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LETTERS TO THE EDITOR

DISCUSSION OF 'THREE-DIMENSIONAL FREE-SURFACE SUSPENDED PARTICLES TRANSPORT IN THE SOUTH BISCAYNE BAY, FLORIDA', BY H. P. MILLER

Miller[1] presented the above paper in the October 1984 issue of this journal. Basically a summary of the sediment transport model developed by Sengupta, Lee and Miller,[2] this paper claims to have developed a general suspended particles transport model which (1) includes 'the state-of-the-art of research in sediment particles transport', (2) is 'most realistic in regard to treating the moving free-surface in computing the hydrodynamic field' and contains 'a more physically appropriate bottom boundary condition' than the model of Sheng[3] and (3) 'can be applied to surface water dispersion of particulates associated with dredging operations and landfill' with only 'particles size' limitation.

Because of the above and other technically erroneous statements contained in Miller's paper, I feel compelled to write this discussion. My major comments are: (1) Despite the vast scientific advancement in the subject areas of sediment transport and hydrodynamic modelling since 1975, Miller totally ignored them. Hence his basic sediment transport model is 10 years old and far from being the 'state-of-the-art'. Miller[1] made frequent references to a 1975 report by Sheng[3] and indeed followed a modelling approach strikingly similar to Sheng's earlier sediment transport model in that report. In fact, except for the model application, the basic numerical formulation of Miller's transport model differs little from Sheng's earlier transport model. (2) Despite this, Miller made many technically erroneous remarks about Sheng's 1975 work. For example, both free-surface and rigid-lid hydrodynamic models were developed by Sheng[3] and both can be used in conjunction with Sheng's sediment transport model, but Miller erroneously claimed that Sheng's model contained the 'rigid-lid approximation'. The use of either a free-surface or a rigid-lid hydrodynamic model depends on the physical environment and scales of interest,[4] and is not an inherent feature of the transport model. (3) In Miller's sediment transport model, the dominant physical processes were either totally ignored (sediment erosion, wave effect, cohesive sediment dynamics) or lumped into *ad hoc* model parameters (turbulent transport, settling and deposition). The 'model application' in Miller's paper is at best a numerical sensitivity study on settling velocity and deposition. No laboratory/field data were used to support the selection of these parameters or to validate the limited model simulation. His conclusion that the settling velocity plays a more major role than the deposition velocity in affecting the sediment concentration is merely a consequence of his *ad hoc* assumption about the deposition process. Any conclusion about the applicability of Miller's model is thus highly speculative.

During the last decade, the scientific community has made great advancement in the areas of sediment dispersion and hydrodynamics in water bodies. Numerous publications dealing with these subject areas can be found in many technical journals (e.g. *Journal of Physical Oceanography, Journal of Geophysical Research, Journal of Water Resources Research, Journal of Great Lakes Research, Journal of Hydraulics Research*, etc.), proceedings of conferences (e.g. *International Conference on Coastal Engineering, ASCE Speciality Conference, American Geophysical Union Meeting*, etc.), and government reports which are regularly indexed and distributed by NTIS.[5] In addition to the works by the present author,[4,6–13] many scientists[14–20] have carried out similar modelling studies on hydrodynamics and sediment dispersion. For example, Sheng[7] studied the transport and resuspension of cohesive sediments by using numerical models of current and wave data from laboratory experiments, field experiments and remote sensing. A three-dimensional free-surface time-dependent model[4] was used to compute the 3-D wind-driven currents which were then used to drive the 3-D sediment dispersion model. Both the current model and the wave model were calibrated with field data. Laboratory/field experiments were conducted to determine the settling velocity, deposition velocity, and erosion rate of realistic sediment particles. The overall sediment dispersion model was able to successfully simulate a realistic sediment transport event in Lake Erie. In addition, the dominant role of wave in affecting the sediment erosion and hence the suspended sediment concentration distribution was quantitatively demonstrated. However, Miller has largely ignored these works in his paper. Out of the 30 references cited by his paper, 22 of them are works published before 1975. All the remaining references, with but a few exceptions, are primarily hydrodynamic modelling work from the group with which Miller was formerly affiliated. In addition, his review of the sediment transport research contains basically the same references (pp. 73–77) and conclusions (pp. 43–44) as Sheng.[3] Consequently, both the physics and the numerics contained in Miller's sediment transport model are at least 10 years old and far from 'the-state-of-art'. Throughout his paper, Miller[1] referred to a 'free-surface' hydrodynamic model developed by his former colleagues and claimed it to be the 'most realistic', although similar free-surface hydrodynamic models had been developed and used by others[3,14,16] more than 10 years ago. Sheng's 1975 report included three hydrodynamic models: a steady-state model, a free-surface time-dependent model and a rigid-lid time-dependent model. A summary of that report was published in 1976.[6] In a later paper, Sheng, *et al.*[4] compared the results of a 3-D rigid-lid model and a 3-D free-surface model in great detail. The more recent free-surface models[10,12,19,20] contain many physical and numerical features (e.g. turbulence closure, mode-splitting, implicit numerical scheme, etc.) which are substantially more advanced than the early free-surface hydrodynamic model (such as the one used by Miller). A thorough review of many of the various numerical hydrodynamic models can be found in Reference 21.

