A CONTRIBUTION TO THE NUMERICAL MODELLING OF DAM RESERVOIR SILTATION CYCLES

M. Bessenasse[1], A. Paquier[2], A.S. Moulla[3]

[1]Saad Dahlab University, P.O. Box 270, Soumaa, Blida, Algeria. E-mail: mbessenasse@yahoo.fr
[2]Irstea, UR HHLY, Hydrology Hydraulics Research Unit, 3 bis quai Chauveau CP 220, 69336 Lyon Cedex 09, France. E-mail: andre.paquier@irstea.fr
[3]Dating & Isotope Tracing Dept., ANRC, P.O. Box 399 Alger-RP, 16000, Algiers, Algeria, E-mail: asmoulla@gmail.com

ABSTRACT

In Algeria, catchment erosion and siltation rates are high enough to significantly reduce the water volumes that can be used for reservoirs. The total capacity of the dams managed by the National Agency for Dams and Water Transfers is estimated to be 6.2 Bm^3 while the silted volume is estimated at 700 Mm^3, which is about 12%. A numerical model that can simulate the deposition in a reservoir as a function of the hydrologic regime is detailed. Flow propagation and sediment deposition rely on two dimensions shallow water equations coupled to an advection-diffusion equation for suspended sediment transport. The model was applied to Zardezas reservoir located in Northern Algeria for the period from 1975 to 1986. Because of a lack of some data, the sediment inputs were defined using a simplified way while the water inputs are estimated from the peak flow discharges of the main floods and the daily discharges. The calculated elevation of the reservoir bottom reflects a correct trend although some details cannot be simulated. Then, one can plan using this model for reservoir management or for the design of new reservoirs.

Keywords: Reservoir siltation, Numerical model, Dam, Shallow water equations, Algeria.

1. INTRODUCTION

In Algeria, catchment erosion and siltation rates are high enough to significantly reduce the useful volumes of dams. The water mobilisation potential represented by reservoirs decreases by 40 Mm^3 yearly which is considerable. The total capacity of the dams managed by the National Agency for Dams and Water Transfers is estimated to be 6.2 Bm^3 while the silted volume is estimated at 700 Mm^3, which is about 12%. This issue is one of the main problems that water policy makers and particularly dams' managers have to face in Algeria (Ouamane, 2009). Therefore, the survey of the silting process is crucial for assessing its intensity and for defining later on the right actions that should be implemented in order to minimize the siltation risk. One specific issue is the choice of the most appropriate sites for new reservoirs. The overall analysis of the watershed inputs helps to determine the quantities of sediments that are susceptible to enter the reservoir. A mathematical model for simulating the deposition in a reservoir is a complementary tool that could help assessing the quantities actually deposited. Such a tool can also help to define the management of the gates and more generally the management of the water cycle in the reservoir in order to minimize long term deposits.

A numerical model for sediment transport is usually defined as the combination of two modules:

1. The first module allows the calculation of the water depth, the flow rate and the flow velocity in each calculation cell for each time increment:
2. A sediment transport module that:
   - Ensures sediment mass conservation,
   - Simulates sediment deposition and erosion using either empirical deposition or erosion equations or using an empirical sediment transport capacity equation

Then, a sediment transport's numerical model aims at calculating the water volume variation and the elevation of a reservoir's bottom as a function of time. These models should be based on unsteady equations of water and solid materials motion and continuity. In recent years, several authors have proposed models with increasing complexity.

Among existing models, it is necessary to distinguish between the following:

- Budget models which either are one-dimensional and typically assimilate and consider solid flows as strong deformations of the bed (Latapie, 2011) or are based on an empirical equation for trapping efficiency of reservoirs (Tamene et al., 2006),
- One-dimensional (Bouchard, 2001) or two-dimensional models (Paquier et al., 1999) based on shallow water equations (liquid phase) as well as on the laws of convection-diffusion (solid phase),
- Three-dimensional models based on the Navier-Stokes equations (liquid phase) considering Eulerian (the solid phase is accounted for as a concentration) or Lagrangian (dynamic equation for the solid particles) transport (Olsson et al., 2011).

Budget models are not appropriate to the event's scale that would enable one to explain the fine particles transit. They estimate the long-term evolutionary trends of reservoir beds as a function of their bed load. Due to their degree of sophistication, other models are more or less adaptable to the studied specific cases. They separately calculate the laws of erosion-deposition and can independently deal with the specific theological behaviour of giving deposits. The design of a whole and complete sedimentation model for a reservoir would require a three-dimensional mathematical representation of water flow and sediment transport. However, such models can be considered to still remain in the state of research only (Rüther et al., 2010).

The conception of a numerical model for predicting the formation and the evolution of fine deposits in a reservoir requires a critical analysis of available data. Its reliability with respect to the accuracy of the expected results needs also to be investigated (Bessenasse et al., 1998).

The required data depend essentially on the chosen model and on the accuracy the latter is able to achieve. In general, there are two types of information to be dealt with: the topography (or bathymetry) of the bottom, and the data about liquid and solid inputs (bed load and suspended sediments). The second type of data can be directly collected from in-situ measurements at a point in the hydrographical network. However, it could be also the result of a more comprehensive analysis of the catchment area (distributed hydrological models or synthetic suspended sediment hydrographs).

