Paper - SIMULATION OF SEDIMENTATION PROCESSES IN RIVER PLATE´S WATERWAYS, 15 YEARS OF HISTORY

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ABSTRACT: Sedimentation processes that occur in Rio de La Plata´s waterways are mainly determined by fine sediment phenomena. For more than 15 years, EIH SA has developed and improved simulation tools specially designed for River Plate´s special characteristics. The present paper describes the distinctive features of the developed tool and its implementation. In addition, the model application to several dredging projects is included, along with satisfactory comparisons between modeled sedimentation results and dredging records.

1. RIO DE LA PLATA, A COMPLEX ESTUARY

In a general way, the Río de La Plata river is part of the homonym estuary, whose behavior is influenced both by the contribution of Parana river and Uruguay River, and by tide waves coming from the Atlantic Ocean.

The tidal regime is of daily differences, having every day both two high tides and two low tides, all of a different magnitude. The tide wave that comes from the ocean, takes approximately twelve hours to travel along the 280km river length up to the interior limit, so that at every moment, there is a whole tide cycle at the river, with the existence of both a high tide and a low tide at the same time.

In addition to the astronomic tides, the winds play an important role on the water surface elevation inside the river. In this way, when winds blow from the East-Southeast / South-Southeast quadrant, water piles up over the coast, resulting in a rise of levels that could be much higher than normal tides when winds and storms come directly from the South-Southeast direction.

On the contrary, when winds blow from the West-Southwest / Northwest quadrant, very low levels are observed, with magnitudes varying with wind intensity and duration. It should be noticed that level variations due to meteorological phenomena may reach amplitudes of up to 4m.

Currents present a relatively more steady component due to river outflows, and an impermanent component whose value fluctuates with tides. Logically, as much as it reaches the external limit, the estuary widens, it becomes deeper, and indeed the river flows component loses importance, with the exception of the waterways, which behave as extensions of rivers and carry the most important flows. It must be pointed out that many times, after that water has piled up due to winds, when these stop blowing, very important return currents are produced, with high speeds that in many cases don´t let tide currents develop. This also happens in situations of unaffected tides, when return currents are even higher than river currents.

Finally, wind generated waves, both inside the estuary and the ones that come in from the ocean and propagate inside, together with speeds produced by tide currents and river currents, shape the complex agitation state, present in the Río de La Plata Estuary.

Río de La Plata sediments are originated in the inflows of the confluent rivers and have the main feature of their fine structure. Indeed, they are constituted of fine sands, silt and clay in high proportions, what produces a high concentration of suspended sediments, with values that vary between 150ppm and 300ppm. The level of pollution of the sediments, is strictly associated to areas where they are transported and deposited, finding high levels of pollution in coastal areas, while in further away areas, it disappears

2. SEDIMENTATION PROCESSES

Sediment transport is a complex physical process that is mainly governed by the sediment properties and the flow turbulence and associated shear stresses. In very general terms, sedimentation and erosion happen due to differences in sediment transport capacity of the flow turbulence over time. More specifically for waterways, when flow goes through a channel or deeper zone, transport capacity inside it becomes lower than outside, due to the decrease in velocity and the increase in depth. Because of this, turbulence is not capable of retaining the same amount of solids in suspension, consequently depositing the excess on the waterway bed. The sediment transport analysis then requires to be capable of modeling transport capacity, which varies from time to time, as long as currents and water elevations change.

Transport capacity depends on flow speed, depth, bottom roughness, sediment grain size distribution, and wave climate in a complex interaction. Therefore, we need to have a good representation of the hydrodynamics that govern the area and a good algorithm to represent thetransport capacity. It is important to note, however, that the adapting process between one certain transport capacity and another is not instantaneous, as it is calculated in many sedimentation models. Indeed, the adaptation depends on settling velocity of suspended solids, which at the same time depend on the grain size and the present turbulence. This fact is vital if we wish to model sedimentation processes in case of very fine sediments, as it is the case in the area of interest.

