Incorporating sediment-transport modeling capabilities to DSM2

A proposal to the California Department of Water Resources

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INTRODUCTION AND OBJECTIVES OF THE PROPOSED RESEARCH

The numerical computation of sediment transport in river networks has become an essential tool for the planning, design, and assessment of the feasibility of river engineering projects. Although the physical processes associated with the entrainment of sediment into suspension in rivers have not yet been completely elucidated, engineers around the world are constantly called upon to provide answers regarding the changes of bed level and the alterations of the sediment transport, at diverse spatial and temporal scales (Holly et al., 1990). In this context, any development of modeling tools for the analysis of sediment transport in rivers should incorporate the most appropriate theoretical models to represent partially-understood, complex phenomena, and should adopt the most robust numerical techniques in order to provide optimized answers in practical cases.

Concerning the Sacramento-San Joaquin Delta (hereafter referred to as the Delta), the California Department of Water Resources (DWR) has been developing for some years now a network flow and water quality numerical model, DSM2, which provides answers to diverse problems corresponding to floods and pollutant transport in the system. This numerical model (which has been in use since 1997) has served the State notably well on many occasions. For instance, DSM2 has been used to reproduce historical flows that have been taken place in the Delta. Although there are still numerous problems in which DSM2 can serve well the State in its present form (in fact, DSM2 is currently being used at UC Davis to model the distribution of Striped Bass in the Delta), the code lends itself to the increment of its capabilities via the addition of suitable sub-models. Several proposals for the future of the Delta are currently being discussed (see Lund et al., 2007), and some of those proposals include actions on the flows and sediment loads in the Delta rivers and tributaries. DSM2 is thus called to play an important role in the assessment of the technical feasibility of those proposals. Further, with the addition of sub-models for sediment transport to DSM2, a more comprehensive assessment of the above proposals can be performed. Specific aspects regarding sediment transport in the Delta of interest to DWR are:

a) The motion of sediment in the diverse rivers of the network coming from dredging operations undertaken in the Delta ship canals;
b) the transport and fate of sediment resulting from activities of marsh restoration;
c) the transport and fate of sediment particles resulting from levee breaches;
d) the transport and fate of metals like mercury, which are usually highly-associated with solid particles in the Delta and San Francisco Bay systems;
e) the evolution of bed levels in the Delta under historical flow conditions.

Several 1-D codes for flow and pollutant transport are customarily used around the world: CCHE1D, MIKE 11, FEQ, Ezeiza V, CHARIMA, FLDWAV, etc. However, only a few of those codes include sub-models to deal with the transport of sediment. In addition, some of the existing sub-models for sediment transport are *not* flexible and/or general enough. Thus, the addition of general sediment-transport sub-routines to DSM2, able to deal with cohesive/non-cohesive sediment, will provide the code with capabilities that are not present in most other models.

Currently, DSM2 is structured in three main modules: HYDRO, QUAL, and DSM2-PTM. HYDRO involves a solver for surface water variables, i.e., the water levels and discharges in the rivers of the Delta. QUAL includes a Lagrangian Transport Model and the solution of advection-dispersion transport components. Constituents that can be modeled in DSM2 are: dissolved oxygen, carbonaceous BOD, phytoplankton, organic nitrogen, ammonia nitrogen, nitrate nitrogen, organic phosphorus, dissolved phosphorus, TDS and temperature. PTM in turn tracks individual particles in a pseudo-three-dimensional space. Hydrodynamic results from DSM2 for the Delta are usually employed as input for two- and three-dimensional (2-D and 3-D) models for the San Francisco Bay (see Smith, 2007).

The aim of the present proposal is to incorporate the capability of simulating sediment transport and bed-level change to DSM2, and to validate the resulting sub-models first with measurements obtained from the literature, and second with observations of sediment concentrations in the Delta. The project will involve the development of adequate theoretical sub-models which will be implemented numerically in sub-routines. These sub-routines will take part in a new module of DSM2 called SEDITRAN, and will allow for addressing the sediment transport as bedload and in suspension, the change in bed elevation due to natural events and/or man-made activities, and will also link the module of water quality (QUAL) with the sediment-transport module in order to simulate cases of pollutants that attach significantly to particles (like mercury and other heavy metals). The resulting sub-routines will become copyrighted by DWR, as the current DSM2 sub-routines. DSM2 will be then used to simulate historical and future conditions of flow and sediment transport in the Delta. Another aim of the project is to organize an inventory with datasets about flow and sediment transport in the Delta.

Research objectives

The project aims to develop a new module for DSM2, to be called SEDITRAN, and to validate it against available data. The module will address cohesive and non-cohesive sediment and will contain the following sub-modules:

(a) A sub-module for the solution of the transport of sediment in suspension, with suitable boundary and internal conditions for the mass conservation at the junctions of several branches, and the presence of structures;

(b) a sub-module for the computation of bedload transport by using well-known formulations developed elsewhere, and formulations obtained specifically for the Delta;

(c) a sub-module for the solution of the Exner equation, which relates to the mass-conservation of sediment in the bed;

(d) a sub-module for the transport of pollutants attached to particles in suspension.

Additionally, the project aims at developing simulations concerning historical and future conditions in the Delta. The project will also aim at organizing an inventory of datasets with information on sediment transport in the Delta. These datasets will be featured in a specific webpage with a link to the DWR webpage.

The working hypotheses of this project are: (i) A one-dimensional (1-D) approach for the sediment transport is enough to characterize the conditions of the motion of solid particles in the rivers of the Delta; this means that 2-D and 3-D flow and sediment-transport features are limited to confined regions; (b) the input of sediment to the network of rivers from the Delta catchment is known, and can be treated through non-point sources; (c) bedload transport formulas developed in laboratory flumes and in other rivers could be adapted for application to the rivers of the Delta; (d) the flow in rivers in the Delta is mainly sub-critical, with no occurrence of hydraulic jumps; (e) the size distribution of sediment can be characterized by a relatively-small number of “classes” (say, 20-30 classes); and (f) sediment fluxes in floodplains have a clear direction.