The whole model must meet the following three criteria:

1. Be able to give an operational response for reservoirs that undergo siltation. In other words, the result should be easily and fairly immediately made available to be used repeatedly in order to enable the comparison of management strategies for the future.
2. Be adaptable to various locations in which different levels of information are available. In the Algerian context, only a few reservoirs have enough records and data or will be surveyed in a way to record sufficient data and observations that would enable accurate modelling to be performed.
3. Take into account in a sufficiently flexible way the exchange between moving particles and the bed of the reservoir.

Three-dimensional models require a detailed topography and a rheological characterization of sediments through the different phases of deposition. In addition, exchanges of particles between the liquid phase and the bottom are not yet fully described even on a theoretical level. As a consequence, such a model is too much time consuming for the accuracy that can be expected in the Algerian operational context.

A two-dimensional model giving a horizontal field of depth-averaged velocity at any point of the reservoir allows one to determine the location of deposits as soon as a term expressing the exchange with the bed is defined. This term would include a representation of the vertical concentration profile for water as well as the definition of the various layers deposited at the bottom of the reservoir. Its use remains demanding especially in cases where sufficient and detailed data are not available.

The vertical two-dimensional models and one-dimensional ones do not provide information on the lateral transfer, which in many cases (e.g. Channelization), can make the use of such models unsuitable.

Consequently, we have chosen to conceive and work with a model of the (horizontal or depth-averaged) two-dimensional kind that appears the most general use convenient in the Algerian scope.

The present paper details at first instance the theoretical model used, then the model is applied to Zardezas reservoir, finally, the results of the model for Zardezas dam are discussed.

2. THE THEORETICAL MODEL

2.1 Description of the Two Dimensional Model

Water depths and velocities are obtained from the resolution of the two-dimensional shallow water equations whereas sediments are represented by a concentration that obeys a convection-diffusion law.

The system of equations to be solved is as follows (Paquier, 2010):

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=0 \quad \textbf{(1)}$$

$$\frac{\partial (uh)}{\partial t}+\frac{\partial (u^2h+g\frac{h^2}{2})}{\partial x}+\frac{\partial (uvh)}{\partial y}$$

$$=-gh\frac{\partial Z}{\partial x}-g\frac{u\sqrt{u^2+v^2}}{K^2{}_s h^{1/3}}+D(\frac{\partial}{\partial x}(h\frac{\partial u}{\partial x})+\frac{\partial}{\partial x}(h\frac{\partial u}{\partial y})) \quad \textbf{(2)}$$

$$\frac{\partial (vh)}{\partial t}+\frac{\partial (uvh)}{\partial x}+\frac{\partial (v^2h+g\frac{h^2}{2})}{\partial y} \quad \textbf{(3)}$$

$$=-gh\frac{\partial Z}{\partial y}-g\frac{v\sqrt{u^2+v^2}}{K^2{}_s h^{1/3}}+D(\frac{\partial}{\partial y}(h\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(h\frac{\partial v}{\partial y}))$$

$$\frac{\partial (Ch)}{\partial t}+\frac{\partial (huC)}{\partial x}+\frac{\partial (hvC)}{\partial y}=\frac{\partial}{\partial x}(hD_x\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(hD_y\frac{\partial C}{\partial y})+E \quad \textbf{(4)}$$

Where E is the sum of the rates of erosion and sedimentation,
C the concentration of suspended particles (kg/m^3),
D_x & D_y the dispersion coefficients in the x and y directions (usually set equal to *D*),
u et v the velocities in the *x* and *y* directions,
h the water depth,
Z_b the bottom elevation,
g the gravity,
D a diffusion constant
K_s The (Manning) Strickler friction coefficient

This suspended sediment modelling classical approach involves the definition of laws of exchange between the particles in the liquid phase and those present on the bottom (deposition and re-suspension). But it must also take into account the evolution of deposits (consolidation).

The current model has been designed based on Cemagref Rubar 20TS hydraulic software (Cemagref, 2001) that uses a finite volume explicit scheme. This software is able to perform a calculation for nearly any hydraulic conditions (e.g. for floods arriving in an empty reservoir). The resolution of the convection-diffusion equation is based on a numerical scheme of the same type (Van Leer-type second order finite volume scheme) (Van Leer, 1979).

In the case of erosion, one can assume that at very low concentrations, suspended particles would be transported without settling. Conversely, at high concentrations, there would be a deposit that should be proportional to the concentration C such that:

$$E = -\alpha w_s (C - C_e) \quad \textbf{(5)}$$

- C_e equilibrium concentration
- α calibration parameter (m/s)
- w_s the sediment particle falling velocity.

2.2. Calculation of the Equilibrium Concentration

The calculation code Rubar 20 offers the choice for calculating the equilibrium concentration. To do so, we have chosen the use of the Van Rijn method that is detailed below.