In the Rio de La Plata river, where many navigation channels can be found, dredged at different depths, all studies require detailed knowledge of the present currents (speed and direction), as well as types, quantities and special features of the transported sediments, both as bed load and wash load. Every hydrodynamic action, together with present waves, affect both transported sediments and bed sediments.

In the studied area, two mail channel systems can be found. One along the uruguaian coastline, formed by Martín García Channels, which take along from the confluence of Uruguay river up to Km 39, in front of Colonia city; and another along argentinian margin, made up by Emilio Mitre Channel, Acceso Channel, and Punta Indio Channel, which extend from the confluence of the Parana de Las Palmas River up to km 239.1, the outer limit of the estuary

Figure 1: Waterway network present at the River Plate.

That is the reason why many years of investigations and efforts have been carried out, starting more than 15 years ago, when the main objective was to develop a simulation tool that could work along with the complex hydrosedimentological processes, including the simultaneous variations on fluxes, wave actions and present grain sizes.

3. THEORETICAL BASIS OF THE MODEL

During the early 1990s several sediment transport models were tested by EIH S.A. and were found to have severe modeling artifacts close to the navigation channel. When currents flow through a navigation channel these models would predict very high deposition upstream, due to the abrupt change of depth and consequent reduction in transport capacity. Then, the opposite would happen on the downstream side of the channel, sediment transport capacity would increase rapidly generating deep erosion. This not realistic behavior originated in the assumption that the transport capacity was instantaneously in equilibrium in the water column (i.e. at all times the suspended sediment equals the transport capacity). This is a reasonable assumption in practice for relatively coaser sediments, but not for the very fine sediments of the Rio de La Plata (65% to 70% clay). Therefore, a sediment transport model was developed with an algorithm that will take into account the time that it takes for the suspended sediments to adjust to the new turbulence conditions.

This tool, completely developed by EIH SA, consists of an advective-dispersive transport algorithm (called EIH-AD32) in which the sources and sinks terms can represent multiple substances either dissolved or suspended. In this case, the applied module is the sediment transport one called EIH-TS. This transport model is coupled with a hydrodynamic model tool, which provides the current and speed fields have already been calculated.

The model resolves the transport equation using a finite difference third order algorithm, named QUICKEST, which also has a control algorithm that avoids typical numerical diffusions of eulerian solutions to the transport equation. In that way, the transport of almost any substance can be modeled with high accuracy.

The differential equation that describes the transport phenomena is a mass conservation equation in which sources or sinks of certain amount of substances are included, along with a term that takes into account the analyzed substance decay. In the case of the sediment transport phenomena, the decay term refers to sedimentation or resuspention of river bed solids.

In a general way, the equation is:

$$\frac{\partial}{\partial t}(hC)+\frac{\partial}{\partial x}(uhC)+\frac{\partial}{\partial y}(vhC)=\frac{\partial}{\partial x}\left[hD_x\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[hD_y\frac{\partial C}{\partial y}\right]-D+S$$

where:

C: concentration (arbitrary units, ej. g/m3).
u,v: horizontal flow speed components, over x and y directions (m/s).
h: water depth (m)
Dx, Dy: dispersion coefficients, over x and y directions (m2/s)
D: sedimentation term (g/m2/s)
S: source (or sink) term (g/m2/s).

The first member of the equation expresses local and convective variation of concentration, that is to say, time and space variations, while the second member includes the dispersion driven variation, to which both decay (in our case due to deposition of particles on the river bed), and solid discharge contribution through a source are added.

The numerical solution to this equation is achieved through its finite difference discretization over a rectangular grid with Δx and Δy spacing, that covers the whole area of interest.

In the particular case of sediment transport analysis, it is also necessary to model the transport capacity, which is time variable, as long as currents and water level vary. Transport capacity then depends on flux speed, depth, bottom roughness, grain size of the studied sediment and wave action.