RELATED RESEARCH

Early 1-D models for rivers date back to the sixties and seventies. Experiences in modeling, and problem-solving associated with different rivers around the world were wisely summarized in the book by Cunge et al. (1980). Since then, numerous papers have contributed to the current state-of-the-art in the knowledge of 1-D models. For instance, Lyn and Goodwin (1987) investigated the stability of the Preissman scheme, the most widely used scheme to solve the fully-dynamic Saint-Venant equations. Herein we comment on a small number of recent contributions to modeling.

Holly et al. (1990) presented a detailed analysis of the model CHARIMA (University of Iowa), which includes sediment-transport modules. The model solves the equation for the mass conservation of the sediment in the bed (Exner equation), but it does not include separation between sediment in suspension and bedload (please see below). Instead, general expressions for the total transport are used. The model solves the Preismann scheme and makes the resulting equations in differences, linear, following the method proposed by Ligget and Cunge (1975). The Exner equation is also solved with a consistent numerical scheme. Holly et al. made available the source code of their model.

Bombardelli et al. (1995, 1997) presented the model EZEIZA V and its modifications to simulate the flow in the Paraná River Delta, Argentina. They found that the stage-conveyance curves needed adjustments in order to reflect the hysteretic behavior of the river.

Wu and Vieira (2002) presented the model CCHE1D (University of Mississippi) with significant detail. The model includes the solution of the mass conservation equation for different classes, and hosts several formulas for bedload transport (please see below).

METHODS AND PROCEDURES FOR THE PROJECT

We approach our research objectives through five major tasks, which we detail below:

Task 1: Development of the sub-module SEDITRAN, able to deal with cohesive and non-cohesive sediment, to be incorporated into DSM2. This sub-module will include the solution of equations for the transport of sediment in suspension, the computation of sediment transport as bedload, the solution of the Exner equation for mass conservation of sediment in the bed, and the incorporation of suitable boundary and internal conditions for the sediment. This task will deal with a distribution of sizes of sediment particles.

Task 2: Verification and validation of the sub-module SEDITRAN with laboratory tests taken from the literature.

Task 3: Organization of an inventory of datasets with information on sediment transport in the Delta.

Task 4: Selection of scenarios from datasets corresponding to sediment transport in the Delta, and validation of the model with those scenarios.

Task 5: Application of the resulting numerical model to assess historical and future conditions in the Delta, of interest for DWR.

Task 1: Development of the module SEDITRAN to be incorporated into DSM2

Although the motion sediment particles in open channels involves the interaction of solids of diverse shape and size with the mean flow and turbulence at different distances from the bed, the transport of sediment is usually classified for simplicity into two main modes, namely the *bedload transport*, and the *transport in suspension*. A third transport mode is also considered, called the *wash load*. Wash load includes very small particles which enter a river in one end, and do not exchange mass with the main channel, exiting the system in the other end (Altinakar and Graf, 1998; García, 1999). A complete numerical model for sediment transport should include the main components, although it is expected that one of the modes will prevail depending on the river under consideration. Figure 1 shows schematics of the two main sediment transport modes.

(a)

(b)

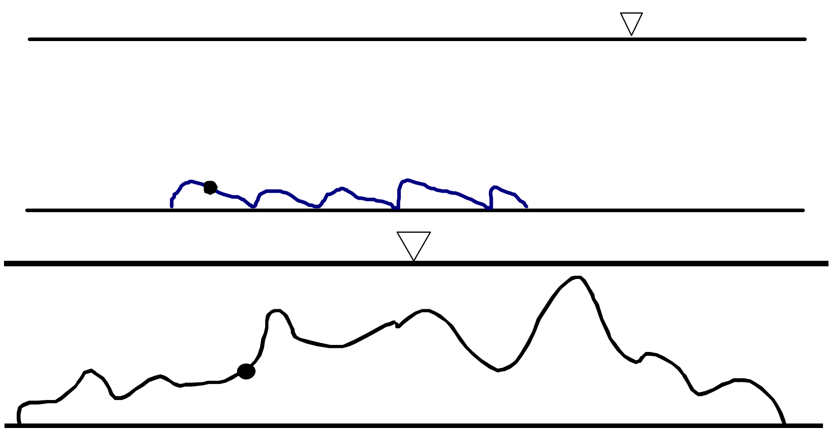

Figure 1: Schematic indicating the different modes of transport of sediment in open channels (taken from Parker, 2004). (a) Transport as bedload. (b) Transport in suspension.

The bedload transport in the Delta can be associated with the motion of dunes. This is explained in more detail below.

Theoretical models

The adopted governing equation for the transport of sediment in suspension is as follows (Rutherford, 1994; DHI Mike 11 Sediment Transport Short Description):

$$\frac{\partial (A\,C_s)}{\partial t} + \frac{\partial (Q\,C_s)}{\partial s} = \frac{\partial}{\partial s}\left[A\,K_s\,\frac{\partial C_s}{\partial s}\right] + E - D + q_L\,C_L + S/S \tag{1}$$

where A is the cross-sectional wetted area (m^2); C_s is the volumetric cross-sectional-averaged concentration of sediment in suspension (-); Q is the discharge (m^3/s); K_s denotes the dispersion coefficient (m^2/s); E indicates the entrainment rate of sediment into suspension per unit width (m^2/s); D represents the deposition rate of sediment per unit width (m^2/s); and q_L (m^2/s) and C_L (-) refer to the lateral discharge (per unit width) and the volumetric concentration of sediment in the lateral discharge. In turn, s and t indicate the spatial and time coordinates, respectively, and S/S denotes sources and sinks of sediment of non-point nature. Closures for E and D are provided in the next section.