As mentioned before, in addition to the physical assumptions, the overall numerical procedures used in Miller's model are also very similar to those in Sheng's 1975 sediment transport model. The basic differential equations, equation (2) of Miller[1] and equation (6.2) of Sheng,[3] are basically the same and are both written in vertically stretched co-ordinates. Pages 50–61 of Sheng's report detailed the complete derivation of finite-difference equations including the uses of the control-volume approach, half-cells at the surface and the bottom, an unstaggered grid, the Du-Fort Frankel scheme in the vertical diffusion term, and a mass-conservative second upwind scheme in the horizontal advection, which are all used by Miller. I am pleased to see that after 10 years, my old work has been so faithfully followed. Being a scientist, however, I would feel embarrassed to claim that my 1975 model is still the 'state-of-the-art'. What surprises me is that, despite how closely he had followed my early work, Miller made the erroneous claim that my 1975 model contained the 'rigid-lid approximation'. As mentioned before, Sheng's 1975 sediment transport model was used in conjunction with both the free-surface and the rigid-lid hydrodynamic models and is not limited to the rigid-lid model. Miller's transport model works the same way. Although he claimed that the hydrodynamic equations are 'directly coupled' to the suspended particles transport equations, the truth is that he used the velocity field computed by the hydrodynamic model to drive the sediment transport model without letting the sediment concentration affect the flow. To support the claim that his model is the 'most realistic', he needs to demonstrate it by comparing his results with those obtained by other models for the same simulation. But that was never done.

Another major contribution claimed by Miller[1] is the use of 'a more physically appropriate bottom boundary condition'. I found this claim without any foundation. Sheng[3] recognized the importance of deposition and erosion in affecting the sediment concentration and modelled the bottom boundary condition as (equation 5.12 of Reference 3)

$$-W_s C + D_v \frac{\partial C}{\partial z} = \beta C - E, \tag{1}$$

where W_s is the settling velocity ($W_s > 0$ vertically upward). C is the suspended sediment concentration in the vicinity of the bed, D_v is the vertical eddy diffusivity, β is the deposition velocity, ($\beta > 0$ vertically downward) and E is the rate of erosion. The equation states that the net downward sediment flux at the bed is equal to the difference between deposition and erosion. Subsequently[7,10] the values of β and E were actually determined by laboratory flume experiments using realistic sediments from fresh-water and marine environments. These parameters were found to depend on the bottom turbulence, sediment composition, water content, salinity, and macrofauna. Miller[1] did not carry out any such studies, but totally ignored erosion and simply assumed that the deposition velocity (β) is a fraction of the settling velocity:

$$-W_s C + D_v \frac{\partial C}{\partial z} = -AW_s C, \tag{2}$$

where A was vaguely defined as the 'probability of suspended particles leaving suspension and depositing on the bottom bed' and was assumed to have a value of 0·3 or 0·9. $|W_s|$ was assumed to be either 0·02 cm/s or 0·04 cm/s. Thus, in addition to the vertical diffusivity, A and W_s are introduced as two more 'tuning parameters' which together contain all the empiricisms of Miller's sediment transport model. In the presence of sufficient data, these tuning parameters may be adjusted by fitting model results with data. However, no such data exist to support his choice of A and W_s and the boundary condition, equation (2). Since the deposition velocity was assumed to be a fraction of settling velocity, Miller's claim that 'settling plays a more major role than the deposition velocity' is merely a consequence of this assumption rather than a conclusion from a physically sound study. A more serious deficiency of the boundary condition (2) is the ignoring of erosion altogether. Previous studies have shown that sediment erosion due to the combined action of waves and currents play a significant role in affecting the suspended sediment concentration in relatively shallow environments, such as Lake Erie[7] and Mississippi Sound.[12] Even currents alone can cause appreciable erosion. The critical shear stresses for sediments from Lake Erie[7] and Mississippi Sound[12] are typically of the order of 1 dyne/cm^2 or less.

Based on the model computed currents shown by Sengupta *et al.*[2] the bottom stress in the Biscayne Bay could easily exceed 1 dyne/cm^2. Ignoring sediment erosion in the shallow Biscayne Bay, as Miller had done, is highly questionable and mostly likely to yield erroneous results. Miller's claim that 'in actual flows the databases for sediment particles transport are virtually non-existent' is technically erroneous. Using this as a justification for neglecting sediment erosion and other physical processes is to shy away from 'the state-of-the-art'. In 'dredging operations and landfill', high sediment concentration is often encountered and there is usually interaction between the turbulent eddies of various sizes and the distribution of sediment particles. The use of Miller's model, which resolves turbulence, settling and deposition with *ad hoc* fixes, is highly questionable.