This method is based on (Van Rijn, 1984) in which this scientist defines the transport parameter T

$$T = \frac{(u'_*)^2 - (u_{*,cr})^2}{(u_{*,cr})^2} \quad \textbf{(6)}$$

Where: u'_* is a friction velocity that is specific to the grain and calculated from a Chézy coefficient related to grains *C'* given by:

$$C' = 18 \cdot \log \cdot \left(\frac{12 \cdot R_H}{3 \cdot d_{90}} \right) \quad \textbf{(7)}$$

Where R_H represents the hydraulic radius of the considered section and d_{90} the diameter of the particle for which 90% of the mass has a smaller diameter.

$$u'_* = \frac{\sqrt{g}}{C'} \sqrt{u^2 + v^2} \quad \textbf{(8)}$$

Van Rijn then suggests the calculation of a reference concentration at the bottom. However, as the bottom is not smooth due to the grains' presence, the reference is suggested to be recorded at a head 'a' such as:

$a = k_s$ with a minimum $a_{min} = 0.01 \cdot h$

With: k_s being the roughness of the bed.

The concentration in head *a,* would thus be equal to:

$$C_a = 0.015 \cdot \frac{d_{50}}{a} \cdot \frac{T^{1.5}}{D_*^{0.3}} \quad \textbf{(9)}$$

Where: $$D_* = d_{50} \left[\frac{(s-1)g}{v^2} \right]^{1/3}$$

d_{50} is the median sediment diameter, s: the sediment density and ν: the water viscosity.

Sediment transport is also described by the Z parameter, which is the ratio between downward gravitational forces and upward turbulence forces:

$$Z = \frac{w_s}{\beta \cdot k \cdot u_*} \tag{10}$$

β is a coefficient that is related to the diffusion of particles: $\beta = 1 + 2\left[\frac{w_s}{u_*}\right]^2$ **(11)**

k, is Von Karman constant. It is in fact a function of the head averaged concentration, the particle falling velocity and the critical friction velocity. These effects are taken into account by introducing φ:

$$\varphi = 2.5 \cdot \left[\frac{w_s}{u_*}\right]^{0.8} \cdot \left[\frac{C_a}{C_0}\right]^{0.4} \tag{12}$$

With C_0 = 0.65 (maximum concentration)
Then:

$$Z' = Z + \varphi$$

By putting:

$$F = \frac{\left[\frac{a}{h}\right]^{Z'} - \left[\frac{a}{h}\right]^{1.2}}{\left[1 - \frac{a}{h}\right]^{Z'} [1.2 - Z']} \tag{13}$$

One will finally end up with an equilibrium concentration as follows:

$$C_e = FC_a \tag{14}$$

2.3 Principles of the whole theoretical model:

The two-dimensional model requires that the user defines its initial conditions and its boundary limits.

a) Initial conditions

These conditions are the following:

1. Initial head or water head.
2. Flowrate or water velocity.
3. Concentration.

b) Boundary limits

These limits are as follows:

1. Calibration law at the downstream of the dam (in order to model the discharges through the spillway and the sluice gates).
2. The flood hydrograph, either from the recorded data or derived from the QdF method (flow-duration-frequency) to represent typical floods. Owing to its appropriateness for watersheds located around the Mediterranean region, the adopted QdF model is that of Florac. This is indeed applicable for a watershed located in northern Algeria.

Both typology and the concept of the hydrological regime are essential and should prevail when trying to apply the model. The definition of the hydrological regime and most particularly the duration of the floods have enabled us to complete some hydrographs for which only the peak flows and/or the daily flow rates were available.

3. APPLICATION TO ZARDEZAS RESERVOIR

Zardezas dam is located on the wadi Saf Saf, near Skikda in the eastern part of Algeria, 40 km from the sea (figure 1). The upstream basin area is 345 km^2. The mean annual water input is 45 Mm^3. Zardezas reservoir had initially a capacity of 34 million of m^3 but presently it has been reduced to half of that figure namely: 17 Mm^3.

Let us try to simulate the sedimentation cycle for Zardezas dam. The adopted principle is simple. It consists of coupling a series of floods with their concentrations to the hydraulic module namely Rubar 20 developed by Cemagref and then observing the volume of deposit sediments after a given duration of time. Having data on bathymetry for two different years 1975 and 1986, we thought it would make sense to take 1975 as a reference year and 1986 as a result of the calibration of the model.

Taking 1975 as a reference, we would input all the floods that were recorded between 1975 and 1986 with their respective concentrations. From there and on, we would have a new configuration for the bottom of the riverbed. At this point, we will be able to compare the geometry of the bed found through the simulation, and the real recorded bathymetric data. Doing so would allow the validation of the model.

Fig. 1: Geographical location of Zardezas dam in Algeria.

3.1. Test of the Hydrodynamic Modelling: Effect of One Single Flood

In order to achieve the modelling for the time period 1975-1986, the required different tasks are the following:

1. Make a detailed description of the topography of the river (figure 2) that feeds the reservoir along the various cross-sections for the two years (1975 and 1986).
2. Proceed with the complete meshing of the reservoir.
3. Establish a calibration rule that accounts for the total volume of water discharged through the dam from both the spillway and the sluice gates.
4. Review in detail the hydrological regime, i.e. by focusing on the majority of floods that are likely to input significant volumes of water and sediment.
5. Identify and deal with the different levels of water that was stored in the reservoir throughout the study period on a monthly basis (1975-1986).