It is worth pointing out that the above equation, which corresponds to the principle of conservation of mass of sediment in suspension (see García, 1999; and Parker, 2004), is valid for a unique particle size. In case of a distribution of sediment, the above equation should be applied to each class size, and the sources/sink term has to include the mass of particles that move from one class size to another. This project will consider a limited number of classes of sediment sizes (about 20 or 30). It is also worth pointing out that other models use a different equation for the mass conservation of suspended sediment. For instance, the equation employed in the model CCHE1D uses the concept of "adaptation length," which relates to the difference between the local sediment discharge and the discharge at capacity (please see below). We believe that this way of computing the sediment transport (Eq. (1)) is more physically-based, and can be easily adapted to consider the transport of cohesive or non-cohesive sediment. In addition, the introduction of a diffusive term is better posed from a numerical point of view.

The transport of sediment as bedload will be computed via empirical relations taken from previous studies. Such relations can be recast as special cases of the following relation:

$$\frac{q_b}{\sqrt{R\,g\,d_P^3}} = f\left(excess\ shear\ stress\right) \tag{2}$$

where q_b is the solid discharge due to bedload per unit width, R is the submerged specific gravity, given by $R = \rho_s/\rho - 1$, with ρ_s and ρ denoting the densities of sediment and water, respectively; g is the acceleration of gravity; and d_p is the particle diameter. These relations are said to pertain to "capacity" conditions, whereby the river can scour sediment according to the load it can actually carry. Again, this equation can be posed for each particle size class. One such relation, albeit for the *total* bedload transport, has been developed for the Delta by the United

States Geological Survey (USGS) through the consideration of the motion of dunes, as follows: $q_{b,w} = 1900\ c\ h/2$, where the solid discharge is expressed in weight per unit time; c is the celerity of the bedform; and h is the height of the bedform (see http://ca.water.usgs.gov/program/sfbay/calfedsed/bedsurveys/equation.html).

Another sub-model to include in SEDITRAN is that of the conservation of mass for the sediment in the bed, namely, the Exner equation (García, 1999; Parker, 2004; DHI Mike 11 Sediment Transport Short Description):

$$B \frac{\partial \eta}{\partial t} = -\frac{1}{(1-\lambda_p)} \frac{\partial Q_b}{\partial s} - E + D \tag{3}$$

where Q_b is the total bedload solid discharge; λ_p indicates the average porosity of the bed material; B is the width of the channel; and η is the bed elevation above a certain datum. (The adequate definition of B for the cross sections of the Delta will be analyzed in detail.) For any specific size class, Eq. (3) needs to be modified to account for the fraction of the class in the overall size distribution of the material.

The model will include several layers that exchange sediment with the water column through the concept of "active layers" (DHI Mike 11 Sediment Transport Short Description). For example, CHARIMA (Holly et al., 1990) and CCHE1D include a series of layers of sediment to represent the availability of sediment to be eroded.

Closure equations

Important aspects that need to be considered in the model are associated with the closures to the above equations. In particular, there are many expressions in the literature to compute the entrainment rate of sediment into suspension (see for example García, 1999; Parker, 2004). Entrainment formulas for non-cohesive and cohesive sediment will be incorporated in the code, which are usually expressed in terms of the wall-friction velocity (u_*) or the shear stress. For instance, the formula by García and Parker (1991, 1993) reads:

$$E_s = \frac{A\, Z_u^5}{1 + \frac{A}{0.3} Z_u^5} \tag{4}$$

where A is a constant equal to 1.3 x 10^{-7}; $Z_u = \frac{u_*}{w_s} 0.586\ \mathrm{Re}_p^{1.23}$, with $\mathrm{Re}_p = \frac{\sqrt{g\ R\ d_p^{\ 3}}}{\nu}$ (the explicit particle Reynolds number); w_s indicates the fall velocity; and ν denotes the kinematic viscosity of water. Once E_s (which is a non-dimensional number) is computed, it follows that: $E = E_s\ w_s\ B$ (Julien, 2002). In turn, $D = C_{sl}\ w_s\ B$, where C_{sl} is the local sediment concentration at a distance from the bed. (This concentration can be related to the cross-sectional concentration of sediment through empirical coefficients; see García, 1999.) The García and Parker formulation is one of the few which include a version for several classes of sediment size.

Numerous expressions have been presented in order to facilitate the computations of the fall velocity, w_s (see Parker, 2004). In this project, the regression proposed by Dietrich (1982) for natural particles will be used.

Internal and boundary conditions

An important aspect of the sediment transport in networks of channels is the distribution of sediment loads in multiple junctions. It is known that the solid discharges do not distribute at capacity at junctions (see discussion in Holly et al., 1990). In Mike 11, the distribution is performed via a weighting function that considers the incoming discharges to the junction and coefficients for calibration (DHI Mike 11 Sediment Transport Short Description). This methodology will be adopted for this work, but several alternatives will be also analyzed.

Internal conditions need also to be developed for the case of in-stream structures. Different formulations will be tested in the framework of the project.

Boundary conditions will be specified mostly as solid discharges or sediment concentrations. The numerical stability of the resulting code corresponding to these boundary and internal conditions will be carefully tested.

Numerical treatment

Equations (1) and (3) will be solved by using an *implicit* formulation which allows for larger time steps and minimizes numerical dispersion. ("Numerical dispersion" refers to the non-physical spreading of mass that occurs in some numerical schemes; see Fletcher, 1997.) This implicit formulation will be in accord with the implicit formulation of the hydrodynamic module of DSM2. One such implicit formulation involving six points, is given below, applied to Equations (1) and (3), respectively. (The subscript i indicates space location while the superscript n refers to time.)