3.1 Sedimentation module

The transport equation that the EIH-AD32 model uses, has a term that represents the solid load that flows from bed towards water column and vice versa. In another word, this term controls the amount of deposition or resuspention of sediments. In order to calculate the value of this term, the EIH-TS module is used, which works as transport model module. The theoretical basis of this model has its origin in an adaptation of the calculus method developed by Fredsoe (1976, 1984) to calculate channel sedimentation. In the next paragraphs the method is explained.

Suspended wash load has a certain vertical distribution that depends on the grain size and the studied flow velocity (Rouse 1937).If by any chance the hydrodynamic flow conditions are changed, then a variation in its transport capacity is produced, along with a consequent variation in the amount of wash load and its vertical distribution.

However, the adaptation of sediments to these new hydrodynamic conditions is not instant, since it depends mostly on grains´ settling velocity. In the case of the Río de La Plata´s sediments, this speed stays lower than 0,0003m/s, a fact from which it can be concluded that adaptation time is not negligible.

For this reason, the following explained method pretends to analyze this temporal stage and quantify the sedimentation that occurs during it.

3.2 General Sedimentation Term

As commented before sedimentation or erosion is related to changes in the hydrodynamic field between two different locations or timesteps. Therefore, two equilibrium situations are defined, one related to the initial hydrodynamic condition and another related to the hydrodynamic conditions to be achieved.

The equilibrium concentration arises from the solution of the following differential equation that represents the balance at steady state between settling velocity and turbulence diffusivity:

$$Cw+\varepsilon\frac{dC}{dz}=0 \qquad \text{Eq. 1}$$

where:

w: settling velocity in still water, function of particles´ grain size.
ε: vertical eddy viscosity/diffusivity.

$$\varepsilon=\frac{0.4u_*h}{6} \qquad \text{Eq. 2}$$

A solution to this differential equation is:

$$C(z)=C_b e^{(-\frac{w}{\varepsilon}z)} \qquad \text{Eq. 3}$$

Where Cb refers to concentration adjacent to the bottom and z is the vertical ordinate, taken positive from the bottom.

Equation 3 is only applicable if eddy viscosity is taken constant (as expressed in Eq. 2). In most of flows, vertical eddy viscosity varies with height. In these cases, solution to equation 1 becomes the following expression, explained by Rouse (Vanoni, 1977):

$$C(z) = C_b \left[\frac{h-z}{z} \frac{r}{h-r} \right]^{\alpha} \qquad \text{Eq. 4}$$

where:

h refers to depth at the analyzed location

r refers to distance from the bottom in which C = Cb, which, based in available bibliography is highly variable and depends mainly on the suppositions made when calculating bottom concentration.

$$\alpha = \frac{w}{\kappa \, v_*}$$

κ = Von Karman constant = 0,4 (clear water)

v* = current and waves friction velocity

The above expressions allow calculation of vertical distribution of sediments in equilibrium from the initial values of bottom concentration. Calculation of the bottom concentration is maybe one of the most delicate parts of the whole sedimentation model and will be analyzed in detail in paragraph 4.1.2.

Widely used available sedimentation models usually restrict calculations to these equilibrium concentrations and their distribution. In fact, these models estimate sedimentation from calculating different equilibrium conditions and then assuming that changes between these ones is instant. By knowing that this fact may alter final results, especially in cases of fine sediments, a special method that takes into account the adapting time to new conditions was used.