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AUTHOR'S REPLY

In reply to Dr. Sheng's discussion of my paper,[1] I wish to thank him for some useful suggestions. I also wish to respond to several of his suggestions with respect to the nature of the suspended particles transport model, and more particularly, Dr. Sheng's conclusions with regard to the hydrodynamic model.[2–4]

It was never my intention to present in the journal paper under discussion a 'general' suspended particles transport model, that is one which would include the vast variety of physical processes governing sediment transport in a fluid.[5,6] Sengupta, Lee and Miller[7] chose to apply their hydrodynamic free-surface model for the South Biscayne, Florida to several mass transport processes, namely dissolved chemical transport and flushing studies,[8] as well as suspended particles transport[1] resulting from an initially sharp concentration gradient. Until Dr. Sheng's recent work[9,10] appeared, the values of β and E, which determine the complex processes of deposition and entrainment, as introduced by Monin and Yaglom,[1] were not well known.[12] Therefore, Sengupta, Lee and Miller[7] selected the form of the bottom boundary condition as used by Jobson.[13] The main thrust of this research was to 'one-way couple'[1,14,15] the hydrodynamic model to a simplified suspended particles transport model for the purpose of computing the effects of dominant transport processes upon the initially steep suspended particles profile. Bottom bed erosion or, rather, viscous turbulent entrainment, was indeed ignored, as well as the complex particle settling effects of hindered settling (due to backscattering), and floccucation (or coagulation). Thus, I limited the suspended particles transport model to ideal gravitational settling and Jabson's bottom boundary condition, since neither controlled laboratory experiments nor extensive field data collection for the South Biscayne Bay had been performed during the course of the code development of the suspended particles mass transport model. In conclusion, the effects of advection, variable settling velocity and variable bottom bed deposition were only 'qualitatively' compared, as clearly stated in the article under discussion. Distortion of the initially steep concentration gradient by artificial numerical effects, such as numerical diffusion,[16-19] numerical dispersion[20] or the well known Gibbs's phenomenon, were not observed, since vertical diffusion and vertical particle settling convection were the dominant transport processes for the South Biscayne Bay.

Regarding the hydrodynamic model, Miller[1] clearly summarizes earlier investigations using free-surface models for bay systems,[21,22] which, indeed, used *ad hoc* empirical forms of the open boundary condition for the ocean–bay interface, as opposed to the exact open boundary condition presented by Sengupta *et al.*[2,3] in an unstaggered horizontal grid system, and by Miller[4] in a staggered Richardson lattice, for which tidal current phase averaging was not required. Liu and Leendertsee[23] offer a comprehensive review of other three-dimensional models.

The 'particle size' limitation, noted by Dr. Sheng in his discussion of my paper, was required,[24-26] so that Stokes law of resistance could be invoked in order to justify ideal gravitational settling. Also, this particle size limitation enabled the justification of the assumption that the eddy diffusion coefficient for the particle be the same as that of the fluid.[27] Sayre[28] concluded that small sediment particles (diameter less than 0·1 mm) with a settling velocity in the Stokes range, very nearly follow the turbulent fluctuations and, consequently, have a diffusion coefficient nearly equal to that of the fluid.

The presentation of a unique mass-conserving explicit finite difference model for solving the concentration equation for suspended particles transport[1] followed earlier work done by Dr. Sheng;[29] however, the implementation of the second upwind differencing[30] of the horizontal convection terms was not apparent in Dr. Sheng's work, although his control volume method was employed by Sengupta, Lee and Miller[7] and by Miller[1] for ensuring against mass leakage in the numerical model at the free-surface and bottom boundaries. However, these two additional boundary finite difference equations were derived,[1,7] in the (α, β, σ) co-ordinate system, allowing for major tide level variations unique to a tide-dominated bay, and, additionally, Jobson's boundary conditions were used.

Thus, it is my feeling that the paper under discussion reflects current 'state-of-the-art' modelling techniques for shallow tidal bay hydrodynamics; and owing to the lack of controlled laboratory experiments[31] and extensive field data for the South Biscayne Bay, in particular, the suspended particles transport model, although simple in nature, yields some rather interesting parametric conclusions regarding the vertical concentration profiles as affected by settling velocity, deposition rate and advection currents. Incidentally, except for the inertial effect of advection upon the vertical concentration profiles, the computed solution has been corroborated by the exact (analytic) solution of the one-dimensional vertical transport problem of unsteady convection–diffusion. Note that a strong exponential functional dependence on the settling velocity resulted.[32] Therefore, I cannot agree with Dr. Sheng that 'the use of Miller's model, which resolves turbulence, settling and deposition with *ad hoc* fixes, is higher questionable'.

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