- Mass conservation of sediment in suspension:

$$\frac{1}{2}\left[\frac{\left(A\,C_s\right)_{i+1}^{n+1}-\left(A\,C_s\right)_{i+1}^{n}}{\Delta t}\right]+\frac{1}{2}\left[\frac{\left(A\,C_s\right)_{i-1}^{n+1}-\left(A\,C_s\right)_{i-1}^{n}}{\Delta t}\right]+\phi\left[\frac{\left(Q\,C_s\right)_{i}^{n+1}-\left(Q\,C_s\right)_{i-1}^{n+1}}{\Delta s}\right]+$$

$$(1-\phi)\left[\frac{\left(Q\,C_s\right)_{i}^{n}-\left(Q\,C_s\right)_{i-1}^{n}}{\Delta s}\right]=\phi\left[\frac{\left(A\,K_s\,\partial C_s/\partial s\right)_{i+1/2}^{n+1}-\left(A\,K_s\,\partial C_s/\partial s\right)_{i-1/2}^{n+1}}{\Delta s}\right]+$$

$$(1-\phi)\left[\frac{\left(A\,K_s\,\partial C_s/\partial s\right)_{i+1/2}^{n}-\left(A\,K_s\,\partial C_s/\partial s\right)_{i-1/2}^{n}}{\Delta s}\right]+E_i^n-D_i^n+\left(q_L\,C_L\right)_i^n+\left(S/S\right)_i^n \quad (5)$$

Other treatments for the advective term (which is the source of the potential numerical dispersion) will be tested. The terms of entrainment, deposition, lateral discharge and sources/sinks are expressed in explicit manner in (5), but implicit versions will also be analyzed. Discretization of the variables at $i-1/2$ and $i+1/2$ are given on page 332 of the book by Cunge et al. (1980).

- Mass conservation of sediment in the bed (Exner equation):

$$B_i^{n+1/2}\left\{\frac{1}{2}\left[\frac{(\eta)_{i+1}^{n+1}-(\eta)_{i+1}^{n}}{\Delta t}\right]+\frac{1}{2}\left[\frac{(\eta)_{i-1}^{n+1}-(\eta)_{i-1}^{n}}{\Delta t}\right]\right\}=$$

$$\frac{1}{\left(1-\lambda_p\right)}\left\{\phi\left[\frac{(Q_b)_{i-1}^{n+1}-(Q_b)_{i}^{n+1}}{\Delta s}\right]+\left(1-\phi\right)\left[\frac{(Q_b)_{i-1}^{n}-(Q_b)_{i}^{n}}{\Delta s}\right]\right\}-E_i^n+D_i^n \quad (6)$$

On Eqs. (5) and (6), ϕ can vary between 0 and 1, yielding fully-implicit schemes for ϕ=1, and fully explicit schemes for ϕ=0. A flow-chart of the DSM2 code with the incorporation of the SEDITRAN module is presented in Figure 2.

Task 2: Verification and validation of the sub-module SEDITRAN with laboratory tests taken from the literature

A required step in the development of numerical models is their verification with analytical solutions and their validation through comparison with measurements found in the literature. In a first stage of this task, we will employ well-known analytical solutions of the advection-diffusion equation to verify the implementation of the numerical scheme. In a second stage, we will follow the validation procedures devised by Wu and Vieira for the model CCHE1D. Wu and Vieira tested the model via comparison of model predictions with the experimental data of Newton (1951) and with data collected at the Saint Anthony Falls Laboratory (Cui et al., 1996). Newton conducted observations of sediment motion and channel degradation in a flume 9.14 m long, 1 ft wide, and 2 ft deep. Sediment was fed at the inlet of the flume. Sand of 0.69 mm of mean size was employed. In turn, Cui et al. (1996) employed a 45-m long flume with a width of 1 ft. The bed slope was 0.002. In both cases, the position of the bed was monitored and reported for different times.

Additionally, the observations of Soni et al. (1980), and Soni (1981), of similar nature than those of Newton (1951) and Cui et al. (1996), will be employed in the validation of the code. These tests pertain to cases of single flumes. Unfortunately, no laboratory data have been reported to validate sediment transport models in networks of channels.

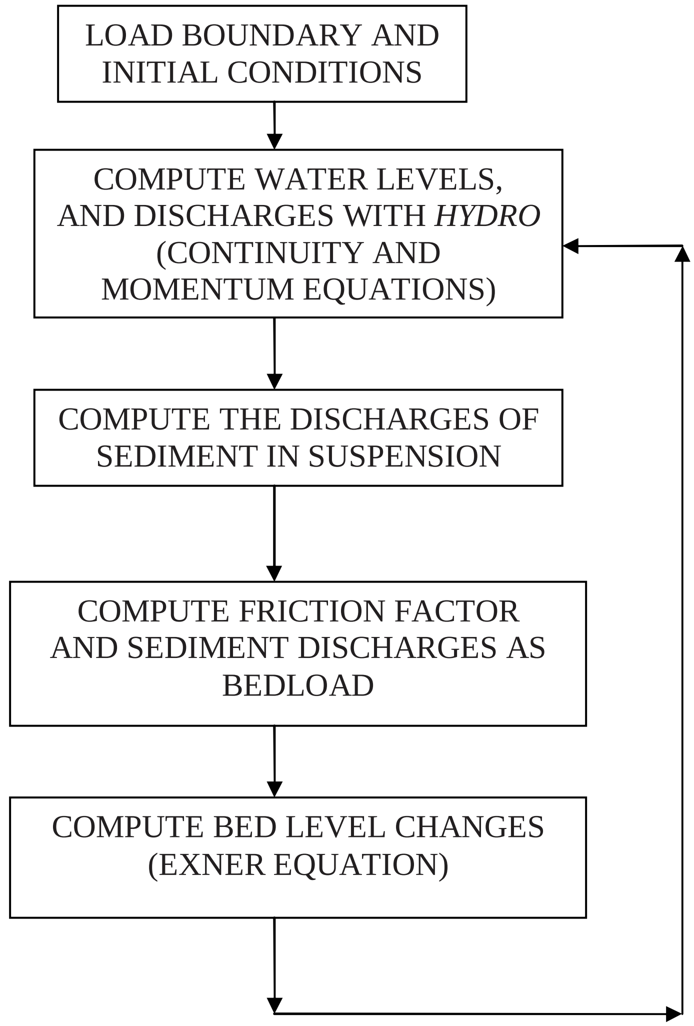

Figure 2. Flow-chart of the resulting code with the addition of SEDITRAN.

