is the reason why the discrepancies in concentration between T1S1 and T1S2 are smaller than the ones

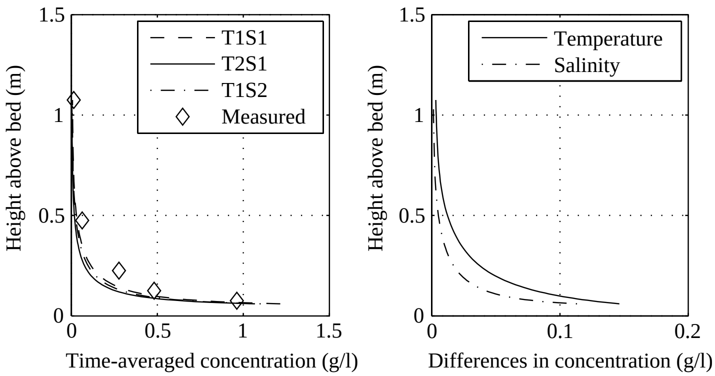

Figure 4.
Left: vertical distribution of time-averaged sand concentration for the test D1; right: differences in concentration of T2S1 and T1S2 compared to T1S1

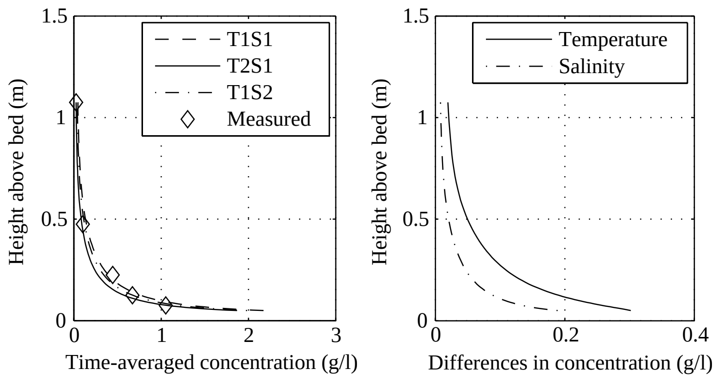

Figure 5.
Left: vertical distribution of time-averaged sand concentration for the test B2A; right: differences in concentration of T2S1 and T1S2 compared to T1S1

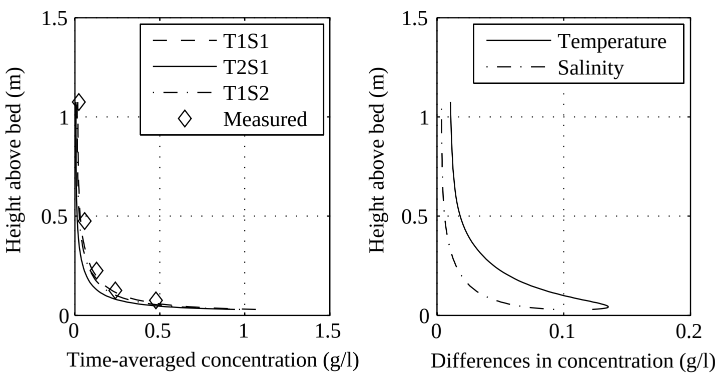

Figure 6.
Left: vertical distribution of time-averaged sand concentration for the test G2; right: differences in concentration of T2S1 and T1S2 compared to T1S1

between T1S1 and T2S1. In addition to the assessment on time-averaged suspended concentration, the suspended sand transport rates, Q_s (including relative changes) for five tests with three cases are also computed and are presented in Table III.

The negative signs of Q_s mean that the time-averaged suspended transport is offshore as mentioned previously by Dang Huu and Van Rijn (2003). The relative changes show that an increase of 10°C in temperature resulted in a decrease of 44 per cent in time-averaged suspended sand transport rate and a decrease in salinity from 35 to 0 caused the transport rate to decrease about 16 per cent.

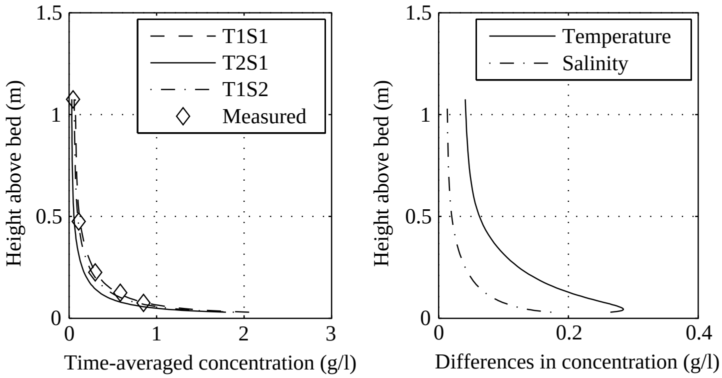

Figure 7.
Left: vertical distribution of time-averaged sand concentration for the test H3; right: differences in concentration of T2S1 and T1S2 compared to T1S1