If a two-dimensional flow is considered in x-z plane, then the mass conservation differential equation, considering a constant eddy viscosity/ diffusivity coefficient is:

$$\frac{\partial C}{\partial t} = w \frac{\partial C}{\partial z} + \varepsilon \nabla^2 C \qquad \text{Eq. 5}$$

Assuming local velocity changes are negligible in contrast to convective acceleration, then a general solution to equation 5 is:

$$C = Ke\left(-\frac{w}{\varepsilon} z \right) + f(z) e^{-\lambda x} \qquad \text{Eq. 6}$$

Where K y λ are taken constant and f(z) is an unknown function. Then, if equation 6 is put in differential equation 5, we get another differential equation in terms of f(z):

$$\frac{d^2 f}{dz^2} + w \frac{df}{dz} + \left(\varepsilon \lambda^2 + \mu \lambda \right) f = 0 \qquad \text{Eq. 7}$$

If this equation is solved to get f(z), and the appropriate boundary conditions are chosen, it is possible to get the unknown constants. In this way, assuming that vertical velocities are negligible to horizontal velocities, and integrating vertically, the following equation is reached:

$$C = C_2 + \left(C_1 - C_2 \right) f(w, \varepsilon, t) \qquad \text{Eq. 8}$$

Where

C is the vertically integrated concentration after a certain time lapse t

C1 is the vertically integrated concentration at initial time step t0.

C2 is the equilibrium concentration that corresponds to the dominant hydrodynamic conditions.

f(w,ε,t) is an adaptation function that depends on the passed time, on the sediments settling velocity and on turbulence.

If this equation is analyzed from a Lagrange´s focus, that is to say with an ordinate system moving along with particles, the C2 would represent the equilibrium concentration for the new condition and C1 would be the initial equilibrium concentration. When applying this to the channel analysis, C1 would represent the equilibrium situation of sediments outside the channel, and C2 would be the equilibrium concentration to be reached if the dominant conditions inside the channel were maintained for a long period.

In order to be able to apply this to a Euler´s model, C2 is taken as the equilibrium condition at the calculation location, and C1 would be the vertically integrated concentration at that same location. So in this way, the new vertically integrated concentration C in such calculation point would be the previous concentration C1 with the corresponding corrections to reach C2 by the adaptation function f that depends on elapsed time, grain size and eddy viscosity.

It should be remarked that the previous numerical methodology requires that Courant number (U*delta t / delta x) is lower than 1 at every time step in order to work correctly.

What is left, then, is to explain how the equilibrium concentration is obtained for every hydrodynamic condition and for each particle diameter

3.3 Calculation of the equilibrium concentration

It is vital to calculate for every flow condition, water level condition and grain size, the equilibrium concentration. That is why, as it was descripted before, it is necessary to know the bottom concentration and its vertical distribution.

The sedimentation model uses the Bijker-Einstein formula, named equation 9, to calculate bottom concentration. In this equation, it is assumed that bottom concentration is acceptable up to a distance from the bed equal to roughness r.

$$C_b = \gamma_d \frac{B\, d_{50}}{r} e^{\left[\frac{-0{,}27\,\Delta\, d_{50}\, g}{\mu\, v_*^2}\right]} \qquad \text{Eq. 9}$$

Where:

γd specific dry weight of the settled material.

d50 particle diameter for which the 50% of the sample, in terms of weight, is smaller.

B empirical constant

r bottom roughness

Δ relative density of bed load

μ bed forms coefficient

v* friction velocity due to wave action and currents.

Before the model was developed, this equation had already been used with good results in previous projects both in Bahia Blanca´s access channel and Río de La Plata river, and for this reason was considered suitable.

As it can also be seen, the equation includes wave shear action´s effect on sediment resuspention. Waves, defined by significative height and period, are included to calculate a certain factor (greater than 1) that increases shear velocity produced only by currents (Bijker, 1967).

Once the bottom concentration at every location of the model and for every time step has been obtained by use of equation 9, it is possible to obtain vertical distribution by use of equation 4. Since the developed model considers a two-dimensional model that integrates vertically, then the obtained distribution is integrated for the whole depth. This value corresponds to the C2 value used in equation 8, and is the one that allows the calculation of vertical transport, either for depositing or resuspending material.