Task 3: Inventory of datasets including information on sediment transport in the Delta

In this task, we plan to organize an inventory of datasets associated with sediment transport in the Delta. We will analyze, classify, and store the data in a repository. A webpage will be created with a link to the DWR webpage allowing access to the repository. UC Davis possesses repositories where key information can be located and accessed relatively easily.

Task 4: Selection of scenarios from the datasets related to sediment transport corresponding to the Delta and validation of the model with those datasets

The USGS has been collecting data on sediment transport in the Delta since 1998, via the use of Optical Backscatter Sensors (OBS) (Wright and Schoellhamer, 2005). OBS outputs, expressed in milivolts (mV), can be assumed to be "linearly proportional to suspended-solid concentrations” (http://ca.water.usgs.gov/program/sfbay/calfedsed/obstuff/sed_pulses.html). Prof. David Schoellhamer, Adjunct Professor at UC Davis, has been the coordinator of those measurements. The observations were made at the stations in Freeport and Rio Vista on the Sacramento River, and at Jersey Point and Stockton on the San Joaquin River. Also, there is a station at Three-Mile Slough, close to the San Joaquin River.

According to the information collected by the USGS, the Sacramento River is the primary contributor of suspended sediment to the Delta, carrying a sediment load about 7 times greater than that of the San Joaquin River (Schoellhamer and Dinehart, 2000). During a flow pulse past Freeport, two peaks in suspended-sediment concentration are usually observed, separated by 4 to 5 days. As flow increases, resuspension decreases the supply of erodible sediment on the bed, and the first peak begins to diminish in 1 to 2 days.

It is proposed herein to simulate the events collected from 1998 to 2002, in order to assess the quality of the prediction of the model. One of the goals of this validation is to address the onset of hydrodynamic and sediment-transport conditions under which the above peaks occur.

Task 5: Application of the resulting numerical model to assess historical and future conditions in the Delta

Diverse scenarios of interest will be defined in dialogue with DWR. In order to be more specific, a scenario associated with dredging activities in the Stockton ship canal will be simulated. An imposed decrease of the location of the bed along the dredged reach, and the associated source of sediment will be implemented in the code to simulate this case.

Other scenarios dealing with the fate and transport of sediment coming from marsh restoration and levee breaches will also be simulated. For these cases, sources of sediment will be located at convenient nodes in the model, and the code will compute where these sediment particles deposit.

SCHEDULE FOR THE TASKS AND DISSEMINATION OF RESULTS

The planned activities for the 5 tasks will span two years, as follows:

Qtr/ Task	1	2	3	4	5	6	7	8
1	XX	XX	XX	XX	XX	XX		
2		XX	XX	XX	XX	XX		
3	XX	XX	XX	XX				
4			XX	XX	XX	XX	XX	XX
5			XX	XX	XX	XX	XX	XX

Table 1: Task scheduling for the project.

Dissemination of results

The following stages are envisioned for dissemination of the results of the proposed project:

a) The findings of the research will be communicated at national and international conferences. In addition, they will be published in international, peer reviewed scientific journals.
b) The results will be communicated to DWR through semi-annual reports. Periodic meetings with researchers of DWR will be hosted at Davis.
c) The results will be also presented at meetings of DSM2, and at meetings of the California Water and Environmental Modeling Forum (CWEMF).

REFERENCES

Altinakar, M., and Graf, W. H. (1998). *Fluvial hydraulics*. John Wiley and Sons.

Bombardelli, F. A., Menéndez, A. N., Brea, J. D., Lapetina, M. R., and Uriburu Quirno, M. (1995). "Hydrodynamic Study of the Paraná River Delta" Reports LHA-INCYTH 137-01/03-95, National Institute for Water, Ezeiza, Argentina (3 different reports).

Bombardelli, F. A., Menéndez, A. N., and Brea, J. D. (1997). "A mathematical model for the lower Paraná River Delta." in *River Flood Hydraulics*, J. Watts (Ed.), *Proc. 3rd Int. Conf. on River Flood Hydraulics*, Stellenbosch, South Africa, pp. 137-146.

Cui, Y., Parker, G., and Paola, C. (1995). "Numerical simulation of aggradation and downstream fining." *J. Hyd. Res.*, 34(2), 185-204.

Cunge, J. A., Holly, F. M., Verwey, A. (1980). *Practical aspects of computational river hydraulics*. Pitman Publishing Inc., Boston, MA.

Dietrich, W. E. (1982). "Settling velocity of natural particles." *Water Resour. Res.*, 18(6), 1626-1636.

DHI Mike 11 Sediment Transport Short Description, Mike 11 ACS & GST – Cohesive and non-cohesive sediment transport model. DHI Water and Environment.

Fletcher, C. A. J. (1997). *Computational techniques for fluid dynamics*. Springer.

García, M. H., and Parker, G. (1991). "Entrainment of bed sediment into suspension." *J. Hyd. Eng.*, ASCE, 117, 414-435.

García, M. H., and Parker, G. (1993). "Experiments on the entrainment of sediment into suspension by a dense bottom current." *J. Geophysical Research-Oceans*, *98*, 4793-4807.