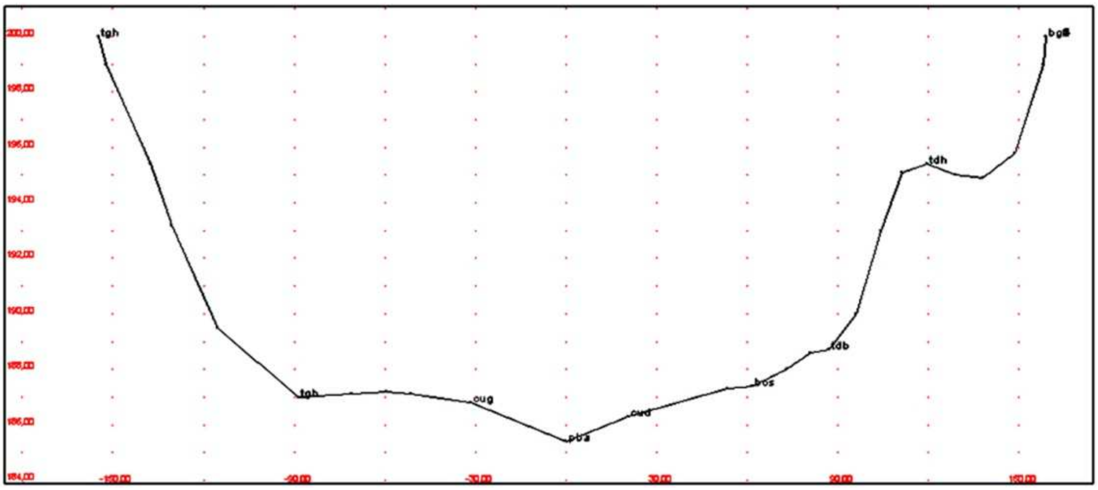

Fig. 2: Typical upstream section in Zardezas reservoir

Initial conditions and boundary limits:

The dam is equipped with five sluice gates whose bottom is located at elevation Z_c=181 m. The central one has on its upper part, a spilling component that may be operated when required in order to evacuate flood.

In order to model this hydraulic structure, we have chosen a classical law for the gates and the following one for the spillway, expressed by:

$$Q = \mu \cdot S \cdot \sqrt{2 \cdot g(Z_o - Z_c)} \cdot \quad \textbf{(15)}$$

We then get the calibration law such as illustrated in the table 1 below:

Table 1: Calibration law

Z_0 (m)	180	181	190	194	199	199.03	199.14	199.42	199.68	200.08
Q (m^3/s)	0	0	0.74	0.89	1.049	2.0508	11.054	51.062	200.75	201.16

Furthermore, given the heterogeneity of rainfall in the region and in order to determine the upstream boundary limits and initial conditions, we were not able to reconstruct the whole precipitation history, which seems much too long. Then, we choose a few representative floods to work with. The representative floods are provided by means of a QdF method based upon probabilities. Nine representative floods whose properties are presented below (Table 2) were then modelled using the two dimensional hydrodynamic model:

Table 2: Simulated floods characteristics

Flood	Q_0 (m^3/s)	Q_p (m^3/s)	Z_0 (m)	C (kg/m^3)	D_u (h)
1	10	105	188	10	48
2	10	105	193	10	48
3	35	200	188	5	24
4	35	200	188	10	24
5	20	160	188	20	48
6	20	160	194.5	10	48
7	20	210	191.56	10	48
8	40	370	194.18	10	48
9	157.5	157.5	195	10	48

Where:

- Q_0: Initial flow rate
- Q_p: Peak flowrate

- Z_0: Initial water level in the reservoir
- C: Concentration during the flood
- D_u: Duration of the flood in hours

The flowrate evolves with time starting initially at Q_0, to reach the value Q_p after 4 hours. It then decreases to get back to the original rate Q_0 for a flood duration D_u. It is to be noted that we have chosen to use a constant concentration throughout the whole duration of the flood, which is in fact an approximation. Indeed, the concentration generally follows the same law as the flowrate (figure 3), but its signal is recorded either in advance or after a delay with respect to that flow rate.