However, if equation 9 is looked in detail, it can be noticed that diameter d50 has to be introduced (where d50 represents a diameter for which 50% of a sample is smaller). This parameter is quite misleading, because the whole sample is taken as if it had a uniform diameter. For this reason, the model has been designed in such way that the sample is divided into several sections, and d50 of each section is taken for each simulation. The final results are achieved by addition, assigning a weight to each individual result, depending on the proportion that each section represents.

On the other hand, equation 9 is only applicable for mostly thicker diameters. For this reason is that bottom concentration can be defined analytically, since for finer diameters wash load does not allow a calculation only dependant on physical characteristics of the environment. This inability to calculate bottom concentration for fine sediments prevents calculation of its vertical average concentration, although its distribution is known from Rouse´s formula. So, in order to model fine sediments, many correlations that permit to estimate average concentration for any hydrodynamic and wave condition, based on available concentration; velocity and wave action measurements, were used.

In such way, calculations of equilibrium concentration for hydrodynamic situations that are different from the measured ones is done by adapting bottom concentration and vertical distribution to this hydrodynamic differences. Vertical distribution is considered as Rouse´s formula states, that is to say with variations depending on depth and shear velocity. Bottom concentration, on the contrary, is taken as a variable dependant on relations of shear stress due to wave and current action, between the simulated situation and the measured situation, with special attention on most of the available bed load transport equations, that relate this transport to shear stress.

Finally, it is possible to get the vertically integrated equilibrium concentration to use as input for the sedimentation module, either relatively fine or thick sediments are analyzed. This module works as input for the transport model, and in this way the calculation scheme is complete.

3.4 Side slope driven sedimentation

Due to gravity forces, sediment particles laying over side slopes tend to be moved towards the channel. This type of sedimentation is more important when main currents have the same direction as the channel alignment.

For this case, a Fredsoe (1978) expression was applied. It considers the resulting effect between gravity and flow dragging, which is directed towards the channel, then producing the deposit of sediments on the bed. Equation 11 expresses this:

$$W = (h_2 - h_1)\sqrt{\frac{S_b}{\pi\,(1-n)\,\mathrm{tg}(\Phi)}}\left[\sqrt{t-t_0} - \sqrt{t_0}\right] \qquad \text{Eq. 11}$$

Where,

W represents mass transported from banks to channel, every m of length, over a period of t seconds. (kg/m)

h2 channel depth (m)

h1 depth at the outer channel

Sb Bed load. In order to calculate this value, equation 9 is used to estimate bottom concentration and then we assume that transport happens at a distance equal to roughness r previously defined (K/m/s)

n porosity

Φ dynamic angle of friction (usually 25°)

t time in seconds

$$t_0 = \frac{\pi}{64}\frac{(h_2 - h_1)(1-n)\,\mathrm{tg}(\Phi)}{S_b\,\mathrm{tg}^2(\beta)}$$

β angle of channel´s side slope

Although this calculation method has been derived for a certain flow aligned with the channel, its author states that it can also be used in cases where flow forms a narrow angle with the channel´s alignment. In such cases, Sb is multiplied by a factor equal to the angle´s cosine.

When analyzing equation 11, it can be noticed that it is a non linear function on time. That is to say that if the intention is to calculate sedimentation after a year, the equation does not reach the same results either the results of two semesters are added or the results of a whole year is calculated. The main reason for this difference is that the calculation algorithm supposes a progressive overfilling of the channel bed. This overfilling lowers the side slopes, and this tends to lower sedimentation due to gravity forces. In this way, if the channel is not modified, sedimentation after a year period (i.e. two semesters) is not two times sedimentation for a single semester.

For this reason it is important to consider the period of time during in which the channel is not modified when calculating settled sediments, that is to say, the period of time between maintenance dredging works that re-shape side slopes.

4. APPLICATIONS OF THE MODEL

The model was finally developed by compiling all the equations previously mentioned (considering many previous sedimentation studies that had been carried out before, with successful results, in order to know that those equations were applicable) and combining them with the special design of a graphical user interface.