García, M. H. (1999). Lecture notes on sediment transport. Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign.

Holly, F. M., Yang, J. C., Schwarz, P., Schaefer, J., Hsu, S. H., and Einhellig, R. (1990). "CHARIMA. Numerical simulation of unsteady water and sediment movement in multiply connected networks of mobile-bed channels." IIHR Report No. 343, Iowa Institute of Hydraulic Research, University of Iowa.

Julien, P. Y. (2002). *River mechanics*. Cambridge Press.

Ligget, J. A., and Cunge, J. A. (1975). "Numerical methods of solution of the unsteady flow equations." Chapter 4 in *Unsteady flow in open channels*, Water Resources Publications, Fort Collins, Colorado.

Lund, J. R., Hanak, E., Fleenor, W., Howitt, R., Mount, J., and Moyle, P. (2007). *Envisioning futures for the Sacramento-San Joaquin Delta*, Public Policy Institute of California.

Lyn, D., and Goodwin, P. (1987). "Stability of a general Preissman scheme." *J. Hyd. Eng.*, ASCE, 113(1), pp. 16-28.

Newton, C. T. (1951). "An experimental investigation of bed degradation in an open channel." Trans., Boston Society of Civil Engineers, 28-60.

Parker, G. (2004). "1D sediment transport morphodynamics with applications to rivers and turbidity currents." e-book downloadable at: http://cee.uiuc.edu/people/parkerg/morphodynamics_ebook.htm

Rutherford, J. C. (1994). *River mixing*. John Wiley & Sons, England.

Schoellhamer, D. H., and Dinehart, R. L. (2000). "Suspended-sediment supply to the Delta from the Sacramento River." CalFed Science Conference, October.

Smith, P. (2007). "A hydrodynamic 3-D model for the San Francisco Bay." USGS Report (in preparation).

Soni, J. P., Garde, R. J., and Ranga Raju, K. G. (1980). "Aggradation in streams due to overloading." *J. Hyd. Div.*, ASCE, 106(HY1), 117-132.

Soni, J. P. (1981). "Unsteady sediment transport law and prediction of the aggradation parameters." *Water Resour. Res.*, 17(1), 33-40.

Wu, W., and Vieira, D. A. (2002). One-dimensional channel network model CCHE1D Version 3.0. Technical Manual.

Wrigth, S., and Schoellhamer, D. H. (2005). "Estimating sediment budgets at the interface between rivers and estuaries with application to the Sacramento-San Joaquin River Delta." *Water Resour. Res.*, 41, W09428.

Investigator Overall Research Experience

Dr. Bombardelli is an Assistant Professor at the Department of Civil and Environmental Engineering at the University of California, Davis. His expertise includes computational fluid dynamics (CFD), computational hydraulics, river mechanics and water quality, turbulence physics, multi-phase flows, environmental hydrodynamics, and flow resistance. He has wide experience in dealing with the development, analysis and use of multi-dimensional open-source and commercial codes for the solution of problems associated with hydrodynamics, sediment transport and water quality in rivers, lakes, and estuaries. As part of his work in Argentina, he developed numerical models for most of the large water courses in the country, including the Paraná, Uruguay, and de la Plata Rivers. Additionally, he developed multi-phase models for aeration bubble plumes as part of his Ph.D. research, and developed a three-dimensional model of density currents for the Chicago River, Illinois. He also participated on a project on dam removal in Illinois, where the main concern was the fate and transport of sediment accumulated behind the dam, after the removal. To this end, he developed his own 1-D code.

Prof. Bombardelli's research has been supported by Caltrans, DWR, CICEET (The Cooperative Institute for Coastal and Estuarine Environmental Technology), and SNPLMA (Lake Tahoe).

Student Training

Prof. Bombardelli will advise one student. While no particular student has been identified yet for the research, it is expected that he/she will be an international student.

BUDGET

	Year : January 1, 2008 – December 31, 2008			Year : January 1, 2009 – December 31, 2009		
	Time (mo)	Rate	Cost	Time (mo)	Rate	Cost
Dr. Fabián A. Bombardelli	1	7,438	7,438	1	7,661	7,661
Graduate Student (GSR) – Step III (50%)	12	1,538	18,456	12	1,584	19,009
Salary total	---	---	25,894	---	---	26,671
Benefits total (PI at 12.7% ; GSR III at 1.3% academic, 3% summer)	---	---	1,263	---	---	1,301
Supplies	---	1,000	1,000	---	1,000	1,000
Travel	---	500	500	---	500	500
Equipment	---	---	---	---	---	---
Graduate student fee remision (GSFR)	---	2,490/ qtr	7,470	---	2,565/ qtr	7,694
Non-resident tuition remision (NRTR)	---	4,898/ qtr	14,694	---	5,045/ qtr	15,135
Total direct costs	---	---	50,821	---		52,301
Indirect costs (25% MTDC)	---	---	12,705	---	---	13,075
TOTAL PER YEAR			63,526			65,376
TOTAL BUDGET						**128,902**

The total budget amounts to $128,902.

Budget Justification

Personnel. The PI will plan, coordinate, and supervise the research to accomplish the objectives of this work. One month summer salary is kindly requested per year. One Graduate Student Researcher, Step III, will receive support at 50% for the four academic quarters each year. The graduate student will assist the PI in performing all modeling and analysis activities. A 3% increase per year has been included in year 2.

Fringe Benefits. Benefit rates are expressed as a percent of salaries. Rates were applied to the graduate student researcher title at 1.3% during the academic year, and 3% during the summer. For the PI, rates were of 12.7%.

Supplies and expenses. Funds for fax, Fedex, and report preparation are kindly requested.

Travel. A modest amount of funding is requested for travel.