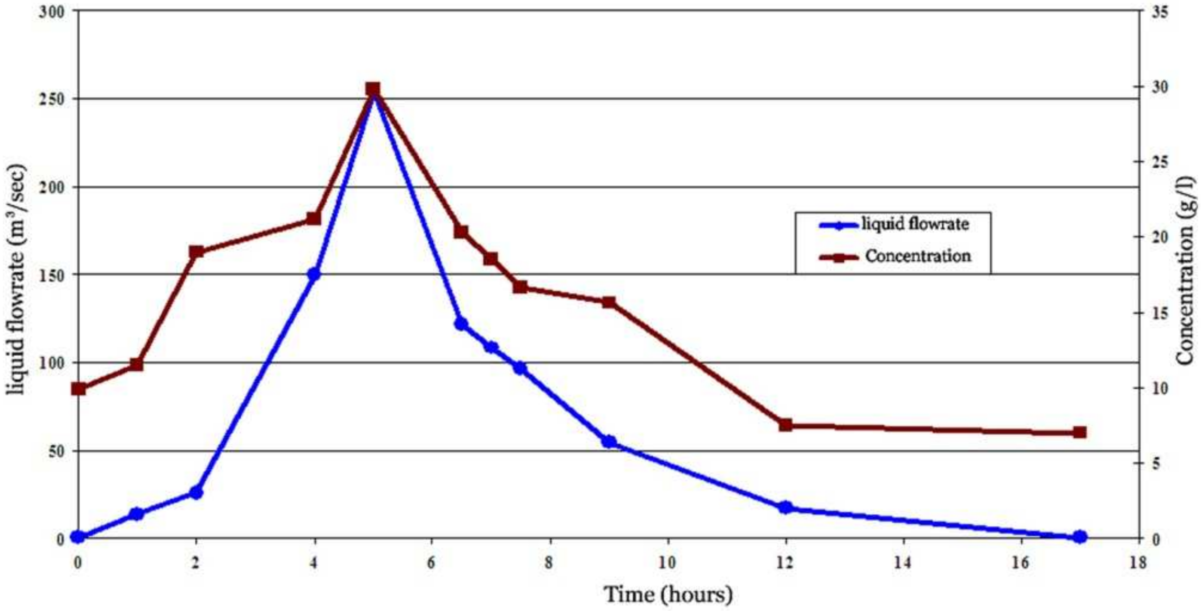

Fig. 3: Measurements recorded during November 3, 1982 flood.

Unfortunately data are not sufficient to extrapolate an equation linking concentration and flow rate.

The obtained water lines (figure 4 for instance) appear to be correct even if the plan view of both the water head and the velocity gradient, reflect a rather complex flow. However, there remain water cells in the mesh that seem to be disconnected from the overall water flow, mainly near river banks and in the right part of specific section No. 15 (figure 5). These are thought to result from an inappropriate definition of the initial conditions for which there is water in the right part.

From these results, it clearly appears that it is preferable to define the initial conditions at a given water elevation in the minor riverbed and to simulate the whole period as one single run to avoid problems at initial conditions.

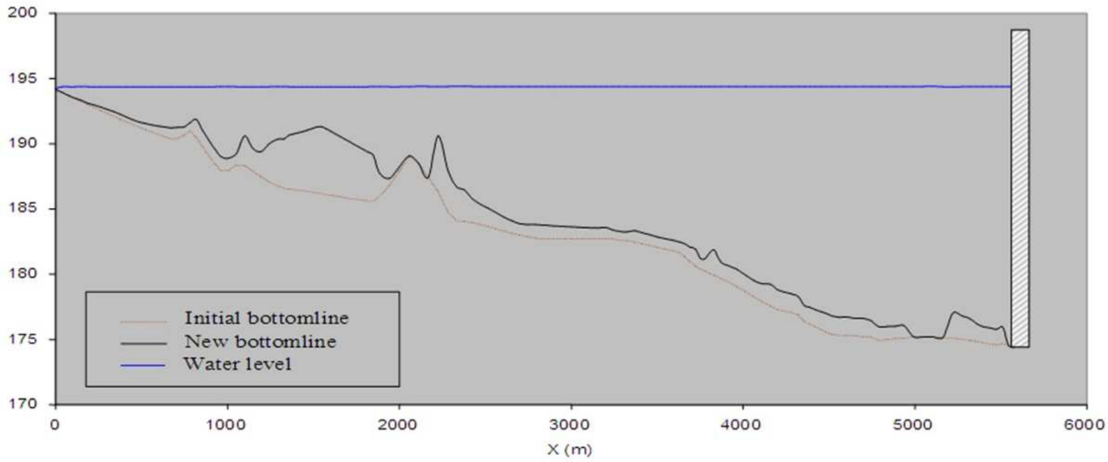

Fig. 4: Longitudinal profile (flood No.1)

3.2. Hydrodynamic Modelling of the period 1975-1986

For the sake of obtaining more reliable results, the meshing was simplified and the calculation was then repeated for an entire period of time.