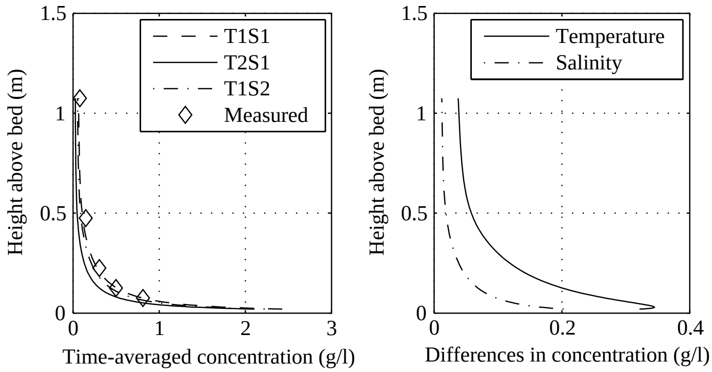

Figure 8.
Left: vertical distribution of time-averaged sand concentration for the test M1; right: differences in concentration of T2S1 and T1S2 compared to T1S1

Table III.
Time-averaged suspended sand transport rates and percentages on the discrepancies

Tests	T1S1 Q_{s1} (kg/m/s)	T2S1 Q_{s2} (kg/m/s)	T1S2 Q_{s3} (kg/m/s)	$(Q_{s1} - Q_{s2})/Q_{s1}$ × 100 per cent	$(Q_{s1} - Q_{s3})/Q_{s1}$ × 100 per cent
D1	−0.00042	−0.00029	−0.00036	30.57	14.47
B2A	−0.00451	−0.00301	−0.00387	33.12	14.10
G2	−0.00050	−0.00021	−0.00040	57.99	18.89
H3	−0.00436	−0.00224	−0.00366	48.56	16.04
M1	−0.00627	−0.00331	−0.00529	47.16	15.61

Figure 9 shows a visual comparison of these quantities according to the five tests and three different cases. Tests D1 and G2 are related to the wave height of 1 m, so the transport rates are much smaller than the other tests. All test results confirmed that the effect of temperature is much stronger than that of salinity. At the same time, also from Table III it is seen that the discrepancies decrease with wave height (between 1 and 1.5 m) for fine sand (tests G2, H3 and M1) due to the dominant effect of wave stirring on the concentrations. For coarse sand (tests D1 and B2A), the effects of temperature and salinity are not much affected by wave height.

Discussion and conclusions

Through the computed results for five tests, it is seen that temperature and salinity are also very important factors and have a strong influence on the vertical distribution of sand concentration and then suspended sand transport besides ripple steepness (Hitching and Lewis, 1999).

In general, a 3D model (Dang Huu and Eppel, 2003) will give a more accurate simulation of the flow field for a computation region with a rippled bed. However, it will take more computation time, so such a 3D model becomes quite expensive for many tests. Moreover, the time-averaged suspended sand concentration profile can be reasonably well simulated, provided that the reference concentration near the bed is modelled with sufficient accuracy and that the vortex-related mixing characteristics are taken into account. Therefore, the use of 1DV model in this situation is acceptable.

For all cases the computed instantaneous velocities and time-averaged sand concentration fit quite well the measured data. Finally, some conclusions can be drawn as follows:

- Temperature and salinity play an important role in the vertical distribution of suspended sand concentration, in which the factor of temperature is stronger. When temperature increases or salinity decreases, the settling velocity as well as the relative density of the particles considerably increases and this speeds up the settling process.

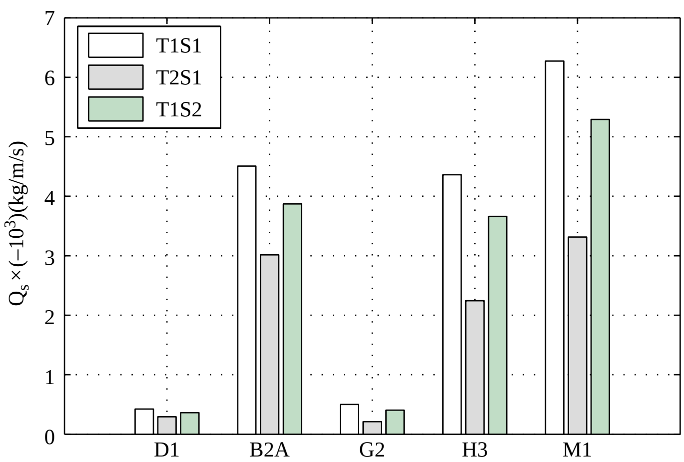

Figure 9.
Time-averaged suspended sand transport rates of five tests for three cases

- The time-averaged modelled suspended transport rate decreased by 44 per cent when temperature was increased from 10 to 20°C and decreased by 16 per cent when the salinity was reduced from 35 to 0 ppt. These comments quantitatively confirmed their strong influence on the sediment transport rate as well as the process of coastal morphology. They should be taken into account for the parameterisation of the mathematical model.
- For fine sand, the discrepancy on transport rates due to temperature or salinity decreases with wave height. For coarse sand, the effects of temperature and salinity on the transport rates are not much affected by wave height. The physical sense of this situation is still not clear and requires some more studies.
- At present, in the condition of the global climate changes due to the warming of the earth, the result of this research may suggest some new ideas on the tendency of evolution of sea bed in the future with more violence.

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