Student Fee Remission. Based upon the University's projected fee rates, In-State fees of $7,470 for the first year (and $7,694 for the second year) are being requested to cover three academic quarters for the graduate student. Non-resident fees for the international student are being requested in the amount of $14,694 for the first year (and $15,135 for the second year).

Because fees are subject to gubernatorial, legislative, and regental action, these fees may change without notice.

Principal Investigator's Qualifications:

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EDUCATION

- *Ph.D. in "Civil and Environmental Engineering,"* University of Illinois, Urbana-Champaign, USA (May 2004; defended September 15, 2003). GPA: Perfect score, 4.0/4.0.
  Dissertation: "Turbulence in multiphase models for aeration bubble plumes."
  Advisor: Prof. Marcelo H. García.
- *Master in "Numerical Simulation and Control,"* University of Buenos Aires, Buenos Aires, Argentina (defended January 5, 1999). Average grade: 8.33/10.
  Dissertation: "A quasi-three-dimensional model for the simulation of wind-induced shallow-water flows." (In Spanish.)
  Advisor: Prof. Angel N. Menéndez (Ph.D. University of Iowa, USA, 1983). This Master degree was chartered in 1996. I was the first student to be awarded this degree.
- Thesis of Scholarship, National Institute for Water (INA), Argentina (1993).
  Title: "Quantification of the pollutant transport in Blanca Bay." (In Spanish.)
  Advisor: Prof. Angel N. Menéndez.
- *Hydraulic Engineer* (a six-year program; equivalent to a Master degree), National University of La Plata, Argentina (1991). Average grade: 9.42/10. 9 more courses were attended, pertaining to the Civil Engineering field.

RESEARCH INTERESTS

Computational fluid mechanics, computational hydraulics, environmental fluid dynamics, river mechanics and water quality, multi-phase flows, turbulence physics, scaling, open-channel flow resistance.

MAIN PROFESSIONAL AND RESEARCH EXPERIENCE

- Assistant Professor, Dept. of Civil and Env. Eng., University of California, Davis, January 2004 to date.
- Research Assistant, University of Illinois, Urbana-Champaign, August 1998 to December 2003.
- National Institute for Water (1992 to 1998; from 1992 to 1993, in use of a scholarship), Argentina.
- Bureau of Public Roads of Buenos Aires Province (1989 to 1991) as an undergraduate student, Argentina.
- Consultant in hydraulics (sewage systems, 1993), flooding in urban areas (1994), and coastal engineering (1997), employing numerical and theoretical techniques. Consultant in structural design (1993 and 1997).

TEACHING EXPERIENCE

- Invited Visiting Professor, University of Concepción, Chile, September and October 2006. Two short courses were taught on “Water Resources Simulation,” and “Introduction to the theory of sediment transport.”
- Instructor of the following courses at the Department of Civil and Environmental Engineering, University of California, Davis: ECI 146, “Water resources simulation;” ECI 289B, “Urban hydraulics and hydrology;” ECI 279, “Advanced mechanics of fluids;” ECI 278, “Geophysical fluid dynamics.” Instructor of a Freshman Seminar on “Computing in Civil Engineering,” together with Profs. YueYue Fan and Amit Kanvinde.
- Teaching Assistant of CEE 353, “Analysis and design of hydraulic systems,” Prof. Marcelo García, instructor, Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign.
- Associate instructor in *international* courses. Instructor and associate instructor of several *graduate* courses in Argentina. Teaching assistant of diverse *undergraduate* courses in Argentina.

AWARDS, HONORS AND RECOGNITIONS

In United States:

- Nominated for the Straub Award to the best Ph.D. thesis in hydraulic engineering of year 2004, University of Minnesota (pending).
- Guest Editor of Special Issue of the journal Environmental Fluid Mechanics.
- Invited, voted Member of the Hydraulic Structures Section of the IAHR (2007-).
- Invited Member of the Scientific Committee of River Flow 2008, to be held in Turkey.
- Invited Member of the Editorial Board of the Open Journal of Civil Engineering (2007-).
- Invited Member of the Scientific Committee and session organizer of ENIEF 2006, XV Congress on Numerical Methods and their applications, Santa Fe, Argentina, November 2006.
- Invited Chairperson and Contributor (invited paper) in the Int. Conference of HydroScience and Engineering, Philadelphia, PA, September 2006.
- Invited Member of the Scientific Committee and session organizer of MECOM 2005, VIII Congress on Computational Mechanics, Buenos Aires, Argentina, November 2005.
- Invited Chairperson, XXXI IAHR Congress, Seoul, Korea, September 2005.
- John Muir Fellowship awarded to my student Arash Massoudieh, 2005.
- Invited Keynote Speaker in ENIEF’04, XIV Congress on Numerical Methods and their applications, San Carlos de Bariloche, Argentina, November 2004; Member of the Scientific Committee of the congress, and session organizer.
- Voted Member of the Hydrologic Sciences Graduate Group, University of California, Davis, June 2004.
- *Marquis Who’s Who in Science and Engineering*, 2005-2006 issue; 2007-2008. *Marquis Who’s Who in America*, 2004-. *Marquis Who’s Who in the World*, 2005.
- *Finalist Award* in the 11th Student Technical Paper Competition, 2003 ASME Pressure Vessels and Piping Conference, Cleveland, OH, ASME International (July). Paper entitled: "Parallel computations of the dynamic behavior of bubble plumes."
- *First Prize* (Best Paper) in the Student Technical Paper Competition for the 2003 World Water & Environmental Resources Congress, Philadelphia, PA, EWRI/ASCE (June). Paper

entitled: “Characterization of coherent structures from parallel, LES computations of wandering effects in bubble plumes.”

- *Glenn and Helen Stout Water Resources Research Award* for “academic achievement and outstanding research in hydrosystems,” 2001, Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign.
- Honor Society Phi Kappa Phi (since 2000).