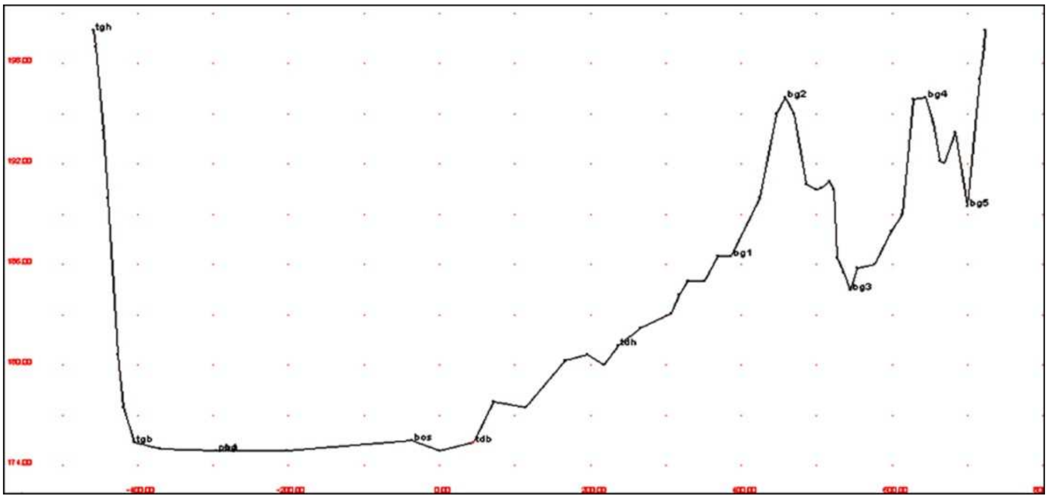

Fig. 5: Specific downstream section No.15 in Zardezas reservoir

3.2.1 Definition of the Inputs for the Calibration of the Simulation

To simulate for the whole 1975-1986 period, the use of ‘realistic’ hydrographs thought to best express the field observed events was preferred. However, except for some cases full details of site recorded hydrographs were lacking. Consequently, such hydrographs were reconstructed using data collected from recorded peak flows and mean daily discharges on the basis of 24 hour multiples flood durations. Finally, we ended up with the flood results (one flood per year on average) for the whole period 1975-1986 as illustrated in Table 3 below.

The deposited sediments are relatively coarse (sands and silts), but their characteristics vary widely over the whole extent of the reservoir. In addition, the general trends of their evolution are not clearly identified. It was therefore decided to use only one grade of sediment whose average evolution was estimated based on a d_{50} of 0.1 mm, a d_{90} of 1 mm and a deposit porosity of 50%. Suspended matter concentrations are estimated from available information and may reach a maximum value of 140 kg/m^3.

Table 3: Simulated floods characteristics (version 2)

Date	Peak flowrate (m^3/s)	Duration (days)	Initial elevation Z_0 (m)
November 18, 1976	95	1	190
April 16 1979	108	3	190
September 12, 1979	127	1	194
March 6, 1980	56	1	190
September 11, 1980	236	1	189
March 7, 1982	53	3	192
November 3, 1982	255	1	190
November 11, 1982	147	2	190
February 3, 1984	996	2	192
December 30, 1984	759	6	186
March 8, 1985	266	3	192

It is to be noted that a clear relationship between flood flow rates and concentrations does not exist. Therefore, a value of 100 kg/m^3 is retained for peak flows and an average of about 50 kg/m^3 is used for flood periods. Such values could also be used to simulate future evolutions. It appears clearly that this parameter is indeed a key-parameter for the simulation. This statement is reinforced by the fact that, when high concentrations are recorded before the peak flowrate occurs, they are followed by a re-deposition of unconsolidated sediments.

3.2.2. Implementation of the Hydrodynamic Model

The boundary limits are in the upstream area: the hydrograph and the concentrations. For the downstream, they consist of a calibration law corresponding to the operation of the dam with sluice gates open.

For the 1975-1986 period simulation, the initial water line is the water level estimated based on the monthly records of floods arrival. The initial concentration is assumed to be the equilibrium concentration. This is consistent with the hypothesis of a slow flood event occurrence. For the sake of simplifying the implementation, a single simulation linking the various floods is carried out. This allows having a baseline for each flood which corresponds to a low flowrate (10 m^3/s) with realistic concentrations (10 kg/m^3).

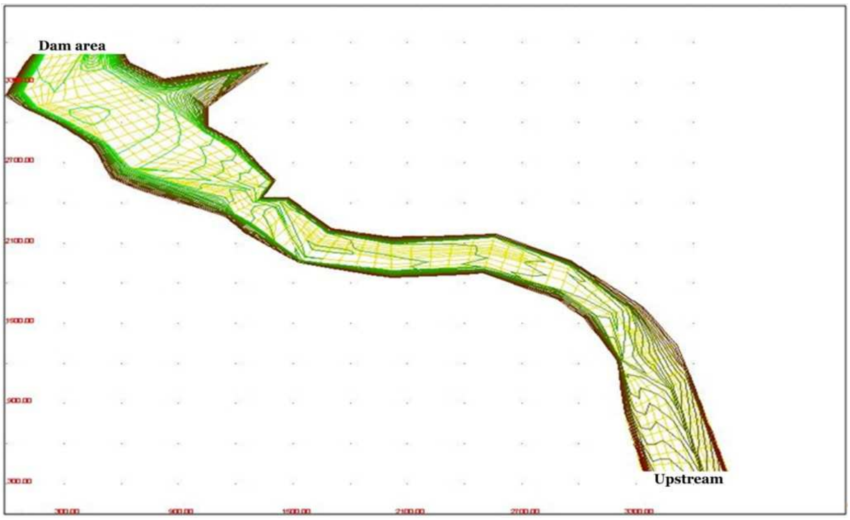

Fig. 6: Mesh for the model and dam topography isolines for 1975.

The time at low flow rate can help to decrease the water level to values close to those actually observed. During these low flowrate phases, releases of sediment are considered virtually nil, which corresponds to the actual situation. The mesh (figure 6) was simplified and consists of only 1005 cells. It is based on profiles across surveys and guidelines joining the most characteristic points of these cross-sections. The cell size varies from 10 to 80 meters. A Strickler coefficient equal to 40 $m^{1/3}/s$ was chosen because of the reservoir bottom topography smoothness that is due to sediment deposition.