4.1 Implementation and validation process

One of the first applications that had great importance were the Feasibility Studies for the Deepening Project of Punta Indio, Canal Intermedio, Banco Chico and Rada Exterior Channels.

These studies were carried out over more than 200Km of existing channels, and the main objective was to estimate the expected sedimentation volume that would occur once the channels were deepened. However, in regards to the model, a detailed previous work of adjusting and validating the model had to be done, in order to get the tool ready for the job, so many historical dredging registers were gathered, in a way to have true data to check simulation results.

In this way, the first part of the project included a series of hydro-sedimentological simulations of the 1998-2004 period in which data was available, and the consequent calculation of sedimentation volumes for the existing channels. The following figure depicts the full extension of the studied area.

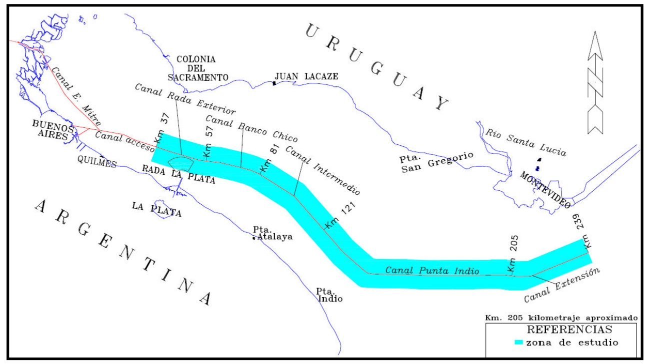

Figure 2: Location of first application of the model.

These simulations were also possible by using a calibrated hydrodynamic model of the entire Rio de La Plata river, configured also by EIH, in order to get the currents and level conditions, necessary to input the model. Added to that, other previous field studies carried out by Freplata in 2001 (SOHMA) and Hidrovia SA were gathered, in order to have an acceptable amount of sediment samples along the studied area. More than 100 samples were analyzed and sectioned along the studied channels, to identify the parameters needed to input the model.

The implementation of the sedimentological model was very satisfactory, achieving accurate results that made it possible to extend studies and estimate volumes likely to settle once the channels were deepened, and that would represent future maintenance dredging works.

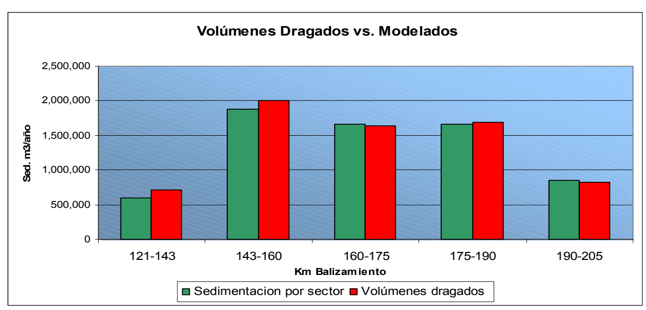

Figure 3: Comparison between modeled results and dredging records.

Fortunately, many other applications, in the whole channel systems present at Río de La Plata were done, also with acceptable results, including Martin García Channels, and other projected and still not executed channels

4.2 Latest application at Magdalena Channel

During year 2014, a new application of the model was carried out, more tan 15 years after its first implementation, taking into account all the satisfactory precedent applications. A new navigation Channel, named Magdalena Channel is projected and all the necessary field studies and the expected sedimentation evaluations were done. With a total length of 61,6 km, the projected channel extends from El Codillo, at Punta Indio Channel, to Beta Zone, in front of Samborombon Bay where natural depths can be found, as it can be seen in the folllowing figure.