In Argentina:

- *Outstanding-performance award*, SINAPA, National Institute for Water, 1994.
- Member of the Scientific Committee of the 7th. Int. Conf. on Lake Management and Conservation, San Martín de los Andes, Argentina, 1997. Rapporteur during the conference.

REFEREE WORK

Water Resour. Res. (1999, 2005, 2006); ASCE J. Hydr. Eng. (2001 to 2007); IAHR J. Hyd. Res. (2002 to 2007); Int. J. for Sediment Research, China (2002), Special issue; Transportation Research. Part B (2004); Nordic Hydrology (2004); ASME Journal of Applied Mechanics (2004, 2005); Environmental Modelling and Software (2004); Computers and Fluids (2005); Water Research (2006, 2007); ASCE J. Env. Eng. (2006); J. Fluid Mechanics (2006-2007); ASCE J. Hydrological Eng. (2006); Geophysical Review Letters (2006); Physics Fluids (2007); Advances in Water Resources (2007); European J. Mechanics – B (Fluids) (2007); Scientia Iranica (2007).

PAPERS AND DISCUSSIONS IN INTERNATIONAL JOURNALS

1) **Bombardelli, F. A.**, Hirt, C. W., and García, M. H. (2001). “Discussion on ‘Computations of curved free surface water flow on spiral concentrators,’ by B. W. Matthews, C. A. J. Fletcher, A. C. Partridge, and S. Vasquez.” *J. Hyd. Engrg.*, ASCE, 127(7), pp. 629-631.

2) Gioia, G., and **Bombardelli, F. A.** (2002). “Scaling and similarity in rough channel flows.” *Phys. Rev. Letters*, 88(1), 014501.

3) Wade, R. J., Rhoads, B. L., Rodríguez, J. F., Daniels, M., Wilson, D., Herricks, E. E., **Bombardelli, F. A.**, García, M. H., and Schwartz, J. (2002). “Integrating science and technology to support stream naturalization near Chicago, Illinois.” *J. American Water Resources Association*, AWRA, 38(4), pp. 931-944.

4) Buscaglia, G. C., **Bombardelli, F. A.**, and García, M. H. (2002). “Numerical modeling of large-scale bubble plumes accounting for mass transfer effects.” *Int. J. Multiphase Flow*, Elsevier, 28(11), pp. 1763-1785.

5) **Bombardelli, F. A.** (2003). “Review of the book ‘The hydraulics of stepped chutes and spillways,’ by Hubert Chanson.” *J. Hyd. Res.*, IAHR, 41, pp. 327-328.

6) **Bombardelli, F. A.**, and García, M. H. (2003). “Hydraulic design of large-diameter pipes.” *J. Hyd. Engrg.*, ASCE, 129(11), pp. 839-846.

7) Rodríguez, J. F., **Bombardelli, F. A.**, García, M. H., Frothingham, K., Rhoads, B. L., and Abad, J. D. (2004). “High-resolution numerical simulation of flow through a highly sinuous river reach.” *Water Resources Management*, Kluwer Academic Publishers, 18, pp. 177-199.

8) **Bombardelli, F. A.**, and García, M. H. (2005). “Closure to Discussion of ‘Hydraulic design of large-diameter pipes,’ by Thomas Walski.” *J. Hyd. Engrg.*, ASCE, 131(3), pp. 224-225.

9) Gioia, G., and **Bombardelli, F. A.** (2005). “Localized turbulent flows on scouring granular beds.” *Phys. Rev. Letters*, 95, 014501.

10) Gioia, G., Chakraborty, P., and **Bombardelli, F. A.** (2006). “Rough-conduit flows and the existence of fully developed turbulence.” *Phys. Fluids*, 18, 038107.

11) **Bombardelli, F. A.**, and Abrishamchi, A. (2006). “Numerical simulation of standing waves driven by surface jets.” Chapter 28 in *Coastal Hydrology and Processes*, V. P. Singh, and Y. J. Xu (Eds.), Water Resources Publication, LLC, Highlands Ranch, CO, pp. 343-354.

12) **Bombardelli, F. A.**, and Gioia, G. (2006). “The scouring of granular beds by jet-driven axisymmetric turbulent cauldrons.” *Phys. of Fluids*, 18, 088101.

13) Rhoads, B. L., García, M. H., Rodríguez, J. F., **Bombardelli, F. A.**, Abad, J. D., and Daniels, M. (2007). “Methods for evaluating the geomorphological performance of naturalized rivers: examples from the Chicago Metropolitan Area.” In: *Uncertainties in River Restoration*, D. Sears, and S. Darby (eds.), John Wiley and Sons, Chichester, U.K. (book chapter).

14) **Bombardelli, F. A.**, Buscaglia, G. C., Rehmann, C. R., Rincón, L. E., and García, M. H. (2007). "Modeling and scaling of aeration bubble plumes: A two-phase flow analysis." In press, *J. Hyd. Res.*, IAHR.

15) **Bombardelli, F. A.**, and González, A. E. (2007). "Discussion on 'Analytical appraoch to calculate rate of bank erosion' by J. G. Duan." accepted for publication, *J. Hyd. Engrg.*, ASCE.

16) **Bombardelli, F. A.**, Buscaglia, G. C., García, M. H., and Dari, E. A. (2007). "Simulation of bubble-plume wandering using a k-epsilon model and a Large-Eddy-Simulation (LES) approach." under review, *J. Applied Mech.*, ASME.

17) **Bombardelli, F. A.**, González, A. E., and Niño, Y. I. (2007). "Non-linear, Lagrangian theoretical models for particle motion close to solid boundaries." under review, *J. Hyd. Engrg.*, ASCE.

18) **Bombardelli, F. A.**, Cantero, M. I., García, M. H., and Buscaglia, G. C. (2007). "Numerical aspects in the simulation of saline underflows." under review, *J. Hyd. Res.*, IAHR.