4. RESULTS OF THE CALCULATION ON ZARDEZAS RESERVOIR

The α coefficient was taken equal to 0.02, a value that is 10 times lower than the one estimated in previous calculations with Rubar 20 (Paquier, 1999). This is done in order to avoid excessive accumulation of sediment upstream of the investigated area. Figure 7 shows the longitudinal profile after calibration. The calibration has been performed based on this single parameter, as it is presumably considered unchanging with time because it is rather related to sediment features than to another property.

This small value and the remaining underestimate of deposition may be attributed to the inaccurate approximation of the currents intensity in the vicinity of the dam where vertical velocities are not anymore negligible. Moreover, the effect of the not modelled smaller floods, or the influence of particle size can extend the list of other possible causes.

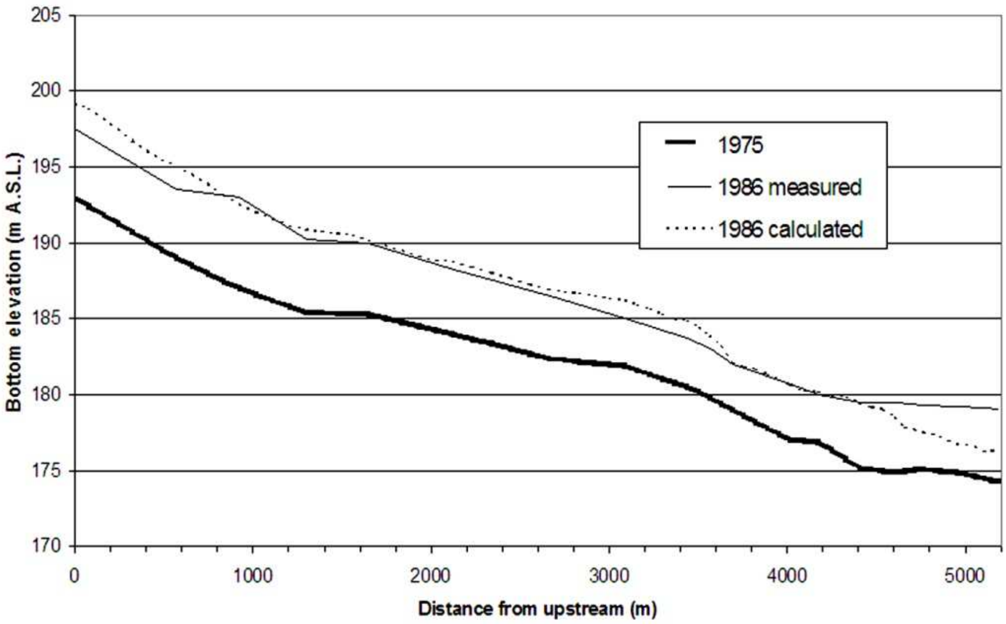

Fig. 7: Longitudinal profile of the reservoir bottom

Figure 7 illustrating a cross-sectional reservoir profile located in the first quarter at 1300 m distance upstream from the dam body, shows clearly that the obtained transverse picture of the deposits is not accurate.

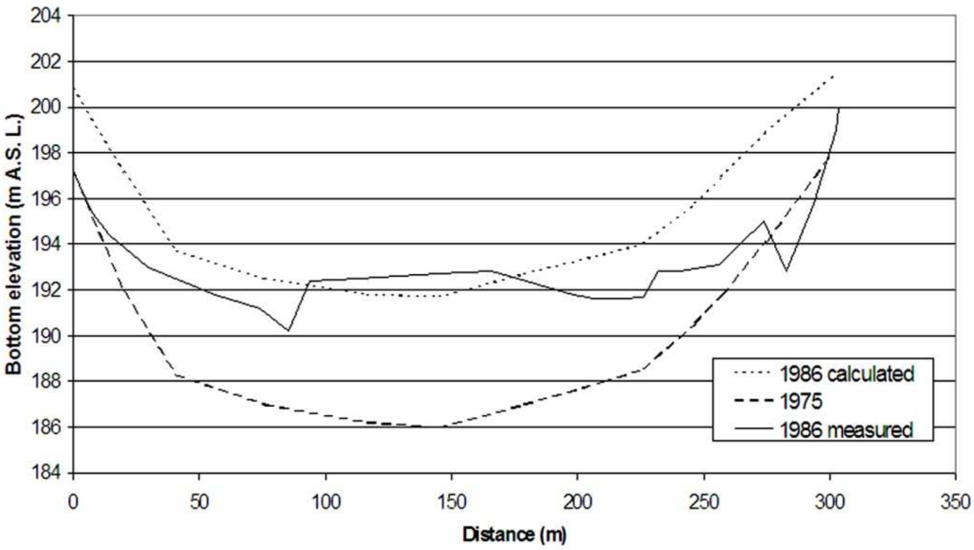

Fig. 8: Transverse profile 1300 m upstream of the dam

In effect, the calculation roughly gives a transversely uniform deposition phenomenon such that except when the branch is cut, the deposit is almost fairly horizontal. That discrepancy could be attributed to the mode of distribution of the deposits within the computer code of the model itself. The latter assumes a uniform distribution within the cell and does not account for the elevation or for the slope. A finer meshing on the reservoir banks and other steep slope areas would partially solve this problem.