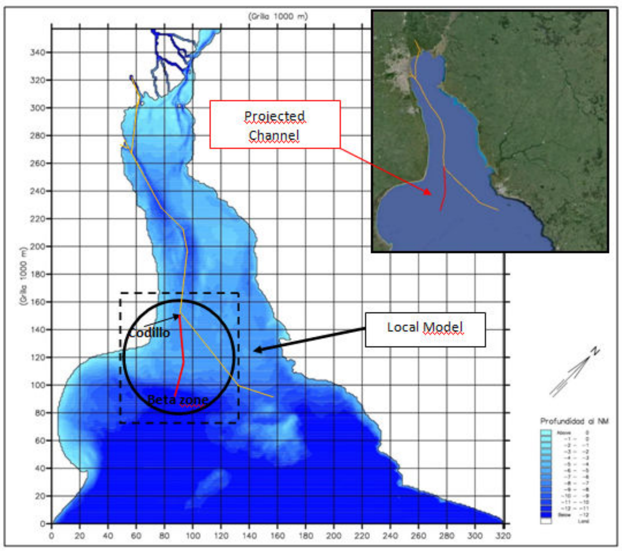

Figure 4: Location of the projected channel.

In the particular case of the model, the aim of the study was to analyze both the channel and the dredged material disposal areas. As for the channels, it was necessary to evaluate the expected volume to be dredged for the projected geometry, and in the case of the disposal areas, the aim was to evaluate impact produced during disposal works.

This application had a new particular characteristic due to the salinity conditions present at the deeper zones. As it has been described before, the Rio de La Plata Estuary is characterized bye the complex behavior of the fluvial regime and a maritime regime. The location of the Magdalena channel makes it necessary to deal with salinity conditions, and the effects of flocculation. In fact, during the field works salinity was one of the measured parameters, in order to analyze salinity conditions.

To estimate the effect of flocculation on the suspended sediment size distribution in the Magdalena Channel, a flocculation model based on the equations described in Xu, 2009 was coupled to the sedimentation model. Xu uses the model of turbulence-induced growth and breakup of flocs as described in Winterwerp, 1998, which determines an equilibrium floc size. Xu expanded on this approach to model the distribution of suspended sediment flocs into different sized bins.

Aggregation (growth) of flocs in the model is caused by collisions between particles caused by turbulent shear and the differential settling rates of different sized particles. When two particles collide to form a larger particle, their masses are removed from the original size bin and added to the newly-formed particle’s size bin. Breakup of flocs is a function of shear rate and floc size. The model assumes that a floc is broken into two equal parts, so the mass of the original floc is removed from its size bin and added to the bin equal to half of its size. This model was run until an equilibrium condition was reached, at which the mass in each size bin changed by less than 0.1% in one time step. Several scenarios were run with this model to simulate the conditions in the Magdalena Channel.

The suspended sediment concentration used in the model was determined by the data from the superficial suspended sediment concentrations measured in samples. Then two representative concentrations were used in the model: an average value, and the maximum value. Also, a representation of the suspended sediment particle size distribution in the Channel was determined using also the data from, resulting in 23 size bins ranging from 1 μm to 200 μm that were used to cover the majority of the particle sizes represented in the available samples. The model was run using velocities of 0.05, 0.35, and 0.85 m/s, representing low, average, and high velocities found in the channel. Also depths of 6, 8, and 10 m were simulated, representing the range of depths found in the channel. Finally, several simulations were done using different combinations of the values described above. The last part is to couple this model to the sedimentation one, by adapting the new size distribution and percentages of each size, in the sedimentation module.

5. CONCLUSION AND FUTURE DEVELOPMENTS

In conclusion, the developed tool has shown to be well suitable for specific environments as the Rio de La Plata, mainly characterized by the specific type of fine and very fine cohesive and non cohesive sediments and the permanent tendency to sedimentation in navigation channels. Added to this, it has been proved that many of the available and widely used tolos are sometimes non suitable for specific conditions and can have misleading results.

At present, EIH is working to develop an updated version of the tool, in which two new aspects will be incorporated. On the one hand, the possibility of automatically including the effects of salinity and flocculation, and on the other hand, the capability of having a three dimensional analysis with different layers.

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