5. CONCLUSION AND RECOMMENDATIONS

The numerical simulation performed for Zardezas dam reservoir in Algeria, making use of a two-dimensional horizontal hydraulic model, gave a total volume of deposit sediments that was fairly close to the actual volume measured in the reservoir for 1975-1986 operation time range. With the setting and the calibration of one and unique parameter, this volume could be on average appropriately determined within the reservoir.

The local discrepancies in thickness and in the deposits' distribution are clear evidence of the difficulty inherent in any sediment transport model calibration. It is therefore a requirement to refine the mesh as much as possible in order that it includes and accounts for local topographical singularities and steep slopes banks.

A further research effort is to be devoted to the assessment of the laws of exchange with the bottom for such dam reservoirs. Nevertheless, it is certain that the essential part of the observed uncertainty in the results is mostly due to that of the input

The application of such a proposed approach both for the management of existing reservoirs or for the choice of new dams' potential sites, is technically possible. It would rely on the generation of scenarios consisting of a succession of floods with given return periods. Their input hydrographs would be developed from a synthetic representation of the local hydrology through QdF models and its translation into MFSH (Mono-Frequency Synthetic Hydrographs). These data are supplemented by the assumption of a small change in mean sediment concentration from a major flood to another. This will only make sense if, enough hydrometric data (water and sediment) are recorded upstream, are properly stored and reliably processed. In addition, the validation of the hydraulic model on several existing reservoirs occurring in similar hydroclimatic settings is required for the sake of obtaining better results.

Although our study is based on quite incomplete data sets, we were hopeful to better know how sediment transport operates in its whole and to better understand the different stages of the sedimentary cycle. Another very important point to note is that making use of such a numerical model, it is possible to forecast reservoir sedimentation. As a result of such an informative simulation, one will become able to estimate the useful life of a reservoir.

REFERENCES

[1]. Bessenasse, M., Paquier, A., Ramez, P. and Massart, S. Sediment deposits in a reservoir. Possible methods of estimation and choice. Proc. Annual International Seminar of FRIEND-AMHY group. Annual report No.6 (1997–1998), Istanbul, Turkey, October 1998, pp. 137-144, 1998.

[2]. Bessenasse M. Dépôt des sédiments fins à l'amont d'une retenue, Thèse de doctorat d'état, Ecole Nationale Polytechnique d'Alger, 218p., 2004

[3]. Bouchard J. P. La gestion des sédiments par chasse (2): outils d'optimisation et de prévision d'impact: La Houille Blanche, N°6/7, pp. 62-66, 2001.

[4]. Cemagref (2001) Logiciel Rubar 20. Notice d'emploi. (Technical report) Cemagref, Lyon, France.

[5]. Galéa, G., Prudhomme, C. Notions de base et concepts utiles pour la compréhension de la modélisation synthétique des régimes de crue des bassins versants au sens des modèles QdF. Revue des Sciences de l'Eau, 1, pp. 83-101, 1997.

[6]. Geokert. Expertise de l'envasement de la retenue du barrage de Zardezas. Agence Nationale des Barrages, Alger, 1987.

[7]. Javelle P., Ouarda, T.B.M.J., Lang M., Bobée, B. Galéa, G., Grésillon, J-M. Development of regional flow-duration-frequency curves based on the index-flood method. *Journal of Hydrology*, 258, pp. 249-259, 2002.

[8]. Latapie, A. Modélisation de l'évolution morphologique d'un lit alluvial: application à la Loire moyenne. PhD thesis, Université de Tours, France, 2011.

[9]. Olsson O., Anatoly Sorokin A., Ikramova M. Modelling scenarios to identify a combined sediment-water management strategy for the large reservoirs of the Tuyamuyun hydro-complex. Irrig. Drainage Syst., 25, pp. 1-18, 2011

[10]. Ouamane, A. Dam engineering in Algeria: Progress, needs and prospects. *International Journal on Hydropower and Dams*, 16 (6), pp. 75-78, 2009.

[11]. Paquier, A. Chapter 11. 2D Model of sediment transport with RUBAR 20TS. Environmental Hydraulic Series 5. Modeling Software, ISTE, Wiley, London, GBR, pp. 129-138, 2010.

[12]. Paquier A., Massart S., Krzyk M., Cetina M. 2-D models for suspended sediment transport. Comparative use for the case of Ptuj Lake, XXVIII IAHR congress "Hydraulic engineering for sustainable water resources management at the turn of the millenium", Graz, Austria, 341, 1999.

[13].Rüther, N., Jacobsen, J., Reidar N., Olsen B., Vatne G. Prediction of the three-dimensional flow field and bed shear stresses in a regulated river in mid-Norway. *Hydrology Research* 41(2), 2010.

[14].L. Tamene, L., Park, S. J., Dikau R., Vlek, P. L.G. Reservoir siltation in the semi-arid highlands of northern Ethiopia: sediment yield–catchment area relationship and a semi-quantitative approach for predicting sediment yield. Earth Surf. Process. & Landforms 31, pp. 1364-1383, 2006

[15].Van Rijn L. Sediment Transport, Part II, Suspended Load Transport: *Journal of Hydraulic Engineering*, 110, pp. 1613-1641, 1984.

[16].Van Leer B. Towards the ultimate conservative difference scheme V. A second-order sequel to Godunov's method: *Journal of Computational Physics*, 32, 101-136, 2001.